NUMERICAL SIMULATIONS OF EFFECTS OF LAND SURFACE PROCESSES ON CLIMATE——IMPLEMENTING OF SSiB IN IAP/LASG AGCM AND ITS PERFORMANCE*

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ABSTRACT

This is an investigation of exchanges of energy and water between the atmosphere and the vegetated continents, and the impact of and mechanisms for land surface-atmosphere interactions on hydrological cycle and general circulation by implementing the Simplified Simple Biosphere (SSiB) model in a modified version of IAP/LASG global spectral general model (L9R15 AGCM). This study reveals that the SSiB model produces a better partitioning of the land surface heat and moisture fluxes and its diurnal variations, and also gives the transport of energy and water among atmosphere, vegetation and soil explicitly and realistically. Thus the coupled SSiB-AGCM runs lead to the more conspicuous improvement in the simulated circulation, precipitation, mean water vapor content and its transport, particularly in the Asian monsoon region in the real world than CTL-AGCM runs. It is also pointed out that both the implementation of land surface parameterizations and the variations in land surface into the GOALS model have greatly improved hydrological balance over continents and have a significant impact on the simulated climate, particularly over the massive continents.

Improved precipitation recycling model was employed to verify the mechanisms for land surface hydrology parameterizations on hydrological cycle and precipitation climatology in AGCM. It can be argued that the recycling precipitation rate is significantly reduced, particularly in the arid and semi-arid region of the boreal summer hemisphere, coincident with remarkable reduction in evapotranspiration over the continental area. Therefore the coupled SSiB-AGCM runs reduce the bias of too much precipitation over land surface in most AGCMs, thereby bringing the simulated precipitation closer to observations in many continental regions of the world than CTL-AGCM runs.

Key words: coupled land-atmosphere model (SSiB-AGCM), improved precipitation recycling model, precipitation recycling ratio, hydrological balance, simulated continental precipitation

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I. INTRODUCTION

It has been increasingly recognized that land surface processes are one of the fundamental physical processes and may affect climate by changing. among other things. the overlying hydrological cycle and energy balances. and thus have a significant influence on the local. regional and even global circulation and climate basic characteristics. However. there still exist many uncertainties in the large-scale moisture balance between land surface and atmosphere for climate change. the regional up to global moisture and energy budgets are little known quantitatively. Land was included in earlier global atmospheric general circulation models (AGCMs) with relatively simplistic and largely data-free algorithms. and even ignored. More recently. many of errors. such as water gap. in surface hydrologic parameterizations for climate models may be ascribed to. or otherwise characterized as. the inadequacy in the calculated continental component of water cycle. Both the unrealistic treatments of precipitation. evapotranspiration and hydrological processes over the land masses. and inappropriate formulation for land processes have impacts on the simulated global and regional AGCM climatologies. It is. therefore. imperative to comprehensively understand land-atmosphere interactions over typical continents for more realistic and accurate calculations of the exchanges of fluxes between these two systems: and to improve the current land surface parameterizations (LSPs) for global climate models in order to examine the mechanisms for land surface change on climate and simulate geophysical and biogeochemical processes in AGCMs as realistically as possible.

The initial AGCMs in the late 1960s incorporated very simple LSPs to estimate the hydrologic processes of soil evaporation and surface runoff. The first parameterizations used simple aerodynamic bulk transfer formula and only a few uniform prescriptions of surface parameters over the continents. The most prevalent parameterization for terrestrial hydrology then is "bucket" model. Accordingly. the links and interactions between various land surface nonbiological attributes and climates were widely examined by ways of sensitivity studies conducted with AGCMs. Nevertheless. the simulated results depended on the improvement in the land hydrological parameterizations in AGCMs to a certain degree. Although this approach was not very realistic. it led itself to the development of land surface parameterizations. Consequently. incorporating explicitly plant physiological and biophysical processes in AGCM made significant advances in land surface schemes during the 1980s (Sellers et al. 1986: Dickinson et al. 1986: 1993). A wide variety of the acronym SVATS for surface vegetation atmospheric transfer schemes intended for models. more than twenty. have recently proliferated. Currently. the dynamical framework of the atmospheric models is matured relatively: the perfected extent for models would depend basically on the most appropriate formulation for physical processes. Earlier model intercomparison studies by Cess et al. (1990) and Randall et al. (1992) have. respectively. shown a wide variety of differences between the cloud/radiation and surface energy flux over continents in the prescribed sea surface temperatures. and thus revealed substantial uncertainties in the model. of being most critical issues as to physical processes in AGCMs. It is most likely that land surface processes are one of the most important directions improving the capability of the current models in the next few years (Dickinson 1995). Further major progress should be made in understanding what the most appropriate formulation for land processes in AGCMs is, which is one of the key points for successful climate simulation and studies.

In view of the above, in pursuing the goal of more realistic representation and simulation of moisture and energy cycle for improving current AGCMs, we have incorporated the simplified simple biosphere model (SSiB) (Xue et al. 1991) by treating the vegetation explicitly and realistically into spectral L9R15 general circulation model developed by IAP/LASG, in which the conventional land surface hydrological model is used in earlier version, and established a coupled global land-atmosphere one. The results of SSiB versus noSSiB comparison serve to illustrate the importance of land surface processes in climate system. Further special insight into the mechanisms for the conspicuous improvements in precipitation will be provided by analytic studies with mechanistic models. The model and experimental design are described in Section II. The improvements in the precipitation recycling model are discussed in Section III. The results from control integrations and the impact of land surface processes on the rainfall, the surface water budget, and atmospheric circulation are discussed in Section IV. Some conclusions and discussions are given in Section V.

II. MODEL DESCRIPTION AND EXPERIMENTS

The atmospheric component of the control AGCM (hereafter called CTL-AGCM) in this paper is a modified version of global AGCM developed by IAP/LASG (Wu et al. 1996). The model is spectral, with rhomboidal truncation at wave number 15 (with a resolution of approximately 4.5°lat. by 7.5°long.), and is discretized into 9 vertical levels of which the planetary boundary layer (PBL) may typically occupy three. Sub-grid scale physical parameterizations include mainly an effective K-distribution radiation scheme (Shi 1981), the horizontal and vertical diffusion of momentum, heat and moisture, the convective adjustment scheme (Manabe et al. 1965) and bulk aerodynamic parameterizations. The surface hydrology scheme is represented very simply, only the surface properties (surface roughness, wetness, snow cover, polar ice, etc.) are considered. Unrealistic prescribed roughness and wetness factors over land are still used for simplicity.

The simplified simple biosphere model (SSiB) of Xue et al. (1991), which has replaced the ground hydrology parameterization described above, is used here. SSiB has one canopy layer and three soil layers. The vegetation is treated as "big leaf". Global vegetation distribution is categorized into 11 different biomes in SSiB, comprising: tall vegetation, short vegetation, arable crops, and desert. It has three hydrological soil layers, composing of thin, deep root zone, and gravitational drainage layer of 0.02, 0.2—0.5 and 0.3—2 m. Each vegetation has a type-varying total root depth, and each terrestrial model grid square is the mosaic of surface properties. Lake is not included in the current model. The main sources of data for the distribution of the world vegetation types are the physiognomic classification of Kuchler (1983) and the land use database of Matthews (1984; 1985). There are 23 parameters in SSiB describing the physical and physiological properties of the vegetation and soil, including optical, morphological and physiological properties of the vegetation, as well as thermal and hydraulic properties of the soil. Values for many of these parameters are given in Dorman and Sellers (1989), Willmott and Klink (1986), some seasonally varying monthly values of leaf index, green leaf fraction in Klink and Willmott (1985), and some from the field observations. From the prescribed physical and physiological properties of the vegetation and soil, the model calculates the radiation, transfer of water vapor, sensible and latent heat, the interception and reevaporation of precipitation from plant canopies, the infiltration, drainage, and storage of the residual precipitation in the soil and so on. The model can capture complex moisture cycle between the atmosphere and land quantitatively, especially for biophysical controls of the vegetation. The upper boundary conditions for SSiB are provided by all grid area average values from the lowest level of AGCM. The coupled atmosphere-biosphere model is referred to SSiB-AGCM.

The prescribed seasonally varying climatological SST and sea ice forcing is taken from the Atmospheric Model Intercomparision Project (AMIP) datasets from 1979 to 1988 for all the integrations described here. In the SSiB-AGCM run, the soil temperature on each layer starts from the ground temperature of last day of many years in the CTL-AGCM run. The soil moisture on each layer is initialized with a constant of 0.25 out of tropics and 0.85 within tropics. The water storages on canopy and ground snow cover are both set to zero. There were two runs for ten model years in each set: one with, and one without SSiB in the L9R15 AGCM, and thus the simulations generated by the SSiB-AGCM and CTL-AGCM runs are compared with each other and with observations. In the next sections, we will focus on the analysis of capability of SSiB-AGCM in reproducing the global climate and hydrological balance choosing some basic atmospheric and other variables in July. The corresponding observed figures will not be shown in this paper.

III. IMPROVEMENT OF PRECIPITATION RECYCLING MODEL

The evaporation and precipitation over the land surface are principal components of the global water cycle. However, the precipitation over land is not totally lost through the surface runoff. Rather much of precipitation, which is defined as recycled precipitation, goes back into the atmosphere through continental evaporation, and falls again as precipitation caused by condensation and its attendant formation of cloud due to rising air motion. The cycling precipitation ratio is a diagnostic measure that describes the relative contributions of locally evaporated atmospheric water vapor to total precipitation for a given region and may also be a potentially significant indicator of climatic sensitivity to land surface hydrology.

Budyko and Drozdov (1953) firstly proposed simple one-dimensional approach for estimating precipitation recycling within given regions (commonly called Budyko's model). Brubaker et al. (1993) extended it to a two-dimensional land region and obtained the average recycling ratio for the total area, with the linear assumptions similar to the model of Budyko. Then Eltahir and Bras (1994) developed this model to determine the seasonal and spatial variability of the precipitation recycling by a trial and error technique based on the equations of conservation for the moisture and the observational data. Yi

(1996) applied the linear average of flux terms in the model of Brubaker et al. to the formula of Eltahir and Bras's model and combined both the models. estimated the distribution of ratio over the reaches of the Changjiang River using the observed data.

The models are derived by the prescribed boundary conditions within the land region. We note that the estimation of precipitation recycling ratio is dependent upon the choice of the boundary conditions within the computed area. These estimates for different regions

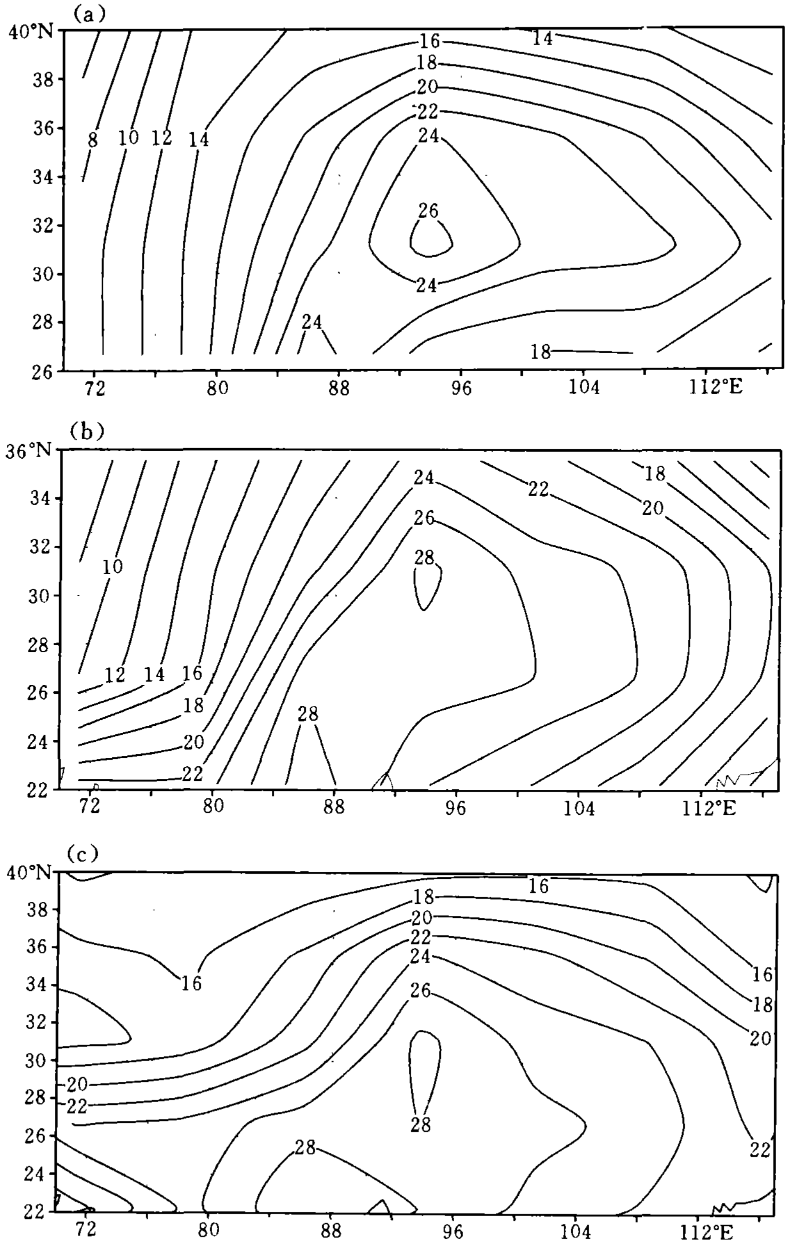

Fig. 1. Spatial distribution of the precipitation recycling ratio calculated by region 1 (a), region 2 (b) from the old model and no boundary (c) from the new model.

selected are shown in Figs. 1a and 1b. It can be seen that these values are obtained differently within the overlying area (i. e. 26 — 36°N) between regions 1 and 2. For example, the value centered at 30—32°N, 92—96°E is 26% for region 1, while 28% for region 2. It seems that the recycling ratio for region 2 is generally 1%—2% larger than that for the region 1, and consequently the solved values are consistently dependent on the prescribed boundary conditions within the region. Besides, the similar results are obtained when various boundary conditions are prescribed within the land region.

Therefore, regions selected would be extended to the total globe and more objective estimation for the ratio would be obtained, avoiding the uncertainty in the prescribed boundary conditions. The modified ratio of recycled precipitation is illustrated in Fig. 1c.

IV. RESULTS

1. *Simulation of July Global Climate*

The surface latent and sensible heat fluxes for July as simulated by CTL-AGCM and SSiB-AGCM with differences (SSiB-AGCM minus CTL-AGCM) are respectively shown in Figs. 2a and 2b. The most significant improvement in the SSiB-AGCM run is noted in the

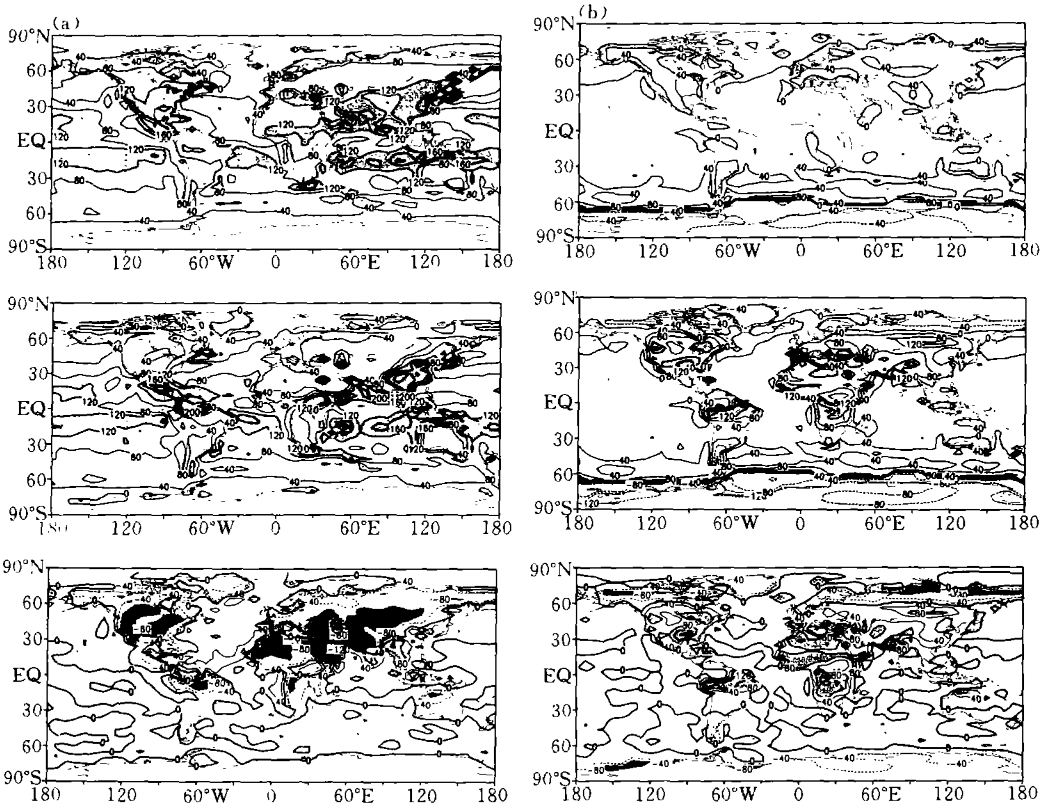

Fig. 2. Global field of mean surface heat fluxes ($W\ m^{-2}$) for July in the CTL-AGCM, SSiB-AGCM simulations for the 1979—1988 period for (a) latent, (b) sensible. Top panel: CTL-AGCM without SSiB. Middle panel: SSiB-AGCM with SSiB. Bottom panel: Differences (SSiB-AGCM minus CTL-AGCM).

reduction in the surface latent heat flux over land regions of the summer Northern. Hemisphere it is above 80 W m^{-2} less over the central regions from the North Africa. West Asia to East Asia. and the North America in SSiB-AGCM than CTL-AGCM. which agrees fairly well with the corresponding observations. In the CTL-AGCM run. however. the surface latent heat flux. which is parallel to that over the tropical oceans. is basically above 120 W m^{-2}over many parts of land regions both of the eastern. southern Asia and the North America. These excessive evapotranspiration rates are mainly conducive to the unrealistically prescribed wetness over continents as well as no resistance of vegetation and surface soil in the CTL-AGCM formulation.

As can be expected. the decrease in the surface latent heat flux presented above is accompanied by a corresponding increase in the surface temperature. thereby producing significantly larger surface sensible heat flux over the continents in the SSiB-AGCM simulations as compared with CTL-AGCM. For example. there are large sensible heat flux at the surface which becomes as high as 120 W m^{-2} in the the Northern Hemisphere over subtropical desert regions. The surface sensible heat fluxes along the coast area of West Africa and North America agree fairly well with the observation. particularly over the Tibetan Plateau. as high as more than 180 W m^{-2}. But the CTL-AGCM simulations produce generally lower surface sensible heat flux over the continents where the sensible heat fluxes as low as 40 W m^{-2} appear over desert regions of North Africa. The differences show that the sensible heat flux is augmented by more than 80 W m^{-2} in the SSiB-AGCM compared with that in the CTL-AGCM over arid and desert regions of the earth.

The improvement in SSiB-AGCM is also striking in the surface temperature simulations (Fig. 3). which the maximum temperature of 35℃ is over North Africa-Arab peninsula. northeastern India in SSiB-AGCM while these maxima can not appear in CTL-AGCM. although the maxima are higher than reality by about 5℃. South of about 50°N. it can be shown from the difference that the surface temperature is generally warmer over the continents in SSiB-AGCM. particularly more than 12℃ over North Africa.

Figure 4 shows that as compared with CTL-AGCM. the SSiB-AGCM simulations improve significantly the sea level pressure in the Northern Hemisphere. For example. both the situation and configuration of the Asian monsoon low are in broad agreement with the observation. with the lack in the northeastward extension of the axis. While both the intensity and configuration seem too strong in the CTL-AGCM run. Meanwhile. the most conspicuous improvement in the SSiB-AGCM run is the configuration of the North Atlantic subtropical high. although the central maximum is about 5 hPa weaker than the observed. But it is even weaker in the CTL-AGCM run. Further studies indicate that some of the increase in the above subtropical high is accompanied by a corresponding increase in the surface temperature over North Africa in the SSiB-AGCM run (Fig. 3). and would lead to increased sensible heating rates ($\partial Q_{SH}/\partial Z < 0$. where Q_{SH} denotes heating rate due to the sensible heat flux) along the western coast area of North Africa during the summer. thereby making not only the low center on the surface but also strong negative vorticity on the upper. Therefore. the subtropical high becomes strong over the ocean on the west side of the continents in consequence of the β-effect (Wu et al. 1999).

Figures 5a and 5b show the precipitation rate for July simulated by CTL-AGCM and

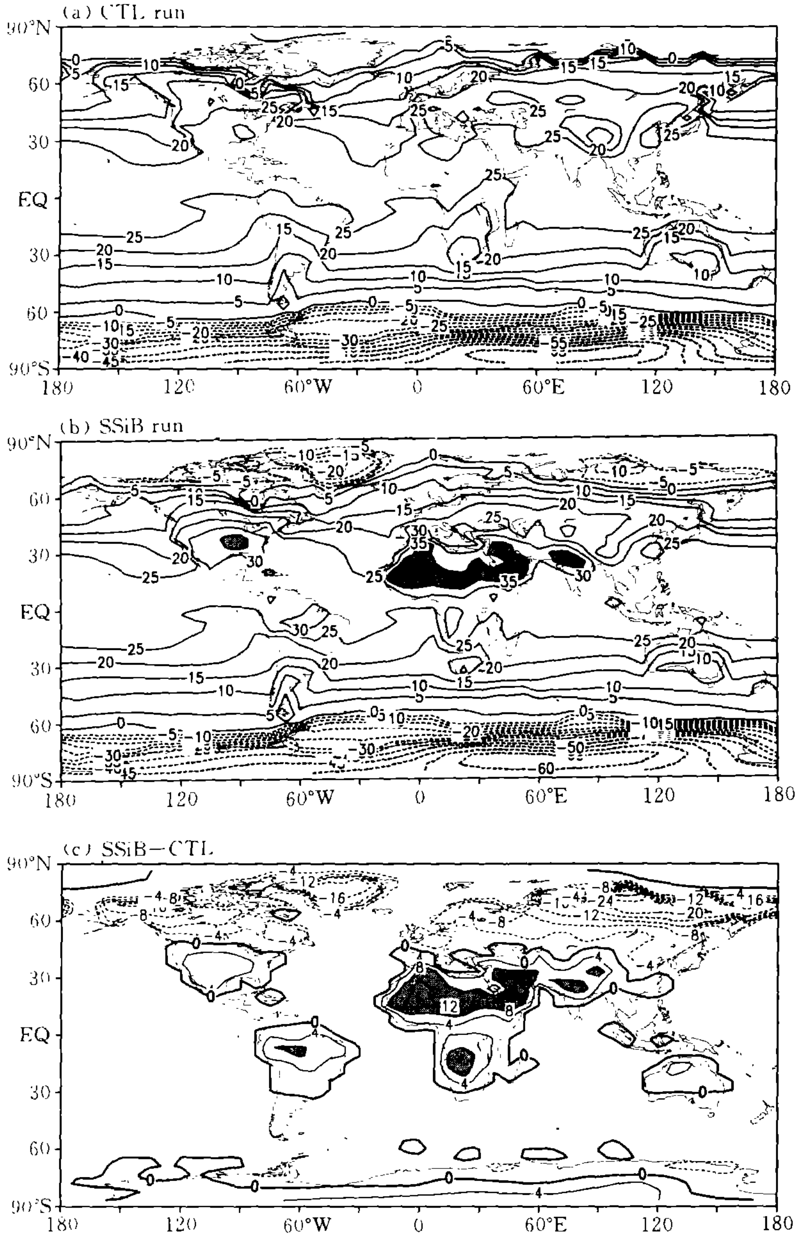

Fig. 3. Global field of mean surface air temperature (°C) for July in the IAP/LASG climate simulations for the 1979—1988 period for (a) CTL-AGCM, (b) SSiB-AGCM and (c) differences (SSiB-AGCM minus CTL-AGCM).

SSiB-AGCM and Fig. 5c the difference between them (SSiB-AGCM minus CTL-AGCM), with the same layout as in Fig. 3, respectively. Generally, the CTL-AGCM field is marked by much higher precipitation rates in most of the humid, vegetated, as well as arid regions. For example, the precipitation rates of more than 2 mm d^{-1} over the equatorialAfrica and Asian monsoon regions are connected together, with larger maxima, and there is also much precipitation, more than 4 mm d^{-1}, in the arid regions over the central, western regions of North America. While there is also much improvement in the

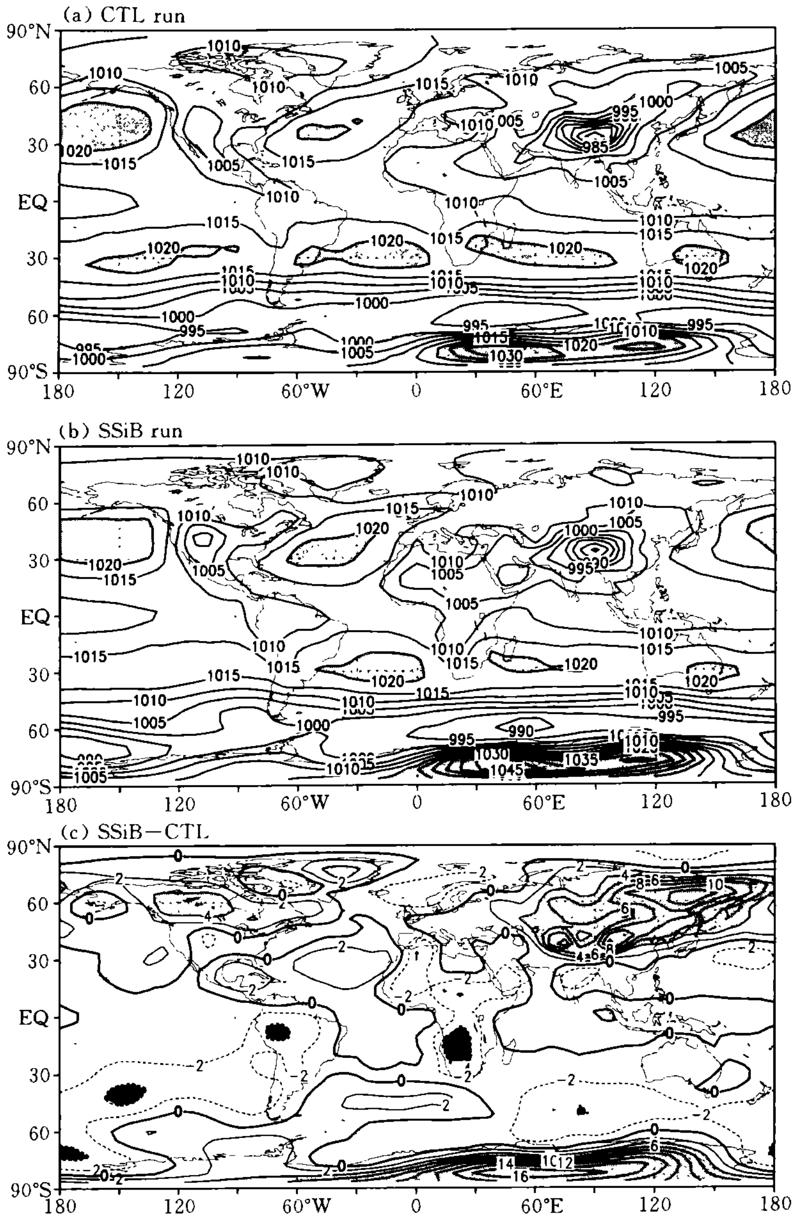

Fig. 4. As in Fig. 3, but for sea level pressure (hPa).

precipitation in SSiB-AGCM relative to CTL-AGCM. The most noticeable improvement is the reduction in the precipitation over land regions of the boreal summer hemisphere. For example, almost the entire area of the contiguous equatorial Africa and the Tibetan Plateau experiences at least a 8 mm d^{-1} decrease, shortfalls over much of eastern North America, northeastern Siberia and Indonesia are generally more than 4 mm d^{-1} too, and consequently making the rainbelt over the Asian monsoon regions and near the equatorial Africa disconnected. The simulated precipitation patterns, more than 2 mm d^{-1}, notably along the eastern China coastal region from SSiB-AGCM are much closer to the observed

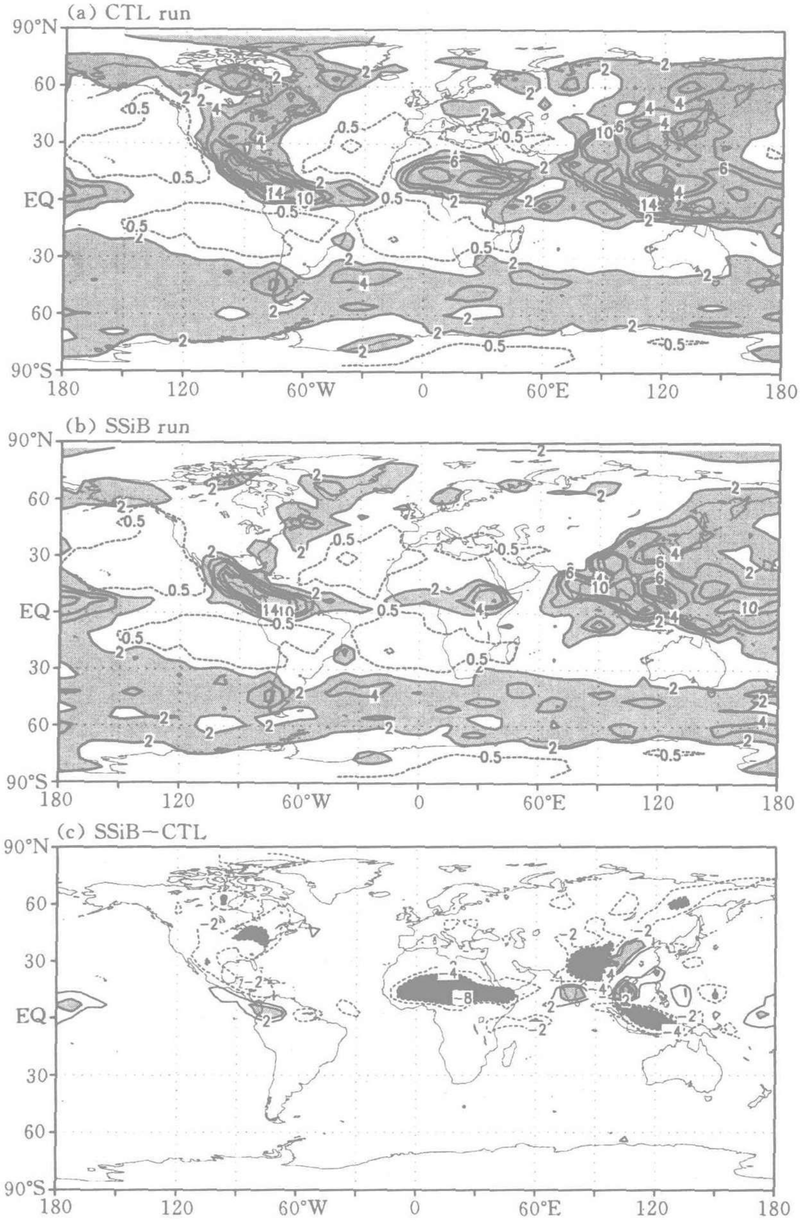

Fig. 5. As in Fig. 3, but for precipitation rate (mm d^{-1}).

summer rainfall. And arid and less precipitation patterns over much of western North America are also in good agreement with the observation. The explanations of the physical mechanisms driving these changes in the SSiB-AGCM run are presented in the following.

The precipitation recycling ratio for July by CTL-AGCM (SSiB-AGCM) is shown in Fig. 6a (6b) with the difference shown in Fig. 6c. It can be seen that the largest precipitation recycling ratio differences (SSiB-AGCM minus CTL-AGCM) appear over land regions of the boreal summer hemisphere. In the CTL-AGCM simulations, not only is there significantly larger ratio for subtropical arid regions, but the CTL-AGCM also

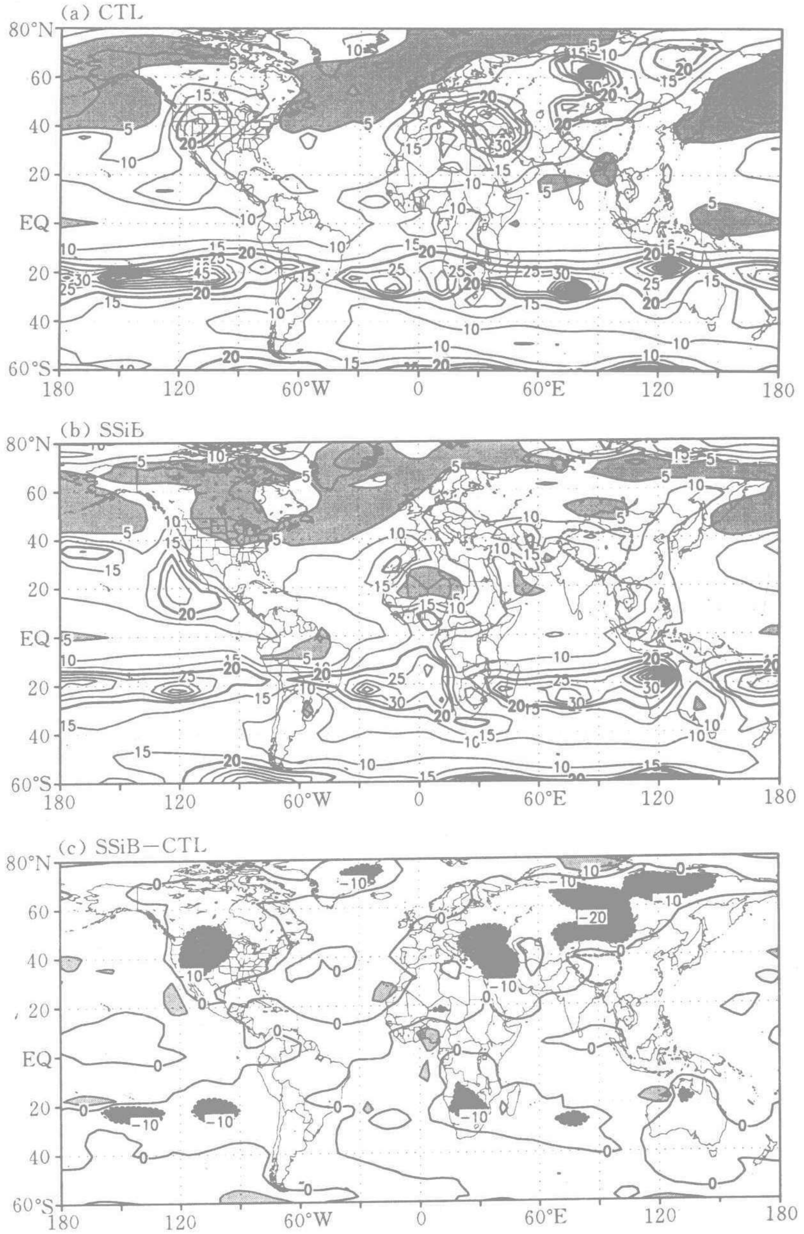

Fig. 6. As in Fig. 3. but for recycling precipitation ratio (%).

produces excessive recycled precipitation over regions of the middle and high latitudes. For example, the ratio is as high as 20%, even 60% over much of Siberia in CTL - AGCM (Fig. 6a). Whereas the precipitation recycling ratio over above regions is generally reduced by 25% in SSiB-AGCM. This is best illustrated by the difference field in the bottom panel of Fig. 6c. Except for the Asian monsoon regions, the precipitation recycling ratio is generally reduced over most of the continents in the SSiB-AGCM experiment. There are large differences in precipitation recycling ratio which become as high as 10% over the semi-arid and desert regions of central Asia, Australia, North America and southern

Africa. It is noted that the decrease (increase) in precipitation recycling ratio is coincident with the negative (positive) surface latent heat flux anomalies (Fig. 2a), in particular, the substantial decrease in the surface latent heat flux corresponds closely to the decrease in precipitation recycling ratio over these continental areas.

These results evidently suggest that the wetness was specified as a simple constant over the continents and the physical processes of hydrological cycle was not included in CTL-AGCM, and thus producing the unrealistical high estimates of the calculated surface evapotranspiration and recycled precipitation; whereas, such bias over the land surfaces is much reduced in SSiB-AGCM which the interactive land-surface processes are included. As a result, the simulated precipitation over continents is greatly improved, and becomes more realistic in many regions of the world.

It should also be noted that the calculated precipitation recycling ratio mentioned above is the averaged value within each grid box, different from the averaged value for a given regions (i. e. scaling in kilometer). Besides, it follows that the impact of local evaporated moisture on precipitation is linearly related to the regional areas. For example, for the scale of 2500 km over Amazon rainforest basin, the estimate of annual recycling is 35% (Eltahir and Bras 1994), while the regional scale is reduced to 2300 km, the estimate 25% (Brubaker et al. 1993). According to the linear formula for recycling ratio and regional area sizes (Eltahir 1993), the estimation of annual recycling on the Gaussian grid located within the aforementioned Amazon basin in SSiB-AGCM is 9% (7%) respectively (not shown). This estimation seems to be in fair agreement with the annual recycling in the Amazon basin using the observational data as was stated in the above. It can be argued that the results from the improved precipitation recycling model are feasible.

It can be seen from the results stated above that the land surface attributes and conditions in SSiB-AGCM exert considerable impacts on the atmospheric circulation through the fluxes of radiation, water vapor, sensible heat and momentum across the lower boundary of the atmosphere. Meanwhile, these processes interact each other and are constrained by the surface energy balance. The hydrological cycling, among other things, plays a unique role in the global climate. The experiments show distinctly that how different land surface parameterizations would produce significant differences in the simulated hydrological cycle.

2. *Simulation of the Mean Global Hydrological Cycle*

The CTL-AGCM and SSiB-AGCM generated fields of precipitable water (PW) (Figs. 7a and 7b) and the difference between them (Fig. 7c) show there is significant improvement over semi-arid and desert regions of the continents, main mountains and tropical oceans in SSiB-AGCM, notably in the arid and desert regions of Sahara, central Asia and northern India. Globally, the PW in CTL-AGCM can be as high as above 55 mm, similar to the maximum water vapor content which occurs in the tropics from Indian Ocean to central Pacific Ocean. Whereas these are basically below 20 mm, and by a factor of two over the Tibetan Plateau, which reproduce the observations fairly well.

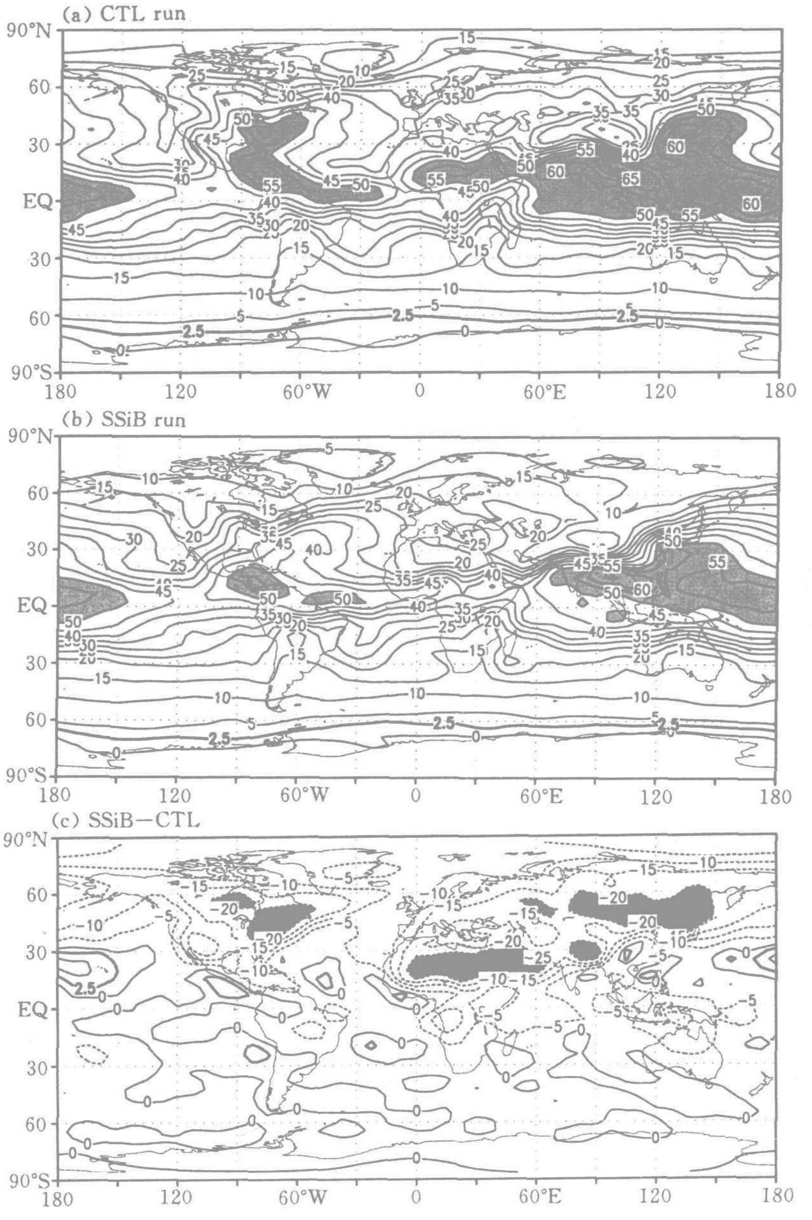

Fig. 7. As in Fig. 3, but for precipitable water (mm).

Additionally, the contour line of 50 mm located from the tropical Indian to western Pacific Ocean, the Amazon Basin corresponds well to the observation. In CTL-AGCM, however, PW in these regions exceeds 10 mm, with the control areas overextending horizontally and so on. Evidently, in the CTL-AGCM simulation, not only is there significantly larger water vapor content for semi-arid and desert regions, but the CTL-AGCM also produces excessive water vapor content in the tropics. The difference map, Fig. 7c, clearly illustrates the general reduction in PW over continents in SSiB-AGCM, particularly in the desert regions from North Africa to West Asia, where the negative difference (SSiB-

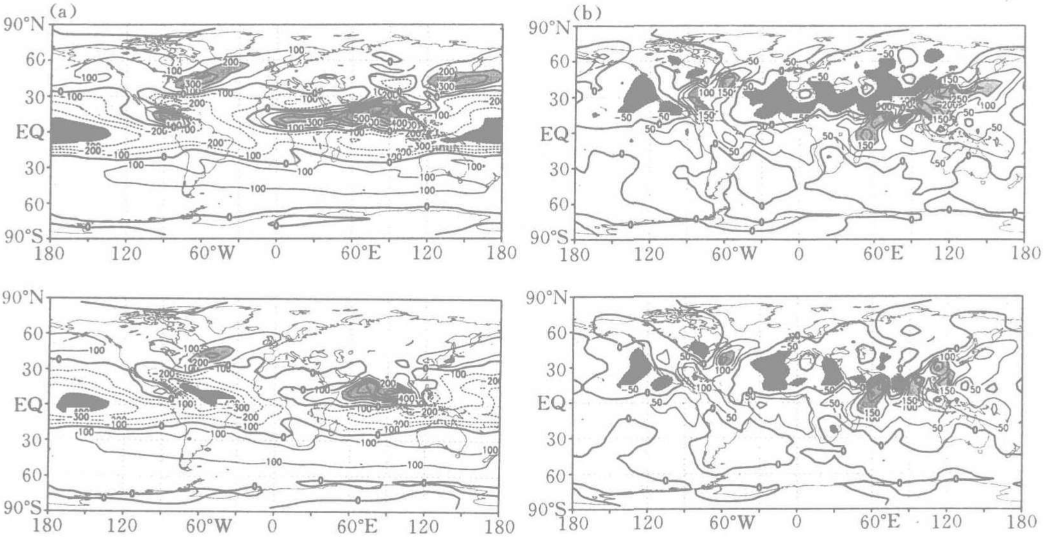

Fig. 8. Global field of mean stationary water vapor transport (kg $m^{-1}s^{-1}$) for July in the IAP/LASG CTL-AGCM (top panel), SSiB-AGCM (bottom panel) simulations for the 1979—1988 period for zonal (a) and meridional (b).

AGCM minus CTL-AGCM) can be as high as 20 mm more in SSiB-AGCM compared to that in CTL-AGCM over these regions, Siberia and central eastern North America. These results correspond well with the significant reduction in the surface latent flux (Fig. 2a). These suggest that the excessive evaporation calculated by CTL-AGCM may in large part be the result of the total holding moisture capacity. It should also be noted that the positive (negative) PW is consistent with the positive (negative) precipitation anomaly (Fig. 5), thereby bringing about an increase (decrease) in the holding moisture content, a decrease (increase) in the atmospheric instability, and consequently an increase (decrease) in the moisture resource.

The fields of mean vertically integrated zonal and meridional transport of water vapor for July simulated by CTL-AGCM and SSiB-AGCM are presented in Figs. 8a and 8b, respectively. As compared with CTL-AGCM, the simulations by SSiB-AGCM significantly improve and reproduce the principal roles in the global hydrologic cycle played by the Asian monsoon fairly well. For example, the zonal asymmetry area (50—110°E) of moisture transport matches quite well with observations over southern Asian monsoon regions of Indian Peninsula and adjacent oceans, while in CTL-AGCM it extended excessively westward along the equator (0—110°E) (Fig. 8a). This comes mainly from significant impacts of various kinds of biomass and concomitant surface roughness (z_0) on the lower stream fields and consequently the moisture transport in SSiB-AGCM. It can also be seen that the seasonal variations in vegetation substantially influence on circulation, especially on monsoon. For example, the surface roughness is augmented by a factor of 2 and 3.6 in July more than in January over India Peninsula and Indochina Peninsula respectively (vegetation type 2, 12), significantly higher than other vegetation types in SSiB-AGCM: on the other hand. z_0 is significant about 72% and 43% lower in July in CTL-AGCM than in SSiB-AGCM respectively largely due to the prescribed z_0 of 29.62 cm over continents for any season in CTL-AGCM. This is more clearly illustrated by the distributions of stationary component of meridional vapor transport in Asian monsoon regions in July. As shown in Fig. 8b. SSiB-AGCM reproduces distinct regional features of observational Asian monsoon realistically. Strong Somalian flows across the equator present anticyclonic circulation over the Arabian Sea. cyclonic circulation in the monsoon trough region from the India Peninsula to the Bay of Bengal. thereby making staggered situation of water vapor transport northward over India. southward over the Bay of Bengal. Another northward water vapor transport lies in the reaches of the Changjiang (Yangtze)-Huaihe River. southern China and South China Sea. of which there are two northward centres of water vapor transport. the maximum value over the lower reaches of the Yangtze River. the other over the central South China Sea: i. e. larger meridional scale feature of vapor transport in the East Asian monsoon regions is reproduced well. These. however. tend to be predominantly horizontal and far away from observations in CTL-AGCM.

3. *Hydrological Balance*

The atmospheric hydrological balance in AGCMs can be vindicated using the water balance equation. The CTL-AGCM and SSiB-AGCM generated fields of $\{\nabla \cdot \ddot{Q}(\bar{E}-\bar{P})\}$ are shown in Fig. 9. We can see that the differences have been reduced tremendously over the continents in SSiB-AGCM. The maximum positive (negative) differences exist over Indochina Peninsula. Indonesia Islands to western Pacific Ocean on the equator. Latin America to northern South America (regions of subtropical high over oceans); whereas in CTL-AGCM. large positive differences. which are more than 14.0 mm d^{-1}. appear over contiguous areas of the Tibetan Plateau.

Overall. SSiB-AGCM appears to give a more consistent and realistic simulation of global hydrological balance. especially in land regions than CTL-AGCM. It should be noted that the diffusion terms in atmospheric water balance equation have been neglected. the pentad average and limited rhomboidal truncation have been used. Undoubtedly. these have a definite impact on the simulated results. but in the view of large-scale circulation. there still reveal the main results qualitatively.

V. SUMMARY AND DISCUSSION

By using 10-year integration results. we examine the capability of the two kinds of land surface parameterizations made with IAP/LASG GOALS climate model in reproducing climate and global hydrological cycle for July. Some simulations have been compared with corresponding observations. Also. precipitation recycling model has been improved. and mechanisms for land surface hydrological processes on climate in the simulations have been further explored by analytic studies with mechanistic models. Major conclusions in this paper are summarized as follows:

Although some further improvements still exist in SSiB-AGCM. it is found that both the treatment of subscale physical processes over the continents. and the realistic

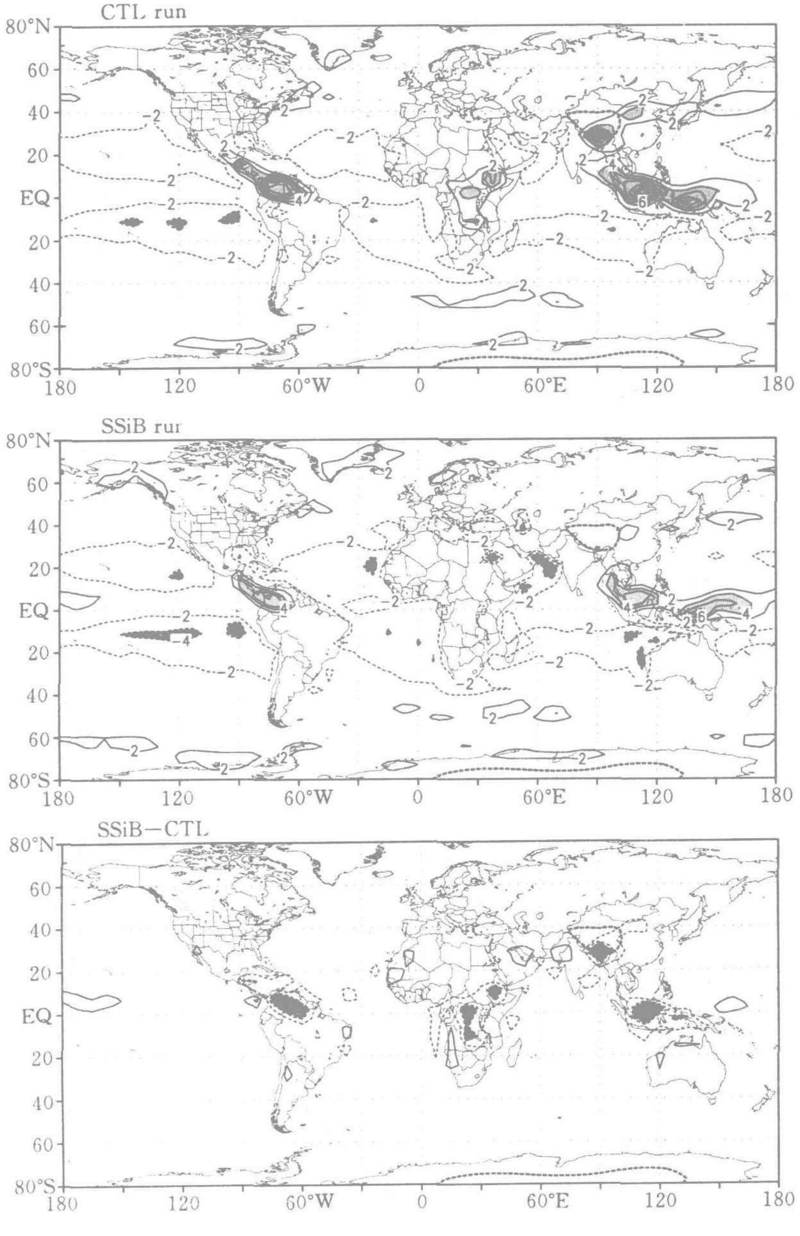

Fig. 9. Global field of 10-year mean hydrological water balance (mm d^{-1}) in the IAP/LASG CTL-AGCM (top panel), SSiB-AGCM (middle panel) simulation and the differences (SSiB-AGCM minus CTL-AGCM) (bottom panel).

calculation of surface fluxes of momentum, sensible heat, moisture have improved the model behaviour remarkably implementing land surface processes into SSiB-AGCM. Accordingly, SSiB-AGCM gives substantial improvements compared with theCTL-AGCM, and produces reasonable climate mean states, mean water vapor content and its transport, particularly in the Asian monsoon region, but the error of intensity also exists in our coupled model as compared with observations. It is also successful in simulating the atmospheric circulation, particularly over the continents in SSiB-AGCM.

The coupled atmosphere-biosphere model has proven that the simulated climate is considerable sensitive to land surface evapotranspiration again. The estimation of precipitation recycling ratio provides a diagnostic measure of the potential for local evapotranspiration or interactions between land surface and atmosphere, and the contribution to local precipitation. There are notably different recycling precipitation ratio for different climate equilibrium. It is shown that the significant reduction in recycling precipitation ratio over land, particularly in the arid and semi-arid regions of the summer Northern Hemisphere, is consistent with the substantially reduced land surface evapotranspiration. Therefore the coupled SSiB-AGCM runs, as compared with the CTL-AGCM, reduce the bias of too much precipitation over land surface in most AGCMs and much improved in the simulated precipitation over land in many regions of the world.

Effects of surface hydrology were incorporated into CTL-AGCM using very simple parameterizations. Evaporation from land surface was modeled as depending on the product of wetness parameter and potential evaporation, that is, this formulation given through some specification of a wetness factor (C_w). This factor was not inferred from the simulated soil moisture. Rather, it was taken to be a fixed 0.25 of potential evaporation, which is different from the wetness factor in the bucket model. Additionally, the potential evapotranspiration was calculated by prescribed roughness 29.62 cm over the continents. In this way, land surface hydrologic cycle and any further surplus water transported from the continents to the ocean were not included in the model, and consequently the CTL-AGCM was intentionally greatly simplified in its hydrologic parameterizations. And complete hydrologic cycle was also interrupted. This simple parameterizations for evapotranspiration was not at all realistically, thereby leading to a high bias in overall land precipitation in CTL-AGCM. On the other hand, many major physical processes were usually ignored related to the hydrologic cycle such as plant surface resistance to water flux in vegetated areas, diffusion of soil water movement, reevaporation from precipitation, large-scale precipitation heterogeneity and so on, and thus greatly influenced the modeling of land surface climate.

In a word, the comparison analyses of numerical experiments indicate that both the land surface characteristics (vegetation in particular) and incorporated parameterizations for the land surface hydrology have greatly improved the global hydrologic cycle in SSiB-AGCM, the interactions between the continental and atmospheric component are of paramount importance to the formation and maintenance of simulated climate system.

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