B-5.4.1 Research on the accurate modeling of the feedback process related to climate change: Evaluation of the feedback process of the atmosphere-land surface process

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Abstract The sensitivity of the land-atmosphere water cycle to the runoff process was investigated through numerical experiments with an AGCM. The magnitude of the difference in ground wetness, evaporation, runoff, or precipitation due to the different runoff treatments was found as much as ten or twenty percent. Based on this fact, the treatment of runoff in climate model was carefully developed. It was also found that the transition from the dry to rainy seasons and in the snowmelt season in high latitudes is particularly important, because the difference in responses of runoff schemes and following feedback effects can be large.

The land-atmosphere interaction was examined with a regional atmospheric model with a cloud-resolving resolution, focusing especially on the interaction between the cumulus convection and the land surface. This study suggests the importance of soil moisture distribution in the interaction between the cumulus convection and the land surface. It is also noticed that thermally induced local circulation accompanying the strong soil moisture contrast affects the initiation of cumulus convections significantly; the resulting interaction is qualitatively different from that without the soil moisture contrast.

Key Words General Circulation Model, atmosphere-land hydrological cycle, run-off process, river basin hydrological cycle

1 Introduction

Land-surface hydrology is one of the most uncertain subjects in studies on the climate change. Though the representations of land-surface processes in numerical climate models are becoming more sophisticated due to contributions from many fields of science, only a poor understanding has been obtained of their interaction with the atmosphere. Therefore, this study focuses on clearly describing the feedback processes that take place in the land-atmosphere hydrological interaction simulated with numerical climate models.

This study consists of two parts. In the first part (Section 2), the sensitivity of the land-atmosphere water cycle to the runoff process is investigated with an atmospheric general circulation model. In the second part (Section 3), the interaction between cumulus convection and the land surface is investigated with a regional atmospheric model.

2 Sensitivity of a Simulated Water Cycle to a Runoff Process with Atmospheric Feedback

2.1 Introduction

Runoff is a process that has long been studied by hydrologists; it therefore seems appropriate to incorporate the hydrological knowledge of the runoff process into the climate study. However, the incorporations of runoff schemes based on hydrological considerations into AGCMs and the quantitative comparisons of the results with observational data does not seem necessarily successful. Therefore, the present study has focused on the qualitative aspect of the sensitivity of the water cycle to runoff. Namely, this study has tried to answer the following question: under what conditions, through what processes, and to what extent does the treatment of modeled runoff have an impact on the simulated climate?

2.2 Model and Experiments

The model used in the present study is the CCSR/NIES AGCM developed by the Center for Climate System Research, University of Tokyo and the National Institute for Environmental Studies. The resolution chosen is T21 horizontal truncation (approximately 5.6° latitude by 5.6° longitude) and 20 vertical levels. The ground wetness is calculated by a simple water balance model with a single-layer reservoir. Two types of runoff, surface saturation runoff and subsurface drainage runoff, are considered and simply modeled as follows:

$$\begin{aligned} &\text{Surface runoff} \quad R = P \cdot (W/W_{FC}) \,, \\ &\text{Drainage runoff} \quad R = R_0 \cdot (W/W_{FC})^n \,, \end{aligned}$$

where R is the runoff rate, P is the precipitation rate, W and W_{FC} are the ground wetness and its saturation value, respectively, R_0 is the drainage runoff rate at saturation, and n is a parameter($n \sim 3$).

To examine the response of the atmosphere-land water cycle to the change in runoff treatment, three experiments summarized in Table 1 have been performed. The first two experiments, DRN and SFC, are AGCM runs incorporating the drainage and surface runoff schemes, respectively. The experiment S_D is an off-line calculation of surface hydrology using the surface runoff scheme with inputs of prescribed atmospheric conditions derived from the results of DRN. The difference between S_D and DRN (S_D − DRN) represents the direct response of the surface hydrology to the change in runoff treatment, while the difference between SFC and DRN (SFC − DRN) represents the total response including atmospheric feedback.

Table 1: Summary of experiments.

	Runoff	Model	Atmospheric condition
DRN	Drainage	AGCM	computed internally
SFC	Surface	AGCM	computed internally
S_D	Surface	Surface hydrology	prescribed sequences of P_e and E_p that have been computed in DRN

2.3 Results and Discussion

The differences in runoff and evaporation among the three experiments are plotted in Figs.1 and 2, respectively. In each figure, the total effect (SFC−DRN; Figs.1a and 2a) and the direct effect (S_D−DRN; Figs.1b and 2b) are shown. Though the two schemes estimate almost the same runoff rate over an annual average, the estimated seasonal patterns have significant systematic differences in the tropics, the subtropics during the rainy season, and high latitudes. Because of the modeled characteristics of the two schemes, drainage runoff estimates larger runoff than surface runoff when ground wetness is sufficiently large and effective precipitation (including snowmelt) is relatively small, and *vice-versa*. The larger runoff causes a negative anomaly in ground wetness, which is then followed by a negative anomaly in evaporation and runoff. The negative anomalies in evaporation and runoff tend to diminish the ground wetness anomaly over a time-scale of less than one month. A positive anomaly caused by a smaller runoff is also diminished in a similar way.

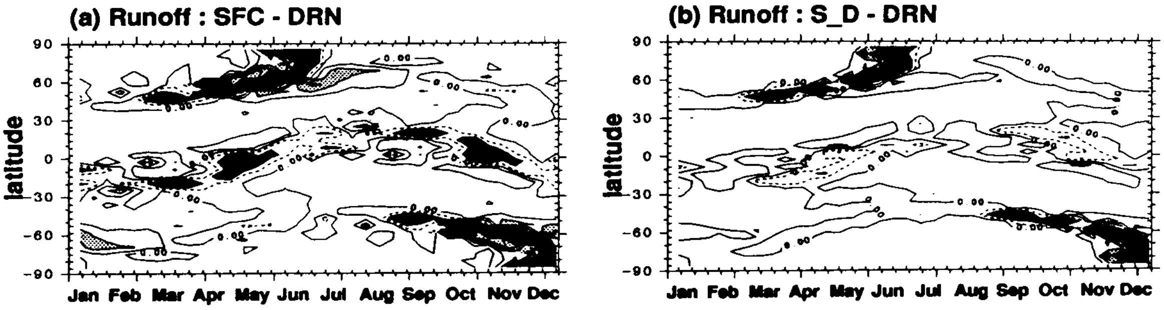

Fig.1: Differences among the experiments in runoff; (a) total difference including atmospheric feedback (SFC-DRN); (b) direct difference (S_D-DRN); Values greater than 10mm/mon and less than -10mm/mon are lightly and densely stippled.

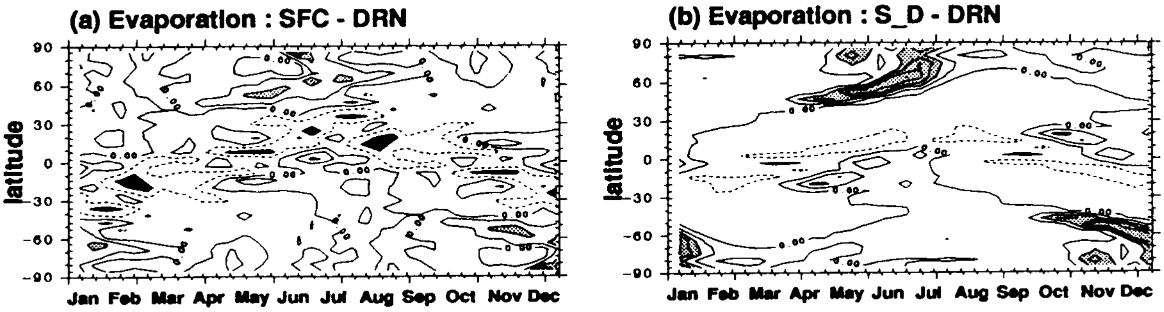

Fig.2: Same as Fig.1 but for evaporation.

A positive anomaly in evaporation generally causes a positive anomaly in precipitation and a negative anomaly in potential evaporation. The anomaly in ground wetness is generally amplified and elongated through the atmospheric feedback. When the atmospheric feedback processes are neglected, the time-scale of anomaly decay is typically less than one month. With the atmospheric feedback, however, the anomaly can persist considerably longer, for a few months. Particularly, the precipitation feedback (recycling), which cancels the anomaly in evaporation, is mainly responsible for this modification. According to an estimation using water balance equation,

$$\frac{\partial W}{\partial t} = P - E - R\,,$$

the decay time-scale is particularly sensitive to the runoff schemes when the ground is sufficiently wet and evaporation occurs at its potential rate (energy-limited) or precipitation recycling is intense (Fig.3).

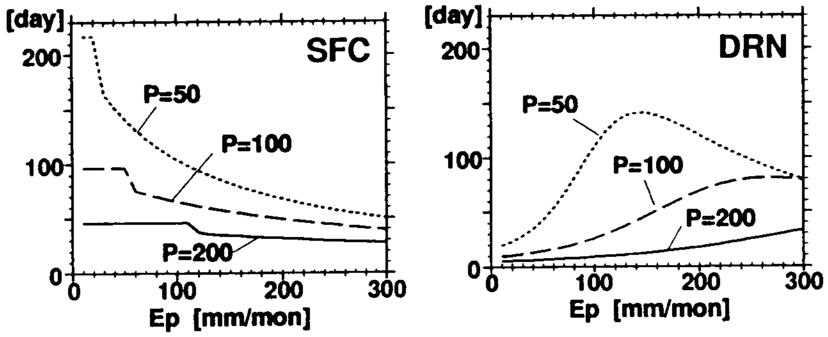

Fig.3: Decay time scales of ground wetness anomaly estimated by the water balance equation; shown as a function of potential evaporation for three cases of precipitation rate (50, 100, 200 mm/mon).

3 Idealized Interaction of Cumulus Convection with the Land-Surface Energy and Water Budgets

3.1 Introduction

The sensitivity of convective precipitation to land-surface conditions is significantly important to consider the feedback mechanisms in the land–atmosphere hydrological cycle. Some studies have explored the deep and shallow cumulus convections over land using regional atmospheric models with a cloud-resolving resolution (Anthes,1988 ; Chen and Avissar,1994). These studies examined only short-term (for hours to a day) responses of atmosphere to prescribed land-surface inhomogeneities. However, in the context of climate study, a further response of land surface to the change in atmosphere, and the resulting mutual interaction between the atmosphere and land surface should be examined. Therefore, long-term (for tens of days) integrations of a cloud-resolving regional atmospheric model have been performed here, after an equilibrium state was reached.

3.2 Model and Experiments

The model used in the present study is the Regional Atmospheric Modeling System (RAMS) developed at Colorado State University. The computational domain is two-dimensional and the Coriolis force is excluded. The horizontal domain (east-west direction) is 500 km wide and represented by 250 grids with a resolution of 2 km. Each convective cell is roughly resolved by 2 km horizontal grids and the cloud processes are represented by a microphysics parameterization. Because the radiation balance must be accurately represented to reproduce a reasonable equilibrium state of the atmospheric temperature profile, a radiation scheme based on the two-stream k-distribution method is incorporated in RAMS.

We have successfully obtained a quasi-equilibrium state of the modeled atmosphere–land system, with which we can integrate the model for tens of days or longer with rather realistic simulated results, though synoptic disturbances are ignored. Two long-term (60-day) integrations, in which the atmosphere–land system is equilibrated to a mean soil moisture of 3 cm (DRY) and 9 cm (WET), are conducted.

3.3 Results and Discussion

In both DRY and WET, a distinct wave-number-one pattern of the distribution of precipitable water is formed and moves at the speed of background wind (1 m/s). The convective precipitation occurs within the region of high-precipitable water. In DRY, strong horizontal contrasts in soil moisture are spontaneously formed due to the distribution of spotty precipitation, though the initial and boundary conditions are horizontally homogeneous (Fig.4a). These soil moisture contrasts cause surface temperature contrasts, which result in thermally induced local circulations in the daytime (Fig.4b).

Most cumulus convection is initiated by the upward motion of this local circulation in the afternoon. Schematic representation of the initiation of cumulus convection is shown in Fig.5. Since the upward motions initiating cumulus convections are closely related to the diurnal cycle of surface temperature, the phase of cumulus convection is rather tightly locked in the diurnal cycle. In the first half of WET (WET-I), on the other hand, the horizontal contrast in surface temperature is weak, which is mainly caused by the radiation contrast rather than the soil moisture contrast. Some cumulus convections are initiated by weak upward motions induced by the weak temperature contrast, while others seem initiated by upward motions propagated by gravity waves from the preceding cumulus convections. In WET-I, an initiation of cumulus convection seems strongly influenced by the preceding convection, as well as by diurnal change of surface temperature, and its phase-lock in the diurnal cycle is looser than in DRY. When substantial soil moisture contrasts are formed in the second half of WET, the occurrence of cumulus convection is more like in DRY than in WET-I. Additionally, strong turbulence motions in clouds sometimes initiate cumulus convections in the morning or at night.

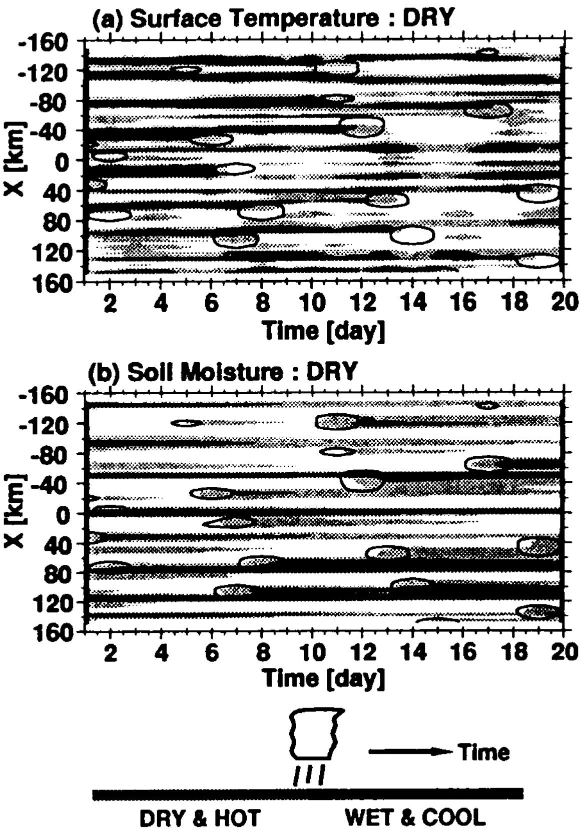

Fig.4: Daily averaged time sequences of (a) surface temperature distribution and (b) soil moisture distribution; denser stippled area denotes higher temperature in (a) and wetter soil in (b); contours for 10mm/day of precipitation denoting cumulus convection events are superimposed.

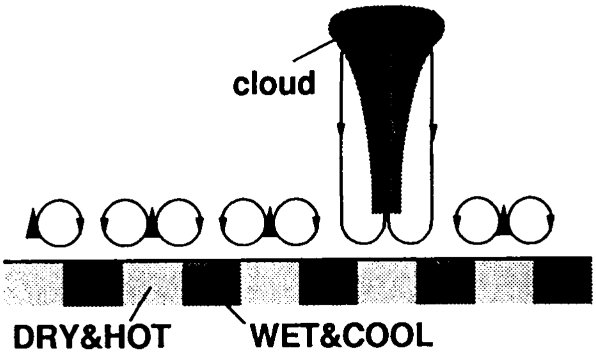

Fig.5: Schematic diagram representing that a cumulus convection is initiated by a thermally induced local circulation accompanying the land-surface processes.

4 Summary and Conclusion

The sensitivity of the land-atmosphere water cycle to the runoff process is investigated through numerical experiments with an AGCM. The magnitude of the difference in ground wetness, evaporation, runoff, or precipitation due to the different runoff treatments is as much as ten or twenty percent. Thus, to develop an accurate climate model, we should carefully consider the treatment of runoff. It is particularly important in the transition from the dry to rainy seasons and in the snowmelt season in high latitudes, where the difference in responses of runoff schemes and following feedback effects can be large.

Moreover, the land-atmosphere interaction is examined with a regional atmospheric model with a cloud-resolving resolution, focusing especially on the interaction between the cumulus convection and the land surface. This study suggests the importance of soil moisture distribution in the interaction between the cumulus convection and the land surface. Thermally induced local circulation accompanying the strong soil moisture contrast affects the initiation of cumulus convections significantly; the resulting interaction is qualitatively different from that without the soil moisture contrast.

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