# Effects of Topographic Slopes on Hydrological Proecsses and Climate

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ABSTRACT

Based on previous research results on river re–distribution models, a modification on the effects of topographic slopes for a runoff parameterization was proposed and implemented to the NCAR's land surface model (LSM). This modification has two aspects: firstly, the topographic slopes cause outflows from higher topography and inflows into the lower topography points; secondly, topographic slopes also cause decrease of infiltration at higher topography and increases of infiltration at lower topography. Then changes in infiltration result in changes in soil moisture, surface fluxes and then in surface temperature, and eventually in the upper atmosphere and the climate. This mechanism is very clearly demonstrated in the point budgets analysis at the Andes Mountains vicinities. Analysis from a regional scale perspective in the Mackenzie GEWEX Study (MAGS) area, the focus of the ongoing Canadian GEWEX program, shows that the modified runoff parameterization does bring significant changes in the regional surface climate. More importantly, detailed analysis from a global perspective shows many encouraging improvements introduced by the modified LSM over the original model in simulating basic atmospheric climate properties such as thermodynamic features (temperature and humidity). All of these improvements in the atmospheric climate simulation illustrate that the inclusion of topographic effects in the LSM can force the AGCM to produce a more realistic model climate.

**Key words:** Hydrological processes, Runoff, Parameterization, Topographic slope, Climate model, Land surface model

## 1. Introduction

Hydrological processes are attracting more and more interest from the global climate modelling community. Runoff is one of the most important hydrological processes and is included in most land surface models. The development of land surface parameterizations has been rapid in recent years. These include the biosphere–atmosphere transfer scheme (BATS) (Dickinson et al., 1993), the simple biosphere model (SiB) (Sellers et al., 1986), the simplified SiB (Xue et al., 1991), the biological ecological system transfer model (BEST) (Pitman 1991), SECHIBA (Ducoudre et al., 1993), the Canadian land surface scheme (CLASS) (Verseghy, 1991: Verseghy et al., 1993) and the most recently developed land surface model (LSM) (Bonan, 1996b; 1996c) at the National Center for Atmospheric Research (NCAR). Readers can find a brief review of these parameterizations in Bonan's papers (Bonan, 1995, 1996b).

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This study is to deal with a particular aspect of the problem: namely the runoff parameterization in all of the models mentioned before, and the LSM in particular. To be specific, we will include the topographic slope effects in the LSM presently used in NCAR's Community Climate Model version 3 (CCM3) (Kiehl et al., 1996; Acker et al., 1996). We found this problem as part of our effort in the Mackenzie GEWEX Study (MAGS) (Krauss, 1995) by comparing the CCM3 / LSM simulations with the National Centers for Environment Protection (NCEP) / NCAR reanalysis data (Kalnay et al., 1996). MAGS is the primary Canadian GEWEX program.

Through this kind of effort, it was found that the flow speed of surface water should not depend very much on topographic height, instead, it should strongly depend on topographic slopes which have large effects on runoff, one of the most important hydrological processes. The slope effects mainly arise in two aspects firstly, the topographic slopes cause outflows from higher topography and inflows into the lower topography points; secondly topographic slopes also cause decrease of infiltration at higher topography and increases of infiltration at lower topography. Then changes in infiltration result in changes in soil moisture, surface fluxes and then in surface temperature, and eventually in the upper atmosphere and the climate.

The organization of this paper will be as follows. The precise effects of topographic slopes on runoff formulation will be presented in the next section in the context of CCM3 and its LSM. Model result analysis on some effects of topographic slopes on the climate are given in Section 3. Conclusions and discussion can be found in Section 4.

## 2. Changes made in LSM scheme

With consideration of lateral water fluxes caused by topographic slopes, the newly proposed surface runoff rate $q_{\text{over}}$ and infiltration rate $q_{\text{infl}}$ should be calculated by

$$q_{\text{over}} = q^{*}_{\text{over}} + q_{\text{flux}}, \tag{1}$$

$$q_{\text{infl}} = q^{*}_{\text{infl}} + q_{\text{flux}}, \tag{2}$$

where $q_{\text{over}}$ and $q_{\text{infl}}$ with a superscript $*$ are the surface runoff rate and infiltration rate respectively, calculated by the original LSM; $q_{\text{flux}}$ is the lateral water flux caused by topographic slopes. It is determined by the next expression

$$q_{\text{flux}} = \nabla \cdot \boldsymbol{F}, \tag{3}$$

where vector

$$\boldsymbol{F} = (F_2 + F_4)\vec{i} + (F_1 + F_3)\vec{j}, \tag{4}$$

if using $F_k$ $(k = 1,4)$ to represent the net lateral water fluxes in each of the four main directions as shown in Fig. 1. In one direction, only one of the inflow or outflow is possible at a given time.

Based on Miller et al. (1994), Coe (1998) proposed an expression for the outflow in his river routing model as, in one direction,

$$F_k = \max[(E_{\text{wl}} - E_{\text{wd}})A, 0]\frac{u}{d}, \tag{5}$$

where $E_{\text{wl}}$ and $E_{\text{wd}}$ are the water elevations of the local grid square and the downstream grid square, respectively; $A$ is the area of the local grid square, $d$ is the grid size, and $u$ is the flow speed caused by topographic slopes between neighboring grid squares defined as

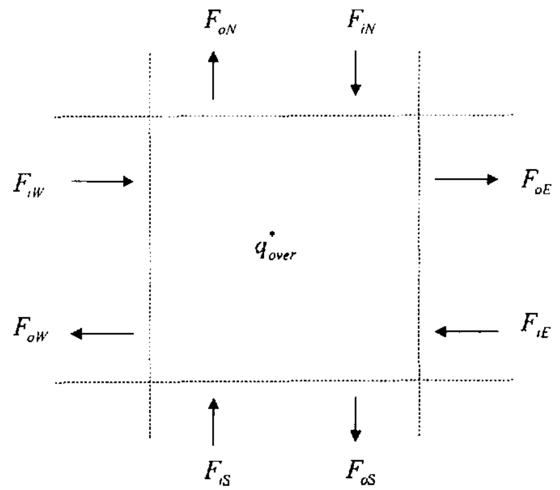


Fig. 1. Schematic showing the lateral water fluxes in the main 4 directions. The lowercase subscripts $i$ and $o$ denote inflow to and outflow from the local grid square, respectively. The uppercase subscripts $W$, $E$, $S$ and $N$ represent the four main directions west, east, north and south, respectively. The net lateral fluxes in (4) are defined as: $F_1 = F_{iN} - F_{oN}$;$F_2 = F_{iW} - F_{oW}$; $F_3 = F_{iS} - F_{oS}$; and $F_4 = F_{iE} - F_{oE}$.

$$u = 0.35\sqrt{\frac{s}{s_0}}, \tag{6}$$

here $s$ is the slope determined by the elevation difference ($\Delta z$) between neighboring grid squares and the grid distance $d$, $s_0$ is called critical slope and set to a constant of 0.00005. The constants $s_0$ and 0.35 depend on the horizontal resolution of the model and were chosen more empirically than physically (Miller et al., 1994). In the current study, as a result of our many experiments of CCM3 / LSM with a horizontal resolution of T42 (approximately $2.8^\circ \times 2.8^\circ$ latitude by longitude), 0.35 has been changed to 0.0035 to allow $0.15 < u < 5$ (Miller et al., 1994; Coe, 1998). This empirical condition helps to restrict the lateral water fluxes to a proper magnitude. According to Hornberger et al. (1998), the water elevation (WE) is given by

$$\mathrm{WE} = z + h, \tag{7}$$

where $z$ is land elevation (topographic height) and $h$ is water depth.

Even though the original purpose of these formula (5 to 7) are for river routing models, we will adopt them to runoff parameterizations for global climate modelling by connecting the water depth $h$ with the surface runoff $q_{over}$. After some equation developments (Liu, 2001), equation (5) is modified to

$$F_k = ABS\{[(q^{*}_{over})_l A_l - (q^{*}_{over})_d A_d]t + [z_l A_l - z_d A_d]\}\frac{u}{d}. \tag{8}$$

Where $t$ (= 10 minutes) is the LSM time step with T42 resolution.

After $F_k$ is calculated in all of the four main directions, the net lateral water flux rate for the local grid square, $q_{flux}$(mm $s^{-1}$), can be estimated by equation (3). At the end, the surface runoff rate and the infiltration rate (both in mm $s^{-1}$) generated by the original model are adjusted accordingly to their new values in the modified model by equations (1) and (2).

## 3. Model result analysis

According to data availability (i.e., SST as lower boundary conditions), two eight–year runs are conducted (1987–1994), excluding a 2.5–year spin–up for each run. One run is based on the original LSM. And the other is with the modified scheme as outlined in Section 2. They will be referred to, hereafter, as the " original" model run and the " modified" model run, respectively.

In this section, we will compare the results of the original and the modified model runs. In particular, comparison will be presented between the model results of temperature and moisture. Some of the results will be presented only in the MAGS area. Large results will only show up in the regional climate for the following reasons: Land only occupies about 30% of all the surface area of the earth. Suppose significant slopes only occur over 20% of the land surface area. Then even if the effect of the modification in the regional climate is 10 K in temperature, the global effect of the modification is only less than 1 degree, a very small figure. However, as you will be convinced by the next analysis, this does not necessarily mean the impact of the modification is not important on the global climate.

### 3.1 *Surface temperature*

As in other studies (Bonan 1996a, and many others), we begin the comparison with the surface temperature. In summer (Fig. 2), the modified model significantly warmed up the mountain tops and even the lee side of the mountains. This can be found by comparing the 278 K and 284 K contours between the original and the modified model results. As a result, at the east side of the mountains the warm ridge was strengthened. In winter (Fig. 3), warm–up can also be found along the mountain tops and the northern part of the domain. The warm–up along the mountain tops is featured by the 261 K and 264 K contours.

One of the directly related variables to the surface temperature is the latent heat flux from the ground (Liu, 2001). Comparisons of latent heat flux between the original and the modified models at the same times present substantially reduced latent heat flux in summer along the mountain tops where the surface temperature was warmed up by the modified model.

These conclusions are consistent with the general conclusions in Bonan (1996a), i.e., " infiltration reduced, resulting in drier soil and less latent heat flux and thus warmer ground surface." While in his Table 6, conflict data were presented for the MAGS area: for the four seasons, the surface temperature in winter, and fall decreased, unchanged in summer and slightly increased in spring, and the annual average decreased. As an explanation for this conflict, he just mentioned that, in basins where soil was very wet (Mackenzie, Yukon Kolyma), infiltration decreased and the soil dried. Latent heat flux decreased during the summer, but the soils were wet enough that surface air temperatures did not significantly increase (Bonan, 1996a). Better consistency of our results with Bonan's general conclusion implies that the modification made in this study did improve the LSM's performance. This has been more clearly confirmed by the point budget analysis at the Andes Mountain vicinities in South America (Liu,

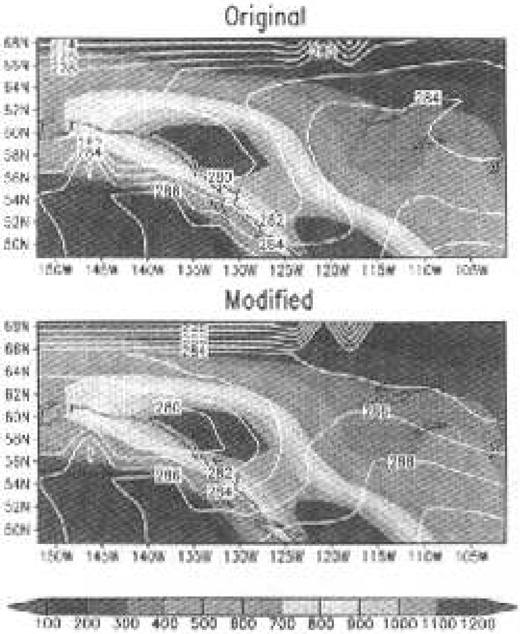


Fig. 2. Surface temperature (K) in August 1994, comparison between the simulated fields by the original and the modified models.

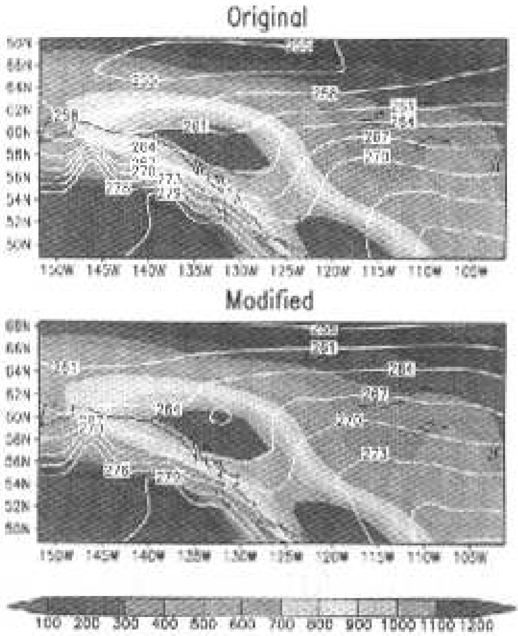


Fig. 3. Same as in Fig. 2, but for January 1995.

2001).

In winter, nearly no changes were found in the latent heat flux between the modified and the original model results, but the surface temperature was still warmed up by the modified model along the mountain tops. This reminds one that surface soil wetness and latent heat flux are not the only two factors affecting the surface temperature. And also note, runoff parameterizations are mainly based on precipitation. The current modification cannot recognize the type of the precipitation, i.e., rain or snow. This could have caused overestimates in the lateral water flux calculation in winter, which is still needed to be improved in the future.

### 3.2 *Atmospheric temperature*

In last section, from a regional scale perspective, the model result analysis has convinced that the modification in the runoff parameterization does have important impact on the surface climate. Now, from a global perspective, let's see what happened to the basic thermodynamic structure after the modification is added into the model by checking the zonal averages of atmospheric temperature and specific humidity.

To interpret the simulation quality of these two fields, Hack et al. (1998) compared them (from the original CCM3 / LSM) to the NCEP / NCAR global reanalysis (Kalnay et al., 1996). As a continuation of his studies, we will compare our modified model result to Hack's results (Hack et al., 1998) to recognize improvements or deficiencies of the modified model. Therefore, readers are referred to Hack et al. (1998) for corresponding figures and discussion during the next analysis.

In the comparison between our modified model simulated temperatures and the original model simulated temperatures (Fig. 4), in winter, the modified model improved much on the simulated temperature at middle and high latitudes in the whole troposphere, by giving a over 1.2 K warmer center at the lower troposphere and another over 1.2 K warmer center at the upper troposphere. At the upper troposphere (around 60°N, 100 hPa), the modified model reduced the warm bias in the original model by 0.2 K. In the tropical upper troposphere, the modified model improved the temperature simulation by 0.4 K. Another improved area is in the middle troposphere between 30°N and 30°S, where the modified model slightly cools down the warm bias in the original model, with the most significant correction (0.2 K) at 30°S between 600 hPa and 250 hPa. A slight warming can also be found in the middle troposphere at the south polar area, where the modified model reduced the cold bias in the original model by over 0.2 K. But the modified model slightly increased the cold bias in the upper troposphere at the south polar region by about 1 K.

In summer, similar with in winter, the most significant improvement is found again in the north polar region but in the middle and lower troposphere, with a maximum correction of over 0.6 K. Another over 0.6 K correction is found in the upper troposphere at the south polar area, where the modified model reduced the cold bias in the original model by about 0.6 K. The warm bias in the middle and lower tropical troposphere was also slightly reduced by the modified model by 0.1–0.2 K, again with a maximum at 30°S between 600 hPa and 200 hPa as in winter. The most exciting point here is that the 0.6 K correction at the upper troposphere at the south polar area shows that the modified model also corrected the " cold

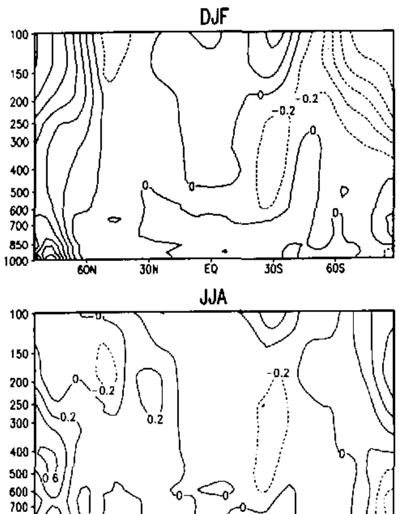


Fig. 4. Cross section of the seasonal zonal averages of atmospheric temperature (K) for winter (DJF) and summer (JJA), plotted is the difference between the original CCM3 / LSM result and the modified model result, i.e. $MODEL_{modified} - MODEL_{original}$.

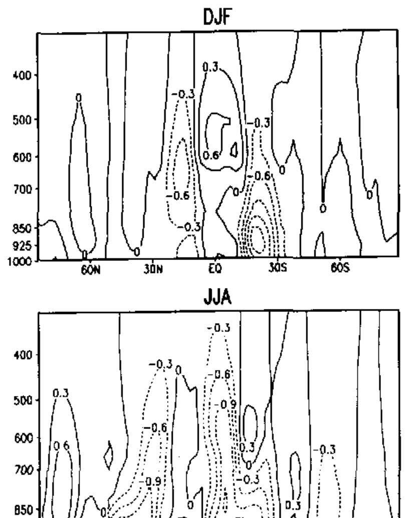


Fig. 5. Same as in Fig. 4, but for atmospheric specific humidity ($\times 10^{-4}$ kg / kg).

polar tropopause simulation" by 0.6 K, a pervasive problem in many AGCMs claimed by Boer (1992). This correction is at an over 80% significance level (T–test) (Liu, 2001). However, the modified model slightly increased the cold bias in the lower troposphere at the south polar region.

3.3 *Atmospheric humidity*

Figure 5 shows the zonally averaged cross sections of specific humidity differences between the original and the modified CCM3 / LSMs. In winter (DJF), the most obvious improvement is found between 15°S and 30°S at lower troposphere, where the modified model reduced the moist bias in the original model by over 0.15 g / kg. Between the equator and 30°N the modified model also slightly reduced the moist bias at the lower troposphere. A slight reduction of the dry bias in the original model can also be found at the polar regions. However, the modified model slightly increased the moist bias at the middle tropical troposphere.

In summer (JJA), the modified model reduced the moist bias up to 0.15 g / kg over the equator and the area between 20°S and 30°S at the lower troposphere. The dry bias at (10°S, 600 hPa) and (15°N, 850 hPa) is also reduced by the modified model by over 0.03 g / kg. At regions around (50°N, 700 hPa) and (75°N, 850 hPa), the modified model reduces the dry bias by over 0.06 g / kg. However, the modified model presents no correction on the big dry bias between 30°N and 60°N in the original model.

T–test results (Liu, 2001) confirmed that most of the improvements mentioned in all the above three sections are significant.

## 4. Conclusions and Discussion

Based on some previous research results on river re–distribution models, effects of topographic slopes is included in a runoff parameterization for AGCMs. This modification was implemented into the original model (NCAR's CCM3 / LSM) in this study. Modification is in two aspects: the topographic slopes cause outflows from higher topography (mountain tops) and inflows into the lower topography points (mountain feet). Topographic slopes will also cause decrease of infiltration at higher topography and increases of infiltration at lower topography. The surface runoff and infiltration are adjusted according to the topographic slopes between neighboring grid cells.

Analysis from a regional scale perspective in the MAGS area shows that changes in the surface hydrological variables (e.g., Liu, 2001) result in changes in surface latent and sensible heat fluxes and consequently, surface temperature is changed. Precisely, at higher (lower) topography points, the modification results in less (more) infiltration into the soil; the reduced (increased) infiltration dries (wets) the soil, reduces (increases) the surface latent heat flux, and consequently raises (lowers) the surface temperature. This mechanism is very clearly demonstrated in the point budgets analysis at the Andes Mountains vicinities (Liu, 2001). The analysis result and its interpretation in this study are more self–consistent than in some previous studies.

More importantly, the modified model improved the original model on simulating the basic atmospheric climate properties such as the thermodynamic features (structures of atmospheric temperature and specific humidity). T–test results demonstrate that most of the improvements are significant (Liu, 2001).

There are many ways in which topography affects regional and global climate. This study affected one aspect of that: an indirect way, i.e., topography affects the regional and global climate via its impact on the land surface hydrological processes. In fact, the whole issue as to where precipitation falls in a mountainous region is very relevant to this study. The study "assumes" that this major problem is a "given" and then it considers the lateral transport of moisture arising from that precipitation and the sloping terrain.

Although improvement over the original model introduced by the modification is dominant in the analysis, some deficiencies can also be found at some areas. Some of the deficiencies are most possibly rooted in the AGCM, CCM3 in this case (Hack et al., 1998), for example, the cold polar tropopause simulations have been documented to be a pervasive problem in atmospheric circulation modeling (Boer, 1992). These kinds of deficiencies can be improved by improving the approximation of the numerical schemes in the AGCMs (Williamson and Olson, 1998).

The calculation of the lateral water fluxes proposed in this study needs to be further refined. For example, the water flux calculation double counted the topographic height. This definitely introduced nonlinear effects on our adjustment on runoff and infiltration. The current modification also needs to be able to recognize the type of precipitation (snow or rain) to better simulate the winter climate. To better testify the efficiency of the modification, longer model runs are also needed, although the current 8–year runs already show many improvements. This will be our next step on this study. Inter–comparison with other land surface schemes will also help for further improvement on the runoff parameterization.

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