Introducing lateral subsurface flow in permafrost conditions in a distributed land surface scheme

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Abstract

This study introduces a quasi-3D land surface scheme, which accounts for both vertical and horizontal hydrological processes in regions with permafrost conditions. The attribute "quasi-3D" implies an explicit linkage between the vertical and horizontal componentss of the model. The model is developed by implementing the land surface scheme (LSS) SiB2, which incorporates a 1-D frozen soil parameterization (FSP), in a Distributed Hydrologic Model (DHM). Comparative simulations, in which the uncoupled SiB2 and the quasi-3D model considering surface lateral flow are applied to a small catchment in Tibet, demonstrate the impact of surface lateral flow on surface water and energy balance. A numerical experiment focusing on the effects of the permafrost conditions confirms the importance of lateral flow in hilly regions with frozen soil, and shows considerable differences in surface water and energy balance between the upper parts of slopes and valleys.

Keyword: Tibet, land surface scheme, permafrost, distributed hydrological model

1. Introduction

The Tibetan Plateau is not totally flat; instead, undulating hills alternate with plains of various extents. The Plateau is also a region with wide areas of frozen soil, either permafrost (50%) or seasonally frozen soil (44%) (Li and Koike, 2003). In regions with uneven terrain, the lateral flow is an important process affecting the spatial distribution of the surface wetness, which in turn essentially influences surface fluxes to the atmosphere. Moreover, specific phenomena are associated with frozen soil in hilly regions. Since the frozen soil serves as an impervious table, liquid water provided by either the melting of the soil ice content or the diffusion of soil moisture from upper layers accumulates above this table. Consequently, the overlying soil becomes saturated and thus saturated flow is initiated along slopes. In addition, if the soil is frozen up to the surface, surface flow occurs in the case of rain or snowmelt. As a result, the upper parts of hills are relatively dry, while the valleys are wet. Due to the lower liquid soil moisture content and hence the lower heat capacity, the upper parts of the slopes thaw much faster than the bottom ones. Accordingly, the active (unfrozen) layer at the bottom is quite shallow in comparison with the top, holding abundant liquid soil moisture, which may produce a saturation excess and a ponding of water on the surface.

Because of its impact on surface fluxes, surface wetness and its spatial distribution must be properly represented in a land surface scheme (LSS). Regarding the specific conditions in Tibet and the phenomena described above, an LSS applied to this region should account for the lateral transport of water as well as the processes associated with the freezing/thawing of soil. However, common LSSs are one-dimensional (1-D) models describing only vertical processes. In this study, we introduce a quasi-3D land surface scheme, which accounts for both vertical and horizontal hydrological processes, while regarding the frozen soil conditions. The attribute "quasi-3D" implies an explicit linkage between the vertical and horizontal components of the model. The model is developed by implementing the land surface scheme SiB2 (*Sellers et al.*, 1996) incorporating a frozen soil parameterization (FSP) (*Li and Koike*, 2003) in a Distributed Hydrological Model (DHM).

We carry out two numerical experiments. In the first experiment, we investigate the effects of surface lateral flow on the spatial distribution of the surface layer soil moisture, surface temperature, and heat fluxes as well as on the spatially averaged values of these variables over the computational domain. For this purpose, we carry out comparative simulations, in which the coupled model and the uncoupled SiB2 are applied to a small catchment in the upper reach of the Naqu basin. The second experiment focuses on the effects of surface and subsurface lateral flows on a local water budget in hilly permafrost regions. The coupled model is applied to a single slope representing typical topography in the Plateau.

2. Model description

The full descriptions of the SiB2, the FSP incorporated in the SiB2, and the DHM adopted in the coupled model are omitted in this paper, since they are available in referred literature: (*Sellers et al.*, 1996) for SiB2, (*Li and Koike*, 2003) for the FSP, and (*Dutta et al.*, 2000) for the DHM. Here, we introduce modifications of individual parts, new features and the coupling scheme.

In the coupled model, the SiB2 incorporating the FSP is embedded into the framework of the DHM and solves all of the vertical processes for each grid cell individually using the meteorological forcing data. It considers vertical interactions between the surface and the overlying atmosphere, while neglecting the horizontal interactions between the neighboring grid cells. Among other prognostic variables, the SiB2 estimates surface runoff as a result of infiltration and saturation excesses, and the thickness of the saturated zone above the frozen table as well as the soil water content available for lateral subsurface saturated flow. These quantities are then treated by the saturated zone component and the surface flow component of the DHM. The updated values of the saturated zone and the surface water storage are used as an initial state in the next time step in the SiB2.

Since the SiB2 is a vertical scheme, the only possible water input is precipitation. In order to introduce the effect of surface lateral flow on the surface wetness and fluxes, a simple procedure analogous to the precipitation-interception-infiltration-runoff scheme was introduced to treat the surface lateral flow contribution (lateral inflow) in the SiB2. The procedure is implemented at the very beginning of the SiB2 calculation. Firstly, the lateral inflow fills the surface water interception store. Then, the lateral inflow, lowered by interception, is partitioned into the infiltration rate and the infiltration excess contributing to the surface runoff. It is assumed that the surface water is transported by means of small rills occupying a fraction of the whole of the grid cell area.

Once the surface runoff contribution has been determined, some calculations are carried out to account for possible phase changes. Prior to the lateral inflow, the ground surface is at a specified temperature T_g and can be covered with snow. An energy balance calculation is performed to calculate a single new temperature for the ground surface, the surface runoff contribution, and the frozen or melted water produced as a result of phase changes. The patchy snow treatment included in the SiB2 is applied when the lateral inflow comes to a grid cell with non-zero snow/ice storage. As a result, some portion of the surface flow may refreeze on the surface if the surface temperature is less than T_f, or some snow melts due to the lateral inflow. When the treatment of the lateral inflow has proceeded, the handling of precipitation starts and the next parts follow as in the original SiB2.

The FSP in the SiB2 is based on an approximation of Stefan solution and predicts frozen/thawed depth and phase changes of soil water content over time. The three-soil-layer structure in the SiB2 is maintained in the original FSP (*Li and Koike*, 2003), but the governing equations of water balance and surface heat balance are modified to involve the soil freezing/thawing process. In the contrast with the original SiB2 (*Sellers et al.*, 1996), the presented model accounts for vertically heterogeneous soil, i.e. different porosities and hydraulic conductivities in the three layers. The resolution of the three SiB2 soil layers is, however, too coarse for the prediction of a saturated zone above the frozen table. Therefore, we introduce a multi-layer soil model in this study. The calculation of liquid water and ice contents is kept unchanged. The solution of vertical unsaturated flow is expanded for the multi-layer structure.

The depth of the saturated zone is determined after the unsaturated flow calculation. Firstly, the layers above the frozen table are checked for saturation, starting from the bottom layer. If there is a continuous saturated zone comprising at least one layer just above the frozen table, it represents the saturated zone. If the bottom layer is not saturated, the concept of *Ishidaira et al.* (1998) is adopted. It is assumed that the bottom layer is wetter than the upper ones. If this assumption is valid, the thickness of the saturated zone is determined from the equation:

$$D\,\theta_{l,b} = D'\theta_{s,b} + \left(D - D'\right)\theta_{l,b-1}, \qquad (1)$$

where D is the thickness of the bottom layer, D' is the thickness of the saturated zone, $\theta_{l,b}$ is the average volumetric liquid content in the bottom layer b, $\theta_{l,b-1}$ is the average volumetric liquid content in the layer b-1, and $\theta_{s,b}$ is the saturated water content in the bottom layer. If the condition $\theta_{l,b} > \theta_{l,b-1}$ is not fulfilled or if the active layer consists of only the uppermost layer, the value of $\theta_{l,b-1}$ in Eq. (1) is replaced with $0.9\theta_{l,b}$.

The 2-D subsurface saturated flow scheme is based on the groundwater component of the DHM, which employs a non-steady Boussinesq equation. . In the case of frozen soil, the impervious bed moves up or down over time according to the freezing/thawing process. Moreover, the thickness of the saturated zone may vary greatly along a slope and over time. Accordingly, the depth of the impervious bed and the saturated zone are calculated in every time step in the SiB2. Interactions between the saturated zone and the overlying soil are neglected in the 2-D subsurface flow routing. The moisture content available for the routing is determined by subtracting the residual liquid content from the saturated value. The obtained value represents the aquifer storage coefficient and is calculated in each time step. The growth/drop of the water head due to the saturated flow is converted into an increase/decrease in the liquid moisture content in the affected layers. The subsurface flow calculation is followed by the 2-D surface flow component and the river flow component in the DHM.

3. Numerical experiments

3.1. Surface lateral flow effects

In this experiment, we intend to demonstrate the effects of the surface lateral flow on the land surface wetness, and hence on the surface fluxes. We perform simulations by both the proposed quasi 3-D model and the uncoupled SiB2 and mutually compare the temporally and spatially averaged values of heat fluxes, surface layer soil moisture and surface temperature. This experiment focuses on surface flow, thus subsurface lateral flow is not considered in the quasi 3-D model.

The small catchment Mardi (350 km^2) in the upper reach of the Naqu basin (Nu-Jiang river) was chosen because of its relative homogeneity in soil conditions and vegetation. The Mardi catchment is located between N 32°22' and N 32°44', and between E 91°38' and E 91°55'. Its altitude varies from 4800 m asl up to 5350 m asl, with the most frequent values around 4850 – 5100 m asl. The vegetation type is short grass combined with bare soil and the soil is classified as a sandy-loam type. The river channel network is quite dense, but consists of many shallow streams.

Two simulations were carried out from July 4th to August 4th with a time step of 1 hour. The first half of the simulation period was rather dry. The rainy phase started on July 20th and continued until the end of the simulation. The summer period was chosen in order to insure a sufficient amount of rainfall for surface runoff generation (monsoon season). The forcing data were assumed to be uniform over the whole of the catchment.

Tab. 1: Statistical parameters of 2D distributed results for the wet period.

Wet period	Sensible heat (Whm^{-1})		Latent heat (Whm^{-1})		Soil moisture (m^3m^{-3})		Temperature (°C)	
	Sim. 1	**Sim. 2**	**Sim. 1**	**Sim. 2**	**Sim. 1**	**Sim. 2**	**Sim. 1**	**Sim. 2**
Average	14200	17100	30500	25900	0.290	0.278	8.9	9.4
St. deviation	350	3	580	5	0.003	0.0001	0.06	0.002
Rel. deviation	3 %	0.02 %	2 %	0.02 %	1 %	0.04%	0.6 %	0.02 %

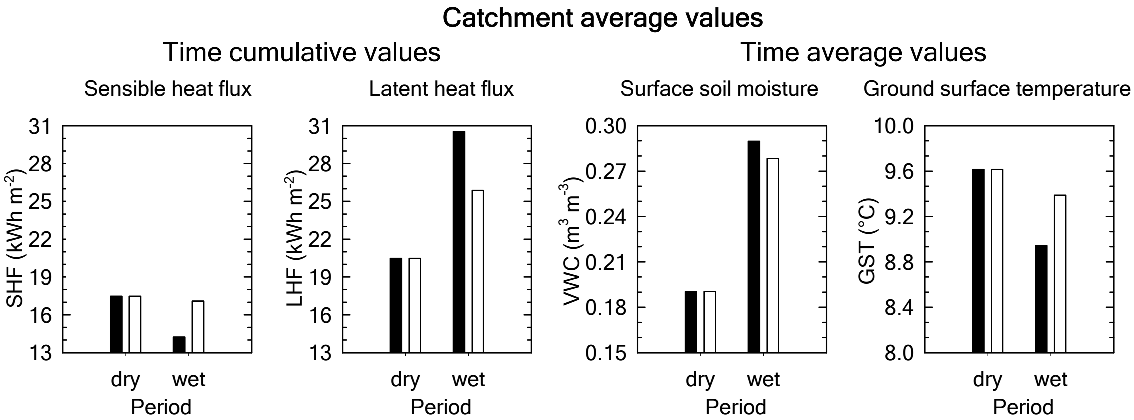

Fig. 1: Comparison of catchment averages: total or averaged values over the dry and wet periods. The black bar represents Simulation 1 (quasi 3-D model); the white bar stands for Simulation 2 (uncoupled SiB2).

Simulation 1 was performed by employing the quasi 3-D model, while Simulation 2 was carried out by applying the uncoupled SiB2 to each grid cell within the catchment. All of the parameters and input data were identical for both simulations and thus the results reveal the effects of surface lateral flow only.

A profound spatial variability in the surface wetness and fluxes is caused by the surface flow acting in two ways: (1) the direct effect on surface fluxes through the temporary surface water storage, and (2) the impact on the surface layer soil moisture through infiltration from the surface flow and in turn on heat fluxes. As a result, flat areas located below slopes are extremely wet with high latent heat and low sensible heat flux, while the tops of hills and declining areas are relatively dry, producing lower latent heat and higher sensible heat fluxes. Such a variability is provided by the quasi 3-D model, while the uncoupled SiB2 produces a uniform spatial distribution of the investigated quantities, which is demonstrated in Table 1, which lists some of the statistic parameters. Because the mesoscale spatial variability of surface fluxes stimulates atmospheric convective activity, such an activity may be missed in mesoscale atmospheric models when coupled with LSSs disregarding lateral flow.

Fig. 1 compares the catchment-averaged values of heat fluxes, surface layer soil moisture and surface temperature from Simulations 1 and 2. The values are either summed (fluxes) or averaged (moisture and temperature) over the dry period and the wet period. There is no difference between Simulation 1 and Simulation 2 during the dry period because surface runoff is not generated. Nevertheless, when surface flow occurs during the wet period, evident differences appear between Simulations 1 and 2. In Simulation 1, the surface runoff generated by the SiB2 is consequently treated by the surface flow component, i.e. the total water is conserved within the catchment. However, in Simulation 2, the surface runoff is lost and thus the total water within the catchment is underestimated. The higher surface and subsurface water contents in Simulation 1 lead to a higher latent heat flux and lower sensible heat flux and surface temperature in comparison with Simulation 2.

3.2. Lateral flow in permafrost conditions

The main aim of this experiment is to show the effects of surface and subsurface lateral flows on a local water budget in hilly permafrost regions. Therefore, we set up a simple catchment represented by a single slope inclining in one direction only. The catchment follows a real slope in the Naqu basin. The model is run using the forcing data provided by the CEOP Tibet 2002 observation. The simulation period is about 40 days starting on April 1st, when the soil is frozen up to the surface along the whole of the slope. Due to the lack of observations of soil moisture and temperature, we apply hypothetical initial conditions. We set up two scenarios. One scenario (C1) starts with homogeneous initial conditions along the slope represented by the water content at saturation (ice + liquid). The second scenario (C2) starts with heterogeneous initial conditions represented by different soil water contents along the slope: saturation at the bottom of the slope and gradually decreasing up the slope. The forcing data and all of the parameters associated with soil and vegetation are homogeneous over the catchment and are identical for both scenarios. The results are shown in Figures 2 – 4.

The C1 scenario reveals a strong impact of the lateral flow on the surface wetness. At the bottom, the soil near the surface stays saturated, while the top of the slope is gradually drying up (Fig. 2). Consequently,

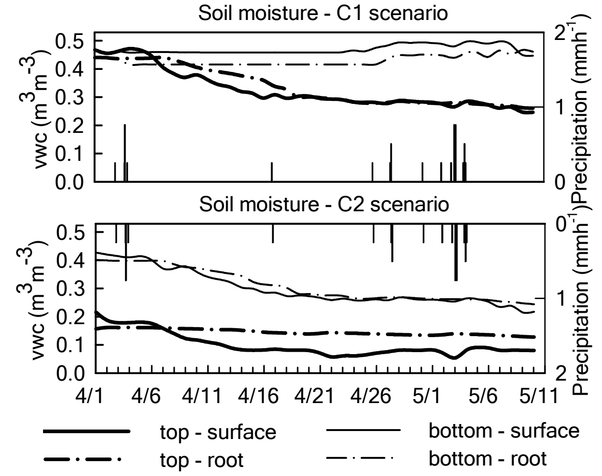

Fig. 2 Volumetric water content (liquid + ice) in the surface layer (full lines) and the root zone (dash-dotted lines) at the top (bold lines) and at the bottom (thin lines) of the slope. The thickness of the surface layer is 4 cm and of the root zone is 16 cm. The top chart – homogeneous initial conditions and the bottom chart – heterogeneous.

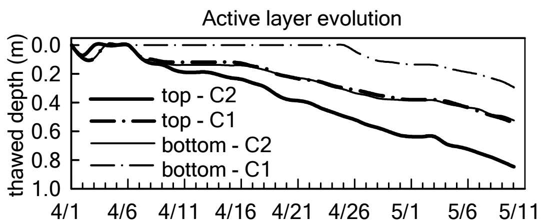

Fig. 3 Evolution of the depth of the active layer over time at the top of the slope (bold lines) and the bottom of the slope (thin lines). Full lines represent the C2 scenario and the dash-dotted lines show the C1 scenario.

thawing occurs faster at the top than at the bottom (Fig. 3). In addition, the wet bottom produces a higher latent heat flux and a very low sensible heat flux (Fig. 4). The extremely low sensible heat flux during the first 20 days of the simulation is caused by the frozen surface covered with an ice film. The C2 scenario demonstrates the effect of the initial conditions prior to thawing. Because there is only a little soil ice content at the top of the slope, there is no moisture available for lateral flow after thawing. In addition, only little rain falls during the simulated period and thus the soil moisture content is lowering even at the bottom of the slope. The results for the bottom in C2 are very similar to the results at the top in C1 because the initial state at the bottom in C2 is the same as at the top in C1 and because of the lack of water supply in C2 (little rain, little moisture in the upper part of the slope).

4. Summary

Regarding the specific conditions in the Tibetan Plateau, which make the lateral transport of water an important factor in determination of the local water and energy budget, we proposed the quasi 3-D land surface model accounting for both the vertical and horizontal hydrological processes. The numerical experiments showed that:

(1) The lateral flow in the quasi 3-D model causes a profound spatial variability in the surface wetness, temperature and heat fluxes. Consequently, the heterogeneity of the surface characteristics may enhance the convective activity in an atmospheric model.

(2) The bulk response of the catchment to the atmosphere is significantly affected by the treatment of surface runoff in the quasi 3-D model, which, in contrast to the 1-D SiB2, assures conservation of water balance within the catchment.

(3) The thawing/freezing of soil in hilly regions is strongly influenced by the lateral flow. The spatially non-uniform evolution of the active layer, together with the lateral flow cause a considerable spatial heterogeneity of surface wetness and surface fluxes.

These results are qualitatively consistent with observations suggesting a realistic performance of the presented model. However, it remains to be validated quantitatively against reliable data before coupling with an atmospheric model.

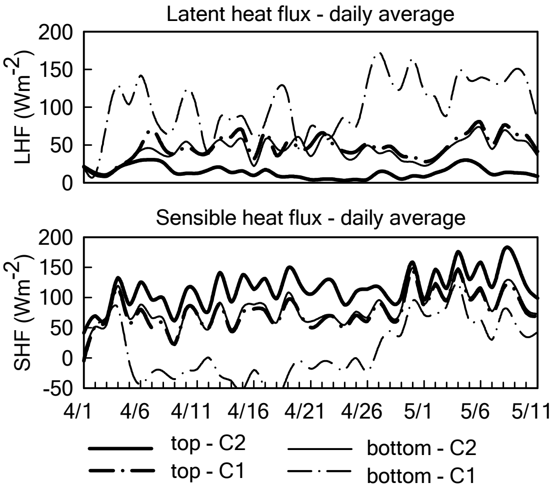

Fig. 4 Daily averages of latent (top chart) and sensible (bottom chart) heat fluxes. The lines have the same meaning as in Figure 2.

References

Dutta, D., S. Herath, and K. Musiake, Flood inundation stimulation in a river basin using a physically based distributed hydrologic model, *Hydrological Processes*, **14**, 497-519, 2000.

Ishidaira H., T. Koike, M. Lu, and N. Hirose, Development of a 2-D soil model for heat and water transfer in permafrost regions, *Annual J. of Hydraulic Eng., JSCE*, **42**, 133-138, 1998, *in Japanese.*

Koike, T., and P. Koudelova: Introducing the lateral surface flow into a land surface scheme, *Proc. of 2003 IUGG conference*, Sapporo, A116, 2003.

Li, S-X., and T. Koike, Frozen soil parameterization in SiB2 and its validation with GAME-Tibet observations, *Cold Region Science and Technology*, **36**, 165-182, 2003.

Sellers, P. J., D. A. Randall, G. J. Collatz, J. A. Berry, C. B. Field, D. A. Dazlich, C. Zhang, G. D. Collelo, and L. Bounoua, A revised land surface parameterization (SiB2) for atmospheric GCMs. Part I: Model Formulation, *J. Climate*, **9**, 676-705, 1996.