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GEO387H – Literature Review: Land surface Models and Surface Water Hydrology

Land covers 30% of the Earth's surface, the variability of weather above land is greater than the one above oceans. Not only is land a shelter for human beings, it is also a storage of freshwater, an essential element for human life. As part of the water cycle, land provides a link (through surface water and groundwater) between the atmosphere and the ocean. Land surface models are a key link between atmospheric models and hydrological models (Boone *et al.* 2004).

The present study will focus on the way land surface models handle surface hydrology. Through a general description of land surface models based on Yang's paper (2004); six additional papers developing improvements and testing of surface water calculation in land surface models will be examined. After a brief description of basic models some limitations and improvements of land surface modeling will be developed.

1 Basic models

1.1 The bucket model

In the bucket model, the most simple land surface model, global soil is assumed to have fixed water capacity. The bucket is filled with precipitation and emptied with evaporation. The excess above its capacity is termed runoff (see Figure 1).

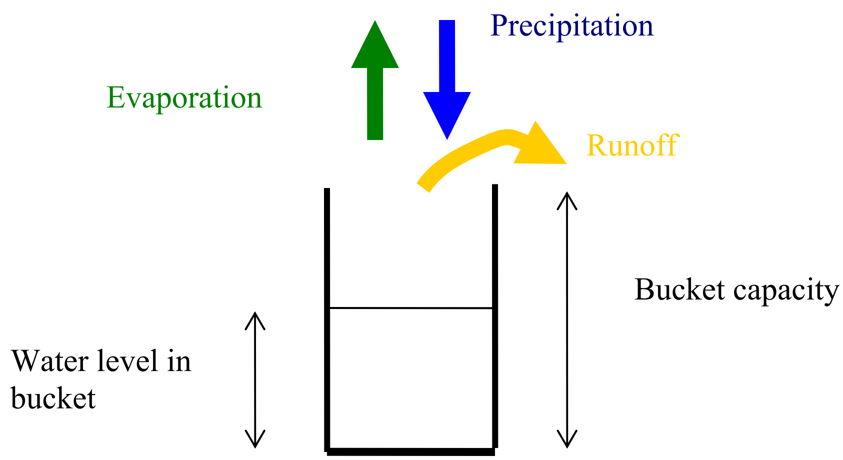

Figure 1 Bucket model

One can note that the bucket model does not take into account vegetation or groundwater at all.

1.2 Biosphere atmosphere transfer scheme (BATS)

The Biosphere Atmosphere Transfer Scheme (BATS) has three soil layers and one vegetation layer. Vegetation in BATS is assumed to be a flat porous and uniform layer.

In BATS, soil moisture contents are computed for three overlapping soil layers: the upper layer, the root zone and the total active layer (see Figure 2). The Leaf Area Index (LAI) is used to account for the attenuation of radiation as light passes through the canopy. The input atmospheric variables are incident shortwave and longwave radiation at the surface, precipitation rate, water vapor mixing ratio and wind velocity at the lowest model level. BATS can be operated in offline as well as coupled mode. BATS does not take groundwater into account, but it does vegetation.

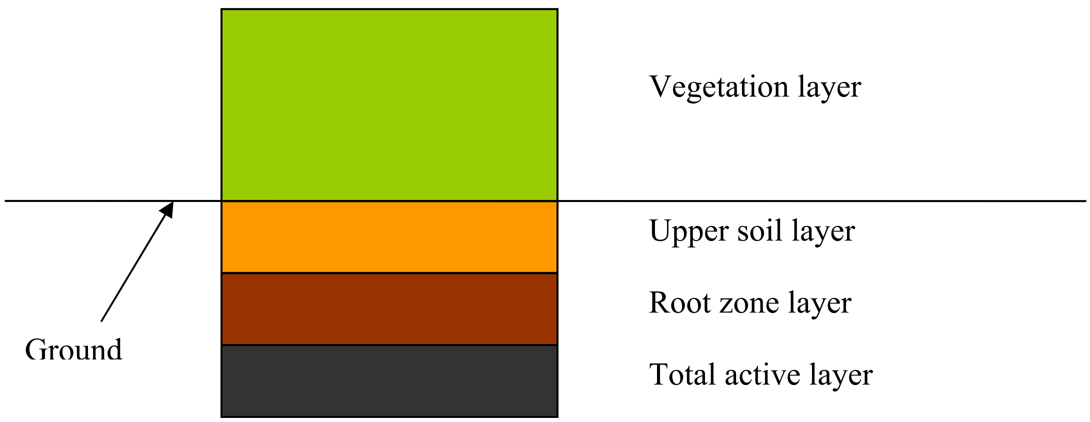

Figure 2 BATS model

1.3 The simple biosphere (SiB) model

The philosophy of the Simple Biosphere (SiB) model is to model the vegetation itself. The motivation behind the parameterization of vegetation is that it plays an important role in incoming radiation absorption. SiB has three soil layers and two vegetation layers. In SiB's two vegetation layers, the top layer consist of trees or shrubs while the ground layer is for grasses (see Figure 3). Unlike BATS, SiB computes canopy heat storage. The three soil layers are the upper thin soil layer, the root zone and an underlying recharge zone. The snow depth prediction is very crude and no treatment of snow temperature. SiB can be operated in offline and coupled mode.

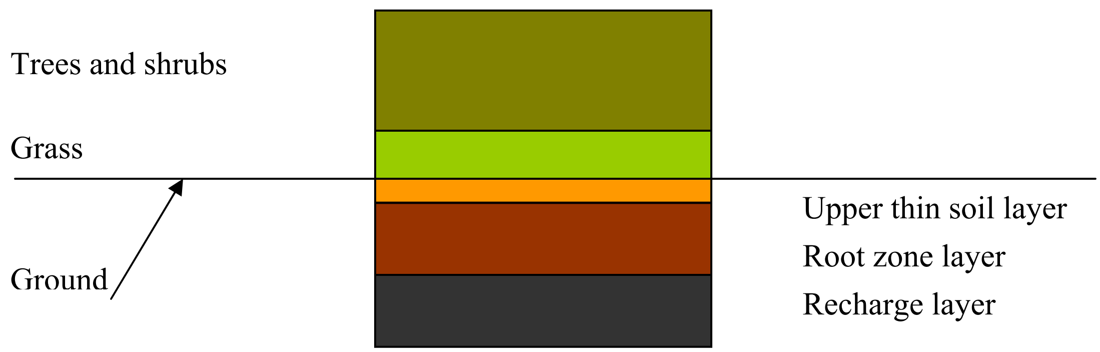

Figure 3 SiB model

2 Major issues in land surface modeling:

The three previous simple models (bucket, BATS and SiB) are only one-dimensional models (in the vertical direction). Although they are to be used ultimately in three-dimensional atmospheric models, these land surface models ignore horizontal interactions between adjacent cells. Furthermore, the following major limitations are to be noticed: runoff is not modeled, vegetation is treated linearly, there are only three land components (soil, snow and vegetation) and vegetation types are not taken into account.

Ongoing research works focus on vegetation datasets, land surface models and global circulation models compatibility, surface temperature, soil moisture and canopy interception, evapotranspiration, stomatal resistance, canopy drip, etc. The present study will focus the scientific research accomplished in the literature that was reviewed: soil moisture, runoff, snow and sub-grid scale variability.

2.1 Soil Moisture

In most land surface models, the soil is considered spatially homogenous with no horizontal water movements, and no melting or freezing within it. The only movement of water is vertical and follows Darcy's law:

$$Q = \frac{-k}{\mu}\Delta P$$

where Q is the discharge, k the permeability of the soil, μ the viscosity of the fluid and P the pressure (see Figure 4).

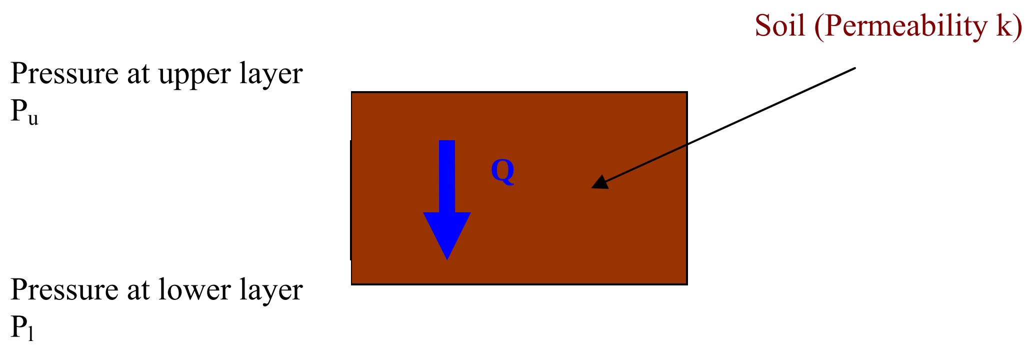

Figure 4 Water discharge in soil (here $P_u > P_l$ and $Q > 0$)

In Liang and Xie (2003), two improvements of the soil moisture calculation of the Variable Infiltration Capacity (VIC) land surface model were made. VIC was originally developed at the University of Washington.

The first improvement completed by Liang and Xie is to include the infiltration excess runoff capacity in VIC, by considering the effects of sub-grid spatial soil heterogeneity. The second improvement is to dynamically take into account the effects of surface and groundwater interactions on soil moisture. In VIC, the upper soil layer (Layer 0) is designed to represent dynamic response of soil moisture to rainfall events, and the lower layer (Layer 1) is used to characterize seasonal soil moisture behavior. A model schematic of VIC can be seen on Figure 5.

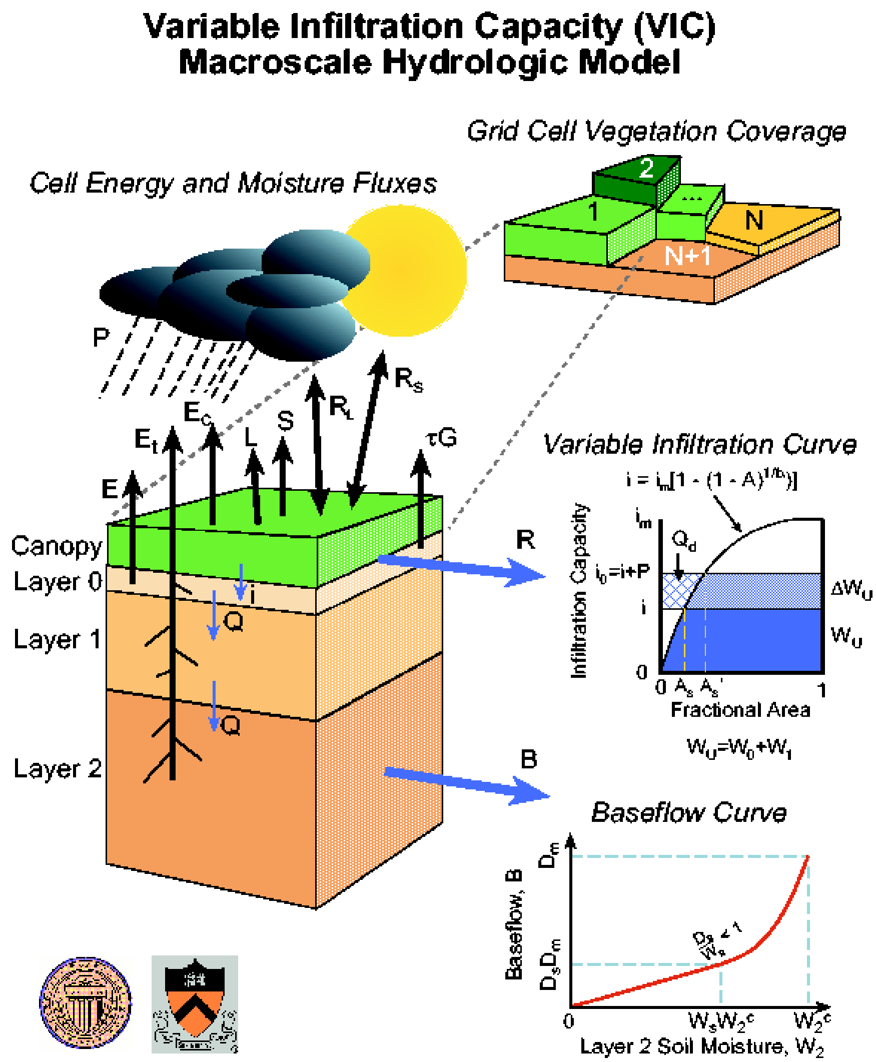

Figure 5 VIC Model schematic (from http://www.hydro.washington.edu/)

Soil infiltration through precipitation or groundwater discharge will influence soil moisture but also runoff (see Section 2.2 also). Using sensitivity analyses and field observations, Liang and Xie have shown that soil moisture plays an important role in the global energy and water budget. Furthermore, the study shows that taking into account surface and groundwater interactions dynamically is important in a land surface model to properly represent the partition of water budget among soil moisture, evapotranspiration and recharge rate.

X. Liang, Z. Xie / Global and Planetary Change 38 (2003) 101–114 105

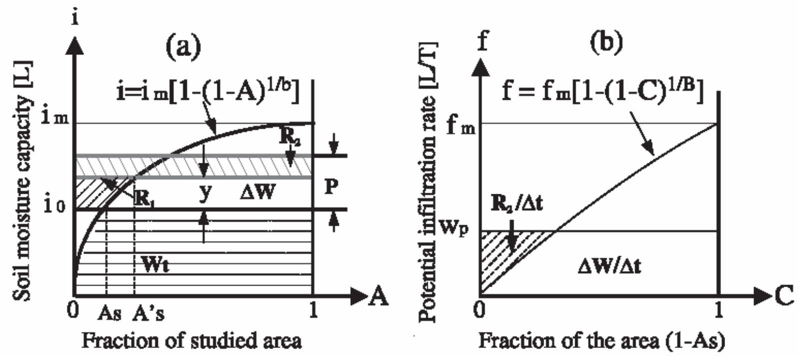

Fig. 1. Schematic representation of the VIC upper soil layer. (a) Spatial distribution of soil moisture capacity (L) for saturation excess runoff. (b) Spatial distribution of potential infiltration rate (L/T) (i.e., infiltration capacity) for infiltration excess runoff.

Figure 6 New surface runoff parameterization for VIC

Figure 6 shows the soil moisture capacity and the potential infiltration rate as a function of the area, as used in the upper layer of the model. The infiltration rate is a measure of how fast the water can infiltrate in a soil and depends on the type of soil but also on the moisture of the soil. The infiltration rate is based upon the area (A_s'-A_s) that becomes saturated between two time steps.

The surface / groundwater interaction through soil moisture is treated using the following diffusive / convective equation:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left(D(\theta)\,\frac{\partial \theta}{\partial z}\right) - \frac{\partial K(\theta)}{\partial z}$$

where θ is the volumetric soil moisture content, K is the hydraulic conductivity, and D is the hydraulic diffusivity and z the vertical coordinate (positive downwards). The parameterization of surface and groundwater interactions is made through the use of porosity, hydraulic conductivity and diffusivity, the groundwater level (moving boundary). The equations used are more representative of the physics than those of the bucket model.

The modified version of VIC was tested on Little Pine Creek near Etna watershed in Pennsylvania and successfully estimates the total runoff and the ground water table over a period of 7 months.

In Niu and Yang (2006) the terrestrial water storage estimated by the Noah Community Land Model (one standard version and one modified version) is compared to high resolution data: the Gravity Recovery And Climate Experiment (GRACE). Noah is the result of common work between several scientific institutions. Figure 7 gives a schematic of the model. GRACE satellites have produced an unprecedented dataset of terrestrial water storage (TWS) change in large scale river basins. GRACE data can be used as means of evaluating the hydrological schemes in a land surface model. Most land surface models are confined to a certain depth thereby excluding the groundwater variation where the water table is deep; therefore it is still unknown how and to what extent a land surface model that excludes groundwater and water storage in lakes and rivers can affect the TWS seasonal variability. For the purpose of the comparison, two models were used: the standard NCAR CLM and a modified version of the model (Proposed by Niu and Yang). The characteristics of the proposed model are developed in a different paper than the one reviewed in this study. The proposed model performs much better in simulating the seasonal variability of TWS in global river basins of various scales.

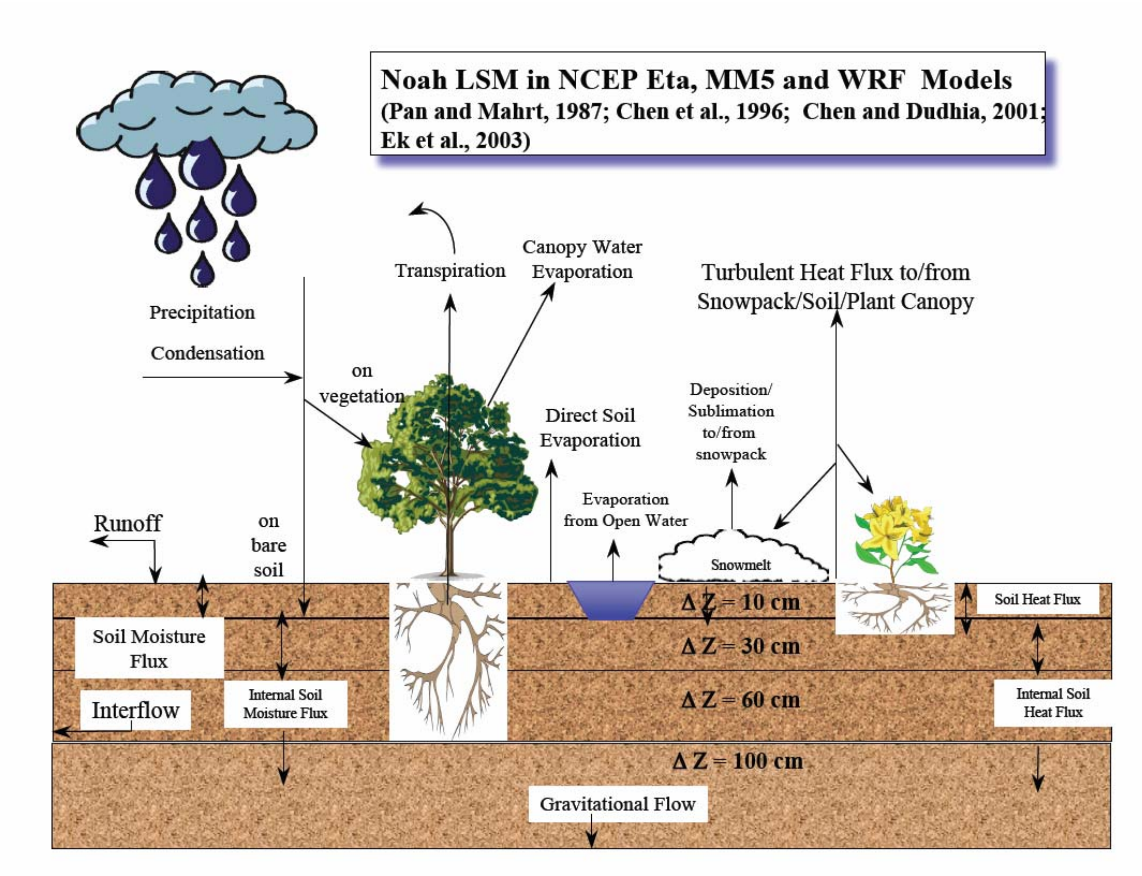

Figure 7 Noah Model schematic (from Chen 2006)

2.2 Runoff

Soil moisture and runoff as closely related. However, hydrologists and climatologists have different interest in the scales of runoff. The former see runoff as a direct result of precipitation whereas the latter see it as the residual to evapotranspiration. With the increase availability of large scale datasets, there is an emergence of large-scale hydrology where both points of view can be met; as a consequence accurate computation of runoff is an increasing need. Several types of causes to runoff can be considered. The infiltration excess runoff happens when precipitation intensity overcomes soil infiltration capacity. Saturation excess runoff is caused by precipitation over saturated or impermeable flow (see Section 2.1 also).

Boone *et al.* (2004) compared fifteen Land Surface Schemes (LSS) in twenty studies over several annual cycles using the Rhône basin as test bed. The Rhône is the largest European river flowing into the Mediterranean Sea. The corresponding basin covers over 86,000 km^2 of south eastern France. The link between atmospheric models and hydrological models is the Land Surface Scheme models, and the LSS is a key component of the simulation of hydrological cycle. In order to investigate the various features of the LSSs tested, each of them was substituted in an Atmospheric Model / LSS / Hydrological model sequence as shown in Figure 8.

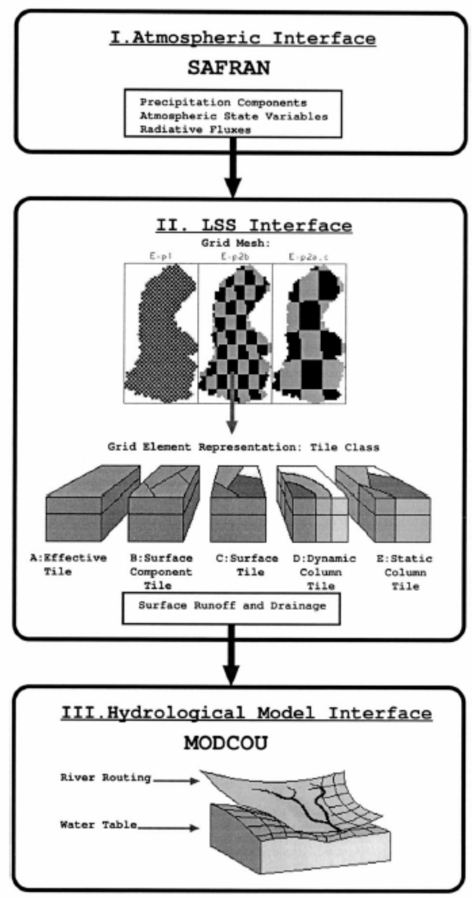

FIG. 2. The Rhône modeling system components. The participating LSSs are substituted into the LSS interface (II) The coupling is one way, and the variables that are transferred between each component are represented in blue. The LSS grids used for the scaling experiments (Exp1: 8 km; Exp2b: 0.5°, Exp2a: 1°) and a basic representation of LSS tiling methods are also shown.

Figure 8 Modeling System used in Boone *et al.*

The atmospheric part of the sequence as well as the hydrological part has been calibrated separately and the LSSs can be easily substituted. Several parameters were compared between different model results but also between model results and *in situ* data. Included in those parameters are: snow water equivalent, snow depth, soil water index and river discharge.

Boone *et al.* concluded that most of the LSSs simulate very similar total runoff and evapotranspiration for thee annual cycles, but the partitioning between the various components varies greatly, therefore resulting in very different soil water equilibrium states and simulated discharge.

The main objective of Schaake *et al.* (1996) was to understand how surface runoff processes might better be represented in an atmospheric model. Schaake *et al.* developed a Simple Water Balance (SWB) model. Unlike the surface energy budget (although crucial for atmospheric models), the water budget is important for hydrologic models. The motivation for SWB was to improve the representation of runoff relative to the simple bucket without introducing the full complexity of more developed models. The Simple Water Balance model can be regarded as a bucket model with conceptually defined physics of surface processes. SWB is based on relationships between spatially averaged fluxes and state variables assuming that surface processes locally behave according to physically based rules. The physics on which SWB is based include water storage (in canopy and soil) evapotranspiration (lower and upper layers) subsurface runoff, and surface runoff and infiltration. Figure 9 gives a schematic of the Simple Water Balance model. SWB was tested using historical data from three basins in the US (in Oklahoma, Mississippi and North Carolina), representing different climatological conditions. SWB was a success for it gave results comparable with other models that have more complex representations of surface runoff processes and the effects of vegetation on evapotranspiration.

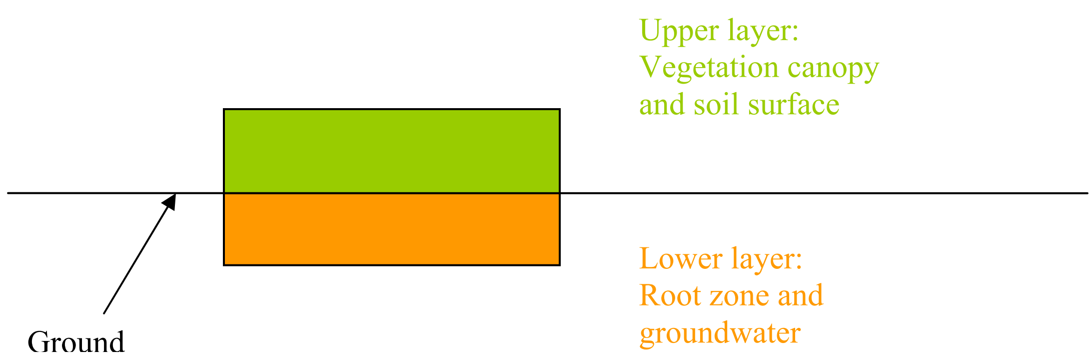

Figure 9 SWB Model

2.3 Snow

Snow cover exhibits the largest spatial and temporal fluctuations of all the large-scale surface features. Associated with these fluctuations are variations of the surface albedo, the radiation balance, the water vapor input to the atmosphere (sublimation) and the water input to rivers (runoff). Therefore snow cover is an important parameter in the Earth climate system.

Ek *et al.* (2003) expressed the results of operational upgrades of the Noah LSM that improve performance in forecasting low-level temperature and humidity. The upgrades were accomplished between 1997 and 1999 and tested in coupled mode with the Eta Model (atmospheric forecast model for North America at the time). The main upgrades concerned frozen soil and snowpack physics, snow albedo and conductivity, soil evaporation and thermal conductivity and transpiration refinements. Figure 10, Figure 11 and Figure 12 show curves of the equations that were used for improvements of snow physics. The analyses of the results of the improvements are made on individual case studies as well as regional studies. One of the main results of the study is that upgrading the snowpack and adding frozen soil physics are crucial in representing wintertime conditions because previous cold biases in the winter time low level temperature were reduced. Furthermore, modifying the bare soil evaporation and soil thermal conductivity formulations is important for typical early spring conditions with wet soil and sparse green vegetation cover.

Surface fluxes provide the necessary lower boundary conditions for numerical weather prediction and climate models.

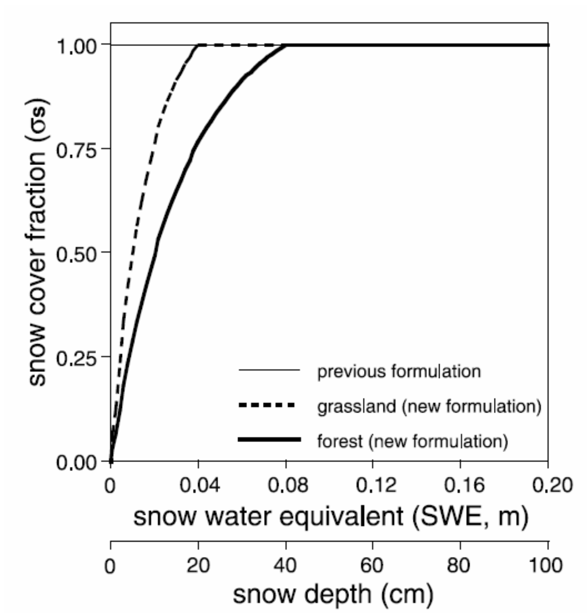

Figure 10 snow cover fraction as a function of snow depth (Ek *et al.* 2003)

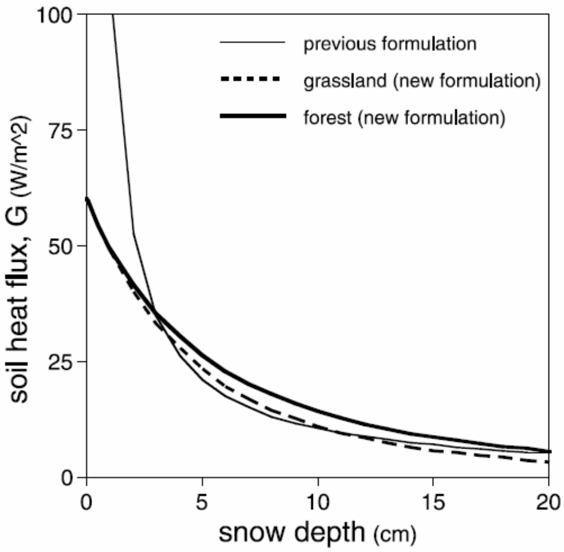

Figure 11 Soil heat flux as a function of snow depth (Ek *et al.* 2003)

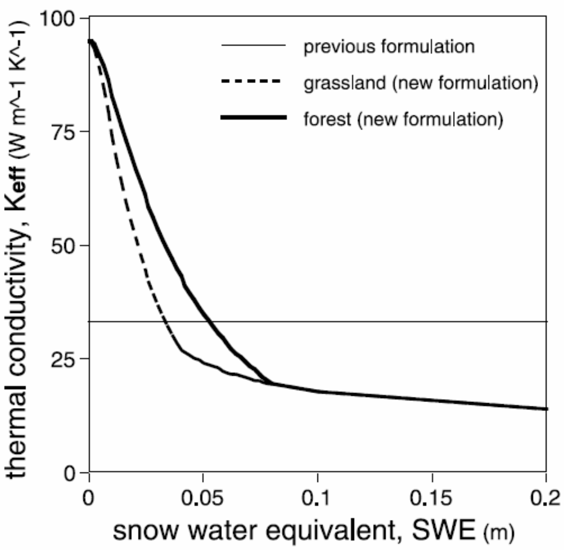

Figure 12 Thermal conductivity as a function of snow water equivalent (Ek *et al.* 2003)

Seneviratne *et al.* (2004) investigate the feasibility of estimating monthly terrestrial water storage variation from water balance equations. The following variables are used: water vapor flux, atmospheric water vapor content, and river runoff. The two formers are from the ERA-40 European Reanalysis project and the latter from USGS gage measurements. The study used the Mississippi River Basin as test bed.

Despite its relevance for both climate and human civilization, continental and subcontinental terrestrial water is not a readily measured quantity and little knowledge is available on its individual components, with most of the available observations being of very limited temporal and spatial scope. In the tropics and mid latitudes soil moisture is generally the main element contributing to seasonal changes in terrestrial water storage. Its key role for global and regional scale climate (sensible and latent heat fluxes) has been recognized in various observational and modeling studies and on numerical weather prediction. Ground water is also an important component of terrestrial water storage in the tropics and mid latitudes.

This study investigates the feasibility of estimating monthly variations in terrestrial water storage from water balance computation using atmospheric weather data and conventional runoff measurements. Ten years of study. The results are very promising because the computed estimates appear realistic within the large Mississippi river basin and are in good agreement with observations in Illinois.

Furthermore it is noted that LSSs having an explicit snow schemes perform better snow simulations (Boone *et al.* 2004).

2.4 Sub-grid scale variability

There are many ways to account for sub-grid scale variability: the component approach, the tile approach and the statistical approach. In the component approach, each grid cell is regarded as the homogeneous combination of basic components. In the tile approach, each grid cell is heterogeneous and divided into smaller grid cells that don't interact with each other. In the statistical approach, some key variables are assumed to have a sub-grid variance that follows a given probability function.

Boone *et al.* (2004) remarked that sub-grid runoff is especially important for discharge at the daily timescale and for smaller scale basin. Very high spatial resolution observational data within the Rhone basin makes it possible to examine the impact of scaling on LSS simulation. Thanks to the results of this study it has been shown that models with sub-grid runoff simulation perform better at predicting the total Rhone discharge on daily timescale than schemes without sub-grid runoff (see Section 2.4 also). The study is declared to be a great step towards a greater understanding of scaling effects in LSSs.

3 References

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