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Hydrology and Earth System Sciences
Discussions

Interactive comment on "Evaluating the Utah Energy Balance's (UEB) snow model in the Noah Land-Surface Model" *by* R. Sultana et al.

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Dear Reviewer, Thank you very much for your comments. We have carefully considered your suggestions and revised the manuscript accordingly. The comments and detailed responses can be summarized as follows:

Response: Noah LSM is 1- D column model but is applied at various spatial resolutions. The purpose of the paper was to evaluate the modified model's performance given grid scale variability. So, the model was not tested at a point location. To understand the results and discussion, a general introduction of the Noah LSM and UEB model has been added in the revised paper in section 2.1 and 2.2 respectively. Revised section 2.1. "The Noah model, originally developed by Mahrt and Pan (1984)

and Pan and Mahrt (1987), applies energy and water balance to simulate land surface conditions. The model's physical representation has been enhanced numerous times and updated versions of the model are periodically published at NCAR website (http://www.ral.ucar.edu/research/land/technology/lsm.php). The model is driven by seven input variables – precipitation, air temperature, surface pressure, wind speed, relative humidity, downward and upward shortwave radiation. This stand-alone, 1-D column version (version 2.7.1) has a multi-layer soil model but a simple canopy and snow model. When air temperature is less than 0oC, precipitation falls as snowfall. Snow cover area fraction within a model grid is determined as a function of SWE using a generalized snow depletion curve. When snow is on the ground, the model considers a bulk snow-soil-canopy layer and computes a single surface temperature for the bulk layer at every time step. The other state variables in the Noah's snow model are – snow depth, snow water equivalent and snow albedo. The model applies a simple snow albedo formulation based on fractional snow cover and maximum snow albedo (Ek et al., 2003). For each location, maximum snow albedo is derived from a database developed based on the work of Robinson and Kukla (1985). The dataset covers the area of 25o North 1o $\times$ 1o resolution." Revised section 2.2 "To overcome the deficiencies in Noah's snow model, snow-surface temperature and snow-melt processes of the Utah Energy Balance (UEB) snow model are evaluated as an alternate method to the existing snow model. The UEB model, originally developed by Tarboton et al. (1994) and Tarboton and Luce (1996), is a physically based energy and mass balance model to simulate snow accumulation and snowmelt at a point location. Snowpack is defined in a single layer by three state variables – snow water content, internal energy of the snowpack, and the dimensionless age of the snow surface. Input variables to the model are – air temperature, precipitation, wind speed, humidity and radiation (Tarboton and Luce, 1996). Tarboton and Luce (1996) assume neutral stability in the UEB model (Hellstrom, 2000). At every time step, the snow surface temperature is computed based on an energy balance between surface forcing and the capacity of snow near the surface to conduct heat into or out of the snowpack and melt outflow is a function of liquid water content (Mahat and Tarboton, 2013). Since its development, the model has been tested and verified at different sites with additional efforts to enhance the model performance (Luce and Tarboton, 2001; You, 2004; and Luce and Tarboton, 2010; Mahat and Tarboton, 2012; Mahat et al., 2013). A detailed discussion of the UEB model and the force-restore method can be found in Tarboton et al. (1994); Tarboton et al. (1995), Tarboton and Luce (1996), and Luce and Tarboton (2001), while a brief discussion of the model's physical processes pertinent to this paper is given below." Section 4 has been divided into 3 subsections – 4.1 Precipitation bias correction, 4.2 California SNOTEL sites, 4.3 Utah site. The modified section 4 is added in the supplemental document. The SWE simulation comparison at Utah site is discussed explaining the rationale for the control model and modified model simulation. Following content was added in the revised paper. "The modified model was also used to simulate snow at a Utah SNOTEL site (Station #1098) near the TWDEF forest and simulation result is shown in Fig. 12. At this site, the SWE predicted by the control model does not show strong negative bias unlike simulation at all the California SNOTEL sites, and completion of the snowmelt by the control model is later than the observation time. Although similar precipitation bias correction routine was applied at the Utah site, primary difference between the input data at stations in California and Utah is the variation in maximum snow albedo which is derived from a database (discussed in section 2.1). Maximum snow albedo at this site is relatively high (0.76) when compared to that of the California stations where most of the stations snow albedo values were less than 0.6. At Utah site, snowpack in the control model has high albedo and reflects most of the solar radiation resulting simulating below freezing snow surface temperature during the winter months. The control model's melt routine which is based on snow surface temperature does not initiate frequent snow melt earlier in the snow season (not shown here) contrary to the control model simulation at a California station (as shown in Fig 1). Therefore, the control model at this site has less SWE bias for high maximum albedo parameter. On the contrary, the modified model has original snow albedo parameterization and

results from Noah-Ts can be attributed to applied UEB's snow surface temperature and snow melt processes. Figure 13 shows that for the first 10 days of May, 2009 snow surface temperature and outgoing longwave radiation from both control and Noah-Ts reasonably agree with observed snow surface temperature although snow surface temperature from Noah-Ts was warmer than that of the control model. The modified model simulates SWE close to the observation, although melts the snowpack few days earlier than observed time. Earlier melt may be attributed to Noah-Ts' melting scheme which increases with increase of liquid water content. " In the revised paper, the following contents have been added in the Introduction section to discuss Noah LSM's snow model : "However, the model has been noted for substantially underestimating snow water equivalent (SWE) (Jin et al., 1999a; Pan et al., 2003; Sheffield et al., 2003; Mitchell et al., 2004, Jin and Miller, 2007; Slater et al., 2001; Livneh et al., 2009; Wang et al., 2010; Barlage et al., 2010; Niu et al., 2011; and Yang et al., 2011) by simulating less amounts of snow during peak winter season as well as melting the snow earlier in the spring. Physical processes that influence the model's prediction of SWE are primarily the (1) representation of snowpack and underlying half of top soil layer as a single bulk layer, (2) snow albedo parameterization, (3) lack of snow water retention and refreeze, and (4) snowmelt based on residual energy from the surface energy balance, (Livneh et al., 2009; Barlage et al., 2010; Niu et al., 2011). First two processes control the availability of energy in the snowpack while the last two processes regulate snow melt. Single layer snowpack combined with vegetation and underlying soil layer underestimates ground heat flux followed by overestimation of snow surface energy (Niu et al., 2011). Further energy is added at the snow surface due to the model's snow albedo parameterization which does not consider high reflectivity of fresh snow and snow aging (Livneh et al., 2009; Barlage et al., 2010). The residual energy in the snowpack is directly used to melt snow instead of using some available energy to warm the snowpack, retain liquid water at night and refreeze the melt water at night. Livneh et al. (2009) and Barlage et al. (2010) suggested that inclusion of snow-aging processes in the snow-albedo decay scheme can reduce Noah's SWE estimation bias.

Livneh et al. (2009) have also implemented snow water retention algorithm which also improved the model's SWE prediction. The limitation of single layer snowpack has been considered by Niu et al. (2011). Since, Noah computes a single temperature for the entire snowpack disregarding temperature variation within the snow depth, Niu et al. (2011) replaced the model's single-layer snowpack representation with multiple layers to explicitly capture the non-linear temperature gradient of the snowpack. Recognizing the difference in snow surface and bottom temperature improves prediction accuracy of snow surface temperature, surface fluxes and ground heat flux. Therefore, most complex snow models (ex, SNTHERM, Jordan, 1991; CLM, Dai 2003; SAST, Jin et al., 1999b) also apply finite-difference models to simulate snowpack temperatures. In addition, snow accumulation and ablation processes are also affected by land covers (Mahat and Tarboton, 2011), which are addressed by several research groups. To enhance the model, Niu et al. (2011) has also tested the model by separately computing temperature and heat fluxes from the canopy layer and included frozen soil scheme to improve soil permeability. Wang et al. (2010) have shown that Noah SWE simulation can be improved by considering the vegetation shading effect, under-canopy resistance, and roughness length adjustment in boreal forests and other grasslands." Response to specific comments 1) Reference to Fig. 1 was added. 2) A general UEB model description is discussed in section 2.2 (given above). 3) Results – Fig 3, corrected. 4) Result is discussed in separate section (supplementary file).

Please also note the supplement to this comment:
http://www.hydrol-earth-syst-sci-discuss.net/10/C7557/2014/hessd-10-C7557-2014-supplement.pdf

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