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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: 1. The introduction should undergo some modifications. While the first part (line 20, page 13364 to line 10, page 13365) is well written and coherent, the second one (line 10, page 13365 to line 10, page 13366) seems to be quite dispersive. I would suggest renewing it, reorganizing the discussion about the causes of the underestimation of SWE data, and trying to sum it up a bit. The state of art is clear and satisfactory; Response: In the revised paper, the following contents have been added in the Introduction: 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.

2. As for Section 2, I would suggest to give a brief, but exhaustive, general introduction to the two models compared in terms of the state variables used, the hypothesis, the parameters, the general laws used in the models, and the input variables required, since the current description results in being insufficient to completely understand the context of this contribution without knowing a great amount of information from other publications;

Response: A brief general description of Noah model and UEB model are added in section 2.1 and 2.2, respectivley. 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 × 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.

3. In section 2.2.2., I would appreciate some specifications about the reason why 20 m/h is felt to "reasonably describe the snowmelt rate and timing at the study sites", since they are at different elevations and geographical locations. Moreover, I would spend some words commenting the pros and cons of a matrix-flow approach, if com-

pared with preferential-flow approaches;

Response: Revised section 2.2.2. n UEB model, whenever internal energy is positive, the snowpack attains sufficient energy to initiate snow-melt and the snow-melt outflow rate Mr from ripened snow is simulated based on Male and Gray (1981) and is (Tarboton, 1994; Tarboton and Luce, 1996): (10) where S is the relative saturation in excess of the liquid water-holding capacity, and Ks is the snow-saturated hydraulic conductivity, which describes the water flux through the porous snowpack and is a function of snow density, porosity, and liquid water-holding capacity. The variation of Ks with a saturated water content of natural snow is not clear (Iida et al., 2000) and, hence, Ks is essentially a calibration parameter for each location (Tarboton and Luce, 1996). Different Ks values are reported in previous studies (Gray and Male, 1981; Tarboton and Luce, 1996; Zanotti et al., 2004; Mahat and Tarboton, 2011; Tarboton, 1994; and You, 2004), but the sensitivity tests (for Ks value from 200 m/s to 20 m/s; the result not shown here) showed snowpack melting rate increases with higher Ks value. The model is sensitive to Ks value only for the end of melting period. A constant Ks value of 20 m/h for all sites reasonably described the snow-melt rate and timing during the accumulation and ablation period. The parameter S in Equation (10) is derived from the following relationship: (11) where the value of variable S increases with increasing liquid water in the snowpack. Liquid water is the amount of water that can be retained in the snow pores against capillary forces, and consideration of capillary retention or liquid water-holding capacity can delay snowmelt during the ripening phase (Dingman, 1994). Amid the ripening phase, liquid water near the surface can refreeze with night-time cooling and thaw during day. This refreeze and thaw cycle can continue for days if the liquid water does not exceed the water-holding capacity of the snowpack. During the day, this cycle might need several hours to warm up and resume melting again (Dingman, 1994). Snow-melt starts once the liquid water in the snowpack exceeds the water-holding capacity. Initially, snow melting is more uniform ("matrix flow" in porous media) but with increased in liquid water content, snow grain size increases and initiates preferential flow resulting increase snow hydraulic conductivity. an But, theoretical

representation of preferential flow is difficult, so even the sophisticated snow models (e.g., like SNTHERM; Jordan, 1991) melt water model based on liquid water content.

4. Section 3.2: firstly, please clarify what you mean stating that NSE is "potentially a reliable statistic". Secondly, I am not sure that a negative NSE denotes a predictor as "not good". Since, as you say, it is a mere comparison with the errors one would have when using a long-term mean in place of the model, its general quality in modeling the data depends on many other considerations. The same can be said about the proposed threshold value of 0.7 (in this case, I would appreciate at least some references for this choice);

Response: Revised section 3.2. To assess the goodness-of-fit of a model, the Nash-Sutcliffe model efficiency (NSE) coefficient is widely used and is defined as: (13) where So is observed SWE, Sm is modeled SWE, and is the mean of observed SWE during the total time period T. NSE can range from $-\infty$ to 1. An efficiency of less than zero (i.e NSE < 0) denotes that the model is not a good predictor of the variable of interest (Krause et al., 2005) whereas an efficiency of 0 (i.e., NSE = 0) indicates that the model predictions are as accurate as the mean of the observed data. The NSE values larger than 0 are suggested for minimally "acceptable performance" (Gupta et al., 1999) although in literature, various threshold values are used for model's "satisfactory performance" (see Table 2 of Moriasi et al., 2007). Because values are not easily interpretable if sampling distribution is not given and users can only provide subjective interpretation (McCuen et al., 2006). In essence, the closer the model efficiency is to 1, the more accurately the model matches with observation. Here, a good NSE values greater than 0.7 are considered (Gupta et al., 1999).

In this context, following references were added in the revised paper: Gupta, H. V., Sorooshian, S., and Yapo, P. O.: Status of automatic calibration for hydrologic models: Comparison with multilevel expert calibration, J. Hydro. Eng, 4, 135-143. Krause, P., Boyle, D. P., and Base, F.: Comparison of different efficiency criteria for hydrological model assessment, Adv. GeoSci., 5, 89-97, 2005. Moriasi, D. N., Arnold, J. G., Van

Liew, M. W., Bingner, R. L., Harmel, R. D., Veith, T. L. : Model evaluation guidelinew for systematic quantification of accuracy in watershed simulations, Amer. Soc. Agr. and Bio. Eng., 50(3), 885-900, 2007. McCuen, R. H., Knight, Z., and Cutter, A. G.: Evaluation of the Nash-Sutcliffe Efficiency Index, J. Hydrol. Eng, 11(6), 597-602, 2006.

5. Section 4 should be separated in subsections, since in this version it is too long;

Response: The section is divided into the following subsections – 4.1 Precipitation bias correction, 4.2 California SNOTEL sites, 4.3 Utah site. The section 4 is added in the supplemental file #2.

6. Figure 3 (probably erroneously indicated as Fig. 2 at line 16, page 13376?): please consider to add to the X axis label the indication of each water year, since at this stage the only way we have to individuate the different years is to count the seasons on the same Figure;

Response: I agree that Figure 3 was erroneously indicated as Fig. 3 in line 16, page 13376. Figure 3 is corrected and shown below.

7. The precipitation correction presented at lines 16-20, page 13377, is just a first attempt to correct the possible biases, since it is not able to remedy to under-catch, evaporation or leaks, which could affect SNOTEL original rain-gauge data. I agree with you that it could be sufficient in such a general context, but please be clearer on this point. In fact, I think that elaborating a more refined routine could help in obtaining better SWE simulations since, in my opinion, much of the underestimation (at least, the residual one after the application of the UEB model) could be ascribable to uncertainties in input data quantification;

Response: Following content has been added to discuss bias from precipitation under-catch.

“Model bias can also increase at sites where additional snowdrifts can result from wind or at sites with precipitation under-catch which is common problem at mountainous

climate stations. A study by Gaudet and Cotton (1998) in Colorado mountain region found more than 20% under-catch. With additional bias correction model forecast can be further improved. “ Minor comments: - Page 13364, line 2 and 21, please define what NCEP-NCAR is; Response: NCEP-NCAR defined as: Natioanal Centers for Environmental Predictions-National Center for Atmospheric Research (NCEP-NCAR)

- In the text, you firstly cite Figure 2, and then Figure 1. This is quite unusual, please consider switching them. Response: Fig 2 and Fig 1 are switched. For example in the content in section 3.1 of the revised paper is “The location of the SNOTEL stations in California and Utah are shown in Fig. 2.” All the other minor comments were corrected.

Please also note the supplement to this comment:
http://www.hydrol-earth-syst-sci-discuss.net/10/C7562/2014/hessd-10-C7562-2014-supplement.pdf

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Interactive comment on Hydrol. Earth Syst. Sci. Discuss., 10, 13363, 2013.

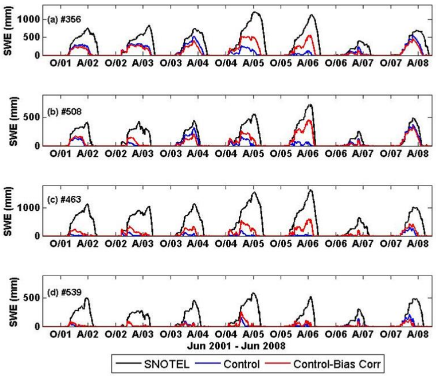

Fig. 3. Simulated SWE with NLDAS precipitation (blue line) and after precipitation bias correction (red line) are compared with observation (black line) sites: (a) #356, (b) #508, (c) #463, and (d) #539. Model run before precipitation bias correction is called 'control', and the model run after precipitation bias correction is called 'control-bias corr'.

Fig. 1.