

4.1 Precipitation bias correction

A comparison between the SWE (blue line) estimated by the Noah model (called ‘control’ in Fig. 1) and the observed SWE at the SNOTEL stations is shown in Fig. 3. In general, the control model underestimates the SWE, although the underestimation of the modeled SWE differs from year to year and from station to station. At some stations and during some years, simulated SWE compares relatively well to that of observed SWE than other locations and years. For example, at Station #356, the SWE during water years 2002, 2003, 2004, and 2008, were certainly less than observed but modestly captured (~40%-60% of the maximum SWE at the ground). Elsewhere, simulated SWE is almost negligible, particularly at Station #463 (less than 20% of the ground observed maximum SWE).

The primary reason for the Noah land-surface model’s negative bias in SWE estimation is because of imperfection in its current snow-physical processes, as discussed earlier. In addition, uncertainty in input can be quite substantial as well, especially in the mountainous environments. Precipitation, a primary input for quantifying snowfall, can be extremely variable in space and time in high-elevated areas. Mitchell et al. (2004) discussed this issue and pointed out that precipitation data in the NLDAS system are based on the National Weather Service (NWS) precipitation gauges. These gauges, located mostly in valleys, are known to underestimate higher-elevation precipitation (Pan et al., 2003). Pan et al. (2003) compared the NLDAS precipitation with SNOTEL precipitation from September 1996-September 1999 and found that SNOTEL precipitation is, on average, more than twice the amount of the NLDAS precipitation data. On the other hand, differences in other forcing data between NLDAS and those of stations were found to be insignificant (Luo et al., 2003).

Therefore, a simple precipitation bias-correction method was applied to NLDAS precipitation data, while no corrections were made to other NLDAS forcing data. Precipitation data were adjusted by first determining the ratio of total yearly winter precipitation (October-May) from SNOTEL to that of NLDAS. Then, NLDAS precipitation was scaled by the corresponding ratio. This simple bias correction shows that, in general, NLDAS precipitation is less than that recorded at the studied SNOTEL sites (Pan et al., 2003); thus, a substantial increase in SWE can be seen in years and stations where SWE was very poorly modeled (e.g., Station #463). There are a few years in which NLDAS precipitation data were more than the total precipitation recorded at the station and, therefore, precipitation bias correction resulted in reduced simulated SWE when compared to the control model (e.g., water year 2004 at Station #356, water year 2008 at Station #539). However, the number of snow-covered days has not been affected significantly (red line in Fig. 3 and termed as 'control-bias-corr') with the bias correction.

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.

UEB model considers effect of wind drift by wind drift parameter but the Noah land-surface model does not incorporate any physical processes for the effect of wind drifts; consequently, the UEB's drift parameter was not included and no additional processing was not done for cases when accumulated SWE exceeded accumulated rainfall. From this point on, the simulated SWE after bias correction will be referred to as the 'control' run of the Noah LSM and will be used for evaluation of the modified approach, which is termed as 'Noah-T_s' run.

4.2 California SNOTEL sites

SWE simulation

Simulation of the Noah LSM modified with the UEB snow model is compared at SNOTEL stations and is shown in Fig. 4. The modified Noah shows substantially improved SWE estimation in terms of increasing the amount of maximum SWE as well as delaying snowmelt. However, water year 2007 (a moderate La Niño year) experiences the least amount of snow in all of the stations compared to the other six years of study, and the improvement from the modified model is not significant compared to the control run because the modified model uses available energy to melt shallow depths (less than 0.1 m) of snow.

While the modified model enhanced SWE simulation by using the Noah LSM, it also shows delayed SWE melting in few years, for example, in water year 2004 at Stations #463 and #508 and in water year 2008 at Station #508. This late melting can be partly explained by comparing the simulated SWE by the control-bias-corr model and the control model (Fig. 4) at Station #508. At this station, NDLAS precipitation was more than that observed in 2004 and 2008 and, therefore, after precipitation bias correction, the control-bias-corr model predicted less snow than the control model. In general, forcing data from NLDAS, other than precipitation, are well validated but, at this location and in these years, forcing uncertainty may still prevail. Fig. 5 shows the maximum and minimum daily temperatures observed at Stations #508 and #463 from 1 April to 20 May, 2004. During this period, NLDAS temperature data were comparatively cooler than observation, but the difference in maximum air temperature can affect the snow-melting process and time (Hamlet et al., 2005).

Nonetheless, the modified approach has improved SWE estimation. Fig. 6 shows the components of water balance-precipitation, sublimation, and snowmelt for the winter of 2001-2002 at California SNOTEL stations #356, #508, #463, and #539. During the accumulation period, snow

is lost because of both sublimation and snow melting but the later is the primary reason for control model's low SWE bias relative to the observation. As discussed earlier, the control model simulates snow melt whenever the temperature of the snowpack reaches freezing point, and then melt water immediately becomes runoff. On the contrary, in the modified approach, snowmelt commences only when the net energy relative to the melting point is positive and snow melting do not start until later in the spring season (Figs 6d, h, l, and p). Loss of snow due to submilation from modified Noah-Ts is less compared to control model, particularly during the period control model has simulated snow on the ground (Figs 6c, g, k, and o). This is because; control model applies penman equation (Wang et al., 2010) to compute snow sublimation while the modified model uses turbulent heat flux equation (Tarboton, 1994).

In the modified model, liquid water holding capacity of the snowpack was considered before the melt water becomes runoff and the effect of the liquid water content is shown in Fig. 7. The modified model was simulated with 0% and 5% liquid water content, and the difference in response is seen only during the ablation period. There is no significant change in melt outflow rate until the beginning of the melt period. The simulation run with 5% liquid water- holding capacity delays the onset of snowmelt, compared to that of 0% liquid water- holding capacity for less than a day to approximately a few days.

An additional review of the effectiveness of the modified model in predicting maximum SWE is presented in Fig. 8, where maximum-modeled SWE as a percentage of ground-observed maximum SWE is shown at the four California SNOTEL stations for seven years of the study period. Although precipitation bias correction improved model SWE estimation, the overall enhancement in maximum SWE prediction by the modified model is evident (Fig. 8). A similar comparison is shown in Fig. 9, which includes the 21 California SNOTEL stations over the

Sierra Nevada Mountains. The control model can reasonably predict SWE at locations where maximum SWE is relatively less ($SWE_{max} < 500$ mm). However, bias is more pronounced at locations with higher snowfall. The modified model has enhanced SWE estimation at all locations, but improvement is more prominent for observation stations where the maximum snowfall is between 500-1,000 mm.

Additionally, the modified model's overall predictive power to simulate SWE is described by the Nash-Sutcliffe coefficient, shown in Table 2. For all stations, the value of the coefficient is almost always positive, which again supports the accuracy of the modified model in SWE estimation.

Other variables - simulation

At the California SNOTEL sites, neither the snow-surface temperature nor the energy flux measurement are available; hence, a comparison between the control model and the modified model simulated snow-surface temperature and turbulent fluxes at SNOTEL Station #356, as shown in Fig. 10. During the month of April 2002, there is no significant difference between the simulated surface temperature of the control model and that of the modified model, although the former is simulating a colder surface compared to the modified model (Fig. 10a). Therefore, latent heat flux computed by the modified model is larger compared to that of the control model (Fig. 10e). The differences in sensible heat flux (Fig. 10c) and outgoing long-wave radiation (Fig. 10d) between the control model and the modified model are found to be small. However, a significant difference between the models can be seen in the snow-melt outflow rate (Fig. 10b). During this time period, in the control model number of melt events reduced the snowpack while modified model did not simulate any snowmelt.

Snow-covered ground can affect soil temperature, as well as moisture content of the underlying soil. Although the scope of the paper is only limited to evaluating alternative processes for snow temperature and snowmelt, soil temperature and moisture from the control and modified models are compared with respective observations at the SNOTEL stations. Fig. 13 shows the comparison of model output with observed soil temperature and soil moisture five mm below the ground at Stations #508 and #463. The control model predicts less snow and, therefore, the ground is more exposed to the cooler atmosphere (during the month of January in Figs 12 c to d). But, the ground is warmer and soil temperature is above the freezing point during most of the snow season. The observation sites initialize the measuring instrument at every water year and so for the first few months, the soil moisture is recorded as zero. Control model, with frequent snow melt event, control model simulates a higher soil moisture fraction while soil moisture content is reduced significantly (Figs 12 e to f) in the modified Noah model because of less snow melt event during the snow season. Additional analysis of improving the soil temperature and moisture content is suggested but is beyond the scope of this study.

4.3 Utah site

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.