Comparison of FASST and SNTHERM in Three Snow Accumulation Regimes

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ABSTRACT

Numerical experiments of snow accumulation and depletion were carried out as well as surface energy fluxes over four Cold Land Processes Experiment (CLPX) sites in Colorado using the Snow Thermal model (SNTHERM) and the Fast All-Season Soil Strength model (FASST). SNTHERM is a multilayer snow model developed to describe changes in snow properties as a function of depth and time, using a one-dimensional mass and energy balance. The model is intended for seasonal snow covers and addresses conditions found throughout the winter, from initial ground freezing in the fall to snow ablation in the spring. It has been used by many researchers over a variety of terrains. FASST is a newly developed one-dimensional dynamic state-of-the-ground model. It calculates the ground’s moisture content, ice content, temperature, and freeze–thaw profiles as well as soil strength and surface ice and snow accumulation/depletion. Because FASST is newer and not as well known, the authors wanted to determine its use as a snow model by comparing it with SNTHERM, one of the most established snow models available. It is demonstrated that even though FASST is only a single-layer snow model, the RMSE snow depth compared very favorably against SNTHERM, often performing better during the accumulation phase. The surface energy fluxes calculated by the two models were also compared and were found to be similar.

1. Introduction

Water stored in snowpacks and soils in the western United States is particularly important for natural ecosystems, public consumption, and industry because snowmelt accounts for approximately 80% of the soil moisture in semiarid environments in the western United States (Marks and Winstral 2001). The intricate process of snow cover depletion and soil moisture recharge is spatially and physically complex, and an assessment of its behavior is essential for water balance approximations, climate-feedback research, remote sensing applications, and hydrological modeling and forecasting (Hinzman and Kane 1991; Shook et al. 1993; Baral and Gupta 1997; Harms and Chanasyk 1998; Liston, 1999; Cline et al. 2003). Because it is impossible to physically measure the full extent and characteristics of the snowpack, numerical models are needed to help estimate the water content of the snow [snow water equivalent (SWE)] and melt-out dates. In this paper, we investigate how well the Snow Thermal model (SNTHERM), a well-established snow model, and the Fast All-Season Soil Strength model (FASST), a new soil–vegetation transfer model, capture observed snow surface temperatures as well as snow depth, SWE, and the individual surface energy terms.

SNTHERM is a multilayered one-dimensional energy and water balance point model designed to predict temperature profiles within strata of snow and frozen soil at nonforested sites (Jordan 1991). SNTHERM uses time series meteorological data combined with initial snowpack depth, density, and stratigraphy to predict snowpack energy and mass fluxes. Multiple studies have demonstrated that SNTHERM successfully simu-
lates snowpack mass and energy exchanges at diverse locations and under varying conditions, both as a stand-alone model and when coupled with models that can account for the presence of vegetation (Davis et al. 1997; Hardy et al. 1997a,b; Hardy et al. 1998; Koivusalo and Heikinheimo 1999; e.g., Colee 2000).

FASST, a year-round state-of-the-ground model, was initially developed to provide information to mobility and sensor performance algorithms for military purposes. It has since been used in nonmilitary situations (Holcombe 2004; Sawyer 2007; Frankenstein et al. 2007). FASST predicts soil moisture, ice and vapor content, and temperature as a function of depth as well as snow and ice accretion/depletion as a function of meteorological forcing and site characteristics. Incorporated into the model are a three-layer canopy and a one-layer lower vegetation (crops, shrubs, grasses) algorithm. The temperature of the lower vegetation layer is solved for using the energy balance equation discussed in section 3, whereas the canopy profiles are calculated separately. Ten low vegetation and five canopy types are currently accommodated based on the Biosphere–Atmosphere Transfer Scheme (BATS) developed by Dickinson et al. (1986). BATS was designed to be applied over an area composed of irregularly shaped polygons as well as at a single location. FASST’s snow module is based on the work of Albert and Krajeski (1998). It was mainly designed to investigate melt flow through the snow.

The fundamental operation of FASST is the calculation of an energy and water budget that quantifies both the flow of heat and moisture within the snow and soil and also the exchange of heat and moisture at all interfaces (ground–air, ground–snow, and snow–air), using both meteorological and terrain data (Frankenstein and Koenig 2004a,b; Frankenstein 2008). FASST is designed to accommodate a wide range of users, from those who have intricate knowledge of their site to those who only know the site location. It allows for 22 different terrain materials, including asphalt, concrete, bedrock, permanent snow, and the Unified Soil Classification System (USCS) soil types. At a minimum, the only weather data required is the air temperature, although FASST has never been used this way.

2. Field observations

a. Data

Field data to which the model output were compared were collected during the winter of 2002–2003 as part of the National Aeronautics and Space Administration’s (NASA) Cold Land Processes Experiment (CLPX). CLPX was developed to identify the role of snowpack in the storage of water resources by quantifying many snowpack properties, improve the representation of snow in models by taking measurements on various distributed spatial and temporal scales, provide high-quality and abundant databases of snow and soil characteristics, and improve remotely sensed measurements of snow properties and soil moisture (Cline et al. 2001). Data collection included an observational and remote sensing dataset of snow and soil conditions. The observational data were confined to three 25 km × 25 km plots (Fraser Experimental Forest, Rabbit Ears Pass, and North Park), also called mesocell study areas (MSAs; Fig. 1). Each MSA is broadly characterized by topography, vegetation, and climate, which represent a significant portion of the major global snow cover environments (Cline et al. 2001).

Each MSA contains three 1-km² intensive study areas (ISAs), with a micrometeorological station located near the center of each MSA that measures snow depth and soil moisture and temperature profiles. We used four of the nine CLPX ISA sites to explore SNThERM’s and FASST’s predictive abilities. The sites chosen were Illinois River (NI) in the North Park MSA, Buffalo Pass (RB) and Walton Creek (RW) in the Rabbit Ears MSA, and Fool Creek (FF) in the Fraser MSA.

Buffalo Pass has moderate relief, rolling hills, and mixed vegetation of coniferous and deciduous forests. The snowpacks are moderate (1 m) to deep (more than 3 m). The vegetation type in this ISA is dominated by Englemann spruce (Picea englemannii) and alpine fir (Abies lasiocarpa). The soil type is a highly organic peat, and the mean elevation is 3144 m. At the meteorological station, the terrain is broad, flat, and treeless.

The terrain within the Walton Creek ISA is similar to that of the Buffalo Pass ISA. It also is characterized by moderate-to-deep snowfall. The soil type is a gravelly sandy loam (USDA Forest Service 1994, personal communication). The meteorological tower (2950-m elevation) is located on an open gentle slope with southeasterly aspect.

Illinois River is characterized as a windy, flat aspect, low relief prairie terrain with vegetation characteristic of wet grasslands including widespread riparian areas. The snow is generally shallow and windswept, which allows for the development of frozen soils. This ISA has a mean elevation of 2480 m and a soil type of inorganic sandy, silty, gravelly clay.

Fool Creek lies within the Fraser MSA. The Fraser MSA is an area of high relief with dense vegetation, consisting of predominantly coniferous subalpine forests, alpine tundra above the tree line, and largely unforested, irrigated grazing lands in the lowest elevations. Moderate-to-deep snowpacks are typical and in-
crease with elevation (Elder and Goodbody 2004; Cline et al. 2003). The Fool Creek meteorological tower (3100-m elevation) is located in a forest clearing on a moderate (20°) slope with southerly aspect. Soil type is a well-drained gravelly–very gravelly sandy loam (Retzer 1962).

b. Methods

Data for this experiment were gathered from the fall of 2002 to the snowmelt season in the spring of 2003. Meteorological data collected as part of CLPX included air temperature, relative humidity, wind speed and direction, incident and reflected solar radiation, upwelling and downwelling longwave radiation, net all-wave radiation, soil moisture, soil temperature, snow depth, and snow surface temperature. Observations made at 30-s intervals were averaged (where appropriate) and recorded at a 10-min resolution. Snow depth, wind direction, and soil temperature were recorded as a single sample measurement at the start of each 10-min period. The snow surface temperature was measured using sensors located at approximately 1 m above the

FIG. 1. NASA CLPX study area. Buffalo Pass and Walton Creek ISAs are located in the Rabbit Ears Pass MSA. Illinois River ISA is in the North Park MSA. Fool Creek ISA is in the Fraser MSA.
expected maximum seasonal snow depth (4 m above ground in the Rabbit Ears MSA, 3 m above ground in the Fraser MSA, and 1 m above ground in the North Park MSA).

Snow depth at each site was obtained from an acoustic depth sensor. Stevens Vitel soil probes recorded 10-min soil temperature and soil moisture values at the soil surface (temperature only), and at soil depths of 0.05, 0.20, and 0.50 m. Observations were recorded using Campbell Scientific CR10X data loggers. Instrumentation specifics and greater detail of measurement techniques are found in Rutter et al. (2008). The soil type was collected from soil surveys.

Precipitation SWE measurements were not directly available at any of the sites. We therefore used the nearest available gauge data. Because the gauges were not collocated with the snow depth sites, we also estimated incoming SWE from the original snow depth data by assuming a new snow density of 100 kg m\(^{-3}\) (Thyer et al. 2004) at all of the ISA sites except Illinois River. There, from 21 February to 13 March when the average air temperature was less than \(-5^\circ C\), we assumed a new snow density of 60 kg m\(^{-3}\). Our results suggest that there is not a significant difference between rain gauge measurements and the SWE, as calculated from the depth sensor measurements and that the gauge data has less noise associated with it.

The meteorological data used in this study were previously processed to a level-1 standard, meaning that raw data that had been downloaded on an approximately monthly basis were combined into one continuous file for each tower and filtered twice for faulty values then averaged to produce hourly time steps. The Fool Creek meteorological data represent conditions under the canopy. We estimated single missing data points from the averaged dataset by calculating the arithmetic mean of the previous and subsequent points. We used a linear regression equation calculated from the previous points and the three subsequent data points to derive consecutive missing data points. If three data points were not available because they were also missing, then we used one point before and one point after the missing data to calculate the linear regression equation. Neither of these methods was applied if the observed data before and after the missing data were of identical value. In this case, we used the unchanged value in place of missing data. Erroneous data values were treated as missing observations to estimate a representative value. If observations recorded from the instrumentation were less than the instrument resolution, we rounded the value to the nearest significant figure. We used the same meteorological forcing parameters for both SNTHERM and FASST.

Snowpack density and temperature profiles were measured along with stratigraphy and grain size near each meteorological station near the end of March 2003. Snow pits could not be dug exactly at the site of the depth sensor but rather at a representative site as near to the sensor as possible. Snowpack density and temperature were measured in 0.10-m increments from the surface downward. Two density samples were collected at each increment and averaged. Snow grain size was measured using the long and short axis of a representative small, medium, and large grain from each layer. Refer to Cline et al. (2003) for more details regarding CLPX field methods.

3. Modeling

a. SNTHERM

SNTHERM has been shown to accurately predict snowpack characteristics such as snowpack ablation (Rowe et al. 1995; Hardy et al. 1998; Groffman et al. 1999; Gustafsson et al. 2001). SNTHERM calculates temperature profile changes, both within the snow and soil. However, it does not allow moisture or vapor movement within the soil, only in the snow (Jordan 1991). FASST allows for moisture and vapor flow in both media.

We initialized SNTHERM using meteorological and snowpack data collected near peak accumulation. SNTHERM requires inputs of snowpack density, temperature, grain size, and stratigraphic layer thickness. Because SNTHERM must be initialized according to stratigraphic layers, we needed to adjust the density and temperature profiles accordingly because these were measured at 0.10-m intervals. We determined average density for each stratigraphic layer by using a weighted density value according to the amount of each 0.10-m increment that falls within a given stratigraphic layer. We made similar adjustments to the temperature. We averaged the grain size for each stratigraphic layer using the length and width measurements from all three grain sizes (small, medium, and large). We divided thicker stratigraphic layers into smaller sublayers, otherwise SNTHERM overpredicted the mass balance.

Pits could not be dug at the exact location as the depth sensors, so an adjustment was made to the pit profiles to match the time series of the snow depth, which SNTHERM uses. The scaling procedure involved resizing each layer by dividing the thickness of each snowpack layer by the total snowpack depth. This ratio was multiplied by the snow depth measured from the acoustic snow depth instrument and served as the new snow depth value.

SNTHERM will not allow precipitation at the initial
time step. Thus, we added any precipitation that occurred at the beginning of the model run to the following time step. This situation occurred at the Buffalo Pass site.

b. FASST

FASST was designed primarily as a multilayer snow model. The snow model in FASST is based on the work of Albert and Krajeski (1998), which is a physically based approach that is more focused on snowmelt; it considers the physics of flow through snow, and the melt is driven by an energy budget at the snow surface that is similar to SNThERM (Frankenstein and Koenig 2004a; Frankenstein 2008). The FASST snow model considers the physics of flow through snow, and the physical approach that is more focused on snowmelt; it is similar to SNThERM (Frankenstein and Koenig 2004a), which is a physically based approach that is similar to SNThERM (Frankenstein and Koenig 2004a, b) and Frankenstein (2008). The FASST energy model and uses only an average snowpack density and grain size rather than stratigraphic layer values. Like the National Operational Hydrologic Remote Sensing Center (NOHRSC) snow model (NSM; Rutter et al. 2008), FASST calculates snowpack changes at the meteorological input data time step, which in this case is hourly. The only initial snow condition required by FASST is snow depth.

Because FASST is not well known, we will present the basic governing equations here. Readers wanting more details should refer to Frankenstein and Koenig (2004a, b) and Frankenstein (2008). The FASST energy balance equation is

\[
\frac{\partial c_p T}{\partial t} - l_{wm} \frac{\partial \theta_i}{\partial t} + l_w \rho_w \frac{\partial \theta_i}{\partial t} = \frac{\partial}{\partial z} \left[ \kappa \frac{\partial T}{\partial z} - u_w c_{p,w} T - u_i c_{p,w} (T - 273.15) \right] + c_{p,w} \rho_w (\text{sources} - \text{losses}) T,
\]

where \( T \) is the temperature (K) of the snow or soil, \( t \) is time (s), \( c_p \) is the specific heat of the soil/snow matrix (J kg\(^{-1}\) K\(^{-1}\)), \( c_{p,w} \) is the specific heat of water (J kg\(^{-1}\) K\(^{-1}\)), \( \kappa \) is the thermal conductivity of the soil/snow matrix (W m\(^{-1}\) K\(^{-1}\)), \( l_w \) is the latent heat of vaporization (J kg\(^{-1}\)), \( l_{wm} \) is the latent heat of fusion of ice (J kg\(^{-1}\)), \( \theta_i \) is the volumetric ice content (cm\(^3\) cm\(^{-3}\)), \( \theta_i \) is the volumetric water content (cm\(^3\) cm\(^{-3}\)), \( u_w \) is the vertical rate of water flow (m s\(^{-1}\)), \( u_i \) is the vertical rate of water vapor flow (m s\(^{-1}\)), \( \rho_i \) is the density of ice (kg m\(^{-3}\)), \( \rho_w \) is the density of water (kg m\(^{-3}\)), and \( z \) is depth (m) measured positive upward from sea level. The second and third terms on the left-hand side of Eq. (1) represent heat lost/gained as a result of ice formation/melting and vapor condensation/evaporation, respectively. The terms on the right-hand side incorporate temperature changes due to vertical heat conduction, water, and vapor flow, as well as plant uptake/release. The boundary conditions at the soil/snow and vegetation (crops, grass, shrubs, and so on) surfaces are

\[
F(T_g) = 0 = (1 - \sigma_f [I_g \frac{1}{\epsilon_f} (1 - \alpha_f) + \epsilon_g I_g - \sigma_g \epsilon_g \frac{1}{\epsilon_f} (T_g - T_f)] - P_g - \frac{\sigma_f \epsilon_f \epsilon_g \sigma_g}{\epsilon_f} (T_g - T_f) + H_g + L_g + l_{wm} \frac{\rho_w}{\rho_i} \frac{\partial \theta_i}{\partial t} \Delta z
\]

and

\[
F_j = 0 = \sigma_f [I_g \frac{1}{\epsilon_f} (1 - \alpha_f) + \epsilon_f I_g - \sigma_f \epsilon_f \frac{1}{\epsilon_f} (T_g - T_f)] + \frac{\sigma_f \epsilon_f \epsilon_g \sigma_g}{\epsilon_f} (T_g - T_f) + H_f + L_f + \sigma_f \epsilon_f \epsilon_g \frac{\partial T_f}{\partial z},
\]

where \( T_g \) is the ground/snow surface temperature (K); \( T_f \) is the foliage surface temperature (K); \( \epsilon_g \) is the ground/snow emissivity; \( \alpha_g \) is the shortwave albedo of the ground/snow; and \( H_g, L_g, \) and \( P_g \) are the sensible, latent, and precipitation heat fluxes (W m\(^{-2}\)), respectively, at the ground/snow surface; \( \sigma \) is the Stefan–
Boltzmann constant \((5.699 \times 10^{-3} \text{ W m}^{-2} \text{ K}^{-4})\); \(I_s^f\) and \(I_r^f\) are the total incoming solar and infrared radiation (\(\text{W m}^{-2}\)), respectively; \(H_f\), \(L_f\), and \(P_f\) are the sensible, latent and precipitation heat fluxes (\(\text{W m}^{-2}\)), respectively, at the foliage surface; \(c_p_{\text{veg}} = 3500 \text{ J kg}^{-1} \text{ K}^{-1}\) and \(k_{\text{veg}} = 0.38 \text{ W m}^{-1} \text{ K}^{-1}\) are the vegetation specific heat and thermal conductivity, respectively (Moore and Fisch 1986); and \(\varepsilon_i = \varepsilon_f + \varepsilon_g - \varepsilon_f \varepsilon_g\). The foliage fractional coverage \(\sigma_f\), shortwave albedo \(\alpha_f\), and emissivity \(\varepsilon_f\) are functions of the vegetation type (high, medium, and low) and season (winter, spring, summer, and fall).

FASST assumes a 75 mW m\(^{-2}\) constant deep-earth heat flux bottom boundary condition. The water flow rate \((v_w)\) takes into account gravity,

\[
\frac{\partial \theta_w}{\partial t} + \frac{\partial \theta_i}{\partial t} + \frac{\rho_i \partial \theta_i}{\rho_w} = \frac{\partial}{\partial z} \left[ K_{\text{sh}} \frac{\partial \Psi}{\partial z} (K_{\text{sh}} + \frac{\partial T}{\partial z}) + \frac{\partial T}{\partial z} (K_{\text{sh}} + \frac{\partial T}{\partial z}) \right] + \text{sources} - \text{losses},
\]

where \(\theta_w\) (cm \(^3\) cm\(^{-3}\)) is the volumetric water content, \(K_{\text{veg}}\) is the temperature-dependent vapor gradient (m\(^2\) K\(^{-1}\) s\(^{-1}\)), and \(K_{\text{sh}}\) is the pressure-dependent vapor con-
ductivity (m s\(^{-1}\)). The flow boundary conditions at the surface and at the bottom of the soil column are

\[
q_{\text{top}} = -E + C_r + P_r + (h_{\text{pond}} + h_{\text{i,melt}} + h_{\text{s,melt}})/\Delta t \quad \text{at} \quad z = 0
\]

\[
q_{\text{bot}} = K_{\text{sh}} \sin(\text{slope}) \quad \text{at} \quad z = z_{\text{bot}},
\]

where \(E\) (m s\(^{-1}\)) is the evaporation rate; \(C_r\) (m s\(^{-1}\)) is the condensation rate; \(P_r\) (m s\(^{-1}\)) is the rate of precipitation; \(h_{\text{pond}}\) (m) is the head as a result of water collecting on the surface; \(h_{\text{i,melt}}\) (m) and \(h_{\text{s,melt}}\) (m) are the heads as a result of melting ice and snow, respectively; and \(\Delta t\) (s) is the time step. No water accumulates if the ground is sloped, and any water that falls on the surface but does not infiltrate becomes runoff.

Like SNTHERM, the meteorological time step is subdivided to meet convergence criteria. If snow is present and the surface temperature is above 273.15 K, the surface energy balance equation is recalculated with the temperature set to 273.15 K; the excess is used to melt or sublimate the snow, depending on the temperature.

FASST allows users to input soil properties, including albedo, density, thermal conductivity, and use model-supplied default values or a combination of both. In the SNTHERM runs, we chose the default soil type of “7,” or sand. To match SNTHERM as closely as possible, we provided soil density (1600 kg m\(^{-3}\)), porosity (0.407), albedo (0.40), emissivity (0.90), quartz content (0.40), thermal conductivity (0.184 W m\(^{-1}\) K\(^{-1}\)), specific heat (730.0 J kg\(^{-1}\) K\(^{-1}\)), and maximum water content (0.407), which we assumed to be equal to the porosity. For all other parameters needed by FASST, we used the model default values for an “SM,” or silty sand, soil (S. Frankenstein 2008, unpublished manuscript; available online at ftp://ftp.erdc.usace.army.mil/pub/PERM/FASST/tech_doc/fasst_user_document.doc). We initialized soil temperature and moisture at the surface and 0.05, 0.20, and 0.50 m below the surface.

4. Results and discussion

For the deeper snowpacks, we began the FASST and SNTHERM simulations near the end of March, corresponding to near-peak accumulations and when snow pits were dug at Buffalo Pass, Walton Creek, and Fool Creek. For the ephemeral snow at Illinois River, we began the models on 21 February 2003, during the first field initiative. We used the same meteorological forcing data for both models. The main differences in model initialization centered on the level of detail concerning the snowpack properties. As we discussed previously, SNTHERM requires detailed knowledge of the snowpack, whereas FASST only needs the total snow
depth. In an effort to keep the SNTHERM and FASST modeling scenarios as similar as possible, we ran FASST in two modes: one in which we used the measured upwelling infrared radiation (FASST) and the other in which we let the model calculate it (FASSTi), as does SNTHERM.

We judged the performance of FASST against SNTHERM, and the observed total acoustic measured snow depth at four of the nine CLPX ISAs using the maximum absolute difference and the root-mean-square error \( \text{RMSE} = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (M_i - O_i)^2} \), where \( M_i \) and \( O_i \) are the model and observed values, respectively. The measurement resolution of the observations is 0.01 m. We investigated the model behavior over the total period of record at each site. On a more figurative level, we compared the FASST and SNTHERM surface energy fluxes to one another and the FASST and SNTHERM computed surface temperatures against the IR sensor values.

\( a. \) Snow depth and snow water equivalent

The snow depths plots are shown in Fig. 2, and the SWE curves are shown in Fig. 3. The time spans between the sets of dashed lines in Figs. 2a–2d and 3a–3d represent the sections in which we will look at the surface energy fluxes and temperatures. At Illinois River where the snowpack is more ephemeral, SNTHERM overall had a slightly smaller RMSE but larger maximum difference compared to observations than FASST and FASSTi (0.027 versus 0.034/0.037 m RMSE, 0.18 m versus 0.15/0.16 m maximum difference; Table 1). SNTHERM performs better than FASST and FASSTi during days 52–73 when there is notable accumulation (0.034 versus 0.058/0.060 m RMSE, 0.07 versus 0.15/0.16 m maximum difference; Table 1). Looking at Fig. 2a during the first accumulation period, FASST does well until day 57 when the measured snow depth decreases, whereas the modeled depth continues to increase. SNTHERM also does well until day 57, at which point it underpredicts until day 62 then it overpredicts until day 65. At this point, both FASST model runs predict equal snow depth and similar melt patterns with SNTHERM ablating slightly slower than FASST. Both models melt-out faster than observed (−2.71/−2.79 days for FASST/FASSTi and −1.92 days for SNTHERM; Table 2). If we look at the SWE during this first snow event (Fig. 3a), the two models differ greatly with SNTHERM predicting a maximum SWE of 0.01 m in an almost cyclical behavior, whereas FASST indicates that the SWE increases with increasing snow depth then decreases as the snow melts. No SWE observations are available at this site for comparison. Table 3 shows for the whole observation period how well the
models correctly predict snow versus no snow at each hourly time step. The difference between when the models predict that no snow is on the ground and the observations say otherwise is a result of the early melt-out of the first snow buildup and the models missing some of the smaller snow accumulation events. Overall, both models do very well predicting when snow is present. As mentioned previously, FASST also has a wind ablation function. Of the four CLPX sites studied, the highest modeled wind ablation rates occurred at Illinois River (0.01 m). This occurred on day 62 when the recorded hourly wind speed was more than 11 m s\(^{-1}\).

At the two Rabbit Ears Pass MSA sites (Figs. 2b and 2c), both models tended to overpredict the snow depth during the accumulation phase, although FASST overpredicted less frequently than SNTHERM and overpredicted more frequently at Walton Creek than at Buffalo Pass. The SWE comparisons are shown in Figs. 3b and 3c. The SNTHERM initial profiles were taken directly from the pit data where the SWE was measured. It is interesting to note that for Buffalo Pass, the SNTHERM and FASST/FASSTi SWE curves are within 0.01 m of each other until day 114.5. The maximum difference in this phase is 0.09 m. FASSTi and SNTHERM again coincide between days 148 and 162, whereas FASST and SNTHERM are the same between days 143–149, day 168, and melt-out. Comparing the models to the observations, both do well predicting the SWE, with the maximum error being on the order of 0.01 m. For Walton Creek, the SNTHERM SWE curve is above both FASST curves until melting begins when the curves coincide. Both models, again, do very well capturing the measured values. At Buffalo Pass and Walton Creek, both SNTHERM and FASST capture the observed diurnal freeze–thaw patterns during ablation. Also at both sites, the FASST simulation using the observed upwelling IR and SNTHERM essentially melt-out on the same day, slightly after the FASSTi run and at the observed time. At all four sights, the FASST model run using the observed upwelling IR melted slower than the run in which the FASST model calculates this term. These observations are corroborated by the RMSE and maximum difference between observations and simulations for these two sites (Table 1). For both the Buffalo Pass and Walton Creek, the FASST/ FASSTi RMSE and maximum difference are smaller than the SNTHERM values during the accumulation period. During the melt phase at Walton Creek, the SNTHERM RMSE and maximum difference values lay between FASST and FASSTi (0.058/0.087 versus 0.071 m RMSE and 0.13/0.19 versus 0.17 m maximum difference), whereas at Buffalo Pass, SNTHERM is slightly better than FASST and FASSTi (0.131/0.075

![Fig. 3. SWE comparisons between the observed, SNTHERM, and FASST for ISAs (a) Illinois River, (b) Buffalo Pass, (c) Walton Creek, and (d) Fool Creek.](image-url)
versus 0.064 m RMSE and 0.28/0.19 versus 0.18 m maximum difference). During the last portion of the ablation period, SNTHERM and FASST melted slower than observed, melting 2.88/2.96 days later for Buffalo Pass and 0.83/0.79 days later for Walton Creek (Table 2). FASSTi melted slightly faster, 0.42 days for Buffalo Pass and 0.83 days for Walton Creek than observed. Reasons for these differences will be discussed further when we investigate the surface energy flux terms.

The most difficult snowpack for both models to capture was at Fool Creek (FF), which can be seen in Fig. 2d. Using the measured hourly meteorological data, SNTHERM grossly underestimates the snow depth at all times, whereas FASST, in general, overestimates it during the accumulation phase and underestimates it during the ablation period. Unlike the Rabbit Ears Pass MSA sites where FASST melted slower and FASSTi melted faster, both FASST and FASSTi ablated more rapidly than observed (−2.75 and −3.17 days, respectively; Table 2). Figure 3d shows the calculated SWE from both models. FASST overestimates the SWE at the beginning of the simulation by 0.15 m, but it is only 0.05 m above the measured value at the beginning of the ablation phase. What is immediately apparent is that the initial measured SWE, and thus SNTHERM’s SWE, is much lower than FASST’s SWE. If we changed the initial profile so that SNTHERM’s initial SWE

<table>
<thead>
<tr>
<th>ISA and time span (day number UTC)</th>
<th>FASST RMSE (m)</th>
<th>FASST max difference (m)</th>
<th>SNHERM RMSE (m)</th>
<th>SNHERM max difference (m)</th>
</tr>
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<tbody>
<tr>
<td>NI 052 1100 to 132 2300</td>
<td>0.034</td>
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<tr>
<td>RB 088 1000 to 140 0000</td>
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<td>0.17</td>
<td>0.177</td>
<td>0.37</td>
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<td>RB 140 0000 to 181 2300</td>
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<td>0.28</td>
<td>0.064</td>
<td>0.18</td>
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<tr>
<td>RW 087 2225 to 161 2325</td>
<td>0.081</td>
<td>0.22</td>
<td>0.211</td>
<td>0.40</td>
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<tr>
<td>RW 087 2225 to 140 1825</td>
<td>0.089</td>
<td>0.22</td>
<td>0.246</td>
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<td>RW 140 1825 to 161 2325</td>
<td>0.058</td>
<td>0.13</td>
<td>0.071</td>
<td>0.17</td>
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<tr>
<td>FF 082 2125 to 173 1025</td>
<td>0.118</td>
<td>0.31</td>
<td>1.010</td>
<td>1.73</td>
</tr>
<tr>
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<td>0.28</td>
<td>1.230</td>
<td>1.73</td>
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<tr>
<td>FF 130 1225 to 173 1025</td>
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<td>0.31</td>
<td>0.687</td>
<td>1.47</td>
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<tr>
<th>ISA</th>
<th>Observed melt-out day</th>
<th>FASST melt-out lead(−)/lag(+) (days)</th>
<th>SNHERM melt-out lead(−)/lag(+) (days)</th>
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</thead>
<tbody>
<tr>
<td>Illinois River</td>
<td>73.375 (March 13)</td>
<td>−2.71</td>
<td>−1.92</td>
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<tr>
<td></td>
<td></td>
<td>−2.79</td>
<td></td>
</tr>
<tr>
<td>Buffalo Pass</td>
<td>175.5 (June 22)</td>
<td>+2.96</td>
<td>+2.88</td>
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<tr>
<td></td>
<td></td>
<td>−0.42</td>
<td></td>
</tr>
<tr>
<td>Walton Creek</td>
<td>154.9 (June 4)</td>
<td>+0.79</td>
<td>+0.83</td>
</tr>
<tr>
<td></td>
<td></td>
<td>−0.83</td>
<td></td>
</tr>
<tr>
<td>Fool Creek</td>
<td>152.9 (June 2)</td>
<td>−2.75</td>
<td>−3.17</td>
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</tbody>
</table>

Table 2. Melt-out date comparisons between observed, FASST and SNHERM. The second line in the FASST columns is for the model runs where emitted IR was calculated.
matched FASST’s, we could delay the time until melt initiated and also slow the rate but SNTHERM still melted too quickly. We also tried making the initial temperature profile colder but this also had no long-term effect; at this point, it is not entirely clear why. We will discuss this further in the next section when we investigate the surface energy flux terms.

b. Surface energy fluxes and temperature

For the two Rabbit Ears MSAs, we conducted in-depth analyses of the surface temperature and energy flux terms during both a section of the accumulation and ablation periods. For the Illinois River site, we concentrated on the two largest accumulation events, whereas for Fool Creek, we looked at the beginning of the time series to try to determine what caused SNTHERM to perform poorly. The results are presented in Figs. 4–10. The 10-min “observed” surface temperature from the IR sensor is very noisy, but it still allows for quantitative comparisons.

Table 4 lists how the two models calculate the individual surface energy terms. For all of the sites investigated, there was essentially no difference in the net shortwave radiation; therefore, we will not present the comparisons, despite the fact that FASST and SNTHERM calculate the surface albedo differently. This is because we used measured values for both the incident and reflected solar radiation. Thus, for the CLPX datasets tested, SNTHERM calculated the albedo as

\[ \alpha = \min(I_{\text{irr}}/I_{\text{ir}}, 1) \]

where \( I_{\text{irr}} \) is the incident shortwave radiation and \( I_{\text{ir}} \) is the reflected shortwave radiation. For FASST, if \( I_{\text{irr}} > I_{\text{ir}} \), then \( \alpha = I_{\text{irr}}/I_{\text{ir}} \) no matter what the surface type. If this is not the case—which occurred occasionally at very low sun angles with the four CLPX meteorological datasets tested—then a different method is used. If snow is falling during the time step then \( \alpha = 0.80 \) else \( \alpha = \min[1, \max(\alpha_{\text{ir}}, \alpha_{\text{irr}})] \), where \( \alpha_{\text{ir}} \) is a snow albedo calculated using the method of Douville et al. (1995) and \( \alpha_{\text{irr}} \) is a snow albedo calculated using the surface temperature dependent method of Roesch (2000). More details concerning how FASST and SNTHERM calculate the albedo as well as the sensible and latent heat terms may be found in Jordan (1991) and Jordan et al. (1999), and Frankenstein (2008) and Frankenstein and Koenig (2004a,b), respectively.

1) Illinois River

Figures 4a and 5a show the difference between the SNTHERM results, the two FASST model runs, and the observed snow depth for the two largest snow accumulation events at Illinois River corresponding to days 57–67 and 113–116, respectively. Very little difference is seen between the models between days 113 and 116. Between days 57 and 67, SNTHERM does better until day 65 when the snow starts to melt, at which point the predicted snow depths from FASST and SNTHERM are similar. Looking at the surface temperature between days 57 and 61.5 (Fig. 4b), both models are warmer at night than the temperatures observed with the IR sensor. It is harder to see a trend during the day. After about day 61.5, the models do very well capturing the observations except when the IR sensor indicates above-freezing surface temperatures when snow is present. Overall, the models tend to perform similarly, although SNTHERM is always colder than FASST. We see the same model behavior between days 113 and 116 in Fig. 5b.

Figures 4c–4f and 5c–5f investigate how the two models quantify the individual and net surface energy flux. In Figs. 4c and 5c, the “FASST” curve corresponds to the measured net longwave radiation. From days 61.5 to 67, both models do very well simulating the observations, reinforcing the results presented in Fig. 4b. Before that, SNTHERM and FASSTi perform equally well during the day, whereas SNTHERM does better at night—again reiterating what was seen in Fig. 4b. In Fig. 5c, both SNTHERM and FASSTi perform equally well. The sensible heat flux is investigated in Figs. 4d and 5d. No measurements are available. Between days 113 and 116, the models agree extremely well with one another. Between days 57 and 67, SNTHERM overall calculates higher sensible heats. These differences are mainly a result of the differences in simulated surface temperatures but also a result of how the models parameterize the drag coefficients \( C_{\text{Hr}} \) and \( C_{\text{Dh}} \) for SNTHERM and FASST, respectively (Table 4). SNTHERM iterates for \( C_{\text{Hr}} \) following the method outlined in Jordan et al. (1999). Because this can be numerically costly, FASST (Frankenstein 2008) combines the algebraic methods outlined in Mascart et al. (1995), Louis (1979), and Jacobson (2005) to calculate \( C_{\text{Dh}} \).

During the snow accumulation event on days 113–
116, FASTT and SNTHERM calculate almost identical latent heat fluxes (Fig. 5e). Between days 57 and 67 (Fig. 4e), the models calculate similar trends in the latent heat flux, whereas SNTHERM is slightly less negative than FASTT at most times.

Figures 4f and 5f plot the net surface energy flux along with the precipitation events during the two periods of interest. From days 57 to 67, the largest differences (~40 W m⁻²) between the two models occur during the accumulation phase and at night. As expected based on the above discussion, the models behave essentially the same between days 113 and 116. Comparing Figs. 4f and 5f, the magnitude of the net surface energy is much larger in the latter, as the incoming solar (shortwave) radiation increases with the progression of spring.

2) BUFFALO PASS

We chose the two 10-day periods spanning the days 100–110 and 143–153 for intense study. The first period is during the accumulation phase, and the second period is during the ablation period. As noted earlier in
our discussion on snow depth, SNTHERM produced a deeper snowpack than observed, whereas FASST/ FASSTi calculated more snow until day 105, followed by less snow then measured (Fig. 6a). During the ablation phase, both models underpredicted the snow depth from days 143 to 149.5, at which point FASST overcalculated it (Fig. 7a). Also noted in Fig. 7a is that FASST and SNTHERM agree very well between days 143 and 147.5, whereas from days 148.5 to 163, the FASSTi and SNTHERM curves are nearly identical. From days 100 to 110 and from days 143 to 153, FASST and SNTHERM calculate daytime surface temperatures at—or nearly at—the melting point (273.15 K). During the accumulation period and the beginning of the melt phase, the observed surface temperatures tend to be a bit colder than 273.15 K but agreement between both models is good. At night, when it is not snowing, FASST tends to be warmer and SNTHERM tends to be colder than observed. SNTHERM tends to do better at predicting the surface temperature than FASST. These same trends were observed during the first snow event at Illinois River.

The net longwave radiation for the two periods is shown in Figs. 6c and 7c. During large—or smaller but
longer duration—precipitation events, both FASSTi and SNTHERM agree very well with observations (FASST). For the larger snow falls, the net longwave radiation is nearly zero. At other times, FASSTi and SNTHERM agree well with one another but have more infrared radiation leaving than is impinging on the surface than is observed. This is especially true during the ablation period.

The sensible heat flux calculated with the two FASST runs agrees well with the SNTHERM result during the day and larger precipitation events in the accumulation phase (Fig. 6d), although the FASST results are a bit noisier. As with Illinois River, the periods of greatest difference occur at night when SNTHERM predicts colder snow surface temperatures than FASST. Overall, the two models calculate similar sensible heat fluxes during the ablation period, although SNTHERM’s values tend to be slightly higher (~5 W m⁻²) at night.

**Fig. 6.** Buffalo Pass ISA comparison between SNTHERM, FASST and FASSTi for days 95–115. Modeled minus measured (a) snow depth (m), (b) surface temperature (K), (c) net longwave radiation (W m⁻²), (d) sensible heat (W m⁻²), (e) latent heat (W m⁻²), and (f) net surface energy flux (W m⁻²).
Again, this difference is minimized during precipitation events. Notice that when the net longwave radiation is negative, the sensible heat flux is positive and vice versa.

The latent heat fluxes are presented in Figs. 6e and 7e. The two models agree very well in both the ablation and the accumulation phases, with the maximum differences being on the order of 10 W m\(^{-2}\). When these differences do occur, SNTHERM almost always simulates a larger latent heat flux than FASST during the accumulation period, and the opposite is true in the melt phase. There is virtually no difference in the net surface energy balance calculated by the two models (Figs. 6f and 7f). SNTHERM, in general, loses more energy than FASST at night, although the daytime highs are identical.

3) WALTON CREEK

The behavior of SNTHERM and FASST at this site is comparable to that at Buffalo Pass, which is expected because the two sites are closely spaced and have simi-
lar characteristics. We chose the two periods spanning days 105–115 and 140–150 for intense study. As with Buffalo Pass, SNTHERM tends to consistently overpredict snow depth during the accumulation phase, whereas FASST both over- and underpredicts the measured values (Fig. 8a). Overall, FASST is better at modeling the observations than SNTEHRM during this period. As with the Buffalo Pass and Illinois River sites, FASSTi does slightly better than FASST when the model overpredicts the snow depth and worse than FASST when the opposite is true. Also in keeping with the other CLPX sites discussed, FASSTi melts out faster than FASST and captures the melt-out date better than FASST or SNTHERM, whereas FASST and SNTHERM display similar melt trajectories (Figs. 2c and 9a). When the measured IR sensor surface temperatures are greater than 265 K, corresponding to precipitation events, both models did very well capturing
the observations (Figs. 8b and 9b). On colder nights, SNTHERM does better than FASST, and we see patterns like those observed at Buffalo Pass. Rarely does SNTHERM predict nighttime surface temperatures that are warmer than observed, whereas FASST almost always does.

Between days 105 and 110, both SNTHERM and FASSTi do very well at modeling the measured net longwave radiation (the FASST curve in Fig. 8c), especially during large precipitation events and at night. When they don’t agree, SNTHERM tends to overpredict the measurements, whereas FASSTi underpredicts. The maximum differences though are on the order of 20 W m$^{-2}$. During the ablation phase (Fig. 9c), both models tend to overpredict the measurements and perform similarly, as was seen at Buffalo Pass. If anything, FASSTi does slightly better at predicting net longwave radiation than SNTHERM during the several small precipitation events during this period. These results corroborate the surface temperature information shown in Fig. 9b.

The modeled sensible heat fluxes are shown in Figs. 8d
and 9d. As with the net longwave radiation discussed in the previous paragraph, the models predict similar values. Differences occur during colder nights, which also correspond to periods when it is not snowing, when the SNHERM values are 10–15 W m$^{-2}$ larger than FASST’s. The SNHERM and FASST latent heat fluxes (Figs. 8e and 9e) agree with one another, especially during the ablation period. There is some “noise” in the FASST results associated with wind speeds less than 1 m s$^{-1}$.

The SNHERM and FASST/FASSTi calculated net surface energy fluxes are shown in Figs. 8f and 9f for Walton Creek. Very little difference is seen between the two models, during either the ablation or the accumulation periods. The largest disagreement occurs on day 111, when SNHERM predicts about 30 W m$^{-2}$ more energy leaving the surface than FASST/FASSTi. This is partly a result of discrepancies in the latent and sensible heat fluxes. As with the modeled net surface energy at Buffalo Pass, SNHERM almost always loses more heat at night than FASST.

4) FOOL CREEK

By looking at the individual surface energy terms, we will try to ascertain why SNHERM failed to capture...
Table 4. Comparison of FASST and SNTHERM surface energy terms, where $I_s^+$ is incoming shortwave radiation ($I_s^+$); $I_s^-$ is reflected shortwave radiation; LW = longwave (infrared) radiation; $T_a$ is air temperature (K); $W$ = wind speed (m s$^{-1}$); $\rho_w$ = air density (kg m$^{-3}$); $c_{p,a}$ = specific heat of air (J kg$^{-1}$ K$^{-1}$); $l$ = latent heat of evaporation/sublimation (J kg$^{-1}$); RH$_g$ = relative humidity of the surface; $q_s$ = specific humidity of air; $q_h$ = specific humidity of the surface assuming that it is saturated; $C_p$ and $C_f$ = sensible and latent heat drag coefficients, respectively, for FASST; and $C_{hr}$ and $C_{fr}$ = sensible and latent heat drag coefficients, respectively, for SNTHERM; $q_{sen}$ is the sensible heat coefficient; frh is the surface wetness factor for SNTHERM; and $M_s$ is the surface wetness factor for FASST.

<table>
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<tr>
<th>Energy term</th>
<th>FASST</th>
<th>SNTHERM</th>
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<tr>
<td>$I_s^+$</td>
<td>measured</td>
<td>measured</td>
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<tr>
<td>$I_s^-$</td>
<td>albedo $\times$ (SW down)</td>
<td>albedo $\times$ (SW down)</td>
</tr>
<tr>
<td>LW down</td>
<td>measured, $I_s^-$</td>
<td>measured, $I_s^-$</td>
</tr>
<tr>
<td>LW up</td>
<td>$(1 - e_s)(LW\text{ down}) + e_s\sigma T_g^4$</td>
<td>$e_s\sigma T_g^4$</td>
</tr>
<tr>
<td>Sensible</td>
<td>$q_{sen}(T_a - T_g)$</td>
<td>$q_{sen}(T_a - T_g)$</td>
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<tr>
<td>Latent</td>
<td>$\rho_a C_p W_l(q_h - M_{f,frh})$</td>
<td>$\rho_a C_p W_l(q_h - frh)$</td>
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<td>$M_s$</td>
<td>${RH_g}$</td>
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sured albedos result from adjustments in both the incoming and reflected solar radiation because of slope effects. The new albedos are much higher than the old ones for both models, although SNTHERM’s albedos tend to be higher than FASST’s and they also exhibit more variation. The calculated reflected solar radiation $I^\uparrow_\text{s}$ is shown in Fig. 11c for days 82–95. The line shows the 1:1 fit between the two models and the observations. As with the albedo, the offset of the original model reflected solar radiation is different than the measurements because of slope adjustments within SNTHERM and FASST. Differences between the two models’ calculated values is directly related to albedo because $I^\uparrow_\text{s} = \alpha I^\uparrow_\text{f}$. As discussed in the beginning of this section, FASST combines several methods, both of which are based on a “bulk” albedo, which are valid over the entire shortwave spectrum, whereas SNTHERM weights the components from the visible and near-infrared wavelengths to arrive at its albedo (Jordan 1991). Either way, the calculated values from both models are greater than observed, resulting in a much lower net radiation balance at the surface. The effect of this can be seen in Fig. 11d, where the net surface radiation between the two scenarios is presented. The daytime net surface radiation with both FASSTiu and SNTHERMu is much smaller than FASSTi and SNTHERM, whereas the nighttime values are similar. The main reason for the smaller daytime energy flux is principally a result of the lower net shortwave radiation flux, although both SNTHERM and FASST exhibit smaller changes in the other surface energy terms as well.

5. Conclusions

It is evident from the previous discussions that both models do a very good job at predicting the melt-out date, snow depth, and SWE, as demonstrated in the results shown in Tables 1 and 2 and Figs. 2 and 3. The models seem to do equally well at predicting snow depth at Illinois River, where the snowpack is characterized as ephemeral with both SNTHERM and FASST melting faster than observed. When both the measured incoming and reflected solar radiations are used to drive the models, FASST did better at Buffalo Pass, Walton Creek, and Fool Creek during the accumulation period. Both models do very well at predicting the slope and diurnal oscillations in the ablation phase at the two Rabbit Ears ISAs, whereas SNTHERM becomes unstable at Fool Creek, melting out much quicker than observed. In all cases, FASSTi melts quicker than FASST, with the former predicting melt-
out before the actual date, whereas FASST and SNTHERM calculate melt-out after the observed time except at Fool Creek, where all runs melt-out prematurely.

If we allow FASST and SNTHERM to calculate the reflected solar radiation, as was done at Fool Creek, then SNTHERM does better than FASST during the accumulation phase, whereas the opposite is true during ablation. Both models melt much slower than observed in this mode. To see if this behavior was true at the other sites, we did the same thing at Buffalo Pass, where both models performed extremely well. Although not shown, we see essentially no difference in the two FASST predicted snow depths at Buffalo Pass until about day 138, when the FASSTiu run ablates slower than FASSTi, melting out one week later. The two SNTHERM curves diverge around day 100, with SNTHERMu calculating greater snow depths than the original SNTHERM. At the end of the SNTHERMu run, there is still nearly 1.5 m of snow remaining. These results suggest that both models may need to reevaluate how they quantify the snow albedo under melt conditions.

The flux and surface temperature information is more difficult to decipher. SNTHERM overall does better at predicting the snow surface temperature on colder nights than FASST. During the day or when it is snowing, both models do equally as well. SNTHERM tends to lose more energy from the surface at night than FASST except when it snows. At these times, the models are nearly identical, unless the snowfall is sporadic or less than 1 mm h⁻¹. This is true even at Fool Creek, where SNTHERM melted too quickly. Clearly something else is happening within the model to cause this behavior.

Even though FASST was not designed as a snow model, it clearly performs well enough to be used as one, unless more detail is desired concerning changes in internal properties as a function of depth because it is a single-layer model. It requires less initial information about the snowpack than SNTHERM, and FASST is also numerically more stable. FASST is well suited for use in snowmelt and SWE investigations.

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