Improved Subgrid Scale Modeling of Surface Energy Balance over Snow

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ABSTRACT

Improvements in modeling the surface energy fluxes with a hybrid boundary-layer scheme have shown that high-resolution modeling in time and space can improve the timing and mass of the modeled snowmelt. The current version of the model's surface energy balance parameterization includes separate energy balance computations over partially snow-covered and non-covered surfaces, including the radiative fluxes, heat and mass fluxes from turbulent transfer, precipitation and surface melt. The effect of including separate snow-covered areas increases the distinct separation between the remaining snowpack and bare ground during the melt season. As with the previous version, model tests are conducted using field observations over snow cover from the Colorado Rockies from the CLPX (Cold Land Processes Experiment) field data. The effects are significant for regions of sporadic snow that does not completely cover bare ground, and with partial open-water subgrid areas. This approach should permit surface process models to include these subgrid snow-covered areas to be modeled with greater fidelity.

Keywords: snow modeling, subgrid processes, atmospheric boundary layer, turbulent energy transfer

INTRODUCTION

Forecast predictions of surface energy fluxes over snow in mountainous terrain on the horizontal scale of 1 km and smaller is limited by multiple factors: inadequate information on terrain features (landscape, vegetation, surface characteristic), the representation of atmospheric physics and air-surface interactions at this scale, and the intrinsic unpredictability created by subgrid-scale turbulence phenomena. In producing meteorological forecasts within the temporal and spatial limits of predictability, typically 1-12 hours for mesoscale forecasts at the 10 km to 20 km scale, it is assumed that improving the input data provided to models and improved model physics can produce more accurate forecasts. On the microclimate scales below 0.5 km, the rapid adjustment of the atmosphere and surface conditions are likely dominated by the surface interaction and turbulence processes over time scales between several seconds to 0.5 hour.

This approach uses an ensemble of physical model parameterizations to determine the distribution of energy fluxes at the 1 km scale for the lowest 1 km of the atmosphere. The physical parameterizations that will be considered for the 1-km scale fluxes include the air-surface heat and moisture transfer, vertical turbulent and convective mixing. The vertical stability and turbulent mixing criteria will be used to determine whether the local boundary-layer effects have significant effect over the larger mesoscale forcing. Each of these parameterizations can be computed at the sub- 1 km scale, and used to determine the net energy fluxes over the snow pack.

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The significance of this approach is that it moves beyond the limitation that the boundary-layer variables have to be treated as uniform at the mesoscale model resolution, and it provides an alternative approach to fully dynamic modeling for the terrain-state predictions. Statistical or dynamic downscaling of meteorological variables from coarse resolution to fine resolution models is a common problem. The pseudo-prognostic model approach described here would determine the boundary-layer variables on the scale determined by the characteristic length scales of the terrain data at 1 km. Computing the vertical processes in the model is significantly faster than the full dynamical modeling at high resolution of 1 km. Alternative approaches to this problem have been either model-observation regressive statistics (model-output statistics), which only succeed where data is available for regression, or using statistical distribution ensembles of the subgrid variables, which lack the physical models underpinning the distribution of temperature and moisture in relation to terrain, and are therefore insensitive to the particular weather regime in place.

MODEL DESCRIPTION

The hybrid boundary-layer model computes the temperatures and humidity at 3 vertical layers in atmosphere between the surface and the height of the meteorological input data (Z_{met} typically 30 m to 100 m). The hybrid boundary-layer model uses only the turbulent heat transfer parameterization from the Advanced Weather Research and Forecast (WRF) model (Skamarock et al. 2005) to update the surface temperature and lowest-layer layer, N=1. The vertical mixing between adjacent layers (*Z1, Z2, Z3*) are determined by thermal instability and turbulent mixing coefficients. The heat fluxes, T_{sfc} and T_{air} over snow cover, bare ground, and water surfaces are computed independently on the 10-minute timestep with concurrent temperatures at *Z1*, (Figure 1). These independent surface flux calculations provide greater subgrid scale information on heat fluxes than is available from the single surface over snow-only or ground-only.

The meteorological forcing at the upper layer Z_{met} is presently in the form of a relaxation time constant, which restores T_1 and q_1 towards the meteorological input variables T_{met} and q_{met} with a time constant (K_{met}) between 0.5 day and 3 days. The heat and moisture vertical exchanges between adjacent vertical levels (Z1 and Z2, etc) are parameterizations of the eddy mixing terms

$$\overline{\rho T' w'} = -\rho K_v \frac{\partial T}{\partial z} \quad , \quad \overline{\rho q' w'} = -\rho K_v \frac{\partial q}{\partial z}$$

where K_v is the vertical mixing coefficient determined from the vertical instability based on the total moist static energy in each layer. The temperatures at each layer are adjusted step-wise from lowest to highest, partially reducing the instability at each increment and timestep.

For this model version, T_{sfc} is computed from a simple slab heat-storage equation that assumes a constant ground-layer heat capacity and ground-layer thickness. The meteorological inputs at Z_{met} include F_{solar}, the visible solar radiative flux, F_{long}(down) the downwelling longwave radiative flux. F_{long}(up) is computed from σT_{sfc}^4. For now, the mixed-layer model atmosphere is assumed to be transparent to visible and longwave radiation, though future versions would have shortwave and longwave effects from low clouds and fog.

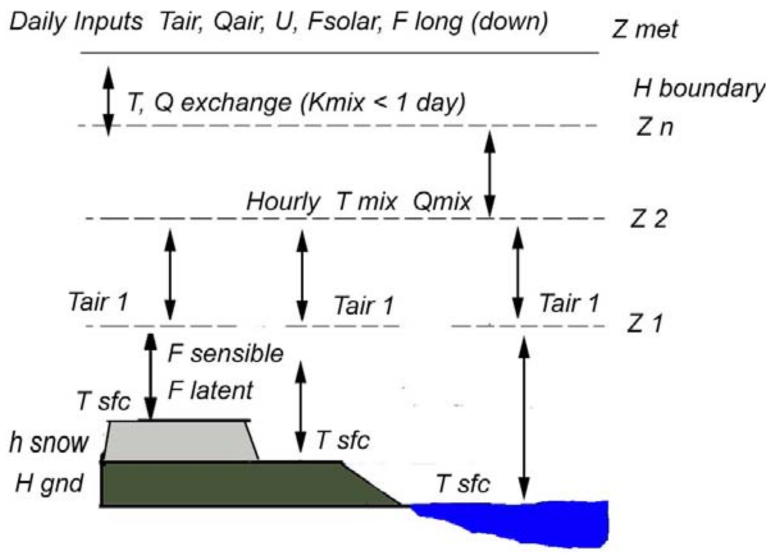

Figure. 1. Schematic of hybrid boundary-layer model with vertical layers Z1-Zn and Zmet, and T_{air} computed separately over snow, ground and water surfaces, which are then combined into a mixed T_{air} at level 2.

DATA

The meteorological data input at Z_{met} is taken from the Cold Land Processes Experiment (CLPX) field experiment data from the Fraser forest HQ site. The CLPX Intensive Study Area (ISA) Main Meteorological Data (Elder, K. and A. Goodbody. 2004) contains meteorological observations at ten sites throughout the Small Regional Study Area (SRSA) of CLPX. The data and results from the Fraser HQ site between 20 September 2002 and 1 October 2003, are shown in these figures. The measurements made at 10 m above ground level (air temperature, relative humidity, radiation, wind speed, and direction) are used to drive the hybrid boundary-layer model over the simple snow-slab model.

MODEL RESULTS

Hybrid boundary-layer model with CLPX meteorological forcing

The hybrid boundary-layer model with a 10-minute timestep was run with CLPX data sampled at 6-hour intervals to determine the effect of the model's temperature adjustment to longer timesteps. The model's boundary-layer air temperature and the surface temperature (Figure 2) respond to the radiative and sensible heat fluxes on the 10-minute timescale, which improves the temporal resolution over the fixed 6-hourly meteorological input data.

The radiative and turbulent heat fluxes (Fig. 3) in the model show the effect of the stability-dependent heat transfer coefficients. The magnitude of the sensible-plus-latent heat fluxes (black line) are greater than $|-5\ Wm^{-2}|$ (negative fluxes cooling the surface) during instability (Tsfc > Tair), and less than 5 W m^{-2} for stable conditions (Tsfc < Tair).

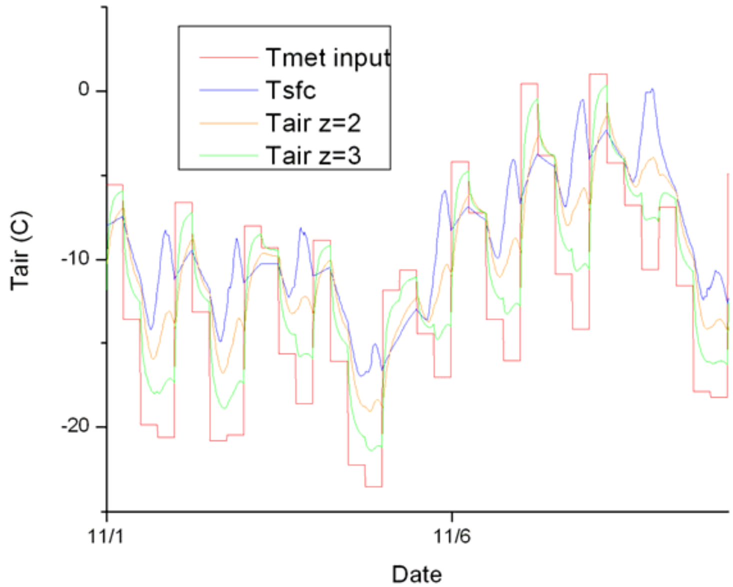

Figure 2. CLPX air temperature (*Tmet*) at 6-hourly intervals (red line), the hybrid model temperatures (orange, green) and predicted surface temperature (blue line).

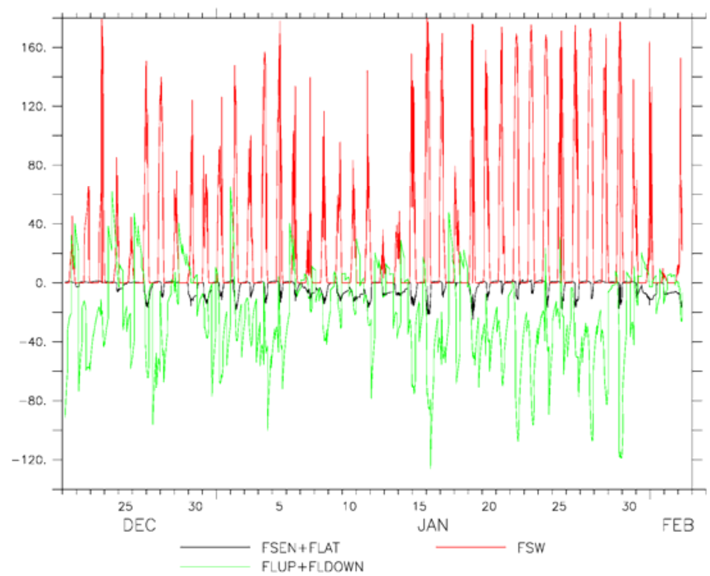

Fig 3. Heat and energy fluxes (Wm^{-2}) in the hybrid model: CLPX solar radiation (red), net longwave flux (yellow), and sensible-plus-latent heat flux (black line) computed from hybrid model.

An extensive series of sensitivity simulations with this model have shown that specific temperatures, humidities and heat fluxes are sensitive to the air-surface transfer coefficients, the vertical mixing coefficients (K_v), the snow/surface albedos, and the ground-layer depth and thermal conductivity.

Boundary layer subgrid-scale mixing over separate surface types

The lowest layer temperature and humidity ($T1$, $q1$) over snow, bare ground and open water are computed from separate energy flux calculations, using updated values of $T1$, T_{sfc} and albedos (α_{sfc}) for each surface. The low-level air temperatures and humidities are combined into mixed boundary layer values (T_{mixed}, q_{mixed}) according to the fractional area of snow cover, bare ground and water. This approach could also be expanded for multiple surface types – rock, sand or soil, vegetation types, ice or ponds. Fig. 4 shows that the separate surfaces (snow, ground, and water) can maintain independent temperature tracks, differing by 20 to 30 C between snow cover of 1 m depth and open water. The water temperature modeling is included here as a virtual demonstration, as there was no significant open water at the Fraser HQ site during CLPX during the snow season. The mixed layer temperature (Fig. 5) is the area average over these surfaces, and it quickly responds to the change from snow cover to bare ground as the snow depth disappears in late March.

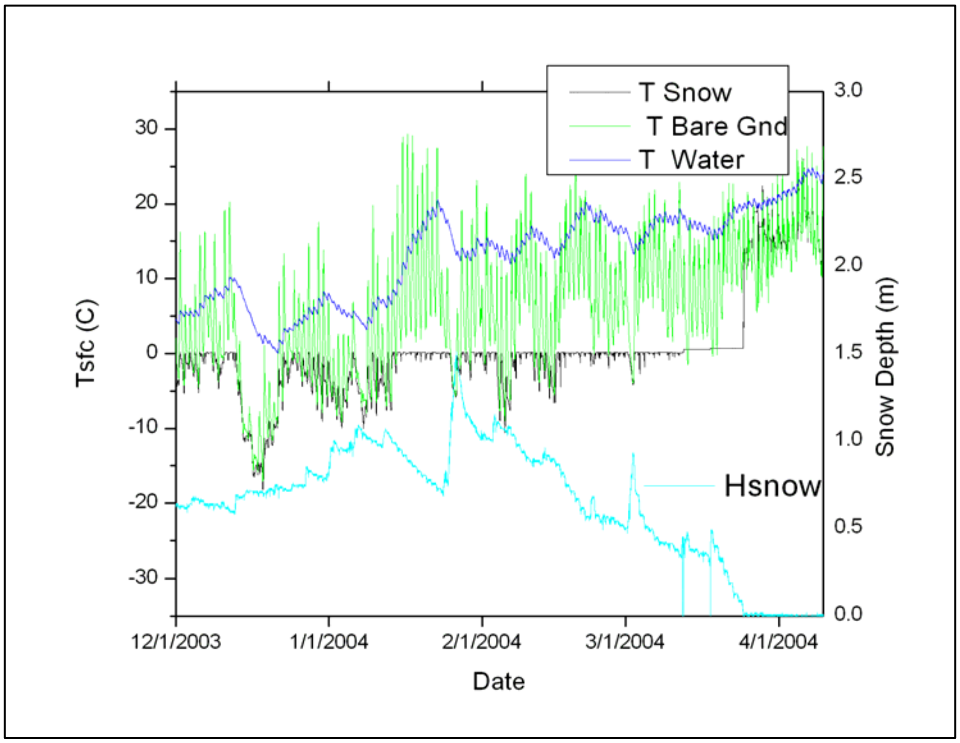

Figure. 4. Hybrid model surface temperatures (Tsfc) over snow (black), bare ground (green), and water (blue) in spring CLPX during snowmelt. Snow depth Hsnow (cyan) at the Fraser HQ site reached zero on about March 22, and Tsfc increases above 0 ºC. (There was no significant open water at CLPX, it is included here as a model demonstration.)

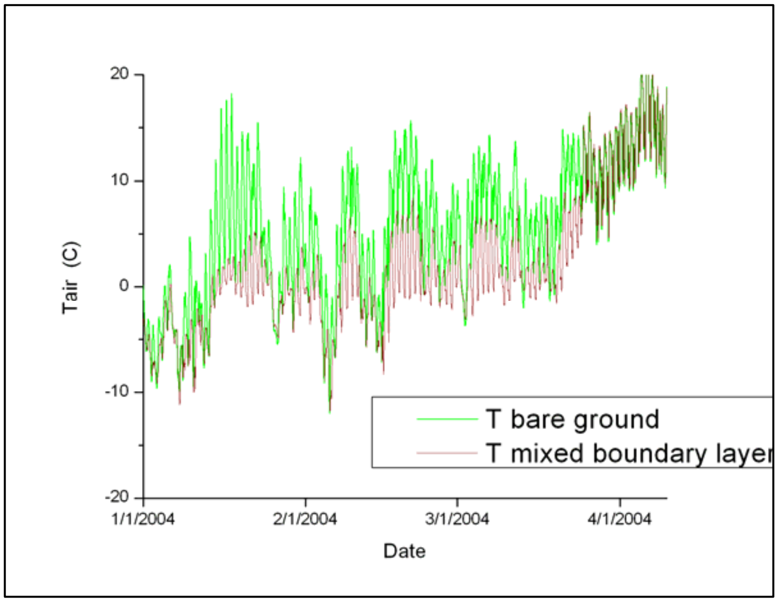

Figure. 5. Hybrid model air temperatures (T1) over bare ground (green), and T2 over mixed snow, no snow and an assumed constant 5% open water. The T mixed boundary layer rapidly adjusts from near 0 ºC over melting snow to over 10 ºC over bare ground in spring.

CONCLUSIONS

The hybrid model provides an efficient method for adjusting (or downscaling) meteorological variables (T and q) that are typically received from gridded forecast models – usually at 10 km to 25 km grid resolution and at 6-hourly time intervals – down to vertical levels of under 100 m heights and 10 minute time intervals. At this shorter time interval, the turbulent heat fluxes, energy exchanges, and boundary-layer variables can respond to the adjustments at the surface that are not fixed to the 6-hour forcing interval.

The model can compute heat and energy fluxes over independent surface types – changing snow depth and area coverage, bare ground, and open water. Each of these surface temperatures are largely independent, and can maintain instability from a temperature gradient with the overlying atmospheric level over one surface type (water) versus over ice or snow. This approach can also be extended to include separate surface types of soil, sand, rock, and ice.

The model's heat transfer coefficients between vertical layers (K_v) and meteorological relaxation (K_{met}) at present are sensitive to the vertical scale and temporal resolution, and still need to be calibrated to the specific depth of vertical layers. A scale-invariant approach to the transfer coefficients is being investigated.

The model's 10-minute timescale response over ice and snow packs can be used to improve the prediction and simulation of atmospheric fluxes in snow and terrain models such as SNTHERM and FASST, in order to scale down the hourly to daily meteorological forcing.

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