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Supplement of

Incorporating moisture content in surface energy balance modeling of a debris-covered glacier

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S.1 Model Parameters

Debris porosity (ϕ) = 0.39	**Thermal Conductivity ($\mathbf{W\ m^{-1}K^{-1}}$)**	**Specific Heat Capacity ($\mathbf{J\ kg^{-1}K^{-1}}$)**	**Density ($\mathbf{kg\ m^{-3}}$)**	**Volumetric Heat Capacity ($\mathbf{J\ m^{-3}K^{-1}}$)**	**Diffusivity ($\mathbf{m^2\ s^{-1}}$)**
Dry debris	**0.94 (Reid and Brock, 2010)**	**948 (Brock et al., 2010)**	**1690**	**948$\times$1690+0.39$\times$1006$\times$0.024 = 1602129**	**5.867 $\times 10^{-7}$**
Air	0.024 (Haynes, 2017)	1006 (Haynes, 2017)	$P/(R_d \times T_v)$	–	–
Water-saturated debris	**0.94+0.39$\times$0.57 $=$ 1.16**	**–**	**–**	**948*1690+0.39$\times$4218$\times$1000 $=$ 3247140**	**3.572 $\times 10^{-7}$**
Water	0.57	4218	1000	–	–
Ice-saturated debris	**0.94+0.39$\times$2.22 $=$ 1.81**	**–**	**–**	**948$\times$1690+0.39$\times$2106$\times$917 $=$ 2355289**	**7.680 $\times 10^{-7}$**
Ice	2.2	2106	917	–	–

Table S1. Thermally relevant properties of dry debris, in which interstitial pore spaces are filled with air; water-saturated debris; and ice-saturated debris of porosity (ϕ) = 0.39. Air density is a function of elevation, air temperature, and air moisture. In the equation for air density, $\rho_{air} = P/(R_d \times T_v)$, P is pressure (Pa), R_d is the gas constant for dry air ($\sim$ 287 J kg^{-1}K^{-1}), and T_v is the virtual temperature (K). Thermal conductivity presented by Reid and Brock (2010) is an “effective" value, from measurements, that is a function of debris’ unspecified porosity and any moisture content at the time of measurement (Collier et al., 2016). Brock et al. (2010) used a published value of specific heat (948 J kg^{-1}K^{-1}). We assume that these values of thermal conductivity and heat capacity (here listed for “dry debris") are valid for dry debris on West Changri Nup glacier and subsequently perform sensitivity tests. Note that diffusivity is conductivity normalized by volumetric heat capacity. Values for which no references are listed are the standard values used by SURFEX (LeMoigne, 2018).

S.2 Model Inputs

The list of continuous meteorological variables required to run SURFEX (found at *www.umr-cnrm.fr/surfex/spip.php?article215*) is reproduced below:

- Tair(time,yy,xx) : Atmospheric temperature (K)
- Qair(time,yy,xx) : Atmospheric humidity (kg kg^{-1})
- PSurf(time,yy,xx) : Atmospheric pressure (Pa)
- Rainf(time,yy,xx) : Rain (kg $m^{-2}s^{-1}$)
- Snowf(time,yy,xx) : Snow (time,yy,xx) (kg $m^{-2}s^{-1}$)
- Wind(time,yy,xx) : Wind speed (m s^{-1})
- Wind_DIR(time,yy,xx) : Wind direction (degrees from N, clockwise)
- LWdown(time,yy,xx) : Long-wave radiation (W m^{-2})
- DIR_SWdown(time,yy,xx) : direct short-wave radiation (W m^{-2})
- SCA_SWdown(time,yy,xx) : diffuse short-wave radiation (W m^{-2})
- CO2air(time,yy,xx) : near surface CO2 concentration (kg m^{-3})

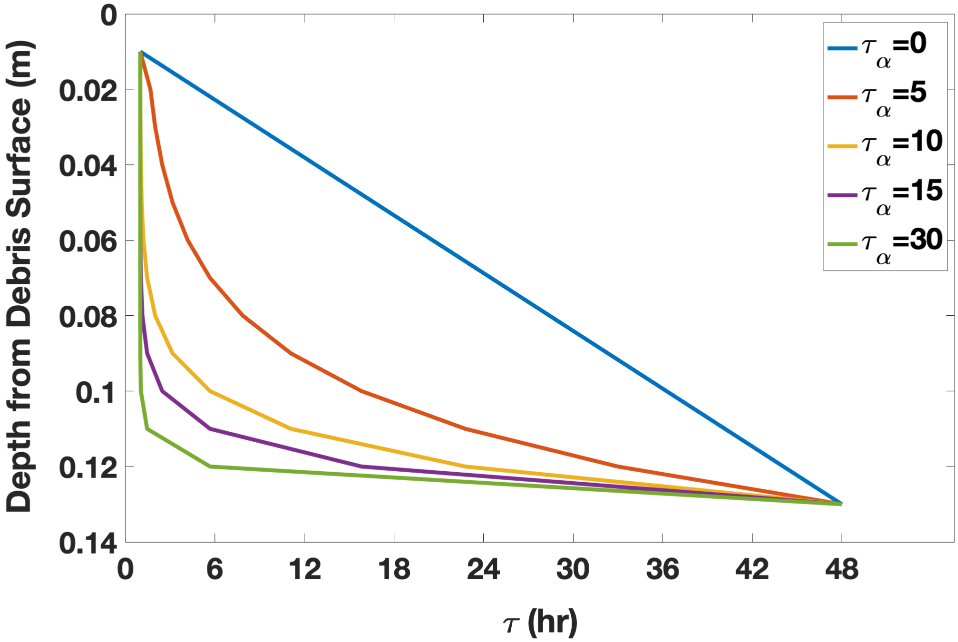

Figure S1. Timescale for lateral slope-induced runoff with the various timescale shape factors used in tuning. For all shape factors, the runoff timescale increases rapidly with depth in the debris, increasing towards the ice-debris interface.

S.3 Budgets

S.3.1 Energy Budget

Energy fluxes in ISBA-DEB are the same as those in ISBA, with the exception of an additional energy flux for melting the glacier (M_{ice}). The energy budget of the debris is

$$\int_{z=z_b}^{z=0} c_g \frac{\partial T_g}{\partial t} dz = \Phi_g + p_{sn} {G_{gn}}^{*} + (1 - p_{sn})\,(R_n - H - LE) - M_{ice} \tag{S1}$$

* In the model, G_{gn}, the net ground flux, is represented by $(G_{gn} + G_{n,corr})$. The additive term is a numerical correction term that also serves to incorporate the effects of a disappearing snowpack on the energy budget.

The left hand side of equation S1 represents the change in total energy stored with the debris, integrated vertically through all k debris layers (total N_g layers). This is a function of the volumetric heat capacity ($c_{g,k}$, J m^{-3}K^{-1}), layer thickness (Δz), time (t), and temperature ($T_{g,k}$, K).

$$\int_{z=z_b}^{z=0} c_g \frac{\partial T_g}{\partial t} dz = \sum_{k=1}^{N_g} \frac{c_{g,k} \Delta z_k}{\Delta t} \left(T_{g,k}^{t+\Delta t} - T_{g,k}^{t} \right) \tag{S2}$$

Φ_g (W m^{-2}) gives the total latent heat flux due to phase changes in the debris (i.e. freezing and thawing). p$_{sn}$ gives the fraction of the model grid cell comprised of snow such that the heat conduction flux at the snow-debris interface (“ground," G_{gn}, W m^{-2}) is multiplied by this fraction and the net radiative, sensible, and latent heat fluxes (R_n, H, and LE, respectively) at the snow-free debris surface are multiplied by the share of the surface that is snow-free ($1-p_{sn}$). Turbulent fluxes are given by the aerodynamic formulae of Louis (1979), as explained for ISBA by Noilhan and Mahfouf (1996).

Incorporating snow gives a total energy budget that contains the enthalpy (i.e. heat content) of the snowpack, including the enthalpy added by any snowfall during the timestep. When combining the energy budgets of debris and snow, the G_{gn} term cancels.

The daily average energy budget for winter is dependent on the absence (Figure S2a) or presence (Figure S2b) of snow and varies from that of summer (Figure S2c).

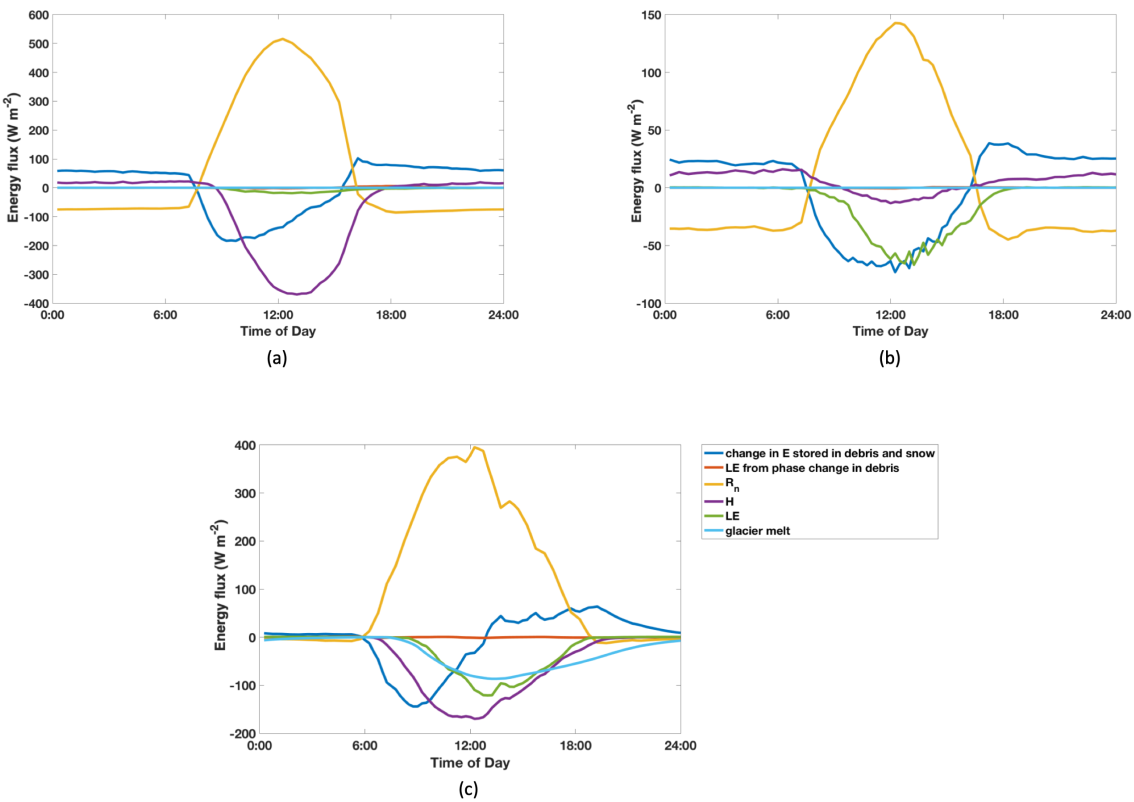

Figure S2. Daily average winter energy fluxes when ground is (a) bare and (b) snow-covered and (c) daily average summer energy fluxes, using the convention that flux is positive when directed toward the surface. Bare winter surface (a) is 1 January – 2 February 2014, snow-covered winter surface (b) is 16 February – 26 March 2013, and summer surface (c) is 1 – 31 July 2013. Note that in both (a) and (b), glacier melt never occurs; in all three periods depicted, phase change within the debris does not supply a flux. The y-axis of (b) is considerably less than that of (a), which is explained by the increased albedo of snow relative to debris (the net shortwave radiation is much lower when a snow cover is present). Time of Day is given in local Nepal time.

S.3.2 Water Budget

Similar to the energy budget, the water budget in ISBA-DEB is identical to the one in ISBA but includes the additional M_{ice}. The change in water stored in debris, $\frac{\partial W_g}{\partial t}$, is

$$\frac{\partial W_g}{\partial t} = Q_s + \frac{M_{ice}}{L_m} + (1-p_{sn})\,P_r - D_r - R - (1-p_{sn})\left(\frac{LE_g}{L_v} + \frac{LE_{gi}}{L_s}\right) - E_{n,corr} \tag{S3}$$

Here, P_r is rain falling on the bare debris, Q_s is snowmelt entering the debris, p_{sn} is the fraction of the debris gridcell covered by snow, LE_g is evaporation from the debris without snow cover, LE_{gi} is the sublimation from the debris without snow cover, R is runoff, and D_r is the drainage (included only for completeness; $D_r = 0$ in ISBA-DEB). $E_{n,corr}$, similar to $G_{n,corr}$ above, is a numerical correction term to ensure a closed mass budget when a snowpack entirely vanishes within a timestep. L_v, L_s, and L_m are the latent heats of vaporization, sublimation, and fusion, respectively, as listed in Table **??**. The total water content in the debris is

$$W_g = \rho_w \sum_{k=1}^{N_g} (w_{g,k} + w_{gi,k})\,\Delta z_k \tag{S4}$$

where w_g and w_{gi} are volumetric liquid water and liquid-water-equivalent volumetric ice content in the debris, respectively, and ρ_w is the density of liquid water.

Incorporating change in water stored in snow, $\frac{\partial W_s}{\partial t}$, into equation S3 gives

$$\frac{\partial W_s}{\partial t} + \frac{\partial W_g}{\partial t} = \frac{M_{ice}}{L_m} + P_s + P_r - D_r - R - (1-p_{sn})\left(\frac{LE_g}{L_v} + \frac{LE_{gi}}{L_s}\right) - p_{sn}\left(\frac{LE_{sl}}{L_v} + \frac{LE_s}{L_s}\right) \tag{S5}$$

Terms not previously defined are P_s, the snowfall rate in water equivalent, and the evaporation and sublimation from the snow: LE_{sl} and LE_s. The total water content of the snow is

$$W_s = \sum_{k=1}^{N_s} W_{s,k}, \tag{S6}$$

where N_s is the number of snow layers and $W_{n,k}$ the snow water equivalent (swe) for each snow layer k. Q_s and $E_{n,corr}$ do not appear in equation S5 because they cancel when adding the snow water budget to equation S3.

S.4 Evolving Debris Properties

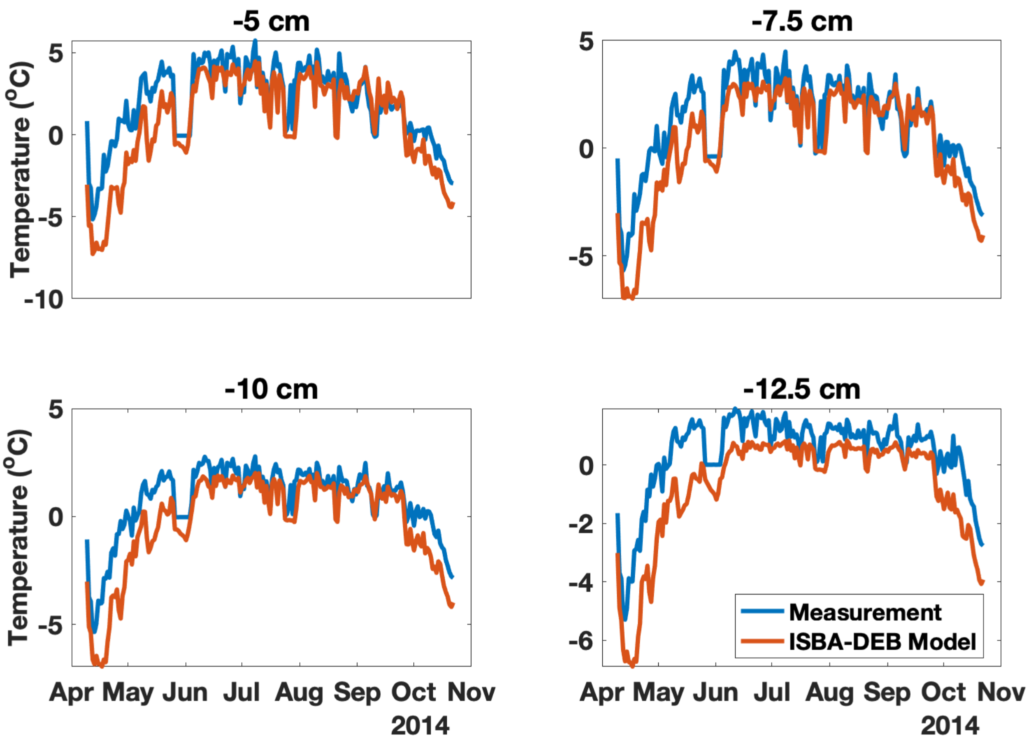

Figure S3. Daily means of measured (blue) and modeled (red) debris temperatures for the calibration period marked by vertical lines in Figure 5.

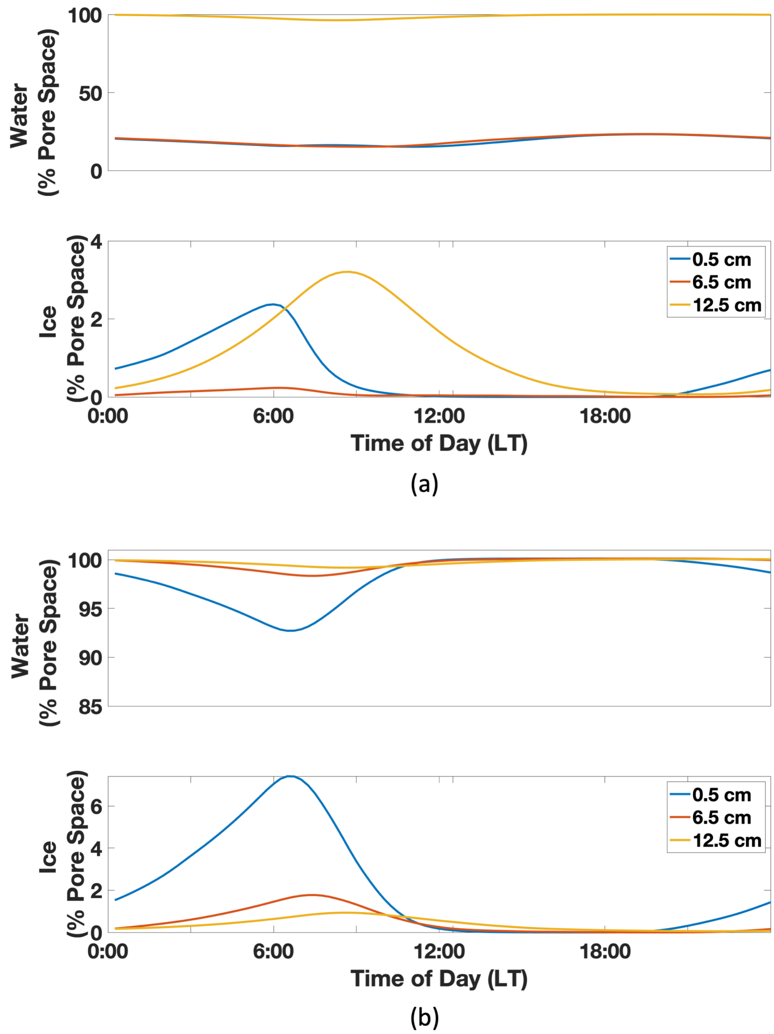

Figure S4. 2013 monsoon season (JJAS) mean diurnal values in local Nepal time (LT) for water (top panels) and ice (bottom panels) for the (a) partially and (b) fully saturated scenarios shown in Figures 10a and b, respectively. Only three layers are shown for figure clarity: debris top (0.5 cm), middle (6.5 cm), and base (12.5 cm).

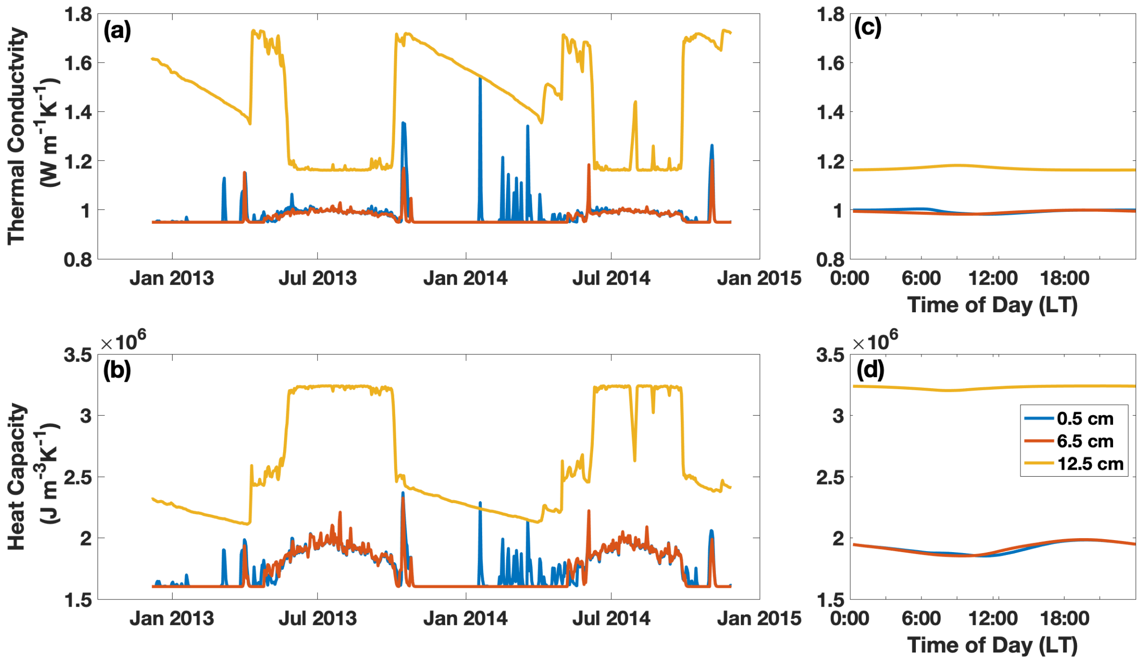

Figure S5. Thermal conductivity (a) and volumetric heat capacity (b) of debris top (0.5 cm), middle (6.5 cm), and base (12.5 cm) layers throughout the time period used for this paper, with the 2013 monsoon season (JJAS) mean diurnal values for each (c, d)

S.5 Sensitivity

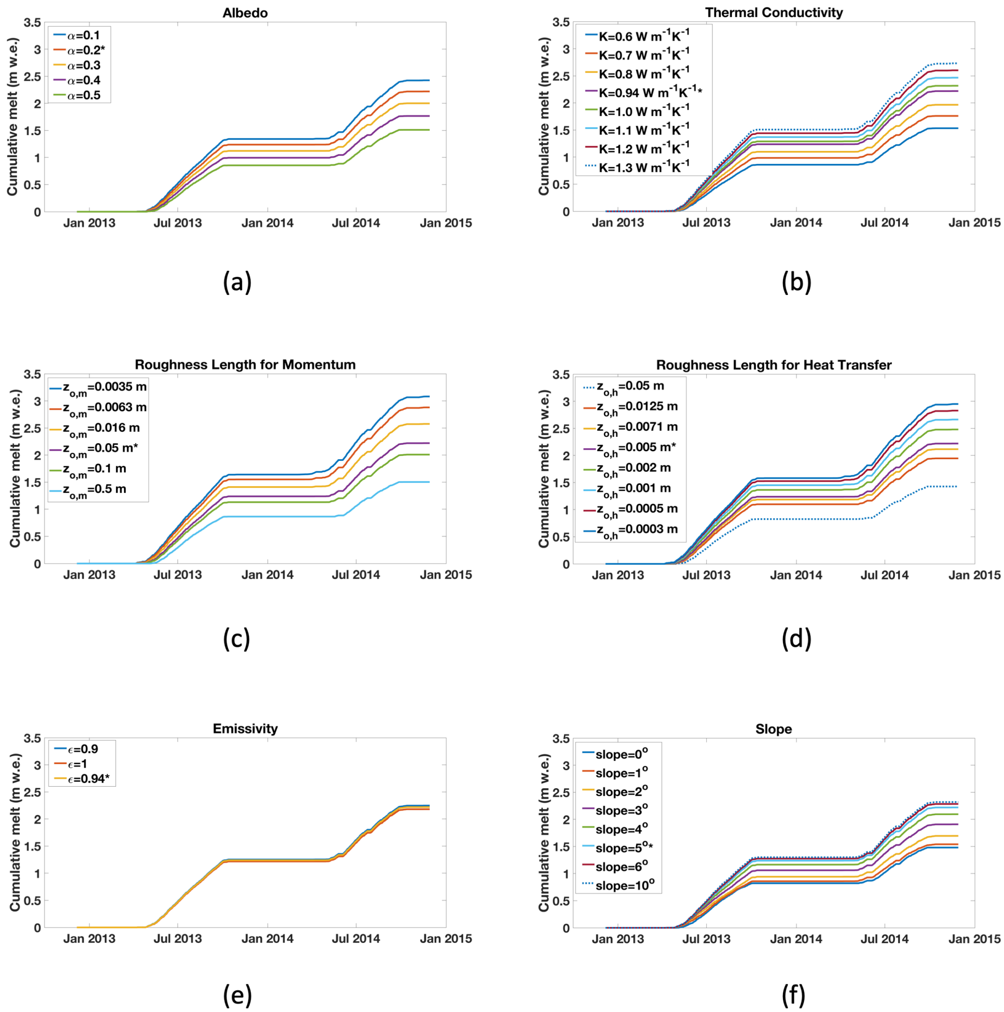

Figure S6. Cumulative glacier melt over the December 2012 – November 2014 period, run with different values of key parameters to test ISBA-DEB's sensitivity. An asterisk in legends indicates values used in the run demonstrating model behavior (Section 5.1), and sensitivities are quantified relative to melt simulated with these values in Table 4.

Additional References:

Louis, J.-F.: A parametric model of vertical eddy fluxes in the atmosphere, Boundary-Layer Meteorology, 17, 187–202, 1979.