About the snow model ESCIMO (v. 4.2)

The one-layer plot scale snow model ESCIMO (**E**nergy Balance **S**now **C**over **I**ntegrated **MO**del) is designed as a physically based model for the simulation of the hourly energy balance, water equivalent and melt rates of a snow cover. The following fluxes are taken into account: short- and longwave radiation, the sensible and latent heat fluxes, the energy conducted by solid or liquid precipitation as well as sublimation/resublimation and a constant soil heat flux. Snow surface albedo is modelled using a function considering the age and the surface temperature of the snow pack. For each hourly time step the following scheme is followed: first, it is distinguished between melting conditions (air temperature ≥ 273.16 K) and no melt (air temperature < 273.16 K). In the first case, a snow surface temperature of 273.16 K is assumed and melt can occur. If air temperature < 273.16 K, an iterative procedure is applied to adopt the snow surface temperature for closing the energy balance. The parameter values and constants as used in ESCIMO are listed in table 1.

Generally, the energy balance E for a snow pack can be expressed as:

$$E = Q + H + V + A + B \tag{1}$$

where Q is the shortwave and longwave radiation balance, H the sensible heat flux, V the latent heat flux, A the advective energy supplied by solid or liquid precipitation, and B the soil heat flux for the current time step. All fluxes are expressed in $W \cdot m^{-2}$.

An important parameter for the shortwave radiation balance is the snow albedo which depends on many factors (mainly grain size, density and impurity content) and varies for different spectral bands. In ESCIMO, snow albedo a is modelled using the ageing curve approach (Rohrer 1992):

$$a = a_{min} + a_{add} \cdot e^{-kn} \tag{2}$$

where k is a recession factor depending on air temperature (which determines snow surface temperature) and n the number of days since the last considerable snowfall (at least $0.5\ mm \cdot h^{-1}$); each time such a snowfall occurs the snow albedo is reset to its maximum value. This function integrates the changing physical properties of the surface grain during its ageing.

Longwave emission of the snowcover $Q_{l\uparrow}$ is calculated with snow emissivity ε and the Stefan-Boltzmann constant σ:

$$Q_{l\uparrow} = -\sigma \cdot \varepsilon \cdot T_s^4 \tag{3}$$

where T_s is the snow surface temperature. If not available as measurement, incoming longwave radiation $Q_{l\downarrow}$ is estimated with air temperature T in K, water vapour partial pressure at measurement level e_l in hPa (calculated using the Magnus formula) and cloudiness C (Brunt 1932):

$$Q_{l\downarrow} = \sigma \cdot \left(0.610 + 0.05 \cdot \sqrt{e_l}\right) \cdot T^4 \cdot \left(1 + B_c \cdot C^2\right) \quad (4)$$

If not measured, cloudiness can be derived from the ratio of recorded global radiation to potential global radiation (e.g. as described in Strasser et al. 2004). The empirical coefficient B_c is set to fixed values for various cloud cover ranges (Escher-Vetter 2001, see table 1).

In ESCIMO simple empirical descriptions of the turbulent fluxes are applied which are valid for medium roughness and a wide range of wind speeds. The such induced loss of accuracy is small in areas where the contribution of the turbulent fluxes to the snow surface energy balance not too large. The used parameterizations have been proposed by Kuchment and Gelfan (1996) and are valid for neutral or stable conditions.

Sensible heat flux H is expressed with wind speed W in $m \cdot s^{-1}$ as

$$H = 18.85 \cdot (0.18 + 0.098 \cdot W) \cdot (T - T_S) \quad (5)$$

and latent heat flux V is calculated as

$$V = 32.82 \cdot (0.18 + 0.098 \cdot W) \cdot (e_l - e_s) \quad (6)$$

where e_s the water vapour saturation pressure at the snow surface in hPa, calculated using the Magnus formula for saturated conditions. The small mass changes δe in mm generated by sublimation or resublimation are simulated with t being the model time step (3600 s):

$$\delta e = \frac{V \cdot t}{l_s} \quad (7)$$

where l_s is the sublimation/resublimation heat of snow.

The advective energy A supplied by precipitation P depends on its phase. A threshold wet temperature T_w is assumed for the distinction between snow and rain; this wet temperature is iteratively determined by solving the psychrometer formula. Then, the energy advected by P in mm is calculated for rainfall on snow (for melting condition, i.e. $T \geq 273.16$) with

$$A = P \cdot c_{sw} \cdot (T - 273.16) \quad (8a)$$

where c_{sw} is the specific heat of water. If rain falls on cold snow (T < 273.16) refreezing is assumed, hence eq. (8a) gets:

$$A = P \cdot (c_i + c_{sw} \cdot (T - 273.16)) \tag{8b}$$

where c_i is the melting heat of ice.

For snowfall, A is computed with

$$A = P \cdot c_{ss} \cdot (T_w - T_s) \tag{9}$$

where c_{ss} is the specific heat of snow.

Any precipitation is added to the existing *SWE*.

For the case of melting condition (air temperature ≥ 273.16 K), the fluxes are calculated with an assumed snow surface temperature of 273.16 K. If the resulting energy balance is positive, melt can occur and the amount of melt water *M* in mm is calculated with

$$M = \frac{E \cdot t}{c_i} \tag{10}$$

In the case of no melting condition (air temperature < 273.16 K), an iterative scheme to close the energy balance by adopting the snow temperature and recalculation of the respective fluxes is applied.

The presence of a forest canopy changes the micrometeorological conditions at the surface of the ground snow cover below. Shortwave radiation, precipitation, and wind speed are reduced, whereas longwave radiation and humidity are increased and the diurnal temperature cycle is attenuated. In ESCIMO, the below-canopy modifications of the micrometeorological conditions over the ground snow surface are explicitly modeled (mainly after Liston and Elder 2006). Effective LAI is the primary forest parameter and represents the only stand characteristic required for the modeling. The meteorological station data (solar and thermal radiation, temperature, humidity, and wind speed) that were collected in the open are therefor modified for forest canopy conditions. These modified meteorological variables are then used to force the modelling of the snow-canopy interaction processes interception, sublimation, and unloading by melt, and the energy and mass balance of the snow surface beneath the trees. Full details of the formulations are given in Strasser (2008).

ESCIMO has been applied for numerous geographical locations and climatic conditions (Förster et al. 2014, Zappa et al. 2003, Prasch et al. 2011, Strasser et al. 2002, Strasser and

Mauser 2001), and within the frameworks of the two international SNOWMIP programmes (Etchevers et al. 2004; Rutter et al. 2009).

For distributed, physically based water balance simulations including sophisticated formulations of the respective fluxes of matter and energy in the soil, the plants and the atmospheric boundary layer ESCIMO has been integrated in the SVAT schemes (i) PROMET - Processes of Radiation, Mass and Energy Transfer (Strasser and Mauser 2001, Strasser 1998) and (ii) DANUBIA-light (Prasch et al. 2011). These model frameworks are used to model actual evapotranspiration as a function of radiative energy, water availability and physiological regulation mechanisms of heterogeneous plant stands at different scales from single fields (1 ha) to regional catchments (100.000 km^2). Furthermore, the ESCIMO snowmelt model is integrated in (i) the hydrological model PREVAH to compute snowmelt rates in a comparative, distributed application for the Dischma catchment (Switzerland) (Zappa et al. 2003), as well as in the hydrological model Panta Rhei where it is applied in the German Harz mountains (Förster et al. 2014).

For distributed simulation of snow processes in high mountain areas, ESCIMO has been integrated into the modular system AMUNDSEN - Alpine MUltiscale Numerical Distributed Simulation ENgine (Strasser 2008). There, it has been further developed with a multilayer scheme, liquid water and cold content parameterizations, lateral redistribution processes, and many other features of an advanced mountain snow cover model (see the respective section and literature there). In AMUNDSEN, the former ESCIMO formulations are continuously further developed and applied in numeruous research projects. However, the original plot scale ESCIMO model code still is of practical use due to its simplicity and performance.

More recently, the fundamental principles of the ESCIMO model have been transferred into a spreadsheet based version – the ESCIMO.spread and the ESCIMO.spread (v2) Excel files (Strasser and Marke 2010, Marke et al. 2016), each including one season of hourly test data. The second version includes the snow-canopy interaction submodule but is slower than the slim simple version. Both can be downloaded from the respective model website, including the papers.

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Table 1: Parameter values and constants used in ESCIMO.

Parameter/constant	Symbol	Value	Unit
Soil heat flux	B	2.0	$W \cdot m^{-2}$
Minimum albedo	a_{min}	0.45	
Maximum albedo	$(a_{min} + a_{add})$	0.9	
Recession factor ($T \geq 273.16$ K)	k	0.12	
Recession factor ($T < 273.16$ K)	k	0.05	
Maximum liquid water storage		7	%
Hourly threshold snowfall for albedo reset		$0.5 \cdot 10^{-3}$	m
Threshold wet temperature for phase detection	T_w	275.16	K
Cloud cover coefficient	B_c	0.08 (cloudiness 0 to 20 %) 0.17 (cloudiness 20 to 60 %) 0.20 (cloudiness 60 to 100 %) 0.24 (precipitation > 0)	
Emissivity of snow	ε	1.0	
Specific heat of snow	c_{ss}	$2.1 \cdot 10^{3}$	$J \cdot kg^{-1} \cdot K^{-1}$
Specific heat of water	c_{sw}	$4.18 \cdot 10^{3}$	$J \cdot kg^{-1} \cdot K^{-1}$
Melting heat of ice	c_i	$3.375 \cdot 10^{5}$	$J \cdot kg^{-1}$
Sublimation/resublimation heat of snow	l_s	$2.8355 \cdot 10^{6}$	$J \cdot kg^{-1}$
Stefan-Boltzmann constant	σ	$5.67 \cdot 10^{-8}$	$W \cdot m^{-2} \cdot K^{-4}$

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