Strasser, U. and Marke, T. (2013): *ESCIMO.spread* – a spreadsheet-based point snow surface energy balance model to calculate hourly snow water equivalent and melt rates for historical and changing climate, *v2*: parameterization of inside-canopy conditions

Strasser, U. [1,*] and Marke, T. [1]
[1] Institute of Geography, University of Innsbruck

ABSTRACT: This paper describes the spreadsheet-based point energy balance model *ESCIMO.spread* which simulates the energy and mass balance as well as melt rates at the snow surface. The model makes use of hourly recordings of temperature, precipitation, wind speed, relative humidity, and incoming global and longwave radiation. In the new second version (*v2*) we include parameterizations for the modification of the meteorological variables inside a canopy, and the interception and sublimation of snow from the trees. The canopy type is described by means of leaf area index, density and height. The effect of potential climate change on the seasonal evolution of the snow cover can be estimated by modifying the time series of observed temperature and precipitation with adjustable parameters. Model output is graphically visualized in hourly and daily diagrams. The results compare well with weekly measured snow water equivalent (SWE). The model is easily portable and adjustable, and runs particularly fast on any spreadsheet-capable computer platform.

KEYWORDS: Snow modeling, canopy interception, spread sheet, energy balance

1 INTRODUCTION

Mountain forests are primarily composed of evergreen conifer species which retain their needles throughout the year and, therefore, intercept snow efficiently throughout the winter. Snow interception and sublimation in a canopy have been identified as important hydrological processes with complex mass and energy exchanges (Marsh 1999, Pomeroy et al. 1998). The processes affecting a snow cover beneath a forest canopy are distinct from those in the open: on one hand, the meteorological conditions relevant for the energy transfer at the snow surface beneath the canopy are different, and on the other hand, a certain amount of precipitation is retained in the interception storage of stems, branches and needles. Snow that is intercepted in the canopy can melt, fall down, or sublimate into the air masses above the canopy. This latter process leads to a reduction of precipitation accumulated and stored in the ground snowpack (Fig. 1).

A forest canopy can have opposing effects on the snow cover beneath the trees, depending on many factors such as canopy density, gap size and distribution, geographical position and meteorological conditions (Pomeroy et al. 2002, Strasser et al. 2011). Since vegetation canopies strongly affect the snow surface energy balance the result can be less SWE and a shorter duration, or more SWE and longer snow coverage. The canopy alters both the shortwave and the longwave radiation balance of the snow cover and affects the turbulent fluxes of sensible and latent heat by reducing the wind speed at the snow surface (Link and Marks 1999a, b).

Fig. 1: Intercepted snow on alpine fir trees in the Bavarian Alps/Germany one day after a heavy snowfall. Photo: U. Strasser.

Likewise, humidity and temperature underneath a canopy differ from those in the open. All the snow–canopy interaction processes have significant effects on the amount and timing of meltwater release from forested areas. Strasser and Etchevers (2005) have shown that the consideration of meteorological conditions at the ground beneath a canopy considerably improves the simulated amount and timing of

Corresponding author address: Strasser, U., Institute of Geography, University of Innsbruck (Austria)
tel: +43 512 507 5404; fax: +43 512 507 2877;
email: ulrich.strasser@uibk.ac.at

meltwater release and in the hydrological modelling of a high alpine catchment.

Pomeroy et al. (1998) report that interception by forest canopies can store up to 60 % of cumulative snowfall resulting in a 30 – 40 % annual loss of snow cover in many coniferous forest environments. Due to its large surface area to mass ratio, and the fact that the snow remaining in the canopy is exposed to a relatively dry and warm atmosphere, relatively high rates of sublimation can occur. For an accurate determination of exposure times, it is important to know the amount of snow intercepted. Snow interception efficiency increases with canopy density, increasing size of falling snow crystals, decreasing density of the falling snow, decreasing temperature and decreasing wind speed (Marsh 1999). The capacity of the interception storage of a canopy is in the range of approximately 10 mm, according to field measurements (Hedstrom and Pomeroy 1998, Pomeroy and Gray 1995). Strasser et al. (2011) have shown the forest canopy effects on the snow cover in a modelling experiment with a virtual mountain to determine and separate the influences of altitude, exposition, and canopy type.

The spreadsheet snow-canopy interaction model *ESCIMO.spread v2* has been developed as an easy-to-use, portable, and scientific tool for the hourly simulation of the energy balance, the water equivalent and melt rates of a snow cover under a forest canopy. *ESCIMO.spread v2* includes a 1-D, one-layer process model which assumes the ground snow cover to be a single and homogeneous pack. *ESCIMO.spread v2* makes use of common bulk formulations for both the latent and sensible heat flux, and criteria like stability of the surface layer or roughness are not considered.The inside-canopy meteorological conditions are derived from point measurements conducted in the open by simple parameterizations considering the type of canopy. On top of that, the amount of intercepted snow, sublimation of intercepted snow, as well as redistribution to the ground by means of falling down and melting are modelled.

ESCIMO.spread v2 solves the energy and mass balance equations for the snow surface by applying simple parameterizations of the relevant processes. Since the underlying physics is independent of space and time, the model represents an adequate tool to be applied for simulation of climate change effects. This is technically facilitated by implementation of climate change parameters for assumed temperature and precipitation trends. The spreadsheet version of the model presented and discussed in this paper includes example meteorological recordings, the complete set of model formulae, both hourly and daily graphical output, and three quantitative measures of goodness of fit. The spreadsheet is freely available and can easily be adopted, modified and applied to other sites where the required input data is also available. Due to its simplicity the model is specifically suitable for educational purposes (e.g., lab courses for students), and to be used with a laptop computer on site in the field. Here, the model can be utilized for a fast visualization of measured/modified meteorological parameters, as well as simulated energy balance, snow water equivalent and snow melt on the ground, and the amount of intercepted snow inside a canopy. Thereby, the model can help to check the measurements for plausability and to explain differences between simulation and observation, e.g. due to wind induced transport of snow. *ESCIMO.spread v2* is public domain and can be obtained, as soon as validation is finished, from the webpage www.alpinehydroclimatology.net.

2 METHODS

An existing forest canopy changes the micrometeorological conditions at the surface of the ground snow cover. Shortwave radiation, precipitation and wind speed are reduced, whereas longwave radiation and humidity are increased and the course of temperature is attenuated (Strasser and Etchevers 2005, Tribbeck et al. 2004, Link and Marks 1999a, b). Consequently, latent fluxes and the associated sublimation rates at the snow surface inside a forest canopy differ from those in the open.

2.1 Meteorological conditions inside-canopy

In *ESCIMO.spread v2* the micrometeorological conditions for the ground beneath a forest canopy are derived from station measurements (if the station is located in the open) by applying a set of modifications for solar and thermal radiation, temperature, humidity and wind speed. To account for the lower amount of incoming shortwave radiation underneath the forest canopy, top-of-canopy incoming shortwave radiation Q_{si} (W/m^2) is reduced following Hellström (2000) in form of

$$Q_{sif} = \tau_v \, Q_{si} \qquad (1)$$

where Q_{sif} (W/m^2) is the shortwave radiation underneath the canopy and τ_v is the fraction of incoming solar radiation transmitted through the canopy. The latter is calculated as

$$\tau_v = \exp(-k \, LAI^*) \qquad (2)$$

where k is a vegetation-dependent extinction koefficient and LAI* is the effective LAI (including stems, leaves, and branches; Chen et al.

1997). Liston and Elder (2006) have achieved best model performance with a k value of 0.71 for a variety of conifers in the Rocky Mountains (USA). Incoming longwave radiation at the snow surface under the canopy is Q_{lif} (W/m^2) is calculated as

$$Q_{lif} = (1 - F_c)\, Q_{li} + F_c\, \sigma\, T_c^4 \quad (3)$$

with Q_{li} representing the top-of-canopy incoming longwave radiation (W/m^2), σ the Stefan-Boltzmann constant and F_c the canopy fraction defined as

$$F_c = a + b \ln(LAI^*) \quad (4)$$

where a and b are constants with values of 0.55 and 0.29 respectively (Pomeroy et al. 2002). Temperature inside the forest canopy T_c (K) is calculated assuming linear dependency on canopy density following Obled (1971) as

$$T_c = T_a - F_c\, (T_a - (R_c\, (T_a - T_{mean}) + T_{mean} - \delta T) \quad (5)$$

with T_a (K) the top–of–canopy air temperature, R_c a dimensionless scaling parameter (= 0.8), T_{mean} (K) the mean daily air temperature and δT (K) a temperature offset depending on T_{mean} and limited to the range $-2\ K \leq \delta T \leq +2\ K$ (Durot 1999):

$$\delta T = (T_{mean} - 273.16) / 3 \quad (6)$$

The relative humidity RH_c (%) inside a canopy is often slightly higher than in the open (Durot 1999), due to sublimation and evaporation of melted snow. In the model, it is modified, again including linear dependency on the canopy density:

$$RH_c = RH_a\, (1 + 0.1\, F_c) \quad (7)$$

For melt conditions, RH_c is set to saturation. The wind speed W_c ($m\ s^{-2}$) inside a canopy with the height h (m) and 0.6 being the canopy wind speed reference level (Essery et al. 2003, Cionco 1978) is calculated as

$$W_c = W_a\, e^{-fi(1-0.6/h)} \quad (8)$$

where f_i is the canopy flow index:

$$f_i = \beta\, LAI^* \quad (9)$$

with β = 0.9 being a dimensionless scaling factor that adjusts LAI* values to be compatible with canopy flow indices defined by Cionco (1978).

2.2 Snow interception and sublimation

The snow interception and sublimation model implemented in *ESCIMO.spread v2* applies the physical understanding of snow interception from the branch scale to the canopy, and scales the corresponding understanding of snow sublimation of a single snow crystal to the intercepted snow in the canopy similar to Pomeroy et al. (1998). When canopy air temperatures are above freezing, intercepted snow is melted and transferred to the ground storage. Absorbed solar radiation Q_{sabs} (W) by a snow particle in the canopy is defined by:

$$Q_{sabs} = \pi\, r^2\, (1 - \alpha)\, Q_{si} \quad (10)$$

with *r* (m) being the radius of a spherical ice particle, assumed to be 500 μm (Liston and Elder 2006) and α the intercepted snow particle albedo, which is assumed to be equal to the simulated snow surface albedo in the open (see Strasser and Marke 2010).

For the description of the mass loss rate, the Reynolds, Nusselt and Sherwood numbers are required in the model. The particle Reynolds number R_e with $0.7 < R_e < 10$ is given by (Lee 1975):

$$R_e = (2\, r\, W_c)/v \quad (11)$$

with v being the kinematic viscosity of air ($1.3\ 10^{-5}\ m^2\ s^{-1}$). The Sherwood number S_h is assumed to equal the Nusselt number N_u which is given by

$$N_u = 1.79 + 0.606 * SQRT(R_e) \quad (12)$$

The saturation vapour pressure e_s (Pa) over ice is estimated according to Buck (1981):

$$e_s = 611.15\, e^{22.452\, (Ta - 273.16) / Ta - 0.61}$$

The absolute humidity at saturation ρ_v ($kg\ m^{-3}$), is computed following Fleagle and Businger (1980) as:

$$\rho_v = 0.622\, e_s/(R_d\, T_a) \quad (13)$$

R_d is the gas constant for dry air ($287\ J\ K^{-1}\ kg^{-1}$). The diffusivity of water vapour in the atmosphere D_v ($m^2\ s^{-1}$) is given by (Thorpe and Mason 1966):

$$D_v = 0.0000206\, (T_c / 273)^{1.75} \quad (14)$$

Now, the mass loss rate dm/dt from an ice sphere, given by the combined effects of humidity gradients between the particle and the atmosphere, absorbed solar radiation, particle size and ventilation influences can be computed.

For this, both temperature and humidity are assumed to be constant with height through the canopy:

$$dm/dt = (2 \pi r (RH_c/100 - 1) - Q_{sabs} \Omega) / (l_s \Omega + 1/(D_v \rho_v S_h)) \quad (15)$$

with l_s being the latent heat of sublimation (2.838 10^6 J kg^{-1}). Ω is computed as:

$$\Omega = (1/ \lambda_t T_c N_u) ((l_s M_w/ R T_c) - 1) \quad (16)$$

λ_t being the thermal conductivity of the atmosphere (0.024 J m^{-1} s^{-1} K^{-1}), M_w the molecular weight of water (0.018 kg $mole^{-1}$) and R the universal gas constant (8.313 J $mole^{-1}$ K^{-1}). The sublimation loss rate coefficient for an ice sphere Ψ_s (s^{-1}) is now computed as

$$\Psi_s = (dm_{sp} / dt) / m_{sp} \quad (17)$$

with m_{sp} (kg) being the particle mass (ρ_i is the ice density = 916.7 kg m^{-3}):

$$m_{sp} = 4/3 \pi \rho_i r^3 \quad (18)$$

The canopy–intercepted load I (mm) at time t is given with t–1 being the previous time step, I_{max} the maximum snow interception storage capacity and P the (snow) precipitation (mm) in the current time step (Pomeroy et al. 1998):

$$I = I_{t-1} + 0.7 (I_{max} - I_{t-1}) (1 – e^{(-P / Imax)}) \quad (19)$$

Liquid precipitation (rain) is assumed to fall through and is added to the ground snow cover; the consideration of rainfall–canopy interaction processes will be the subject of a future model version.

After Hedstrom and Pomeroy (1998), the maximum interception storage capacity I_{max} is equal to 4.4 · LAI*. Finally, the sublimation loss rate Q_{cs} (mm) for the snow held within the canopy is:

$$Q_{cs} = C_e I \Psi_s dt \quad (20)$$

with C_e being a non–dimensional canopy exposure coefficient, accounting for the fact that sublimation occurs only at the surface of the intercepted snow (Pomeroy and Schmidt 1993):

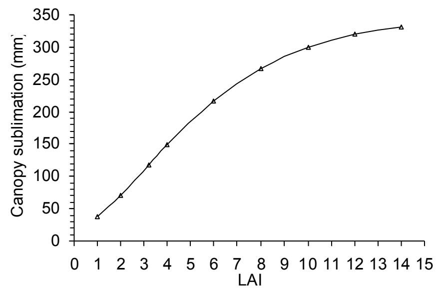
$$C_e = k_c (I / I_{max})^{-0.4} \quad (21)$$

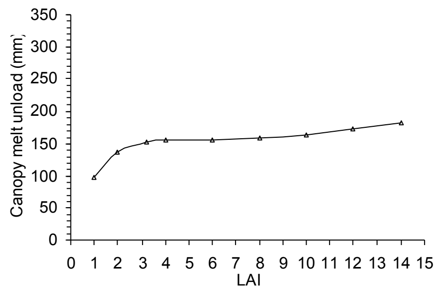
k_c = 0.01 is a dimensionless coefficient describing the shape of the intercepted snow deposits (Liston and Elder 2006).

Apart from sublimation, snow can also be removed from the interception storage by melt unload. The snow masses are hereby assumed to fall down to the ground after a partial melt at the surface. Melt unload L_m (kg m^{-2}) is estimated for temperatures above freezing using the temperature index melt model of Pellicciotti et al. (2005). For the estimation of the load of snow falling to the ground, the following scheme is applied: Using field observations, Liston and Elder (2006) estimated a daily unloading rate of 5 kg m^{-2} d^{-1} K^{-1}. By applying a scaling factor of 3.3, the temperature index melt model was calibrated to fit this estimate. The resulting unloaded mass is calculated in each timestep, and added to the ground snow cover beneath the trees.

By means of this snow–canopy interaction model, the processes of interception, snow sublimation, and melt unload are simulated. In a period of heavy snowfall, the interception storage can be filled up to its maximum. From the interception storage, snow is removed by sublimation and melt unload induced by a period of positive temperatures.

Both, the simulated rates of sublimation and the combined effect of melt and fall down of intercepted snow strongly depend on the LAI which integratively represents canopy characteristics in the described model: LAI modifies canopy transmissivity for solar radiation, wind speed, canopy density and the maximum interception storage capacity. To exhibit the sensitivity of the model on LAI, it was run at the point scale with data from the station Reiter Alm in the National Park Berchtesgaden (Germany) (1615 m a.s.l., winter season 1999/2000) LAI values ranging from 0 to 14 (Fig. 2). It becomes evident that canopy sublimation (top) and melt unload (center) increase with LAI, whereas ground melt (bottom) decreases with LAI.





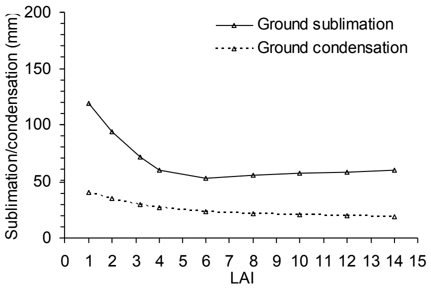


Fig. 2: Sensitivity of the snow–canopy interaction model on LAI modelled with data from Reiter Alm (National Park Berchtesgaden, Germany, 1615 m a.s.l.) for the winter season 1999/2000.

Ablation of snow amounts accumulated at the land surface beneath the canopy as a result of precipitation throughfall, sublimation and melt unload in *ESCIMO.spread v2* is calculated using an energy balance approach as described in detail by Strasser and Marke (2010).

3 RESULTS

Model results of canopy snow interception, sublimation, fall down and melt are particularly difficult to obtain, since complex measurements of tree weights are required to provide rates of mass changes with appropriate temporal resolution. For this paper, data from the SnowMIP2 project will be used to derive proper validation for the spreadsheet version of the snow-canopy model. So long, model results of sublimation of snow intercepted in an evergreen forest canopy were compared by Liston and Elder (2006) against observations from a continental climate site located within the U.S. Department of Agriculture (USDA) Fraser Experimental Forest (39°53’ N, 105°54’ W) near Fraser, Colorado, U.S.A.. In this study, a 2.7 m tall subalpine fir tree (*abies lasiocarpa*) was cut, suspended, and continually weighed at two sites at 2920 and 3230 m a.s.l. from 1 January to 1 May 2001 to estimate sublimation from the tree (Montesi et al. 2004). The validation analysis included 21 storm–free sublimation periods between 9 and 53 hours. The model was driven with hourly observed within–canopy air temperature, relative humidity, and wind speed for both sites. As an example, Fig. 3 shows two diurnal cycles of hourly sublimation rates for the two sites, and the general agreement between observation and simulation. While for individual hours the model over– or underestimated the observed sublimation rates, the errors overall cancelled each other out as the winter progressed and the modelled mass balance was very similar to the measured one for the sublimation period (Fig. 4).

The inside–canopy modification of the meteorological parameters has been measured and the respective parameterization derived for the *Col de Porte observation site* (1420 m a.s.l.) in the French Alps by Durot (1999).

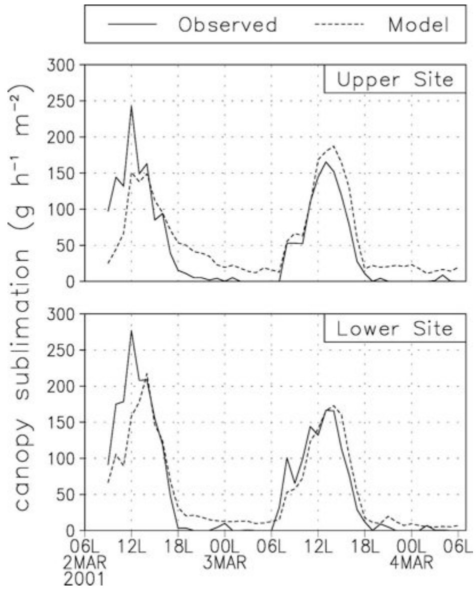


Fig. 3: Observed and modelled sublimation rates for intercepted snow in an evergreen forest. From Liston and Elder (2006).

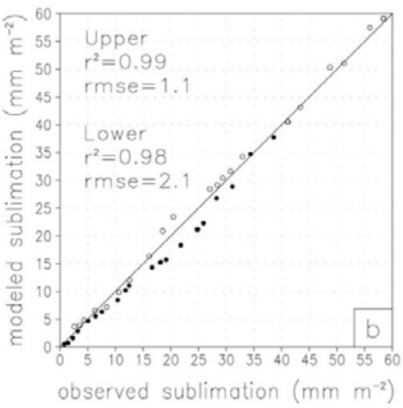


Fig. 4: Total observed and modelled sublimation for two tree sites during a 4–month winter period with 21 sublimation periods. The model was forced to fit the total of observed sublimation at the end of the sublimation season by adjusting the parameter k_c (eq. (21)). From Liston and Elder (2006).

4 DISCUSSION & OUTLOOK

This paper describes the application of the spreadsheet-based, point snow surface energy and mass balance model *ESCIMO.spread v2*. This second version comprises special consideration of forest canopy processes. The model formulae are packed together with example data, the parameters and the graphical visualization of both the observations and the model results in a spreadsheet file which can be obtained from the authors webpage www.alpinehydroclimatology.net. Beyond the application for past climate conditions, the model allows to simulate the effect of potential future climate change by means of parameters which modify observed temperature and/or precipitation. The model runs fast on any standard PC and platform with common spreadsheet programs, it is easy to handle and hence, it is suitable to be applied for educational purposes such as student courses.

The representation of the physical processes in *ESCIMO.spread v2* has proven to be robust and transferable in many applications already. The portability of the spreadsheet version of the model makes it particularly suitable to be taken to the field, and model the course of the seasonal evolution of a snow cover in situ by hooking up to a datalogger at any AWS, reading the data and performing the simulations directly.

Acknowledgements. Numerous colleagues have contributed to the development and application of the model described here with their experience and practical support, namely Nick Rutter (Newcastle upon Tyne, UK) and Glen E. Liston (Fort Collins, US) The SnowMIP2 project provides the data which lateron comes with the model.

5 REFERENCES

Buck, A.L. (1981): New equations for computing vapour pressure and enhancement factor. J. Appl. Meteor., 20, 1527–1532.

Chen, J., Rich, M., Gower, S. T. , Norman, J. M. and Plummer, S. 1997: Leaf area index of boreal forests: Theory, techniques, and measurements. J. Geophys. Res., 102, 29, 429–443.

Cionco, R.M. (1978): Analysis of canopy index value for various canopy densities. Bound. Lay. Met., 15, 81–93.

Durot, K. (1999) : Modélisation hydrologique distribuée du bassin versant nivo–pluvial de Sarennes. Validation des données d'entrée et développement d'un module de fonte nivale sous forêt. Ph.D. dissertation, LTHE, 332 p, Grenoble.

Essery, R.L.H., Pomeroy, J.W., Parvianen, J. and Storck, P. (2003): Sublimation of snow from boreal forests in a climate model. J. Clim., 16, 1855–1864.

Hedstrom, N.R. and Pomeroy, J.W. (1998): Measurements and modelling of snow interception in the boreal forest. Hydrol. Process., 12, 1611–1625.

Hellström, R.Å. (2000): Forest cover algorithms for estimating meteorological forcing in a numerical snow model. Hydrol. Process., 14, 3239–3256.

Lee, L.W. (1975): Sublimation of snow in a turbulent atmosphere. Ph.D. dissertation, 162 p, University of Wyoming.

Link, T. and Marks, D. (1999a): Point simulation of seasonal snow cover dynamics beneath boreal forest canopies. J. Geophys. Res, 104(22), 27841–27857.

Link, T. and Marks, D. (1999b): Distributed simulation of snowcover mass– and energy–balance in the boreal forest. Hydrol. Process., 13, 2439–2452.

Liston, G. E. and Elder, K. (2006): A Distributed Snow-Evolution Modeling System (SnowModel), J. Hydromet., 7, 1259–1276.

Marsh, P. (1999): Snowcover formation and melt: recent advances and future prospects. In: Hydrol. Process., *13*, 2117–2134.

Montesi, J., Elder, K., Schmidt, R.A. and Davis, R.E. (2004): Sublimation of intercepted snow within a subalpine forest canopy at two elevations. J. Hydrometeor., *5*, 763–773.

Obled, Ch. (1971): Modèle mathématique de la fusion nivale. Ph.D. dissertation, Institut de mécanique de Grenoble, 170 p, Grenoble.

Pellicciotti, F., Brock, B., Strasser, U., Burlando, P., Funk, M. and Corripio, J.G. (2005): An enhanced temperature–index glacier melt model including shortwave radiation balance: development and testing for Haut Glacier d'Arolla, Switzerland. J. Glaciol., 51(175), 573–587.

Pomeroy, J.W., Gray, D. M., Hedstrom, N.R. and Janowics, J.R. (2002): Prediction of seasonal snow accumulation in cold climate forests. Hydrol. Process., 16, 3543–3558.

Pomeroy, J.W. and Gray, D.M. (1995): Snowcover: Accumulation, Relocation, and Management. National Hydrology Research Institute, Saskatoon, Canada. NHRI Science Report, 7, 144 p, Saskatoon.

Pomeroy, J.W. and Schmidt, R.A. (1993): The Use of Fractal Geometry in Modelling Intercepted Snow Accumulation and Sublimation. Proceedings of the 50th Annual Eastern Snow Conference, Honour Paper, 1–10.

Pomeroy, J.W., Gray, D.M., Shook, K.R., Toth, B., Essery, R.L.H., Pietroniero, A. and Hedstrom, N. (1998): An evaluation of snow accumulation and ablation for land surface modelling. Hydrol. Process. *12*, 2339–2367.

Strasser, U. and Etchevers, P. (2005): Simulation of Daily Discharges for the Upper Durance Catchment (French Alps) Using Subgrid Parameterization for Topography and a Forest Canopy Climate Model. Hydrol. Process., 19, 2361–2373.

Strasser, U. and Marke, T. (2010): ESCIMO.spread - a spreadsheet-based point snow surface energy balance model to calculate hourly snow water equivalent and melt rates for historical and changing climate conditions. Geosci. Model Dev., 3, 643-652.

Strasser, U., Warscher, M. and Liston, G.E. (2011): Modelling snow-canopy processes on an idealized mountain. J. Hydrometeor. Vol. 12, No. 4, 663-677, doi: 10.1175/2011JHM1344.1.