

FSM2 for hyper-resolution applications with enhanced canopy representation:

Documentation of the model code

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The following documentation aims at outlining the development leading to the version of FSM2 available in this GitHub branch (https://github.com/GiuliaMazzotti/FSM2/tree/hyres_enhanced_canopy).

This overview includes:

1. A compilation of the FSM2 model equations which corresponds to the Appendix of Mazzotti et al. (2020a) with minor adaptations. The model version used in their publication and described is FSM2 version 2.0.1 (doi: 10.5281/zenodo.2593345); for further detail, the reader is directed to the scientific documentation and the user guide included therein.
2. A section on local application and computation of respective canopy structure metrics, also adapted from Mazzotti et al. (2020a), which they demonstrated to yield successful within-stand snow distribution simulations (2m resolution).
3. A description of model modifications included in this branch, which were introduced to optimize model performance in hyper-resolution simulations even in more complex canopy settings such as forest discontinuities (Mazzotti et al., 2020b).
4. An outline of the new user settings specific to this FSM2 version that were not included in the existing user documentation (c.f. master branch: <https://github.com/RichardEssery/FSM2>).

1. Model equations of the original FSM2 (version 2.0.1)

The canopy energy balance in FSM2 largely follows Bewley et al. (2010). Shortwave transmission through the canopy is

$$\tau = \exp(-0.5VAI)$$

and the above-canopy albedo is

$$\alpha = (1 - \tau)\alpha_c + \tau^2\alpha_g$$

for dense canopy albedo α_c and ground albedo α_g , neglecting multiple reflections and assuming diffuse radiation. Snow cover fractions f_{cs} on the canopy and f_{gs} on the ground are used to interpolate between snow-free and snow-covered albedos (Essery, 2015). Net shortwave radiation absorbed by vegetation and the ground are

$$SW_v = (1 - \tau)(1 - \alpha_c + \alpha_g\tau)SW_{\downarrow}$$

and

$$SW_g = (1 - \alpha_g)\tau SW_{\downarrow},$$

where SW_{\downarrow} is the downwards shortwave radiation flux above the canopy. Assuming that vegetation and snow on the ground are blackbodies with surface temperatures T_v and T_g , net longwave radiation is

$$LW_v = (1 - \tau)(LW_{\downarrow} + \sigma T_g^4 - 2\sigma T_v^4)$$

and

$$LW_g = \tau LW_{\downarrow} - \sigma T_g^4 + (1 - \tau)\sigma T_v^4,$$

where σ is the Stefan-Boltzmann constant and LW_{\downarrow} is the downwards longwave radiation flux above the canopy. Momentum roughness lengths z_{0f} for snow-free ground and z_{0s} for snow are combined to give a ground roughness length

$$z_{0g} = z_{0f}^{1-f_s} z_{0s}^{f_s}.$$

For vegetation of height h covering fraction f_v of the ground, the roughness length and displacement height are $z_{0v} = 0.1h_c$ and $d = 0.67f_v h_c$. The combined roughness length is

$$z_0 = z_{0g}^{1-f_v} z_{0v}^{f_v}.$$

Neglecting the influences of atmospheric stability, aerodynamic resistances for heat transfer are

$$r_a = \frac{1}{ku_*} \ln \left(\frac{z - d}{z_0} \right)$$

between the canopy air space and the atmosphere,

$$r_g = \frac{1}{ku_*} \left[\frac{1 - f_v}{\ln 10} + 0.004f_v \right]^{-1}$$

between the ground and the canopy air space, and

$$r_v = \frac{20}{VAIu_*^{1/2}}$$

between the vegetation and the canopy air space, where k is the von Kármán constant, z is the meteorological measurement height and

$$u_* = kU_a \left[\ln \left(\frac{z - d}{z_0} \right) \right]^{-1}$$

is the friction velocity for above-canopy wind speed U_a .

Sensible heat fluxes are parametrized as

$$H = \frac{\rho c_p}{r_a} (T_c - T_a)$$

between the canopy air space at temperature T_c and above-canopy air at temperature T_a ,

$$H_g = \frac{\rho c_p}{r_g} (T_g - T_c)$$

between the ground and the canopy air space, and

$$H_v = \frac{\rho c_p}{r_v} (T_v - T_c)$$

between the vegetation and the canopy air space. Similarly, moisture fluxes are parametrized as

$$E = \frac{\rho}{r_a} (Q_c - Q_a)$$

between the canopy air space with humidity Q_c and above-canopy air with humidity Q_a ,

$$E_g = \frac{\rho}{r_{ag}} [Q_{\text{sat}}(T_g) - Q_c]$$

between the ground and the canopy air space, and

$$E_v = \frac{\rho}{r_{av}} [Q_{\text{sat}}(T_v) - Q_c]$$

between the vegetation and the canopy air space, where Q_{sat} is the temperature-dependent saturation humidity if the vegetation and the ground are snow-covered. If they are not, moisture fluxes are limited by water availability factors depending on soil moisture.

The energy and mass conservation equations

$$H = H_g + H_v,$$

$$E = E_g + E_v,$$

$$LW_g + SW_g = G + H + L_s E_g + L_f M$$

and

$$LW_v + SW_v = H_v + L_s E_s + C_{\text{can}} \frac{dT_v}{dt}$$

form a set of equations for the unknown Q_c , T_c , T_s , T_v , ground heat flux G and melt rate M ; L_f and L_s are latent heats for melting and sublimation of snow, and C_{can} is the canopy heat capacity, assumed to be proportional to VAI. The equations are linearized and solved iteratively.

The model for interception of falling snow by the canopy is based on Hedstrom and Pomeroy (1998) as implemented by Essery et al. (2003). If the canopy holds a mass of S_v at the beginning of a timestep of length δt with snow falling at rate S_f , the increase in intercepted mass over the timestep is

$$\delta S_v = (S_{\text{max}} - S_v) \left[1 - \exp\left(-\frac{f_v S_f \delta t}{S_{\text{max}}}\right) \right]$$

where $S_{\text{max}} = 4.4\text{VAI}$ is the maximum canopy snow holding capacity. Snow unloads from the canopy at rate $\tau_u^{-1} S_v$ with different values of the time constant τ_u for cold and melting snow.

2. Hyper-resolution application using local canopy structure metrics

At every modelled forest location, canopy parameter input needs to be provided to FSM2. By default, only vegetation area index (VAI) and canopy height (h_c) are specified and transmissivity τ and vegetation fraction f_v are computed internally as functions of VAI. However, f_v and τ can be specified as optional user inputs if respective values are available. In the context of local-scale modelling, this versatility permits integration of canopy structure metrics that incorporate different viewing perspectives and / or portions of the canopy relevant to the process in question. This diverse set of canopy metrics also means that while point simulations are principally independent, (i.e. neglecting lateral energy exchange between neighbouring points), lateral canopy influences are accounted for by way of the canopy structure representation: conditions at each location are affected by processes in both surrounding and overhead canopy elements. While simulations of all points within each study area were driven by meteorological data from the same AWS, canopy structure parameters were point-specific.

The simulations at 2-m spatial resolution performed by Mazzotti et al. (2020a) used local canopy structure information derived from two sources:

1. Hemispherical images (real or synthetic, c.f. Moeser et al. (2014)) yielded sky-view fraction
2. Canopy height models (obtained e.g. from lidar data, c.f. Khosravipour et al. (2014) allowed deriving canopy cover fraction and mean canopy height. These were computed over circular domains of 5m radius around each point of interest.

Canopy cover fraction and mean canopy height were used as input to FSM2 (for h_c and f_v). To ensure consistency between canopy structure metrics, Mazzotti et al. (2020a) suggest approximating local VAI with a linear function scaling with h_c and f_v :

$$VAI = VAI_{max} \cdot f_v \cdot \frac{h_c}{h_{c,max}}$$

Prior knowledge of typical LAI and h_c values for the species / stand of interest is required to apply this parametrization; values can be retrieved e.g. from coarse-resolution datasets.

In addition to local canopy metrics, Mazzotti et al. (2020a) proposed two model features for hyper-resolution simulations: 1) separate effective temperatures of near and distant canopy elements and 2) the conceptual representation of preferential deposition of snow in canopy gaps. These entail minor modification to the model code described as follows:

1. Distinction between near and distant canopy elements is achieved by splitting transmissivity into non-local and local components f_{sky} and τ_{loc} . The temperature of distant canopy equals air temperature, while near-canopy elements enter the coupled snow and canopy energy balances. The two parameters f_{sky} and τ_{loc} are constrained by total hemispherical sky view (SVF = τ). Fractional canopy cover and sky-view fraction thus combine to:

$$\begin{aligned} \tau_{loc} &= 1 - f_v \\ f_{sky} &= \frac{SVF}{\tau_{loc}} \end{aligned}$$

2. Preferential deposition of precipitation and redistribution of snow intercepted by the canopy are accounted for by local precipitation scaling:

$$S_{f,corr} = S_{f,raw} (ps_f - ps_r \cdot f_v),$$

Where the limits of this rescaling (+/- 10%, i.e. $ps_f = 1.1$, $ps_r = 0.2$) are consistent with Mahat and Tarboton (2014).

3. Modifications implemented in this branch (FSM2 hyper-resolution with enhanced canopy)

Model enhancements implemented in this version address limitations within the original FSM2 identified by Mazzotti et al. (2020a) and are introduced in Mazzotti et al. (2020b). These modifications were implemented as additional parametrization options for existing model switches (Essery et al. 2015), meaning they could each be applied independently. The below descriptions are thus adapted from Mazzotti et al. (2020b), main article + appendix.

3.1 Transfer of shortwave radiation: integration of time-varying transmissivity for direct shortwave radiation (*model option SWPART = 1*)

Particularly, the original FSM2 assumed all shortwave radiation to be diffuse, which entails potential shortcomings at forest discontinuities where the directionality of solar radiation is relevant (Mazzotti et al. 2020). To differentiate between direct-beam and diffuse shortwave radiation components (SW_{lb} and SW_{ld}), the partitioning scheme after Erbs et al. (1982) is implemented in FSM2:

$$SW_{ld}/SW_d = \begin{cases} 1 - 0.09 \tau_{atm} & \text{for } \tau_{atm} \leq 0.22 \\ 0.95 - 0.16 \tau_{atm} + 4.39 \tau_{atm}^2 - 16.64 \tau_{atm}^3 + 12.34 \tau_{atm}^4 & \text{for } 0.22 < \tau_{atm} \leq 0.8 \\ 0.165 & \text{for } 0.8 < \tau_{atm} \end{cases}$$

The fraction of diffuse radiation is described in terms of the atmospheric transmissivity

$$\tau_{atm} = SW_d / [I_0 \cdot \cos(\theta)], \quad (5)$$

where θ is the solar zenith angle, and $I_0 = 1367 \text{ Wm}^{-2}$ is the solar constant.

Canopy transmissivity for diffuse shortwave radiation is treated as outlined above ($\tau_d = (1 - f_v)f_{sky} = SVF$). Transmissivity for direct radiation (τ_b) is provided as time-varying, point specific input to FSM2. This allows preserving a relatively simple formulation of radiative transfer that does not require additional canopy structure parameters to be specified. Instead, this approach leverages detailed three-dimensional radiative transfer information obtained with an external radiative transfer model (e.g. Jonas et al., 2020). Net shortwave radiation absorbed by local vegetation and the ground thus modify to:

$$SW_v = (1 - \alpha_c)f_v f_{sky} SW_{ld} + \alpha_g f_v \tau_d SW_{ld} + (1 - \alpha_c + \alpha_g)f_v \tau_b SW_{lb}$$

and

$$SW_g = (1 - \alpha_g)(\tau_b SW_{lb} + \tau_d SW_{ld}).$$

Note that the absorption of direct shortwave radiation by vegetation elements is taken to be proportional to direct-beam transmissivity and canopy cover fraction. This representation yields strongest absorption at locations that receive most direct insolation, which is consistent with findings by Webster et. al (2017), but only applicable to local-scale simulations.

3.2 Turbulent exchange between the atmosphere and the sub-canopy snowpack: forest wind profiles and sub-canopy wind speed diagnostics (*model option SFEXCH = 2*)

Turbulent exchange in the original FSM2 is represented with a bulk aerodynamic scheme with exchange coefficients dictated by above-canopy meteorology and local canopy structure metrics (CC_5 , mCH_5). In the enhanced FSM2, we explicitly include wind attenuation. This representation means sub-canopy wind velocity can be diagnosed at any arbitrary reference level, and allows turbulent exchange between the snow surface and the canopy air space to be parametrized based on sub-canopy wind velocity at a constant reference height. To reflect that the footprint affecting wind flow extends beyond the spatial scale of our local canopy structure metrics, the wind profile at any specific location is based on stand-scale metrics (CC_{50} and mCH_{50}).

Wind speed information is required to compute aerodynamic resistances. In the enhanced FSM2, a wind profile for dense canopies is defined as in Sellers et al. (1986) or Mahat et al. (2013), with logarithmic wind speed decay above the canopy, exponential reduction from the canopy top h to a level z_{sub} below the canopy (set to 2m in this study), and again logarithmic attenuation between z_{sub} and the ground. Exponential profiles in the canopy layer

are commonly used in atmospheric boundary layer research (Choudhury and Monteith 1988, Finnigan 2000) and applied in both, snowmelt models and land surface schemes (Mahat et al. 2013, Bonan et al. 2018, Boone et al. 2017). Wind speed at height z is thus computed from atmospheric wind speed U_a measured at height z_U as:

$$U(z) = \begin{cases} U_a \ln \frac{z-d}{z_{0v}} \left[\ln \frac{z_U-d}{z_{0v}} \right]^{-1} & z \geq h \\ U(h) e^{\eta(z/h-1)} & z_{sub} \leq z < h \\ U(z_{sub}) \ln \frac{z}{z_{0g}} \left[\ln \frac{z_{sub}}{z_{0g}} \right]^{-1} & z < z_{sub} \end{cases}$$

where h is stand-scale canopy height (mCH_{50}), $d = 0.67h$ is zero-plane displacement, $z_{0v} = 0.1h$ is vegetation roughness length, $\eta = 2.5$ is a wind decay factor and z_{0g} is the ground roughness length.

For sparse canopies with stand-scale canopy cover fraction f_{vs} ($= CC_{50}$), a wind profile (U_{sc}) is obtained as weighted average of the open-site logarithmic profile (U_{opn}) and the dense-canopy exponential profiles (U_{dc}):

$$U_{sc}(z) = f_{vs}^{0.5} U_S(z) + (1 - f_{vs}^{0.5}) U_{opn}(z)$$

For dense canopy, aerodynamic resistance between canopy air space (at canopy source height z_c) and the atmosphere is:

$$r_{a,dc} = C_r \left(\frac{1}{ku_*} \ln \frac{z_T - d}{h - d} + \frac{h [e^{\eta(1-(d+z_{0v})/h)} - 1]}{\eta K_H(h)} \right)$$

where Eddy diffusivity for heat K_H is given by the Prandtl hypothesis above the canopy top and features an exponential decay within the canopy:

$$K_H(z) = \begin{cases} ku_*(h-d) & z \geq h \\ K_H(h) e^{\eta(z/h-1)} & z < h \end{cases}$$

The correction factor C_r (range: 0.3 – 1) accounts for the fact that eddy diffusivities have been observed to be up to three times larger than predicted by the above representation (Finnigan, 2000). Indeed, we found that ensuring sufficiently low resistance (i.e. facilitating turbulent transfer) between the canopy air space and the atmosphere is necessary to avoid unrealistic canopy air space temperature conditions.

Similar to wind speed, aerodynamic resistance is weighted for vegetation cover fraction as

$$\frac{1}{r_{a,sc}} = \frac{f_{vs}^{0.5}}{r_{a,dc}}$$

Aerodynamic resistance between the canopy air space and the ground is parametrized using the sub-canopy wind speed at height z_{sub} and neglecting atmospheric stability corrections:

$$z_g = \frac{1}{k^2 U(z_{sub})} \ln \left(\frac{z_{sub}}{z_{0g}} \right) \ln \left(\frac{z_{sub}}{z_{0h}} \right)$$

where $k = 0.4$ is the von Kármán constant, and $z_{0h} = 0.1z_{0g}$ is the roughness length for heat transfer from the ground.

3.3 Spatial variability of snow properties within forest stands: sub-canopy snow albedo (*model option ALBEDO = 2*)

Snow surface properties are treated equally for open and forest site simulations in the original FSM2. This is consistent with many other existing models (Boone et al. 2017, Gouttevin et al. 2015, Broxton et al. 2015), but differences between open and sub-canopy snow surface properties arise due to processes such as drip unloading, litterfall, and snow metamorphism. We therefore introduce simple adjustments in the enhanced FSM2.

Sub-canopy snow albedo is derived by adjusting open-site snow albedo. This simplified, conceptual treatment of sub-canopy snow albedo is meant to account for the following differences between open-site and sub-canopy

conditions: 1) altered decay rates due to different rates of snow metamorphism; 2) generally lowered albedo due to the presence of litter.

In this conceptual formulation, we suggest relating snow metamorphism to canopy radiative transfer properties (where more incoming radiation leads to faster sintering and hence a more rapid decay), and scaling litter effects with canopy cover fraction (where more canopy is associated with higher litter concentration).

At every time step, the decay rate of sub-canopy snow albedo is obtained from the open-site value ($t_{\alpha,opn}$) as follows:

$$t_{\alpha,sc} = \frac{t_{\alpha,opn}}{(1 - \tau_d)(1 + c_L \tau_b) + c_S \tau_b}$$

This adjustment is applied to decay for both cold and melting snow. c_L and c_S are proportionality factors used to tune the relative weights of longwave radiation enhancement and shortwave radiation transmissivity, which could differ depending on e.g. latitude (due to different absolute amounts of shortwave irradiance). We set $c_L = 2$ and $c_S \sim 2-3$ for our simulations.

A correction factor is further applied to snow albedo resulting at each time step to obtain the final sub-canopy snow albedo value (α_{sc}) accounting for litter content:

$$\alpha_{sc} = (1 - 0.1f_v)\alpha_{sc,raw}$$

4. Amendments to the FSM2 user guide

Model enhancements implemented in the new FSM2 version with enhanced canopy require additional model parameters and input data to be specified. Parameters not contained in the existing user guide are summarized in the table below.

Namelist	Additional parameter	Default value	Description
&drive	tv_file	'tv'	Transmissivity data file name
&params	adfs	1	Albedo adjustment factor accounting for SWR
	adfl	1	Albedo adjustment factor accounting for LWR
	fsar	0	Albedo adjustment range (spread $f_v = 0$ to $f_v = 1$)
	psf	1	Scaling factor for solid precipitation (applies to $f_v = 0$)
	psr	0	Range of solid precipitation (spread $f_v = 0$ to $f_v = 1$)
	wcan	2.5	Wind attenuation parameter
	zsub	2 m	Sub-canopy reference height
	zgf	1	Sub-canopy roughness length adjustment factor
	zgr	0	S.-c. roughn. length adjustment range (spread $f_v = 0$ to $f_v = 1$)
	khcf	1	Correction factor for diffusivity above canopy

The transmissivity input file is provided as text file with rows corresponding to the model timesteps and columns to the modelled locations. Consistency with meteorological driving data input and the value of the parameter N_x must be ensured. Note that the option $SWPART = 1$ with external time-varying input is not currently compatible with two-dimensional (gridded) input, i.e. $N_y = 1$ is a requirement. Note also that no stability correction are implemented in the option $SFEXCH = 2$.

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