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. (2020) 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. (2020), 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., *under review*).
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

$$\tau = \exp\left(-0.5\mathrm{VAI}\right)$$

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

$$SW_g = \left(1-\alpha_g\right)\tau SW_\downarrow,$$

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

$$r_v = \frac{20}{\mathrm{VAI}u_*^{1/2}}$$

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,

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

between the ground and the canopy air space, and

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

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

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

where $S_{\max} = 4.4\text{VAI}$ 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.

The simulations at 2-m spatial resolution performed by Mazzotti et al. (2020) 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. (2020) suggest approximating local VAI with a linear function scaling with h_c and f_v:

$$VAI = VAI_{max} \cdot f_{\mathrm{v}} \cdot \frac{h_{\mathrm{c}}}{h_{c,max}}$$

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. 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:

$$\tau_{loc} = 1 - f_v$$

$$f_{sky} = \frac{SVF}{\tau_{loc}}$$

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

$$S_{f,corr} = S_{f,raw}\left(\mathrm{ps}_f - \mathrm{ps}_r \cdot f_{\mathrm{v}}\right),$$

   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. (2020).

3.1 Integration of time-varying transmissivity for shortwave radiation

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 ($SW_{\downarrow b}$ and $SW_{\downarrow d}$), the partitioning scheme after Erbs et al. (1982) is implemented in FSM2:

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

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

$$\tau_{atm} = SW_{\downarrow}/[I_0 \cdot \cos(\theta)], \tag{5}$$

where θ is the solar zenith angle, and I_0 = 1367 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:

$$SW_v = (1 - \alpha_c)f_v f_{sky} SW_{\downarrow d} + \alpha_g f_v \tau_d SW_{\downarrow d} + (1 - \alpha_c + \alpha_g) f_v \tau_b SW_{\downarrow b}$$

and

$$SW_g = (1 - \alpha_g)(\tau_b SW_{\downarrow b} + \tau_d SW_{\downarrow d}).$$

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 Forest wind profiles and sub-canopy wind speed diagnostics

Rather than treating wind attenuation implicitly as in the original FSM2, an exponential within-canopy wind profile for dense canopies is explicitly included here. Wind speed above and within dense canopies is:

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

for roughness length z_{0v} = 0.1h_{cs}, with canopy wind decay factor η = 3 and h_{cs} denoting stand scale canopy height (other than the local metric introduced above). Aerodynamic resistance between the canopy air space at any reference level z_c and the atmosphere is

$$r_{a,DS} = \frac{1}{ku_*}\ln\frac{z_T-d}{h_{cs}-d} + \frac{h_{cs}\left[e^{\eta(1-z_c/h_{cs})}-1\right]}{\eta K_H(h_{cs})},$$

where Eddy diffusivity above the canopy top is given by the Prandtl hypothesis

$$K_H(h_{cs}) = ku_*(h_{cs} - d)$$

and has an exponential form within the canopy.

For a sparse canopy stand with stand-scale canopy cover fraction f_{vs}, a wind profile (U_{SS}) is obtained as weighted average of the open-site logarithmic and the dense-canopy exponential profiles (U_{OS}, U_{DS}):

$$U_{SS} = f_{vs}U_{DS} + (1 - f_{vs})U_{OS},$$

and aerodynamic resistance between the sparse canopy layer and the atmosphere is:

$$r_{a,SS} = \left[f_{vs}r_{a,DS}^{-1} + (1 - f_{vs})r_{a,OS}^{-1}\right]^{-1}$$

This representation of wind attenuation allows a sub-canopy diagnostic wind speed at a user-defined reference height to be generated as FSM2 output. Here, we use a fixed sub-canopy reference height of 2m. Assuming sub-canopy wind speed in a sparse canopy follows a logarithmic profile below the 2m reference level as in Mahat et al. (2013), aerodynamic resistance between the ground and the canopy air space is:

$$r_{g,SS} = \frac{1}{k^2 U_{SS}(z_c)} \ln\frac{z_c}{z_{0h}} \ln\frac{z_c}{z_{0g}}$$

3.3 Within-stand variability of snow properties

Differences in snow surface properties that exist between under-canopy locations and canopy gaps due to litterfall and canopy snow unloading. To account for this variability in a simplified manner, we introduce a canopy-density dependence of local sub-canopy snow albedo, analogous to Lundquist et al. (2013):

$$a_{s,loc} = (1 - 0.2f_v)a_{s,OS}$$

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	psf psr hce fve etau z1	1 0 0 m 0 3 2 m	Scaling factor for solid precipitation (applies to $f_v = 0$) Range of solid precipitation (spread $f_v = 0$ to $f_v = 1$) Stand-scale canopy height Stand-scale canopy cover fraction Sub-canopy reference height

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 Nx 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. Ny = 1 is a requirement.

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