Appendix A: Description of the Crown Snow Load Model of FMI

In the crown snow load model of FMI (FMI model), the total crown snow load (S_{tot}) is a sum of rime (S_{rime}), dry snow (S_{dry}), wet snow (S_{wet}) and frozen snow (S_{frozen}). The amounts of different snow types are calculated cumulatively for each 1-hour time step. The snow load can change it form from one type to another, and it can be increased and decreased due to snow and rime accretion and removal. Here, we present the equations on which the calculations are based.

A1. Snow Load Type Transformations

S_{dry} is transformed to S_{wet} due to rainfall as follows:

$$\Delta S_{dry,rain} = \frac{-P_{rain}}{2\beta} \qquad \text{(A1)}$$

$$\Delta S_{wet,rain,dry} = \frac{P_{rain}}{2\beta^2} \qquad \text{(A2)}$$

where $\Delta S_{dry,rain}$ and $\Delta S_{wet,rain,dry}$ are the changes in the amounts of S_{dry} (kg m^{-2}) and of S_{wet} (kg m^{-2}) due to rainfall, respectively, P_{rain} is the amount of rainfall (mm) and $ß$ is a constant ($ß = 0.7$) describing the proportions of snow and liquid water in S_{wet}. In this study, P_{rain} is defined as follows:

$$\begin{aligned} P_{rain} &= 0\text{, when } T \leq 0.8\ °\text{C} \\ &= \left(\frac{10T}{7} - \frac{8}{7}\right)P\text{, when } 0.8\ °\text{C} < T < 1.5\ °\text{C} \\ &= P\text{, when } T \geq 1.5\ °\text{C} \end{aligned} \qquad \text{(A3)}$$

where T is 2-metre air temperature (°C) and P is liquid water equivalent of precipitation (mm). When the FMI model is run in operational use, P_{rain} is achieved directly from the numerical weather prediction model or from the Mesan analysis.

S_{frozen} is transformed to S_{wet} due to rainfall as follows:

$$\Delta S_{frozen,rain} = \frac{-P_{rain}}{4\beta} \qquad \text{(A4)}$$

$$\Delta S_{wet,rain,frozen} = \frac{P_{rain}}{4\beta^2} \qquad \text{(A5)}$$

where $\Delta S_{frozen,rain}$ and $\Delta S_{wet,rain,frozen}$ are the changes in the amounts of S_{frozen} (kg m^{-2}) and S_{wet} (kg m^{-2}) due to rainfall, respectively.

S_{dry} is transformed to S_{wet} due to melting as follows:

$$\Delta S_{dry,melt} = -f_{dry} S_{dry} \tag{A6}$$

$$\Delta S_{wet,melt,dry} = -\Delta S_{dry,melt} \tag{A7}$$

where $\Delta S_{dry,melt}$ and $\Delta S_{wet,melt,dry}$ are the changes in the amounts of S_{dry} (kg m^{-2}) and S_{wet} (kg m^{-2}) due to melting, respectively, and f_{dry} is the proportion of S_{dry} that is transformed and it is determined as follows:

$$\begin{aligned} f_{dry} &= 0, \text{ when } T < 0\ °\text{C} \\ &= 0.5, \text{ when } 0\ °\text{C} \leq T \leq 0.5\ °\text{C} \\ &= \frac{T}{19} + \frac{9}{19}, \text{ when } 0.5\ °\text{C} < T < 10\ °\text{C} \\ &= 1, \text{ when } T \geq 10\ °\text{C} \end{aligned} \tag{A8}$$

S_{frozen} is transformed to S_{wet} due to melting as follows:

$$\Delta S_{frozen,melt} = -f_{frozen} S_{frozen} \tag{A9}$$

$$\Delta S_{wet,melt,frozen} = -\Delta S_{frozen,melt} \tag{A10}$$

where $\Delta S_{frozen,melt}$ and $\Delta S_{wet,melt,frozen}$ are the changes in the amounts of S_{frozen} (kg m^{-2}) and S_{wet} (kg m^{-2}) due to melting, respectively, and f_{frozen} is the proportion of S_{frozen} that is transformed and it is determined as follows:

$$\begin{aligned} f_{frozen} &= 0, \text{ when } T \leq 0\ °\text{C} \\ &= 0.25, \text{ when } 0\ °\text{C} \leq T \leq 0.5\ °\text{C} \\ &= \frac{3T}{38} + \frac{4}{19}, \text{ when } 0.5\ °\text{C} < T < 10\ °\text{C} \\ &= 1, \text{ when } T \geq 10\ °\text{C} \end{aligned} \tag{A11}$$

S_{wet} is transformed to S_{frozen} as follows:

$$\Delta S_{wet,freez} = f_{wet} S_{wet} \tag{A12}$$

$$\Delta S_{frozen,freez} = -\Delta S_{wet,freez} \tag{A13}$$

where $\Delta S_{wet,freez}$ and $\Delta S_{frozen,freez}$ are the changes in the amounts of S_{wet} (kg m^{-2}) and S_{frozen} (kg m^{-2}) due to freezing, respectively, and f_{wet} is the proportion of S_{wet} that is transformed and it is determined as follows:

$$\begin{aligned} f_{wet} &= 1, \text{ when } T \leq -10\ °\text{C} \\ &= \frac{-T}{10}, \text{ when } -10\ °\text{C} < T < 0\ °\text{C} \\ &= 0, \text{ when } T \geq 0\ °\text{C} \end{aligned} \tag{A14}$$

Total changes in the amounts of different snow types due to phase transitions are:

$$\Delta S_{dry,trans} = \Delta S_{dry,rain} + \Delta S_{dry,melt} \tag{A15}$$

$$\Delta S_{wet,trans} = \Delta S_{wet,rain,dry} + \Delta S_{wet,rain,frozen} + \Delta S_{wet,melt,dry} + \Delta S_{wet,melt,frozen} + \Delta S_{wet,freez} \tag{A16}$$

$$\Delta S_{frozen,trans} = \Delta S_{frozen,rain} + \Delta S_{frozen,melt} + \Delta S_{frozen,freez} \tag{A17}$$

S_{rime} cannot be transformed to any other snow types.

A2. Snow Load Accretion

Accumulation of S_{rime} is calculated as follows:

$$\Delta S_{rime,accum} = 0.048 f_{pr} f_{T,rime} f_{RH} f_N f_{topo} U \tag{A18}$$

where U is 10-metre wind speed and f_{pr}, $f_{T,rime}$, f_{RH}, f_N and f_{topo} are coefficients related to precipitation, air temperature, relative humidity, cloudiness and topography, respectively. They are determined according to the following equations:

$$\begin{aligned} f_{pr} &= 1, \text{ when } P = 0 \text{ mm h}^{-1} \\ &= -5P + 1, \text{ when } 0 \text{ mm h}^{-1} < P < 0.2 \text{ mm h}^{-1} \\ &= 0, \text{ when } P \geq 0.2 \text{ mm h}^{-1} \end{aligned} \tag{A19}$$

$$\begin{aligned} f_{T,rime} &= 1, \text{ when } T \leq 0\ °\text{C} \\ &= -T + 1, \text{ when } 0 < T < 1\ °\text{C} \\ &= 0, \text{ when } T \geq 1\ °\text{C} \end{aligned} \tag{A20}$$

$$\begin{aligned} f_{RH} &= 0, \text{ when RH} \leq 93\% \\ &= \frac{RH}{5} - 18.6, \text{ when } 93\% < \text{RH} < 98\% \\ &= 1, \text{ when RH} \geq 98\% \end{aligned} \tag{A21}$$

where RH is 2-m relative humidity (%).

$$\begin{aligned} f_N &= 0, \text{ when } N \leq 70\% \\ &= \frac{N}{20} - 3.5, \text{ when } 70\% < N < 90\% \\ &= 1, \text{ when } N \geq 90\% \end{aligned} \tag{A22}$$

where N is total cloudiness (%). In this study the effect of cloudiness is omitted and f_N is set to 1.

$$f_{topo} = 1, \text{ when msl} \leq 160 \text{ m}$$

$$= 1 + \frac{msl - 160}{240}, \text{ when } 160 \text{ m} < \text{msl} < 400 \text{ m} \qquad \text{(A23)}$$

$$= 2, \text{ when msl} \geq 400 \text{ m}$$

where msl is the elevation above mean sea level (m).

0.048 in Eq. (A18) is an empirical constant based on the studies on riming by Tammelin and Säntti (1998). Originally, a higher value provided by Ahti and Makkonen (1982) was used but then rime loads proved to increase too rapidly. We note that in reality, the riming intensity is much affected also by the type of the forming rime (Baranowski and Liebersbach 1977).

Accumulation of S_{dry} is calculated as follows:

$$\Delta S_{dry,accum} = f_U \, f_{load} \, f_{dryload} P_{dry} \qquad \text{(A24)}$$

where f_U is a coefficient related to wind speed, f_{load} is a coefficient related to the amount of already loaded S_{tot}, $f_{dryload}$ is a coefficient related to the amount of already loaded S_{dry} and P_{dry} is the amount of P that falls down as dry snow. These coefficients are determined according to the following equations:

$$f_U = 1.5, \text{ when } U \geq 14 \text{ m s}^{-1}$$

$$= 1 + \frac{\sin\left(\frac{\pi U}{28}\right)}{2}, \text{ when } U < 14 \text{ m s}^{-1} \qquad \text{(A25)}$$

$$f_{load} = 0.6, \text{ when } S_{tot_{n-1}} = 0 \text{ kg m}^{-2}$$

$$= \frac{S_{tot_{n-1}}{}^{0.8}}{25} + 0.6, \text{ when } 0 < S_{tot_{n-1}}{}^{0.8} < 10 \text{ kg m}^{-2} \qquad \text{(A26)}$$

$$= 1, \text{ when } S_{tot_{n-1}}{}^{0.8} \geq 10 \text{ kg m}^{-2}$$

where $S_{tot_{n-1}}$ is the amount of S_{tot} after the previous time step.

$$f_{dryload} = 1, \text{ when } S_{dry_{n-1}} = 0 \text{ kg m}^{-2}$$

$$= \frac{-S_{dry_{n-1}}}{15} + 1, \text{ when } 0 < S_{dry_{n-1}} < 15 \text{ kg m}^{-2} \qquad \text{(A27)}$$

$$= 0, \text{ when } S_{dry_{n-1}} \geq 15 \text{ kg m}^{-2}$$

where $S_{dry_{n-1}}$ is the amount of S_{dry} after the previous time step.

$$P_{dry} = P, \text{ when } T \leq -0.5 \text{ °C}$$

$$= -2TP, \text{ when } -0.5 \text{ °C} < T < 0 \text{ °C} \qquad \text{(A28)}$$

$$= 0, \text{ when } T \geq 0 \text{ °C}$$

Accumulation of S_{wet} is calculated as follows:

$$\Delta S_{wet,accum} = f_U\, f_{load} P_{wet} \qquad \text{(A29)}$$

where P_{wet} is the amount of P that falls down as wet snow and it depends on temperature as follows:

$$\begin{aligned} P_{wet} &= 0 \text{, when } T \leq -0.5 \text{ °C or } T \geq 1.5 \text{ °C} \\ &= \left(\frac{13T}{7} + \frac{13}{14}\right)P \text{, when } -0.5 \text{ °C} < T \leq 0.2 \text{ °C} \\ &= \left(\frac{-T}{2} + \frac{7}{5}\right)P \text{, when } 0.2 \text{ °C} < T \leq 0.8 \text{ °C} \\ &= \left(\frac{-10T}{7} + \frac{15}{7}\right)P \text{, when } 0.8 \text{ °C} < T < 1.5 \text{ °C} \end{aligned} \qquad \text{(A30)}$$

In Eq. (A30) the attaching of wet snow on tree branches has been overemphasized purposely between temperatures 0 °C and 0.8 °C.

The amount of S_{frozen} can be increased only by freezing of S_{wet}, not directly due to snowfall.

A3. Snow Load Removal

Removal of S_{rime} is calculated as follows:

$$\Delta S_{rime,remov} = f_{U,rime}\, f_{T,rime}\, f_{rad} S_{rime} - S_{rime} \qquad \text{(A31)}$$

where $f_{U,rime}$, $f_{T,rime}$ and f_{rad} are coefficients related to wind speed, air temperature and solar radiation, respectively. They are determined according to the following equations:

$$\begin{aligned} f_{U,rime} &= 1\text{, when } U \leq 5 \text{ m s}^{-1} \\ &= \frac{-U}{13} + \frac{18}{13}\text{, when } 5 \text{ m s}^{-1} < U < 18 \text{ m s}^{-1} \\ &= 0\text{, when } U \geq 18 \text{ m s}^{-1} \end{aligned} \qquad \text{(A32)}$$

$$\begin{aligned} f_{T,rime} &= 1\text{, when } T \leq 0 \text{ °C} \\ &= \frac{-T}{20} + 1\text{, when } 0 \text{ °C} < T < 20 \text{ °C} \\ &= 0\text{, when } T \geq 20 \text{ °C} \end{aligned} \qquad \text{(A33)}$$

$$\begin{aligned} f_{rad} &= 1\text{, when } G \leq 250 \text{ Wm}^{-2} \\ &= \frac{-G}{2750} + \frac{12}{11}\text{, when } 250 \text{ W m}^{-2} < G < 3000 \text{ W m}^{-2} \\ &= 0\text{, when } G \geq 3000 \text{ W m}^{-2} \end{aligned} \qquad \text{(A34)}$$

where G is global radiation (W m^{-2}).

Removal of S_{dry} is calculated as follows:

$$\Delta S_{dry,remov} = f_{U,dry} f_{T,dry} f_{rad} S_{dry} - S_{dry} \quad \text{(A35)}$$

where $f_{U,dry}$ and $f_{T,dry}$ are coefficients related to wind speed and air temperature, respectively. They are determined according to the following equations:

$$\begin{aligned} f_{U,dry} &= 1, \text{ when } U \le 3 \text{ m s}^{-1} \\ &= \frac{-U}{17} + \frac{20}{17}, \text{ when } 3 \text{ m s}^{-1} < U < 20 \text{ m s}^{-1} \\ &= 0, \text{ when } U \ge 20 \text{ m s}^{-1} \end{aligned} \quad \text{(A36)}$$

$$\begin{aligned} f_{T,dry} &= 1, \text{ when } T \le 0\ °\text{C} \\ &= \frac{-T}{25} + 1, \text{ when } 0\ °\text{C} < T < 25\ °\text{C} \\ &= 0, \text{ when } T \ge 25\ °\text{C} \end{aligned} \quad \text{(A37)}$$

Removal of S_{wet} is calculated as follows:

$$\Delta S_{wet,remov} = f_{U,wet} f_{T,wet} f_{rad} S_{wet} - S_{wet} \quad \text{(A38)}$$

where $f_{U,wet}$ and $f_{T,wet}$ are coefficients related to wind speed and air temperature, respectively. They are determined according to the following equations:

$$\begin{aligned} f_{U,wet} &= 1, \text{ when } U \le 6 \text{ m s}^{-1} \\ &= \frac{-U}{18} + \frac{4}{3}, \text{ when } 6 \text{ m s}^{-1} < U < 24 \text{ m s}^{-1} \\ &= 0, \text{ when } U \ge 24 \text{ m s}^{-1} \end{aligned} \quad \text{(A39)}$$

$$\begin{aligned} f_{T,wet} &= 1, \text{ when } T \le 0.8\ °\text{C} \\ &= \frac{-5T}{71} + \frac{75}{71}, \text{ when } 0.8\ °\text{C} < T < 15\ °\text{C} \\ &= 0, \text{ when } T \ge 15\ °\text{C} \end{aligned} \quad \text{(A40)}$$

Removal of S_{frozen} is calculated as follows:

$$\Delta S_{frozen,remov} = f_{U,frozen} f_{T,frozen} f_{rad} S_{frozen} - S_{frozen} \quad \text{(A41)}$$

where $f_{U,frozen}$ and $f_{T,frozen}$ are coefficients related to wind speed and air temperature, respectively. They are determined according to the following equations:

$$\begin{aligned} f_{U,frozen} &= 1, \text{ when } U \le 5 \text{ m s}^{-1} \\ &= \frac{-U}{19} + \frac{24}{19}, \text{ when } 5 \text{ m s}^{-1} < U < 24 \text{ m s}^{-1} \\ &= 0, \text{ when } U \ge 24 \text{ m s}^{-1} \end{aligned} \quad \text{(A42)}$$

$$
\begin{aligned}
f_{T,\,frozen} &= 1\text{, when } T \le 0.5\ ^{\circ}\mathrm{C} \\
&= \frac{-2T}{39} + \frac{40}{39}\text{, when } 0.5\ ^{\circ}\mathrm{C} < T < 20\ ^{\circ}\mathrm{C} \\
&= 0\text{, when } T \ge 20\ ^{\circ}\mathrm{C}
\end{aligned}
\tag{A43}
$$