**RHEM-Snow Technical Documentation**

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**1) Introduction**

RHEM-snow is a computationally efficient snow model that is designed for use with the USDA’s RHEM / Kineros2 (K2) models with daily Cligen forcing data. It is a moderately complex model, having treatments for the snowpack mass and energy balance, but was designed to be computationally efficient with low data requirements. This makes it ideal for running the model over large sets of stations, or in applications where rapid results are required. RHEM-Snow is designed to be run with the standard set of forcing inputs produced by the CLIGEN weather generator (daily inputs of precipitation, maximum and minimum temperature, dewpoint temperature, solar radiation, and wind speed), but can also be run using other similar sets of daily forcing data, optionally, including longwave radiation as well as precipitation inputs that are already partitioned between rainfall and snowfall. The codes are available in Python and have been coupled to K2 using a Fortran code for running Python modules. This manual only covers the snow modelling portion of RHEM-Snow (as well as a subsurface hydrology model that will be used in forthcoming releases of RHEM-Snow). The publication for RHEM-Snow is Broxton et al., 2023. For details about K2, see the K2 documentation.

**2) Model Process Description**

RHEM-Snow calculates snowmelt and sublimation using a hybrid approach between simple degree-day modelling, and more complex energy balance modelling. It calculates all snowpack mass and energy balance terms. However, due to the desired computational constraints of the model (computational efficiency and daily forcing information), computation of energy balance is somewhat simplified (i.e. the snow surface temperature is an empirical function of air temperature, humidity, and net incoming radiation). The model also estimates changes in snow density, and optionally, canopy interception. Furthermore, it also includes formulations to compute necessary adjustments to forcing data if needed: partitioning between rainfall and snowfall, computation of incoming longwave radiation, and adjustment of solar radiation on inclined surfaces. There is also a simple model for keeping track of the temperature / moisture in the top soil layer. Below is a comprehensive set of model formulations for various processes in RHEM-Snow.

**2.1) Precipitation and Humidity**

RHEM-snow can either incorporate already partitioned rainfall and snowfall, or it has algorithms to separate the rainfall and snowfall based on air temperature. If required, rainfall-snowfall partitioning in RHEM-Snow is accomplished using a temperature range, the lower limit of which is all snowfall, and the upper limit of which is all rainfall. We use a continuous function to model this transition:

(1)

In this expression, , , , and . , the air temperature threshold, and , the range over which the rain-snow transition occurs, are user defined parameters.

In addition to the rain-snow transition, there are also expressions to compute vapor pressure, saturated vapor pressure, and ultimately, relative humidity (the ratio between the two).

Vapor pressure, , is computed from the daily dewpoint temperature, , using Teten’s formula (Monteith and Unsworth, 2008):

(2)

Similarly, saturated vapor pressure, , is computed from the air temperature, :

(3)

**2.2) Solar Radiation**

Solar Radiation is given as a forcing input. However, RHEM-Snow also computes potential solar radiation for a particular location, including on inclined surfaces. This potential radiation is used in two cases. First, if longwave radiation is computed, the ratio of given to potential flat-surface solar radiation is used to estimate a cloud fraction, which affects the computation of incoming longwave radiation (see ‘Longwave Radiation’ section below). Second, if shortwave radiation is adjusted for slope and aspect influences, given solar radiation values are multiplied by the solar forcing index computed for the hillslope, where

(4)

is the potential solar radiation on the inclined surface and is the flat surface potential solar radiation.

The potential solar radiation (both and ) is computed using a computer code developed by Dr. Felix Hebeler, dept. of Geography, University of Zurich, slightly modified to accept the slope-aspect conventions in RHEM-Snow, and to output daily solar radiation values (and converted from Matlab to Python). The code follows the approach of Kumar et al. 1997 (note that specific equations related to the algorithm can be found in that reference). It calculates clear sky radiation corrected for the incident angle (self-shading) plus diffuse and reflected radiation. Seasonal timeseries of are also further adjusted to ensure a match between observed and modeled clear sky conditions by multiplying by a seasonally varying correction factor, , where

(5)

In this formula,

(6)

and and are the ratios between the given and potential solar radiation () during the summer and winter months, respectively. and are found by dividing maximum observed solar radiation values with the potential flat surface solar radiation values for ~1 month periods centered on the summer and winter solstices.

There is also a user-adjustable parameter that applies a simple multiplier to the shortwave radiation (after any adjustments are made for slope and aspect) so the final downward shortwave radiation is computed is:

(7)

where is the observed solar radiation, , is the solar forcing index (from 1) and is the user-defined multiplier.

**2.3) Longwave Radiation**

If specified, incoming longwave radiation is computed using the Stefan-Boltzmann equation:

(8)

where is the Stefan-Boltzmann constant ( is the air temperature (in Kelvin), and is the effective emmisivity from the sky. Emissivity is calculated as:

(9)

where is the cloud fraction, and is the clear sky emmisivity. Parameterization of clear sky emmisivity follows Satterlund (1979):

(10)

where is the vapor pressure in Pa. Here, the cloud cover fraction is estimated from the Bristow and Campbell (1984) transmission factor;

(11)

where the transmission factor, , is calculated here as the ratio between observed and calculated clear sky solar radiation for the modeled location. is a user defined parameter. Cloud fraction is also limited such that a precipitation value over a certain threshold (right now set to 1 inch = 25.4 mm) always results in a cloudy day:

(12)

where is the daily precipitation amount in mm. This is done to reduce the impact of a mismatch between dewpoint temperature and precipitation (days with lots of precipitation can occur on days where the humidity is pretty low in the Cligen data).

Like with shortwave radiation, there is a user defined parameter that applies a simple multiplier to the incoming longwave radiation (either measured or calculated).

**2.4) Net Radiation and Albedo**

Net Radiation is computed as:

(13)

where is the incoming solar radiation, is the incoming longwave, is the outgoing longwave radiation, and is the snow albedo.

is calculated using the Stephan-boltzmann equation:

(14)

where is the snow emissivity (0.99), is the Stefan-Boltzmann constant ( and is the snowpack temperature. Due to the computational constraints of the model, rather than iteratively solving the energy balance, surface snow temperature is estimated using an empirical equation based on air temperature, relative humidity and net incoming radiation, fitted to field data from a field site in Arizona which has detailed measurements of radiation components and surface temperature:

(15)

where is the snow surface temperature, is the air temperature, is net (incoming-outgoing) solar radiation, is incoming longwave radiation, and is the relative humidity (in percent). Note that at the site where it was developed, this equation explains daily variation in with an R2 of 0.78 and an RMSE of 0.86oC, with similar performance at other sites (see Broxton et al., 2023).

Snow albedo, , is computed as a function of the age of the snow surface (since the last significant snowfall):

(16)

is the albedo of fresh snowfall, is the albedo of old snow, is the age of the snow surface, and is a decay constant. Every day, increments by one day, but on days that it snows, is adjusted (to 0 if the storm is large enough) using:

(17)

Where is the snowfall, is a parameter specifying the snowfall size that will completely reset the snow surface albedo. , , , and are user defined parameters.

**2.5) Sensible and Latent heat**

Sensible heat flux when the temperature is computed as:

(18)

Here, is the air specific heat capacity (), is the sensible heat conductance, is the air density, is the air temperature, and is the snow temperature.

The variation of , the air density, with elevation is estimated because air pressure is not given. is calculated as:

(19)

Where pressure is estimated to be:

(20)

Here, , the specific gas constant for dry air, is 287.058 , , the acceleration due to gravity, is 9.81 , and , is an estimated lapse rate (6.5 ), is standard sea level pressure (101.325 kPa) and is the elevation.

The latent heat flux is computed as:

(21)

where is the latent heat conductance, is the saturated vapor pressure at the snow surface, is the air vapor pressure, is the dry gas constant, is the latent heat of sublimation (2834 kJ/kg).

The water equivalence depth of sublimation is:

(22)

is the density of water (1000 kg/m3), and is the model timestep.

The heat conductance terms are given by expressions of turbulent transfer in the boundary layer (Anderson, 1976; Male and Gray, 1981; Brutsaert, 1982). For neutral conditions:

(23)

Here, is von karman’s constant (0.4), is the wind speed at measurement height, , and is roughness height at which the logarithmic boundary layer profile predicts zero velocity. Both and can be specified as model parameters. A stability correction is applied based on the Richardson number, which is approximated as (ref):

(24)

is used to adjust and following Price and Dunne (1976):

(25)

(26)

As in Tarboton and Luce, 1996, there is also a stability factor to control the extent that these correction factors are applied:

(27)

is a user defined parameter ranging from 0-1 (0 uses neutral conductances and 1 gives full stability corrections).

**2.6) Heat from Precipitation**

Heat from precipitation considers heat from rainfall and snowfall separately (assuming that rainfall temperature is the maximum of air temperature and freezing temperature, and snowfall temperature is the minimum of air temperature and freezing temperature):

(28)

is the snow rate, is the rain rate, is the specific heat of ice (2.05 ), is the specific heat of water (4.181 ), is the density of water (1000), and is the latent heat of fusion (334).

**2.7) Ground Heat**

Ground heat flux is given by:

(29)

is the soil thermal conductivity (which is a user definable model parameter at this point, in the absence of information about soil type or wetness), is the distance between the damping depth (also a user definable parameter) and the middle of the snowpack, and is the temperature difference between the damping depth (also a user definable parameter) and the middle of the snowpack.

**2.8) Melt and Snowpack Mass and Energy Balance**

RHEM-Snow computes potential melt energy based on energy contributions of other energy balance terms:

(30)

Here, is the net radiation, is the sensible heat, is the latent heat, is the precip heat, is the ground heat, is the model timestep, and is the cold content.

In this expression, is the snow water equivalent, is the density of water (1000), is the specific heat of ice (2050), and is the lesser of the average of the last days temperatures and 0oC (where is a user-defined parameter).

Melt mass flux is computed as:

(31)

Melt is limited such that it cannot exceed SWE (note that the energy flux is also limited).

RHEM-Snow does not account for the liquid holding capacity of water, so this melt is immediately removed from the snowpack. The resulting mass balance of the snowpack is:

(32)

where is snowfall (which includes both throughfall and unloaded snow, if under canopy), is rainfall (which includes both rainfall and drip from the canopy), is sublimation, and is snowmelt.

The energy balance is:

(33)

Where cold content is limited so that the bulk snowpack temperature is between the snow surface and 0oC. Note that if there is an imbalance, then excess heat is added to the sensible heating term.

**2.9) Canopy Interception of snowfall**

Canopy interception of snowfall is calculated from:

(34)

where is the intercepted snow for the current timestep, is the intercepted snow for the previous timestep, is the snowfall, is the maximum interception capacity, given by is the snow unloading rate, is the canopy sublimation rate, and is the melt-drip rate. The maximum interception capacity is given by (Hedstrom and Pomeroy 1998):

(35)

where is the total leaf area index (that includes stems, leaves, and branches). The term for new snow interception () is based on formulations from Liston and Elder, 2006 and Pomeroy et al., 1998. The amount of snow unloading () is estimated as a function of the amount of intercepted snow:

(36)

where is intercepted snowfall (after the addition of new snowfall, but before subtractions from sublimation and drip), and is a user definable parameter specifying snow unloading rate. The amount of sublimation of intercepted snowfall () is tied to calculation of sublimation from the snowpack by:

(37)

where is snowpack sublimation, and is a user-defined multiplier representing how much faster canopy sublimation occurs relative to snowpack sublimation. Finally, the melt drip rate is given by a temperature index formulation:

(38)

where is the temperature (in celcius), and is a user defined parameter representing the melt drip rate.

**2.10) Snow Density**

Snow density in RHEM-Snow is given by:

(39)

Here, is the snow density for the current timestep, is the snow density for the previous timestep, is a user-definable parameter representing the density of new snowfall, is the maximum allowable snow density, is the fraction of pack that is contributed by new snowfall (, where is the new snow depth, and is the total snow depth (including new snowfall). is the densification due to overburden, which is parameterized as:

(40)

where is the snow water equivalent, is the snow density (after the addition of new snow) and is a user-definable parameter specifying densification rate due to overburden. is the densification due to wind effects, which is parameterized here as:

(41)

where is the wind speed, and is a user-definable parameter specifying densification rate due to wind. is the densification due to liquid water in the pack, and is parameterized here as:

(42)

where is a flag specifying whether the snowpack is ripe (1 if ripe, and 0 if not ripe), and is a user-definable parameter specifying densification rate due to liquid in the snowpack.

**2.11) Near Surface Hydrology Model**

After the rainfall and snowmelt are combined, it is infiltrated into the soil. Infiltration runoff is computed as

(43)

where is the net water input, is the maximum possible fraction of infiltration excess runoff (e.g. at saturated conditions), is the soil moisture content, is the soil moisture at which infiltration excess runoff is maximized.

Next, evapotranspiration is computed as:

(44)

where and are, respectively, critical moisture content, and wilting point. is a function of daily incoming solar radiation and air temperature as in Martel et al., 2017:

(45)

where is the extraterrestrial radiation in MJ/m2/day, is the density of water (1000 kg/m3), is the latent heat flux (2.26 MJ/kg), and is the daily mean temperature.

Percolation out of the top soil layer is computed as:

(46)

where is the saturated hydraulic conductivity, is the soil moisture, is the saturated soil moisture, is the residual soil moisture, and is the pore size distribution index. As in Kineros2, the soil specific residual soil moisture content is computed as an empirical function of the soil capillary drive parameter,

(47)

Capillary rise, itself, is computed as:

(48)

where is , is the saturated hydraulic conductivity, is the air entry pressure, is the thickness of the upper soil layer, and is the pore size distribution index.

Below the top soil layer, there are two conceptual layers representing 1) the rest of the vadose zone, and 2) the phreatic zone, which enables computation of baseflow originating from the deep soil layers.

Discharge from both reservoirs is computed as:

(49)

where is the storage in each reservoir, and and , are constants. There is also a leakage term between the two reservoirs, which is simply computed as

(50)

where is the vadose zone storage, and is a constant.

In addition to simulating water flow into and out of the top soil layer, RHEM-Snow also simulates heat conduction through this layer, as well as soil freezing / thawing. Temperature is computed similarly to the snowpack, where energy can be added / removed from the soil layer from above or below:

(51)

where and are heat fluxes into and out of the top and bottom of the soil layer are computed using equation 29 (where the surface / snowpack temperature are used to compute the flux at the top, and a constant temperature and a damping depth are used to compute the flux at the bottom.

When the soil temperature is above or below freezing, the energy is used to warm and cool the soil temperature, where:

(52)

where is the energy content of the soil layer, is the mass of ice in the soil layer, is the amount of liquid water in the soil layer, is the soil layer thickness, , , and are the specific heats of ice, liquid water, and soil, and , , and are the densities of ice, water, and dry soil.

When the temperature drops to freezing or rises to freezing, the energy is used to drive soil melt / freezing. This is calculated using equation 31, except is the cold content of the soil layer, and the amount of ice produced is limited between 0 (unfrozen condition) and the soil moisture content (all water is frozen), and excess energy is used to raise and lower the soil temperature using equation 52.

**2.12) Coupling with K2**

Liquid water input (LWI; rainfall plus snowmelt) from the snow module is used to drive K2, which simulates overland flow and erosion. K2 is an event-oriented model that simulates infiltration, Q, and E resulting from precipitation events at high temporal frequency (Hernandez et al., 2017). In RHEM (without snow), K2 is forced with disaggregated CLIGEN daily precipitation inputs directly using a double exponential function (Wei et al., 2007) and parameters describing the intensity, duration, and timing of the precipitation. RHEM-Snow uses the same method to disaggregate rainfall inputs, but snowmelt inputs are disaggregated to mimic a daily distribution that peaks in the afternoon using a beta function, as in Webb et al. (2017).

To simplify the combination of inputs, all LWI inputs are disaggregated to a 5-minute timestep in RHEM-Snow. When there is both snowmelt and rainfall (e.g. which occurs on days with rain-on-snow), snowmelt is added to the rainfall input that percolates through the snowpack. The amount of water that percolates through the snowpack during the ROS event depends on the thermodynamic properties of the snowpack (i.e. the cold content), the rainfall amount, and the energy exchange that occurs during the event (Figure S1). To match how events are simulated in RHEM (without snow), each day’s net water input is regarded as a single “event”, and initial conditions (e.g., prescribed initial soil moisture) are the same as in RHEM.

**3) Forcing Data**

RHEM-Snow is designed to be forced with daily weather data available from the CLIGEN weather data generator. As such, it requires a minimal number of forcing variables as input. These are provided to the model as CLIGEN forcing data (.stm) files.

**Required Forcing Inputs:**

* **Daily Precipitation** – mm/day
* **Daily Max, Min Temperature** – degrees-C
* **Daily Humidity (Dewpoint Temperature)** – degrees-C
* **Daily Incoming Solar (Shortwave) Radiation** – langleys/day
* **Daily Wind Speed** – m/s

**Optional Forcing Inputs:**

* **Daily Incoming Longwave Radiation** - langleys/day
* **Daily Snowfall** – mm/day

The CLIGEN files only contain the required forcing variables. When run with CLIGEN files, the optional forcing inputs are estimated using the rainfall / snowfall partitioning and longwave schemes. Each CLIGEN file contains data for one station, although multiple files can be given to RHEM-Snow for simultaneous execution for multiple sites (in which case, the timesteps must match). As described in section 4, each station can also have different model parameters.

RHEM-Snow will automatically simulate all of the days and locations for which forcing data is provided, and so decisions about simulation length and location are made during the selection of the forcing data. There is currently no functionality to stop or start simulations in the middle of the forcing timeseries.

**4) Model parameters**

There are 63 model parameters in RHEM-Snow, which can broadly be divided into eight categories: spatial parameters, initialized values, model forcing parameters, those related to the snow albedo model, those related to the snow density model, those related to the snow interception model, miscellaneous snowpack parameters, and hydrology model parameters.

**Spatial Parameters (note that default values are defined in Preprocess.py, though they can be adjusted)**

* latitude – for computing sun angles if either slope / aspect influences or cloudiness for incoming longwave radiation are calculated by RHEM-Snow [degrees]
* elevation - elevation
* slope – slope angle [degrees]

aspect – aspect [degrees from north, clockwise]

* lai – leaf area index (for computing canopy interception) [m2/m2]

**Initialized Values:**

* swe\_i – Initial snow water equivalent [mm]
* swe\_age\_a\_i – Initial effective age of snow surface since last snowfall [day]
* density\_i – Initial snow density [g/cm3]
* cansnowstor\_i – Initial canopy intercepted snow storage [mm]
* Tm\_i – Initial snowpack temperature [C]
* T\_soil\_i – Initial soil layer temperature [C]
* ice\_fraction\_soil\_i – Initial soil ice fraction [cm3/cm3]
* sm\_i – Initial soil moisture [cm3/cm3]
* q\_vadose\_i – Initial water content in the vadose zone (below the top soil layer) [mm]
* q\_phreatic\_i - Initial water content in the preatic zone [mm]

**Forcing Data Parameters:**

* srad\_mult – Shortwave Radiation Multiplier (simple correction for forcing bias, e.g. if simulation is for a different spatial position as forcing data)
* lrad\_mult – Longwave Radiation Multiplier (simple correction for forcing bias, e.g. if simulation is for a different spatial position as forcing data)
* snow\_mult – Snowfall Multiplier (simple correction for forcing bias, e.g. for things like snowfall undercatch)
* temp\_adj - Adjustment to air temperature [C]
* RainThresh - Rain / Snow Transition Temperature [C] (at which rain and snow make up equal parts)
* RainThresh\_dh - Range of temperatures over which the rain/snow transition occurs [C]
* CloudTransmission - Fraction of potential solar radiation to be considered cloudy (for calculating longwave radiation) [-]
  + e.g. a value of 0.4 would mean that if observed shortwave radiation is ≤ 0.4 that of potential shortwave radiation, then it would be considered to be cloudy
* use\_tdew\_ppm – Flag to specify whether to use dewpoint temperature instead of air temperature when computing the rain-snow transition (true = use dewpoint)

**Snow Albedo Parameters:**

These parameters relate to the time-varying snow albedo parameterization based on the age of the snow surface since the last significant snowfall

* albedo\_snow\_reset – Size of daily snowfall to reset the snowpack surface age [mm]
* albedo\_decay - Snow albedo decay rate [fraction/day]
* albedo\_i - Albedo of fresh snowpack [-]
* minalbedo - Minimum snowpack albedo [-]

**Snow Density Parameters:**

* density\_min - Density of new snow [g/cm3]
* density\_max - Maximum snow density [g/cm3]
* apar - Snow densification rate due to age [Fraction / day]
* dpar - Snow densfication rate due to overburdin [Fraction / cm [SWE]]
* rpar - Snow densfication rate due to liquid in snowpack [Fraction when isothermal snowpack]

**Snow Interception Parameters**

* melt\_drip\_par - Melt Drip Rate [mm/day per deg-C above freezing] snow\_unload\_par - Fraction of canopy snow that unloads each day [-]
* canopy\_sub\_mult - Canopy sublimation multiplier applied to potential sublimation rate [which is computed for snowpack surface] [-]

**Miscellaneous Snowpack Parameters**

* Ch - Multiplier applied to sensible heating equation
* ground\_sub\_mult - Ground sublimation multiplier applied to potential sublimation rate [-]
* sroughness - Snow surface roughness length [m]
* windlevel - Height of windspeed measurement [m]
* fstab – Stability parameter[-] (0-1; 1: totally on Richardson number corrections; 0: assumes neutral atmospheric stability)
* kappa\_snow - Snow thermal conductivity [W/m2/K]
* kappa\_soil - Soil thermal conductivity [W/m2/K]
* tempdampdepth - Temperature at damping depth underneath a snowpack [C]
* dampdepth - Damping depth [m]
* albedo\_0 - Albedo of snow-free ground
* groundveght- Ground Vegetation height [m]

**Hydrology Model Parameters**

* PET\_Mult – Potential evapotranspirataion multiplier [-]
* max\_infil\_mult – Fraction of incoming water that becomes infiltration excess when the soil moisture is above the level specified by sm\_max\_infil [-]
* sm\_min\_infil – Soil moisture content below which infiltration excess runoff is minimized [-]
* sm\_max\_infil – Soil moisture content above which infiltration excess runoff is maximized [-]
* H – Thickness of surface soil layer [mm]
* ssat – Saturated water content [-]
* psi\_s – Soil air entry pressure [cm]
* g – g Parameter for calculating residual soil moisture
* b\_soil – Pore size distribution index [-]
* k\_soil – Saturated hydraulic conductivity [mm/day]
* wp – Wilting Point [-]
* cmc – Critical Moisture Content [-]
* coef\_vadose – Vadose Zone Reservoir Decay Parameter (multiplier) [-]
* coef\_vadose\_exp – Vadose Zone Reservoir Decay Parameter (exponent) [-]
* coef\_vadose2phreatic – Leakage Rate between Vadose and Phreatic Reservoirs [-]
* coef\_phreatic – Phreatic Zone Decay Parameter (multiplier) [-]
* coef\_phreatic\_exp – Phreatic Zone Decay Parameter (exponent) [-]

Model parameters can either be adjusted on a global or per-site basis. If changing the global calibration, it is recommended to set them in the script that is running the model (snow.py). For example, to change the minimum snow albedo to 0.5, enter the line “modelpars[‘minalbedo’] = 0.5” right after “model\_pars = Preprocess.default\_model\_pars(nlocs)”. The default model parameters can also be changed on a site-specific basis. To do this, GetSiteSpecificParameters needs to be set to “True” in snow.py, and there needs to be a file called SiteSpecificParameters.csv in the same directory as snow.py. SiteSpecificParameters.csv has columns for the CLIGEN site name, as well as each parameter to be treated as site specific. The name of each of these columns is the same name as the parameter name given above. For example, if there is a column called “RainThresh”, it will overwrite modelpars.RainThresh in the model.

Below are some general notes about parameter adjustments.

* To change the amount of snow accumulation adjust modelpars.RainThresh to change the partitioning between rain and snow or modelpars.snow\_mult to apply a simple multiplier to snowfall
* modelpars.CloudTransmission affects the incoming longwave radiation under cloudy skies, though radiation adjustments can also be accomplished by changing modelpars.srad\_mult and modelpars.lrad\_mult.
* Changing the albedo parameters will have the greatest effect on snowmelt rate
* Changing the snow density parameters changes the relationship between snow depth and SWE (without much affecting other aspects of the model)
* The interception parameters only affect snow interception processes
* The miscellaneous snowpack parameters affect the computation of cold content, turbulent heat fluxes, and ground heat flux. The most consequential of these parameters are modelpars.sroughness, which primarily affect latent heat flux and sublimation amounts: higher values of modelpars.sroughness will result in more sublimation.
* At this point, the soil model is still experimental. Ultimately, it is designed to simulate near surface soil temperature and moisture content for initializing kineros2 runs.
* The spatial parameters as well as the forcing multipliers are designed to be given a priori (to account for spatial characteristics or known forcing deficiencies), but these can be changed for model testing, or as a way to account for site-specific characteristics such as shading or enhancement of longwave radiation by trees. Note that interception is not calculated unless LAI is non-zero. Also note that typically, at least latitude and elevation are given (e.g. they are read automatically from CLIGEN files).

**5) Running RHEM-Snow**

**5.1) Input Data**

The first step when running RHEM-Snow is to prepare the forcing data input for the simulation period, consisting of daily timeseries of at least precipitation, max/min temperatures, dewpoint temperature, wind speed, and solar radiation, and optionally snowfall and incoming longwave radiation. The required variables are included in CLIGEN files and there is a built-in function to read these files (subroutine **get\_forcing\_cligen** in snow.py). These stations will be run with the default parameter set (defined in subroutine **default\_model\_pars** in snow.py) unless site specific parameters are used (and are defined in SiteSpecificParameters.csv).

**5.2) Model Execution**

RHEM-Snow can either be run as a standalone snow model, or it can be run coupled to K2. See the Readme file for an example of how to run RHEM-Snow, its requirements, and required inputs, and how to specify model outputs in Readme.txt.

**5.3) Model Output**

Once RHEM-Snow has been run, model output will be saved depending on whether the flags SaveDailyTable and SaveAllRHEMSnowOutputs are set to true or false in snow.py. When SaveDailyTable is true, a daily mass balance table will be produced. This option is useful for understanding fluxes into and out of RHEM-Snow. If SaveAllRHEMSnowOutputs is true, the model will dump all model outputs. This option is mostly used for debugging the model. If RHEM-Snow is run fully coupled with K2, then it will automatically disaggregate model estimates of liquid water input (rainfall + snowmelt) and pass to K2, which uses them to calculate runoff and erosion.

**6) Explanation of Model Codes**

The functions for running RHEM-Snow (including auxiliary functions as well as those to import forcing data and write output files) are all contained in snow.py. These functions are not reproduced here, but below is a description of the purpose of each one.

**default\_model\_pars** – Sets default model parameters for all modeled locations. Note that after default model parameters have been loaded, they can be changed manually.

**get\_soil\_pars** – Populates soil model parameters based on soil type (uses Clapp and Hornberger, 1978 lookup table)

**get\_forcing\_cligen** - Gets cligen forcing data from one or more cligen files, prepare the data for RHEM-snow, and get their associated site-specific parameter values from parameter files (if any).

**solarradiation** – Calculates solar radiation for a digital elevation model (DEM) for all days of the year for clear sky conditions following the approach of Kumar, 1997.

**run\_model** – Runs RHEM-Snow

**f** and **eqroot** – Functions used for the generation of the rainfall double exponential from the cligen data

**get\_ts\_data** – Disaggregates net water input from RHEM-Snow

**collect\_ts\_output** – Formats disaggregated model output from RHEM-Snow for K2, as well as to write optional RHEM-Snow specific output data (such a mass balance table and a model dump file).

**run** – Performs a complete RHEM-Snow run. Note that this function can either be used to run RHEM-Snow independently or fully coupled with K2. Note that in the later case, the K2 executable calls this function directly

**get\_next\_event**, **get\_npoints**, **get\_times**, **get\_depths**, **get\_sat**, **get\_ice** – Functions used for model coupling with K2

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