Soil Temperature

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*General description*

Simulates soil temperature given minimal input information using a numerical scheme. This implementation is largely based on the method described by Campbell (1985) but has some modifications to make it compatible with APSIM. There are also some updates since the version released in APSIM Classic. Here we add some changes intended to facilitate potential future developments in other APSIM modules.

*Theory*

The node/element scheme for the numerical simulation is shown in Figure 1. All heat storage is assumed to occur at the nodes while resistance to heat transfer is assumed to take place between nodes. [relationship to layers]

Following Campbell (1985), heat flux density (*h*, the rate of heat movement in the soil; W /m2) is given by:

, [Eq. 1]

where λ is the thermal conductivity (W /m /K), *T* is the soil temperature (C), and *z* is depth in the soil (m). When this equation is combined with the equation for continuity of energy the change in temperature with time emerges as:

[Eq. 2]

where *C* is the volumetric specific heat of the soil (J /m3 /K) and *t* is time (s). This equation is amenable to discretisation and numerical solution when accompanied by air temperatures from the weather file as the upper boundary condition and a constant temperature lower boundary condition placed at an appropriate depth.

Implementation of the numerical solution requires that the thermal properties of the soil (λ and C) are provided and, because the numerical solution requires sub-daily timesteps, some assumptions about the pattern of air temperature during the day. These are documented below.

*Volumetric Specific Heat of the Soil (C)*

The volumetric specific heat of the soil is the amount of energy required to raise the temperature of the soil by 1 °C. It is calculated from the soil constituents and includes quantities that change during the simulation. This key soil characteristic is calculated from the weighted sum of the soil constituents as:

[Eq. 2]

where C is the volumetric specific heat of the constituent, ϕ is the volumetric fraction of the constituent in the whole soil and subscript *i* indicates the soil constituent which has values of rocks, OM (organic matter), sand, silt, clay, water, ice and air. Note that these volumetric fractions are slightly different to those frequently used in APSIM as they need to account for rocks and organic matter in the whole-soil volume.

The calculation method is somewhat complicated by the basis of the soil property inputs in APSIM. For example, the clay percentage is the percentage of clay in the soil fines (i.e., excluding stones) after removal of the organic matter. Given these considerations, the calculations, with their order of calculation, is:

1. ϕrocks = Rocks% / 100
2. ϕOM = Carbon% / 100 \* 2.5 \* ρb / ρOM
3. ϕsand = (1 - ϕOM – ϕrocks) \* Sand% / 100 \* ρb / ρs
4. ϕsilt = (1 - ϕOM – ϕrocks) \* Silt% / 100 \* ρb / ρs
5. ϕclay = (1 - ϕOM – ϕrocks) \* Clay% / 100 \* ρb / ρs
6. ϕwater = (1 - ϕOM) \* θ
7. ϕice = (1 - ϕOM) \* θice
8. ϕair = 1 - ϕrocks - ϕOM - ϕsand - ϕsilt - ϕclay - ϕwater - ϕice

where notes on each calculation are as below:

1. Rocks% is the % by volume of stones/rocks in the intact soil layer as entered in APSIM
2. Carbon% is the % by mass of carbon in the soil fine fraction, the factor of 2.5 is to convert from carbon to organic matter by weight, ρb is the soil bulk density as the mass of fine earth in the intact soil volume, and ρOM is the density of organic matter
3. Sand% is the % by volume of sand in the fine earth fraction of the soil as entered in APSIM, and ρs is the particle density of the soil fines
4. Silt% is the % by volume of sand in the fine earth fraction of the soil, as entered in APSIM
5. Clay% is the % by volume of clay in the fine earth fraction of the soil, as entered in APSIM
6. θ is the volumetric soil water content (liquid form only) as simulated by APSIM
7. θice is the volumetric ice content which may be simulated in a future version of APSIM

and

* ρOM is given a value of 1.3 Mg /m3 (Campbell, 1985)
* ρs is throughout APSIM given a value of 2.65 Mg /m3 but there would be more flexibility for a greater range of soils if this was specified in the soil properties rather than being inherently assumed
* ϕOM is often overlooked when calculating soil thermal properties as usually the organic matter content of the soil is sufficiently low that it may be ignored. However explicitly including it will maintain flexibility for soils with high organic matter and particularly for peat soils
* θice is only considered here only for forward compatibility – in the current version it will have a value of 0

Note that the soil surface layers, particularly in perennial systems can have a high root content. Logically, it would be reasonable to expect that high root contents would affect the thermal properties, but such an effect is not currently included.

*Thermal conductivity (*λ*)*

The thermal conductivity (λ) of the soil is a quantification of the propensity of the soil to conduct heat from locations of high temperature to those of low temperature. This key soil characteristic can either be determined (see Jury, 1991 for an example) or can be approximated from empirical or regression equations. We have adapted the ‘simplified de Vries’ method from Tian et al. (2016) as this seems suitable for implementation in APSIM. However, Tian et al. (2016) included several features that we do not consider. We do not include the extension of λ to completely dry soils as the soil water models in APSIM do not permit soils to dry below a defined “air dry” water content which is approximately at a suction of 30 bar. Nor do we consider the extension for soil water contents less than 0.09 m3 /m3.

Thermal conductivity is calculated from the weighted sum of the soil constituents as:

[Eq. 2]

where ϕ is the volume fraction as defined above, *k* is a weighting factor, and the subscript *i* indicates the soil constituent as above except that the mineral components are considered together (therefore *i* has values of rocks, OM, mineral, water, ice and air). Eq ?? introduces a weighting factor:

[Eq. 2]

where *g* is a shape factor which is given by the values and equations in Table X.

Table 1. Specific heat (C), thermal conductance (λ) and shape factor (*g*) of soil constituents. Values from Campbell (1985) unless otherwise noted.

|  |  |  |  |
| --- | --- | --- | --- |
| Constituent, *i* | Ci (MJ /m3 /K) | λi (W /m /K) | gi (W /m /K) |
| Rocks1 | 7.702 | 0.1822 | Eq Y |
| Organic matter | 0.25 | 2.50 | 0.53 |
| Sand | 7.702 | 0.1822 | 0.182 |
| Silt | 2.742 | 2.39 | 0.125 |
| Clay | 2.92 | 1.392 | 0.00775 |
| Minerals | n/a | note 4 | note 5 |
| Water | 0.57 | 4.18 | 1.0 |
| Ice | 2.18 | 1.73 | note 6 |
| Air | 0.025 | 0.0012 | note 7 |
| 1 – rocks or stones were not considered by Tian et al. (2016). We assume that, thermally, they behave similarly to sand | | | |
| 2 – value from Tian et al. (2016) | | | |
| 3 – value from de Vries (1963) but Tian et al. (2016) notes that this value would stand further evaluation | | | |
| 4 – | | | |
| 5 – | | | |
| 6 – | | | |
| 7 – | | | |

*Numerical stability*

The node/element scheme for the numerical simulation is shown in Figure 1. All heat storage



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In Temperature,

The lower boundary condition is taken as a zero flux condition, ie. constant temperature, in which Tnz+1 equals a constant which is usually taken as the average annual temperature.

 [17]

The upper boundary condition is more complex. Usually the known temperature is the air temperature at some height above the soil and d1 is expressed as,

, [18]

where KBL is the boundary layer conductance (J s-1 m-2 K-1), Tair is the temperature at the top of the boundary layer, Rn is the net radiative input (J s-1 m-2), and Esoil is the evaporative loss of energy from the soil surface (J s-1 m-2).

*Implementation*

Soiltemp is designed to independent of the Apsim timestep. To allow for the numerical solution, the equations above are solved 48 times within each Apsim timestep. This allows for a half-hourly internal time step when Apsim is running on its customary daily step, which should be more than sufficient for numerical stability. When the Apsim timestep is 24 hours Soiltemp estimates the changes in air temperature, the upper boundary condition, in the following manner.



Figure 2. Diagram showing the interpolation of air temperature within a day based on minimum and maximum temperature.

Air temperatures occurring between midnight and mint\_time are linearly interpolated from the air temperature at midnight, calculated at the end of the previous Apsim timestep, and mint. There is a linear rise in temperture from the day’s minimum to maximum. After maxt\_time until midnight, air temperature is calculated as decreasing at the same rate at which it rose.

If the Apsim timestep is less than 24 hours it is assumed that the user is supplying enough detail of the diurnal changes in air temperature that such interpolation is not required. In that case air temperture is taken as the average of mint and maxt for each Apsim timestep.

*Initialisation*

There are two sections required for initialisation of the Soiltemp module; constants and parameters. Where a variable name is followed by “[nz]” the variable is an array and the appropriate number of values must be supplied.

Constants

|  |  |  |  |
| --- | --- | --- | --- |
| Name | Unit | Description | Value |
| nu | - | forward/backward differencing | 0.6 |
| vol\_spec\_heat\_om | J m-3 K-1 | volumetric specific heat of organic matter | 5.00e6 |
| vol\_spec\_heat\_water | J m-3 K-1 | volumetric specific heat of water | 4.18e6 |
| vol\_spec\_heat\_clay | J m-3 K-1 | volumetric specific heat of clay minerals | 2.39e6 |

Parameters

|  |  |  |  |
| --- | --- | --- | --- |
| Name | Unit | Description | Range |
| clay[nz] | - | proportion of clay | 0.0 - 1.0 |
| bound\_layer\_cond | J s-1 m-2 K-1 | boundary layer conductance | 0.0 - 100.0 |

The higher the value of bound\_layer\_cond the greater the difference between air and soil surface temperature. If its value is unknown, Campbell (1986) suggests that a value of 20 J s-1 m-2 K-1 is an appropriate initial estimate.

A further, optional, parameter is,

|  |  |  |  |
| --- | --- | --- | --- |
| soil\_temp[nz] | °C | initial soil temperature | -100.0 - 100.0 |

which used to initialise soil temperature. If it is not supplied the soil temperature array is initialised to the average annual temperature. Simulations will eventually ‘forget’ the effect of poor initial guesses of soil temperature, but this may take some time. Testing of this module showed that it took approximately 40 days for the temperature at 1.5 m deep to converge to within 0.5 °C of the analytical solution when the initial temperature difference was 7 °C. The discrepancy will be greatest deeper in the soil profile, and where *C* is high or λ is low. In general, where soil temperature is only important in the soil surface layers the convergence will occur within the first 10 days or so.

Where the time taken to ‘forget’ the initial conditions might cause significant error, there are two strategies for overcoming this problem. The first is to run a dummy simulation prior to the start of the real simulation to estimate the starting soil temperature. The second option is to estimate the initial soil temperatures from an analytical solution. A solution for the heat flow equation assuming a sinusoidal upper boundary condition. which might for example be the annual cycle in air temperature, is (Carslaw and Jaeger, 1959),

, [19]

where

, [20]

Tave is the average annual temperature (°C), Tamp is the annual amplitude in temperature (°C), and ω is the angular frequency (radians). Thermal conductivity and heat capacity can be estimated, using soil profile averages, from equations 3, 5, and 6.

*Time step inputs from other modules*

Soiltemp must be accompanied by the input module and a soil water module in order that other inputs are supplied. These inputs are.

|  |  |  |
| --- | --- | --- |
| Name | Unit | Description |
| Variables from the Input module | | |
| temp\_average\_annual | °C | Average annual temperature, used to set the initial soil temperature if soil\_temp is not supplied. Also determines the temperature at the lower boundary. |
| timestep | min | Simulation timestep, converted to seconds internally. |
| mint\_time | hours | Specifies the hour of the day when the minimum air temperature occurs. |
| maxt\_time | hours | Specifies the hour of the day when the maximum air temperature occurs. |
| mint | °C | Minimum air temperature. |
| maxt | °C | Maximum air temperature. |
| Variables from the soil water module | | |
| dlayer[nz] | mm | Array of layer depths used to specify the nodes, converted to m internally. |
| sw[nz] | m3 m-3 | Volumetric soil water content. |
| bd[nz] | Mg m-3 | Soil bulk density. |
| eo | mm | Potential soil water evaporation, or the water-depth equivalent of the net radiation reaching the soil surface, converted to J s-1 m-2 K-1 internally. |
| es | mm | Actual soil water evaporation, or the water-depth equivalent of the evaporation from the soil surface, converted to J s-1 m-2 K-1 internally. |

To allow compatibility with modules where changes in the soil occur with time, dlayer and bd are requested at every Apsim time step. If eo and es are not available they are assumed equal to zero.

*Time step outputs*

|  |  |  |
| --- | --- | --- |
| Name | Unit | Description |
| final\_soil\_temp[nz] | °C | Soil temperature at the end of the final internal Soiltemp timestep. |
| soil\_temp[nz] | °C | Average soil temperature during the Apsim timestep. |
| mint\_soil[nz] | °C | Minimum soil temperature found in each layer during the Apsim timestep. |
| maxt\_soil[nz] | °C | Maximum soil temperature found in each layer during the Apsim timestep. |
| therm\_cond[nz] | J s-1 m-1 K-1 | Thermal conductivity for each layer. |
| heat\_store[nz] | J m-3 K-1 | Volumetric specific heat for each layer. |
| airt | °C | Average air temperature during the Apsim timestep. |

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Figure 1. A diagrammatic representation of the node structure of the numerical simulation. T is temperature, Z is depth, K is thermal conductance, S is heat storage, nz is the number of nodes in the simulation, BL stands for boundary layer, Ta is the air temperature, and Tave is the annual average soil temperature.

Needs updating with phantom nodes