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Development and evaluation of the SoilClim model for water balance and soil climate estimates

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A B S T R A C T

The newly developed SoilClim model is introduced as a tool for estimates of reference (*ETo*) and actual (*ETa*) evapotranspiration, presence of snow cover, soil temperature at 0.5 m depth and the soil moisture course within two defined layers. It enables one to determine the soil moisture and temperature regimes according to the United States Department of Agriculture (USDA) soil taxonomy. SoilClim works with daily time steps and requires maximum and minimum air temperature, global solar radiation, precipitation, vapor pressure and wind speed as meteorological inputs as well as basic information about the soil properties and vegetation cover. The behavior of SoilClim was assessed using observations at 5 stations in central Europe and 15 stations in the central U.S. The modeled *ETo* was compared with atmometers so that the coefficient of determination (R^2) was 0.91 and root mean square error (RMSE) was 0.53 mm. The estimated *ETa* was compared against eddy-covariance and Bowen ratio measurements (R^2 varied from 0.74 to 0.80; RMSE varied from 0.49 to 0.58 mm). The soil temperature (at 0.5 m depth) was estimated with good accuracy (R^2 varied from 0.94 to 0.97; RMSE varied from 1.23 °C to 2.95 °C). The ability of the SoilClim model to mimic the observed soil water dynamics was carefully investigated (relative root mean square error rRMSE varied from 2.8% to 34.0%). The analysis conducted showed that SoilClim gives reasonable estimates of evaluated parameters at a majority of the included stations. Finally, a spatial analysis of soil moisture and temperature regimes (according to USDA) within the region of the Czech Republic and the northern part of Austria under present conditions was conducted and diagnosed the appearance of Perudic, Subhumid Udic, Dry Tempudic (the highest frequency), Wet Tempustic and Typic Tempustic. The simulated mean soil temperature (0.5 m depth) varied from less than 7.0 °C to 11.0 °C throughout this region. Based on these results, the SoilClim model is a useful and suitable tool for water balance and soil climate assessment on local and regional scales.

1. Introduction

Soil water content variation is one of the major factors for field crop yields cultivated within rain fed agriculture. Low soil moisture negatively influences plants through drought stress. In such cases, both the quality and quantity of yields (if irrigation is not available) are often dramatically reduced (e.g., Quiring and Papakryiakou, 2003; Hlavinka et al., 2009). The information about available soil moisture can be measured or estimated by a wide range of methods (e.g., Strangeways, 2003). In this context, the determination of other water balance components, such as run-off, infiltration, or the sum of actual evapotranspiration (*ETa*) are also crucial. *ETa* can be derived using various measurement methods or estimated by models. Unfortunately, no ideal and universal approach exists to identify *ETa* because each of the available methods has some limitations. Among the direct methods, lysimeters are considered very proper and accurate equipment (e.g., Strangeways, 2003), but the main shortcoming and limitation of their broader adoption are

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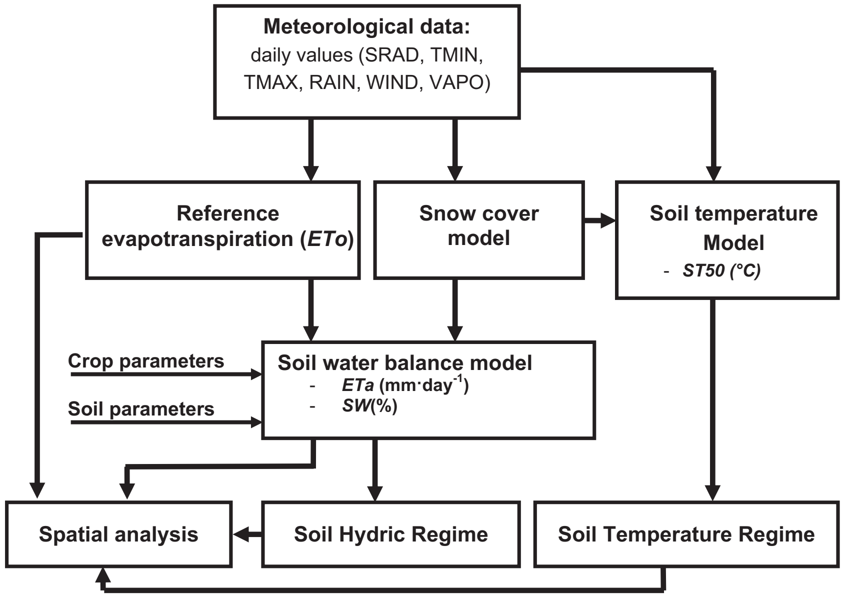

Fig. 1. Structure of the SoilClim model (SRAD – Solar radiation; T_{min} and T_{max} – minimum and maximum daily temperature; RAIN – precipitation; WIND – wind speed; VAPO – vapor pressure; *ETo* and *ETa* – reference and actual evapotranspiration; *ST50* – soil temperature in 0.5 m depth; SW – volumetric soil moisture).

their relatively high cost, complicated construction and immobility as well as the density differences between the lysimeter and outside vegetation (Rana and Katerji, 2000). There are also some indirect methods and measurements that can be used for actual evapotranspiration detection such as eddy-covariance, the Bowen ratio (Bowen, 1926; Steduto and Hsiao, 1998) or scintillometers (Chehbouni et al., 2000; Meijninger et al., 2006). The sap flow method can be used for transpiration estimates (Rana and Katerji, 2000; Čermák et al., 2004).

In many cases, for instance when measurements are unavailable, the water balance components are estimated through modeling (e.g., Eitzinger et al., 2004). Such models are used in decision making within irrigation management, the identification of drought intensity and drought stress, environmental research and policy formulation. The water balance models are also frequently utilized to study the potential impacts of climate change and risk assessment (Christensen et al., 2007). Adequate use for a particular purpose depends on whether the model complexity is appropriate to the question being asked. Generally, both complex and simple models are needed. In some cases, simple models are not appropriate because they do not address a particular phenomenon, but complex models usually demand very detailed and accurate input data (e.g., soil parameters, weather, crop properties, exposition and slope of locality), which limit their usage (e.g., Boote et al., 1996).

This paper presents the recently developed, semi-empirical SoilClim model for soil water balance, soil temperature and soil climate regime estimates. Based on the Penman–Monteith approach for reference evapotranspiration, the methodology for water balance estimates proposed by Allen et al. (1998) was modified and integrated with a snow cover model, a parsimonious soil temperature model and the sets of algorithms for the soil climate (soil hydric and temperature regimes) identification according to the U.S. Department of Agriculture (USDA) classification (Soil Survey Staff, 1975). The module for spatial interpolation of the results is also included. The user friendly framework allowing work on site level or in the predefined spatial domain connects several individual models (modules) and provides the model's originality and distinction. The synergistic character of the created structure is represented by the possible utilization of the snow cover model for preprocessing input data to account for the presence or absence of snow cover and snow melting in water balance estimates. Outputs of the snow model are crucial for both water balance and soil temperature estimates at the depth 0.5 m, within the areas with a significant presence of snow cover during the year. Then, the set of criteria necessary for soil climate identification could be directly processed so hydric and temperature regimes, which are crucial ecological parameters, could be easily identified. The actual evapotranspiration (*ETa*) and reference evapotranspiration (*ETo*) as well as soil water course within two defined layers are the partial outputs.

This paper first describes the model structure and then presents the results of SoilClim under various climatic and soil conditions through central Europe and the central United States. As a presentation of the spatial analysis, the present soil climate regimes (according to the USDA classification) of central Europe, focusing on the Czech Republic and Austria, were determined by SoilClim.

2. Materials and methods

2.1. SoilClim description

The semi-empirical SoilClim model was programmed using Borland Delphi™ 7 (Borland Software Corporation) as a modular system (see Fig. 1). During the run, operations and calculations within separate modules were finished in this order: the list of stations and the list of soils (including soil properties) were loaded; daily meteorological data for the first station were loaded enabling the completion of the *ETo* calculation; snow model simulation was accomplished; soil temperature was estimated; soil water balance model was realized; and soil moisture and temperature regimes (according to the USDA taxonomy) were identified. This process was repeated for the rest of the included stations analogously. The model works with daily time step and requires six meteorological parameters: global solar radiation (MJ m^{-2} day^{-1}), maximum and minimum air temperature (°C), precipitation (mm), vapor pressure (kPa) and average wind speed (m s^{-1}). The outputs from the basic modules (e.g., reference evapotranspiration calculation, snow presence and melting estimates) were then used as inputs for the connected modules (e.g., the model of the soil temperature at 0.5 m or the soil water balance model). For the soil moisture and *ETa* estimates, defined wilting point and field capacity within the profile, described by an arbitrary number of layers, are necessary. The above-mentioned variables and their derivatives identify the soil