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Effects of meteorological models on the solution of the surface energy balance and soil temperature variations in bare soils

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SUMMARY

A complete evaluation of the soil thermal regime can be obtained by evaluating the movement of liquid water, water vapor, and thermal energy in the subsurface. Such an evaluation requires the simultaneous solution of the system of equations for the surface water and energy balance, and subsurface heat transport and water flow. When only daily climatic data is available, one needs not only to estimate diurnal cycles of climatic data, but to calculate the continuous values of various components in the energy balance equation, using different parameterization methods. The objective of this study is to quantify the impact of the choice of different estimation and parameterization methods, referred together to as meteorological models in this paper, on soil temperature predictions in bare soils. A variety of widely accepted meteorological models were tested on the dataset collected at a proposed low-level radioactive-waste disposal site in the Chihuahua Desert in West Texas. As the soil surface was kept bare during the study, no vegetation effects were evaluated. A coupled liquid water, water vapor, and heat transport model, implemented in the HYDRUS-1D program, was used to simulate diurnal and seasonal soil temperature changes in the engineered cover installed at the site. The modified version of HYDRUS provides a flexible means for using various types of information and different models to evaluate surface mass and energy balance. Different meteorological models were compared in terms of their prediction errors for soil temperatures at seven observation depths. The results obtained indicate that although many available meteorological models can be used to solve the energy balance equation at the soil–atmosphere interface in coupled water, vapor, and heat transport models, their impact on overall simulation results varies. For example, using daily average climatic data led to greater prediction errors, while relatively simple meteorological models may significantly improve soil temperature predictions. On the other hand, while models for the albedo and soil emissivity had little impact on soil temperature predictions, the choice of the atmospheric emissivity models had a greater impact. A comparison of all the different models indicates that the error introduced at the soil atmosphere interface propagates to deeper layers. Therefore, attention needs to be paid not only to the precise determination of the soil hydraulic and thermal properties, but also to the selection of proper meteorological models for the components involved in the surface energy balance calculations.

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Introduction

A complete evaluation of the movement of liquid water, water vapor, and heat in the subsurface can be obtained by simultaneously solving the system of equations describing the surface water and energy balance, and subsurface heat transport and water flow. The use of a coupled liquid water, water vapor, and heat transport model to simulate continuous changes in water contents, soil temperatures, and a variety of fluxes has been presented by, among many others, Nassar and Horton (1989), Noborio et al. (1996a), Fayer (2000), and Saito et al. (2006). When simulations are conducted at the field scale, boundary conditions at the soil–atmosphere interface for water, vapor, and heat transport are usually determined using the surface water and energy balance (e.g., van Bavel and Hillel, 1976; Boulet et al., 1997). However, direct, continuous measurements of all the components needed to fully evaluate such surface mass and energy balances rarely exist. Usually, only standard daily climatic data from nearby weather stations and/or daily irrigation schedule are available. If detailed predictions of water and heat fluxes are needed, components of the surface mass and energy balance at much smaller time steps than those taken at daily intervals will need to be evaluated using daily standard climatic data.

The energy balance at the soil–atmosphere interface is expressed as

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$$R_n - H - LE - G = 0 \tag{1}$$

where R_n is the net radiation (W m^{-2}), H is the sensible heat flux density (W m^{-2}), LE is the latent heat flux density (W m^{-2}), L is the latent heat (J kg^{-1}), E is the evaporation (kg m^{-2} s^{-1}), and G is the surface heat flux density (W m^{-2}). While R_n and G are positive downward, H and LE are positive upward. To solve Eq. (1) for the surface heat flux G, which is needed as the upper boundary condition in the solution of the heat transport equation, continuous variations in R_n, H, and LE must be calculated or measured. When only daily information is available, continuous values for various components in the energy balance equation must be obtained using existing estimation and parameterization methods.

Continuous diurnal cycles in climatic variables, such as air temperature, are usually generated from their mean daily values using the analogy between their cycles during the day and trigonometric functions (e.g., Jury and Horton, 2003). Once the values for air temperature, relative humidity, precipitation, and wind speed at any given time are obtained, they can be further used in parameterization formulas to calculate the components of the energy and water balance equations (Saito et al., 2006). It was not our intention to separately consider above functions and formulas. Therefore, in the remainder of this manuscript, the functions for generation of continuous diurnal cycles of climatic variables and the parameterization formulas for components of the energy balance equation are both referred to as "meteorological models". A number of comparative studies, in which measured components were compared to calculated ones, have appeared in the literature. For example, Ortega-Farias et al. (2000) compared measured and predicted air emissivities. As there are a number of available and accepted meteorological models to calculate the atmospheric variables, it is hard to determine which model is most suitable for a particular application. In addition, an extensive amount of work has been carried out over the last few decades to develop meteorological models that accurately predict evaporation rates from the soil and vegetation (e.g., Brutsaert, 1982; Monteith and Unsworth, 1990). Because of the high complexity of both air and subsurface conditions, it is extremely difficult to choose the best model to estimate evaporation rates from a particular soil. To our knowledge, the impact of the choice of particular meteorological models on simulated water flow and heat transport in the vadose zone has, so far, not been discussed or investigated. Since all the components of the surface mass and energy balance affect each other more or less in the coupled water flow and heat transport model, investigating their mutual interactions is not a straightforward task. A change in one variable can easily alter all the others.

Thus, the main objective of this study is to quantify the impact of the choice of particular meteorological models on the prediction of bare soil temperatures. We use various meteorological models in the surface energy balance equation, and then evaluate how these methods affect soil temperatures calculated with the coupled liquid water, water vapor, and heat transport model. We compare predicted soil temperatures at different soil depths with measured values. The results will allow investigators and/or practitioners to evaluate their choice of meteorological models, and provide a quantified assessment of the effects these models have on predictions of soil temperatures.

A variety of meteorological models are reviewed and tested in this study, using a dataset collected at a proposed low-level radioactive-waste disposal site in the Chihuahua Desert in West Texas, 10 km east of Sierra Blanca, where prototype engineered covers were installed (Scanlon et al., 2005). The energy balance assessment in the engineered covers is as important for evaluation of their performance as the mass (water) balance analysis. While the long-term water balance of the site was evaluated by Scanlon et al. (2005), who showed that a capillary barrier can significantly reduce drainage in arid and semi-arid regions, the energy balance of the site has not yet been fully assessed. The coupled liquid water, water vapor, and heat transport model, based on the modified HYDRUS-1D software package (Saito et al., 2006), is used in this study to simulate soil temperatures in the engineering cover, the surface of which was kept bare during the analyzed time period. The modified version of HYDRUS provides a flexible way to use various types of climatic information to evaluate surface mass and energy balance when continuous changes in water contents, temperatures, and fluxes are simulated.

Method description

Generating diurnal cycle of climatic data

The solution of the energy balance equation (Eq. (1)) at a time interval of interest requires knowledge of the values of climatic variables such as air temperatures, atmosphere relative humidities, and wind speeds at the same or similar time intervals. However, weather stations do not always provide standard data at time intervals of interest. Thus, diurnal changes in these variables need to be calculated from available daily average values using meteorological models (e.g., Ephrath et al., 1996). In this study, we compared relatively simple approaches for generating the diurnal cycles of climatic variables from available daily information.

Air temperature

Continuous values for air temperature, T_a, can be obtained from the daily maximum and minimum air temperatures usually available from the weather station using a trigonometric function with a period of 24 h as follows (Kirkham and Powers, 1972):

$$T_a = \bar{T} + A_t \cdot \cos\left[2\pi\left(\frac{t-13}{24}\right)\right] \tag{2}$$

where $\bar{T}$ is the average daily temperature (°C), A_t is the amplitude of the cosine wave (°C) calculated from the difference between the daily maximum and minimum temperatures, and t is a local time during the day (h). The argument of the cosine function shows that the highest temperature is assumed to occur at 1 p.m. and the lowest at 1 a.m.

Wind speed

It is well known that wind transports heat and effectively mixes the soil–atmospheric boundary layer. Wind is generally highly variable in speed and direction, since it involves mostly turbulent flow characterized by random fluctuations (Campbell, 1977). Because several parameterization formulas for components in the energy balance equation require continuous inputs of the wind speed, continuous diurnal changes of the wind speed must somehow be calculated even when daily average values are all that is available. At present we have two simple approaches, in addition to using a constant daily value for the entire day. Both approaches use the following maximum to minimum wind speed ratio U_r, which is defined as

$$U_r = \frac{U_{\max}}{U_{\min}} \tag{3}$$

where U_{max} and $U_{\min}$ (m s^{-1}) are the unknown minimum and maximum wind speeds of the day, respectively. This ratio may be determined from prior knowledge or calibration using available data. The maximum and minimum wind speeds can then be calculated from the daily average wind speed as follows:

$$U_{\max} = \frac{2U_r}{1+U_r}U \tag{4}$$

$$U_{\min} = \frac{2}{1+U_r}U \tag{5}$$

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