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Calibration of an energy balance model to simulate wintertime soil temperature, soil frost depth, and snow depth for a 14 year period in a highland area of Iran

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ABSTRACT

A physically-based heat and mass transfer model, CoupModel, is calibrated to simulate wintertime soil temperature, soil frost depth, and snow depth for a 14-year period in a highland area of Iran. A Monte Carlo based approach is used for calibration process based on subjective performance criteria. Sensitivity and uncertainty analyses of the model were performed by selecting 30 parameters and the model was run using 22,000 samples taken from the uncertainty range of the parameters. By using the Nash–Sutcliffe Index to evaluate the performance of the model and applying a cutoff threshold for the performance to snow depth and soil temperature, 161 behavioral simulations were recognized and considered as the accepted ensemble to represent the field conditions. Sensitivity analysis of the model revealed some parameters associated with soil evaporation, soil hydraulic properties, and snow modeling as sensitive and highly important parameters. Uncertainty analysis of the model for wintertime soil temperatures showed a reasonable agreement between simulations and observations in most cases. However, a systematic error occurred at some periods because of high uncertainty of the actual snow density and details of snow melting. Uncertainties were also due to the simplified model assumptions regarding snow thermal properties and temperature within snow cover. The snow depth at the accumulation and melting stages were described well by the model in most cases.

1. Introduction

Soil temperature is an important variable affecting a variety of physical, chemical, and biological processes occurring in the soil (Hillel, 1998). It also influences exchange rates of mass and energy between the soil surface and the atmosphere and the partitioning of surface available energy into sensible and latent heat fluxes (Hu and Feng, 2003). During cold seasons, the presence of snow on the surface and formation of ice within the soil significantly affect soil temperature variations (Cherkauer and Lettenmaier, 1999; Stahli and Jansson, 1998). A lack of snow cover results in lower soil temperatures and more extensive soil freezing (Edwards and Cresser, 1992) and the presence of ice not only changes soil thermal and hydraulic properties (Jame and Norum, 1980), but also alters heat balance components by releasing heat due to freezing of water. Therefore, it is important to study meteorological conditions together with soil temperature and soil freezing during long time period.

A variety of factors affect wintertime soil temperature and soil frost depth. These factors can be classified in three groups: within soil profile and the corresponding upper and lower boundary conditions. The energy balance of the soil-snow-atmosphere constitutes the upper boundary processes; including air temperature (Williams and Smith, 1989; Zhao et al., 2004), partitioning of the available energy between sensible and latent heat at the soil surface for different soil covers (snowpack, vegetative cover, etc.) (Kennedy and Sharratt, 1998; Ling and Zhang, 2004; Schaetzl and Tomczak, 2001). The within soil processes are represented by the thermal and hydraulic soil properties (Newman and Wilson, 1997; Zhang et al., 2007), the soil moisture content (Flerchinger, 1991; Washburn, 1979; Zhao et al., 2004), the soil organic matter (Flerchinger, 1991), and Bouyoucos effect that is associated with water migration from lower unfrozen layers towards the frost front (Jame and Norum, 1980; Van Vliet-Lanoe, 1998). The lower boundary condition corresponds to upward heat transfer from deeper towards upper soil layers. Physical based modeling of the

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involved processes can improve our understanding and reduce the uncertainty for estimating wintertime soil temperatures and soil frost depth.

Based on how the ice pressure is considered, Hansson and Lundin (2006) have classified physically based soil freezing models into two groups including Harlan type hydrodynamic models and frost heave models. Harlan (1973) proposed a model for frozen soils, based on the Philip and de Vries (1957) theory for coupled heat and water flow and by considering the analogy between freezing–thawing and drying–wetting processes. The Harlan model has been adopted in hydrodynamic models such as SHAW (Flerchinger and Saxton, 1989), SOIL (Jansson, 1996), HYDRUS-1D (Simunek et al., 1998), and CoupModel (Jansson and Karlberg, 2010) for simulating freezing–thawing processes. There are some non-linear complex processes in these models, such as the dependencies of water content and hydraulic conductivity on the pressure head and relations between ice content and temperature (Hansson and Lundin, 2006). Along with the uncertainty in the structure of these models, the existence of numerous parameters and errors in the measurements are other sources of uncertainty. Therefore, it is essential to perform calibration and uncertainty analysis if such models should be applied. A popular method for calibration and uncertainty analysis of environmental models is the Generalized Likelihood Uncertainty Estimation (GLUE), proposed by Beven and Binely (1992). Sensitivity analysis is performed to investigate the parameter effects on the simulation results and to obtain valuable information about interactions between different physical processes of the system (Flerchinger, 1991). When the value of a parameter is poorly defined or not accurately measured, the uncertainty of the model will be influenced by the sensitivity of that parameter (Pirhodko et al., 2008).

The objective of the present paper is to quantify how well and in which conditions a physically based model can describe the wintertime soil temperature, soil frost depth, and snow depth during a long and continuous period with many climatic events. The uncertainty bands of the obtained parameters will identify to which extent the measurements can be described by certain properties of the atmosphere-soil system. Discrepancies between simulated and measured conditions will be understood as (1) a failure of the model structure to account for the physical processes; (2) a change in the soil-atmosphere system that was not considered in the model.

2. Materials and methods

2.1. Study site and measurements

Ghorveh synoptic station is located in the west of Iran (47°48′N, 35°10′E, and 1906 m altitude) representing high altitude and cold winters. Fig. 1 shows the geographical position of this station on the Digital Elevation Model of the region. Three-hourly meteorological data of the site since 1989 were obtained from Iran Meteorological Organization. Snow depth data, based on observations at a measuring scale, are available with a daily time resolution since 1993. Soil temperatures at 0.05, 0.1, 0.2, 0.3, 0.5, and 1 m depths are available 3 times per day at 3, 9, and 15 G.M.T. hours since 1993. A continuous period of high quality data and negligible data gaps are some advantages of this station for

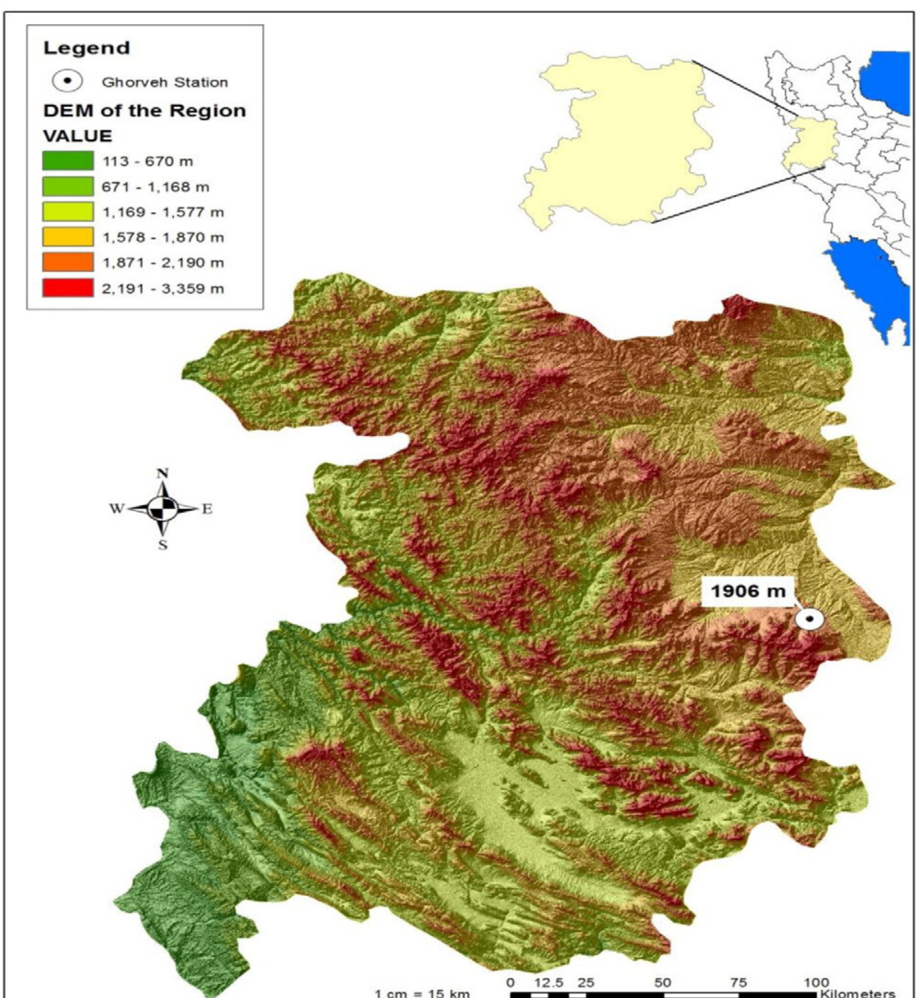

Fig. 1. Geographical position of Ghorveh station with a Digital Elevation Model of the region.