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The Influence of Different Initial Conditions on the Soil Temperature Profile of Egypt Using a Regional Climate Model †

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Abstract: Soil temperature is an important indicator for monitoring the root environment of natural vegetation or crops. Also, regional Climate Models (RCMs) are valuable tools for simulating the soil temperature profile on a hierarchy of time scales ranging from daily to annual. Focusing on the daily time scale, two eight-year simulations (2011–2018) were conducted to examine the influence of different initial conditions on the simulated soil temperature profile of Egypt using a regional climate model (RegCM4). The two simulations were driven by ERA-Interim reanalysis, and the output (of each simulation) was compared to the in-situ observation. The first simulation was initialized with an arbitrary initial condition (i.e., from bare soil), and it was referred to as RegCM4-S1; the second one was initialized with a long-term spin-up file, and it was designated as RegCM4-S2. The results showed that the RegCM4-S2 performs better than the RegCM4-S1 in simulating the shallow soil temperature profile. Moreover, the RegCM4-S2 shows poor performance in simulating the soil temperature of deep depths but still outperforms the RegCM4-S1 with respect to the in-situ observation. Focusing on deep depths, the soil temperature parameterization needs to be revised and it is necessary to implement a numerical scheme to reduce the spin-up time.

Keywords: Egypt; regional climate model; spin-up; soil temperature

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1. Introduction

The soil layer of Earth plays a vital role in maintaining plant life. Soil acts as a major storage mechanism of heat because it collects energy during the day from the sun and releases it as heat to the surface during the night. Soil temperature is necessary for the growth of plants, and it is influenced by important factors such as aspect and slope, tillage, soil texture, and organic matter [1]. In addition, climate prediction can be improved by providing a more accurate long-term surface soil temperature dataset as a boundary condition for state-of-the-art weather/climate models [2]. Soil temperature is controlled by two major properties: thermal conductivity, heat capacity [3].

The performance of General Circulation Models (GCMs), Regional Climate Models (RCMs), and offline land surface models (e.g., North American Land Data Assimilation: NLDAS or Global Land Data Assimilation System: GLDAS) was evaluated for simulating the soil temperature profile of different regions across the world. Ref. [4] used the regional climate model (CMM5) to simulate the soil temperature in the United States with respect to the NCEP-DOE AMIP II reanalysis (R-2) derivatives, NLDAS products, and in-situ observations. They showed that the CMM5 model has a better performance for simulating the annual cycle and inter-annual variability of soil temperature than the one using the R-2 and NLDAS products with respect to observation (provided by the National Climate Data Center: NCDC). Misrepresentation of short grass in the model was responsible for the inconsistency between the model and observations.

Heat transfer between soil layers is an important land-surface process, which needs proper spin-up to initialize either the off-line land surface or regional climate model (as in this study); however, no previous study has discussed the importance of spinning up the off-line land-surface or Regional Climate Models (RCMs) to obtain a good initial condition of soil temperature particularly of deep depths. In addition, no previous study was performed utilizing the RegCM4 model to simulate the daily soil temperature profile of Egypt until the present day. Therefore, the present study aims to:

1. Modify the Community Land Model (CLM45; which is coupled to the RegCM4) to properly simulate the daily soil temperature profile of Egypt.
2. Adapt a spin-up procedure to initialize the regional coupled RegCM4-CLM45 model with a good initial condition of the soil temperature.

The manuscript is organized as follows: Section 2 describes the study area, data and methodology; Section 3 shows the results of the study over Egypt and Section 4 provides the discussion and conclusions.

2. Materials and Methods

2.1. Model Description and Experiment Design

In this study, the Abdus Salam International Centre for Theoretical Physics (ICTP) regional climate model version 4.7 (RegCM-4.7.0, [5], hereafter RegCM4) was used. The CLM45 land model was used in this study because it offers substantial improvement such as: a revised canopy radiation scheme, canopy scaling of leaf processes and an updated soil temperature parameterization [6]. In addition, the CLM45 simulates a variety of complex biogeophysical processes such as absorption, reflection, and transmittance of solar radiation and, absorption and emission of long wave radiation. Fluxes of momentum, sensible heat (ground and canopy), and latent heat (ground evaporation, canopy evaporation, transpiration) are also represented. In addition, it includes heat transfer in the soil and snow, soil hydrology (surface runoff, infiltration, sub-surface drainage and ground water).

Biogeophysical processes are simulated for each subgrid land unit, column, and plant functional type (PFT) independently and each subgrid unit maintains its own prognostic variables, while simulating the soil temperature and heat exchange between soil layers occurring at the column level [7]. The CLM45 model has fifteen soil layers, and the heat transfer rate between any two successive layers is calculated as:

$$F = \lambda \times \nabla T \tag{1}$$

where F is the amount of heat conducted across a unit cross-sectional area in unit time (W m^{-2}), λ is the thermal conductivity ($Wm^{-1}K^{-1}$), and ∇T is the spatial gradient of temperature (Km^{-1}). For the one-dimensional case, the equation becomes:

$$F_z = -\lambda \frac{\partial T}{\partial z} \tag{2}$$

where z is in the vertical direction (m) and is positive downward and F_z is positive upward. The principle of energy conservation in the form of the continuity equation—to account for non-steady or transient conditions—becomes:

$$c \frac{\partial T}{\partial t} = \frac{-\partial F_z}{\partial z} \tag{3}$$

where c is the volumetric snow/soil heat capacity (J $m^{-3}K^{-1}$) and t is time (s). By combining Equations (2) and (3), the second law of heat conduction in one-dimension takes the form:

$$c \frac{\partial T}{\partial t} = \frac{\partial}{\partial z} \left[\lambda \frac{\partial T}{\partial z} \right] \tag{4}$$

To properly simulate the soil temperature profile of Egypt, modifications were inserted into the CLM45 model. The soil temperature of depth 2 cm (an example of shallow depth) is calculated as a function of the soil temperature of depth 2.79 cm and the soil temperature of depth 100 cm (an example of deep depth) is calculated as a function of soil temperature of depth 103.8 cm. Spin up files of the National Center for Atmospheric Research (NCAR) don't include the new depths (as in this study); however the inserted modifications enable the CLM45 land surface model to produce a restart file with the new depths (which are produced during the spin-up phase and required for initializing the actual simulation).

In the present study, the model domain was customized with 30° latitude, 27° longitude, 40 grid points, and 60 km grid horizontal resolution (Figure 1). Two eight-year simulations were integrated from 01 January 2011 until 31 December 2018 and driven with the ERA-Interim 1.5° × 1.5° resolution (EIN15; [8]) reanalysis as a lateral boundary condition. This time period was chosen for two reasons: (1) the availability of the observed data and (2) EIN15 ends at the year 2018. It is worth mentioning that version 4.7 of the RegCM4 doesn't support ERA5 reanalysis [8] as a lateral boundary condition, therefore EIN15 was used instead. The first was designated as RegCM4-S1 and the other was designated RegCM4-S2. The RegCM4-S1 was initialized using arbitrary initial conditions (i.e., from bare soil); meanwhile the RegCM4-S2 was initialized using a long-term spin-up file. The RegCM4-S2 simulation has two phases:

1. Spin-up phase: In this phase, the model was driven with the climatological mean of the EIN15 (EIXXX) to eliminate climate trends and inter-annual variability. To approach the equilibrium state (for shallow and deep depths), the model needs to cycle through the EIXXX 150 times.
2. Experiment phase: To initialize this phase, the last file from the spin-up phase was interpolated on the first restart file (from the real simulation) using the interpinic. Interpinic is an executable program (provided by the offline CLM45 land surface model) and was originally created for interpolating the CLM restart file from one resolution to another.

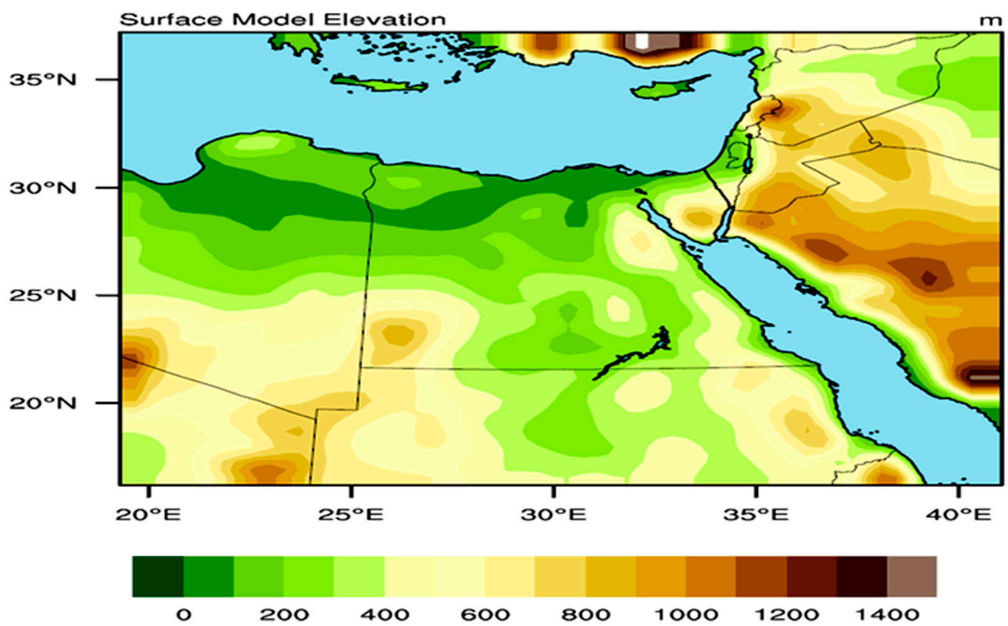

Figure 1. Model domain dimension and topography elevation (in meters).

2.2. Validation Data

To evaluate the RegCM4 simulations, the soil temperature network of Egypt was used. The network comprises five stations (Asyut, Kharga, Giza, Tahrir and Malawi). For the purpose of the present study, only Assyut, Kharga, Tahrir, and Malawi stations were used because they have no missed records. Soil temperature of depths 2, 5, 10, and 20 cm are taken every 3 hours and then the daily average is calculated; meanwhile, for depths 50, 100 and 200, the soil temperature is recorded once per day. Furthermore, soil temperature records were taken in dry soil. Table 1 shows the coordinates of the stations, available soil depths, and the evaluation period for each station.

Table 1. The coordination of soil temperature stations, available soil depth and evaluation period for each station.

Station Name	Latitude	Longitude	Available Soil Depths	Available Period
Assyut	27.2	31.16	2, 5, 10, 20, 50 100, and 200 cm	2013–2018
Kharga	25.45	30.53	2, 5, 10, 20, 50, 100, and 200 cm	2012–2018
Tahrir	30.65	30.7	2, 5, 10, 20, 50, 100, and 200 cm	2012–2018
Malawi	27.7	30.75	2, 5, 10, 20, 50, and 100 cm	2012–2018

3. Results

3.1. Spin-Up Phase

For brevity in the analysis, a plot of the monthly mean soil temperature was set for Assyut station as an example (for depths 50, 100, and 200 cm) to ensure that the model approaches the equilibrium state. For deep depths (i.e., 50, 100, and 200 cm), the RegCM4-CLM45 model needs to cycle 150 years to approach the equilibrium state. The spin-up phase consists of two stages: the first one is characterized by rapid fluctuations of the soil temperature, and it took around 70 years. After this period, the soil temperature begins to stabilize with time. The spin-up phase ends when the soil temperature does not vary over time or there is no trend, as can be observed in Figure S1. The model requires this long time because heat transfer in the soil depends on the liquid water content [9], which is quite low in the static data of the CLM45 over arid/hyper-arid regions leading to the generation of a high resistance for transferring the heat flux from one soil layer to another.

3.2. Experiment Phase

For brevity in analysis, we took Assyut station as an example. In general, both RegCM4-S1 and RegCM4-S2 are able to reproduce the daily variability of the simulated soil temperature profile with respect to the observation of Assyut station (see Figure 2). However, the performance of the RegCM4 varies with time and depth. For instance, there is no noticeable difference between the two simulations and observations for calculating the soil temperature at 2 cm depth. Moreover, they both severely underestimate the soil temperature against the observation. For 5 cm depth, the model performance varies with time as it underestimates the soil temperature in years 2013, 2014, and 2015; meanwhile the model is close to observation in the years 2016, 2017, and 2018. On the other hand, the model shows a good capability in simulating the soil temperature at 10 cm depth, and the RegCM4-S2 slightly improves the simulated soil temperature relative to the RegCM4-S1.

At 20 cm depth, both simulations show a good ability to capture the daily variability of soil temperature. However, the RegCM4-S2 outperforms the RegCM4-S1 with respect to the observation. In addition, the RegCM4-S2 outperforms the RegCM4-S1 for calculating the soil temperature of 50 cm depth (see Figure S2) in the years 2013, 2014, and 2015; meanwhile, both simulations overestimate the soil temperature in the years 2016, 2017, and 2018 with respect to the observation. Although the RegCM4-S2 overestimates the soil temperature at 100 and 200 cm depths (see Figure S2), it is in good agreement with the observation relative to the RegCM4-S1. The noted behavior in different years can be attributed to (1) adopted physical schemes, (2) soil temperature parameterization of the CLM45, and (3) uncertainty associated with the EIN15 as a lateral boundary condition.

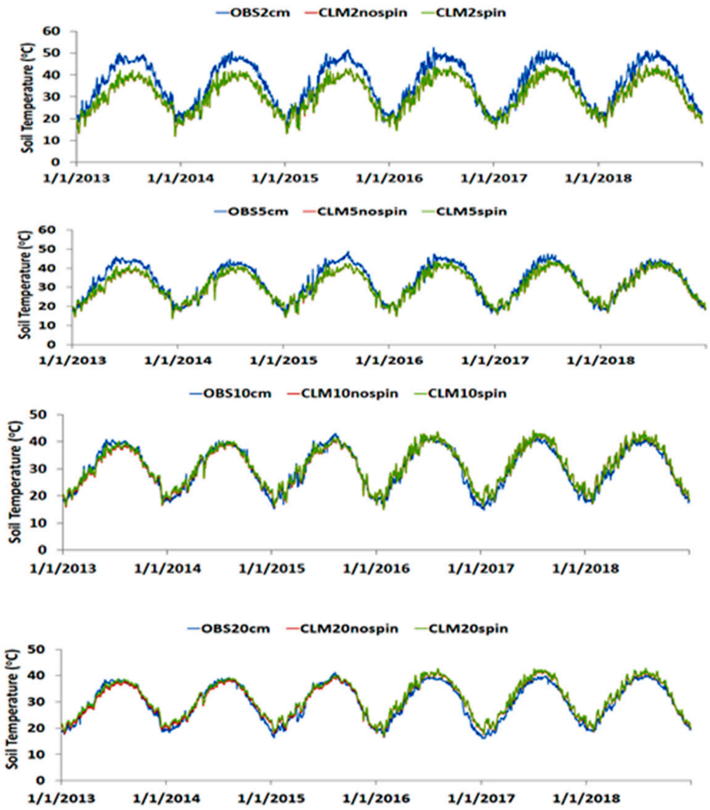

Figure 2. Daily soil temperature of Assyut (in °C) using arbitrary initial conditions (no spin, in red) using a long-term spin-up file (spin, in green) against observation (OBS, in blue). The first panel is for 2 cm depth, second is for 5 cm depth, third is for 10 cm depth, and the fourth is for 20 cm depth. The unit is displayed in °C to match observations.

To explore the added value of initializing the RegCM4-CLM45 with a long-term spin-up file (versus bare soil), a time-depth of the in-situ observations, RegCM4-S1-simulated, and RegCM4-S2-simulated daily soil temperature profile was plotted. The contour plots of the observed and simulated soil temperatures at each station are shown in Figure 3. According to the observations, the seasonal temperature changes are strong close to the surface but reduce with depth. At Assyut station, both simulations result in a similar cold bias throughout the warm seasons of the years, which extends to at least 5 cm depth. However, they provide a good representation of soil temperature evolution to the depth of 50 cm. For deeper layers, RegCM4-S1 simulations indicate a slightly cold bias with a decreasing trend over the years. The low heat transfer of the model can be attributed to the combined effects of soil water contents and soil heat transfer parameters. The spinning-up process in RegCM4-S2 provides a better initial condition of the soil moisture and thereby soil thermal properties. Therefore, despite the fact that RegCM4-S2 shows a slightly biased simulation, it provides a much-improved soil temperature simulation compared to RegCM4-S1.

At Kharga station, both simulations show a better representation of temperature at shallower layers of the soil and in comparison, to other stations. In the case of the RegCM4-S1 simulation, the colder deep layers' temperatures at this station reveal the obstruction of heat penetration from the surface. Moreover, RegCM4-S2 reflects a better simulation of the temperature profile even to the deeper layers. The higher underestimation of soil temperature in the whole soil profile at Tahrir station demonstrates an evident lower heat transfer of the model. However, RegCM4-S2 has an effective role in improving the simulations. The comparison between the observed and simulated soil temperatures at the Malawi station shows that RegCM4-S2 outperforms RegCM4-S1. Altogether, the results demonstrate that the spinning-up process improves the simulation performance.

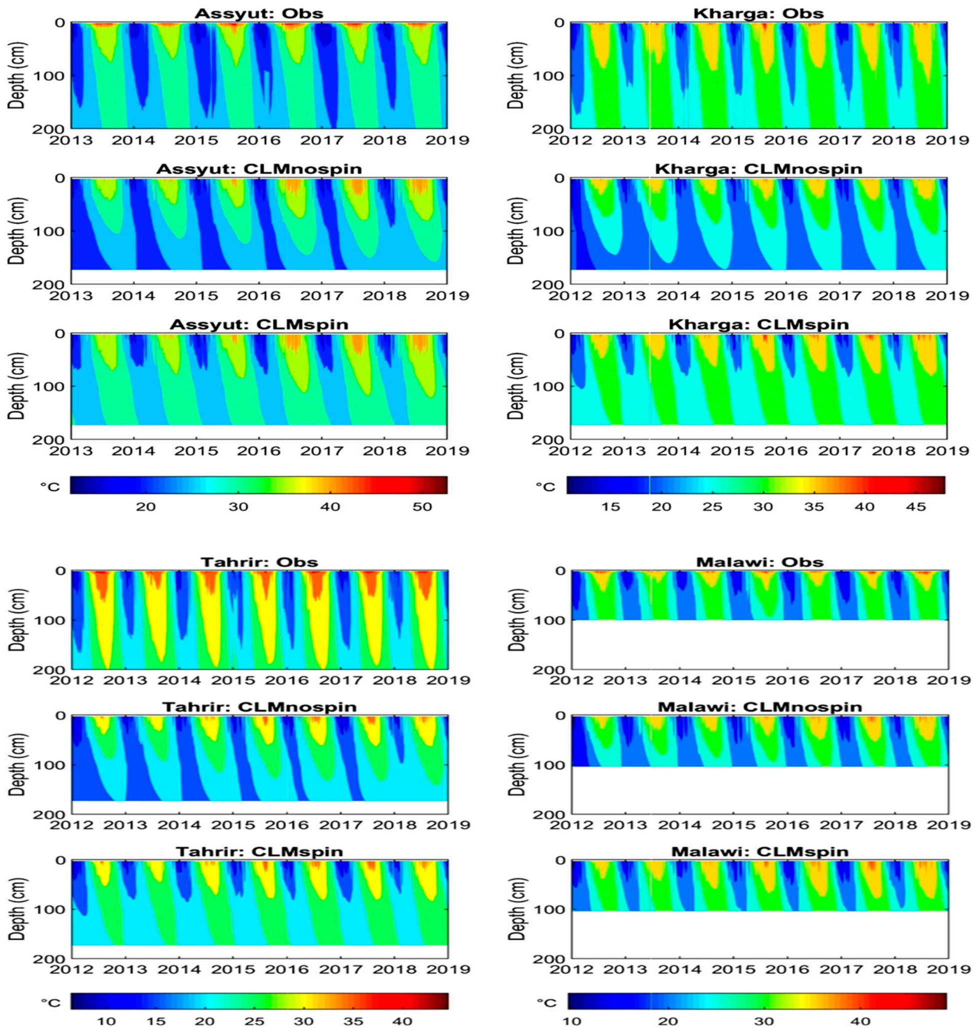

Figure 3. Time-depth plot of the observed, RegCM4-S1-simulated and RegCM4-S2-simulated daily soil temperature (in °C) for the period of simulation at different stations.

4. Discussion and Conclusions

Simulating the soil temperature profile is critically important because of its direct influence on the surface climate, agricultural activities, and ecosystem services. Additionally, it contributes to surface water and energy exchange because of the strong influence on the physical properties of soil. Accurate knowledge of the soil temperature is necessary for short-term forecasts, sub-seasonal and seasonal forecasts, and vegetation growth. Moreover, measurement of the soil temperature profile is difficult to accomplish either at a regional or global scale. In this study, the regional climate model (RegCM4-CLM45) was used to examine the potential influence of different initial conditions on the simulated daily soil temperature profile of Egypt. The results showed that the RegCM4-S2 outperforms the RegCM4-S1 at all depths particularly for the deep ones (despite noted biases) with respect to the observation. Such a finding confirms the importance of spin-up to realistically simulate the heat transfer process between the soil layers. In addition, the model performance varies with respect to depth, time, and location for shallow depths.

Spinning-up process is critically important to obtain a good initial condition for a real simulation, particularly for arid/hyper-arid regions for deep depths. Also, it improves the model capability for simulating the soil temperature profile more than when the arbitrary initial condition is used. Such good capability was indicated by a low model bias and the ability to capture the daily variability with respect to the observation. It is worth mentioning that this study provides a first insight into simulating the soil temperature at any particular depth over Egypt using a regional climate model RegCM4-CLM45. Despite noted biases, the RegCM4-S2 still outperforms the RegCM4-S1, and therefore it can be recommended for predicting the daily soil temperature and conducting long-term simulations. To gain an overall improved performance of the RegCM4-S2, future work will consider the following points:

1. Incorporating a high-resolution soil map of Egypt into the global static dataset (to account for the local soil features), which considerably affects the heat transfer in soil from one layer to another.
2. Implementing a numerical scheme to reduce the spin-up time of deep soil depths.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/ASEC2022-13850/s1.

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