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Simulating Daily Soil Temperature in Egypt Using a High-Resolution Regional Climate Model: Sensitivity to Soil Moisture and Temperature Initial Conditions †

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Abstract: In this study, a high-resolution regional climate model (RegCM4) was used to forecast the daily soil temperature at a depth of 40 cm (hereafter ST40). The RegCM4 was downscaled by the Global Forecast System (GFS of one degree horizontal resolution) to 25 km grid spacing. To examine the sensitivity of the ST40 to different initial conditions of the soil moisture and temperature, four experiments were conducted and grouped into two cases. The first case considered the comparison between initialing the RegCM4 from bare soil and from the global satellite soil moisture product (ESACCI). On the other hand, the second case examined the influence of initializing the soil temperature from the Century reanalysis product (Century) versus initializing from zero values. The results showed that initializing the RegCM4 with the ESACCI has a notable impact on the simulated ST40 with respect to the bare soil. Additionally, when the RegCM4 is initialized with the Century product, the simulated ST40 is improved in the sense that the ST40 trend becomes smoother than when the RegCM4 is initialized with zero values. In comparison with the Century reanalysis product, the RegCM4 shows good performance when it is initialized with the ESACCI and Century products. In conclusion, the RegCM4 can give a reliable forecast of the ST40 when it is initialized with the ESACCI satellite soil moisture and Century reanalysis soil temperature products especially in data-scarce regions.

Keywords: Egypt; ESACCI; RegCM4; satellite; soil moisture

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1. Introduction

Soil temperature is an important variable in the climate system because it modulates the surface energy balance components (sensible and latent heat fluxes); therefore, it controls the water and energy fluxes exchanged between the land surface and the atmosphere, as well as the mesoscale circulations [1]. Additionally, soil temperature controls the physical and biological activities beneath the earth surface and, eventually, agricultural productivity [2]. In arid regions (e.g., Kuwait), the authors of [3] found that there is a strong correlation between soil temperature at shallow depths (up to 20 cm) and air temperature and a weak correlation between soil temperature of deep depths (50–100 cm) and the air temperature. They concluded that air temperature can be used as a predictor to estimate soil temperature when either spatial or temporal station observations are not available.

Because of the limited availability of soil temperature records, regional climate models or offline land surface models can be alternative useful tools to estimate soil temperature at particular depths. For instance, the authors of [4] examined the potential skills of the fifth-generation PSU-NCAR Mesoscale Model (MM5)-based regional climate model (CMM5) concerning the annual cycle and interannual variability of the soil temperature and moisture of soil from the United States. They found that the bias of the CMM5 can be attributed to the inconsistencies between measurements taken under short grass versus model representations beneath other land cover types. Regarding the offline land surface model, the authors of [5] found that version 3.5 of the community land model (CLM3.5) gave satisfactory performance in simulating soil temperature over a range of time scales (hours to monthly) with respect to in situ observations. Also, they reported that the CLM3.5 is a useful tool for understanding the regional and vertical characteristics of soil temperature in Xinjiang.

In Egypt, the authors of [6] used the regional climate model (RegCM4; [7]) to simulate soil temperature profiles with respect to in situ observations. They found that the RegCM4 is able to reproduce the daily variability despite the presence of notable biases between the RegCM4 and the observations. Additionally, they reported that the RegCM4 gives satisfactory results when it is initialized by a long-term spin-up file rather than initializing from a bare soil. However, in the aforementioned studies, the sensitivity of the regional climate models (e.g., CMM5 or RegCM4) or the offline land surface model (e.g., CLM3.5) to different initial conditions of the soil temperature/moisture has not been examined. Therefore, the present study aims to address this issue in Egypt using the RegCM4 model for a five-day forecast. The remainder of this study is organized as follows: Section 2 describes the study area and experiment design. Section 3 describes the results of the study, and finally Section 4 presents a discussion of our results and the conclusions that can be drawn from them.

2. Materials and Methods

2.1. Experimental Design

In the present study, the International Center of Theoretical Physics (ICTP) regional climate model (RegCM4; [7]) was used. The RegCM4's domain was centered at 27° latitude and 30° longitude with 60 grid points in zonal and meridional directions and 25 km horizontal grid spacing following [8]. This study adopted the physical configuration of [9]. To provide the lateral boundary condition and sea surface temperature (SST), the Global Forecast System of one degree grid spacing (GFS; [10]) was used. The reader can find more details of the GFS in [10], as well as at the website: https://www.emc.ncep.noaa.gov/emc/pages/numerical_forecast_systems/gfs.php (accessed on 20 May 2023). To simulate the soil temperature of depth 40 cm (ST40), the RegCM4 was configured with version 4.5 of the community land model (CLM45; [11]) following the procedure adopted in [6].

To examine the sensitivity of the simulated ST40 to different initial conditions of the soil moisture and temperature, four experiments were conducted and grouped into two cases. The first case considers the initialization the RegCM4 from the bare soil and ESACCI global satellite soil moisture product [12,13]. The ESACCI is based on integrating different microwave sensors and it is available at 0.25 degree grid spacing. Readers can refer to [12,13] for more details regarding the ESACCI. Figure 1 shows the interpolated ESACCI on the curvilinear grid of the RegCM4. The second case examines the sensitivity of the simulated ST40 to two initial conditions: bare soil and version 3 of the Century reanalysis product [14]. The Century product contains available data from 1836 to 2015.

For the purposes of the present study, the long-term average of the Century was calculated. In the first case, the RegCM4 started at 18 May 2023 and ended at 23 May 2023. For the second case, the RegCM4 started at 20 May 2023 and ended at 25 May 2023. It is worth noting that the first day (in each case) was discarded from the analysis to bring the atmosphere to the equilibrium state. Also, in the first case, both simulations began with zero values of the ST40. On the other hand, the second case considered initializing the soil moisture from the ESACCI. Please note that initializing the RegCM4 with a long-term spin-up of the soil temperature, following the procedure in [6] was not feasible in the present study because it was found that the RegCM4 is not stable in generating the daily restart files needed for acquiring the equilibrium state from the long-term spin-up file. Instead, the RegCM4 was initialized by means of the long-term average of the Century to overcome this point.

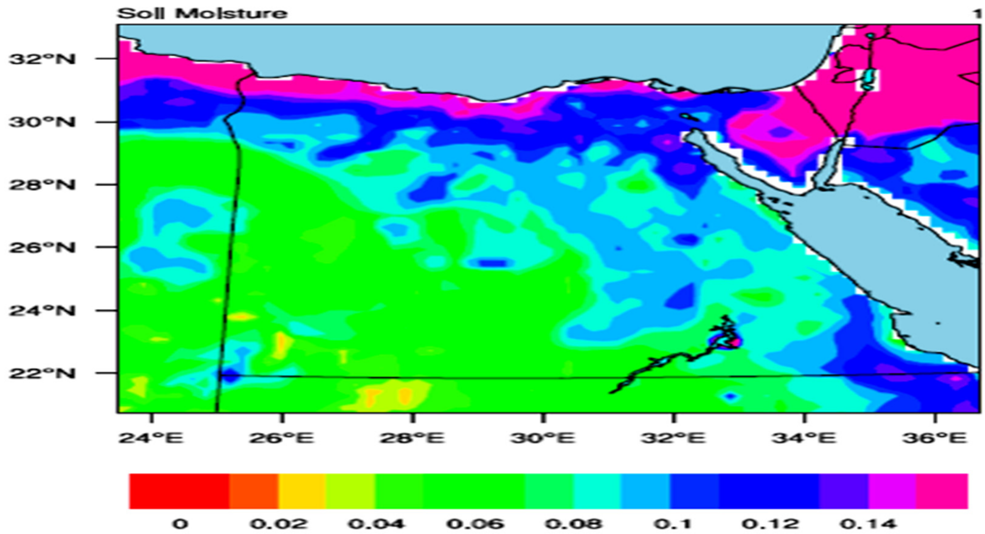

Figure 1. This figure shows the interpolated ESACCI satellite soil moisture product on the RegCM4 curvilinear grid.

2.2. Observational Dataset

The authors of [6] reported that the soil temperature profile is defined by the depths of 2, 5, 10, 20, 50, 100, and 200 cm. However, during the time of the simulations, there were no in situ observations for the soil temperature at a depth of 40 cm. Instead, the daily climatology of the Century product was used to evaluate the RegCM4 performance in each case. The mean bias (MB) was used as a statistical metric to quantitatively assess the RegCM4's performance. Concerning the Century reanalysis product, the authors of [15] reported that this product has two advantages: (1) it contains data from over a long period of time (spanning from 1836 to 2015) and (2) it provides good estimates of atmospheric variables.

3. Results

3.1. Qualitative Assessment

Figure 2 shows the simulated ST40 (in degree Celsius) initialized with bare soil (No Moisture) and ESACCI (Moisture). From Figure 2, it can be observed that both simulations exhibit an obvious trend attributable to the fact that the ST40 (in the two simulations) began with zero values. Also, initializing the RegCM4 with the ESACCI has a considerable impact on the simulated ST40, as the Moisture is warmer than No Moisture by 1.4 to 1.9 °C (depending on the forecast day; see Table 1). One can note from Figure 1 that despite the small soil moisture values (ranging from 0.01 to 0.14), the simulated ST40 showed a good sensitivity to the ESACCI compared to initialization with bare soil. A possible explanation for the physical effects (associated with the ESACCI) is indicated by the flow chart in Figure 3.

Figure 4 shows the simulated ST40 initialized from zero values and from the Century. From Figure 4, it can be noted that initializing from zero values (Without Century) indicates an obvious trend, and the simulated ST40 ranges between 20.5 and 24.5 °C in the five-day forecast (see Table 2). On the other hand, when the RegCM4 was initialized by the Century (Century), the trend becomes smooth and the ST40's range narrows (starting at 22.7 °C and ending at 23.8 °C). This noted behavior is quantitatively confirmed as the difference between Century and Without-Century decreases with time (see Figure 5).

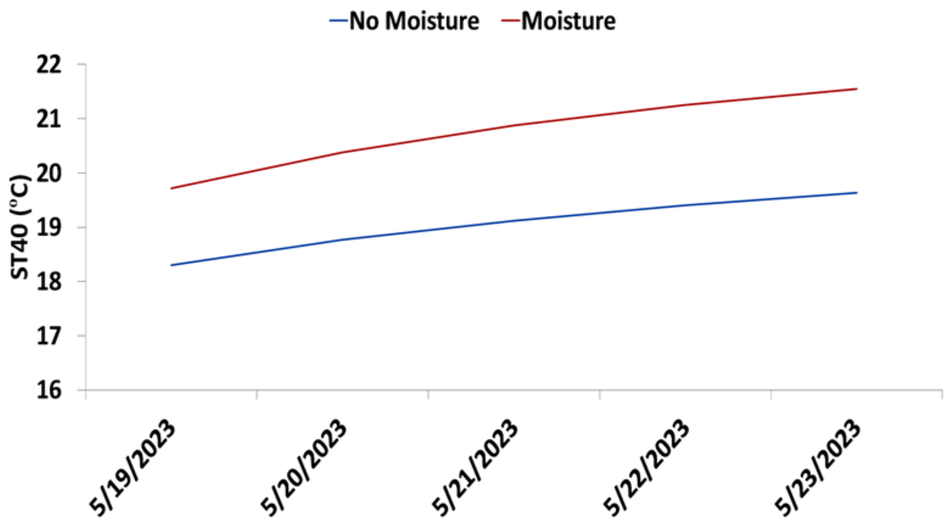

Figure 2. This figure shows the simulated ST40 (in °C) over the period ranging from 19 May 2023 to 23 May 2023. Initializing from bare soil (No Moisture) is shown via the blue line, while initializing from the ESACCI (Moisture) is presented via the red line.

Table 1. This table shows the simulated ST40 (in °C) initialized by bare soil (No Moisture), along with the ESACCI (Moisture) and the difference between them.

Day	No Moisture	Moisture	Diff
19 May 2023	18.3043	19.7198	1.4155
20 May 2023	18.7751	20.3834	1.6083
21 May 2023	19.1178	20.8762	1.7584
22 May 2023	19.4009	21.2561	1.8552
23 May 2023	19.6374	21.5524	1.915

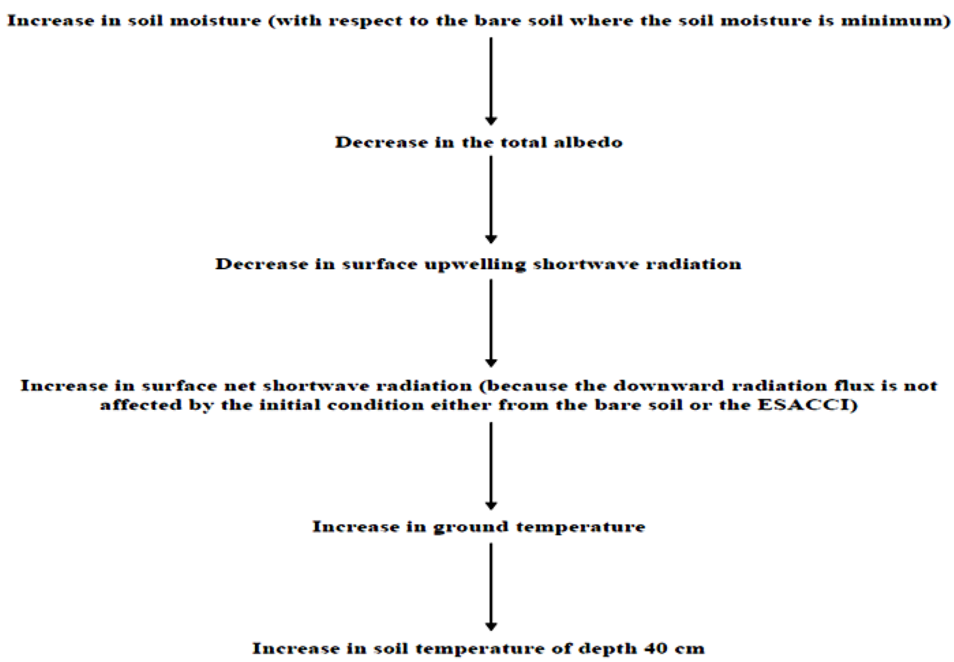

Figure 3. This figure shows the ESACCI mechanism of action on the simulated soil temperature at a depth of 40 cm (ST40).

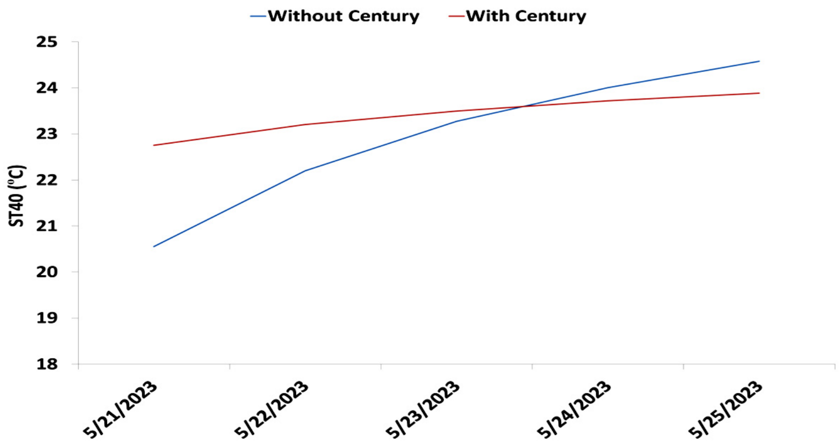

Figure 4. This figure shows the simulated ST40 (in °C) over the period from 21 May 2023 to 25 May 2023. Initializing from zero values (Without Century) is shown via the blue line, while initializing from the Century (With Century) is presented via the red line.

Table 2. This table shows the simulated ST40 (in °C) initialized by zero values (Without Century), along with the simulated ST40 (in °C) initialized with the Century (With Century) and the difference between them.

Day	Without Century	With Century	Diff
21 May 2023	20.5555	22.7506	2.1951
22 May 2023	22.2006	23.207	1.0064
23 May 2023	23.2726	23.4991	0.2265
24 May 2023	24.0068	23.7183	−0.2885
25 May 2023	24.5794	23.8854	−0.694

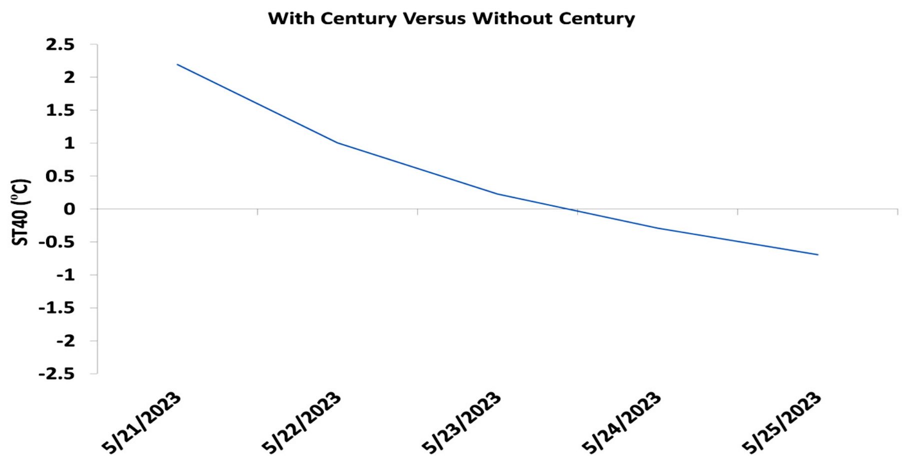

Figure 5. This figure shows the difference between (in °C) Century and Without Century over the period from 21 May 2023 to 25 May 2023.

3.2. *Evaluating the RegCM4 using the Century Reanalysis Product*

In Section 3.1, a qualitative assessment of initialization from bare soil and initialization from ESACCI/Century products was presented (conducted by the difference between the two simulations in each case). To determine which configuration is suitable for initializing the RegCM4, the two simulations (of each case) were compared using the Century reanalysis dataset (hereafter OBS). Figure 6 shows the comparison between NoMoisture and

Moisture with respect to the OBS. From Figure 6, it can be observed that both simulations underestimate the ST40 compared with the OBS. However, the Moisture is closer to the OBS than the NoMoisture.

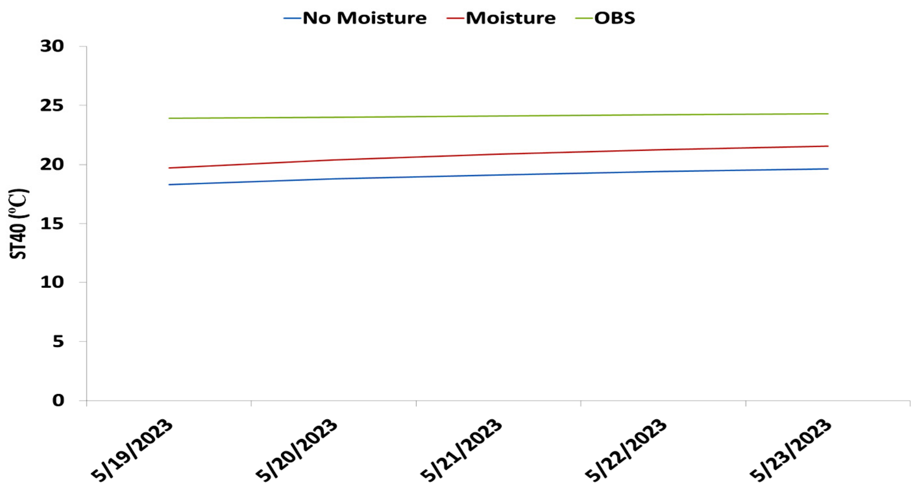

Figure 6. This figure shows a comparison between the No Moisture (in blue) and Moisture (in red) values with respect to the Century reanalysis product (OBS; in green).

Such behavior has been quantified as No Moisture, which has a value of MB of −5.05 °C, while Moisture has a value of MB of −3.3 °C. Concerning initialization via using the RegCM4 with the bare soil/Century product, it can be noted from Figure 7 that there is a considerable difference between Without Century and OBS (MB = −1.34 °C) because the RegCM4 shows a notable trend compared to the OBS. On the other hand, when the RegCM4 was initialized with the Century, the RegCM4 shows a smooth trend similar to the one noted in the OBS. Also, the RegCM4 has a value of MB of −0.85 °C in this case.

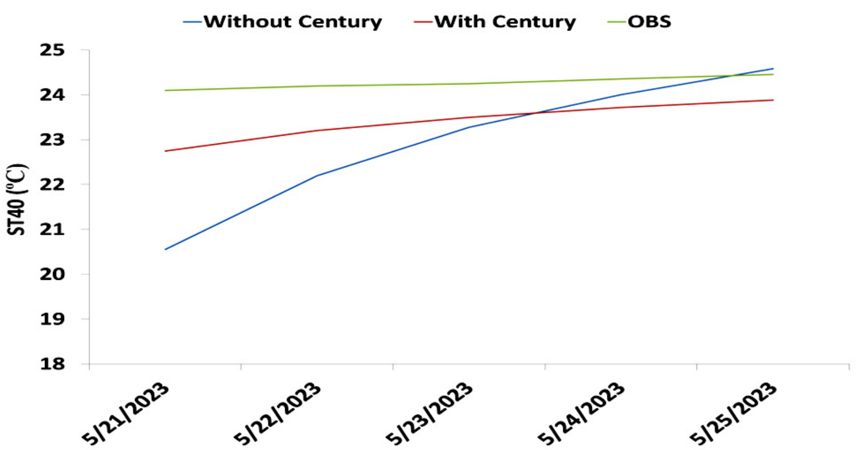

Figure 7. This figure shows a comparison between the Without Century (in blue) and With Century (in red) values with respect to the Century reanalysis product (OBS; in green).

4. Discussion and Conclusions

Soil temperature is important in monitoring the daily agricultural activities and controlling the status of the land surface. When station observations are limited or not available, regional climate models (e.g., RegCM4) are valuable tools that can be used to simulate soil temperature with a high-resolution at any grid point. Hence, it was necessary to examine the RegCM4's performance, as reported by [6]. Moreover, in arid regions (as in the present study), the RegCM4 is sensitive to different initial conditions of the soil temperature and moisture. To handle this issue, it was necessary to initialize the RegCM4 (with different initial conditions) to ensure a reasonable accuracy of the simulated ST40.

In the present study, the sensitivity of the simulated ST40 (to different initial conditions of the soil moisture and temperature) was investigated using the high-resolution grid-spacing of the RegCM4. To this end, four simulations were conducted and grouped into two cases. The RegCM4 model output was evaluated with respect to the Century reanalysis product (OBS). The results showed that the simulated ST40 is considerably sensitive to the soil moisture initial conditions. This can be clearly seen as Moisture is warmer than No Moisture. Furthermore, initializing the RegCM4 with the Century product showed a smoother trend and a narrower range of the simulated ST40 than initializing from zero values. In comparison with the Century reanalysis product (OBS), the RegCM4 gives a good performance when it is initialized with the ESACCI/Century products.

In conclusion, the RegCM4 can give a reliable forecast (of the simulated ST40) when it is initialized with the ESACCI satellite soil moisture and a long-term Century reanalysis products. Additionally, a future study will consider the following points:

1. Using a long-term spin-up soil temperature file (as an initial condition in accordance with [6]) and check its added value with respect to the results reported in the present study.
2. Addressing the sensitivity of the simulated ST40 to different global reanalysis products of the soil moisture such as the Climate Prediction Center (CPC; [16]) and the ECMWF's atmospheric reanalysis of the 20th century (ERA-20C; [17]).

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Conflicts of Interest: The author declares no conflict of interest.

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