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Bias-correcting the temperature extremes of Egypt using a high-resolution regional climate model (RegCM4)†

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Abstract: The regional climate model (RegCM4) was used to project the temperature extremes of Egypt considering the worst case scenario: Representative Concentration Pathway 8.5 (RCP8.5). To achieve this goal, the spatial pattern of the simulated temperature extremes was first examined. After that, the simulated temperature extremes were bias-corrected in the historical period with respect to station observations using Linear-Scaling (LS) technique. Finally, the LS was used to correct the two future scenarios. To downscale the RegCM4, the medium resolution of the Earth System Model of the Max Planck Institute (MPI-ESM-MR) was used to provide the lateral boundary condition and sea surface temperature. The results showed that temperature extremes exhibit the highest increase in the far-future period (2081-2100) particularly over Western Egypt, Red Sea and Upper Egypt (by 4 – 6°C). Also, the RegCM4 performance is remarkably improved when the LS method is used. Such performance is indicated by a low mean bias in the validation period compared to the evaluation period over majority of stations. Further, the added value of the LS is noted in T_{min} more than T_{max}. Therefore, the RegCM4 can be used to project the temperature extremes using the LS over the location of interest. In addition, using multiple General Circulation Models (GCMs) is necessary to account for uncertainty associated with the atmospheric forcing.

Keywords: Egypt; future scenario; linear-scaling; regional climate model; temperature extremes

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1. Introduction

Extreme weather events (e.g., heat waves) become more destructive and frequent with severe impacts on communities, cities, and island nations and agricultural activities. In particular, General Circulation Models (GCMs) - participated in the fifth phase of the coupled model intercomparison project (CMIP5) - show a gradual increase of annual temperatures in Northern Africa, higher than average [1]. Ref. [2] examined the changes in temperature and precipitation using latest Coupled Model Intercomparison Project (CMIP6) simulations for Africa under the three Shared Socioeconomic Pathways (SSPs). They found that future warning is not uniform over Africa and varies regionally, which demand the necessity of downscaling GCM dataset using RCM. However, GCMs are not suitable for studying extreme phenomena over a region like MENA where climate fluctuations are subject to enhanced spatial heterogeneity, due to their coarse spatial resolution.

Ref. [3] used the Regional Climate Model ALADIN-Climate to investigate future changes of temperature, precipitation, and associated extreme events in the Middle East and North Africa (MENA) region. They found that the model shows a good ability to capture the numbers of heatwaves (HWN) with an absolute mean bias not exceeding 0.4 in approximately all the domain. Also, the length of the longest heat wave (HWD) modelled is as well satisfactory compared with reanalysis despite some overestimation in parts of Saudi Arabia and Egypt and underestimations along the African monsoon regions south of the domain. Moreover, they found that the heat wave magnitude will intensify the most over Morocco, Western Algeria, Libya, Egypt and Iran. Such intensification is more noted under the RCP8.5 future scenario than the RCP4.5 scenario.

Bias-correction techniques are valuable tools for correcting the future projections of the temperature extremes. For instance, ref. [4] examined the effect of climate change on the simulated temperature extremes as well as the total rainfall of Egypt using five GCMs and a high-resolution gridded observational dataset. They reported that Linear and Variance Scaling are promising methods for bias-correcting the total rainfall and temperature extremes of the historical GCMs. The purpose of the present study is to:

1. Examine the spatial pattern of the temperature extreme of Egypt in the reference period (1985-2005; RF) as well as under the extreme future scenario (RCP8.5).
2. Evaluate and bias-correct the RegCM4 output in comparison with station observation of the RF.

3. Correct the RCP85 future scenario at the locations where the bias-correction shows its potential skills.

Section 2 describes the study area and experiment design; section 3 shows the results of the study. Section 4 provides the discussion and conclusion.

2. Materials and Methods

2.1. Study area

Egypt is located in northern Africa, between Libya and the Gaza Strip, on the Mediterranean Sea, with a 3,500-kilometer-long coastal strip overlooking the Mediterranean Sea to the north and the Red Sea to the east. The low-lying Nile Delta is the most prominent characteristic of the northern coastal zone. Egypt's climate is characterized by semi-arid, with hot, dry summers and mild winters with minimal precipitation. The country is known for its exceptional wind regimes and locations along the Red Sea and Mediterranean shores. Egypt has a hot desert climate (Köppen climate classification BWh). Except for the northern Mediterranean coast, which receives winter rainfall, the country's climate is generally extremely dry. In addition to the rarity of rain, Egypt experiences extreme heat during the summer months, though daytime temperatures are more moderate along the northern coast.

2.2. Experiment design

In this study, model domain and physical configuration were customized following a study conducted by [5]. In this study, daily observed data of the 2-m maximum (T_{max}) and minimum air temperature (T_{min}) (from eleven Egyptian surface weather stations; see table 1) has been used to evaluate and bias-correct the RegCM4 performance in the RF. It is worth mentioning that the selected stations were considered in the present study based on two important points: 1) data availability with high quality control and 2) ability to cover different climate zones of Egypt. The aforementioned period is divided to two time segments: the first period is 1985-1995 (considered as the evaluation period), while the second period is 1996-2005 (as the validation period). In the present work, Linear Scaling (LS; [6]) was used to bias-correct the RegCM4 output with respect to the OBS. According to [6], the corrected RegCM4 output (hereafter RCM) is calculated as:

$$\mathbf{RCM_{new,(i)}} = \mathbf{RCM_{(i)}} + \left(\mathbf{OBS_{clim,(i)}} - \mathbf{RCM_{clim,(i)}}\right)$$

Where RCM_{new} is the corrected temperature, RCM is the raw output from the RegCM; OBS_{clim} and RCM_{clim} are the monthly climatology of the station observation and the RCM respectively; (i) refers to the month considered in the analysis. The RegCM4 model performance (before and after using the LS method), was quantified using the Mean bias (MB) as a statistical metrics.

2.3. Validation Data

In this study, daily observed of the 2-m maximum and minimum air temperature (from eleven Egyptian surface weather stations; see table 1) has been used to evaluate and bias-correct the RegCM4 performance in the historical period (1985-2005). It is worth mentioning that the selected stations were considered in the present study because of data availability and they cover different climate zones in Egypt The aforementioned period is divided to time segments: the first period is 1985-1995 (referred to as evaluation period), while the second period is 1996-2005 (designated as the validation period). A quality control (QC) procedure has been applied to ensure high-quality consistent records. First, the quality control procedure was used to identify possible errors (e.g., finding missing values, outliers). Second, outlier values were excluded to ensure data homogeneity. Two programs have been used to ensure that the observed data passed the QC check and make data analysis: 1) Statistical Packages and Software Services (SPSS), 2) Microsoft Excel program.

Table 1 shows the Egyptian meteorological stations used in the present study to evaluate the RegCM4 performance in the reference period (RF).

Station Name	Lat	Lon	Elevation (m)	Lat	Lon	Elevation (m)
Arish	31.08°	33.82°	30.57	Hurgada	27.18°	33.80°
Dabaa	31.03°	28.43°	17	Sharm	27.98°	34.38°
Marsa Matrouh	31.33°	27.22°	25	Kossir	26.18°	34.25°
Mansoura	31°	31.45°	3.73	Assyut	27.5°	31.16°
Cairo	30.13°	31.40°	64.12	Asswan	23.97°	32.78°
Farafra	27.05°	27.98°	77.79			

3. Results

3.1. Projecting the temperature extremes under RCP8.5 scenario

Figure 1 shows the future changes of the 2-m maximum air temperature (T_{max}) for the time segments: 2021-2040, 2041-2061, 2061-2080 and 2081-2100 under RCP8.5 scenario. From Figure 1, it can be noticed that T_{max} exhibits a notable increase in different time segments particularly in the far periods. For instance, the period 2041-2060 shows an increase (by 1 – 3°C) overall Egypt. On the other hand, in the time segment 2061-2080, an increase (by 3 – 4°C) is noted over Western Egypt, Red Sea and Upper Egypt. While in the period 2081-2100, T_{max} exhibits the largest increase over Western Egypt, Red Sea and Upper Egypt (by 4 – 6°C) and by 3 – 4°C elsewhere. Concerning the 2-m minimum air temperature (T_{min}), an increase by 1 – 3°C is observed overall Egypt in the time segments 2041-2060 and 2061-2080. While in the period 2081-2100, an increase of 3 – 4°C overall Egypt relative to the RF (Figure 2). Projecting the T_{max} and T_{min} under the RCP4.5 scenario is provided in a supplementary file.

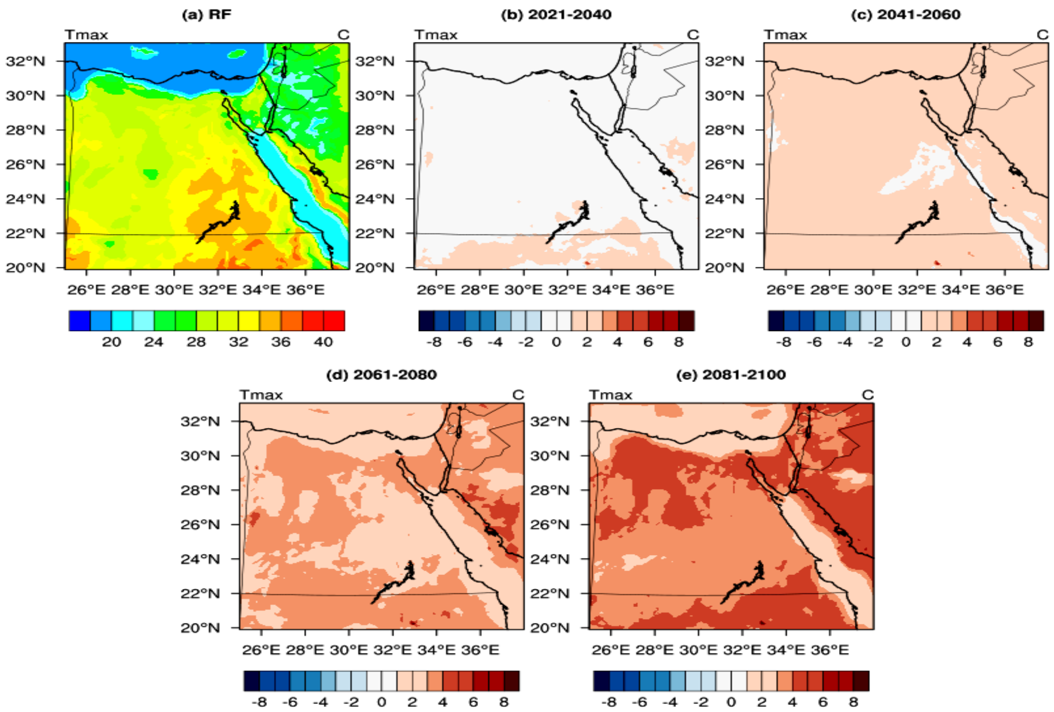

Figure 1 shows the T_{max} for the: (a) reference period (RF), future periods: (b) 2021-2040, (c) 2041-2060, (d) 2061-2080, (e) 2081-2100

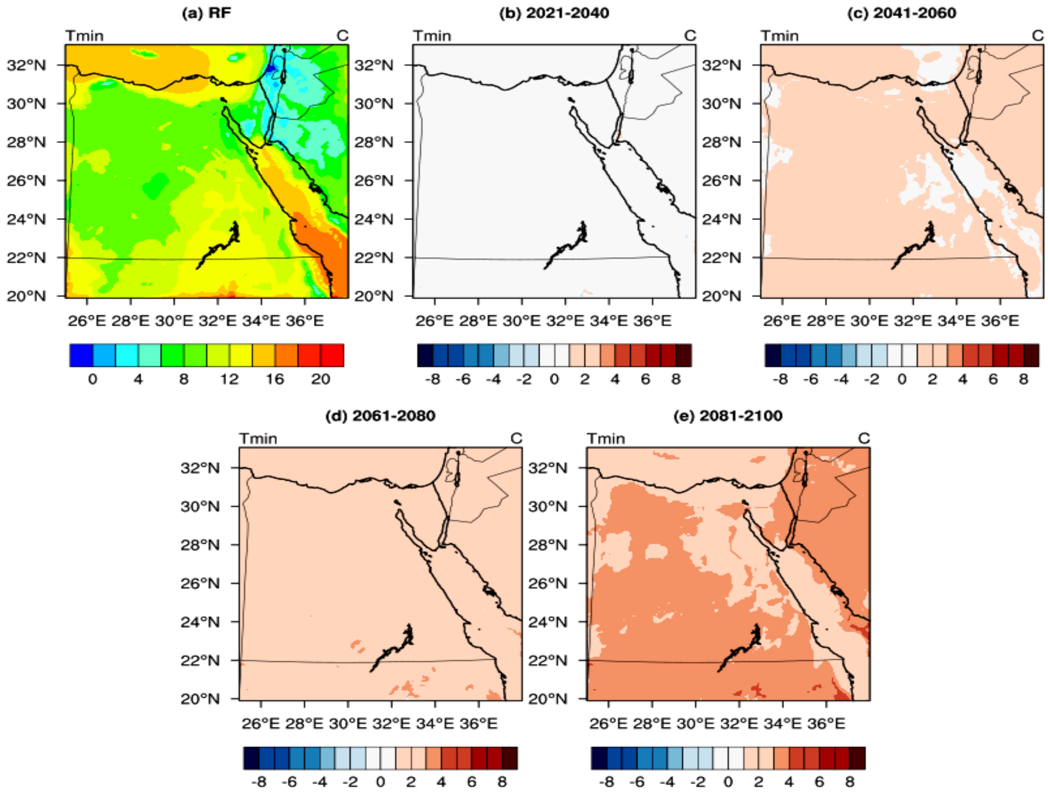

Figure 2 shows the T_{min} for the: (a) reference period (RF), future periods: (b) 2021-2040, (c) 2041-2060, (d) 2061-2080, (e) 2081-2100

3.2. Evaluating the RegCM4 with respect to station observations

For brevity in analysis, only five stations are considered: Arish, Dabaa, Matrouh, Mansoura and Cairo. The rest of stations are provided in a supplementary file. Figure 3 shows the monthly T_{max} (in °C) time series for the RegCM4 output (before and after applying the LS) for the five stations (reported in table 1) in comparison with the OBS. In general, it can be noted that the RegCM4 is able to reproduce the monthly variability of the T_{max} with respect to the OBS. Also, the model bias differs with respect to the season as well as the location of interest. For instance, in the EP the RegCM4 majorly overestimates the T_{max} over Arish with a MB of 1.94°C (before applying the LS) and a MB around zero (after applying the LS). Also, the RegCM4 is closer to the OBS (when the LS is applied) more than when the LS is not used. In the VP, the applicability of the LS is noted as the RegCM4 stays close to the OBS. However, substantial biases are noted as the RegCM4 shows a MB of 0.48°C (before applying the LS) and a MB of -1.61°C (after applying the LS).

Over Dabaa, the RegCM4 overestimates the T_{max} (in the EP) in the summer months (June-July-August) and underestimates in the winter months (December-January-February) by 0.65°C (before using LS) and around zero degrees (after using LS). In the VP, the LS majorly shows its potential skills in the winter months; while the RegCM4 stays close to the OBS in the summer months. Quantitatively, the RegCM4 possesses a MB of -2.28°C (before applying the LS) and -1.62°C (after applying the LS). Since Matrouh is geographically close to Dabaa, therefore a similar behavior is noted in the two locations for both EP and VP (before and after using the LS). For Mansoura, the situation is quite different as the RegCM4 overestimates the T_{max} by 7.36°C (in the EP) and by 7.08°C (in the VP) with respect to the OBS. On the other hand, when the LS is applied the RegCM4 is considerably improved as the RegCM4 shows a MB around zero (in the EP) and -0.28°C (in the VP). Moreover, the RegCM4 is very close to the OBS in both EP and VP (when the LS is used). Before applying the LS, the RegCM4 is quite close to the OBS with MB of -0.34°C (in the EP) and -1.6°C (in the VP) in Cairo. After applying the LS, the RegCM4 has MB around zero (in the EP); while it shows MB of -1.25°C (in the VP).

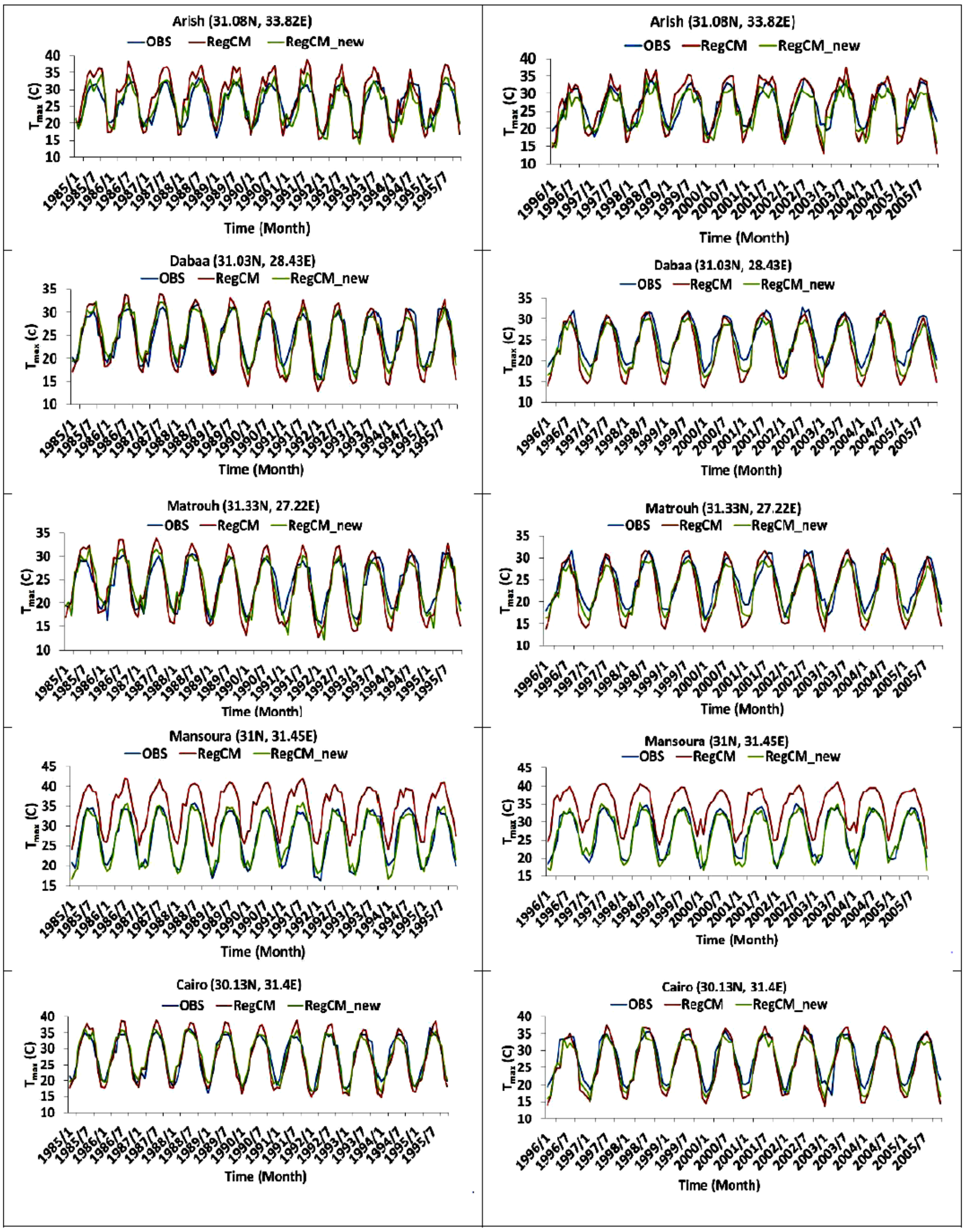

Figure 3 shows the T_{max} for the stationobservation (in blue), RegCM before applying LS (in red) and RegCM_new after applying LS (in green).

Concerning T_{min} (Figure 4), the situation is quite because the RegCM4 underestimate the T_{min} in all sites except for Mansoura station (where the RegCM4 overestimates/underestimates the T_{min} depending the season). From Figure 4, it can be observed that the RegCM4 is able to capture the monthly Tmin with respect to the OBS; however the bias varies with the site. For instance, the RegCM4 underestimates the Tmin over Arish by 6.17°C (in the EP) and by -6.29°C (in the VP) when the LS is not used. On the other hand when the LS is applied, the noted underestimation quite disappears because the MB is around zero (in the EP) and it is -0.11°C (in the VP). Also, it can be noted that the RegCM4 is close to the OBS when the LS is used (either in EP or VP). Like T_{max}, there is a similarity in the RegCM4 behavior between Dabaa and Matrouh (concerning the T_{min}). For example in Dabaa, the RegCM4 underestimates the T_{min} by 2.7°C (3.36°C) in the EP (VP) before using the LS. Moreover, using the LS leads to a remarkable performance in the simulated T_{min} because the MB is around zero (-0.57°C) in the EP (VP). In Matrouh before applying the LS, T_{min} is underestimated by 3.02°C (3.55°C) in the EP (VP). After using the LS, the situation becomes better since the MB is around zero (-0.53°C) in the EP (VP). Unlike the T_{max}, there is no considerable difference between the EP and VP either before or after applying the LS. For instance, the MB is -0.96°C (-2.31°C) in the EP (VP) before using the LS. After using the LS, the MB becomes around zero

(-1.36°C) in the EP (VP). However, both simulations (i.e., before and after applying the LS) are close to each other and they underestimate the Tmin in comparison with the OBS.

In Cairo, the RegCM4 underestimates the T_{min} by 3.86°C (4.6°C) in the EP (VP) before using the LS. An improved performance of the LS is obviously noted since the MB is -0.017°C (-0.8°C) in the EP (VP). In comparison with the T_{max}, both Hurgada and Sharm highly underestimate the T_{min} with respect to the OBS. For instance, the RegCM4 underestimates the Tmin by 5.93°C (7°C) in the EP (VP) before applying the LS. Also, the LS shows its potential skills because the MB is around zero (-1.1°C) in the EP (VP) when the LS is used. In Sharm, the situation is more obvious than in Hurgada because the MB is -10.62°C (-10.76°C) in the EP (VP) when the LS is not used. After applying the LS, the RegCM4 performance is notably improved since the MB is around zero (-0.15°C) in the EP (VP) when the LS is considered.

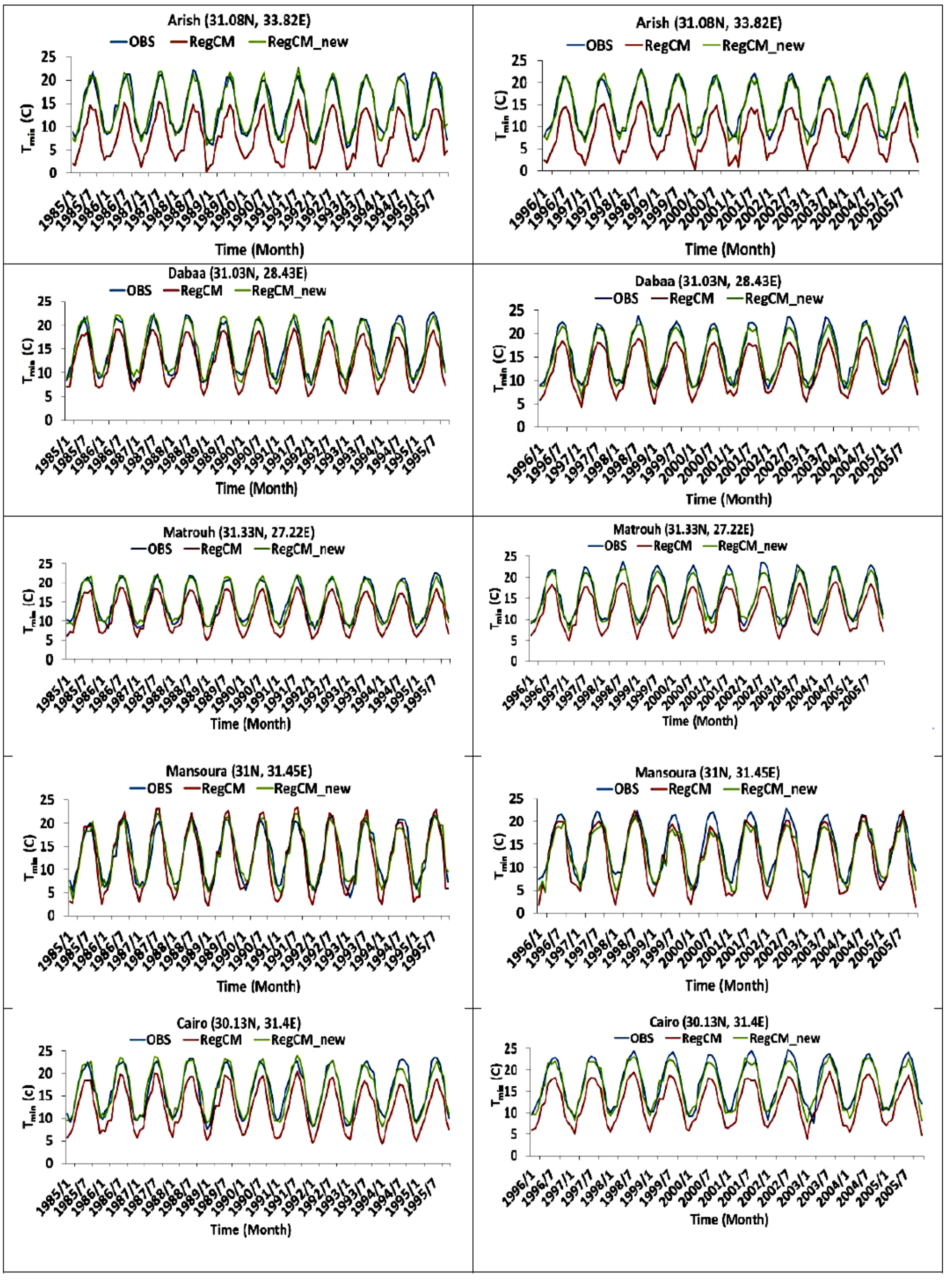

Figure 4 shows the T_{min} for the stationobservation (in blue), RegCM before applying LS (in red) and RegCM_new after applying LS (in green).

3.3. Correcting the future Probability of Occurrence

Figure 5 shows the Probability of Occurrence (POO) for the stations: Arish, Matrouh, Mansoura and Cairo in the future period 2021-2100. These stations were selected based on the LS potential skills in improving T_{max} and T_{min} respectively. From Figure 5, it can be noted that POO peaks at 0.03 (for T_{max}) over a range of 6 - 42°C (before applying the LS) at Arish. After applying the LS, the POO doesn't show considerable change in its peak but the POO curve is shifted to include a range of 4 - 38°C. Concerning T_{min}, the POO peaks at 0.04 (before and after applying the LS). Moreover, the POO shows an obvious shift over a range from 1 - 28°C (before using the LS) to a range of 6 – 30°C (after using the LS). At Matrouh, the situation is different from the one noted at Arish. For instance, the POO shows a shift of the T_{max} range from 8 - 38°C to 10 - 40°C. In addition, a peak shift is also noted (from 0.03 to 0.04). Regarding T_{min}, there is no notable shift in the POO curve peak, but a considerable shift in the T_{min} range (from 4 - 26°C to 7 - 29°C). The POO shows a notable shift in its peak (0.03 – 0.04) as well as in the range (from 2 - 40°C to 8 - 46°C) concerning T_{max} at Mansoura. For T_{min}, a small shift is noted in the POO curve (from 1 - 33°C to 2 - 32°C). However, an obvious change in the POO peak is observed (0.03 – 0.04). Finally at Cairo, there is a shift in both: T_{max} range (6 - 46°C to 8 - 44°C) and POO curve peak (0.02 – 0.032). Concerning T_{min}, an obvious shift is also noted in its range (1 - 30°C to 5 - 34°C) and POO curve peak (0.032 – 0.038).

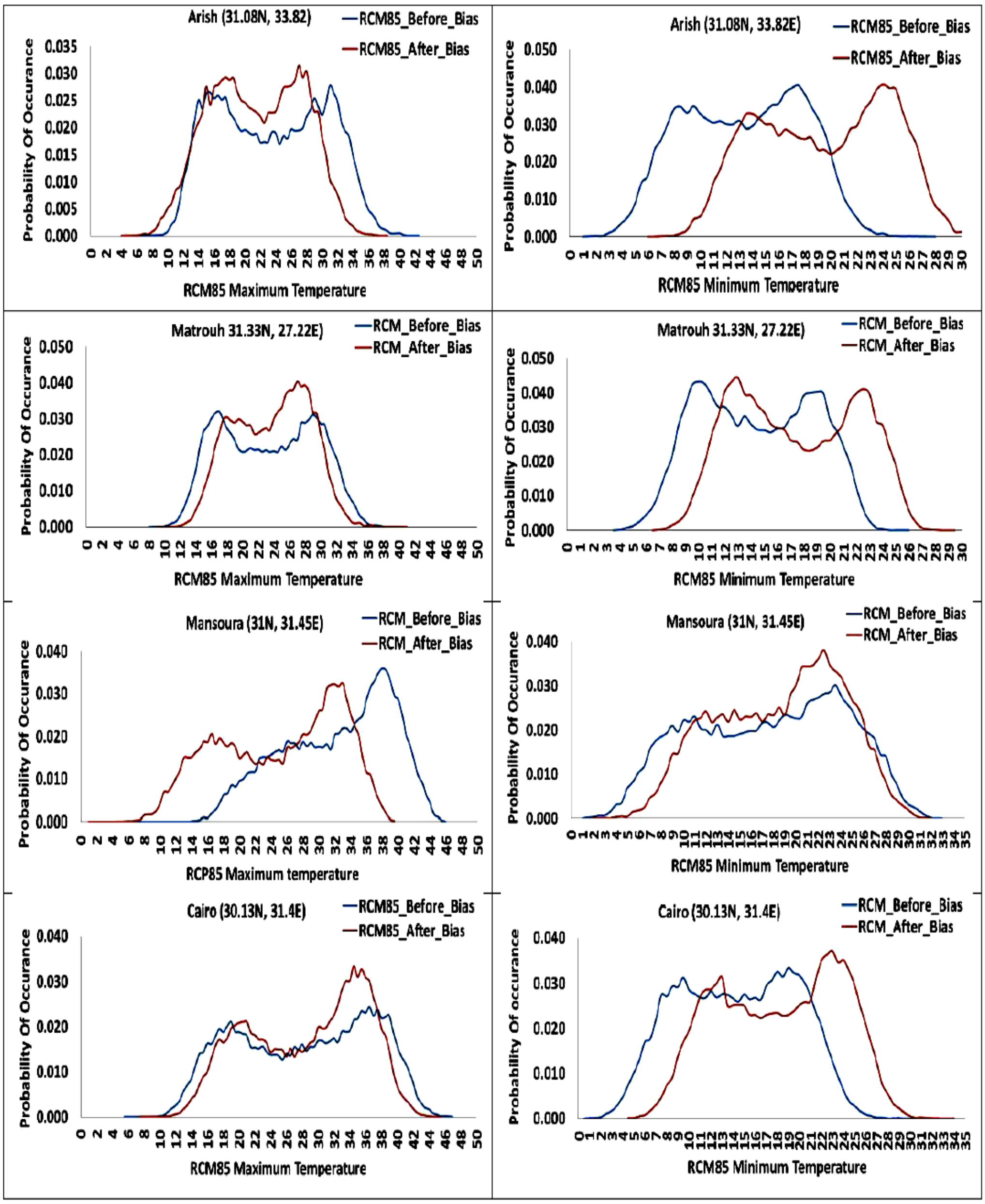

Figure 5 shows the Probability of Occurrence for T_{max} (left side) and Tmin (right side) before applying LS (in blue) and after applying LS (in red). RCM stands for the RegCM4 model output.

4. Discussion and Conclusion

Regional Climate models (RCMs) are valuable tool to examine the influence of climate change on the daily temperature extremes, number of heat-waves as well as the number of hot-days under different future scenarios. Many studies examined the effect of climate change on temperature indices in the MENA region as in [2, 3]. Ref. [4] used different bias-correction techniques (e.g., LS) to correct the future projection of temperature extremes and total rainfall. The bias-correction was applied to the whole region of the North Egypt. However, the LS method wasn't used to correct the future projection at the location of the station observation.

In the present study, the RegCM4 was downscaled (by the MPI-ESM-MR) over Egypt following [5]. The RCP85 was considered as the future scenario. First, the spatial pattern of the simulated temperature extremes was examined overall Egypt. Then, the future projection was corrected using the bias-correction factors between the RegCM4 (in the RF) and OBS. The corrected future projected temperature extremes were applied to the POO (as an example) to explore the potential effects of the LS. The results showed that the RegCM4 has the highest increase of the simulated temperature extremes (with respect to the RF) in the far period (2081-2100) of the RCP8.5 scenario.

In the RF, the RegCM4 noted bias (either for T_{max} or T_{min}) can be attributed to the following reasons: 1) mismatch of the geographic features between the RegCM4 and OBS, 2) RegCM4 physical parameterization particularly the short/long-wave radiation, 3) using a prescribed value of ground emissivity during the RegCM4 simulations (which is supposed to vary with each season) and 4) uncertainty propagation from the lateral boundary condition as reported by [7]. As discussed in section (3.2), the RegCM4 performance is improved when the LS method is used. Such performance is confirmed with a low MB in both: EP and VP. Also, the potential skills of the LS appear in T_{min} more than T_{max}.

In some stations; the LS cannot show a notable improvement because the RegCM4 is close to the observation or it cannot explicitly represent the local geographic feature of station under study. It is important to highlight that the static data (which represents the initial condition of the RegCM4) is an important source of uncertainty. Therefore, uncertainty of the static data propagates to the RegCM4 physical parameterization and eventually the simulated temperature extremes particularly over the arid-to-hyper-arid region (as in this study). Despite of the aforementioned sources of uncertainty, the RegCM4 shows an improved performance using the LS method over majority of stations.

To ensure a robust performance among all stations, the static data needs to be updated to account for the local geography features of each station. Also, the RegCM4 physical parameterization needs to be revised; and additional sensitivity studies need to be conducted. After that, the RegCM4 can be re-evaluated with respect to the OBS. A future study will consider using multiple GCMs (CMIP5/CMIP6; [8, 9 and 10]) and their ensemble to further examine the impact of climate change on the simulated T_{max}/T_{min}. In addition, a comparison between direct downscaling (using multiple GCMs with different spatial resolutions) and one-way nesting (using one GCM) to see which approach is suitable for simulating the temperature extremes of Egypt as recommended by [7]. For stations didn't show a remarkable improvement or show a bad performance; other bias-correction techniques (e.g., Variance Scaling and Empirical Quantile Mapping) can be considered to further evaluate the RegCM4 as reported by [4, 11].

Supplementary Materials: Applicable

Author Contributions: Conceptualization, Anwar SA; methodology Anwar SA; software, Anwar SA and Mostafa SM; validation, Mostafa SM; formal analysis, Anwar SA and Mostafa SM; investigation, Anwar SA and Mostafa SM; resources, Zakey SA; data curation, Mostafa SM; writing—original draft preparation, Anwar SA and Mostafa SM; writing—review and editing, Anwar SA, Mostafa SM, Zakey SA and Wahab MM. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

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