



# Article **Regional Climatic Features of the Arabian Peninsula**

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**Abstract:** The climate of the Arabian Peninsula is characterized by significant spatial and temporal variations, due to its complex topography and the large-scale atmospheric circulation. Furthermore, the role of dust in the formation of regional climate is considered to be crucial. In this work, the regional climatology for the Arabian Peninsula has been studied by employing a high resolution state of the art atmospheric model that included sophisticated physical parameterization schemes and online treatment of natural aerosol particles. The simulations covered a 30-year period (1986–2015) with a temporal resolution of 3 h and a spatial distance of 9 km. The main focus was given to the spatial and temporal variations of mean temperature and temperature extremes, wind speed and direction, and relative humidity. The results were evaluated using in situ measurements indicating a good agreement. An examination of possible climatic changes during the present climate was also performed through a comprehensive analysis of the trends of mean temperature and temperature extremes. The statistical significant trend values were overall positive and increased over the northwestern parts of the examined area. Similar spatial distributions were found for the daily minimum and maximum temperatures. Higher positive values emerged for the daily maxima.

**Keywords:** regional climate; Arabian Peninsula; intra-annual variability; trend analysis; dynamical downscaling

## 1. Introduction

The Arabian Peninsula (AP) experiences some uniform climatic characteristics and at the same time a considerable variability, due to the physical and chemical processes taking part in the atmosphere, its complex physiographic characteristics, and the seasonally-changed atmospheric circulation patterns. The regional climate is highly affected by the Indian summer monsoon in the South, and the Mediterranean synoptic scale systems in the North. The landscape consists of highlands in the western and southwestern regions (Sarawat Mountains), the vast arid and extra arid lands of the interior (Najd), the world's largest sand desert, and the Rub Al–Khali in the southeast. Concurrently, most of the region is surrounded by ocean. All these features have an important role in the formation of the climatic regime.

Overall, the region is mainly characterized by a desert-type climate with extreme heat, particularly during the day-hours and infrequent low rainfall. The extremely hot and dry climatic conditions represent about 80% of the area [1,2]. According to the Koeppen–Geiger classification, the climate can be classified as Hot Desert Climate (BWh). On the contrary, the southwestern part features mild steppe climate [3], due to increased convective precipitation throughout the year. Four climatological seasons can be distinguished, representing different climatological regimes [4], the northeast monsoon

(December–March), the spring transition (April–May), the southwest monsoon (June–September), and the fall transition (October–November).

A considerable amount of previous studies were temperature-oriented as the AP frequently experiences extreme temperatures with serious adverse impacts on the economy, the human society, and the natural environment. An example is the year 2010 that was recorded as the hottest year, in the instrumental observational period of Saudi Arabia [5]. Climatological analysis of temperature extremes has also been performed by AlSarmi and Washington [6], employing station data. Furthermore, El Nesr et al. [7] examined temperature extremes on a climatological basis for Saudi Arabia, Nasrallah and Balling [8] for Kuwait, and Smadi [9] for Jordan. A potential temperature increase, particularly when accompanied by a decrease in precipitation, could have a major impact on application-oriented sectors, such as agriculture, water resources, energy demand, biodiversity, migration, and food security [10,11]. These impacts might become even more severe in the future, as a consequence of the global climate change [12]. There is a variety of studies dealing with the trend analysis of temperature in the region for different time periods, on an annual or seasonal basis, employing station data or gridded data from various sources. The overall conclusion is that there are positive trends concerning the temperature, and at the same time a higher frequency of cold and hot extremes [3,5,6,13,14].

The sparseness or unavailability of surface datasets and the lack of continuous and reliable observations for most of the countries in the AP are major problems in performing a detailed analysis of the regional climatology. Therefore, the use of such time-series for trend analysis is not always recommended, as it may lead to biased results. The employment of modeled datasets serves as an appropriate and useful tool for deriving climatic information for the area. Almazroui [15] performed day to day simulations employing the regional climate model RegCM4 for the period 1978–2000, with a spatial resolution of 50 km, and compared the mean climatology with gridded observations provided by the Climatic Research Unit (CRU [16]). However, in the regional model simulations, an increased positive temperature bias was evident in some areas. Similar biases for the mean climatology of Saudi Arabia and especially over the sand desert of Rub Al-Khali were found by Almazroui [17], with the aid of the regional model PRECIS, employing a resolution of 50 km.

Apart from the fact that the previous modeling work was coarse for the description of mesoscale and local features, an additional issue was the absence of the desert dust impact. Desert dust is a significant characteristic that affects the regional climate of AP, and is found in high concentrations in the atmosphere, throughout the whole year. Mineral dust has a profound effect on the radiative budget and energy distribution of the atmosphere. The amount of energy reaching the surface is reduced through the absorption and the scattering of the solar radiation by aerosols. In addition, aerosols enhance the greenhouse effect, by absorbing and emitting long-wave radiation. Saeed et al. [18] studied the aerosol's characteristics and the direct radiative force during a dust storm, while Tegen et al. [19] showed that dust might cause a decrease in the net surface radiation. The inclusion of the dust direct radiative forcing in the RegCM4 by Islam et al. [20] (in the wet season) with a spatial resolution of 50 km, significantly decreased the simulated warm bias, however, with small improvements in the spatial distribution. Marcella and Eltahir [21] examined the role of land-surface processes, such as dust emissions and irrigation, in shaping the summer regional climate of semi-arid regions, with the aid of the regional model RegCM3, and concluded that these can help in partially correcting the significant overestimation of the temperature.

Furthermore, the role of aerosols that act as a Cloud Condensation Nuclei (CCN) or Ice Nuclei (IN), is considered important, modifying the microphysical, microchemical, and, hence, the optical properties of clouds [22]. Collectively, changes in cloud processes due to aerosols are referred to as aerosol indirect effects (IF). Finally, the absorption of solar radiation by particles, contributes to a reduction in cloudiness, a phenomenon referred to as the semi-direct effect [23]. The amount of particles that will nucleate and form cloud droplets, depends on the number concentration, size distribution, and chemical composition. Changes in the partitioning between hygroscopic and non-hygroscopic particles, can affect the cloud cover, the radiative properties, and precipitation.

In order to study the regional climatic features of the AP, including areas where observational data are scarce or unavailable, the employment of a high resolution atmospheric model is more than necessary. Furthermore, the complexity of the microphysical features dominating the AP climate, render the need for an integrated modeling approach with the explicit resolving of various physical and dynamical processes. Taking all these into consideration, a climatological analysis regarding the AP has been performed. This analysis has been carried out for thirty years, with the aid of a state-of-the art non hydrostatic limited area atmospheric modeling system, encompassing a high spatial resolution of 9 km and a temporal one of 3 h. The employment of the Integrated Community Limited Area Model (ICLAMS) version of the Regional Atmospheric Modeling System (RAMS) (RAMS/ICLAMS) [22,24], provides the advantage of highly sophisticated physical parameterizations, including the dust sub-model, the radiative transfer model, cloud microphysical processes, detailed surface parameterization, as well as advanced numerical schemes. An extensive database has been developed, including the various parameters derived from the model simulations, in order to be utilized in this particular study and other scientific purposes, in a user-friendly environment.

In this paper, the atmospheric model set up has been described and the outcome has been evaluated. The spatial distribution of the parameters under study have been presented and discussed. Emphasis has been given on the trends of temperature and temperature extremes, as well as on their spatial variations over the area under consideration.

#### 2. Materials and Methods

## 2.1. Data and Model Set Up

The data used for the analysis were the product of dynamical downscaling, based on hindcast numerical simulations, embedded in a database, for easier processing. The integrated model used in this study was RAMS/ICLAMS [22,24–26]. The model has two-way interactive nesting capabilities, an explicit cloud microphysical scheme, with seven categories of hydrometeors and a detailed surface parameterization sub-model. Natural aerosol particles (mineral dust and sea salt) were taken into account in the model physics with the concentrations, size distributions, and optical properties of all elements to be computed online. Natural aerosols contributed to the calculation of the meteorological conditions, through feedback mechanisms (direct, semi-direct, and indirect effects), while CCN and IN were considered to be the predictive parameters. The two-way interactive features of this model were also a desired characteristic for the simultaneous simulation of regional and local dust cycle properties [27]. More publications for the RAMS/ICLAMS modeling system can be found in [28].

The model was run for the period 1986–2015 (30 years). The spatial resolution was 9km and the domain covered the entire AP and the neighboring regions (Figure 1). Vertically, it stretched up to 20 km in 30 levels. The time step used for the model runs was 15 s and the temporal resolution of the model output was 3 h.

The initial and lateral boundary conditions used for the model runs were retrieved from the ERA-Interim dataset [29], which is the latest global atmospheric reanalysis produced by the European Centre for Medium-Range Weather Forecasts (ECMWF), starting from 1979, and was updated continuously in real-time. A significant advantage behind the use of the reanalysis product, compared to the operational analyses, was the consistency in terms of model outputs. For studies like the present one, which spanned across several decades, it was essential to rely on datasets that were not affected in any way by changes that took place in the operational setup, throughout the years.

Daily Sea Surface Temperature (SST) gridded data, provided by National Centers for Environmental Prediction (NCEP) was used. The soil texture and properties for the neighboring countries were derived from the Food and Agriculture Organization of the United Nations (FAO), whereas inside the boundaries of the Kingdom of Saudi Arabia, a fine-detailed soil categorization was used, based on a high resolution soil database of Saudi Aramco (personal communication). The geological categories were grouped into twelve soil textural categories, based on their properties. The elevation data set

used was of a high resolution (90 m  $\times$  90 m), in order to obtain a detailed topography representation in the model. The vegetation and land use were acquired by the United States Geological Survey (USGS) and the Olson Global Ecosystem categorization was used. The horizontal resolution of the datasets was 30 arcsec (~900 m). The vegetation, together with soil categorization and slope inclination, were combined in ArcGIS, in order to produce the brand new classification of the dust uptake areas.



**Figure 1.** The model domain displayed as a topographical chart of the Arabian Peninsula. The locations and the codenames of the stations used for the evaluation study are also depicted.

## 2.2. Model Evaluation

To assess the quality and performance of the model-derived parameters, an evaluation was performed. Measurements from surface meteorological stations, operating in the AP and reporting to the World Meteorological Organization (WMO) network [30] were used. Based on the WMO requirements, the stations were limited to the ones that frequently collect and supply data in near real-time. Relevant information of stations included a station number, station name, latitude, longitude, and altitude. Weather stations registered in the WMO database were ones that ordinarily operate in the main airports and the most populated cities. In the current assessment, thirty eight stations have been used (Figure 1). The evaluation period covered approximately 22 years, based on observational data availability, starting from April, 1993.

The performed model evaluation was for surface wind speed and temperature. More precisely, wind speed was recorded at a height of 10 m and temperature data were recorded at 2 m. The selection of these parameters is attributed to the fact that these comprise the most applied and characteristic climate parameters in relevant studies [31,32].

The model data were extracted by applying the "nearest model grid point" methodology. This approach is considered to be conventional, for the provision of model outputs in a specific location; however, it might not always be as accurate in areas with significant topographic variations or near the coastline.

The statistical evaluation was based on the following statistical indicators—the Bias or Mean Bias Error (BIAS), the Mean Absolute Error (MAE), the Root Mean Square Error (RMSE), and the Correlation Coefficient (R).

Mean Bias Error (MBE), indicates the difference between mean values of the two compared parameters and informs whether and to what extend the model systematically overestimates (BIAS > 0) or underestimates (BIAS < 0) the observations.

The Mean Absolute Error (MAE), and the Root Mean Square Error (RMSE), refer to the absolute value of the discrepancies, providing, at the same time, a quantification of the error variability.

The Correlation Coefficient indicates the correlation between two different quantities, ranging from -1 to 1. Values close to 1 correspond to a positive linear relationship, values close to -1 correspond to a negative linear relationship, and values close or equal to 0 suggest there is no linear relationship between the two data.

Beginning with the parameter of surface wind speed (Figure 2), the results suggest that modeled and measured values were in close agreement in the majority of the examined stations, presenting an increased level of model simulation accuracy. This was illustrated by the majority of the derived statistical indicators of performance. More precisely, the vast majority of the MBE values were close to zero (Figure 2a). Overall, a small tendency for underestimation could be witnessed. Noted overestimations in the mean wind speed values were traced in one station in the west region of the Peninsula (station 41030), one in the north-west (station 40296) and three in the eastern coastal part. This could be attributed to the sub-grid scale effects.



**Figure 2.** Wind speed evaluation map for (**a**) Mean Bias Error (MBE), (**b**) Mean Absolute Error (MAE), (**c**) Root Mean Square Error (RMSE), and (**d**) the Correlation Coefficient.

With respect to the MAE and RMSE indices, the derived values suggest a small variability of error, since in the majority of the examined locations, the values were positioned below the 2.5 m/s (Figure 2b,c). A limited number of stations, mainly in the eastern and western coastal locations of the AP, as well as some stations in the northwestern region, exhibited the highest error variability.

Following the correlation coefficient results, a low positive linear relationship was found between the modeled and observed wind speed values (Figure 2d). Nevertheless, the results of the correlation coefficient in wind resource assessment studies were not considered as important for the determination of model accuracy, but were mainly used as indicators of the linear relationship. This was due to the inherit variability of the wind speed, compared to other meteorological parameters, such as the temperature.

The statistical evaluation of the model, concerning the temperature, is summarized in Figure 3. The model efficiently simulated the recorded temperatures. Specifically, the results in the bias error state that the mean values of the modeled and measured quantities were very close (Figure 3a). A safe conclusion concerning a regular overestimation or underestimation of the observed temperature could not be derived, since the deviations in mean values were both positive and negative. This could be related to the topography representation of the model at the grid points.



**Figure 3.** Temperature evaluation map for (**a**) MBE, (**b**) MAE, (**c**) RMSE, and (**d**) the Correlation Coefficient.

In the majority of the stations, error variability remained low, as demonstrated by the MAE and RMSE results (Figure 3b,c). The larger discrepancies could be spotted in the coastal stations, in the Southwest and East of the Peninsula. This could be attributed to the locations of the stations and the location of the nearest model grid point. Moreover, the resolution of model's domain apparently did not manage to capture all the related sub-grid scale phenomena. In most of these cases, the increased variability was accompanied with a slight underestimation in the mean temperatures. This indicated that the model outputs stemmed from the grid points closer to the land, while the stations values exhibited a micrometeorology related more to coastal conditions.

Regarding the correlation coefficient, the derived statistics manifested a well-established correlation between the modeled and the observed temperatures, as all values were close to 1 (Figure 3d).

The inter-annual evaluation of model performance was pursued by weighting error plots, showing the median, maximum, and minimum values, as well as the inter-quantile ranges in the statistical indicators, on a monthly basis, for the whole examined period. This is depicted in Figure 4 by employing the weighting plots of MBE, MAE, and RMSE.



**Figure 4.** Inter-annual evaluation statistics for wind speed (**a**–**c**) and temperature (**d**–**f**). Central red marks indicate the median, the box edges indicate the range between the 25th and 75th percentiles and the whiskers indicate the minimum and maximum values, respectively.

In wind speed, results were centralized close to zero m/s in MBE, 1.5 m/s in MAE, and close to 2 m/s in RMSE. For MBE, the higher values were positive and referred to the months July and August. Likewise, equivalent results were presented in the MAE and RMSE indicators, where the range of errors was also wide for these months.

For the parameter of temperature, the inter-annual evolution disclosed an amplified variability, mainly in MBE. This was related to the extension of the domain under study, which covered locations with different micrometeorology and climatic characteristics. Larger discrepancies could be found in the winter months. MBE was centered in values close to zero degrees, 1.5 °C to 2 °C in MAE, and 2 °C to 2.5 °C in RMSE.

## 3. Results and Discussion

#### 3.1. Climatological Patterns

#### 3.1.1. Temperature at 2 m

The mean annual temperature at 2 m exhibited significant spatial variations over the AP. In the southeastern part, the temperature was around 30 °C and decreased northwards, reaching 20 °C, over the North (Figure 5). The highest value was found over the desert area of Rub Al Khali. The southwestern coastal areas presented values of 28 °C, while inland, the temperature decreased to 20 °C, due to the distance from the sea and the high mountains, at 2,000 m altitude in the areas of Makkah and Azir. This distribution exhibited a quite similar general behavior to the one provided by the gridded observations of CRU, for the period 1978–2000 (see [3,5]), although considerable differences existed, mainly in the areas with topographic variability or near the coastline. On the contrary, significant differences existed between the present work and the results discussed in Almazroui [15]. As reported there, the estimated temperature bias was rather high in the southwestern inland, reaching values

as high as 4.5 °C. Such high biases could be attributed to the horizontal resolution used in RegCM4 configuration (in an area with significant topographic variability) and the inability to resolve convective activities that are quite frequent.



Figure 5. Spatial distribution of the annual mean temperature at 2 m for the period 1986–2015.

A detailed seasonal analysis revealed a profound distinction between the North and the South, during the winter months (Figures 6a, A1 and A2). Lower mean temperatures appeared in the North, with values near 10 °C, which increased southwards, reaching 20 °C. This regime was attributed to (a) the cold invasions from northeast due to the Siberian high, (b) the passage of the Mediterranean cyclones and the fronts in the northern regions, and (c) the formation of the cold fronts, associated with the upper level troughs, moving southeastwards along Saudi Arabia, producing strong Northerly or North Westerlies flows behind the fronts, the so-called Shamal winds. At this point, it should be noted that an analysis for all months could be found in the Appendix A.

It was also characteristic that the coastal areas of the Red Sea presented higher mean air temperature values than the inland. More specifically, the northern Red Sea presented lower values of 15 °C, as compared to the southern basin, due to the strong North Westerlies that prevailed over the northern and central parts of Red Sea and opposed the South Westerlies blowing over the South (see also chapter 3.1.3.). Following this distribution, the coastal area along the southern Red Sea presented high temperature values, of 20 °C. Alongside this region, a narrow zone with lower values (15 °C) was formed, due to the high mountains of 2000 m altitude, in the areas of Makkah and Azir. In March, the average temperature further increased over the whole region, especially in the northern part.

The difference between the northern and central parts of the area was attributed to the tracks of the Mediterranean cyclones that cross the Peninsula southeastwards. In April, the mean temperature regime followed the reversal of the atmospheric circulation. In the South, the temperature became as high as 35 °C over the eastern parts, 30 °C over the South Red Sea and inland areas, and decreased gradually to 20 °C in the North and over the mountains of the southwestern part of the region. A gradual temperature increase in the whole peninsula, but mainly in the northeastern part took place in May. From June to September, the temperature patterns were quite similar (Figure 6b and Appendix A). Most of the region experienced temperatures between 35 and 40 °C. Along the Red Sea coast, the temperature was lower, about 30 °C, due to the North Westerlies and the effect of the sea breeze that became dominant during the summer period. For the same reason, the coastal area of the Arabian Gulf was characterized by slightly lower temperature, compared to inland. The hottest month was July, while the temperature gradually decreased from August to December. The reversal of the synoptic circulation during October, contributed to a significant temperature drop in the North, reaching values of 20–25 °C. November was the period when the mean temperature significantly decreased, as the cold invasions started acting from the northeast, and the Mediterranean cyclones passed across the AP. The temperature was around 15 °C in the North, 20 °C in the central inland, and 25 °C in the South, including the coasts in the West and the East.



Figure 6. Mean 2 m temperature for January (a) and July (b).

The annual mean of daily maximum temperature showed a similar behavior with the mean temperature (Figure 7a). On an annual basis, the maximum temperature was around 30 °C in the north, increased to 35 °C in the central parts, and reached 40 °C in the south and the southwest. The lowest values were observed in January (15–25 °C) and the highest in July and August (Figure 7b), reaching 45–50 °C inland, in the southeastern regions and mainly over the Rub Al-Khali, the world's largest sand desert (see also Appendix A).



**Figure 7.** Annual mean of daily maximum temperature (**a**) and mean daily maximum temperature in July (**b**).

Similar patterns were also evident in the annual distribution of the daily minimum temperature (Figure 8a). The minimum temperature was around 15 °C in the north and reached 20 °C in the south. Furthermore, low values close to 5 °C were also traced over the mountains in the southwestern parts, while it was less than 15 °C, over the mountainous areas of Tabuk and Al Madina. The lowest values were found in January (2–5 °C) and the highest were found in July, reaching 30–35 °C in the East (Figure 8b and Appendix A).



**Figure 8.** Annual mean of daily minimum temperature (**a**) and mean daily minimum temperature in January (**b**).

It should be noted that the mean annual values of daily maximum/minimum temperatures were in good agreement with the ones derived from the observational datasets presented by Almazroui et al. [3], contrasting the overall underestimation/overestimation of the corresponding CRU values.

To further analyze the warm and cold extremes, the 5th and 95th quantiles of the temperature probability distribution function were calculated on an annual basis. Beginning with the 5th quantile (Figure 9a), the distribution was similar to the mean monthly temperature of the winter months (see Figure 6a). More specifically, it gradually decreased as the latitude increased, dropping below 10 °C in the North and even lower over the mountainous areas. In a similar way, the spatial distribution of the 95th quantile (Figure 9b) followed the spatial pattern of the mean monthly temperature, during the summer months (see Figure 6b), with values exceeding the 40 °C, along the eastern part.



Figure 9. Mean annual distribution of the (a) 5th and (b) 95th quantile of temperature at 2 m.

Consequently, the northeastern part faced higher intra-annual temperature variations, compared to the other AP regions, due to the different synoptic scale atmospheric circulation, between winter and summer. There was a cold air advection, due to the Mediterranean fronts and the Siberian air that was forced by the orography to spill southwards in winter [4]. In summer, there was a warm advection, via a secondary thermal low that formed by the extension of the Pakistan low, over Southern Iran, affecting the NE Saudi Arabia [33].

#### 3.1.2. Relative Humidity

The AP was surrounded by warm waters, a source of humid air in coastal zones, while showing high temperatures and large variations during the year. In addition, humidity played an important role in the comfort and the life quality. At the same time, the water content of the atmosphere interacted with the dust particles affecting the radiation properties and the temperature. For these reasons, relative humidity was a very significant parameter in the AP climate.

Humidity was generally low with an exception along the coasts where saturation was often reached. On an annual basis, the relative humidity was around 30%, in almost the entire region, increased to 40%–60% in the coastal areas of the Red Sea and the Arabian Gulf, and was about 40% over the eastern and northern parts (Figure 10). The relative humidity generally decreased from January to May and mainly during summer. In October, it started increasing again until December. This could be attributed to the warm seas during this time of the year.



Figure 10. Annual distribution of mean relative humidity for the period 1986–2015.

More specifically, in January, relative humidity was around 50% in almost the entire region, increased to 60% in the coastal areas of the Red Sea and the Arabian Gulf, and decreased to 40% over the desert area of Nagran. In February, the 40% relative humidity contour extended inland and covered almost the whole peninsula, except for the northeastern part, where the humidity was 50%. The coasts of the Arabian Gulf and the Southern Red Sea were also characterized by higher values of 60%. In March, the humidity further decreased to 30% in most areas, while it remained at higher levels of 60%, along the coasts. In April and May, it further decreased inland to 20% and 10%, respectively. In May, the coastal areas of Southern Red Sea experienced high values of 60%, contrary to the decrease of relative humidity along the Arabian Gulf to 40%. A similar pattern was found in June. In July, August, and September, the humidity remained low (20%) inland and increased to 40% in the East. In October, the humidity increased in general except for the central areas where it remained at 20%. In November, it continued increasing to 40% in the central region and 60% in the northern region. In December, the pattern was similar to that of January. A characteristic example of the spatial distribution of the monthly-mean relative humidity for the cold and the warm season is depicted through January and July in Figure 11, while all the monthly averages are displayed in Appendix A.



Figure 11. Mean relative humidity for the months (a) January and (b) July.

## 3.1.3. Wind Speed and Direction

Flow patterns affected the local climate of AP in multiple ways. Light winds could improve the comfort index by reducing, both, the relative humidity and the temperature. On the contrary, wind speed above a threshold value might have led to dust production through the saltation bombardment mechanism. This could cause severe problems in health and onshore/offshore constructions, as described in the introduction. In addition, the predominant wind direction on a local scale, played an important role in various social and economic sectors, including energy applications. Therefore, our analysis includes the spatial distributions of the mean wind speed, the 95th percentile of wind speed frequency distribution (Figure 12), and the prevailing wind directions over the AP (Figures 13 and 14).



**Figure 12.** Annual distribution of (**a**) mean wind speed and (**b**) wind speed of the 95th percentile at 10 m.



Figure 13. Prevailing wind speed directions from January to June (a-f).



Figure 14. Prevailing wind speed directions from July to December (a-f).

The spatial distribution of the mean annual wind speed showed that weak winds of 2-3 m/s prevailed over the whole region (Figure 12a). The highest values (of 3 m/s) were observed along the

Red Sea coast, in the western region, and along the Arabian Gulf (particularly in the northern coastal area). Higher speeds were observed over the Northern Red Sea, being attributed to the high intensity of the North Westerlies that blow during winter [34]. Furthermore, this region is frequently affected by the Mediterranean cyclonic activity in winter [35].

Following the monthly distribution of the wind speed (not shown), no remarkable intra-annual variations have been found. In February and March, the wind speed increased to 3 m/s, over almost the entire region, a pattern quite similar to the one of June and July. In September and October, the whole area was characterized by very low winds. In November, December, and January, the pattern resembled the annual one.

According to Figure 12b, the 95th percentile wind speed attained values of 8 m/s over the land and 11 m/s over the Red Sea and Arabian Gulf. Higher values were observed near the Gulfs of Aqaba and Suez, as well as near the strait in the southern part of the Red Sea and the Gulf of Aden. This was due to the wind channeling effect, observed throughout the year. There were high values of wind speed at around 16–18 m/s over the Arabian Sea and the Socotra Island, for wind blowing from the western sector, during summer (Figures 13 and 14), with mean monthly values that reached 15 m/s being more likely associated with the monsoon activity.

Figures 13 and 14 illustrate the prevailing winds on a monthly basis. It can be seen that from December to March, South Easterlies dominated over the Southern Red Sea (see Figures 13 and 14). This was due to the wind shift caused by the topography of the Southern AP. On the contrary, North Westerlies prevailed over the Northern Red Sea. The two opposing flows met in the Red Sea forming the Red Sea Convergence Zone (RSCZ) [34]. The zone of South Easterlies tended to increase from October to January, at the expense of the North Westerlies and then decreased up to May. From May to September, the North Westerlies covered the whole Red Sea (Figures 13 and 14) and replaced the South Easterlies that spread across the Southern Red Sea during winter.

The Arabian Gulf and the Eastern coast were mainly characterized by the North Westerly winds, throughout the whole year. On the contrary, the North Easterlies flow prevailed over the central regions. This was mostly due to the shift of the Shamal winds from NW to NE, over the central-south inland of the AP [36]. The southern part of the AP, across the Aden Sea, was affected by the South Easterlies in winter and the Southerlies in summer. The latter was a result of the large scale monsoonal flow. However, the southern inland of the AP was not affected due to the influence of the topography.

From November to February, the Easterlies' flow predominated over the northern areas, as a result of the monsoonal activity of the cold season. After March, this flow was replaced by a zone of the North Westerlies' flow that gradually spread across the peninsula in the summer months and reduced after October.

Over the northern regions, the North Westerlies' direction partially reflected the Shamal winds that frequently developed both in winter and summer. In winter, they mainly resulted from the intensification of a low system moving eastwards/southeastwards, out of the Eastern Mediterranean, creating a cold front, moving southeastwards along the AP [37,38]. The winds tended to be stronger behind the front, stirring up sand and dust, and producing dust and sand storms. The Shamal winds lasted for 24–36 h, producing the most widespread hazardous weather in the examined region. In summer, the Shamal winds constituted the major climatic factor for NE that were triggered and modulated by the secondary thermal low, over Southern Iran [33]. These were characterized by a higher intensity in June and July, causing sandstorms [39].

The predominant wind directions faced intra-annual and spatial variations, over the inland central regions of the AP, more likely associated with the low wind intensity, especially in summer. The wind blew from the southern or southeastern sector, from October to April, and then shifted to the northeastern sector in June and August, northeastern and northwestern in July, and northeastern and eastern in September (Figure 14).

Along the Red Sea coast, the wind direction was mostly western, throughout the whole year, accounting for the effect of the Soudan Low from October to May and the establishment of the sea

breeze. Sea breeze in the Northerly/North Westerlies direction developed in the Red Sea and penetrated 10–20 km inland [40]. The wind direction pattern was more complicated in the regions of Asir and Jizan, due to the complex terrain. The Al-Sarawa and Al-Hijaz Mountains restricted the inland propagation of the sea breeze and significantly affected the structure of the flow, while the anabatic/katabatic winds could also develop along the mountains [34]. The limited zones of the Easterlies along the eastern coast of the Saudi Arabia, from May to October, in the Arabian Gulf, could be attributed to the formation of sea breeze.

## 3.2. Trends

In this part the 30-year high resolution hindcast dataset has been adopted to provide a general overview of the spatial distribution of trends. As previously discussed in the model evaluation section, the output could be considered as reliable for such an analysis. The spatially and temporally dense dataset could provide accurate information regarding the temperature trends since 1985, even for areas that lacked observations. The main advantage of this methodology is the continuous cover of the entire area and the derivation of conclusions for areas where observations did not exist or were of reduced credibility.

The trends were calculated using the nonparametric approach by Sen [41] on the mean daily values of temperature at 2 m, along with the daily maximum and minimum temperature values. This is a robust approach that has been used in several climate studies [42–45]. The significance of the trends was tested at a 0.05 significance level using the Mann–Kendall test [46,47]. For simplicity, the results were integrated into a ten-year period.

Since the majority of previous studies approached the estimation of temperature trends in the AP, based on observational time series [3,5,6,14], in the current work, a quantification of the uncertainties, incorporated by the utilization of time series with periods of missing data, was pursued. To illustrate this, a pairing of existing observations with model estimates was performed (removing the modeled values that corresponded to missing observational data). As a next step, the trends were estimated based on observational and modeled time series (the paired ones), as well as the complete time series extracted from the entire modeling period. In numerous cases, it was found that the existence of missing values led to a bias regarding the trend calculation. A characteristic example is the case of the station 41,061, where the trend estimation based on observations, was found to be -0.972 °C/decade, and the one based on the model outcome (paired to the observational data—same missing data) was -0.985 °C/decade. These two trends were close to each other, illustrating that the model and the observations gave similar results. However, these two trends differed almost 1 °C from the one resulting from the complete modeled dataset (-0.018 °C/decade) for the same time period (The same was the case for other stations, as well, such as the st41084 with values -1.468/-1.179/0.320, respectively, the st40356with values 0.436/0.494/0.574, and more). This could be attributed to the presence of several months with missing data or the persistent lack of observational data in specific time periods, within the day. Regarding the last, an example could be that missing values during nighttime (or particular hours), for a large time-period, would affect the trend analysis (since daily mean/min/maxima values are used). It is also important to note that, in many cases, the pairing of the model values to the observational ones resulted in an outcome that lacked statistical significance. For these reasons, the analysis was based only on modeled and gridded data. The outcome of this study was also compared with other works, as it can be seen in the following paragraphs, but from a more general perspective.

The spatial distribution of the trends of mean temperature at 2 m, on an annual basis, over the AP, is presented in Figure 15. Positive trends were found over the whole AP, apart from the southwestern edge of Oman, where low negative values were found, which were not, however, statistically significant. The warming trend varied between 0.1 and 0.4 °C/decade, over the major part of the examined area and increased with latitude, reaching values of 0.6 °C/decade over the northern part. There, the trends were found to be statistically significant, suggesting that the warming had mostly affected areas characterized by lower average temperatures, compared to the rest of the AP and the passage of

organized synoptic systems. Similar behavior was evident over the Red Sea. The northern parts experienced higher trend values, compared to the South. Small and even negative trends were evident over the lee sides of the mountains, along the western side and along the coastal areas of the Red Sea. On the contrary, the trend increased over the mountains where the mean temperature decreased.



Figure 15. Mean temperature change per 10 years (yrs).

These results were in general agreement with previous works that estimated the temperature changes in AP, based on observations. Islam et al. [14] found an overall trend of 0.73 °C/decade during the period 1981–2010, which was higher in spring and summer, employing 27 stations. Furthermore, AlSarmi and Washington [6] demonstrated higher values, compared to this study, along the eastern coast, using data from 20 stations. At the same time, there is a well-known slowdown in the global warming trend after 2000 [48–51]. This is the reason why an additional analysis was performed in order to examine the potential impact on the study area. However, in this case, there was no clear evidence of such behavior.

Other than discussions on the mean values, it was quite interesting to analyze the trend behavior of the maximum and minimum temperatures, since a possible increase of the upper tail of the temperature probability distribution could mean more intense and frequent extreme events. Towards this direction, a trend analysis for the daily maximum and minimum values was performed (Figures 16 and 17), following the same methodology as with the mean temperatures.



Figure 16. Daily maximum temperature change per 10 years (yrs).

Concerning the maximum temperatures (Figure 16), an overall warming was found over the whole examined region. The trends were found to be slightly greater, compared to the mean temperature ones. The spatial pattern of the trend values regarding the maximum temperature was similar to the one of the mean (Figure 15). In the North, an increase greater than 0.5 °C/decade was evident, while the rest of the regions experienced values in excess of 0.25 °C/decade. The eastern part of the Southern AP was characterized by statistically non-significant trend values. The warming trend of maximum temperatures, compared well with the increasing trend of hot extremes, as demonstrated by Almazroui et al. [13].

The minimum temperature appeared to also have positive trend values, that were, however, smaller than those of the mean and maximum temperature. Furthermore, the increasing trend of the modeled minimum temperature was consistent with the increasing trend calculated by Almazroui et al. [13], despite the fact that the values were higher. The southern part of the region did not face any significant changes, while for the near shore areas, a small statistically non-significant decrease was evident. The spatial distribution of the minimum temperature resembled those of the mean and maximum temperatures. One major difference between them was the large positive values found along the Red Sea coast and mainly over the mountain range of Al Sarawat in the South, reaching 0.4 and 0.6 °C, respectively.



Figure 17. Daily minimum temperature change per 10 years (yrs).

## 4. Conclusions

The limited surface observational datasets for most of the AP was a major drawback in performing a detailed regional climatological analysis. To overcome this, within the current study, the regional climatology of the area was investigated, employing a state-of-the art atmospheric model, with a high resolution of 9 km and a temporal one of 3 h for 30 years. This study was focused on analyzing the climatological patterns of three basic meteorological parameters, temperature, relative humidity, and wind speed.

For the analysis, a regional scale model was used with features that are necessary to describe the role and include the impact of desert dust, through its direct, semi-direct, and indirect effects. The modeled meteorological parameters have been organized in a database, with a high spatial and temporal resolution, which allowed a fast and effective statistical analysis. This database is also available for the extraction and statistical analysis of parameters that were not included within this publication.

The atmospheric model simulated the spatial and temporal variations of climatic parameters over AP, showing a more reliable and detailed behavior, as compared to previous results of the regional climatic models. The mean and extreme temperature distribution was efficiently captured, depicting small-scale patterns, as well as intra-annual variations associated with topographical effects. Despite

the fact that the wind speed was low in general, the model succeeded in simulating the prevailing wind direction and local wind flows, such as the Shamal winds and the sea breeze.

The model results represented the spatiotemporal variability of mean temperature in an accurate way. In the southeastern part of the AP, the temperature was found to be around 30 °C and decreased northwards, reaching 20 °C, over the North. The highest value was found to be over the desert area of Rub Al Khali, while the lower ones were found to be in the mountainous areas in the Southeast. During the cold period of the year (December, January, and February), the low values in the North were attributed to the cold invasions from the northeast, due to the Siberian high, the passage of the Mediterranean systems and the Shamal winds. From June to September, most of the examined area experienced temperatures of 35–40 °C. Along the Red Sea and the Arabian Gulf coasts, the temperature was lower, due to the North Westerlies, which covered the whole Red Sea and the effect of the sea breeze. The spatial distribution of the annual mean of daily maximum/minimum temperatures, followed the mean temperature during summer/winter.

Relative humidity was generally greater during winter, with peak values in December and January. The lowest values were found during the summer season. In July, August, and September, the humidity remained low inland (20%) and increased in the East.

Weak mean winds of 2–3 m/s prevailed, while the stronger ones were observed over the specific regions. The 95th percentile showed even higher values, overseas, and specifically over the Gulf of Aden and the islands of Socotra, suggesting possible exploitation for renewable energy applications. Concerning the prevailing directions from December to March, South Easterlies dominated over the Southern Red Sea and North Westerlies dominated the northern parts. Over the northern regions of AP, the North Westerlies' direction partially reflected the Shamal winds that frequently develop both in winter and summer. In winter, the Shamal winds blew towards southeast AP, stirring up sand and dust and producing dust and storms. The summer Shamal winds blew over the area with higher intensity in June and July, causing advection and rising of the sand, restricting visibility.

Positive temperature trends with values between 0.1 and 0.4 °C/decade were dominant in the AP. The warming trends decreased towards the south. Smaller and even negative trends were evident over the lee sides of the mountains and in the coastal areas in the South that were non-significant in most cases. Similar spatial patterns were found for the daily maximum temperature, with slightly greater values. The trends for the daily minimum temperature were also positive with lower values as compared to the mean and maximum temperature. An interesting feature was the higher warming trends of the minimum temperature, along the mountainous regions of the southeastern region, along the Red sea, suggesting a decrease of the cold extremes.

The aforementioned changes affected large parts of the population and had different socioeconomic implications. Therefore, the examination of the behavior of other parameters, as well, could provide additional information, which, combined with the current study, might lead to significant findings and a more robust approach to the changes that might affect the area in the forthcoming years. The modeled climatological patterns of precipitation, soil moisture at various depths, and the dust concentration and load over AP, were also derived and should be discussed in separate future studies.

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## Appendix A



Figure A1. Mean 2 m Temperature for the months January to June (a–f).



Figure A2. Mean 2 m Temperature for the months July to December (**a**–**f**).



Figure A3. Mean values of daily maximum temperature for the months January to June (a–f).



Figure A4. Mean values of daily maximum temperature for the months July to December (a-f).



Figure A5. Mean values of daily minimum temperature for the months January to June (a–f).



Figure A6. Mean values of daily minimum temperature for the months July to December (a-f).



Figure A7. Mean relative humidity for the months January to June (**a**–**f**).



Figure A8. Mean relative humidity for the months July to December (a–f).

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