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Assessing Drought Patterns in Al-Baha: Implications for Water Resources and Climate Adaptation

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Abstract: Due to growing water demands and changing hydro-meteorological variables brought on by climate change, drought is becoming an increasingly serious climate concern. The Al-Baha region of Saudi Arabia is the subject of this study because it is susceptible to both agricultural and meteorological droughts. This study investigates how climate change affects patterns of drought in Al-Baha by analyzing four drought indices (Agricultural Standardized Precipitation Index (aSPI), the Standardized Precipitation Index (SPI), the Rainfall Deficiency Index (RDI), and the Effective Reconnaissance Drought Index (eRDI)) for the years 1991–2022. Analysis of rainfall data was carried out to classify drought events according to their duration, frequency, and severity. Results showed that severe droughts occurred in 2009, 2010, 2012, 2016, and 2022, with 2010 being the worst year. Results also indicated a notable decrease in precipitation, which has resulted in extended dry spells. Several indices indicate that this tendency has significant ramifications for agriculture, particularly in areas where farming is a major economic activity. In addition, the possible occurrence of hydrological drought was also observed based on the negative values for the Reservoir Storage Index (RSI) in Al-Baha. Projections for the future under two Representative Concentration Pathways (RCPs) showed notable variations in temperature and precipitation. Both the RCP4.5 (low emission) and the RCP8.5 (high emission) projection scenarios indicate that drought conditions will likely worsen further. Depending on the emission scenario, it is projected to show a temperature increase of 1–2 °C, whereas the variability in precipitation projections indicates significant uncertainty, with a reduction change in the range of 1.2–27% between 2050 and 2100. The findings highlight the urgent need for proactive adaptation strategies, effective water resource management, and the development of sophisticated drought prediction tools. Addressing these challenges is crucial for sustaining agriculture and managing water scarcity in Saudi Arabia in the face of increasing drought risk.

Keywords: climate change; drought indices; temperature increase; rainfall variability; water scarcity; future projections; drought management; Al-Baha; arid regions

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1. Introduction

Climate change represents a grave global concern, permeating all aspects of human existence [1,2]. The available evidence indicates that the ongoing shifts in the climate will lead to global warming and altered precipitation patterns. It is projected that the Earth's average temperatures could rise by a range of 1.4 to 5.8 °C by the close of the 21st century [3]. These changes are expected to trigger variations in seasonal water availability, particularly impacting various certain regions [4]. Moreover, there is a forecast of heightened frequency and intensity of extreme weather events such as droughts and floods, particularly in less resilient and less-prepared regions, especially in developing nations [5].

Among many climate change effects, drought dynamics have become a serious worry, especially in arid and semi-arid areas where a lack of water poses a threat to both agricultural output and ecological stability. Several intricately interacting climatic factors, including temperature and precipitation patterns affect the dynamics of drought. To ensure sustainable water resources and food security in vulnerable areas, it is imperative that mitigation and adaptation measures be developed with a thorough understanding of these dynamics.

The hydrological cycle and climate change are inextricably linked, which presents serious obstacles to global water security [6]. Changes in precipitation patterns are anticipated as a result of greenhouse gas emissions contributing to global warming, which will affect the quantity and quality of water. The effects of these changes are most noticeable in subtropical regions at lower latitudes, where freshwater resources are already scarce and are threatened by less precipitation, increased temperatures, and increased evapotranspiration. Water scarcity is therefore becoming a serious issue that is endangering human health and welfare due to lowered water quality and elevated disease risks [7,8].

Significant climate variability has been recorded in Saudi Arabia, highlighting the need for a more thorough understanding of the localized effects of these changes [9,10]. Saudi Arabia's climate is mostly dry with little precipitation, yet there are significant differences in the weather and climate parameters in various parts of the Kingdom [11–13]. Comprehending these fluctuations is crucial for efficacious management approaches, particularly considering the Kingdom's persistent struggles with land degradation, food security, and water scarcity, all of which are intensified by climate change [14].

One of the most important threats in the Kingdom of Saudi Arabia (KSA) is drought. Arid regions are particularly susceptible to drought due to their reliance on a few significant rainfall events. The connection between droughts and its development is complex. When droughts strike, millions of people face food scarcity [7]. Drought arises from a natural decline in precipitation levels over an extended period, typically a season or more, often compounded by other climatic factors like high temperatures, strong winds, and low humidity, which can escalate its severity. Drought represents an extreme weather event characterized by a deficit in precipitation compared to the long-term average, resulting in water scarcity [8].

From a range of scientific viewpoints, four distinct categories of droughts have been delineated: meteorological, agricultural, hydrological, and socioeconomic droughts [9]. Meteorological drought refers to a lack of precipitation over an extended period, leading to overall dry conditions. When soil moisture inadequacy adversely impacts specific agricultural crops due to drought, it is termed agricultural drought [10]. Hydrological drought is related to reduced water supply in rivers, reservoirs, and groundwater, while socioeconomic drought emerges when water shortages start affecting society and the economy. Drought, being the most intricate of natural hazards, affects more individuals than any other calamity [11,12]. Its occurrence spans most parts of the globe, even in humid regions, as drought is defined relative to the local normal condition. Therefore, recognizing and addressing droughts is crucial for integrated and efficient management strategies. Effective management strategies to mitigate the negative impacts of droughts and rapid transitions necessitate the ability to forecast droughts at various time scales. Emergency response planning and early warnings rely on drought forecasts spanning from hourly to seasonal scales [13,14].

To estimate drought likelihood for specific return periods, a prevalent method involves fitting a generalized extreme value distribution to the annual minima or maxima of temperature and rainfall records [15]. For projecting future hydrological extremes, potential approaches encompass driving a hydrological model with meteorological data from a global/regional circulation model [16,17] or utilizing hybrid statistical–dynamical techniques, incorporating projections as covariates within a statistical modeling framework [18]. In simple scenarios, forecasts, predictions, and projections are developed for a single type of extreme event (droughts or floods) based on an observed or simulated time series, which is focused on a single catchment and current flow conditions. However, the challenge of prediction becomes more intricate when there are numerous cases. Two critical parameters in drought monitoring are precipitation and evapotranspiration [19]. Precipitation, a complex natural phenomenon in the hydrological cycle, exhibits substantial geographical and temporal diversity. Ensuring precise and accurate precipitation measurement is crucial. It forms a fundamental basis for climate change prediction, environmental research, water resource assessment, and the monitoring of hydrological extremes like droughts and flood forecasts.

Al-Baha is a major agricultural region located in the southwest of the Kingdom of Saudi Arabia (KSA). Due to its dry climate, which is characterized by high temperatures and little precipitation, the area is especially vulnerable to drought. In Al-Baha, droughts can trigger severe societal, ecological, and economic repercussions. The Al-Baha region is experiencing a steady rise in temperature alongside a notable decrease in precipitation rates. Between the years 1995 and 2019, the region saw an average temperature increase ranging from 1.1 to 1.6 °C, coupled with a decline in annual rainfall ranging from 24% to 41% [20]. Therefore, there is a necessity of localized research in regions like Al-Baha to develop effective adaptation strategies in response to evolving climate conditions, ultimately supporting sustainable water management and agricultural practices.

To the best of our knowledge, there are no comprehensive studies on the long-term effects of climate change on drought patterns in the Al-Baha region, KSA. Gaps in knowledge still exist in terms of effectively translating well-acknowledged climate change models and projections into actionable insights for understanding and mitigating drought impacts. The purpose of this research was to close important knowledge gaps about how drought patterns in Saudi Arabia's Al-Baha region are affected over the long term by climate change. To accomplish this goal, this study analyzed drought indicators and evaluated past, current, and projected drought scenarios. The specific research objectives were to: (1) assess the historical patterns of drought in the Al-Baha region; (2) evaluate current patterns of meteorological, agricultural, and hydrological droughts in the Al-Baha region; and (3) predict future drought conditions under different emission scenarios by the year 2100 in the Al-Baha region.

2. Materials and Methods

2.1. Description of the Study Area

The Al-Baha region lies within the latitudinal range of 19°27′17″ to 20°49′75″ N and longitudinal range of 40°46′30″ to 42°10′10″ E, covering a total area of 11,221 km^2, with an altitude of 1655 m above sea level (Figure 1). It encompasses six administrative areas (Al-Mkhwah, Al-Aqiq, Al-Mandq, Belgrashi, Qolwah, and Al-Qora) in addition to the city of Al-Baha.

The geological features of the Al-Baha region, particularly its location within the Arabian Shield with a crystalline basement overlaid by basalts [21], are important for understanding droughts. These formations influence groundwater recharge, surface water flow, and soil water retention, all of which affect water availability during dry periods. Therefore, the region's geology is a significant factor in determining its vulnerability to drought.

The region experiences a range of temperatures from warm to cold during winter and moderate to hot during summer, with mean annual temperatures spanning from 12 °C to 23 °C. Annual precipitation averages between 150 and 200 mm, with humidity levels typically falling between 50% and 70% [22,23]. The highest recorded temperature at Al-Baha weather station is 25.19 °C, indicating that the area can experience significant heat, especially during summer months. The lowest temperature recorded is 21.49 °C, which suggests mild nights, especially considering the high altitude. The average temperature is 23.24 °C, reflecting a generally warm climate throughout the year.

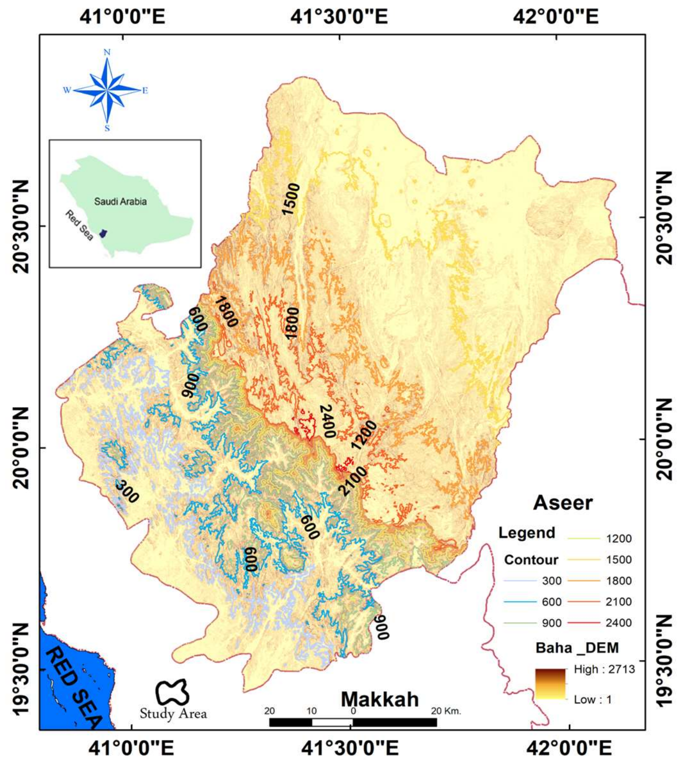

Figure 1. Digital elevation model of 30 m obtained from the Shuttle Radar Topography Mission for the Al-Baha region.

The highest relative humidity is 97.97%, indicating very humid conditions at certain times, likely during cooler periods or when there is significant moisture in the air. The lowest relative humidity is 10.06%, which suggests very dry conditions, likely during the hottest parts of the day. The average relative humidity is 35.07%, showing that, on average, the air is moderately dry, which is typical for many high-altitude, arid, or semi-arid regions.

The Al-Baha weather station recorded an average annual rainfall of 120.9 mm (1991–2022), which is relatively low, confirming that Al-Baha is an arid to semi-arid region. This limited rainfall underscores the importance of understanding drought conditions and their impact on the environment and agriculture in the area. The mean wind speed was 7.52 m s^{-1}, indicating moderate winds, which can influence local weather patterns and potentially exacerbate conditions like wind erosion or dry spells.

2.2. Collection of Historical Climatic Data

The dataset utilized for this study consisted of rainfall and temperature records spanning the time interval from 1991 to 2022, as sourced from the General Authority of Meteorology and Environmental Protection (GAMEP). The choice of this thirty-year time series allows for a comprehensive analysis of long-term trends while balancing the need for sufficient data points. The time intervals selected for evaluation (e.g., ten-year intervals) were intended to provide a clear understanding of trends over short and long-time intervals, and to facilitate an effective visualization of the results. To ensure the reliability and consistency of the dataset, a quality control procedure was administered, following the guidelines outlined by Almazroui et al. [24]. This involved implementing a constancy check to address potential factors that could introduce heterogeneity into the dataset, including station relocations, instrument upgrades, and shifts in the surrounding environment. By undergoing this quality control test, the rainfall dataset was validated and standardized for further analysis.

2.3. Climatic Data Analysis

The research methodology comprised several stages, beginning with the collection and analysis of historical climate data for Al-Baha, covering the years 1991 to 2022. This dataset included critical information on temperature, precipitation, humidity, and other relevant climate variables. Following data collection, a detailed analysis of drought conditions was conducted, focusing on climatic drought (e.g., rainfall deficits), hydrological drought (e.g., groundwater levels), and agricultural drought (e.g., crop yield and soil moisture).

For the drought assessment, the Reservoir Storage Index (RSI) was used to evaluate hydrological drought based on groundwater levels, and index-based approaches were employed to assess climatic and agricultural drought impacts. The methods also included the use of the Mann–Kendall test as a statistical analysis technique to detect trends, anomalies, and significant deviations from normal conditions.

The USDA's Agricultural Research Service developed the Soil and Water Assessment Tool (SWAT) hydrological model, which this study used to simulate water balance components such as precipitation, percolation, and soil moisture storage [25]. The analysis focused on the identification of drought types (climatic, hydrological, or agricultural) and the determination of the most affected locations in the Al-Baha region, with particular attention to the severity and duration of the drought events. The trend analysis techniques used in this study include the Mann–Kendall test.

Finally, the study projected future drought conditions for Al-Baha up to the year 2100, considering potential impacts of meteorological, agricultural, and hydrological droughts, based on the data and analysis conducted.

2.4. Drought Indices

A large number of drought indices have been proposed, each designed to quantify and characterize different aspects of drought. These indices cover various types of droughts, including meteorological, agricultural, and hydrological droughts. Some drought indices are operational tools used to characterize drought conditions at regional and national levels. They provide valuable information for drought early warning systems, monitoring, and contingency planning. Drought indices are designed to quantify the severity of drought events, enabling comparisons across different periods and locations. They can help identify the onset and end of drought episodes. The presence of a wide array of methods for drought mapping and monitoring, coupled with the existence of over 100 different drought indicators [26,27], poses a considerable challenge when it comes to selecting the most suitable indicator for a specific region or situation.

2.5. Selecting the Best Drought Indices for Drought Assessment in Al-Baha

Drought indices quantify drought severity, aiding in the comparison of events across different times and places. As our understanding of drought and data collection improves, these indices evolve to remain relevant for effective drought characterization. Four indices were selected for assessing Al-Baha's drought patterns: the Standardized Precipitation Index (SPI), the Agricultural Standardized Precipitation Index (aSPI), the Reconnaissance Drought Index (RDI), and the Effective Reconnaissance Drought Index (eRDI). These indices provide varied insights into drought conditions. Additionally, the Reservoir Storage Index (RSI), a key hydrological drought index, was calculated for the region based on available data.

2.5.1. The Standardized Precipitation Index

By measuring precipitation deficits in comparison to a long-term average, the SPI is frequently used to evaluate meteorological droughts. Understanding precipitation patterns over different time periods is extremely important, especially in dry locations like Al-Baha where rainfall variability is substantial. The SPI is a widely recognized index, employed globally to identify historical drought events [28,29]. It is distinct from other drought indicators in that it uses negative values to denote drought and positive values for wet conditions. The SPI quantifies how unusual the observed precipitation is compared to the long-term historical record for a specific location and time scale. It is often used to identify meteorological drought based on precipitation deficits. SPI focuses solely on precipitation data and provides a standardized measure of how current precipitation levels compare to the long-term average for a specific location and time period. The equation for SPI is typically computed as follows [30]:

$$SPI = \frac{P - P_m}{\sigma} \tag{1}$$

where P is the seasonal precipitation (mm), Pm is the mean precipitation over a selected period (e.g., months, years) for the same location, and σ is the standard deviation of precipitation over the same period.

2.5.2. The Agricultural Standardized Precipitation Index

The SPI can be determined relatively easily as it is based on precipitation data; however, the index does not take into account differences in evaporative demand or soil moisture storage [30,31]. Therefore, the aSPI, which is an agricultural drought index, was used to assess and monitor drought conditions specifically in the context of agriculture practices in Al-Baha. This was achieved by replacing total precipitation with effective precipitation, which describes more accurately the amount of water that can be effectively used by plants. The aSPI measures deviations in current rainfall from the long-term average, standardizing the values to facilitate comparison and analysis of drought conditions over time and across regions. Effective rainfall (ER) refers to the amount of water required for crop cultivation without external water support [32]. Designed with agricultural contexts in mind, the aSPI gauges the intensity of drought by examining how precipitation affects crop productivity. By directly connecting climatic conditions to agricultural outputs, this indicator contributes to the understanding of food security in the Al-Baha region. The aSPI is particularly valuable for assessing and monitoring agricultural drought because it specifically considers the impact of precipitation deficits on crops and vegetation. Calculation of the aSPI was carried out by the transformation of a proper statistical distribution fitted to a time series of effective precipitation into a normal distribution using the equation [32]:

$$aSPI = t - \frac{C_0 + C_1 t + C_2 t^2}{1 + d_1 t + d_2 t^2 + d_3 t^3} \qquad 0.5 < H(x) \leq 1.0 \tag{2}$$

and

$$t = \sqrt{ln\left(1/\left[1 - H(x)^2\right]\right)} \tag{3}$$

where x is the effective precipitation value, t is the transformed value of effective precipitation (calculated as (x/β), where β is a scale parameter, and both x and β are >0), and $H(x)$ is the probability function of effective precipitation. The parameters C_0, C_1, C_2, d_1, d_2, and d_3, are fitting parameters that are equal to: 2.515517, 0.802853, 0.010328, 1.43278, 0.189269, and 0.001308, respectively.

2.5.3. The Reconnaissance Drought Index

The RDI, which is a drought index used to assess the severity and extent of drought conditions based on rainfall data was also assessed in this study. The RDI focuses on the amount of rainfall that is deficient relative to the required amount for specific crops, making it particularly useful for agricultural drought assessment. Its application in this study allows for a clear understanding of how drought conditions affect agricultural productivity in the Al-Baha region. RDI quantifies the deficit between actual rainfall and a reference (typically historical) rainfall, allowing for the measurement of drought severity over a given area or region [33]. RDI values are typically expressed in numerical numbers where greater values indicate that the area has received more rainfall than the reference period, and lower values indicate a rainfall deficit, which is indicative of drought conditions. Lower RDI values imply more severe drought conditions. The RDI is calculated in three stages as outlined by Tsakiris et al. [33]: First, the initial RDI (RDI_0) is calculated for the i^{th} year based on the ratio of the sum of precipitation (P) to potential evapotranspiration (PET) over a 12-month period (j) for each hydrological year. Second, the normalized RDI (RDIn) is calculated. Finally, the standardized RDI (RDIst) is computed using the following formula:

$$\mathrm{RDIst(i)} = \frac{\left(\mathrm{y(i)} - y^{\backslash}\right)}{\sigma \mathrm{y}} \quad (4)$$

where $y(i) = \ln(RDI_0(i))$; $y^{\backslash}$ is the arithmetic mean of y(i); σy is the standard deviation of y(i).

2.5.4. The Effective Reconnaissance Drought Index

In a similar manner, the Effective Reconnaissance Drought Index (eRDI) was also calculated based on the amount of effective rainfall. eRDI is a useful tool for evaluating hydrological drought conditions because it takes temperature and precipitation into account. This is especially crucial in Al-Baha since the effects of insufficient precipitation are made worse by rising temperatures.

The Drought Indices Calculator (DrinC) software (version 1.7 (97)), was used for the calculation of the four drought indices (SPI, aSPI, RDI and eRDI), and for the assessment of drought occurrence based on the outcome values of the drought indices [34,35]. The DrinC software is extensively utilized for research on droughts all around the world as it offers a straightforward approach to determining drought occurrence and impact. The SPI, aSPI, RDI and eRDI index values were categorized as listed in Table 1 [34,35].

Table 1. Values for the drought categories based on the different drought indices.

Drought Category	Index Values *
Extreme wet	≥2.00
Severe wet	1.50 to 1.99
Moderate wet	1.00 to 1.49
Mild wet	0.50 to 0.99
Normal conditions	−0.49 to 0.49
Mild drought	−0.50 to −0.99
Moderate drought	−1.00 to −1.49
Severe drought	−1.50 to −1.99
Extreme drought	≤−2.00

* Average index values for the indices SPI, aSPI, RDI, and eRDI.

2.5.5. The Reservoir Storage Index

The RSI is considered a crucial indicator in assessing hydrological drought, which is an essential aspect of water resource risk management. Hydrological drought indices focus on the impact of drought on water resources and the hydrological cycle, considering factors such as groundwater levels, reservoir storage, and other hydrological variables.

The RSI provides valuable information about the availability of water for various uses, including agriculture, and drinking water. As continuous climatic drought may eventually lead to hydrological drought, there is conceptual value in linking climatic and hydrological droughts when attempting to predict the latter, as most impacts of droughts stem from hydrological droughts [30]. The equation for RSI is typically computed as follows [36]:

$$RSI = \frac{V - V_m}{\sigma} \quad (5)$$

where V is the current water volume in the reservoir, V_m, is the mean water volume in the reservoir for the same record period, and σ is the standard deviation of water volume in the reservoir for the same record period. The RSI values are categorized as listed in Table 2 [34,35].

Table 2. Values for the categories of the Reservoir Storage Index (RSI).

RSI Category	Index Values
Extremely low groundwater storage	0–10
Very low groundwater storage	11–20
Moderately low groundwater storage	21–30
Near-normal groundwater storage	31–40
Moderately high groundwater storage	41–60
Very high groundwater storage	61–70
Extremely high groundwater storage	>70

2.6. Climate Change and Future Drought Scenarios in Al-Baha, Saudi Arabia

Climate change may alter the frequency and severity of droughts. This study examines future drought scenarios in Al-Baha based on precipitation anomalies from Global Climate Models (GCMs). Two Representative Concentration Pathways (RCP4.5 and RCP8.5) were used to compare present and future drought conditions, with projections spanning 2022–2100.

We utilized observed and bias-corrected precipitation and temperature data for the reference period (1991–2022) and future projections. The data underwent dynamic downscaling and linear transformation to align GCM outputs with local meteorological stations. Bias correction methods, including quantile mapping, were applied to improve model accuracy.

The GCMs from the Coupled Model Intercomparison Project Phase 5 (CMIP5) and the Weather Research and Forecasting (WRF) model were used to project future climate under RCP4.5 and RCP8.5 for the periods 2022–2050 and 2050–2100. These projections were then compared with the reference period data to assess changes in temperature and rainfall patterns [37].

2.7. Quality Control, Validation, and Statistics Methods

Strict quality control methods were applied to the gathered data to identify and correct any missing values or inconsistencies. This process included data validation, where the accuracy of the obtained data was verified by cross-referencing it with different sources. Missing data in the temperature and precipitation records were treated using statistical techniques such as moving averages and linear interpolation to ensure continuity in the time series. Additionally, outlier detection was performed by examining data distributions to identify and eliminate outliers that could distort the findings, using techniques such as the Z-score approach to measure deviations from the mean.

After processing, the data were analyzed using various statistical tools to calculate the drought indices. The consistency of the methodology was maintained by applying established formulas for each specific drought indicator. Temporal analysis was conducted to provide a comprehensive examination of drought trends, aggregating the data into monthly, seasonal, and annual periods. Furthermore, correlation analysis was employed to explore the relationships between drought indices and agricultural output, offering insights into how drought conditions affect crop yields.

The performance of the Global Climate Models (GCMs) was validated using statistical measures, such as correlation coefficients and root-mean-square errors (RMSE), to assess the accuracy of their outputs compared to historical climate data. The GCM models showed a reasonable level of accuracy in reproducing the historical climate patterns, particularly for key variables such as precipitation and temperature, which are critical for calculating drought indices. This validation process demonstrated a good fit between model outputs and observed data, providing confidence in using these models to project future changes in precipitation and temperature under the selected RCP scenarios (RCP4.5 and RCP8.5).

3. Results and Discussion

3.1. Annual Rainfall and Temperature Distribution and Trends (1991–2022)

The annual rainfall distribution across Al-Baha, KSA showed that the mean annual rainfall in Al-Baha over the 31 years from 1991 to 2022 varies from 256.1 mm year^{-1} in 1998 to 23.6 mm year^{-1} in 2009 (Figure 2A). Examining annual rainfall and its fluctuations holds great significance for devising approaches to water balance and conservation. The coastal region of Al Baha is influenced by Indian Ocean monsoons occurring typically between October and March, resulting in an annual occasional rainfall of up to 300 mm year^{-1}. Over the past 31 years, April experiences the greatest variability in precipitation compared to other months, with a standard deviation of 29.09 mm, while September has the lowest variability with a standard deviation of 1.77 mm, (Figure 2B). The year 2021 ranked as the fifth driest year, while 2007 marked the driest year in terms of annual precipitation and 1997 stood as the wettest year.

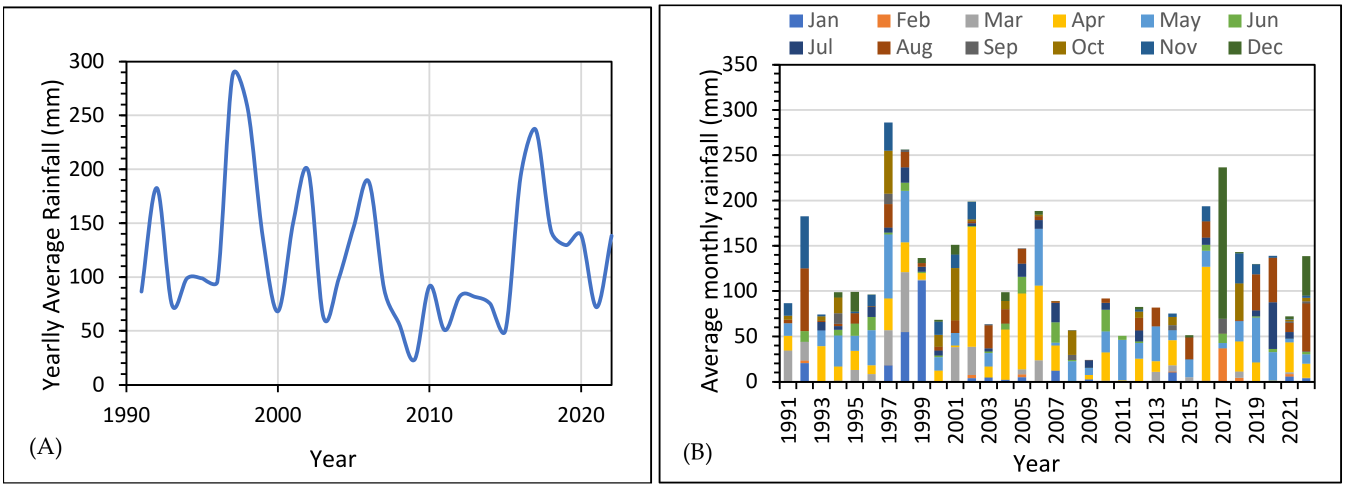

Figure 2. Long-term average annual, (**A**); and monthly, (**B**) rainfall across Al-Baha, KSA from 1991 to 2022, sourced from the General Authority of Meteorology and Environmental Protection (GAMEP).

Rainfall patterns within Al-Baha exhibit noteworthy variations both within a single month and across different months. Throughout the examined timeframe, the northern part of the region experienced its heaviest rainfall between November and April, a period of crucial significance for bolstering groundwater reservoirs and supporting the agricultural sector in that area, as rainwater harvesting stands as the primary mechanism for recharging groundwater in this region.

On a monthly scale, the analysis also revealed that there are variations in the magnitudes of slopes among different warm months. Slope refers to the rate of change in monthly rainfall over time, calculated from linear regression analysis of the rainfall data for each month across the years 1991 to 2022. A positive slope indicates an increasing trend in rainfall during that month, while a negative slope indicates a decreasing trend. The variations in slope magnitudes among different warm months suggest that the extent of change in rainfall is not uniform and can differ significantly. These months exhibit differing trend magnitudes and even have varying slope directions (positive or negative), which helps us understand how rainfall patterns are shifting across these months. Consequently, the use of a monthly time scale would obscure the distinctions evident in the individual monthly data. Specifically, the variations in rainfall patterns we observed can interact with temperature changes, highlighting how climate change may exacerbate hot weather events, particularly during the nighttime hours in Al-Baha. Our findings align with studies of Pattnayak [38], indicating that the assessment of rainfall variations over time is crucial for the understanding of changes in weather patterns and their impact. By analyzing trends over the longer term and incorporating findings from other research, we aim to provide a more comprehensive understanding of climate impacts in the Al-Baha region.

Average rainfall statistics were evaluated at ten-year intervals from 1991 to 2022, as shown in Figure 3. The intervals were selected to allow for clear comparisons over time and to align with standard temporal analysis practices. Between 2001 and 2010, a noticeable decrease in the average rainfall was observed, while from 2011 to 2022, a slight increase in rainfall occurred. This approach ensures consistency in evaluating the trends across the full period of analysis. The data indicates some variety in rainfall patterns as it clearly shows a drop throughout the first several periods and a slight comeback in the last period. The decrease might point to a trend toward drier weather, which could influence agriculture and water supplies. The slightly observed increase in the last time period can be an indication of differences brought on by other climate causes or a return to heavier rainfall.

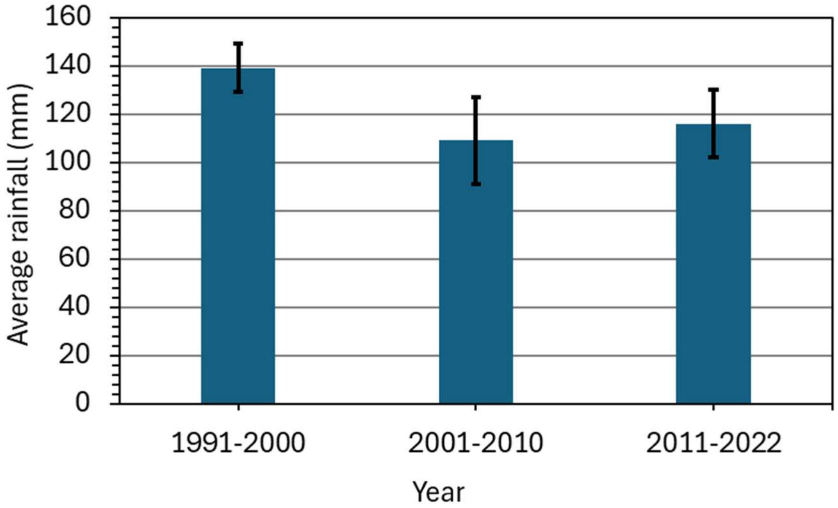

Figure 3. Average yearly rainfall trends for different ten-year intervals from 1991–2022 in the Al-Baha region. Error bars represent the standard deviation of average rainfall for each time interval. Sourced from the General Authority of Meteorology and Environmental Protection (GAMEP).

The maximum monthly mean temperatures were recorded in July 2021 and July 2022, at 31.1 °C and 31.2 °C, respectively. The minimum monthly mean temperature was observed in January 1992, at 13.5 °C (Figure 4A,B). Generally, July tends to have the highest temperatures across the years, while January consistently shows the lowest.

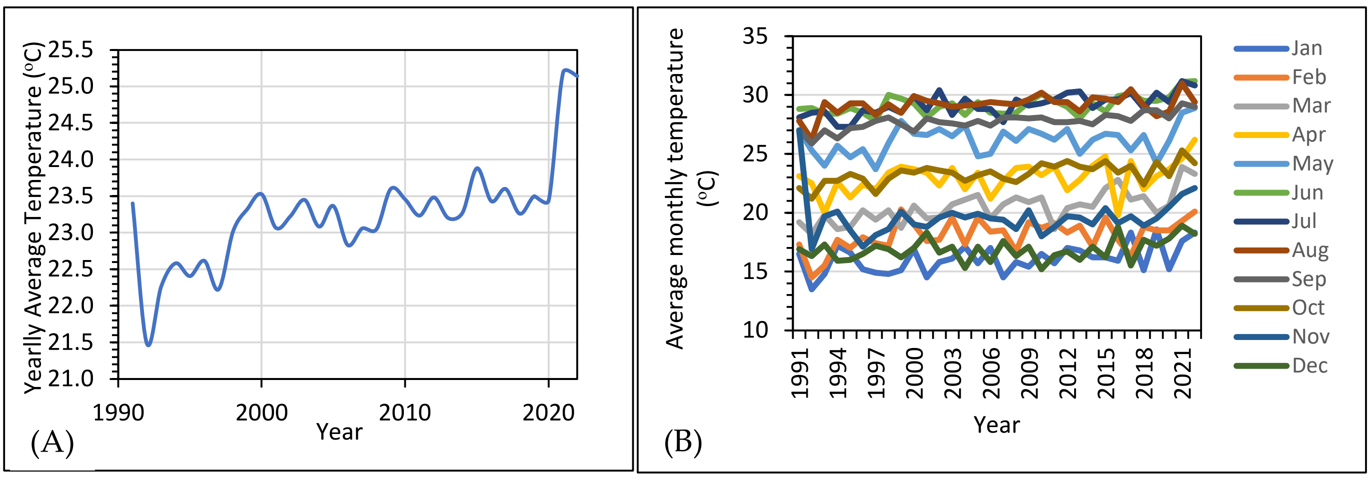

Figure 4. Average annual, (**A**); and monthly, (**B**) temperature distribution from January to December for the years 1991–2022 in the Al-Baha region, sourced from the General Authority of Meteorology and Environmental Protection (GAMEP).

The lowest average temperature mentioned in the text refers to the seasonal average temperature. Specifically, for the spring season of 2021 (March to May), the average temperature was 26.6 °C, which was 1.3 °C above the normal rate. This increase was primarily driven by higher-than-normal temperatures recorded in March, where temperatures exceeded the usual range by 2.7 °C. The year 2021 witnessed a rise in the number of warm days and a significant decline in cold nights compared to historical norms. This trend has also been observed in several years preceding the year 2021, indicating a consistent pattern of gradual reduction in the number of cold nights.

The average temperatures for ten-year intervals between 1991 and 2022 are displayed in Figure 5. These intervals were chosen to facilitate clear comparisons and align with standard temporal analysis practices. Over the specified periods, the average temperature shows a generally increasing trend. This implies that throughout these decades, temperatures have been rising on average. An increase of approximately 1.0 °C exists between the intervals. Climate data may exhibit frequent variations in this type because of natural variability, volcanic activity, and El Niño/La Niña events. The average temperature increased by almost 1.0 °C from the first period to the final, suggesting a steady pace of temperature rise. The average temperature is trending upward, which might be a sign of more significant climate change. There could be a number of effects on ecosystems, weather patterns, and human activity if this trend keeps up. The data showed a distinct warming trend during the studied periods, which is consistent with more general scientific findings of rising global temperatures as a result of climate change. The importance of climate dynamics is emphasized by recent research, especially in light of the rise in global temperatures linked to climate change. Our results are consistent with Awasthi [39], who found that studies using CMIP6 models on North Indian states show how temperature behavior under 1.5 °C and 2 °C warming scenarios can intensify extreme heat occurrences. These studies indicate a significant increase in temperature compared to preindustrial levels, aligning with our findings on the projected temperature increases in the Al-Baha region.

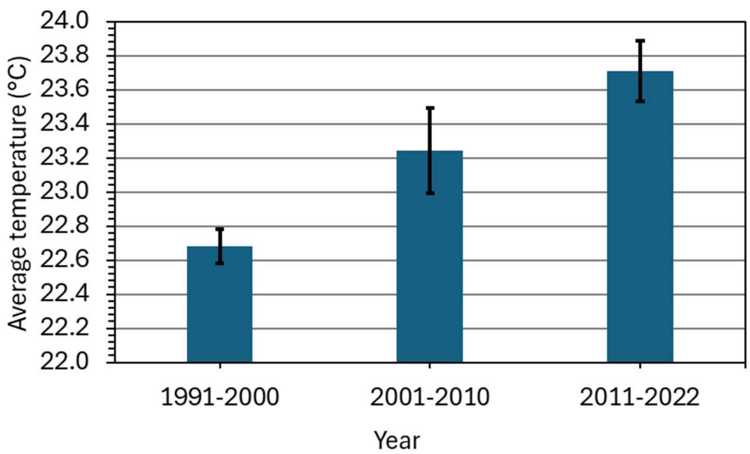

Figure 5. Average yearly temperatures for different ten-year intervals from 1991 to 2022 in the Al-Baha region. Error bars represent the standard deviation of average rainfall in each time interval. Sourced from the General Authority of Meteorology and Environmental Protection (GAMEP).

3.2. Types and Durations of Drought in Al-Baha

This study employed 31 years of monthly rainfall data (1991–2022) gathered from the Al-Baha station, which were combined with climate data sourced from the World Data Center for Meteorology and the NASA Tropical Rainfall Measuring Mission (TRMM) [40]. In Figure 6, we present SPI data categorized by drought levels over specific quarterly periods (January–March, April–June, July–September, and October–December) from 1992 to 2022. Figure 6 illustrates the variations in drought conditions across these quarterly periods. Negative SPI values generally signify severe drought levels, which we have highlighted in our analysis. The months and years that appear to be drier according to these values are May 1993, May 2000, May 2003, May 2005, May 2006, April 2009, August 2012, August 2015, April 2016, April 2018.

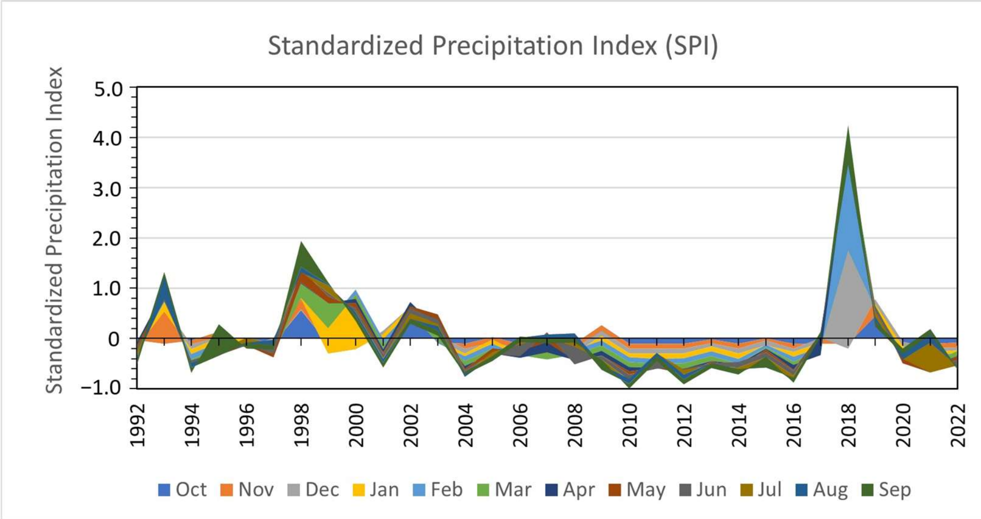

Figure 6. Values of the Standardized Precipitation Index (SPI) showing drought levels in the Al-Baha region during different months from 1991 to 2022. Sourced from the General Authority of Meteorology and Environmental Protection (GAMEP).

RDI values showed slightly more negative values indicating higher levels of drought (Figure 7). Over the period from 1991 to 2021, Al-Baha experienced frequent occurrences of moderate drought, with specific months repeatedly showing drought conditions across multiple years. The data reveals a pattern where certain months, such as January, February, September, and December, consistently experienced moderate drought conditions almost every year. For instance, February saw drought conditions in 24 of the 30 years, indicating a persistent issue during this period. Similarly, September and January also emerged as critical months with frequent drought occurrences. The repetitive nature of these drought events highlights a concerning trend that has likely impacted water availability, agriculture, and overall environmental conditions in the region. This pattern underscores the need for continuous monitoring, drought preparedness, and effective water management strategies to mitigate the adverse effects on the local ecosystem and community livelihoods.

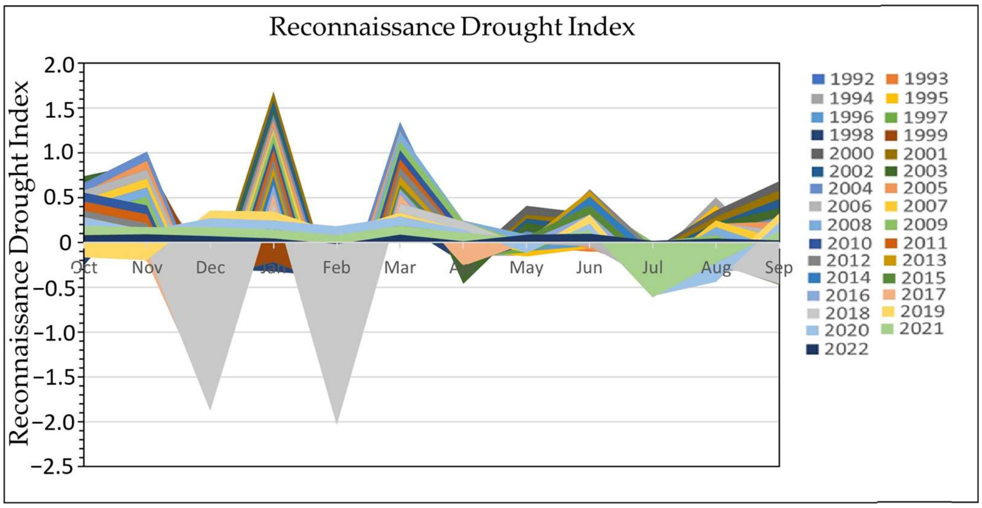

Figure 7. Values of the Reconnaissance Drought Index (RDI) showing drought levels in the Al-Baha region during different months from 1991 to 2022. Sourced from the General Authority of Meteorology and Environmental Protection (GAMEP).

Values of the eRDI index (Figure 8) showed a persistent and recurring pattern of moderate drought occurring in specific months across multiple years. The most frequently affected months include January, February, September, and December, with some years experiencing drought conditions in these months consecutively for several years. The months of January and February are consistently marked by moderate drought nearly every year. January experienced droughts in 24 out of the 30 years, and February in 29 out of the 30 years, indicating a recurring dry spell during the early months of the year. The month of September is also frequently affected, with droughts occurring in 23 out of the 30 years, suggesting it is a critical period for water scarcity in the region. The final quarter of the year (October to December) is particularly prone to moderate droughts, with November and December showing repeated drought conditions, especially from the late 1990s onward.

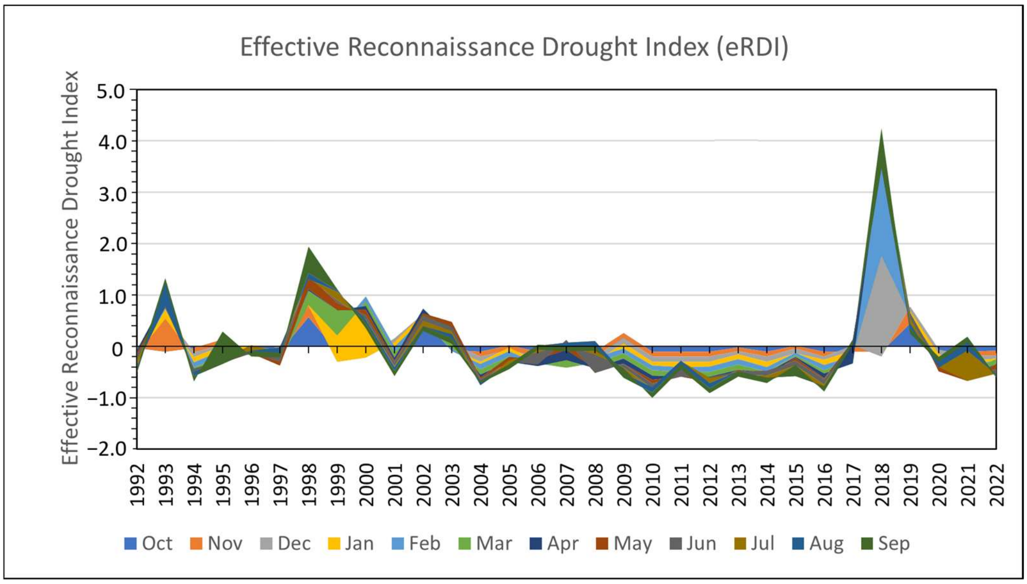

Figure 8. Values of the Effective Reconnaissance Drought Index (eRDI) showing drought levels in the Al-Baha region during different months from 1991 to 2022. Sourced from the General Authority of Meteorology and Environmental Protection (GAMEP).

Additionally, several other months, including June, July, and March, also show significant drought occurrences, although these are less consistent than in the primary months. This consistent pattern of moderate drought across these specific months highlights the region's vulnerability to drought, emphasizing the need for robust drought management strategies, especially during these critical periods. Understanding these patterns can help in developing better predictive models and preparedness plans to mitigate the impacts of drought on the local environment and communities. The aSPI values (Figure 9) reveal a noticeable pattern of drought severity across different seasons from 1992 to 2022. The data indicates that the early months of the year (January to March) frequently experience periods of drought, with several years showing severe or moderate drought conditions. Notably, 2000 (April–June), 2001 (January–March), 2010 (April–June), 2012 (July–September), 2013 (January–March), and 2019 (July–September) each had severe drought conditions in at least one of these months. In contrast, the periods from April to June generally see more variability, while others, like 1998 and 2007, show moderate moisture levels. The summer months (July to September) exhibit less consistency, with several years like 2008 and 2014 reporting moderate drought conditions, though some years, like 2021, show exceptional moisture. The final months of the year (October to December) often reflect near normal to moderate drought conditions, particularly in 2003, 2008, and 2014. This recurring pattern highlights the critical periods for water scarcity and the variability in drought severity throughout the year.

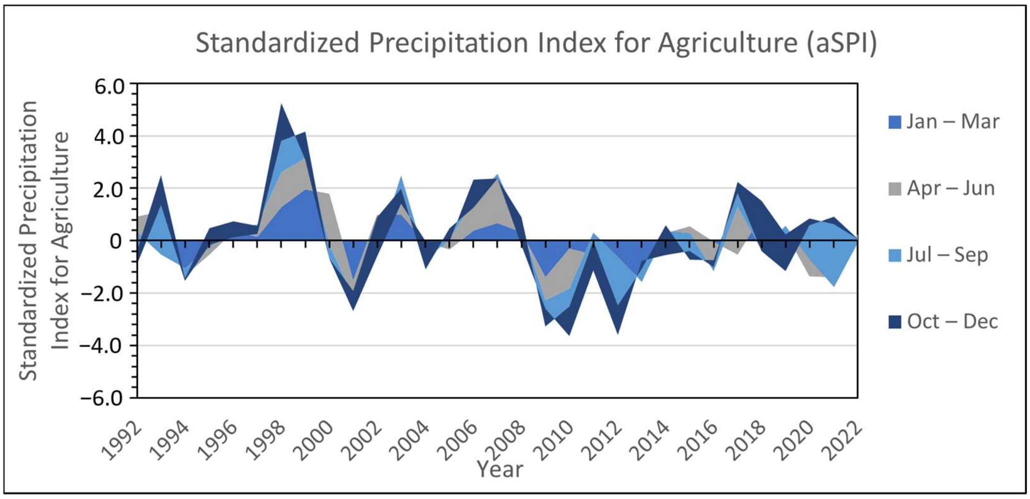

Figure 9. Values of the Standardized Precipitation Index for Agriculture (aSPI) showing drought levels in the Al-Baha region during different months from 1991 to 2022. Sourced from the General Authority of Meteorology and Environmental Protection (GAMEP).

3.3. Drought Vulnerability and Severity Analysis in Al-Baha, KSA from 1991 to 2022

The drought severity in Al-Baha was analyzed using various indices (SPI, aSPI, RDI, and eRDI) across different timescales (April–September and October–March). This comprehensive analysis aids in understanding the frequency, severity, and impacts of droughts on agriculture, water resources, and environmental stability. The updated Tables 3 and 4 show years with significant drought events (Severe Drought and Exceptional Drought) based on drought indices for April–September (Table 3) and October–March (Table 4). Years with notable wet conditions are also highlighted. Generally, higher index values indicate wetter conditions, while lower values indicate more severe drought conditions.

Table 3. Drought Severity by the different indices (SPI, aSPI, RDI, eRDI) in the Al-Baha region during the months April to September for the period 1992 to 2022.

Year *	SPI		aSPI		RDI		eRDI	
	Value	Category	Value	Category	Value	Category	Value	Category
1992	−1.09	Moderate D.	−1.10	Moderate D.	−1.00	Moderate D.	−1.00	Moderate D.
1998	1.50	Severe wet	1.55	Severe wet	1.68	Severe wet	1.74	Severe wet
1999	1.27	Moderate wet	1.35	Moderate wet	1.18	Moderate wet	1.25	Moderate wet
2000	−1.87	Severe D.	−1.92	Severe D.	−1.84	Severe D.	−1.88	Severe D.
2002	−1.29	Moderate D.	−1.31	Moderate D.	−1.25	Moderate D.	−1.26	Moderate D.
2003	1.31	Severe Wet	1.03	Moderate Wet	1.19	Moderate wet	0.92	Normal Cond.
2006	1.24	Moderate wet	1.23	Moderate wet	1.22	Moderate wet	1.21	Moderate wet
2007	1.62	Severe wet	1.60	Severe wet	1.70	Severe wet	1.67	Severe wet
2009	−1.29	Moderate D.	−1.32	Moderate D.	−1.27	Moderate D.	−1.30	Moderate D.
2010	−1.69	Severe D.	−1.73	Severe D.	−1.70	Severe D.	−1.74	Severe D.
2012	−0.53	Mild drought	−0.57	Mild drought	−0.57	Mild drought	−0.60	Mild drought
2015	−0.72	Mild drought	−0.72	Mild drought	−0.74	Mild drought	−0.74	Mild drought
2016	−0.73	Mild drought	−0.73	Mild drought	−0.79	Mild drought	−0.80	Mild drought
2017	1.86	Severe wet	1.73	Severe wet	1.76	Severe wet	1.62	Severe wet
2018	−1.16	Moderate D.	−1.17	Moderate D.	−1.23	Moderate D.	−1.24	Moderate D.
2020	0.99	Mild wet	1.05	Moderate wet	0.94	Mild wet	1.00	Moderate wet
2021	1.29	Moderate wet	1.35	Moderate wet	1.19	Moderate wet	1.24	Moderate wet

* The years that are not listed from the study period (1992–2022) provided normal drought conditions based on the drought. indices value and were omitted from the table to simplify the presentation of results. SPI, the Standardized Precipitation Index; aSPI, the Standardized Precipitation Index for Agriculture; RDI, the Rainfall Deficiency Index; eRDI, the Effective Reconnaissance Drought Index; D., drought; and Cond., Conditions.

Table 4. Drought Severity by the different indices (SPI, aSPI, RDI, eRDI) in the Al-Baha region during the months October to March for the period 1992 to 2022.

Year *	SPI		aSPI		RDI		eRDI	
	Value	Category	Value	Category	Value	Category	Value	Category
1992	0.56	Mild wet	0.60	Mild wet	0.41	Normal Cond.	0.44	Normal Cond.
1993	1.24	Moderate wet	1.28	Moderate wet	1.43	Moderate wet	1.48	Moderate wet
1994	−0.82	Mild drought	−0.83	Mild drought	−0.80	Mild drought	−0.80	Mild drought
1998	1.59	Severe wet	1.66	Severe wet	1.64	Severe wet	1.71	Sever Wet
1999	1.44	Moderate wet	1.45	Moderate wet	1.48	Moderate wet	1.49	Moderate wet
2000	1.42	Moderate wet	1.32	Moderate wet	1.38	Moderate wet	1.29	Moderate wet
2002	1.45	Moderate wet	1.50	Severe wet	1.43	Moderate wet	1.48	Moderate wet
2003	0.68	Mild wet	0.73	Mild wet	0.69	Mild wet	0.74	Mild wet
2004	−1.03	Moderate D.	−1.05	Moderate D.	−1.04	Moderate D.	−1.05	Moderate D.
2008	−0.53	Mild drought	−0.52	Mild drought	−0.52	Mild drought	−0.51	Mild drought
2010	−1.34	Moderate D.	−1.37	Moderate D.	−1.33	Moderate D.	−1.35	Moderate D.
2011	−1.67	Severe D.	−1.71	Severe D.	−1.64	Severe D.	−1.67	Severe D.
2012	−1.92	Severe D.	−1.97	Severe D.	−1.87	Severe D.	−1.91	Severe D.
2013	−0.51	Mild drought	−0.50	Mild drought	−0.53	Mild drought	−0.52	Mild drought
2014	−0.60	Mild drought	−0.59	Mild drought	−0.62	Mild drought	−0.61	Mild drought
2016	−0.81	Mild drought	−0.81	Mild drought	−0.84	Mild drought	−0.84	Mild drought
2018	2.17	Extreme wet	1.95	Severe wet	2.09	Extreme wet	1.88	Sever Wet
2019	1.05	Moderate wet	1.10	Moderate wet	1.02	Moderate wet	1.07	Moderate wet
2020	−0.57	Mild drought	−0.56	Mild drought	−0.60	Mild drought	−0.59	Mild drought
2021	−1.36	Moderate D.	−1.39	Moderate D.	−1.34	Moderate D.	−1.37	Moderate D.

* The years that are not listed from the study period (1992–2022) provided normal drought conditions based on the drought indices value and were omitted from the table to simplify the presentation of results. SPI, the Standardized Precipitation Index; aSPI, the Standardized Precipitation Index for Agriculture; RDI, the Rainfall Deficiency Index; eRDI, the Effective Reconnaissance Drought Index; D., drought; and Cond., Conditions.

In the analysis, we focused on years with notable drought intensity. Based on SPI and aSPI indices, years with Severe Drought included 2000, 2009, 2010, and 2016, marked by significantly negative index values that signal extreme rainfall deficits. These deficits resulted in severe impacts on water resources, agriculture, and the environment. Moderate Drought years, indicated by aSPI and SPI values from April to September and October to March, included 2001, 2002, 2003, 2004, 2005, and 2009, where precipitation was below average but less severe than in peak drought years.

Exceptional Drought conditions, the most severe category, reflect periods of extremely low precipitation with critical impacts on water, agriculture, and ecosystems. On a 12-month timescale (Table 5), the years with the most extreme drought values included 2009, 2010, 2012, and 2022. The drought indices in these years—especially in 2010—indicated prolonged dry conditions that significantly affected local ecology and agriculture. In contrast, 1998 and 2018 showed Severe Wet conditions with index values indicating substantial rainfall, which likely helped to temporarily alleviate water scarcity.

The analysis of temperature and precipitation trends over the past three decades further underscores Al-Baha's vulnerability. Since 1991, the region has experienced a 1.5 °C rise in average temperature and a 15% decline in annual rainfall. This dual trend of rising temperatures and declining precipitation suggests an increasing risk of future drought events and highlights the region's susceptibility to prolonged water scarcity.

Our findings show that severe drought years, such as 2009, 2010, 2012, 2016, and 2022, were critical in terms of drought intensity, with indices indicating extreme deficits in precipitation. For example, in 2010, drought indices like SPI and RDI reached their lowest values, demonstrating the severity of the drought and its profound impact on water availability and agriculture. This troubling trend aligns with global patterns of climate change, underscoring the urgent need for sustainable water resource management in the Al-Baha region.

Furthermore, we observed a troubling trend of rising temperatures, with an average increase of approximately 1.5 °C since 1991, consistent with global climate change patterns [3]. Precipitation data indicate a significant downward trend, with a reduction of around 15% in annual rainfall over the past three decades. This decline in precipitation, coupled with increasing temperatures, suggests a heightened risk of future droughts and underscores the vulnerability of the Al-Baha region to prolonged water scarcity.

Table 5. Drought Severity by the different indices (SPI, aSPI, RDI, eRDI) for different months in the period 1992 to 2022 in Al-Baha, Saudi Arabia (timescale of 12 months).

Year *	SPI-12	Category	aSPI-12	Category	RDI-12	Category	eRDI-12	Category
1993	1.02	Moderate wet	1.06	Moderate wet	1.29	Moderate wet	1.34	Moderate wet
1994	−0.69	Mild drought	−0.69	Mild drought	−0.53	Mild drought	−0.52	Mild drought
1998	2.11	Extreme wet	2.24	Extreme wet	2.28	Extreme wet	2.41	Extreme wet
1999	1.82	Severe wet	1.92	Severe wet	1.75	Severe wet	1.83	Severe wet
2001	−0.83	Mild D.	−0.80	Mild D.	−0.85	Mild D.	−0.82	Mild D.
2002	0.62	Mild wet	0.68	Mild wet	0.61	Mild wet	0.66	Mild wet
2003	1.21	Moderate wet	1.06	Moderate wet	1.12	Moderate wet	0.97	Mild wet
2004	−0.95	Mild drought	−0.95	Mild drought	−0.94	Mild drought	−0.92	Mild drought
2006	0.56	Mild wet	0.55	Mild wet	0.53	Mild wet	0.51	Mild wet
2007	1.09	Moderate wet	1.09	Moderate wet	1.14	Moderate wet	1.13	Moderate wet
2009	−1.13	Moderate D.	−1.15	Moderate D.	−1.08	Moderate D.	−1.09	Moderate D.
2010	−2.30	Extreme D.	−2.38	Extreme D.	−2.27	Extreme D.	−2.33	Exceptional D.
2012	−1.29	Moderate D.	−1.36	Moderate D.	−1.26	Moderate D.	−1.33	Moderate D.
2013	−0.52	Mild D.	−0.47	Normal Cond.	−0.55	Mild D.	−0.51	Mild D.
2014	−0.53	Mild D.	−0.52	Mild D.	−0.50	Mild D.	−0.49	Mild D.
2015	−0.67	Mild D.	−0.64	Mild D.	−0.67	Mild D.	−0.63	Mild D.
2016	−1.27	Moderate D.	−1.30	Moderate D.	−1.32	Moderate D.	−1.34	Moderate D.
2017	1.16	Moderate wet	1.04	Moderate wet	1.04	Moderate wet	0.92	Mild wet
2018	1.63	Severe wet	1.34	Moderate wet	1.42	Moderate wet	1.13	Moderate wet
2019	0.51	Mild wet	0.58	Mild wet	0.46	Normal Cond.	0.53	Mild wet
2022	−0.74	Mild D.	−0.72	Mild D.	−1.07	Moderate D.	−1.07	Moderate D.

* The years that are not listed from the study period (1992–2022) provided normal drought conditions based on the drought indices value and were omitted from the table to simplify the presentation of results. SPI, the Standardized Precipitation Index; aSPI, the Standardized Precipitation Index for Agriculture; RDI, the Rainfall Deficiency Index; eRDI, the Effective Reconnaissance Drought Index; D., drought; and Cond., Conditions.

Our findings align with studies indicating a significant increase in temperature and a notable decline in precipitation across various regions in Saudi Arabia, reinforcing the notion of climate change exacerbating drought conditions. For instance, research by Almazroui et al. [24] and others has documented similar trends of increasing temperatures and decreasing rainfall in KSA, which supports our findings regarding the correlation between exceptional drought years and broader climatic shifts.

Over the recent two decades, the entirety of KSA has confronted prolonged, severe, and even extreme drought episodes. An example of this is evident in areas such as Al-Baha, which have been experiencing extreme drought conditions as indicated by the analysis of the climatic data for the years 1991 to 2022 (Table 5). This finding raises a concerning alarm, given that the Al-Baha region is primarily an agricultural region. The precariousness of the situation escalates if the current downward trajectory of rainfall persists, leading to more intensively severe drought occurrences. The timescale used when assessing drought patterns is critical as it determines the expected impact on agricultural production and hydrological resources. Therefore, we compared the outcome values of the different drought indices at the three different timescales (3, 6, and 12 months) used in the assessment. Table 6 provides the percentage of the probability of drought occurrence by the different indices (aSPI, SPI, RDI, eRDI) at timescales of 3, 6, and 12 months for the years 1992 to 2022 in Al-Baha.

At the 3-month timescale, there was a severe drought that happened in 7 years with a probability of 5.65, and 5.7% based on the values of the SPI and the aSPI indices, respectively. When applying the same analysis at the 12-month timescale, there was a 3.33% probability of exceptional drought with all the indices (Table 6). This emphasizes the importance of the long-term assessment when determining drought patterns, particularly when assessing implications on agricultural and hydrological aspects. At the 6-month timescale, there was a 6.45% probability of a severe drought occurrence during April–June for the years

1993, 2000, 2012, and 2013. In addition, there were multiple instances of moderate drought spread over various time periods, making it more common.

Table 6. The probability (%) of drought occurrence by the different indices (aSPI, SPI, RDI, eRDI) at timescale of 3, 6, and 12 months for the years 1992 to 2022 in Al-Baha, Saudi Arabia.

Drought Severity	SPI	aSPI	RDI	eRDI
	Timescale of 3 Months			
Exceptional Drought	-	-	-	-
Severe Drought	5.65	5.70	-	-
Moderate Drought	15.32	15.35	12.10	12.10
Mild Drought	29.82	24.19	56.45	54.03
Normal conditions	37.90	37.90	16.94	19.35
Moderate wet	8.06	12.10	4.03	4.84
Severe wet	1.61	4.03	4.03	3.23
Exceptional wet	1.61	0.81	6.45	6.45
	Timescale of 6 Months			
Exceptional Drought	-	-	-	-
Severe Drought	6.45	6.45	6.45	6.45
Moderate Drought	11.29	9.68	9.68	9.68
Mild Drought	33.87	35.48	33.87	30.65
Normal conditions	25.81	24.19	27.42	30.65
Moderate wet	12.90	14.52	14.52	14.52
Severe wet	8.06	9.68	6.45	8.06
Exceptional wet	1.61	-	1.61	-
	Timescale of 12 Months			
Exceptional Drought	3.33	3.33	3.33	3.33
Severe Drought	-	-	-	-
Moderate Drought	10.00	10.00	13.33	13.33
Mild Drought	43.33	43.33	40.00	33.33
Normal conditions	20.00	20.00	20.00	33.33
Moderate wet	13.33	16.67	16.67	10.00
Severe wet	6.67	3.33	3.33	3.33
Exceptional wet	3.33	3.33	3.33	3.33

SPI, the Standardized Precipitation Index; aSPI, the Standardized Precipitation Index for Agriculture; RDI, the Rainfall Deficiency Index; and eRDI, the Effective Reconnaissance Drought Index.

In RDI-3 (3-month timescale), there was a moderate drought with a 15-year probability of 12.10%. Less often, severe droughts were reported. Periods of moderate drought that recur every January to March and October to December are noted. RDI-6 (6-month timescale): There was a severe drought that happened in 4 years with a 6.45% chance. Several growth seasons and off-seasons saw moderate drought. The year 2010 included both mild and severe droughts, emphasizing protracted arid weather. Exceptional Drought happened in 2010 (3.33% chance) according to RDI-12 (12-month timeline).

In eRDI-3 (3-month timescale), there was a moderate drought with a 15-year probability of 12.10%. Moderate drought trends recur from January through March and every October through December. On the other hand, eRDI-6 (6-month timescale) showed 4.45% risk of a severe drought in 4 years. Again, the year 2010 was a year marked by intermittent episodes of moderate and severe drought. eRDI-12 (12-month timescale): The year 2010 had a 3.33% likelihood of experiencing an exceptional drought. The moderate drought that occurred in 2009, 2012, 2016, and 2022 had noticeable but controllable effects. Overall, the data provides a comprehensive view of drought severity across different time scales, emphasizing the frequency and likelihood of severe drought conditions based on the values of the drought indices at both short-term and extended time periods.

3.4. Drought Management in Al-Baha

Frequent drought events in the Al-Baha region can put a strain on water supplies and agriculture. Drought-resistant crops, water conservation, and increased irrigation efficiency are examples of effective management techniques. Drastic and unusual droughts, like the ones that struck in 2010 and beyond, emphasize the importance of being ready for emergencies and implementing thorough water conservation measures. The extreme drought that occurred in 2010 emphasizes the need for strong reaction plans that include expanded capacity for storing water and disaster aid. Different times are affected differently by droughts. For example, there are frequently severe droughts from April to September that harm the growing season, and there may be moderate droughts from October to March that influence water replenishment. To lessen the effects, targeted management techniques should focus on these timeframes. The need for adaptive management solutions arises from the variability of drought intensity across various timelines and metrics. Regular monitoring and planning are essential to respond effectively to both moderate and extreme drought conditions.

Our results suggest that the precipitation-based indices (SPI and aSPI) are fully capable of identifying drought and its intensity just as effectively as the temperature and precipitation-based indices (RDI and eRDI). The dry years and their intensities determined by the effective precipitation indices (aSPI and eRDI) are similar to those identified by the SPI and RDI. Typically, temperatures are elevated and remain so throughout Saudi Arabia. Therefore, the precipitation and temperature indices do not show any change in drought intensity or severity. Based on these results, it has been established that a single index is sufficient to determine drought (type and intensity) in arid regions where the annual precipitation rate is less than 250 mm. Our findings line up with studies of Adnan et al. [41], who emphasize that the choice of time duration (1, 3, 6, 9, 12 months, etc.) is crucial for both the SPI and aSPI indices in determining drought intensity.

3.5. Severity of Hydrological Drought in the Al-Baha Region

Figure 10 illustrates the monthly average reservoir storage volume (in cubic meters) for the Al-Baha region during the period from 2018 to 2023. The data were compiled and calculated (from January 2018 to April 2023) from the Daily Reservoir Bulletin of the Water Agency. Ministry of Environment, Water, and Agriculture—Kingdom of Saudi Arabia. (https://mewa.gov.sa/ar/Ministry/Agencies/TheWaterAgency/Topics/Pages/13-11-2018-1.aspx, accessed on 20 October 2024). The Reservoir Storage Index (RSI) was used as a hydrological indicator for the assessment of hydrological drought in Al-Baha during the period from January 2018 to April 2023. The RSI works as an indicator for the quantity of water stored in reservoirs.

Overall, it was noted that the Al-Baha region has a negative value of $-14{,}328.7$ m^3 for the current average storage volume (the Standard Deviation was 225,470.9 m^3). The value of the RSI in Al-Baha was 0.234, indicating extremely low groundwater storage (see Table 2), and subsequently the presence of hydrological drought in the Al-Baha region. Negative values indicate negative storage volume in some months, meaning that the stored water volume may have fallen below the normal level during these periods. This could be due to rainfall deficiency or excessive water consumption.

According to statistics from the Ministry of Environment, Water, and Agriculture in 2020 (https://mewa.gov.sa/ar/Ministry/Agencies/TheWaterAgency/Topics/Pages/13-11-2018-1.aspx, accessed on 20 October 2024), the total surface water resources amounted to 121,231,100 m^3. The Jazan region had the highest share of surface water resources, reaching 112,070,330 m^3. The remaining provinces of Makkah came second with 21,072,910 m^3, followed by Asir in third place with 20,222,460 m^3, Al-Baha in fourth place with 19,676,420 m^3, and Riyadh, Jeddah, and Taif jointly ranked fifth with 5,476,095 m^3. This result raises alarming concerns, especially since many of these areas are agricultural. The situation's severity would escalate if the current downward trend in precipitation continues, leading to more severe drought waves.

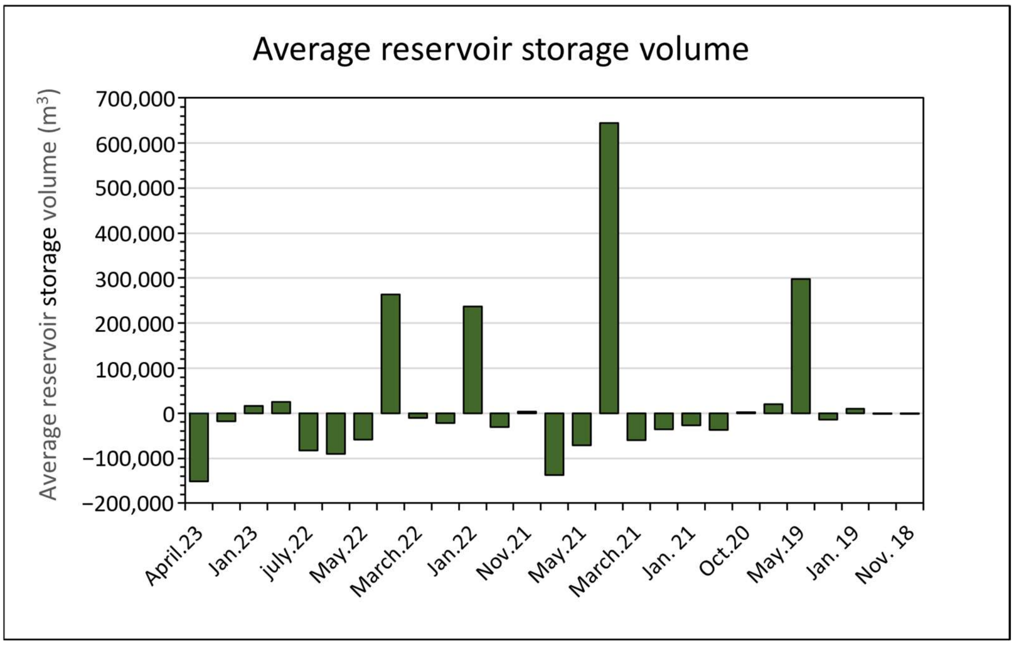

Figure 10. The monthly average reservoir storage volume for the Al-Baha region during the period from 2018 to 2022. Sourced from (https://mewa.gov.sa/ar/Ministry/Agencies/TheWaterAgency/Topics/Pages/13-11-2018-1.aspx, accessed on 20 October 2024).

3.6. Drought and Its Correlation with Climate Change in the Al-Baha Region

To evaluate the impact of climate change on drought patterns in the Al-Baha region, the analysis of drought results in relation to climate change indicators (gradual increase and decrease in climate indices) involved the adoption of time series analysis using the non-parametric statistics known as the Mann–Kendall test, which is a non-parametric test used to detect trends in time series data to identify any trends in the studied meteorological variables. Daily temperature data from climate monitoring stations for the period from 1991 to 2022 were analyzed, and monthly and annual averages of minimum, mean, and maximum daily temperatures were calculated. The monthly average values of maximum temperatures ranged from about 15 °C in January and rose to 33 °C in July, which is the hottest month of the year, then temperatures dropped again to reach 16 °C in December. The average minimum and maximum temperatures in July ranged from 25 to 40 °C, respectively. The corresponding temperatures in the coldest month of the year, January, were 9 and 21 °C, respectively. The significant variation in temperatures throughout the year and within the month makes regional planning for water resources and agricultural production more challenging. Figure 11 shows the monthly trends in temperatures as estimated through the sinusoidal statistics for Al-Baha.

In the Al-Baha region, the minimum temperature trend is 0.08 °C per year, the average temperature trend is 0.034 °C per year, and the maximum temperature trend is 0.12 °C per year (Figure 11). These values indicate that all temperature trends in March are positive, with the maximum temperature showing the greatest increase. This situation suggests a consistent warming pattern for minimum, average, and maximum temperatures during this month. On the other hand, the data also shows for January that the minimum temperature trend is −0.03 °C per year and the mean temperature trend is 0.034 °C per year. The decline in minimum temperatures, especially in January, may seem counterintuitive in the context of global warming; however, several factors could contribute to this phenomenon. First, localized climate patterns can diverge from broader global trends due to specific geographical and meteorological conditions. The Al-Baha region may be experiencing unique climatic influences that lead to such variations. Second, variability may also be attributed to natural cycles, such as El Niño and La Niña, which can significantly affect temperature patterns over short timescales. Third, the temperature trends can be sensitive to the specific years included in the analysis. For instance, if a significant number of colder years fell within this range, they could influence the overall trend.

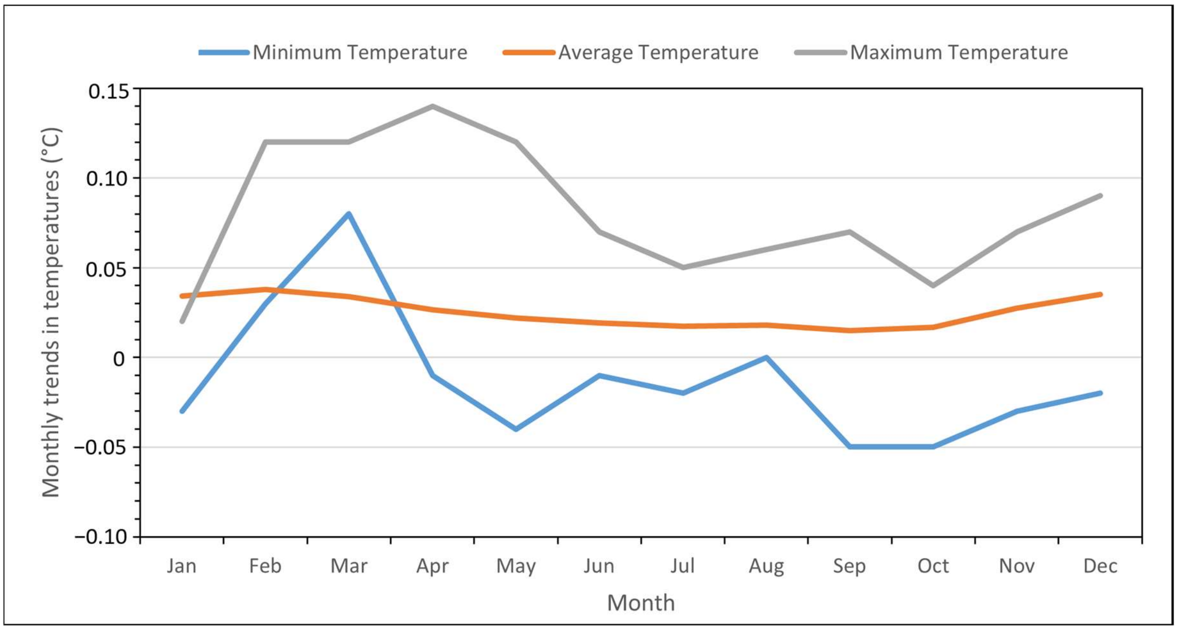

Figure 11. Monthly trends in minimum, average, and maximum temperatures for Al-Baha, KSA, from 1991 to 2022, as estimated through sinusoidal statistics. The trends represent changes in temperature (°C) per year, highlighting variations in temperature patterns across the different months.

Based on these research results, our findings align with previous research, indicating that Al-Baha has observed a significant and consistent rise in temperature over the past few decades, aligning with global climate change trends [8,23]. Figure 4 already shows the rise in temperature; however, this conclusion highlights the broader significance of these changes, aligning them with global climate change patterns and emphasizing the long-term impact on the region. This warming trend is characterized by higher average temperatures, longer and more intense heatwaves, and increased evaporation rates. Our findings line up with studies of the World Bank [42], which suggest that this warming trend is expected to continue, further increasing the risk of drought events and water scarcity. The rising temperatures in Al-Baha have significant implications for drought events and water scarcity in the region. The projected changes in rainfall patterns carry significant implications for drought conditions in Al-Baha. Al-Baha faces a critical challenge in the depletion of its water resources, particularly its heavy reliance on non-renewable groundwater sources for its water supply [42]. The overexploitation of these resources increases vulnerability to droughts and water shortages.

The results suggest that the exceptional drought years that have been recorded in the Al-Baha region (namely, 2009, 2010, 2012, 2016, and 2022) are not isolated occurrences, but rather are likely to be correlated with wider climatic occurrences, especially in light of the major findings. Al-Baha may be facing the consequences of changing weather patterns due to the notable rise in temperature and sharp drop in precipitation. The severe drought intensities that have marked these years are indicative of a worrying trend in national and potentially regional drought patterns that are being made worse by climate change. As indicated by the study by Wang et al. [43], which emphasizes how prolonged La Niña episodes may significantly influence drought duration and severity, one significant factor that could contribute to these drought conditions is the role of multi-year La Niña events. This is in line with the extreme drought events that were observed in Al-Baha. This emphasizes how crucial it is to take into account these climatic occurrences and their long-term cumulative effects. Furthermore, in light of global warming, the drop in minimum temperatures—especially in January—may appear paradoxical. However, several reasons could be responsible for these phenomena. First, the Al-Baha region's distinct geographic and meteorological characteristics can cause regional climate patterns to diverge from more general global trends. Second, natural cycles like El Niño and La Niña, which have a major impact on temperature patterns over shorter durations, may also have an impact on this variability. Finally, temperature trends may be influenced by the years that are included in the analysis; for instance, if a significant portion of this range consists of cooler years, this could distort the trend as a whole.

3.7. Predicting Temperature and Precipitation Characteristics for the Period (2022–2100)

Given that Al-Baha is an arid region and is characterized by pronounced aridity [44], precipitation variability is crucial, and water is becoming an increasingly precious natural resource. Thus, it is imperative to scrutinize past, present, and future climate changes and their ramifications on hydrology, agriculture, human activities, and occurrences of drought or floods. Climate models and projections were employed to simulate potential future drought scenarios in Al-Baha, under different greenhouse gas emission trajectories. The grid outputs of GCM, specifically RCP4.5 and RCP8.5, were utilized in this study to derive projected precipitation and temperature data (and consequently SPI), along with time series for the near-future (2022–2050) and future (2050 and 2100) periods.

3.7.1. Expected Future Temperature Scenarios in 2050 and 2100

Indicators provide valuable insights into the projected alterations in specific precipitation as opposed to the reference span from 1991 to 2022. These fluctuations offer valuable data concerning potential changes in precipitation patterns and trends expected in the coming decades. Figure 12 illustrates the projected temperature increases for two distinct scenarios of future temperatures. In a scenario characterized by low (RCP4.5) emissions of greenhouse gasses (GHGs), the projected temperature variations are expected to remain within 2 °C by both 2050 and 2100. This suggests that efforts aimed at mitigating GHG emissions would result in a relatively modest increase in temperatures over these timeframes. However, in a high emissions scenario (RCP8.5), where no significant reduction in GHG emissions occurs, much more significant temperature anomalies are anticipated for both 2050 and 2100 (up to more than 4 °C). This indicates that without substantial efforts to curb GHG emissions, the increase in temperatures could be substantially higher, potentially leading to more pronounced and adverse climate impacts.

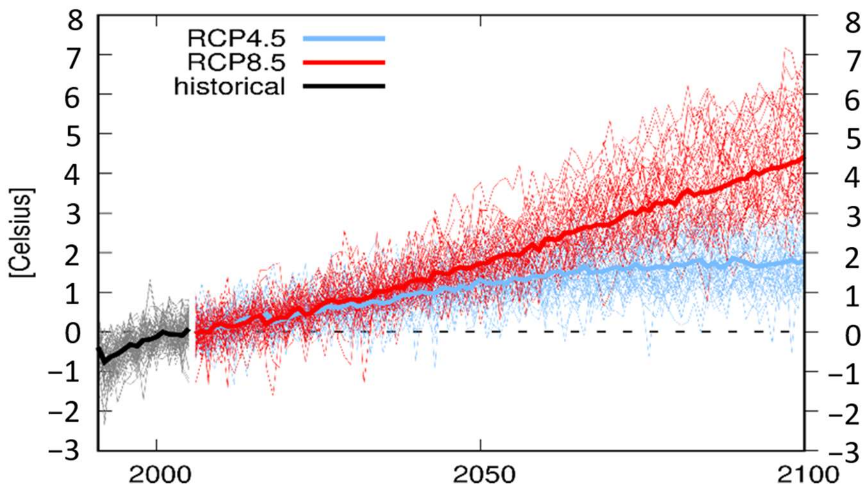

Figure 12. Temperature change at Al Baha using AR5 CMIP5 data. On the left side, each scenario is represented by one line per model along with the multi-model mean. On the right side, percentiles of the entire dataset are shown, the horizontal line denotes the median (50%).

3.7.2. Future Precipitation Scenarios in 2050 and 2100

Effective drought monitoring and climate impact assessments require the use of multiple indicators to capture the complexity of environmental changes. In this context, rainfall-based indices and up-to-date climate data play a critical role in understanding and responding to climate variations. The indicators offer insights into the expected changes in particular precipitation characteristics for a 30-year period centered on the year 2050, in contrast to the reference period spanning 1991–2022. These variations provide valuable information regarding potential shifts in precipitation patterns and trends anticipated in the forthcoming decades. Figure 13 depicts the forecasted precipitation rises for two separate scenarios of future climate. In the scenario of RCP4.5, it is projected that by 2050, the mean annual rainfall will decrease by 1.2%. Similarly, for the year 2100 under the same scenario, there persists a downward trend in annual rainfall with a decrease of 1.5%. Conversely, under the RCP8.5 scenario, the declining trend is expected to intensify, with annual rainfall decreasing by 15–27% by 2100. Overall, the projection models indicate a declining trend in mean annual precipitation. Our findings align with the work of Smakhtin and Hughes [45], who highlight that a range of indicators based on rainfall are employed for drought monitoring. Additionally, as emphasized by the IPCC [46], the availability of up-to-date climate information is crucial for effectively assessing climate change and its impacts, particularly in relation to global warming and shifts in climate patterns.

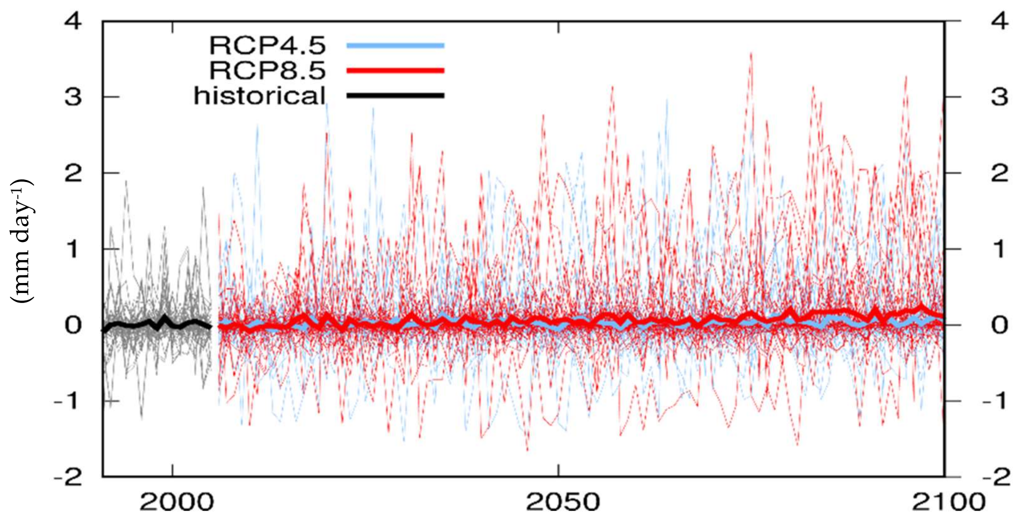

Figure 13. Precipitation changes at Al-Baha (AR5 CMIP5). On the left, for each scenario one line per model is shown plus the multi-model mean, on the right percentiles of the whole dataset, the horizontal line denotes the median (50%). The variability in precipitation projections indicates significant uncertainty, particularly in the range of 1.2–27% change by 2050 and 2100.

By scrutinizing the anticipated changes in precipitation characteristics, researchers and stakeholders can gain a better understanding of how the climate might evolve and the potential impacts of these changes on various aspects of the environment, society, and economy. This result is vital for adapting to potential challenges posed by shifts in precipitation, such as alterations in water availability, agricultural practices, and flood risk management. Additionally, it assists in making informed decisions regarding land use planning, infrastructure development, and resource allocation.

3.7.3. Potential Scenarios for Drought Occurrences in the Al-Baha Region

Historically, the primary driver of drought events in Al-Baha has been insufficient rainfall during the dry season, typically spanning from June to September an average of 0–69.1 mm and increase temperature (average of 25.9–31.2 °C). However, in recent decades, the influence of climate change has become increasingly discernible. Climate projections up to the year 2100 suggest that rainfall patterns in Al-Baha will be affected, consequently influencing the occurrence of droughts. Forecasts indicate a slight potential decrease in precipitation by 2050, which is expected to intensify by the year 2100. This projected decrease in rainfall and the simultaneous expected increase in evapotranspiration (evapotranspiration, comprising the combined losses of moisture due to evaporation from surfaces and transpiration from vegetation) demand during the same period is expected to exceed the replenishment from rainfall, resulting in diminished water availability.

The findings highlight that under a high carbon emissions trajectory, temperatures could potentially increase by up to 2.3 °C by 2050. In contrast, under a low carbon emissions trajectory, this temperature rise is projected to be limited to 1.8 °C. This nuanced analysis draws upon state-of-the-art climate models to provide insights into how different carbon pathways are poised to shape the climate landscape in Al-Baha, Saudi Arabia, across various timeframes.

In scenarios represented by RCP4.5 and RCP8.5, values of the Standardized Precipitation Index (SPI) anticipated severe droughts above a threshold of −2. Projected SPI-12 data suggested three extreme drought events from 2022 to 2041, albeit with short durations. Under the RCP 4.5 scenario, future drought severity for the period from 2041 to 2100 is projected to maintain a similar trend to present levels across various climate ensembles. However, in some ensembles, future drought severity may surpass present severity under the RCP 8.5 scenario. Overall, the outcomes point to increased severity, intensity, and duration of droughts under different future scenarios compared to historical data, emphasizing the crucial role of Global Climate Model (GCM) projections in assessing future drought trends.

Finally, the climate projections outlined in this study suggest a future with reduced rainfall and increasing drought across Al-Baha. Over the past two decades, Al-Baha has frequently experienced prolonged and severe droughts, posing significant risks given its predominantly agricultural nature. Should the trend of declining rainfall persist, the risk of increasingly severe droughts will escalate, further confirming the prediction model's indication of a general decrease in annual rainfall in Al-Baha.

4. Conclusions

Analysis of drought patterns in the Al-Baha region was carried out using historical climatic data (1991–2022) and several drought indices (aSPI, SPI, RDI, and eRDI) for the Al-Baha region. The years 2009, 2010, 2012, 2016, and 2022 were the most severe drought years in Al-Baha, as indicated by the lowest values on a variety of drought indicators. These results point to a worrying tendency of extreme weather events occurring frequently in the area as well as a trend of increasing drought intensity. In addition, a notable increase in temperature has been noted in recent decades, supporting trends of global climate change. Water scarcity is made worse by the diminishing trends in precipitation, which suggests that the Al-Baha region is likely suffering from abnormally low rainfall or other drought-friendly conditions. The Al-Baha region is suffering from precipitation that is much below average based on the collected historical climatic data. Precipitation deficits are a hallmark of exceptional drought conditions, which have detrimental effects on ecosystems, agriculture, civilization, and water supplies. Given that the region is a major agricultural area in KSA, this situation is concerning. During the period from 2018 to 2022, the Reservoir Storage Index (RSI) for the Al-Baha region was generally negative, indicating a hydrological drought in the region. Negative RSI values in several months indicate that the volume of water stored may have decreased below the average levels during these times. If the current low trend in precipitation continues, more severe drought waves will result, making the situation even worse.

The results point to a future with more severe droughts and less rainfall. Projections for the future show notable variations in precipitation and temperature. Temperature increases are predicted for both the low (RCP4.5) and high (RCP8.5) emissions scenarios, with the consequences being more noticeable for the higher emissions. Under both emission scenarios, temperatures are predicted to climb by 2050 and 2100. Within 2 °C, temperature rises are predicted to stay moderate under a low emissions scenario (RCP4.5). Though, large emissions (RCP8.5) can cause temperature anomalies to become more noticeable, which could exacerbate the effects of climate change. There is a projected decrease in precipitation, which might drop under the low emissions scenario (RCP4.5) by 1.2 and 1.5% by 2050 and 2100, respectively. Under the high emissions scenario (RCP8.5), the situation might become worsened as the projected decrease in precipitation is expected to reach 15–27% by 2100. These modifications are likely to make the drought and water scarcity worse.

According to the climatic estimates presented in this research, Al-Baha may see decreasing rainfall and growing drought in the future. Al-Baha is mostly an agricultural region. Therefore, it is extremely important to emphasize that Al-Baha's water resources and agricultural activities need to be managed through proactive climate adaptation techniques. In addition, routine monitoring and analysis are necessary to increase Al-Baha's resistance to upcoming climate-related problems, and to provide policy makers, stakeholders, and local farmers with the necessary information to implement best management practices for future adaptation and resource management in the Al-Baha region.

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