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# Spatial and Temporal Analysis of Maximum and Minimum Temperature Trends in Northern Sudan during (1990-2019)

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## Abstract

The study addresses an urgent and globally significant issue of climate change by focusing on the detailed spatial and temporal analysis of temperature trends in Northern Sudan. It fills a critical research gap by providing localized data over a substantial period (1990-2019), which could help in understanding the nuanced impacts of climate change in Sahel regions like Northern Sudan. In addition, the comprehensive coverage of both spatial and temporal dimensions, supported by a substantial dataset from five meteorological stations, provides a thorough understanding of the subject area. The utilization of robust statistical methods (Mann-Kendall test and Sen's slope analysis) for analyzing temperature trends adds scientific rigor and credibility to the findings. Our results reveal a consistently increasing trend in maximum temperatures across most stations, particularly during the hot season (AMJ). However, the wet season (JAS) shows high maximum temperatures but no significant trend. Moreover, significant increasing trends in minimum temperatures were observed in all stations except Abu Hamed, where the trend, although increasing, did not reach statistical significance during the hot and cold seasons, and the coldest temperatures were observed during the cold season. These findings underscore the complex temperature dynamics in Northern Sudan and highlight the need for continued monitoring and adaptive measures in response to ongoing climate changes in the region.

## Keywords

Climate Change, Northern Sudan, Temperature Trend, Seasonal Analysis

## 1. Introduction

Climate change is an essential global issue that has received more significant concern from scientists, governments, and the general public in recent decades, which can be observed via changes in temperature and rainfall, which have important effects on ecosystems, agriculture, water resource management, energy supplies, and human health (IPCC, 2007). There is high confidence that developing countries will be more vulnerable to climate change than developed countries, and there is medium confidence that climate change will exacerbate income inequalities between and within countries (Smith et al., 2001). In this way, it has been shown that a slight temperature increase would have net negative and positive impacts on market sectors in many developing countries (Kotir, 2010). In addition, the impacts of climate change are expected to worsen existing vulnerabilities in Africa and the region already endures high temperatures and low precipitation, frequent droughts, food insecurity, and water scarcity (Kabubo-Mariara, 2008; Kotir, 2010; Ozor et al., 2012). The Intergovernmental Panel on Climate Change (IPCC) predicts higher temperature increases in the region than the global mean temperature increase. This would mean an increase in hot nights, and longer and more frequent heat waves, as the Sahel region will experience the strongest drying, with a significant increase in the maximum length of dry spells (Yvonne et al., 2020). However, Sudan is among the nations most vulnerable to the impacts of climate change and climate variability in the Sahel region (Hamadalnel et al., 2021), and multiple stresses at various levels, such as endemic poverty, institutional weaknesses, limited access to capital, including markets, infrastructure, and technology, ecosystem degradation, complex disasters, and conflicts aggravate this situation. These have weakened people's adaptive capacity, increasing their vulnerability to projected climate change (Mohamed & Bannari, 2016). Additionally, the country has experienced a rise in both maximum and minimum temperatures, consistent with global warming trends attributed to human-induced greenhouse gas emissions (IPCC, 2014).

Previous studies have documented the increasing trend in temperatures across Sudan over the past few decades. Therefore, while studies have examined temperature trends at the regional scale, there remains a need for localized analyses focusing on specific regions within Sudan, such as Northern Sudan, to capture the nuances of temperature variability and change. Additionally, understanding the dynamics of the climate in a specific region requires examining the temporal and spatial analysis of maximum and minimum temperatures. Therefore, this study aims to investigate the trends of maximum and minimum temperatures in Northern Sudan for 30 years (1990-2019) using the observation data from 5 meteorological stations due to the limited number of stations in the region as well as the whole country (**Table 1**) to provide insight into the ongoing climatic shifts in the region and provide the policymakers and stakeholders with critical facts for policies connected with adaptation and mitigation (Thornton et al., 2008).

## 2. Data and Methods

### 2.1. Study Area

The North region of Sudan is located between longitude (24.9˚E - 35.8˚E) and latitude (15.8˚N - 22.1˚N), and it includes 2 states; the Northern state to the West and the River Nile state to the East. The two states are bounded by Egypt to the North, the Red Sea and Kassala states to the East, Gedaref, Khartoum, and North Kordofan states to the South, North Darfur to the Northwest, and Libya to the West (**Figure 1**). The study area is characterized by a warm-desert climate, with hot and dry conditions prevailing for most of the year. The climate is influenced by various factors, including its proximity to the Sahara desert in the North, the Red Sea in the East, and the Ethiopian highlands in the southeast. The region experiences two distinct seasons: a dry season from October to May and a wet season from June to September, with precipitation mainly occurring during the latter period (World Bank Group, 2021). Elagib & Mansell (2000a; 2000b) defined the seasons in Northern Sudan as winter or cold season (January-March and October-December), summer or hot season (April-June), and autumn or wet season (July-September), which are considered in this study.

### 2.2. Data

The data used in this study were obtained from the Sudan Meteorological Authority (SMA) for the period (1990-2019) collected from 5 meteorological stations (**Table 1**), and the data included:

1) Monthly Mean Maximum Temperature ($T_{max}$).

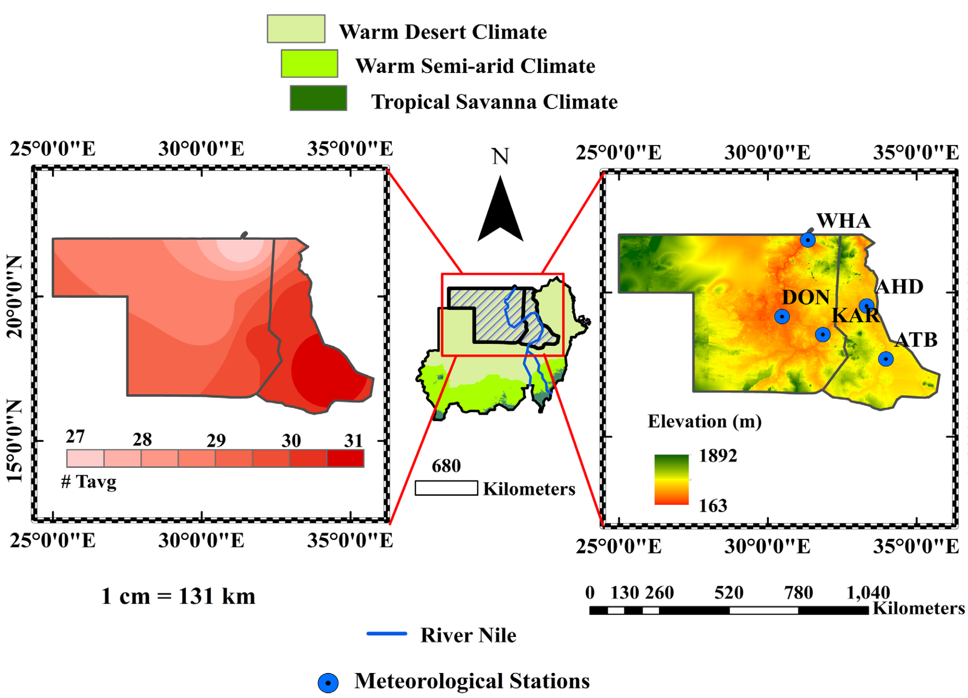



**Figure 1.** The Study area map (the meteorological stations are shown in the blue circles), the elevation data obtained from https://earthexplorer.usgs.gov/.

**Table 1.** Geographical locations of representative meteorological stations.

| No | WMO ID | Name | Code | Latitude | Longitude | Elevation (m) |
|---|---|---|---|---|---|---|
| 1 | 62600 | Wadi Halfa | WHF | 21.82 | 31.35 | 183 |
| 2 | 62640 | Abu Hamed | AHD | 19.54 | 33.32 | 312 |
| 3 | 62650 | Dongola | DON | 19.17 | 30.48 | 226 |
| 4 | 62660 | Karima | KAR | 18.55 | 31.85 | 249 |
| 5 | 62680 | Atbara | ATB | 17.70 | 33.97 | 345 |

The station's latitude, longitude, and elevation were obtained from (https://opendata.dwd.de/climate_environment/CDC/help/stations_list_CLIMAT_data.txt).

2) Monthly Mean Minimum Temperature ($T_{\min}$).

The data was preprocessed by filling in the missings and quality control.

## 2.3. Methods

### 2.3.1. Standardized Anomaly Index (SAI)

Normalized data from a distribution with a mean and standard deviation are referred to as the standardized Anomaly Index (SAI). They were employed to analyze the seasonal and annual variations in temperature. The monthly station-based observation data were normalized as the difference in each time step from the mean was divided by the standard deviation (Alriah et al., 2022). Thus, the stations within the areas were averaged using the following equations:

$$\overline{x} = \frac{1}{n}\sum_{i=1}^{n} x_i$$

Concerning time, the average sum of all observations is the variable's mean ($x$).

Standard deviation ($\sigma_x$), or the square root of variance, is used to calculate the variability,

$$\sigma_x = \sqrt{\frac{1}{n}\sum\nolimits_1^n \left(x_i - \overline{x}\right)^2}$$

$$\text{SAI} = \frac{x_i - \overline{x}}{\sigma_x}$$

As the standard deviation from the mean series is denoted by $\sigma_x$, the monthly temperature is represented by $x_i$, and $x$ is the mean of the entire series (Wilks, 2016).

### 2.3.2. Trend Analysis

The trend reflects the long-term temporal pattern of the data. It shows the rate of change (increasing or decreasing) in a series of times, and its pattern may be determined using graphical and statistical techniques. The use of analytical techniques to data allowed for the trend analysis in this study. This research used the World Meteorological Organization's suggested using Kendall (1975) and Sen (1968) methods, respectively (Partal & Kahya, 2005), particularly for long-term investigations, it's helpful to inquire into time series with predictable increasing or decreasing patterns (Zhang et al., 2009; Alriah et al., 2022).

A non-parametric method for identifying patterns in time series is the Man-Kendall test (MK). In this test, the relative values of the data are compared instead of the actual values (Gilbert, 1987). The advantage of this test is that no specific distribution has to be confirmed by the data. Each data value in the time series is compared with every subsequent value in this test. When a data value in a later period exceeds that in an earlier period, the Mann-Kendall statistics ($S$) is incremented by 1, and vice versa. Initially, $S$ is supposed to be zero. The ultimate value of $S$ is the net consequence of all these increases and decreases (Kumar et al., 2017). The following is the Mann-Kendall statistics ($S$):

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \text{sign}\left(x_j - x_i\right)$$

Note that: $n$ is the number of data points, while $x_i$ and $x_j$ are the time series observations.

By assuming that: $\left(x_j - x_i\right) = \theta$, the value of sgn(θ) is determined from:

$$\text{sgn}\left(\theta\right) = \begin{cases} +1 & \theta > 0 \\ 0 & \theta = 0 \\ -1 & \theta < 0 \end{cases}$$

When considering independent and randomly distributed variables, the σ statistic for large samples ($n \geq 10$) appears to be normally distributed, with zero mean and variance:

$$\sigma^2 = \frac{n\left(n-1\right)\left(2n+5\right)}{18}$$

Therefore, the standardized normal deviation (Z-statistics) distribution can be obtained using the following formula:

$$Z_{mk} = \begin{cases} \dfrac{S-1}{\sqrt{V\left(S\right)}} & S > 0 \\ 0 & S = 0 \\ -\dfrac{S+1}{\sqrt{V\left(S\right)}} & S < 0 \end{cases}$$

As can identified, increases are represented by positive $Z$ values, and decreasing trends are represented by negative $Z$ values.

On the other hand, to evaluate the relative significance of the MK trend test in time series data, Sen (1968) used non-parametric slope estimator techniques to estimate the trend size. According to (Jain & Kumar, 2012), Sen's slope estimator is widely used to determine the trend magnitude in hydro-meteorological time series. It is a trusted estimator because of its low sensitivity to extreme values (Chattopadhyay & Edwards, 2016). Sen's slope (Chakraborty et al., 2013) is used as a base to compute the slopes of each data pair, providing an estimate of the slope ($b_i$). That is illustrated as follows:

$$b_i = \frac{X_j - X_i}{j - 1}, \quad i = 1, 2, 3, \cdots, N, \quad j > i,$$

As $X_j$ and $X_i$ are the values at times *j* and *i*, Sen's estimator of the slope is the median *N* values of $b_i$

$$b = \begin{cases} b\dfrac{N+1}{2}, & \text{if } N \text{ is odd} \\ 0.5\left[b\dfrac{N}{2} + b\left(\dfrac{N+2}{2}\right)\right] & \text{if } N \text{ is even} \end{cases}$$

A positive *b* indicates that the value is increasing over time, whereas a negative value indicates that the value is decreasing (Haldar et al., 2023).

On the other hand, the data was interpolated using the inverse distance weight IDW technique to create a raster layer due to the limitations of the study area, available data, and a limited station number (Mohamed et al., 2021). The geographical distribution of temperature and precipitation data is shown spatially using the IDW tool for spatial analysis. The IDW measures the distance between adjacent stations in a time sequence. It is more adaptive in locations near challenging terrain when complex interactions between rain and orography are considered (Ahrens, 2005; Suhaila et al., 2008), for example, Mekonen & Berlie (2019) used IDW interpolation to illustrate the seasonal geographical distribution of rainfall and temperature.

## 3. Results and Discussion

The results of the spatial and temporal distribution of the annual and seasonal temperature and the trends with their significance at the 95% confidence level in Northern Sudan are shown in **Figures 2-15**. Sen's slopes represent annual and seasonal values in the hot (AMJ), cold (ONDJFM), and wet seasons (JAS). Meanwhile, the Mann-Kendall trend analysis is used to analyze the temperature trends as mentioned (Chakraborty et al., 2013).

### 3.1. Spatial and Temporal Distribution of Maximum Temperature

**Figure 2** shows the spatial distribution of the maximum temperature over

**Table 2.** The average of the maximum and minimum temperature (annually and seasonally).

| Station | Maximum Temperature | | | | Minimum Temperature | | | |
|---|---|---|---|---|---|---|---|---|
| | Annual | Hot | Cold | wet | Annual | Hot | Cold | wet |
| Wadi Halfa | 34.4 | 41.5 | 30.2 | 35.5 | 20.5 | 23.9 | 15.5 | 26.8 |
| Abu Hamed | 38.1 | 43.3 | 34.8 | 39.4 | 22 | 25 | 17.4 | 28.1 |
| Dongola | 37.1 | 43.3 | 33.5 | 38.2 | 20.1 | 23.8 | 14.7 | 27.1 |
| Karima | 37.8 | 43.2 | 34.5 | 39. | 21.7 | 25 | 17.1 | 27.7 |
| Atbara | 38 | 41.8 | 35.6 | 39.1 | 22.8 | 26.1 | 18.7 | 27.8 |
| Average | 37.1 | 42.6 | 33.7 | 38.3 | 21.4 | 24.8 | 16.7 | 27.5 |

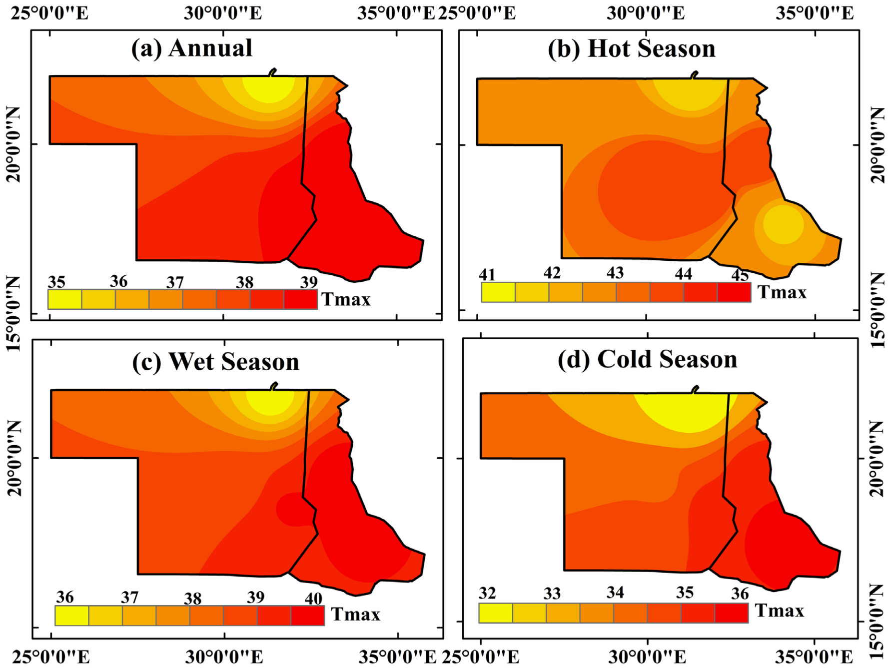



Figure 2. Spatial distribution of the maximum temperature over Northern Sudan.

Northern Sudan annually and during hot, wet, and cold seasons. However, the spatial distribution of annual maximum temperature reveals a predominance of higher temperatures, ranging from (35˚C - 39˚C), with a slight drop in the northern region. In addition, the annual average of the maximum temperature over the region is (37.1˚C). Consequently, the highest annual maximum temperature is observed over Abu Hamed station (38.1˚C), and it also has the highest maximum temperature during the wet season. Meanwhile, Atbara and Dongola stations showed the highest maximum temperature during the cold and hot seasons (35.6˚C and 42.6˚C) respectively, and the highest maximum temperature is observed during the hot season, then in the wet season with the average temperature (42.6˚C and 38.3˚C) respectively (Table 2). On the other hand, Wadi Halfa station showed the lowest maximum temperature annually and in all seasons. Overall, the spatial distribution of the maximum temperature shows that the temperature is higher in the Southern and southeast of the region, except in the hot season which shows that the area in the Central part has a higher maximum temperature (Figure 2).

Figure 3 shows the temporal variations of the annual and seasonal maximum temperature, as colored with brown, green, blue, and red to represent the annual, wet, hot, and cold seasons respectively. In addition, the figures show that the region experienced the highest maximum temperature during the wet and hot seasons.

## 3.2. The Trend of the Maximum Temperature

Figure 4 shows the annual and seasonal trends of the maximum temperature observed at several meteorological stations and shows the spatial distribution of

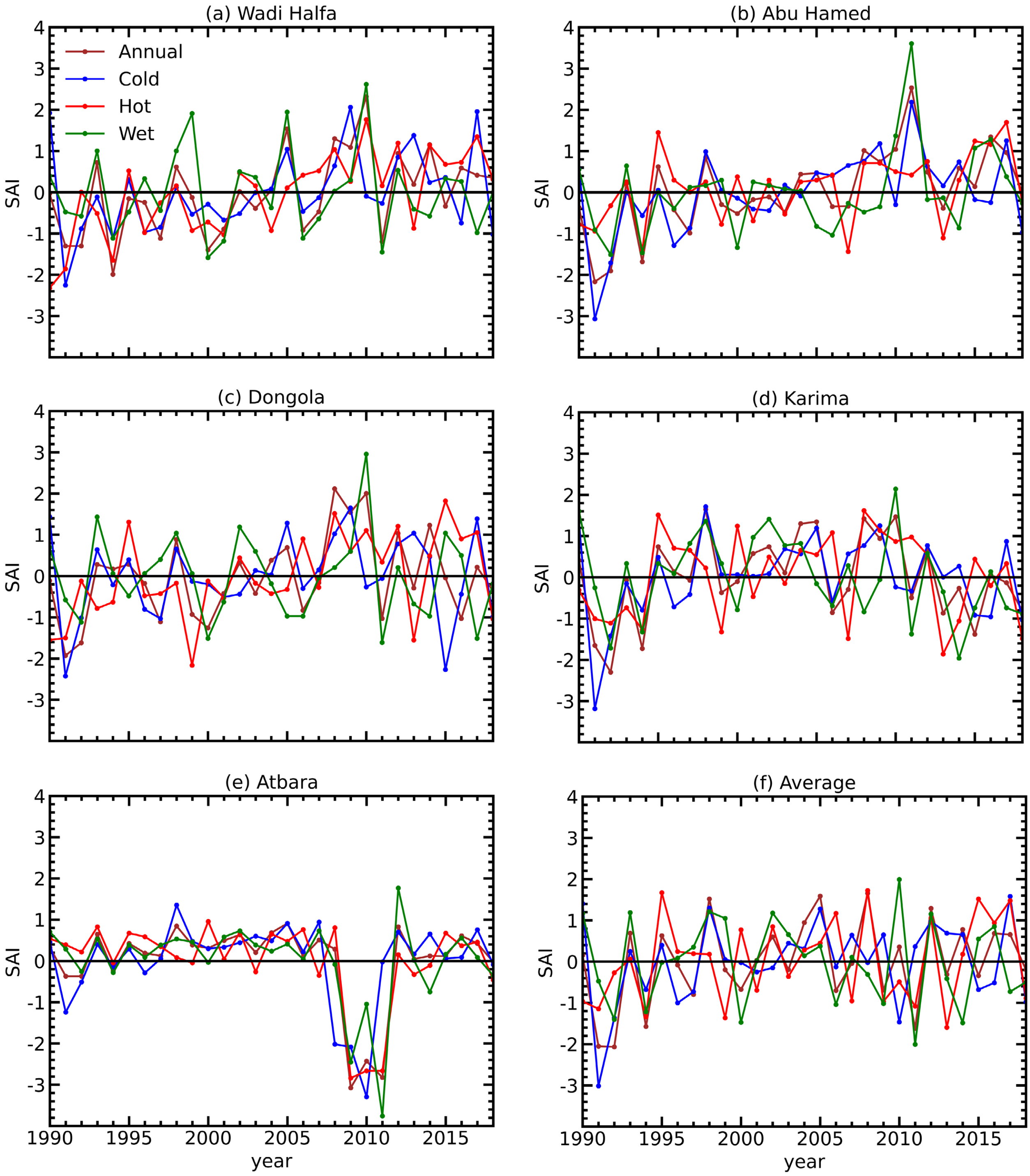



**Figure 3.** The variation of the maximum temperature for the meteorological stations over Northern Sudan and its seasonality.

the minimum temperature trends (as shown with the slope) in Northern Sudan.

The investigation of maximum temperature changes across Northern Sudan observes different patterns and variations across the stations and seasons. The Wadi Halfa station shows a significant increase in maximum temperature trends annually and over the hot, and cold seasons, indicating a consistent increasing trend for most of the year (**Figure 5**). In contrast, no notable trend was observed

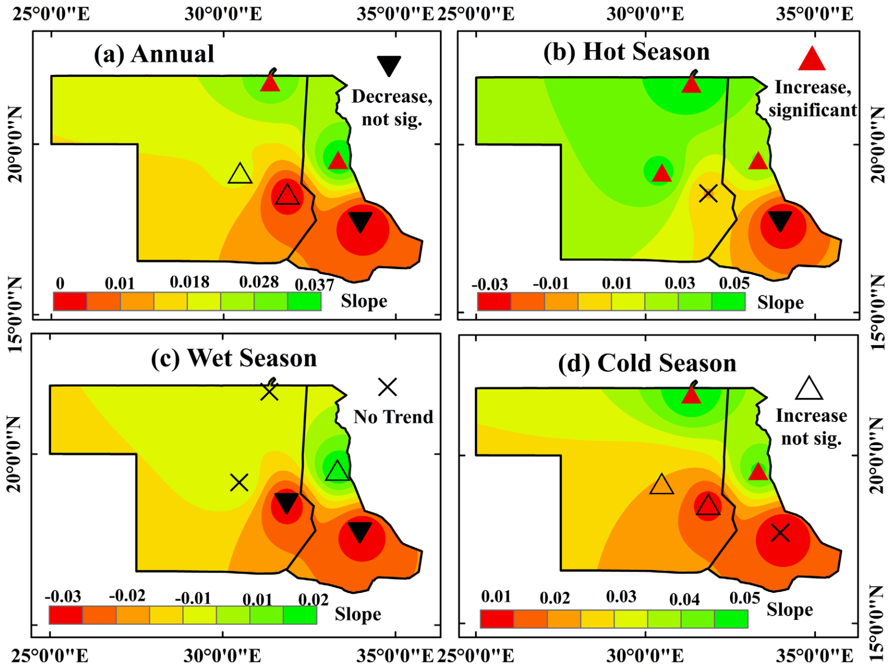



**Figure 4.** Spatial distribution of the maximum temperature trend over Northern Sudan.

in the wet season, suggesting a possible response to or stabilizing of temperatures when there is more rainfall. Similarly, Dongola station shows a significant increase in maximum temperature patterns during the hot season under the projected heat increase in the region's arid summertime. However, the absence of significant trends throughout annual and hot seasons suggests a more detailed temperature system in which variations may influence atmospheric circulation patterns or geographic surface features. The absence of a trend during the rainy season highlights the unique meteorological dynamics that influence changes in temperature in Northern Sudan. The Abu Hamed station demonstrates a significant increase in maximum temperature trends across all seasons, with significant increases observed during the annual, hot, and cold seasons. However, the rainy season also experiences significant temperature increases, indicating a complex connection between rainfall patterns and temperature changes in the region. This finding illustrates the significance of simultaneously discussing both climatic variables when evaluating climate trends and effects (Kurukulasuriya & Rosenthal, 2003).

In contrast, the Atbara station shows a decrease in maximum temperature trends, particularly during the annual and hot seasons, but this decrease is not statistically significant. This unforeseen pattern may need more investigation into factors that influence the region's temperature variations, such as changes in land cover, urban development, or particular atmospheric circulation patterns. The absence of an ongoing trend throughout the cold and wet (rainy) seasons shows the variability in temperature trends across various regions and periods in Northern Sudan. Karima station demonstrates inconsistent findings since no notable trends are identified over the annual and cold seasons (**Figure 4**).

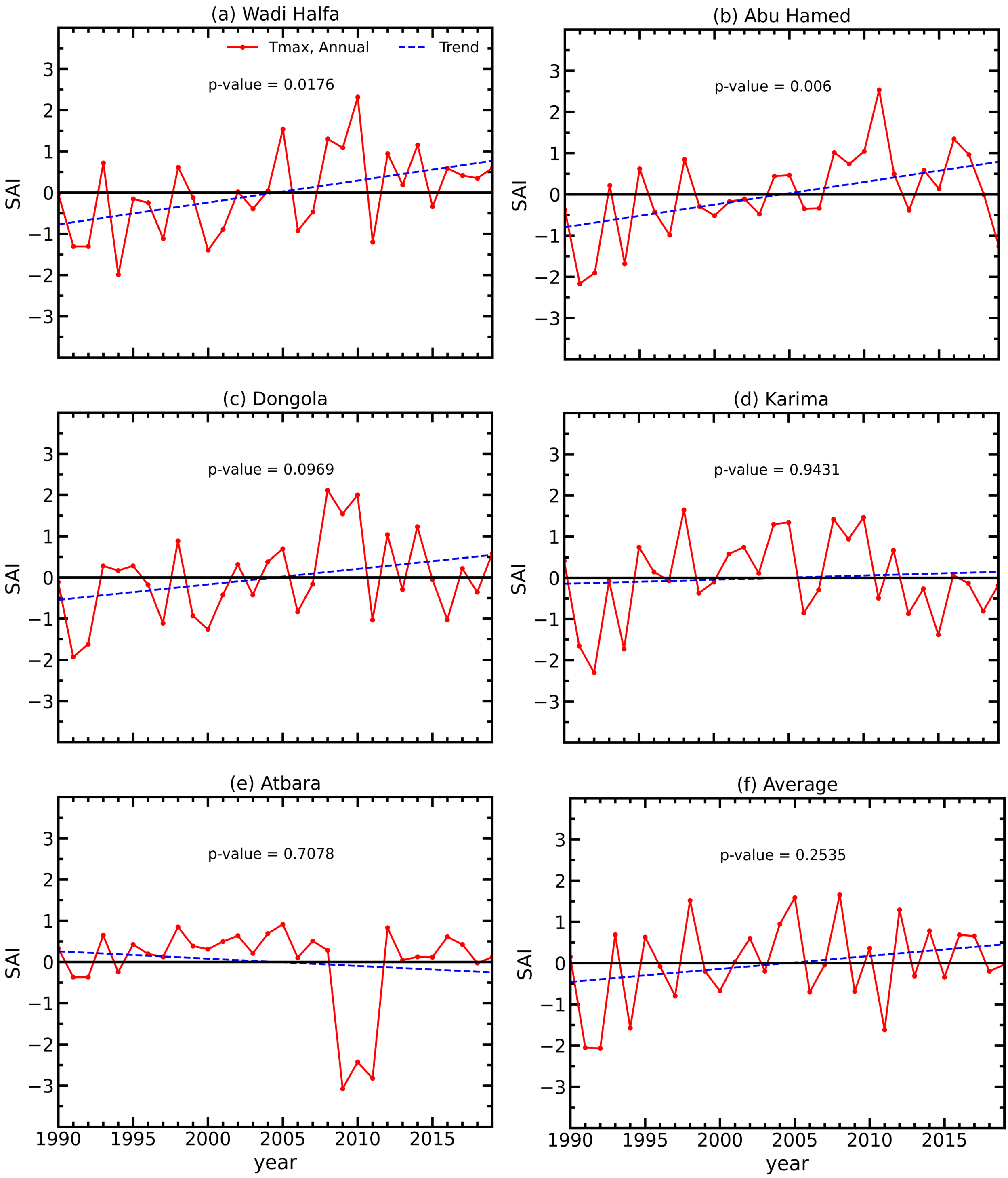


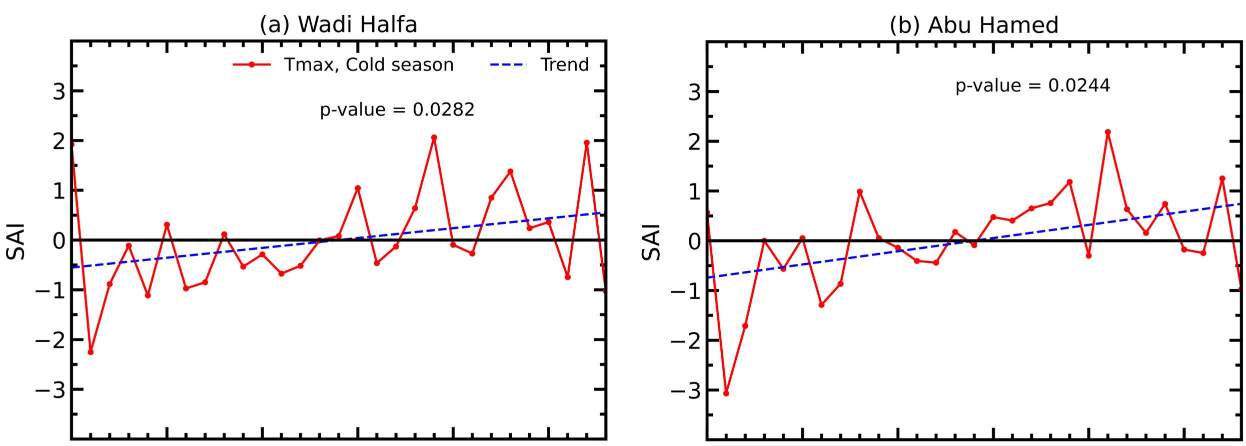

**Figure 5.** The trend of the annual maximum temperature for the meteorological stations over Northern Sudan.

Nevertheless, a decreasing trend is found during the wet season but is not statistically significant. This suggests that possible cooling effects are associated with higher amounts of rainfall. Additionally, no discernible trend is shown during the hot season, demonstrating consistent maximum temperature conditions across the region's arid summertime.

#### 3.2.1. Annual Maximum Temperature

Figures 5-8 show the temporal annual and seasonal trends during cold, hot, and wet seasons respectively of the maximum temperature. In 2010, the highest temperature was observed in Wadi Halfa station annually (Figure 5(a)), in the rainy (wet) (Figure 8(a)) and hot seasons (Figure 7(a)). In the season of 2009, the cold season additionally experienced higher maximum temperatures (Figure 6(a)). The region is vulnerable to extreme temperatures, as shown by these extreme heat instances. Meanwhile, annually and during the cold and rainy seasons, Abu Hamed station recorded the hottest maximum temperature; in 2017, as the highest temperature was recorded during the hot season (Figure 7(b)). Extreme temperatures highlight the importance of looking for temperature-related risks, especially when there is a lot of heat stress (IPCC, 2021). Many remarkable maximum temperature events have been observed at Atbara station, including the annual maximum temperature peak in 2005 (Figure 5(e)), the wet season of 2012 (Figure 8(e)), the hot season of 2000 (Figure 7(e)), and the cold season of 1998 (Figure 6(e)). Among the hottest seasons recorded at Dongola station were the winter (cold season) of 2009 (Figure 6(c)), the wet season of 2010 (Figure 8(c)), the hot season of 2015 (Figure 7(c)), and the annual occurrence in 2008 (Figure 5(c)). Additionally, extreme maximum temperatures have been observed at Karima station on many occasions, including the winter of 1998 (Figure 6(d)), the wet season of 2010 (Figure 8(d)), the hot season of 2008 (Figure 7(d)), and the same year in 1998 (Figure 5(d)). These periods of extreme heat lead to attention to how vulnerable the area is to temperature variations and highlight the significance of understanding the factors that influence temperature variations to manage climate risk effectively. On the other hand, the extraordinary maximum temperatures observed at a few stations in Northern Sudan show the region's vulnerability to climatic extremes and fluctuation (IPCC, 2021).

#### 3.2.2. The Maximum Temperature in the Cold Season



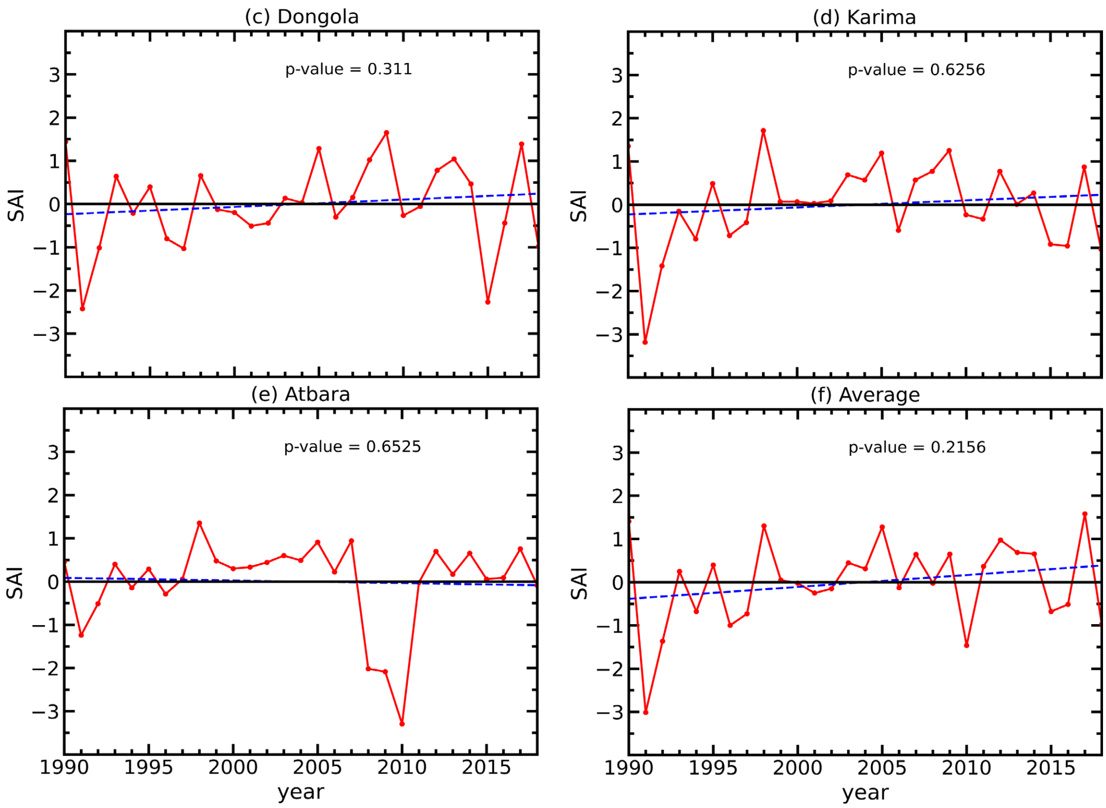
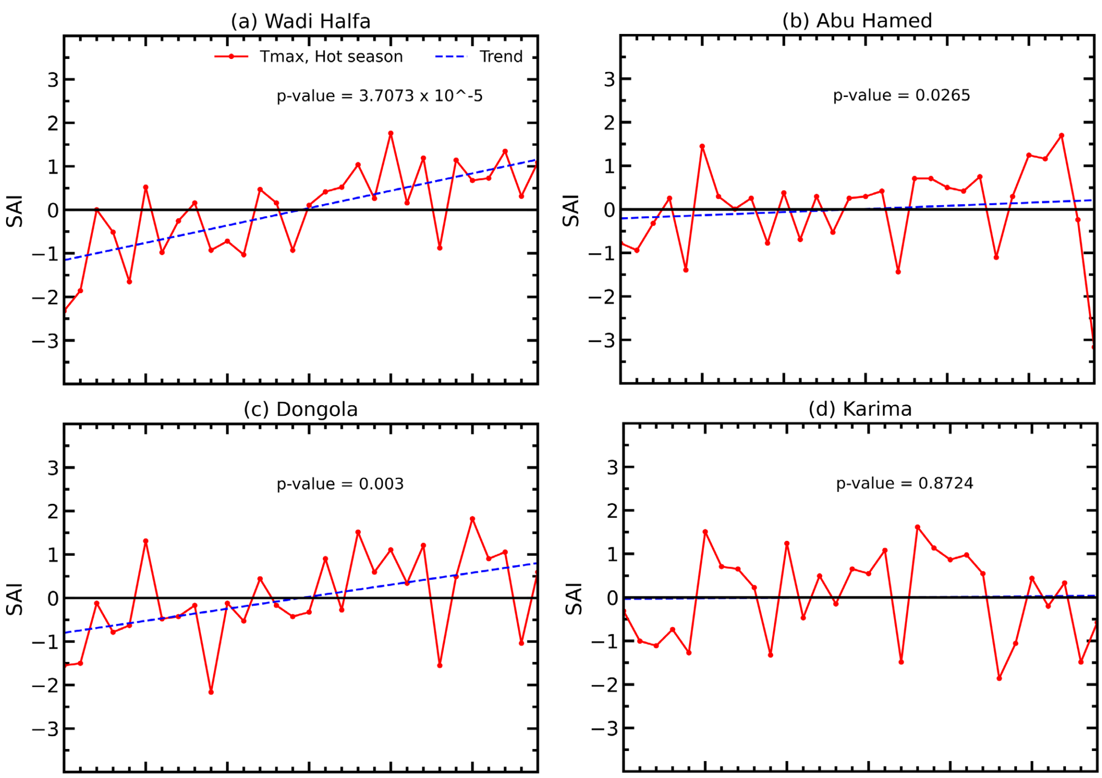



**Figure 6.** The trend of the maximum temperature for the meteorological stations over Northern Sudan (Cold Season).

### 3.2.3. The Maximum Temperature in the Hot Season



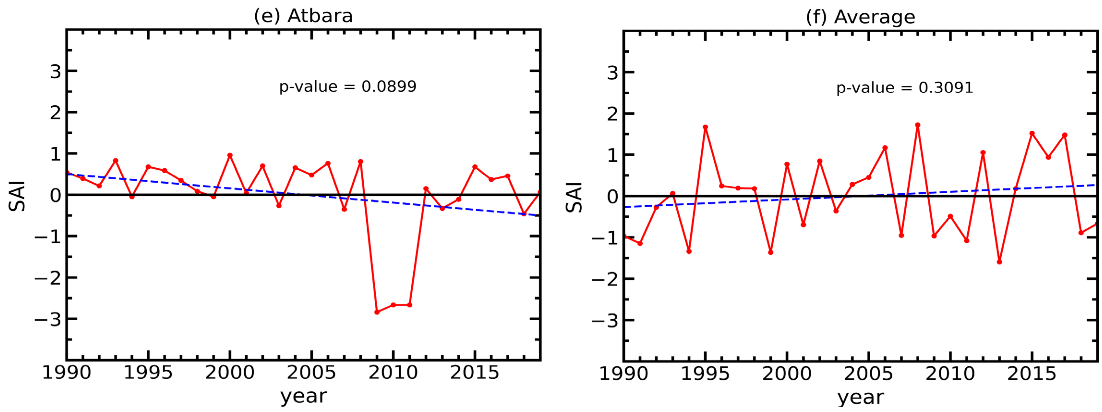



**Figure 7.** The trend of the maximum temperature for the meteorological stations over Northern Sudan (Hot Season).

### 3.2.4. The Maximum Temperature in the Wet Season

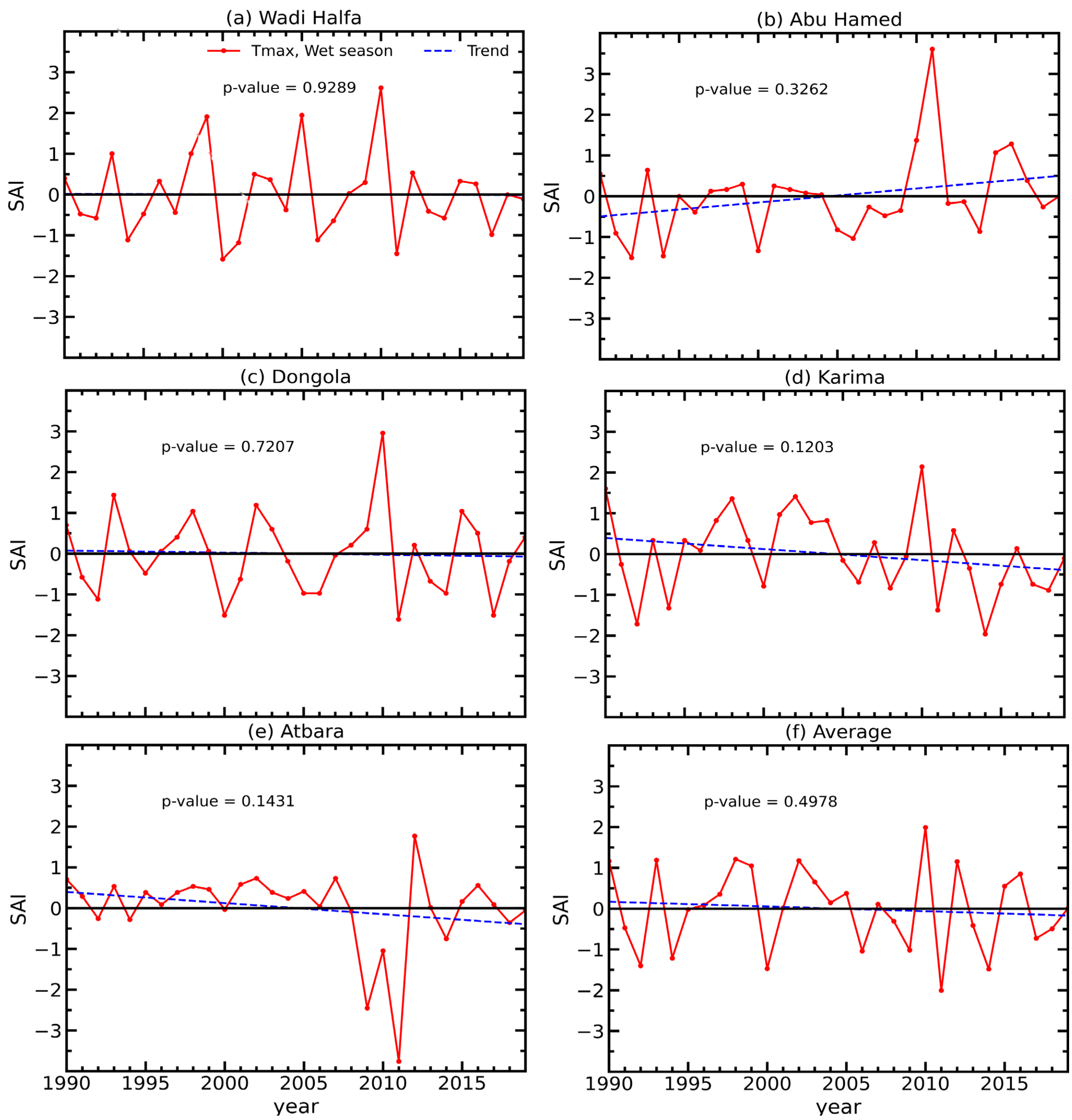



**Figure 8.** The trend of the maximum temperature for the meteorological stations over Northern Sudan (Wet Season).

### 3.3. Spatial and Temporal Distribution of Minimum Temperature

Figure 9 shows the spatial distribution of the minimum temperature over Northern Sudan annually and seasonally during hot, wet, and cold seasons. However, the spatial distribution of annual minimum temperature reveals a predominance of higher temperatures, ranging from 15˚C - 30˚C), with a slight increase in the East and Northeast areas. In addition, the annual average of the minimum temperature over the region is (21.4˚C).

Consequently, the highest annual minimum temperature is observed over Atbara station (22.8˚C), and it also has the highest minimum temperature during hot and cold seasons. Meanwhile, Abu Hamed showed the highest minimum temperature during the wet season at (28.1˚C) (Table 2). On the other hand, Dongola station showed the lowest minimum temperature during the wet season, and the lowest minimum temperature during the wet season was observed in Wadi Halfa station. Overall, the spatial distribution of the minimum temperature shows that the temperature is lower in Northern and Central Northern areas (Figure 9), and the highest minimum temperature was observed during the wet season as the cold season experienced the lowest minimum temperature over the region (Figure 10).

### 3.4. The Trend of the Minimum Temperature

The analysis of the minimum temperature trends in Northern Sudan indicates significant increases in various stations across the different seasons. Mainly, all stations show significant increases in minimum temperatures; perhaps these patterns vary in significance based on the season.

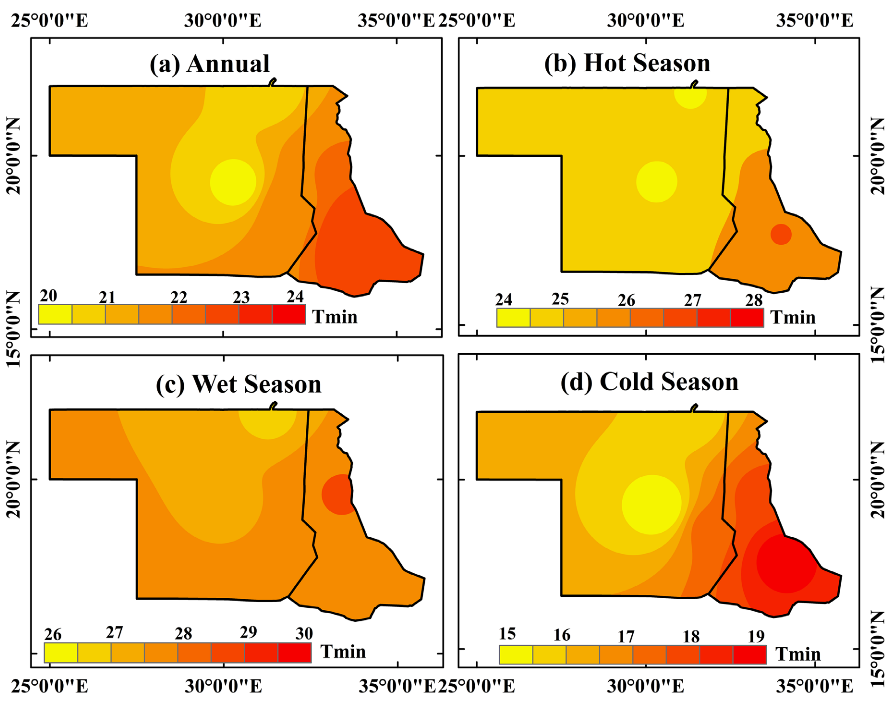



Figure 9. Spatial distribution of the minimum temperature over Northern Sudan.

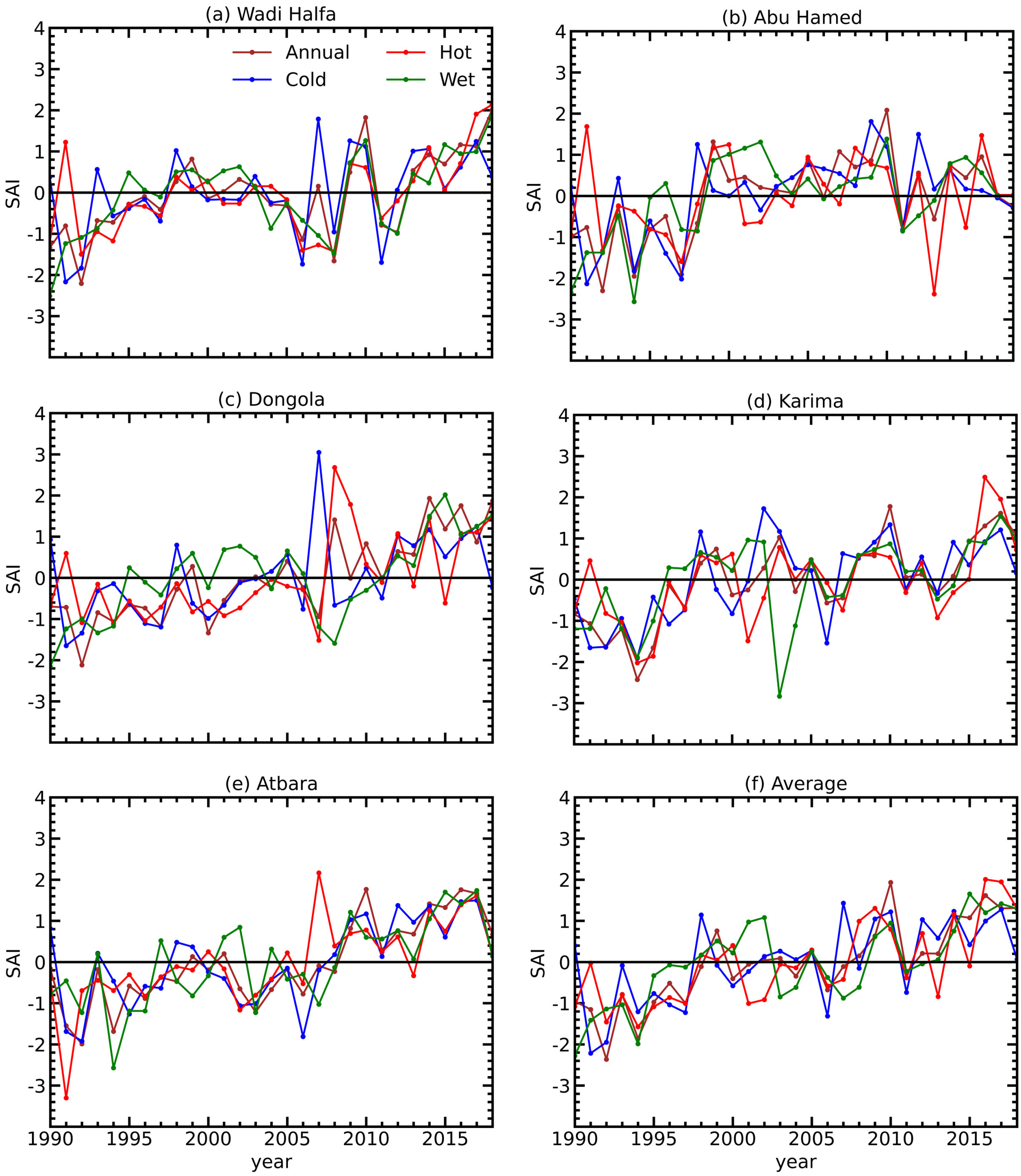



**Figure 10.** The variation of the minimum temperature for the meteorological stations over Northern Sudan and its seasonality.

Minimum temperature trends at Wadi Halfa station have significantly increased over all seasons, suggesting a continually warming trend. The finding highlights how vulnerable Northern Sudan is to increasing temperatures and is consistent with global climate change estimates (Christy & Spencer, 2023).

Dongola station significantly increases minimum temperature trends during the year, similar to Wadi Halfa. The area's dry conditions and low humidity

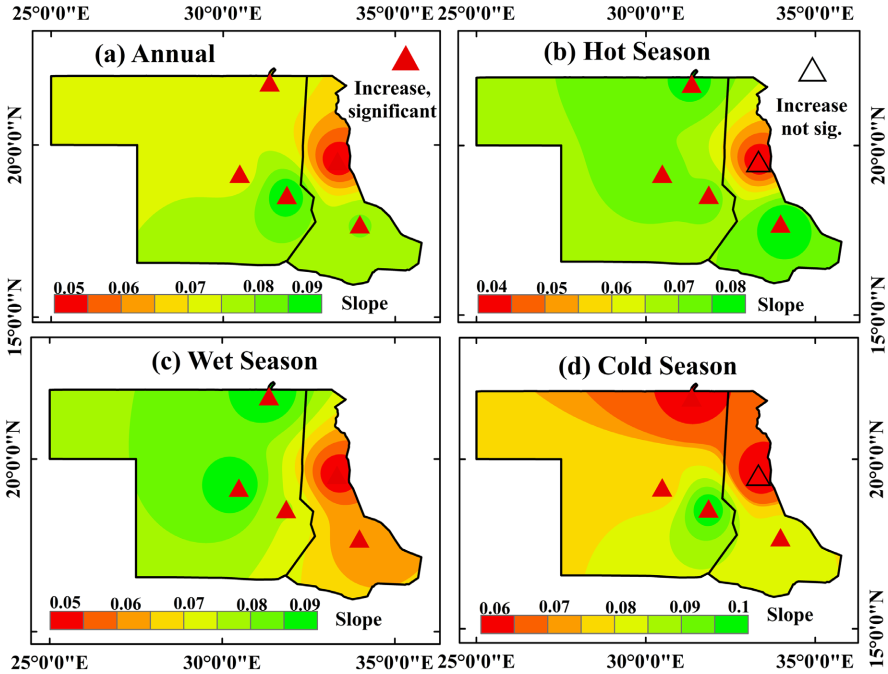



**Figure 11.** Spatial distribution of the minimum temperature trend over Northern Sudan.

make it more vulnerable to heat stress and heat waves, which is why this pattern is particularly evident during the hot season. Consequently, Significant minimum temperature increase trends are observed at the Karima and Atbara stations for the whole year as same as in Wadi Halfa, and Dongola.

On the other hand, during the wet and cold seasons, Abu Hamed station shows increasing minimum temperature trends; however, these trends are not statistically significant during the hot and cold seasons. In addition, due to variations in trend significance, seasonal and regional variations in temperature trends must be considered when examining the impacts and vulnerabilities associated with climate change, and the absence of significant trends in the hot season might be related to factors such as cloud cover, atmospheric moisture content, or specific land surface features that influence variations in the area during dry summer.

### Annual Minimum Temperature

This section reviewed trends currently identified and highlighted significant examples of extremely minimum temperatures in various seasons and years. Thus, Figures 12-15 represent the annual and seasonal trends of the minimum temperature during cold, hot, and wet seasons respectively. The Wadi Halfa station's seasonal trends show that the highest minimum temperature ever measured occurred during the wet (rainy) season of 2018, which also appears to correspond to the year considered to have the highest minimum temperature observed (Figure 15(a)). Thus, in the rainy season of 2010 and the cold season of 1991, respectively, Abu Hamed station recorded the highest (Figure 14(b)) and lowest minimum temperatures (Figure 13(b)). These distinct extremes illustrate

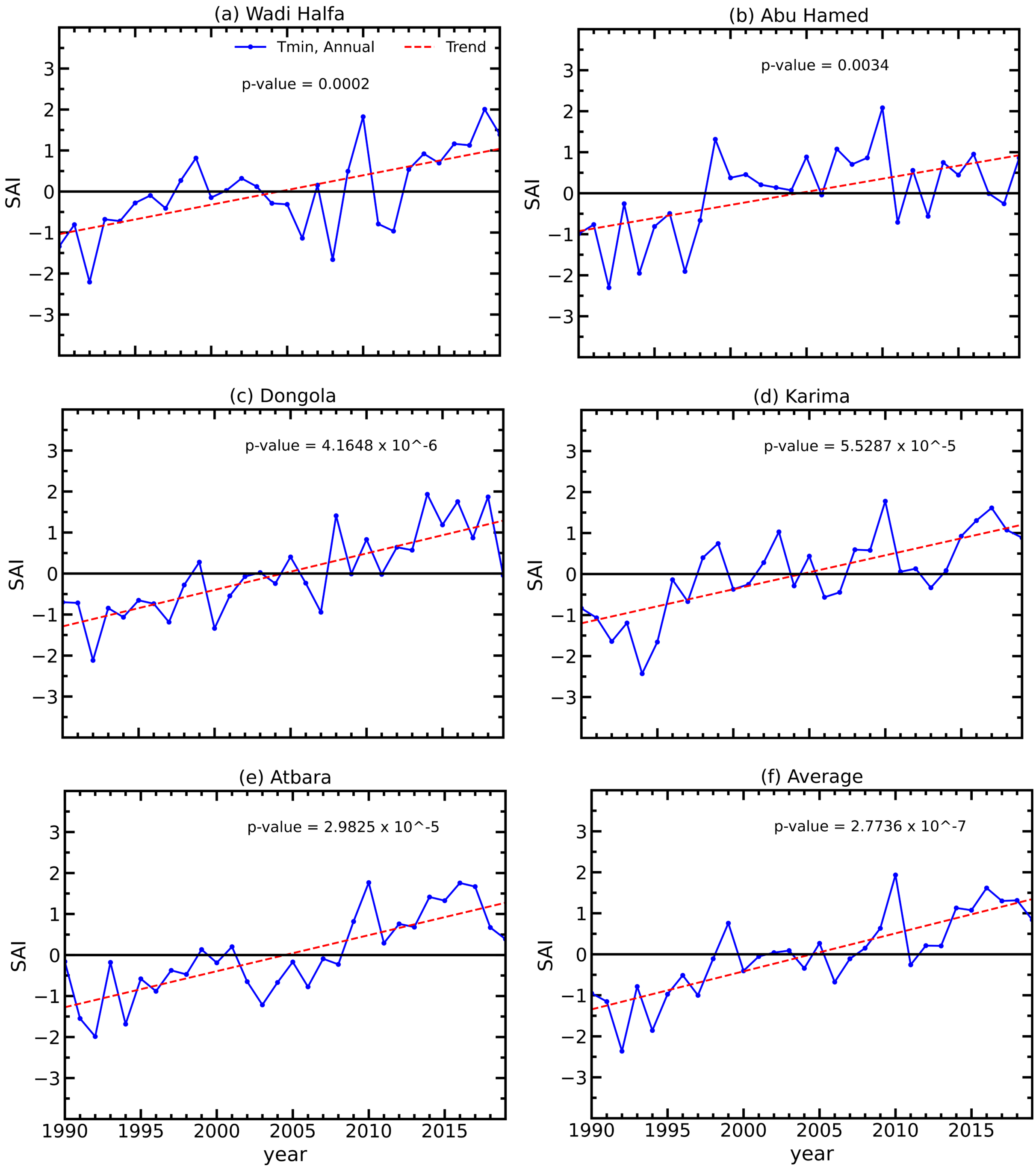



**Figure 12.** The trend of the annual minimum temperature for the meteorological stations over Northern Sudan.

how rapidly temperatures vary in the area and how significant it is to understand the factors influencing temperature variations throughout every season. Additionally, Dongola station experienced certain hot seasons, such as the 2015 wet season (Figure 15(c)) and the lowest temperature recorded in the 1991 cold season (Figure 13(c)). The wet season of 2017 (Figure 15(d)) and the cold season of 1994 (Figure 13(d)) were the two seasons at Karima station, with the highest and the lowest minimum temperatures. Consequently, Atbara station,

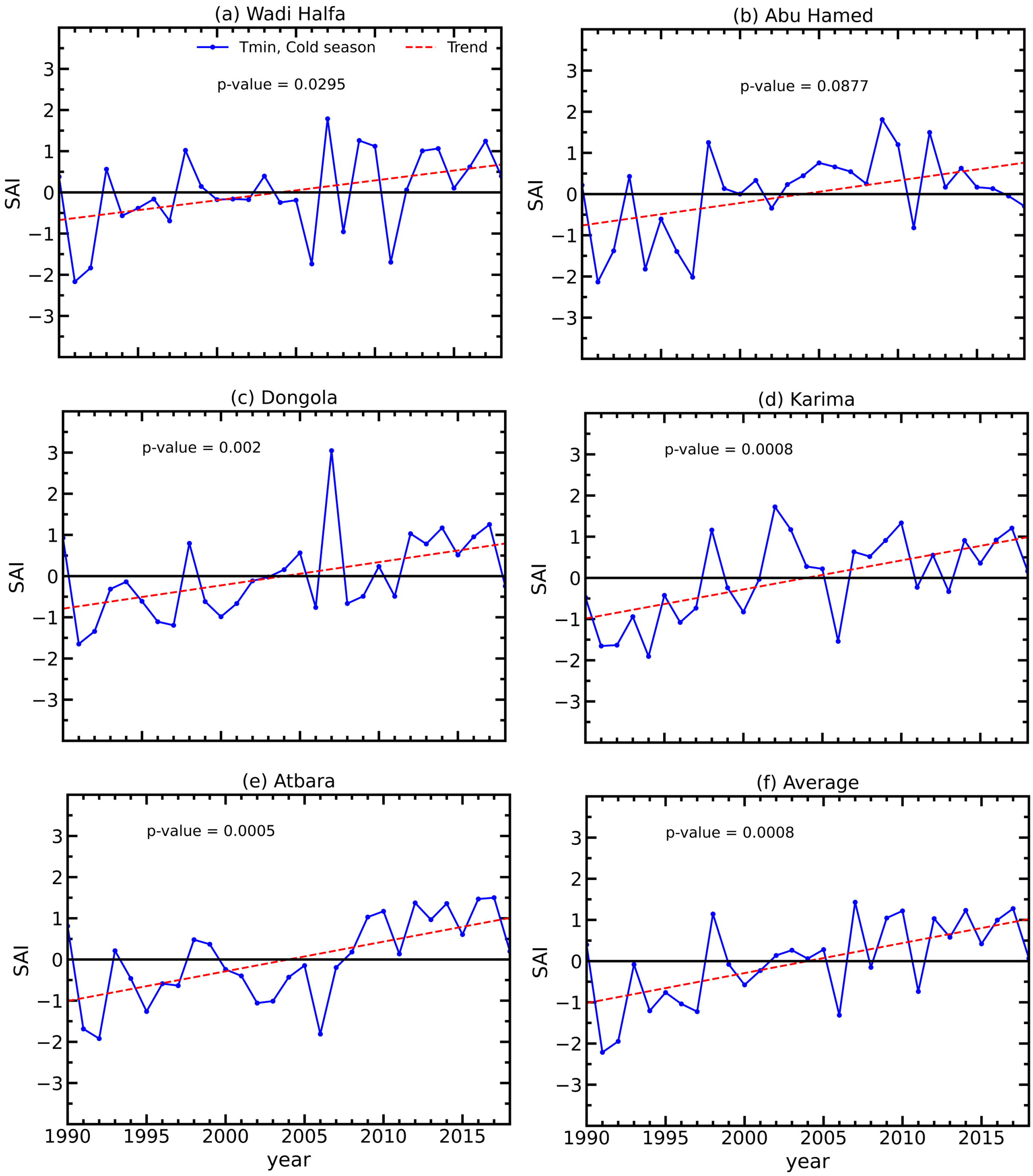



**Figure 13.** The trend of the minimum temperature for the meteorological stations over Northern Sudan (Cold Season).

similar to Karima station, observed the lowest minimum temperature in 1992 during the cold season (Figure 13(e)) and the highest minimum temperature in 2017 during the rainy season (Figure 15(d)). These results highlight the significance of seasonal variations in temperature trends and the impact of climate conditions on temperature extremes and indicate the importance of adaptive methods to mitigate the effects of temperature variations on nearby communities and ecosystems and the spatial and temporal variability of temperature

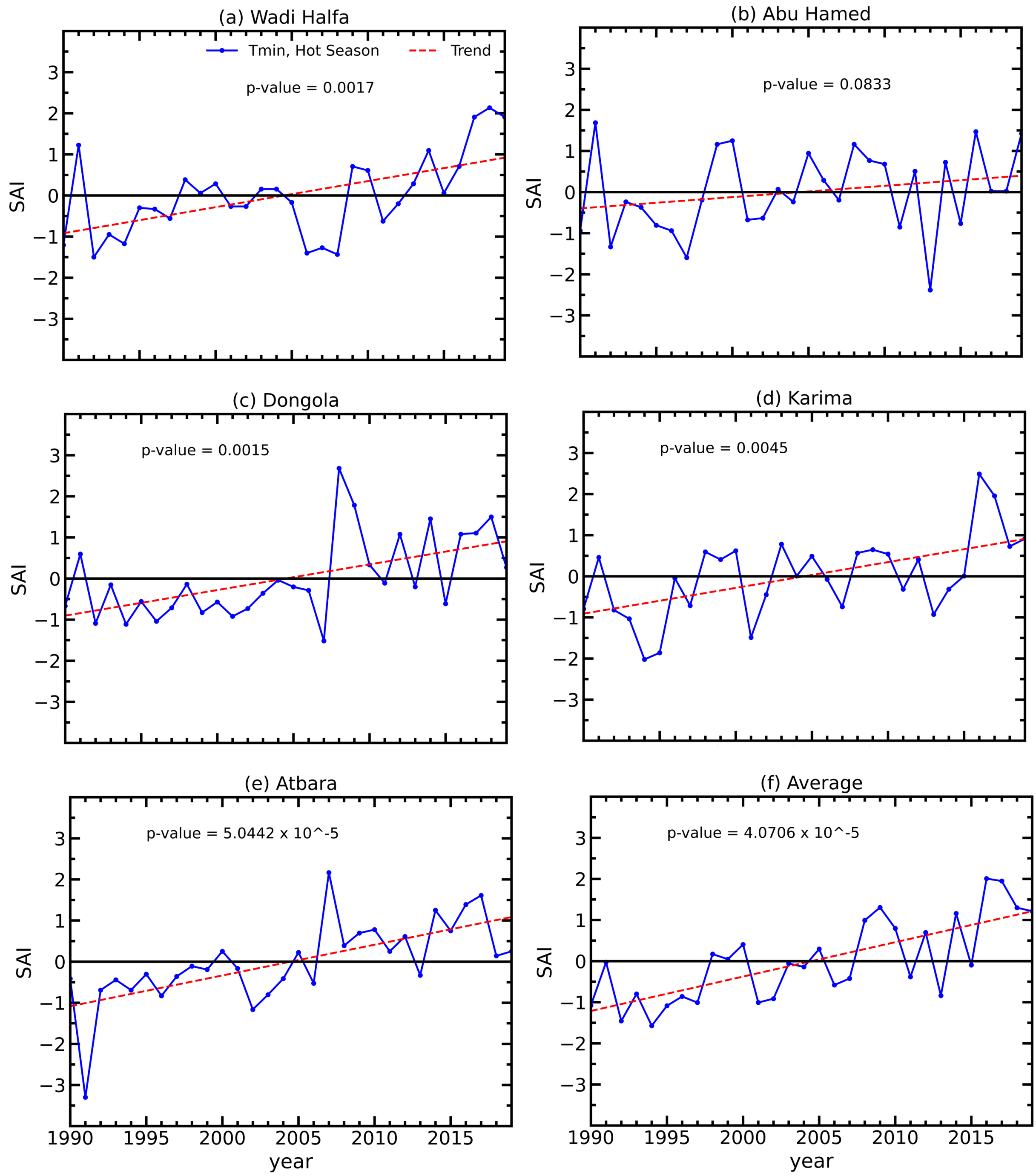



**Figure 14.** The trend of the minimum temperature for the meteorological stations over Northern Sudan (Hot Season).

extremes in Northern Sudan. In addition, the region's vulnerability to temperature extremes and Changes is shown by the outstanding minimum temperatures that have been shown at many locations in Northern Sudan. Developing adaptation strategies for mitigating the impact of climate change on different sectors, such as agriculture, water resources, and public health, requires an understanding of the temporal patterns and causes of temperature changes (IPCC, 2021; Kurukulasuriya & Mendelsohn, 2008).

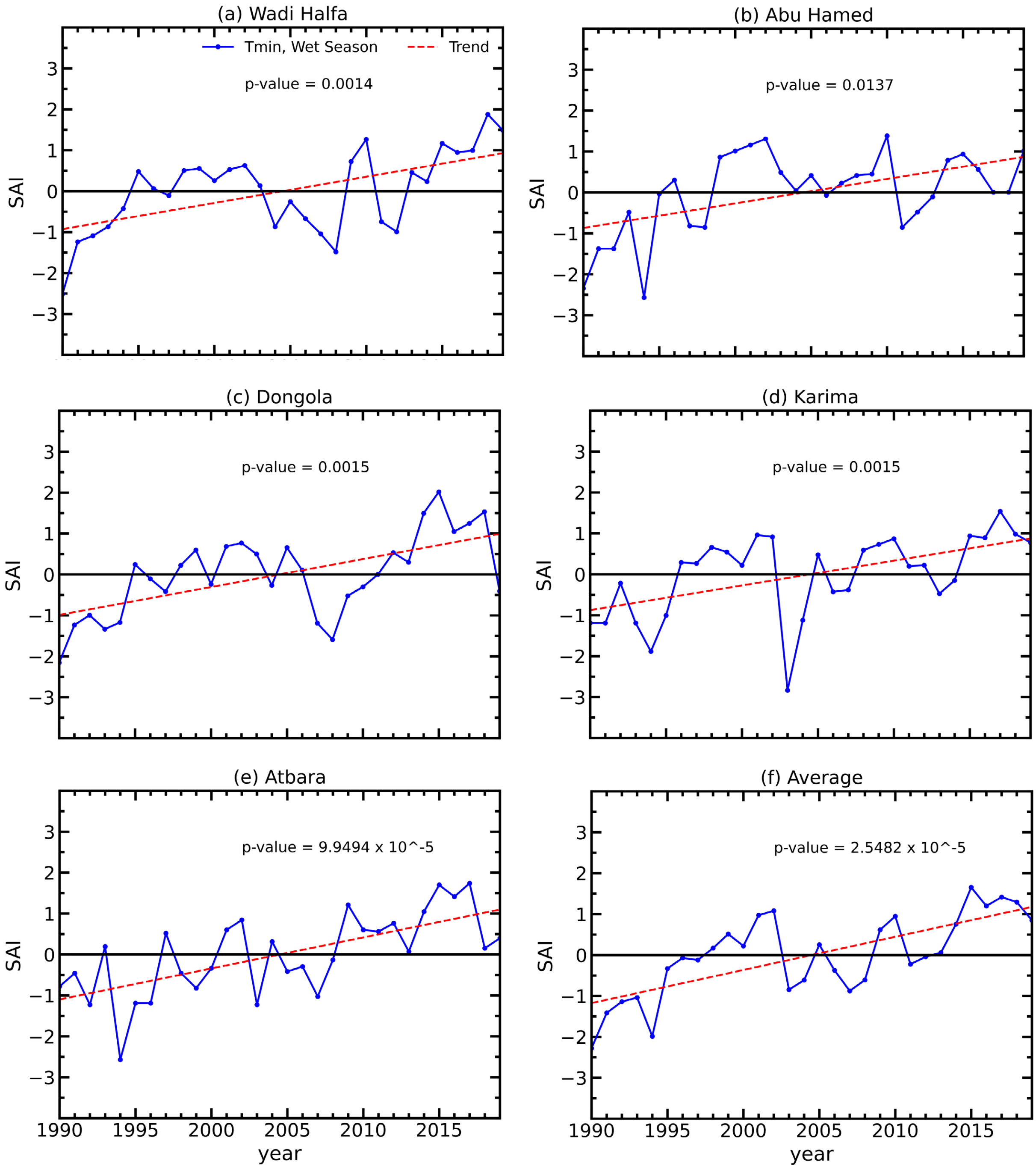



**Figure 15.** The trend of the minimum temperature for the meteorological stations over Northern Sudan (Wet Season).

## 4. Conclusion and Recommendations

In this study, we investigate the spatial and temporal analysis of the maximum and minimum temperature trends over Northern Sudan annually and during the hot (AMJ), wet (JAS), and cold (ONDJFM) seasons from 1990 to 2019 by employing the Mann-Kendall trend and Sen's slope estimator methods. Our results show a mix of decreasing and increasing and no trends in maximum temperature observations at various stations. Therefore, our findings indicate that the region experienced the highest maximum temperatures during the hot season, underscoring the seasonal variability in temperature patterns. On the other hand, all stations showed significant increasing trends in minimum temperatures, with the lowest temperature observed during the cold season, indicating a consistent warming trend in the region over the studied period. Notably, the Abu Hamed station showed no significant increasing trend in minimum temperature, highlighting localized variations in temperature dynamics.

We recommend making further investigations and conducting a deeper analysis of the factors driving the temperature trends in Northern Sudan, such as land use changes, urbanization, and climate change impacts, to provide a more comprehensive understanding of the observed patterns as well as establish a more extensive and robust meteorological monitoring network in Northern Sudan to capture a wider geographical representation and ensure more accurate and reliable temperature data collection for future studies. Consequently, climate change adaptation strategies and mitigation measures should be developed based on the observed temperature trends to enhance the region's resilience to potential temperature fluctuations and extreme weather events. For the local impact assessment, we need to conduct localized impact assessments to understand the implications of temperature trends on various sectors, such as agriculture, water resources, and public health, to implement targeted interventions and policies in addition to the educational initiatives that can raise awareness about the significance of temperature trends and their implications for local communities, policymakers, and stakeholders through educational programs and capacity-building workshops as well as advocating for evidence-based policy formulation and integration of temperature trend analysis findings into regional development plans and climate change adaptation strategies to promote sustainable environmental management and resilience-building initiatives.

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## Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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