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Analysis of Temperature Trends and Variations in the Arabian Peninsula's Upper Atmosphere

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Abstract

In this study, the trends of upper-air temperatures are analysed by utilising radiosonde observations for the barometric levels at 700, 500, 300, 200, 150, 100 and 50 hPa from five meteorological stations within the Arabian Peninsula from January 1986 to August 2015. The mean monthly variations of the temperatures at these levels are characterised and established. The magnitudes of the annual trends of the mean temperatures for each site for the selected barometric levels are studied and statistically tested using Mann-Kendall rank statistics at different significance levels. The temperature trends at different pressure levels show that the upper troposphere and lower stratosphere are warming, while the middle troposphere is cooling which is consistent with the findings of other studies. The variations in upper air temperature observed in this study can be attributed to a range of factors, including increasing greenhouse gas concentrations, changes in atmospheric circulation patterns, variations in solar activity, aerosols and volcanic eruptions, and land use and land cover change.

Keywords

Upper-Air Temperature Variability, Long-Term Trend, Arabian Peninsula, Climate Change, Mann-Kendell

1. Introduction

Climate change, with its associated increase in the surface temperature of the Earth, has become an important topic that is attracting researchers from many different fields. However, climate change is not only limited to the surface temperature, it is also linked to variations in the upper-air temperatures; mainly tropospheric and stratospheric temperatures [1]. The tropospheric and stratospheric temperatures are important components (which complement the surface temperature) of the Earth's climate system. Hence, knowledge of their variations and understanding their trends is of great importance to establishing theoretical bases for global climate modelling. While upper-air temperatures are related to the surface temperature, their variations are somehow different from the surface temperature and have large uncertainty [2] [3] [4].

Several studies of the long-term variations of upper-air temperatures [e.g. [5] [6] [7] [8] [9]] have been carried out and established at different locations around the world. The main results from these investigations show that while the tropospheric temperature has increased significantly since the middle of the last century, the stratosphere temperature has experienced significant cooling. Nevertheless, the magnitude and strength of the cooling and heating are different from one season to another and from one region to another [8] and [10].

A number of studies have related the stratospheric cooling to the modulation of the solar ultraviolet radiation by the 11-year solar cycle [11] [12] [13]. This is because the ultraviolet modulation affects the ozone concentration, which subsequently affects the photochemistry of the stratosphere, resulting in the change in temperature [14]. In contrast, the tropospheric temperature variations may be of terrestrial or extra-terrestrial origin. The terrestrial aspects affecting the tropospheric temperature include regular seasonal variations, quasi-biennial oscillation, variations in greenhouse gases and atmospheric aerosols from different sources [15] [16]. The extra-terrestrial factors may include variations in solar parameters and the modulation of cosmic rays [13] [16] [17] [18] [19] [20].

To better understand and characterise the variations in upper-air temperatures, it is important to study their variations from different climatic regions. Since studies of the long-term variations of upper-air temperatures are sparse for the Arabian Peninsula, it is the purpose of the current study to investigate them for this area. The longest record of radiosonde observations for this region, which covers the period 1986-2015 for different atmospheric levels from five meteorological stations, is utilised for this purpose. The nonparametric Mann-Kendall (MK) test and Sen's slope estimator are used to identify the presence of trends and characterise their magnitude during the study period.

2. Data and Methodology

2.1. Experimental Data

In this study, radiosonde observations from five sites in Saudi Arabia during the period 1986-2015 were obtained from the Saudi Presidency of Meteorology and Environment and used for the purpose of the current study. The selected sites are Riyadh, Abha, Jeddah, Dammam and Tabouk (**Figure 1**). These sites were chosen because they have the longest series of observations, are relatively homogeneous and cover a broad range of the climatic and atmospheric conditions experienced in the region.

Several quality control procedures were applied to the available data to reduce the experimental errors associated with radiosonde observations. These include

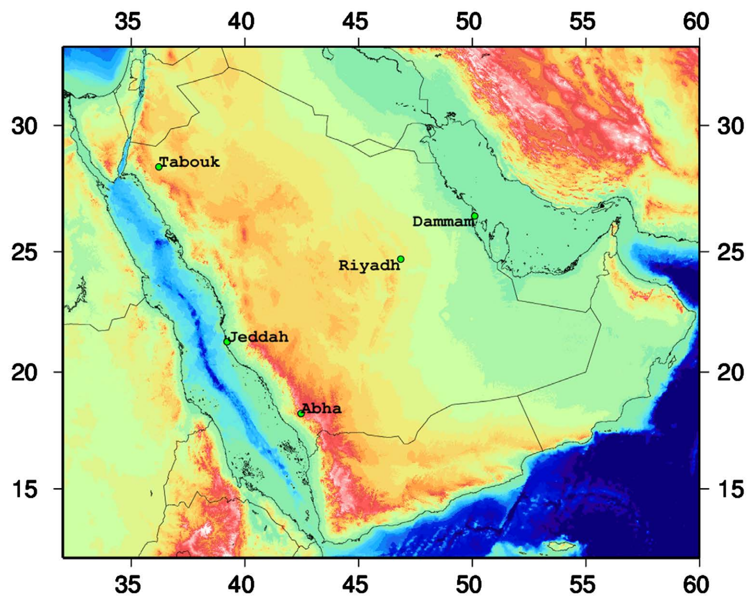

Figure 1. Map of Saudi Arabia and the surrounding regions showing the locations of the selected sites.

homogenisation of the sequence of the radiosonde observations with NCEP reanalysis data (which was used as a reference sequence) using the regression method [1] [21] [22] [23].

For the purpose of the current study, the atmospheric temperatures were extracted from each radiosonde profile for seven standard pressure levels. These levels are 700, 500, 300, 200, 150, 100 and 50 hPa.

The mean temperature values for each layer from each site were binned into twelve categories to investigate their monthly variations. Similarly, data were divided into four seasonal groups to study the seasonal variations of atmospheric temperature at the selected pressure levels for each individual site. The arithmetic mean of the temperatures for each layer, from all the considered sites, was calculated and utilised to investigate their yearly and seasonal variations (T_{mean}). Table 1 summarises some of the basic statistics of the atmospheric temperature at the selected pressure level for each site and the mean values for all the sites.

For the levels from 50 to 500 hPa, the mean temperatures at the Tabouk site were the highest and the temperatures at Abha were the lowest. At 700 hPa, the lowest mean temperature was in Tabouk while the highest was in Abha. The mean temperatures at 50, 100, 150, 200, 300 and 500 hPa were −64.4˚C ± 0.06˚C, −74.9˚C ± 0.09˚C, −63.7˚C ± 0.06˚C, −52.57˚C ± 0.06˚C and −8.56˚C ± 0.07˚C, respectively. At 700 hPa, the mean temperature ranges between 12.1˚C in Abha and 7.35˚C in Tabouk with a mean value of 9.9˚C.

2.2. Analysis Methods

The MK test and Sen's slope estimator were used to identify the presence of any trends in the temperature data. Detailed descriptions of these tests are given in several research articles [e.g. [24]]. These procedures are nonparametric statistical

Table 1. Geographical coordinates, mean and standard errors, for the mean temperature for each site, as well as the mean temperature (˚C), for all the sites for the selected atmospheric layers during the period 1986-2015.

	Abha	Riyadh	Dammam	Jeddah	Tabouk	T_{mean}
Latitude	18.24˚N	24.71˚N	26.39˚N	21.28˚N	28.38˚N	
Longitude	42.51˚E	46.67˚E	49.97˚E	39.23˚E	36.56˚E	
T at 50 hPa	−65.55 ± 0.08	−64.37 ± 0.06	−64.31 ± 0.1	−64.93 ± 0.06	−63.26 ± 0.09	−64.48 ± 0.06
T at 100 hPa	−78.20 ± 0.10	−74.88 ± 0.10	−73.83 ± 0.10	−76.59 ± 0.09	−71.21 ± 0.13	−74.94 ± 0.09
T at 150 hPa	−65.87 ± 0.08	−63.57 ± 0.07	−62.75 ± 0.08	−64.78 ± 0.07	−61.64 ± 0.10	−63.72 ± 0.06
T at 200 hPa	−52.74 ± 0.06	−52.35 ± 0.08	−52.44 ± 0.08	−52.75 ± 0.07	−52.13 ± 0.10	−52.58 ± 0.06
T at 300 hPa	−31.82 ± 0.05	−33.66 ± 0.08	−34.44 ± 0.09	−32.76 ± 0.07	−36.27 ± 0.12	−33.79 ± 0.06
T at 500 hPa	−7.11 ± 0.06	−8.49 ± 0.11	−9.12 ± 0.09	−7.82 ± 0.07	−10.42 ± 0.14	−8.59 ± 0.07
T at 700 hPa	12.18 ± 0.07	9.61 ± 0.09	9.09 ± 0.12	11.35 ± 0.09	7.35 ± 0.14	9.91 ± 0.09

tests that are widely used for the analysis of trends in climatologic time series [25] [26].

For each of the selected atmospheric levels, the MK results for the yearly variations of the atmospheric temperature were discussed first, followed by the results of the seasonal variations.

3. Results and Discussion

3.1. Temperature Trends at 50 hPa

Figure 2 shows the yearly variations of the atmospheric temperature at 50 hPa for all the considered sites and their mean values (T_{mean}). The most obvious trend during this period is a sharp decrease in the temperature after 1992. The maximum changes in the yearly and seasonal temperature trends amongst the seven layers were observed in this layer. The temperatures for all the sites and their mean values, at this layer, show significant decreasing trends.

MK analyses for the yearly and seasonal variations of the average temperature for each site and the mean temperature from all the sites (T_{mean}) are presented in Table 2. The values are approximated for the first decimal.

The mean yearly temperatures at this layer are characterised by a significant decreasing trend with different magnitudes and significant levels. The mean temperatures at Riyadh, Dammam and Tabouk, and T_{mean} decreased by about −1.2˚C with a 99% confidence level. In contrast, the temperature at the Abha site decreased by −1.5˚C (95% significance level) and by −1.2˚C at the Jeddah site with a 90% confidence level.

3.2. Temperature Trends at 100 hPa

The yearly mean values of the temperatures at the 100 hPa level for all the sites and their mean values during the study period are indicated in Figure 3. During this period, the temperatures experience significant decreasing trends between

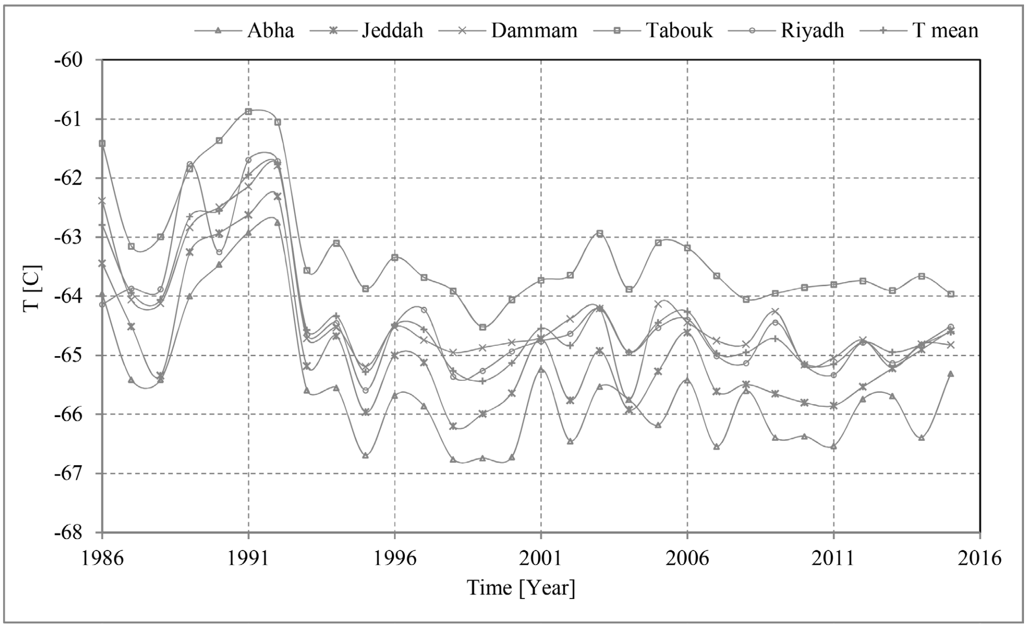

Figure 2. Trends of annual temperatures at 50 hPa pressure level for all the sites and their mean temperature (T_{mean}) for 1986-2015.

Table 2. Summary of MK test results and the Sen slope (Q) values for the yearly variations for the atmospheric temperature at 50 hPa for the five selected sites and their (T_{mean}) for 1986-2015. The changes in the temperatures during the 30-year period are presented in the last column.

	Test Z	Q	Change/30 years
Abha	−2.14*	−0.05	−1.5
Jeddah	−1.78+	−0.04	−1.2
Dammam	−3.31**	−0.04	−1.2
Tabouk	−3.21**	−0.04	−1.2
Riyadh	−2.84**	−0.04	−1.2
T_{mean}	−2.78**	−0.04	−1.2

*** trend at α = 0.001 level of significance. ** trend at α = 0.01 level of significance. * trend at α = 0.05 level of significance. + trend at α = 0.1 level of significance

1992 and 1996 and between 1997 and 1999. The MK results of the yearly and seasonal variations of the average temperature for each site and the mean temperature from all the sites (T_{mean}) are presented in **Table 3**. It is clearly seen that the yearly mean temperature values in Abha, Tabouk, and T_{mean} are decreasing at this height with different significance levels and magnitudes. It decreases by 99.9% in Tabouk by about −1.5˚C. The temperatures, with a 95% confidence level, are decreased by −0.9˚C and −0.6˚C in Abha and the mean temperature from all the considered sites (T_{mean}), respectively.

3.3. Temperature Trends at 150 hPa

The yearly mean values of the temperatures at the 150 hPa level for all the sites

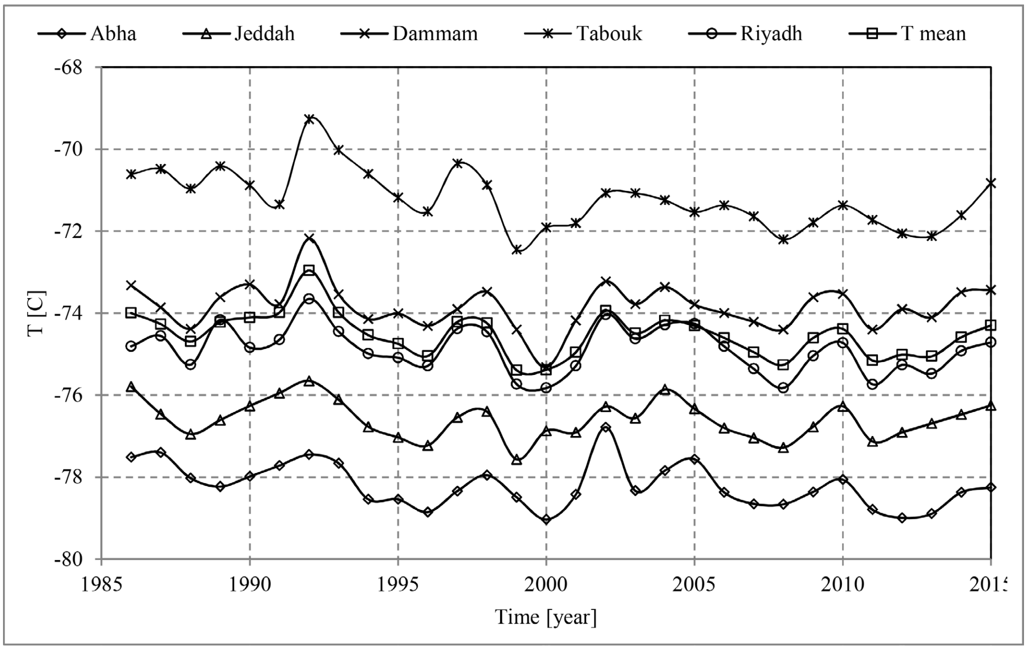

Figure 3. Trends in the annual temperatures at 100 hPa for all sites and their mean temperature (T_{mean}) during the period 1986-2015.

Table 3. Summary of MK test results and the Sen slope (Q) values for the yearly variations for the atmospheric temperature at 100 hPa for the five selected sites and their (T_{mean}) for the period 1986-2015. The changes in temperatures during the 30-year period are presented in the last column.

	Test Z	Q	Change/30 years
Abha	−2.46*	−0.03	−0.9
Jeddah	−1.07	−0.01	−0.3
Dammam	−0.57	−0.01	−0.3
Tabouk	−3.43**	−0.05	−1.5
Riyadh	−1.53	−0.02	−0.6
T_{mean}	−2.21*	−0.02	−0.6

and their mean values during the study period are indicated in **Figure 4** and their MK results are presented in **Table 4**. This layer separates the trends of the atmospheric temperatures, in which layers above this layer have decreasing trends whereas layers below this layer have increasing trends. The 30-year period MK test results indicate that the yearly values of the atmospheric temperature trend at this layer have no significant variation. In contrast, the Tabouk and Abha sites, and the mean temperature from all sites (T_{mean}) present a decreasing trend, with the rest of the sites showing an increasing trend.

3.4. Temperature Trends at 200 hPa

The yearly mean values of the temperatures at the 200 hPa level for all the sites and their mean values during the study period are indicated in **Figure 5** and

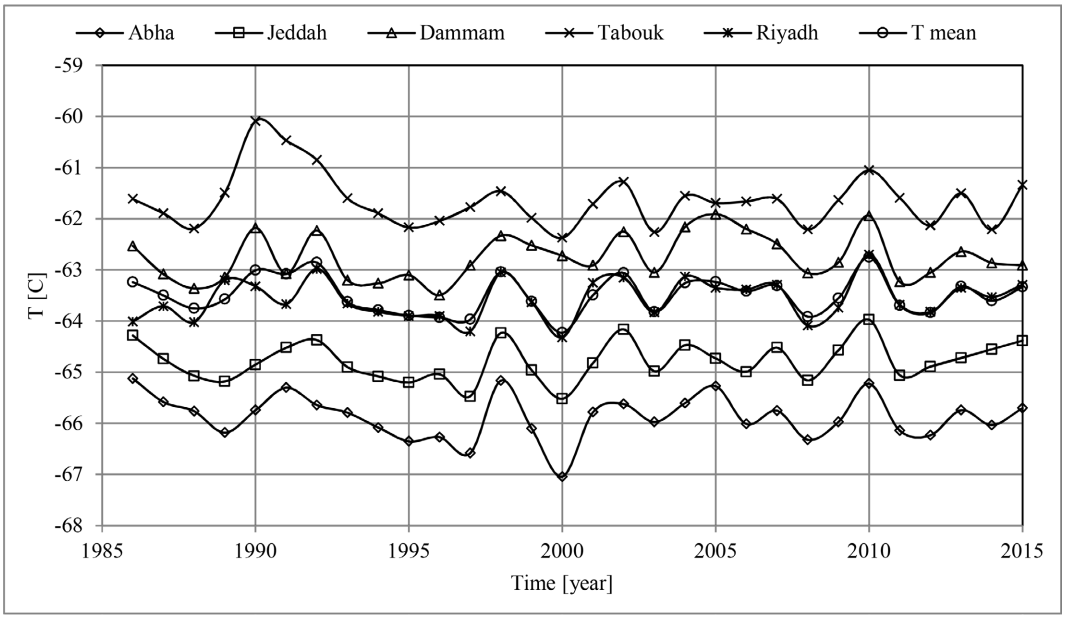

Figure 4. Trends of the annual temperatures at 150 hPa for all the sites and their mean temperature (T_{mean}) during the period 1986-2015.

Table 4. Summary of MK test results and the Sen slope (Q) values for the yearly variations for the atmospheric temperature at 150 hPa for the five selected sites and their (T_{mean}) for the period 1986-2015. The changes in temperatures during the 30-year period are presented in the last column.

	Test Z	Q	Change/30 years
Abha	−0.71	−0.01	−0.3
Jeddah	0.95	0.01	0.3
Dammam	1.29	0.01	0.3
Tabouk	−0.20	0.001	0.03
Riyadh	0.89	0.01	0.3
T_{mean}	−0.32	0.001	0.03

their MK results are presented in **Table 5**. At this layer, the yearly mean temperature values in Dammam increased by 0.6˚C with a 90% confidence level and by 0.9˚C in Tabouk with a 95% confidence level. In contrast, the yearly mean temperatures for the rest of the sites and the mean temperature from all the sites (T_{mean}) show a non-significant increasing trend.

3.5. Temperature Trends at 300 hPa

Figure 6 indicates the yearly variations of the atmospheric temperatures at the 300 hPa level for all the sites and their mean values during the study period and their MK results are presented in **Table 6**. At this layer, the mean temperature for all the sites (T_{mean}) showed an increasing trend by 0.6˚C with a 90% confidence level. The yearly mean temperature in Tabouk increased by 0.9˚C (α = 0.05

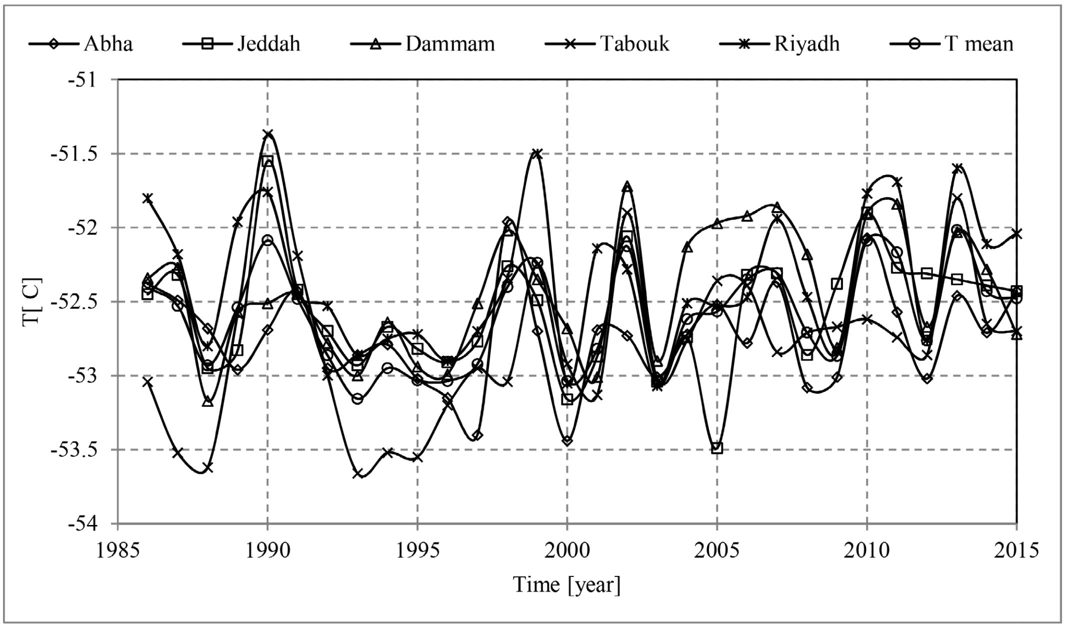

Figure 5. Trends of the annual temperatures at 200 hPa for all the sites and their mean temperature (T_{mean}) during the period 1986-2015.

Table 5. Summary of MK test results and the Sen slope (Q) values for the yearly variations for the atmospheric temperature at 150 hPa for the five selected sites and their (T_{mean}) for the period 1986-2015. The changes in temperatures during the 30-year period are presented in the last column.

	Test Z	Q	Change/30 years
Abha	0.11	0.001	0.03
Jeddah	1.07	0.007	0.21
Dammam	1.77+	0.02	0.6
Tabouk	2.36*	0.03	0.9
Riyadh	0.82	0.01	0.3
T_{mean}	1.499	0.01	0.3

significance level). The rest of the sites showed no significant trend in their annual mean temperatures during the study period.

3.6. Temperature Trends at 500 hPa

The yearly variations of the atmospheric temperatures at the 500 hPa level for all the sites and their mean values during the study period are shown in **Figure 7**. The MK analyses for temperature trends at this layer are presented in **Table 7**. The mean temperature from all the sites (T_{mean}) and temperature at Abha increase significantly at the $\alpha = 0.01$ significance level by 0.6˚C. Tabouk showed an increasing trend of 1.2˚C at a confidence level of 99%. The rest of the sites showed no significant variations in their temperatures at this level during the study period.

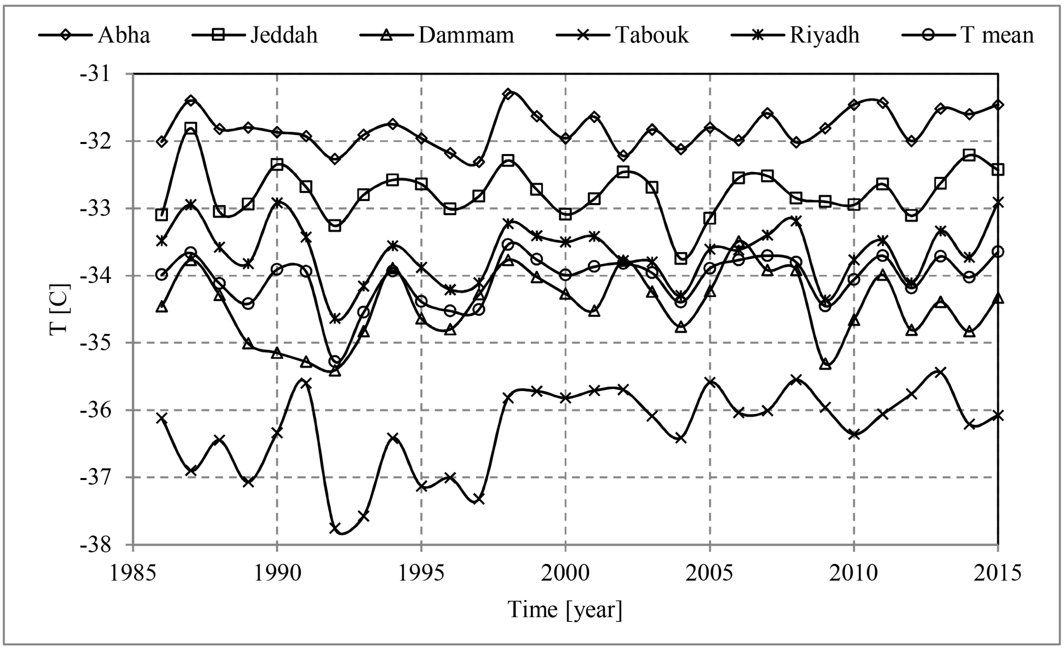

Figure 6. Trends of the annual temperatures at 300 hPa for all the sites and their mean temperature (T_{mean}) during the period 1986-2015.

Table 6. Summary of MK test results and the Sen slope (Q) values for the yearly variations for the atmospheric temperature at 300 hPa for the five selected sites and their (T_{mean}) for the period 1986-2015. The changes in the temperatures during the 30-year period are presented in the last column.

	Test Z	Q	Change/30 years
Abha	1.34	0.01	0.3
Jeddah	0.59	0.01	0.3
Dammam	0.63	0.01	0.3
Tabouk	2.48*	0.03	0.9
Riyadh	0.21	0.001	0.03
T_{mean}	1.762+	0.02	0.6

3.7. Temperature Trends at 700 hPa

The yearly variations of the atmospheric temperatures at the 500 hPa level for all the sites and their mean values during the study period are presented in **Figure 8**. The MK analysis results given in **Table 8** indicate a significant increase in the yearly temperature (confidence level of 95%) by ~0.9˚C in Jeddah and the mean temperature from all sites (T_{mean}) and by 1.2˚C in Tabouk. The yearly mean temperature at Abha increased by ~0.6˚C with a 90% confidence level.

4. Discussion

This study investigates variations in upper air temperature trends across different pressure levels and locations in Saudi Arabia using the longest available

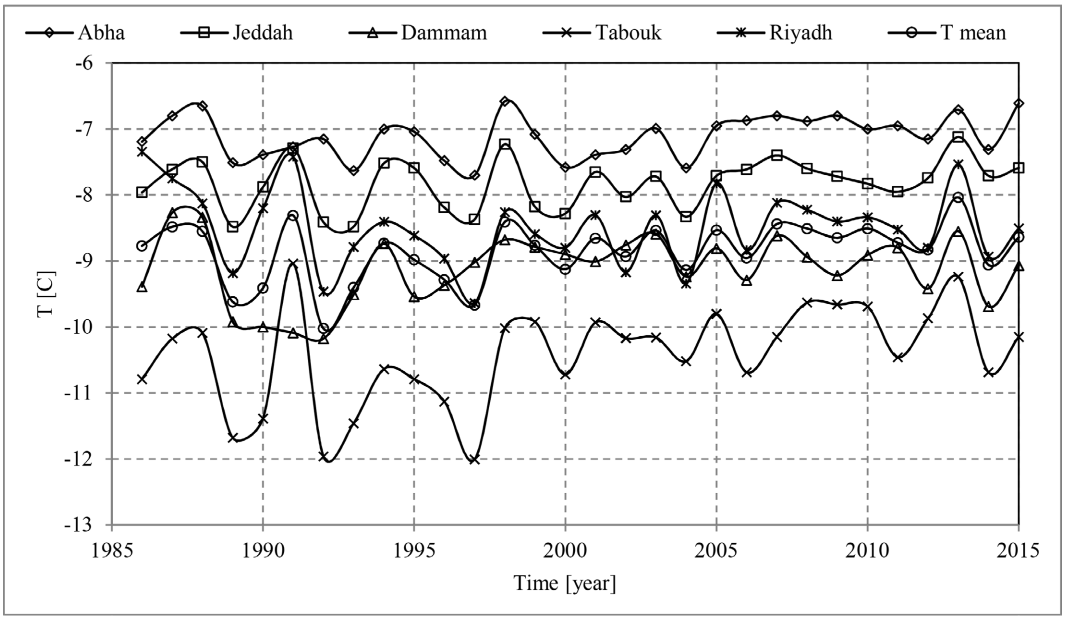

Figure 7. Trends of the annual temperatures at 500 hPa for all the sites and their mean temperature (T_{mean}) during the period 1986-2015.

Table 7. Summary of MK test results and the Sen slope (Q) values for the yearly variations for the atmospheric temperature at 500 hPa for the five selected sites and their (T_{mean}) for the period 1986-2015. The changes in temperatures during the 30-year period are presented in the last column.

	Test Z	Q	Change/30 years
Abha	1.79^{+}	0.02	0.6
Jeddah	1.268	0.01	0.3
Dammam	0.85	0.01	0.3
Tabouk	2.66^{**}	0.04	1.2
Riyadh	−0.678	−0.01	0.3
T_{mean}	1.785^{+}	0.02	0.6

historical data from 1985 to 2015. Understanding these variations is important for comprehending the complex interactions between the atmosphere and climate, as temperature trends can differ based on altitude, latitude, and local conditions. The results reveal significant decreasing trends in temperature at higher pressure levels (50 hPa and 100 hPa) and increasing trends at lower levels (200 hPa to 700 hPa) for some sites. The observed temperature trends can be attributed to several factors, including increasing greenhouse gas concentrations, changes in atmospheric circulation patterns, variations in solar activity, aerosols and volcanic eruptions, and land use and land cover change. The variations in upper air temperature observed in this study can also be influenced by altitude, latitude, and seasonal variations.

Increasing concentrations of greenhouse gases, such as carbon dioxide and

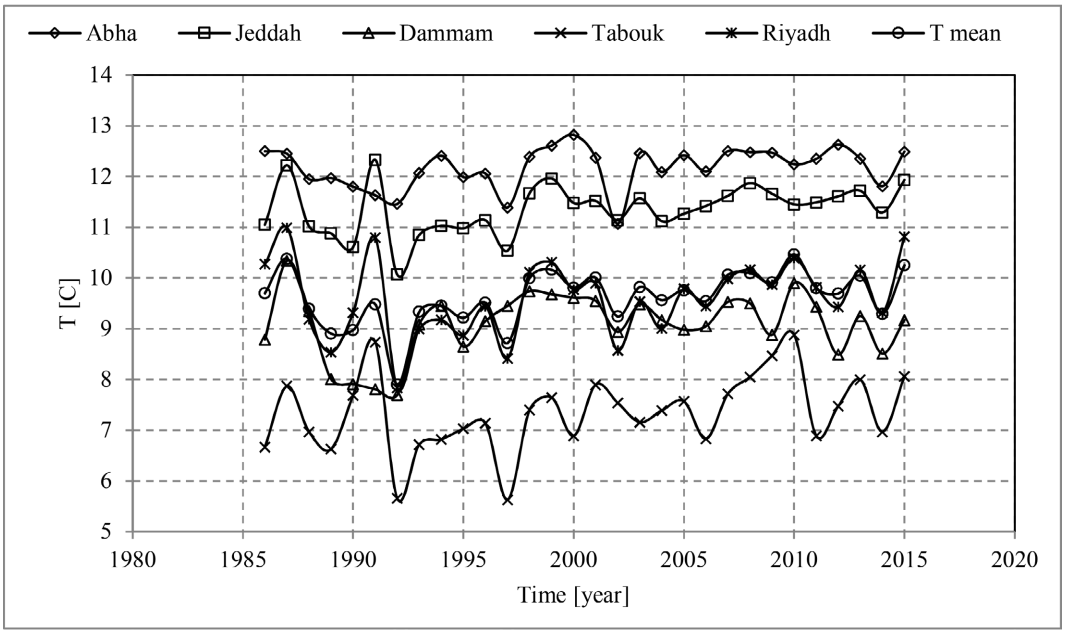

Figure 8. Trends of the annual temperatures at 700 hPa for all the sites and their mean temperature (T_{mean}) during the period 1986-2015.

Table 8. Summary of MK test results and the Sen slope (Q) values for the yearly variations for the atmospheric temperature at 300 hPa for the five selected sites and their (T_{mean}) for the period 1986-2015. The changes in the temperatures during the 30-year period are presented in the last column.

	Test Z	Q	Change/30 years
Abha	1.74+	0.02	0.6
Jeddah	2.55*	0.03	0.9
Dammam	0.54	0.01	0.3
Tabouk	2.46*	0.04	1.2
Riyadh	1.43	0.03	0.9
T_{mean}	2.49*	0.03	0.9

methane, traps heat in the lower atmosphere and cause cooling in the upper atmosphere (Santer *et al.*, 2003; Randel *et al.*, 2009; Randel *et al.*, 2016). The cooling of the upper atmosphere has been observed to be stronger in the polar regions due to the polar vortex. Moreover, changes in atmospheric circulation patterns, such as the strength and location of the polar vortex, can affect the transport of heat and moisture to different parts of the atmosphere and lead to temperature variations (Jiang *et al.*, 2017 a and b; Cohen *et al.*, 2018).

Variations in solar activity, such as changes in the intensity of solar radiation, cosmic ray modulation, and magnetic fields, can affect the temperature and density of the upper atmosphere [27] [28] [29]. Aerosols and particles in the atmosphere, such as those released by volcanic eruptions, can affect the amount of solar radiation that reaches the Earth's surface and alter atmospheric temperature and circulation patterns [30] [31].

Changes in land use and land cover, such as deforestation and urbanization can alter the surface energy balance and affect atmospheric temperature and circulation patterns [23]-[33]. In our case, the rapid urbanization and expansion of infrastructure in the central city of Riyadh can lead to higher temperatures due to the urban heat island effect. In addition, replacing vegetation with impervious surfaces such as roads and buildings can lead to higher temperatures.

Localized factors, such as land use changes and general circulation patterns, can also influence temperature trends. For example, in the southern city of Abha, the rapid expansion of agriculture and irrigation can lead to cooling in the lower atmosphere through evapotranspiration. However, the increased humidity in the lower atmosphere can also lead to warming through the greenhouse effect. In addition, the general circulation patterns associated with the Indian monsoon can bring moisture and precipitation to the region, affecting temperature trends [34].

In the eastern city of Dammam, the observed temperature trends can be influenced by the city's proximity to the Arabian Gulf, the prevailing winds, and the general circulation patterns associated with the subtropical high-pressure system [35]. The warm waters of the Gulf can lead to higher temperatures near the coast, while the prevailing winds can transport warm air from the surrounding desert regions inland. The subtropical high-pressure system can also influence temperature and precipitation patterns in the region.

The observed temperature variations in the coastal city of Jeddah can be influenced by increasing greenhouse gas concentrations, the general circulation patterns associated with the Red Sea trough, and the city's rapid industrialization and population growth. The observed temperature trends in the city of Tabouk are influenced by the general circulation patterns associated with the subtropical high-pressure system [35].

The fact that temperature trends vary across different sites is an important finding, as it suggests that local conditions and regional climate patterns can play a significant role in shaping the upper air temperature trends and variations. This highlights the need for more detailed and localized studies of upper atmospheric temperature trends and variations in different regions around the world.

5. Conclusions

Radiosonde observations for the period 1986 to 2015 from five sites in Saudi Arabia were utilised to characterise the variations of the temperatures at seven pressure levels (700, 500, 300, 200, 150, 100 and 50 hPa) and investigate their trends. Nonparametric Mann-Kendal tests were used to detect the magnitude of these trends.

The study found that the temperature at the 50 hPa layer shows a sharp decrease after 1992, with significant decreasing trends observed for all the sites and their mean values. The yearly mean temperatures at this layer decreased by about −1.2˚C to −1.5˚C, depending on the site, with varying levels of significance. At the 100 hPa layer, significant decreasing trends were observed between 1992 and 1999, with yearly mean temperatures decreasing by −0.6˚C to −1.5˚C, depending on the site. The 150 hPa layer showed no significant variation in the yearly mean temperature trend during the 30-year period, except for Tabouk and Abha, which showed a decreasing trend. At the 200 hPa layer, yearly mean temperatures increased in Dammam and Tabouk with significance levels ranging from 90% to 95%, while the other sites showed no significant trend in their annual mean temperatures. The 300 hPa layer showed a significant increasing trend in the yearly mean temperature for all the sites and their mean values, with an increase of 0.6˚C observed with a 90% confidence level. The yearly mean temperatures at 500 hPa level showed an increasing trend at Abha, Tabouk and the temperature from all the sites T_{mean} during the study period. At 700 hPa, the yearly mean temperature increased significantly at Tabouk, Abha, Jeddah and the mean temperature from all the sites by 1.2˚C, 0.6˚C, 1.2˚C and 0.9˚C, respectively. The findings suggest that changes in atmospheric temperatures are occurring at different rates and with varying significance levels across different layers of the atmosphere. The temperature of the upper atmosphere is subject to a number of variations, including those due to altitude, latitude, season, and human activities. Localized studies are crucial to understanding the specific temperature trends and variations in different regions of the world. Understanding the causes of the observed variations in upper air temperature is essential for predicting and mitigating the impacts of climate change on the environment and society.

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Statements & Declarations

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Author Contributions

All the work presented in this paper was conducted by the author.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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