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Variability of CPT and tropopause characteristics over the Arabian Peninsula

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सार – अरब प्रायद्वीप जैसे उपोष्णकटिबंधीय क्षेत्र में शीत-बिंदु क्षोभमंडलीय सीमा (सीपीटी) और क्षोभमंडलीय विशेषताओं की जलवायु विज्ञान की जांच सीपीटी विशेषताओं के रेडियोसॉन्डे डेटा और क्षोभमंडलीय विशेषताओं के एनसीईपी के पुनर्विश्लेषित डेटा का उपयोग करके की जाती है। सऊदी अरब में मदीना, तबुक और दम्मम नामक तीन स्टेशनों के जनवरी और जुलाई माह के मासिक औसत डेटा का विश्लेषण किया गया है। सीपीटी के रुझान और दबाव, ऊंचाई, तापमान, तापमान विसंगतियों, सापेक्ष आर्द्रता, पवन की गति और संभावित तापमान की क्षोभमंडलीय सीमा की विशेषताओं का भी विश्लेषण किया जाता है। इन विशेषताओं की प्रवृत्तियों से पता चलता है कि इनमें 1990 के दशक के दौरान एक तेज बदलाव और 2000 से 2016 की अवधि में एक महत्वपूर्ण परिवर्तन का अनुभव किया गया है । इस अध्ययन की पूरी अवधि में, जुलाई के महीने में, सीपीटी और क्षोभमंडलीय दबाव लगभग 5 एचपीए तक कम हो गया, जबकि ऊंचाई 100 मीटर से अधिक बढ़ गई। 1990 के दशक की शुरुआत के दौरान तापमान में अचानक गिरावट और बाद के वर्षों में जनवरी में एक सहज गिरावट का अनुभव हुआ। इसके अलावा, 90 के दशक की अवधि के दौरान सीपीटी तापमान और सौर चक्र के बीच एक मजबूत सहसंबंध पाया गया, फिर इस अवधि के बाद इसमें तेजी से कमी आई।

इसके अलावा, 70 hPa, CPT और 100 hPa के स्तरों के तापमान के बीच तुलना की गई है। विशेष रूप से 1990 के दशक के दौरान उनके बीच सहसंबंध जनवरी में मजबूत है, लेकिन जुलाई में थोड़ा कमजोर है।

ABSTRACT. The climatology of the cold-point tropopause (CPT) and tropopause characteristics in a subtropical area like The Arabian Peninsula is examined using the radiosonde data of the CPT characteristics and NCEP Reanalysis data of the tropopause characteristics. The monthly mean data for January and July are analyzed for three stations, namely Medina, Tabuk and Dammam in Saudi Arabia. The trends of CPT and tropopause characteristics of pressure, height, temperature, temperature anomalies, relative humidity, wind speed and potential temperature are also analyzed. The trends of these characteristics show that they experienced a sharp change during the 1990s and a significant change for the period from 2000 to 2016. For the whole period of study, the month of July, CPT and tropopause pressure decreased for about 5 hPa, whereas the height increased for more than 100 m. The temperature experienced a sudden drop during the beginning of the 1990s and a smooth decrease during the following years in January. Furthermore, a strong correlation is found between the CPT temperature and the Solar Cycle during the ‘90s period then it decreased sharply after this period.

Moreover, a comparison between the temperature of the levels of 70 hPa, CPT and 100 hPa is made. The correlation between them is strong in January, but a little bit weaker in July, in particular during the 1990s.

Key words – Tropopause, Cold-point tropopause, The Arabian Peninsula, Temperature, Pressure, Height, Humidity, Wind speed, Potential temperature.

1. Introduction

The cold point tropopause is defined as the level of lowest temperature separating the troposphere from the stratosphere. The characteristics of this level experienced significant changes during the last decades. Most studies now focus on tropical cold point tropopause (CPT) and give less attention to its changes in subtropics. In fact, many studies have demonstrated a strong relation between tropopause and stratospheric characteristics. The troposphere and stratosphere are characterized by different dynamical and chemical properties (Holton *et al*., 1995). The tropical tropopause temperature is the main factor controlling stratosphere water vapor variations (Simmons *et al*., 1999; Fueglistaler *et al*., 2005; Rosenlof and Reid, 2008; Gettelman *et al*., 2010; Wang *et al*., 2015; Dessler *et al*., 2016). Small changes of stratospheric water vapor can significantly modify the global radiation budget (Forster and Shine, 1999; Dessler *et al*., 2013) demonstrated a close connection between interannual variations in tropical tropopause temperatures and stratospheric water vapor. Randel *et al*. (2006) show that

Fig. 1. The studied are. Source http://weather.uwyo.edu/upperair/sounding.html (Modified)

the sudden decrease in the stratospheric water vapor after 2001 is attributed to the reduced tropical tropopause temperature.

The analysis of the tropical tropopause temperature is significantly sensitive to climate variability and climate change and it has therefore drawn a great deal of attention over the past decades (Gettelman *et al*., 2009; Son *et al*., 2009; Feng, 2012). Several studies have shown that changes in tropical tropopause temperature are the result of combined effects. Zhou *et al*. (2001b) show that the leading modes of CPT temperature variability are associated with the quasi-biennial oscillation (QBO) and El Niño-Southern Oscillation (ENSO). Several studies have also confirmed that QBO and ENSO are the primary drivers of variations in tropical tropopause temperature from 1950 to 1980 (Randel *et al*., 2000; Gettelman and Forster, 2002l; Hatsushika and Yamazaki, 2001). There are also studies related to the cooling trend in the CPT temperature for the period of 1973-1998 (Zhou *et al*., 2001 a).

In addition to its long-term trend and interannual variability (Hatsushika and Yamazaki, 2001), tropical tropopause temperature sometimes shows extreme warming or cooling in a year, for example, Randel et al. (2000) found an abrupt decrease in tropical tropopause temperature (approximately - 1 K) in 2001, leading to a sudden decrease of stratospheric water vapor during the same period. On the other hand, the case associated with the strong warming of the tropical tropopause needs to be analyzed. This study is primarily focused on investigating the trends of CPT and tropopause characteristics of the subtropical tropopause during the period 1990-2016 and its correlation with the geopotential levels 100 hPa and 70 hPa. The paper is organized as follows: Section 2 gives a description of the data and methods used in the study, the results are discussed in Sections 3 and the conclusions are presented in Section 4.

TABLE 1

Homogeneity test results of the CPT temperature yearly series in Tabuk and Medina [1990-2016] and for Dammam in the period [1998-2016]

City/Station	*P*-value	Alpha	Test result
Tabuk	0.98	0.05	Accept the null hypothesis H_0
Medina	0.35	0.05	Accept the null hypothesis H_0
Dammam	0.30	0.05	Accept the null hypothesis H_0

2. Data and methodology

The CPT is defined in this study as the position where the temperature is the coldest in the temperature profile. The CPT is studied over the subtropical part of The Arabian Peninsula in January and July for the period from 1990 to 2016 for three meteorological stations: Medina (24.55° N, 39.7° E), Tabuk (28.38° N, 36.60° E) and Dammam (26.4° N, 50° E) (Fig. 1). The data used is sounding data which is obtained from the website of University of Wyoming (http://weather.uwyo.edu/upperair/sounding.html). Daily soundings for the two months January and July for 0000 UTC are analyzed. January sounding data for years 2000, 2001 and 2002 for Medina and January 1995 data for Tabuk are missed. In these cases the missing data are interpolated. Data for Dammam station started from 1998. The tropopause and the levels H100 hPa and H70 hPa data and ENSO, Quasi-Biennial Oscillation (QBO) and Solar Cycle Indices are derived from NCEP/NCAR Reanalysis data.

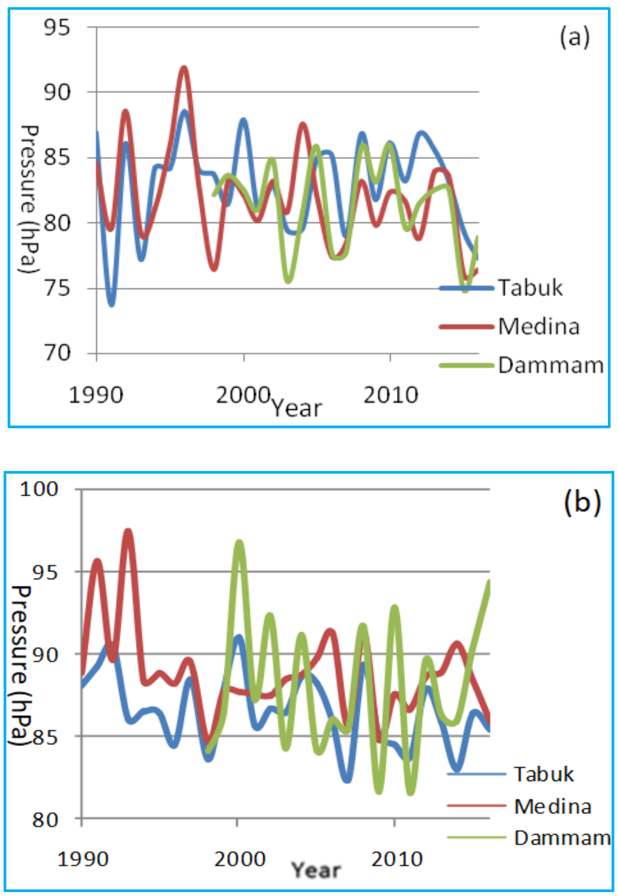
Initially a homogeneity test of the data is done. The CPT temperature data set for the 3 stations was subjected to homogeneity testing. For this purpose, a standard normal homogeneity test (SNHT) is used. The SNHT is applied for detecting abrupt homogeneity breaks in the temperature series (Alexandersson, 1986; Moberg and Alexandersson, 1997). It is well worth mentioning that the test is more sensitive to breaks near the beginning and the end of a series (Martinez *et al*., 2009), station relocations, changes in instrument exposure, or abrupt changes in the immediate environment can cause such unrepresentative shifts in the data.

The results of the test are shown in Table 1. The SNHT assumes a null hypothesis (H_0) which indicates that

TABLE 2

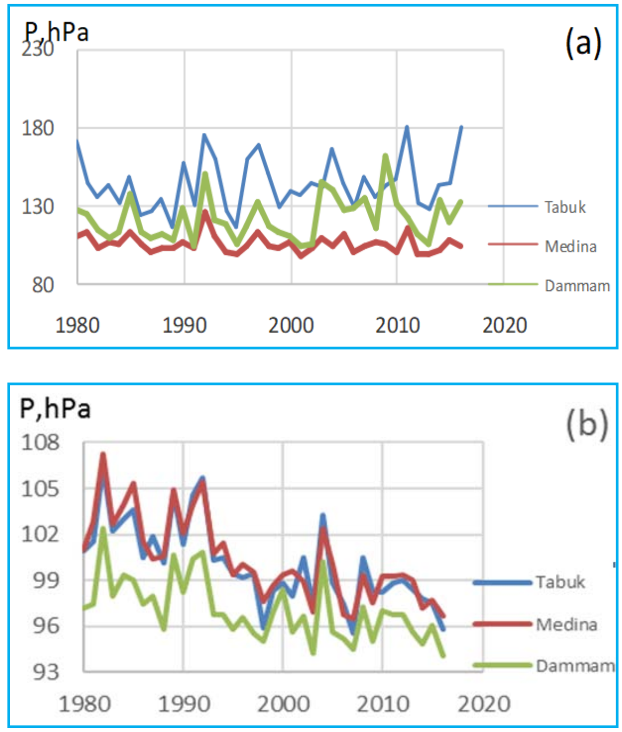
Mann-Kendall trend test results for the CPT temperature series (Alpha 5%)

City/Station	*P*-value	Value of trend	Test result
Tabuk	0. 9335	-0.0013	Cannot reject the null hypothesis H_0
Medina	0.5594	-0.0372	Cannot reject the null hypothesis H_0
Dammam	0. 3630	0.0692	Cannot reject the null hypothesis H_0



Figs. 2(a&b). Long-term CPT pressure trend for (a) January and (b) July

data are homogeneous in comparison with the alternative hypothesis (H), which states that there is a change in the data. This means, that (H_A) assumes that a step-wise shift (a break) in the mean is present. The test results indicate that the CPT mean Temperature series of our data is homogenous and there are no significant shifts in their mean values, due to a change in surrounding conditions of the stations or relocations.



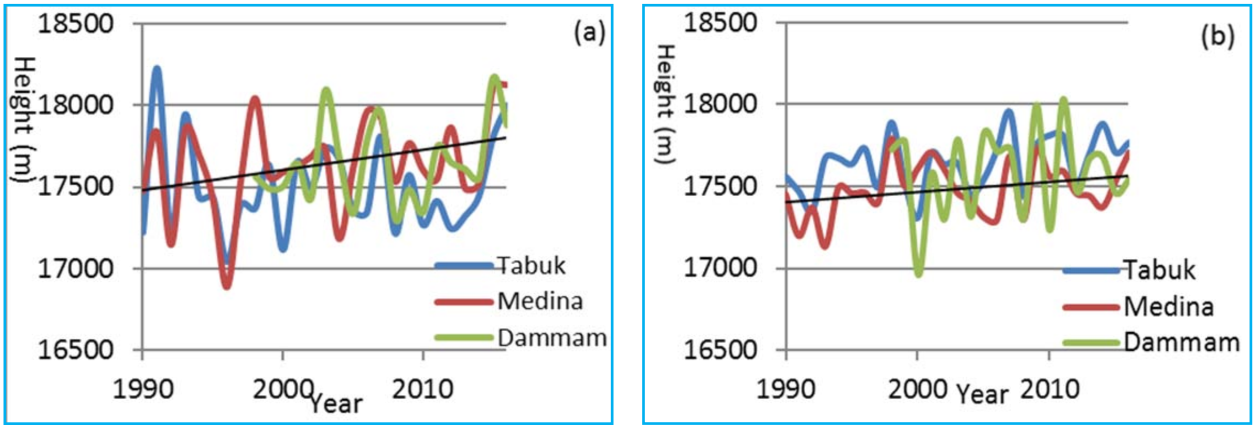
Figs. 3(a&b). Long-term tropopause pressure trend for (a) January and (b) July

To test the trend in the data, we use the Mann-Kendall trend test (Mann, 1945; Kendall, 1975) to determine if they reveal significant trends. According to this test, the null hypothesis (H_0) assumes that there is no trend and this is tested against the alternative hypothesis (H_0), which assumes that there is a trend. If no trend is detected, the data is assumed to be independent and randomly ordered. The result of the trend test is shown in Table 2.

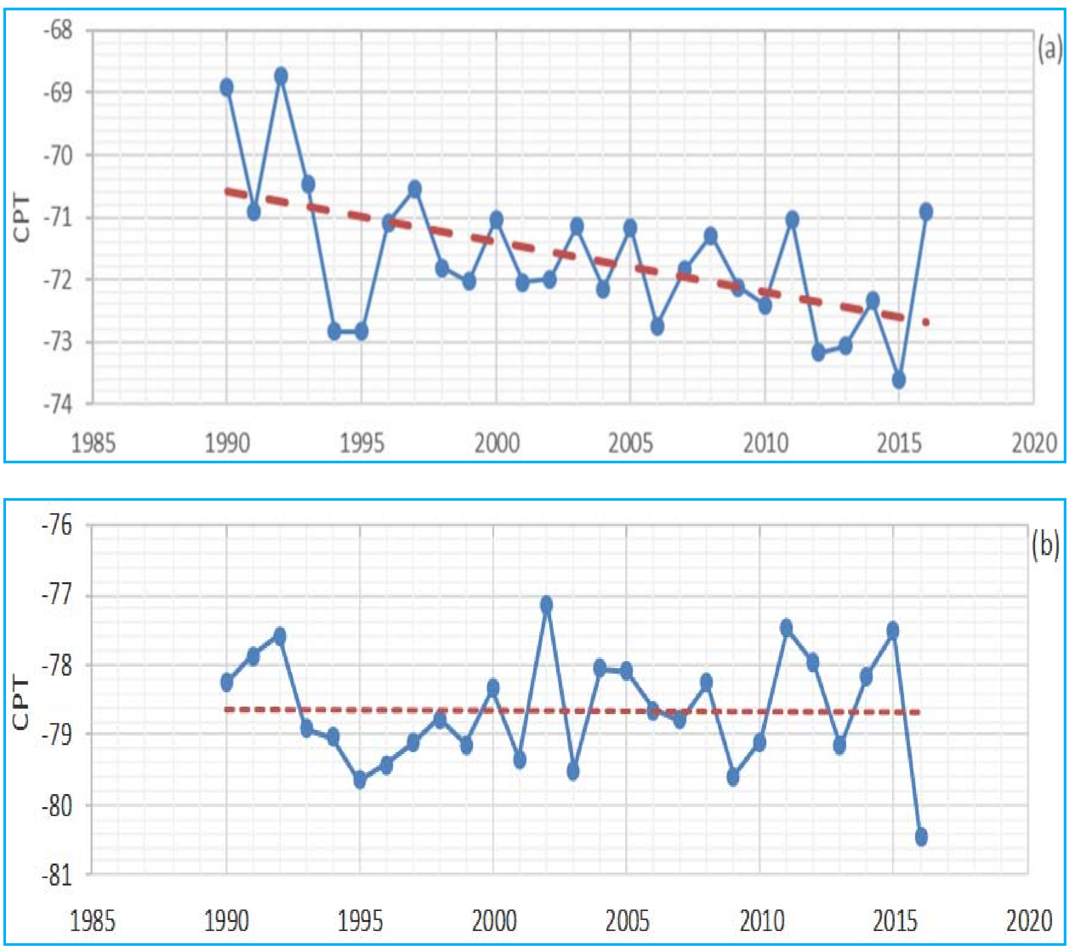
3. Results

The analysis of long-term monthly mean of the pressure of the CPT [Figs. 2(a&b)] shows that it has a clear decreasing trend in July. Also, it decreases more uniformly in Tabuk than in Medina and Dammam. During the period of study (1990-2016), the July monthly mean pressure decreased by about 5 hPa. Although the January monthly mean pressure is more irregular for all stations, it is also showing a decreasing trend (weak for Tabuk and Dammam and strong for Medina).

The long term monthly mean of tropopause pressure for the same stations is shown in Figs. 3(a&b). The January monthly mean pressure is fluctuating irregularly for both stations, Tabuk and Dammam and showing a gradual decrease for Medina (around 3-4 hPa). The behaviour of the tropopause pressure is similar to the CPT



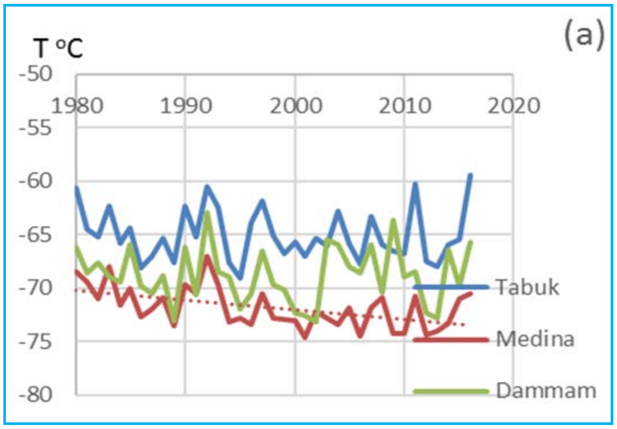
Figs. 4(a&b). Long-term CPT height for (a) January and (b) July

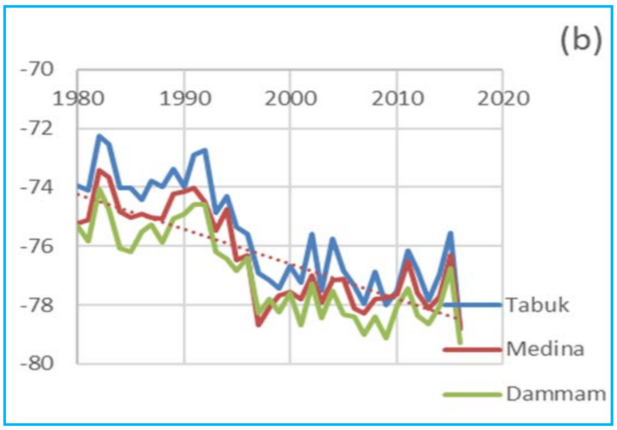


Figs. 5(a&b). Long-term CPT temperature for Tabuk in (a) January and (b) July

pressure trend particularly for July (mean tropopause pressure decreased about 5 hPa and showed a sharp decrease during 1992-1995.

However, the behaviour of January means of the CPT height is more fluctuated; it shows an increasing trend for both stations Medina and Dammam [Fig. 4(a)]. The long-





Figs. 6(a&b). Long term tropopause temperature trend for (a) January and (b) July

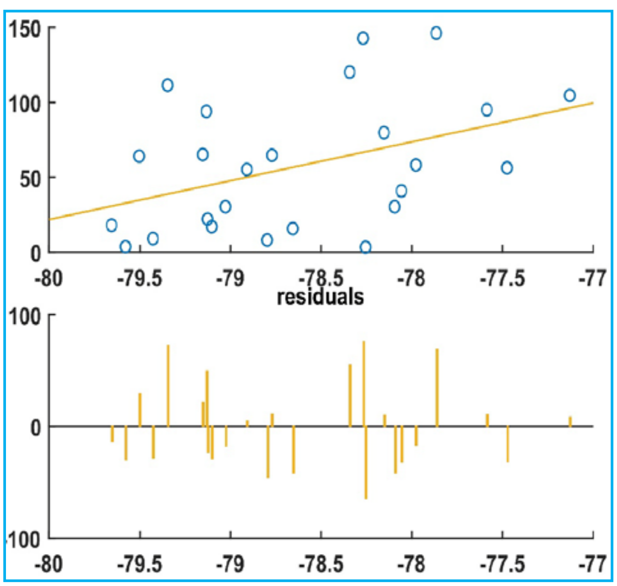


Fig. 7. Regression linear line for Tabuk in July (upper subplot) and the residuals (lower subplot)

TABLE 3

Correlation between CPT temperature and Solar Cycle and linear fit

CPT Temperature Data Set	Correlation coefficient (ρ)	Linear fit: $Y = a + bX$
Data 1990-1999	0.7977	a = 4789.8, b = 59.951
Data 2000-2014	0.1638	a = 754.83, b = 8.9224

term July monthly mean of the height of the CPT shows that it increased for about 100 m for Medina and 200 m for Tabuk [Fig. 4(b)].

The CPT temperature is colder for about 4-6 °C in July than in January for all stations [Figs. 5(a&b)]. Nevertheless, the long term shows a significant drop in temperature during 1993-1995 in both months, the drop is stronger in January (for about 2-3 °C). The trend of the following years shows a weak decrease in January and an increase and becoming more fluctuating in July.

The tropopause temperature is more fluctuating in January especially for Tabuk and Dammam, but shows slow decreasing trend in Medina [Figs. 6(a&b)].

A detailed analysis of CPT temperature in July is performed to investigate the substantial changes in CPT temperature during the 1990s. For this purpose, the correlations between the CPT temperature and the three indices: ENSO, QBO and Solar Cycle are calculated. Furthermore, a multivariable regression analysis has been conducted using these variables.

ENSO and QBO show weak correlation while the Solar Cycle index which is highly correlated. Fig. 7 with 2 subplots shows the relation between the CPT temperature and the Solar Cycle considering all the data from 1990-2014. The upper subplot shows a scatter plot of the data together with the liner fit given as:

$$Y = 2094.1 + 25.904X$$

where, X represents the solar cycle index and Y stands for the CPT temperature. Moreover, the correlation coefficient is found to be 0.4182. The subplot below shows the residuals of the fitting equation.

The correlation is checked again between those two variables (CPT temperature and Solar Cycle) by considering two intervals; the first is from 1990 to1999, while the second one is from 2000 to-2014 (Table 3). Fig. 8 shows the corresponding plot for these two periods.

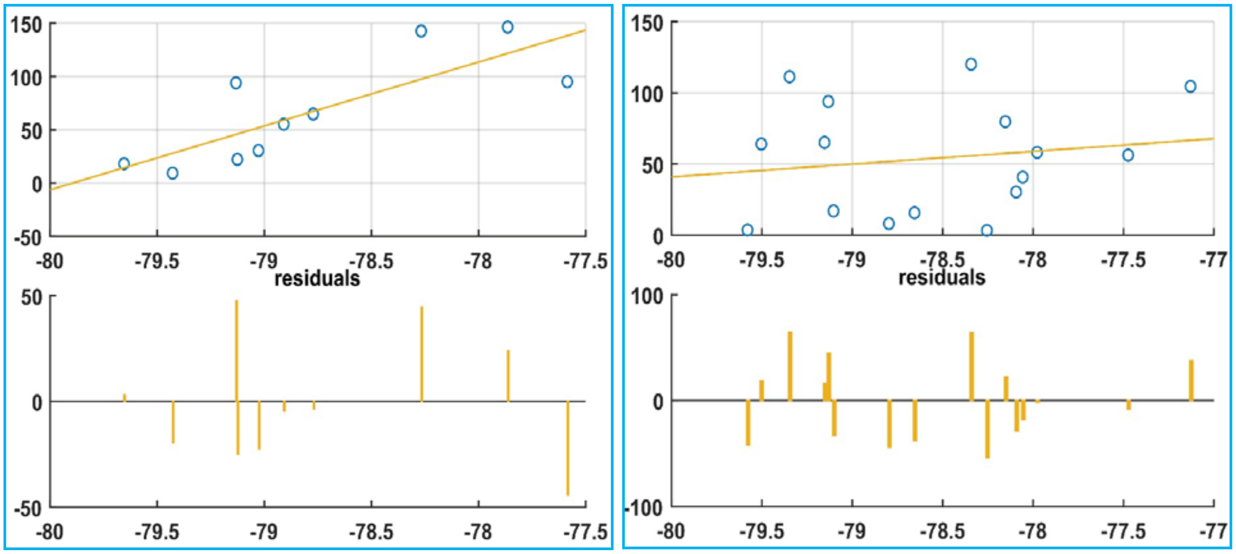
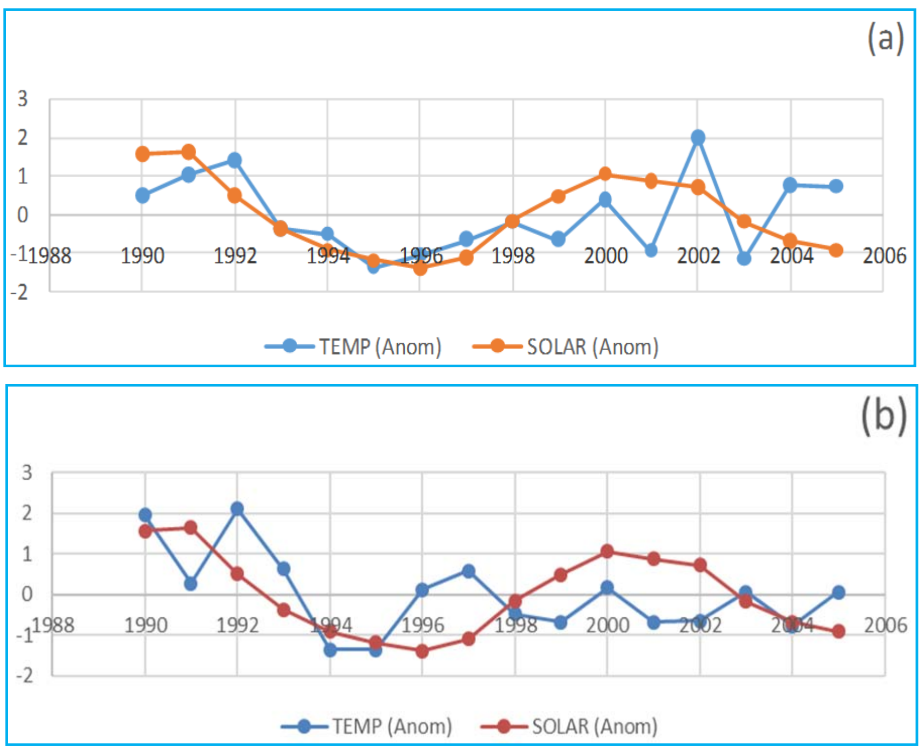


Fig. 8. Regression linear line and residual for Tabuk in July for the period 1990-1999 (Left subplot) and for the period 2000-2014 (Right subplot)

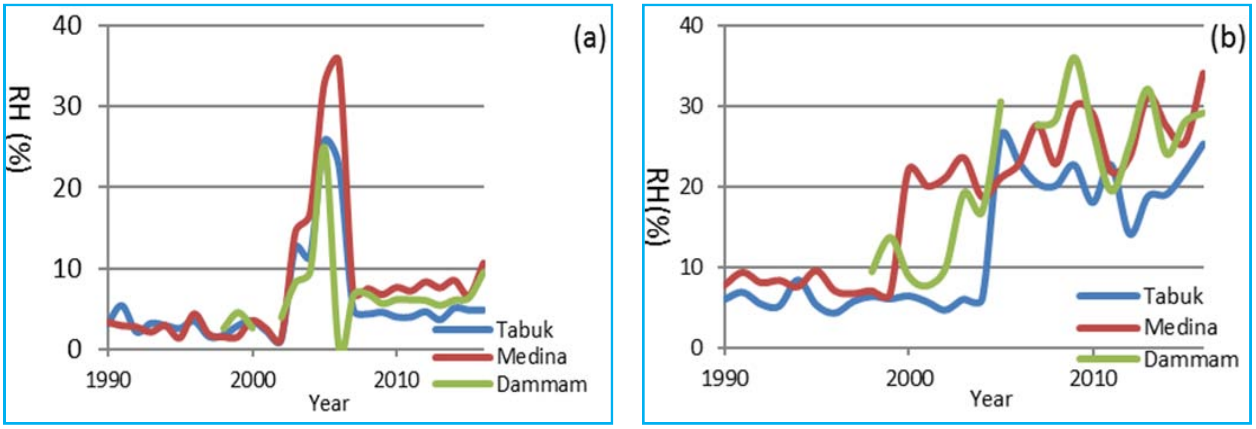


Figs. 9(a&b). Standardized anomalies plots between CPT temperature and solar cycle for Tabuk in (a) January and (b) July

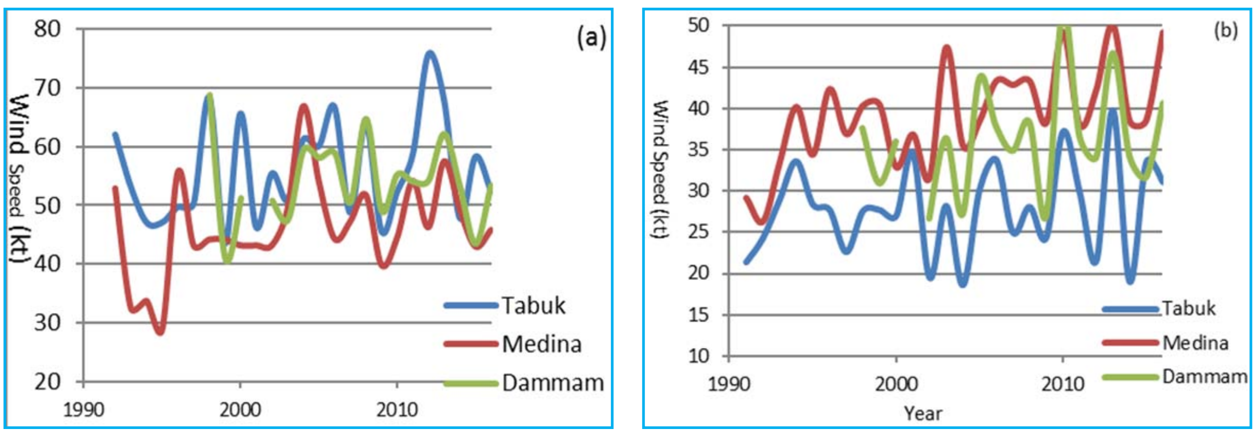
From these results, it is seen that during the 1990s the CPT temperature is highly correlated with the Solar Cycle whereas it is weak in the second period.

Following works of Chakrabarty *et al*. (2000); Raman and Chen (2014); Randel *et al*. (2000) and Zhou *et al*. (2001b), multivariate linear regression analysis of these variables have been utilized. The regression relation for the CPT temperature for Tabuk station is represented as:

$$CPT_t = A + Bt + \alpha ENSO_t + \beta QBO_t + \delta Solar_t + residual$$



Figs. 10(a&b). Long term CPT relative humidity (%) in (a) January and (b) July



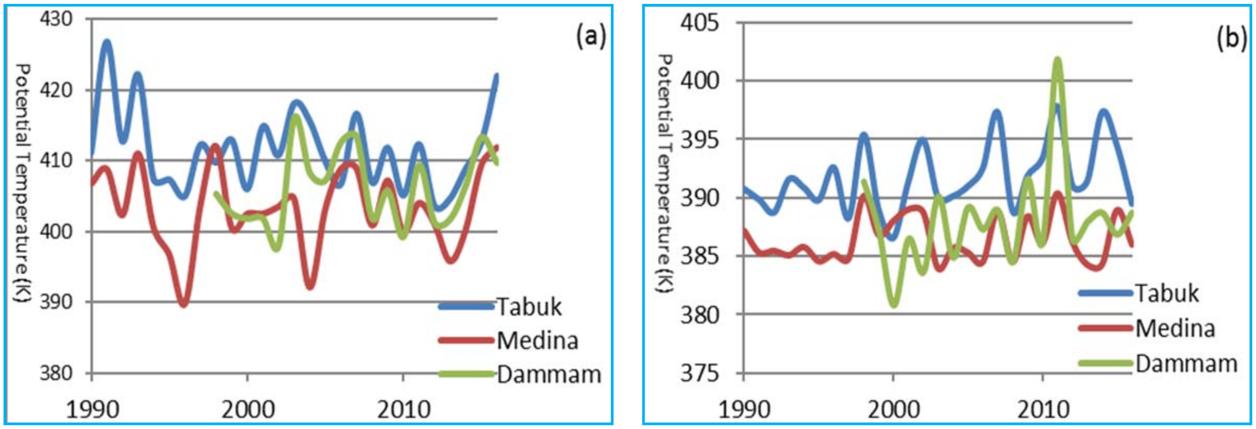
Figs. 11(a&b). Long term CPT wind speed (knot) in (a) January and (b) July

where, t = 1, 2, 3,… stand for the period 1990-2005. A is the constant term, B is the linear trend, QBO is the 30-hPa zonal monthly-mean wind at the equator, ENSO is the multivariate ENSO index, "Solar" is the monthly-mean sunspot number. The regression coefficients of QBO, ENSO and Solar factors are α, β and δ respectively and "residual" is the residual of the time series.

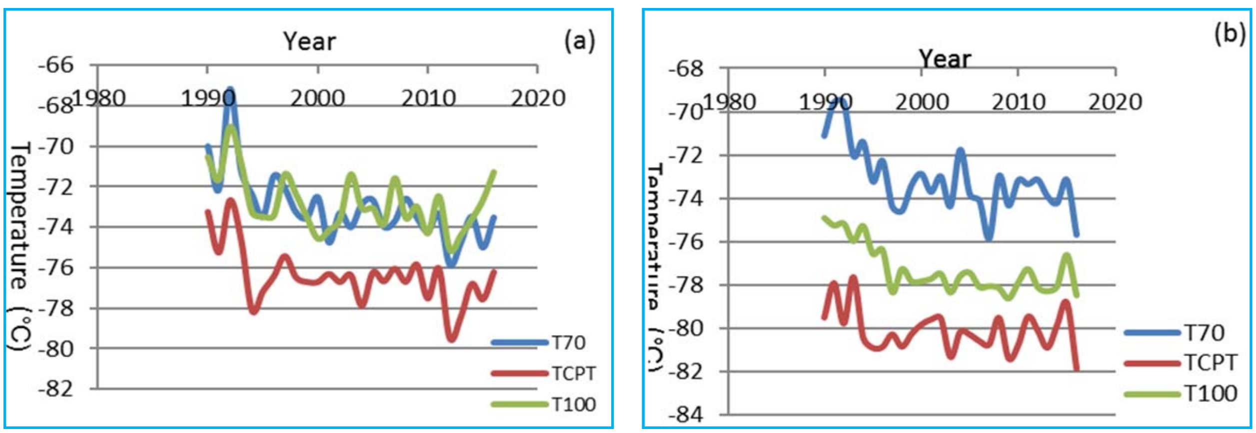
We adapt the stepwise forward and backward elimination regression to find the most useful X variables to be part of the regression. At each step of the procedure, each X variable is evaluated using a set of criteria such as the absolute value of the t-statistics. The variable that is retained is the variable whose coefficient has the highest absolute t-value. The result shows that the most significant variable is the solar cycle index (X_3). Adding ENSO (X_1) and QBO (X_2) does not improve the T-statistic of the regression. The results are tested with p-value of 0.1. The result of the multivariate regression emphasizes our first analysis using the correlations between the variables. Figs. 9(a&b) show plots of January and July for Tabuk using the standardized anomalies of the CPT and the Solar Cycle.

Humidity relatively increased for both months [Figs. 10(a&b)]. Meanwhile, it doubled in January. It, however, increased 3-4 times in July. Also, its values sharply increased in the period 2004-2006, though it decreased again in January and remained at this high level in July. It is of significant importance to mention that the July monthly mean continued to in increase especially over Medina and Dammam.

Although, wind speed is more changeable from year to year in January, it shows an increasing trend [Fig. 11(a)]. In July it increased uniformly for all stations (about 10 knots for Medina and 5 knots for Tabuk and Dammam) [Fig. 11(b)].



Figs. 12(a&b). Long term CPT potential temperature in (a) January and (b) July



Figs. 13(a&b). Comparison between temperatures at H70 hPa, CPT and H100 hPa Medina in (a) January for and (b) July

The behaviour of the potential temperature is not well-studied, particularly their long term changes. Some studies, *e.g*., Holton *et al*. (1995) demonstrated the relation between the potential temperature on stratospheric and tropospheric dynamics. This study showed its changes during the past 27 years. The analysis made demonstrated a sharp decrease during the early 1990s in January and almost no changes on the following years while the July one showed a clear increase throughout the whole period. It was 10 K for Tabuk and Dammam stations and about 5 K for Medina [Figs. 12(a&b)].

A comparison between temperatures of the three levels 100 hPa, CPT and 100 hPa for the two stations Tabuk and Medina is made (only figures for Medina are shown : Figs. 13(a&b). By comparing the values of the mean monthly temperatures for the three levels (H70 hPa, CPT and H100 hPa), it is obvious that the temperatures are much colder in July than in January: the values are about 6-7 °C colder for Tabuk and 3-4 °C for Medina. In both months, for both stations Medina and Tabuk, the temperature behavior in the three levels is almost the same. It shows an abrupt drop during 1993-1998 in the three levels. The drop is about 7-8 °C for both levels 70 hPa and 100 hPa and about 3-4 °C for the CPT. Since the beginning of the 2000s, the temperature mean decreased almost smoothly. Also the temperature values at H70 hPa and H100 hPa match for both stations in January. Although the temperatures of the three levels are different (it is coldest in the CPT level and warmest in the H70 hPa), the trend behavior of temperature for the three levels is the same. However the sharp drop of temperature during the 1990s appears clearly, after that the behavior of the monthly mean temperature is almost steady.

Table 4 shows the correlation between the different levels. The values for January show a strong correlation between TCP and other levels (more than 0,82) for both stations for the whole period. In July the correlation

TABLE 4

Correlation between monthly mean temperatures at 70 hPa, CPT and 100 hPa levels for Tabuk and Medina

Month	For the period	Station	H70 with TCP	TCP with H100
January	1990-2016	Tabuk	0.847948	0.82581
		Medina	0.814152	0.82917
July	1990-2016	Tabuk	0.45067	0.510529
		Medina	0.59773	0.537982
	2000-2016	Tabuk	0.630506	0.865088
		Medina	0.618638	0.793286

is weaker for the whole period. But it becomes stronger for the period of 2000-2016, in particular between the TCP and 100 hPa levels, which is above 0.81. This good correlation may indicate that the cooling trend became approximately similar in both layers TCP and H100 hPa during the last 16 years.

4. Summary

The location of the area of study in a transition subtropical continental zone and its contribution to Midlatitude weather makes a deeper study of its climate significant. Although the CPT has been widely researched in the tropics, the Arabian Peninsula and North Africa have not been thoroughly studied. The CPT has been widely researched in which the focus was on the tropics. In this study we focused on an important area which have not been thoroughly studied. The importance of this area arises from its location in a transition subtropical continental zone, which is considered as an interaction area between tropics and Midlatitudes and hence a major contributor of changes in weather in the Midlatitudes over the Mediterranean. Our focus is to investigate the behavior of the CPT and tropopause in this area during the period of (1990-2016). The characteristics of the CPT are analyzed and it was found that they experienced long-term trends. Moreover, the study shows that there was a pressure decrease of about 5 hPa in July and the height increased for about 100-200 m in the same month. The temperature change is more noticeable in January than in July, where there is a decrease of about 2 °C. In January, the temperature anomalies show a decreasing warming effect in the first half of the period and then a cooling effect in the second half. The July anomalies have a complicated behaviour similar to the thermal one.

However, relative humidity increased in both months, but has rapidly increased since the 2000s during July. The wind speed steadily increased especially during this month, when the potential temperature experienced a steady increase.

A comparison between the sounding data of the CPT and the NCEP reanalysis data of the two levels 100 hPa and 70 hPa showed a good correlation between the values of temperature in January, whereas there was a poor correlation in July for the whole period and a significant correlation between the CPT and 100 hPa level for the period 2000-1016.

With regard the CPT and the Solar Cycle during 90s, it is found that there is a strong correlation between them. On the other hand, this correlation between them becomes weak after this period. Although the reason of change of the correlation between the two variables in the two considered periods is not fully understood, the change in temperature in the last 15 years might be related to anthropogenic factors, which needs further investigation.

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Disclaimer

The contents and views expressed in this research paper/article are the views of the author and do not necessarily reflect the views of the organization he belongs to.

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