



Daytime and nighttime heat wave characteristics based on multiple indices over the China–Pakistan economic corridor

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Abstract

The sharp rise in temperature has increased the frequency, intensity, duration, and timing of heat waves (HWs) over different regions of the world. Due to climate change, the China–Pakistan Economic Corridor (CPEC) is one of the highly vulnerable regions to HWs and needs comprehensive research studies to investigate the HW phenomenon in the region. This study analyzed the spatial and temporal changes in the daytime and nighttime HW characteristics based on multiple indices over the CPEC region. We used daily maximum and minimum temperatures (hereafter T_{\max} and T_{\min}) of 48 meteorological stations for the time period of 1980–2016. The non-parametric modified Mann–Kendall, Theil–Sen’s test, least square method, student t-test, and chi-square goodness-of-fit test techniques were used to analyze the long-term spatiotemporal changes in the daytime and nighttime HW characteristics. The results of the study show that the number of annual daytime/nighttime HW events, annual sum of participating daytime/nighttime HW days, the average length of annual daytime/nighttime HW events, duration of the longest annual daytime/nighttime HW event, the average magnitude of all annual daytime/nighttime HW events, amplitude of the hottest annual daytime/nighttime HW event, and the ending date of annual last daytime/nighttime HW event exhibited significant increasing trends at the rate of 0.78/1.43 events decade⁻¹, 10/11.82, 2/1.74, 2.16/1.52 days decade⁻¹, 0.40/0.59, 0.24/0.73 °C decade⁻¹, and 12.29/10 days decade⁻¹, respectively. Despite all, the onset date of the annual first daytime/nighttime HW event has shown a significant decreasing trend of $-5.71/-5$ days decade⁻¹. The obvious positive trend of HW behaviors indicates that the country has experienced more frequent, stronger, more intense, and longer HWs during the study period. The spatial pattern of the trend indicates that the southern, central and eastern parts of Pakistan exhibited prominent and consistent HW activities, while the northwestern mountainous regions showed high spatial variability with some stations exhibited decreasing trends in HW indices. The findings of this study will be a base for the projection and mitigation of HWs in the region. Based on the study findings, we recommend that the mechanism of HW and its natural and anthropogenic drivers should be thoroughly investigated over the study region.

Keywords Heat waves · Multiple indices · CPEC · Theil–Sen’s (TS) test · Modified Mann–Kendall (m-MK) test

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1 Introduction

According to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR5), the global warming induced climate change has increased the global mean temperature by $0.85\text{ }^{\circ}\text{C decade}^{-1}$ since 1880 (IPCC 2013). The inevitable rise in temperature has intensified heat wave (HW) activities in terms of frequency, magnitude, duration, and timing both at the global and regional scales (Perkins and Alexander 2013; Cowan et al. 2014; Luo and Lau 2017; Lin et al. 2018) and are anticipated to increase in the future with more severe impacts on human society (Li et al. 2018; Nasim et al. 2018; Zhang et al. 2018). HWs seriously threaten the social and natural systems of mankind (Habeeb et al. 2015; Perkins 2015; Rauf et al. 2017) and are directly associated with human mortality, morbidity, loss of agricultural production, deterioration of ecosystems, and forest fire (Teixeira et al. 2013; Unal et al. 2013; Nairn and Fawcett 2014; Masood et al. 2015). Due to increasing threats, HWs have gained much attention in the scientific community and becomes the main subject for research in recent times (Cowan et al. 2014; Rohini et al. 2016; Luo and Lau 2017). Irrespective of the critical subject, the topic is still challenging and needs improved knowledge to better understand HWs and their synoptic behaviors (Fischer 2014; Perkins 2015; Luo and Lau 2017). The spatiotemporal analysis of HWs and their characteristics is crucial in defining their geographical extent and vulnerable zones (Khan et al. 2018b). Moreover, the comprehensive analysis of HWs and their behaviors are very important in evaluating and quantifying the adverse impacts of climate change on mankind (Miralles et al. 2014; Lin et al. 2018). The information obtained from such assessment plays an important role in the prediction and mitigation of future HWs.

During the last century, a number of research studies have analyzed the spatiotemporal patterns, trends, occurrence, and duration of HWs on regional and global scales (Meehl and Tebaldi 2004; Rahmstorf and Coumou 2011; Cowan et al. 2014; Perkins 2015; Li et al. 2018). According to Meehl and Tebaldi (2004); IPCC (2013); Perkins (2015), HW extremes exhibit high spatiotemporal variability over different climatological regions of the world. In recent decades, an increasing trend has been reported in HW events over Europe (Stefanon et al. 2012; Tomczyk and Bednorz 2016; Hoy et al. 2017), South Asia (Rohini et al. 2016; Im et al. 2017; Mazdiyasnı et al. 2017; Panda et al. 2017), Africa (Lelieveld et al. 2016; Waha et al. 2017; Ahmadalipour and Moradkhani 2018), North America (Wu et al. 2012; Bumbaco et al. 2013; Lorenzo and Mantua 2016), Russia (Lau and Kim 2012; Trenberth and Fasullo 2012; Schubert et al. 2014), China (Wang

et al. 2016; You et al. 2017a; Luo and Lau 2018, 2019; Zhang et al. 2018), and Australia (Lewis and Karoly 2013; Cowan et al. 2014). Despite all, a very limited number of studies have been conducted to examine HW characteristics and their changes over space and time. In recent years, HW behaviors have been investigated in China (Luo and Lau 2017, 2019; Lin et al. 2018), Russia (Galarneau et al. 2012; Trenberth and Fasullo 2012), and Europe (Trenberth et al. 2015; Ward et al. 2016). These characteristics are crucial in defining the frequency, intensity, duration, extent, and timing of HW events (Panda et al. 2017; You et al. 2017a; Lin et al. 2018), therefore, such behaviors should be investigated thoroughly in order to assess and quantify the adverse impacts of HWs on human society.

Pakistan is highly vulnerable to climate extremes due to its geographical location, complex topography, climate variability, high population density, expanded urbanization, and low adaptive capacity (Haider and Adnan 2014; Nasim et al. 2018). The sharp increase in temperature usually results in severe HW events in the country with substantial impacts in the central and southern parts (Zahid et al. 2017; Ullah et al. 2018a; Khan et al. 2018b). Since its independence, Pakistan has faced many deadly HW events, which claimed thousands of human lives across the country (Chaudhry et al. 2015; Zahid et al. 2017). Recently, many studies have reported that the frequency and intensity of HWs have been increased over Pakistan and neighboring countries during the past few decades (IPCC 2013; Rohini et al. 2016; Panda et al. 2017; You et al. 2017a; Zahid et al. 2017; Khan et al. 2018b). Similarly, climate models have also projected a sharp rise in regional temperature compared to the global mean temperature, which will certainly intensify the frequency and intensity of HWs in the region (Im et al. 2017; Saeed et al. 2017; Li et al. 2018; Nasim et al. 2018; Zhang et al. 2018). Based on the findings of the related studies, it can be predicted that Pakistan and the neighboring countries are highly vulnerable to HWs in the near future with substantial socio-economic impacts. Therefore, there is an urgent need to adopt proper risk reduction measures to tackle the adverse impacts of future HW events in the region.

Though HWs caused extensive devastation in Pakistan each year still, the topic has been ignored for a long time (Zahid and Rasul 2012; Khan et al. 2018b). Regardless of the sustained threats, very limited studies have been conducted on HWs in Pakistan (Chaudhry et al. 2015; Masood et al. 2015). Recently, Khan et al. (2018b) considered the 95th percentile threshold of daily maximum and minimum temperatures (T_{max} and T_{min}) for consecutive 5 days or more to assess changes in HW characteristics over different parts of Pakistan. They reported that catastrophic HWs have mostly occurred in the southeastern and southwestern regions of the country. Nasim et al. (2018) categorized future HWs on the topography of Pakistan, considering $5\text{ }^{\circ}\text{C}$ or above the mean

T_{\max} for 8 successive days. They revealed that the majority of the meteorological stations situated in Punjab and Sindh provinces of Pakistan are highly vulnerable to HWs. Saeed et al. (2017) used an absolute threshold of 45 °C or above the T_{\max} for 5 successive days to project future HWs in Pakistan. They anticipated an obvious increase in HW events over the eastern and southern parts of Pakistan. According to Zahid and Rasul (2012), HW events with maximum temperatures of 40 °C and 45 °C for consecutive 5, 7, and 10 days have been increased in the southern, western, and eastern zones of Pakistan.

Although, the above-mentioned studies have thoroughly assessed the HWs events in Pakistan; however, most of these studies have either used a fixed threshold, or less number of stations, or minimum temporal/spatial coverage, or different datasets, or/and different statistical tools. Moreover, these studies focused on either the spatial or temporal variability of HWs in the country. Therefore, a comprehensive study was much needed to examine both the spatial and temporal variations in HW characteristics in the study area. In this regards, the present study was designed to better understand the spatiotemporal variability of the daytime and nighttime HWs and their behaviors using multiple indices approach over the China–Pakistan Economic Corridor (CPEC) region. The novelty of this study is the use of a higher number of stations, extended temporal scale, intended study (CPEC) region, updated HWs definition, multiple indices, and additional statistical techniques. The findings of the study will play a key role in the projection and mitigation of future HW events over the CPEC region.

2 Study area

In September 2013, the Chinese President Xi Jinping announced the Belt and Road Initiative (BRI) to connect China with different regions of the world through multiple corridors (Shah 2018). Among these, the CPEC is one of the prominent corridors, situated in the south of the OBOR (Irshad et al. 2015). The CPEC connects the northwestern Chinese city of Kashgar in Xinjiang autonomous region with Gwadar port in southwestern Pakistan through 4918-km network of highways and railways (Ullah et al. 2018a). This project is intended to invest more than \$50 billion USD in up-gradation of the Gwadar port, the establishment of special economic zones, development of mass transit routes, industries, infrastructure, and energy schemes across the whole country (Esteban 2016; Ullah et al. 2018b). According to Abid and Ashfaq (2016); Ahmar (2016), CPEC is a game changer project for the entire region in terms of socio-economic and geo-political development. The network of the CPEC related projects is expanded to the entire country, therefore, we considered

entire Pakistan as a target region. Pakistan lies in South Asia with the long latitudinal extent stretching from the Himalayan Hindukush Mountainous range in the north to the Arabian Sea in the south. The total estimated area of Pakistan is 796,095 km² with geographical coordinates of 61°–78° east longitude and 23°–38° north latitude (Khan et al. 2018b; Sajjad and Ghaffar 2018). The agro-based classification of the country shows that 70–90% area of Pakistan is dominated by arid to semi-arid climate, predominantly characterized by hot summer and cold winter (Haider and Adnan 2014). Due to complex topography, the climate of Pakistan exhibits a high spatial variability in temperature from very low '< 0 °C' in the northern parts to extremely high '> 55 °C' in the central and southern parts (Nasim et al. 2018). Moreover, the deviations of seasonal and annual heat accumulation are highly influenced by the tropical climate, which ultimately affects the overall climatology of the country (Haider and Adnan 2014; Rahman and Dawood 2017).

3 Materials and methods

3.1 Datasets and data quality control

The study used daily T_{\max} and T_{\min} of 48 meteorological stations provided by the Pakistan Meteorological Department (PMD) for the period of 1980–2016. The details of the target stations are shown in Table 1 and Fig. 1. We selected the stations on the basis of data homogeneity, continuity, completeness, temporal coverage, and their proximity to the CPEC routes. The region experiences high temperatures and frequent HW events during the summer season, therefore, the summer months (May–September) were considered for this study. These months are widely used by different researchers to assess HW activities over different climatological regions of the world (Meehl and Tebaldi 2004; Luo and Lau 2017; Panda et al. 2017; Khan et al. 2015, 2018a, 2018b; Lin et al. 2018). Prior to proper statistical analysis, we employed runs test to ensure the quality, consistency, and homogeneity of the data. The purpose of using this technique was to detect artificial alterations occurred due to inevitable noise in data and errors in data collection methods (Iqbal et al. 2016; Ullah et al. 2018a). Due to reliable results, the said technique is strongly suggested by the World Meteorological Organization (WMO) for ensuring quality, consistency, and uniformity of hydrological and climatological datasets. The test has been extensively used by many scientists in their recent research studies (Nasri and Modarres 2009; Dikbas et al. 2010; Firat et al. 2012; Del Río et al. 2013; Iqbal et al. 2016; Ullah et al. 2018a). All the datasets were found homogenous and consistent at the 95% confidence level.

Table 1 Details of the target meteorological stations across the CPEC routes

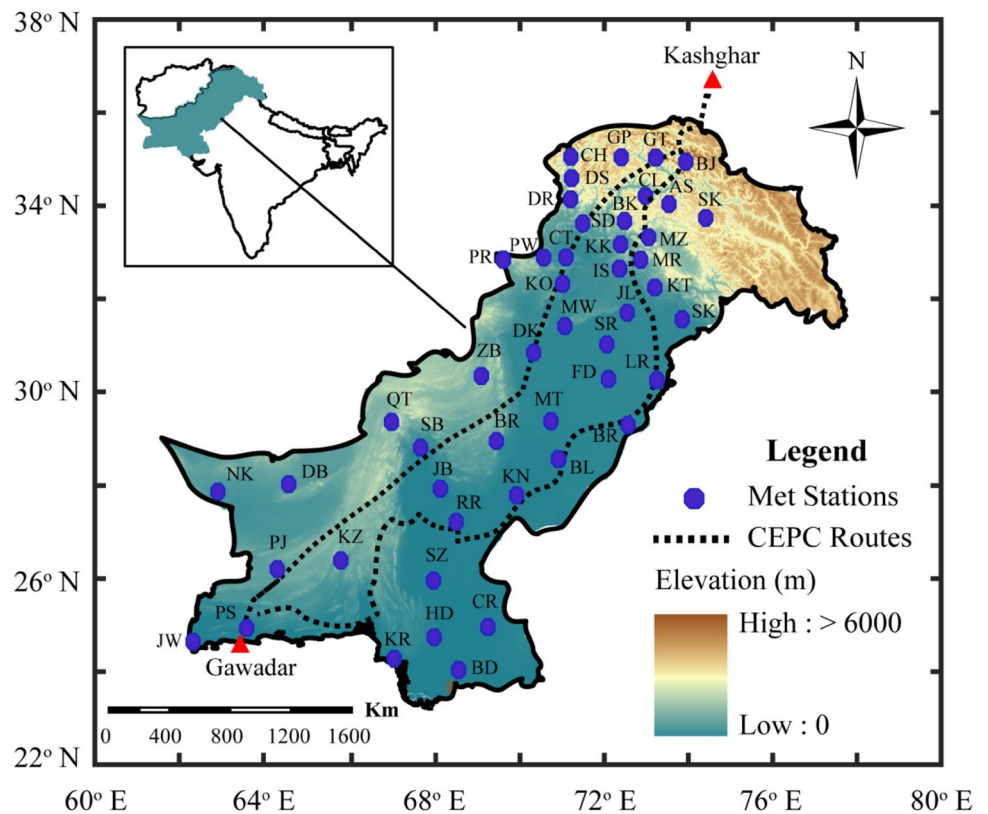
Code	Station	Latitude (°)	Longitude (°)	Elevation (m)
AS	Astore	35.35	74.86	2168
BD	Badin	24.38	68.54	9
BR	Bahawalnagar	29.82	73.28	161
BL	Bahawalpur	29.40	71.70	110
BK	Balakot	34.55	73.21	995
BR	Barkhan	29.88	69.72	1097
BJ	Bunji	35.67	74.63	1372
CT	Cherat	33.92	71.90	1372
CR	Chhor	25.31	69.47	5
CL	Chilas	35.42	74.10	1250
CH	Chitral	35.83	71.78	1498
DB	Dalbandin	28.53	64.24	848
DK	Dera Ismail Khan	31.49	70.56	171
DR	Dir	35.20	71.85	1375
DS	Drosh	35.55	71.85	1465
FD	Faisalabad	31.26	73.10	185
GT	Gilgit	35.92	74.33	1460
GP	Gupis	36.17	73.40	2156
HD	Hyderabad	25.23	68.25	28
IS	Islamabad	33.80	73.08	508
JB	Jacobabad	28.18	68.28	55
JL	Jhelum	32.56	73.44	287
JW	Jiwani	25.04	61.8	56
KK	Kakul	34.18	73.15	1308
KR	Karachi	24.89	67.16	22
KN	Khanpur	28.39	70.41	88
KZ	Khuzdar	27.50	66.38	1231
KO	Kohat	33.45	71.53	564
KT	Kotli	33.31	73.54	614
LR	Lahore	31.35	74.24	214
MW	Mianwali	32.58	71.55	205
MT	Multan	30.12	71.26	122
MR	Murree	33.90	73.40	2134
MZ	Muzaffarabad	34.37	73.48	838
NK	Nokkundi	28.49	62.45	682
PJ	Panjur	26.58	64.10	968
PR	Parachinar	33.90	70.10	1775
PS	Pasni	25.22	63.28	9
PW	Peshawar	34.02	71.58	328
QT	Quetta	30.11	67.57	1719
RR	Rohri	27.69	68.85	66
SD	Saidu Sharif	34.73	72.35	961
SR	Sargodha	32.03	72.40	187
SZ	Shaheed Benazirabad	26.15	68.22	37
SK	Sialkot	32.31	74.32	255
SB	Sibbi	29.33	67.55	133
SK	Skardu	35.18	75.68	2317
ZB	Zhob	31.21	69.28	1405

3.2 Definition of HW

HWs have no universal definition. However, many researchers have studied the spatiotemporal patterns, occurrence, and duration of HWs previously with different definitions and indices. Most of these studies are based either on the relative threshold (fixed percentile) or absolute threshold (fixed absolute values). Pakistan has a complex topography characterized by a diverse climatology (Khan et al. 2019; Ullah et al. 2019b). The country is dominated by a humid climate in the northern mountainous region, semi-arid and arid climate in the central plains, and hyper-arid and coastal climate along the south and eastern belt (Saeed et al. 2017; Ullah et al. 2019b). These climatic regions exhibit high variability in terms of T_{\max} and T_{\min} during the summer season. The highest (lowest) summer temperature can be observed in the central and southeastern (northern) parts of the country with a daily average of 55 °C (10 °C) (Iqbal et al. 2016; Khan et al. 2018b). Therefore, the high spatial variability of temperatures makes it challenging to use the absolute (fixed absolute values) threshold for HW definition (Smith et al. 2013; You et al. 2017a), as it does not account for all climatic regions of Pakistan (Saeed et al. 2017; Khan et al. 2019). Moreover, the application of an absolute threshold would give high weight to daytime (nighttime) HWs in hot/dry (cold/humid) regions of the country (Perkins and Alexander 2013; Smith et al. 2013). Thus, for a country like Pakistan, the relative threshold is a better criterion to define HWs as it gives area specific and time specific results (Vautard et al. 2014; You et al. 2017a). In addition, a relative threshold can uniformly distribute daytime and nighttime HWs within a climatic region (Perkins and Alexander 2013; Smith et al. 2013). Therefore, due to its effectiveness, we preferred the relative threshold to define daytime and nighttime HWs and their related characteristics in the study region. These HW thresholds can be defined either by daily T_{\max} or T_{\min} or/and T_{mean} (Bumbaco et al. 2013; Perkins and Alexander 2013; Rohini et al. 2016; Luo and Lau 2017; Panda et al. 2017; You et al. 2017a; Li et al. 2018; Lin et al. 2018). In recent years, daily T_{\max} and T_{\min} are widely used to assess daytime and nighttime HW activities around the globe, respectively. According to Meehl and Tebaldi (2004); Perkins (2015); Cowan et al. (2014), the occurrence of daytime HW events coupling with several consecutive hot nights poses serious threats to human health. Similarly, consecutive hot days and nights with extreme heat stress can increase the number of deaths and casualties (Hansen et al. 2008; Masood et al. 2015; Lin et al. 2018). Hence, looking into the significant role of T_{\max} and T_{\min} in HWs, we selected daily T_{\max} and T_{\min} to define and assess daytime and nighttime HW characteristics, respectively.

The present study followed the relative threshold definition of HWs, which is based on a definite number of

Fig. 1 Study area and target stations along the CPEC routes



consecutive days exceeding a fixed percentile of the daily T_{max} and T_{min} during the summer months (May–September) over a specific time period (Luo and Lau 2017; Meehl and Tebaldi 2004; You et al. 2017a). In this study, we used two thresholds for daily T_{max} and T_{min} distributions to define daytime and nighttime HW events, respectively. Here, threshold-1 (T1) was defined as the 90th percentile and threshold-2 (T2) as the 75th percentile of the daily T_{max} and T_{min} distributions. A daytime/nighttime HW event is then defined as the longest period of successive days/nights fulfilling the following three conditions: (1) The daily T_{max}/T_{min} must be higher than T1 for a minimum of 3 consecutive days/nights (2) the average daily T_{max}/T_{min} must be higher than T1 for the entire period, and (3) the daily T_{max}/T_{min} must be above T2 for each day/night of the whole event.

To study the long-term spatiotemporal changes in the daytime and nighttime HW characteristics, we adopted a multiple HW indices approach from recent studies (Lau and Nath 2014; Luo and Lau 2017; Lin et al. 2018; Panda et al. 2017). These indices include: the annual number of daytime and nighttime HW events (HWN), the annual sum of participating HW days/nights (HWP), the average length of all annual daytime and nighttime HW events (HWL), length of the longest annual daytime and nighttime HW event (HWD), the average magnitude of all annual daytime and nighttime HW events (HWM), amplitude of the hottest annual daytime and nighttime HW event (HWA), the annual onset date of the first daytime and nighttime HW event (HWO), and the annual end date of the last daytime and nighttime HW event (HWE) (Table 2). Here, the onset (end) date is defined as

Table 2 List of HWs Indices

ID	Definition	Unit
HWN	Annual number of daytime and nighttime HW events	Events decade ⁻¹
HWP	Annual sum of participating HW days and nights	Days decade ⁻¹
HWL	Average length of all annual daytime and nighttime HW events	Days decade ⁻¹
HWD	Length of the longest annual daytime and nighttime HW event	Days decade ⁻¹
HWM	Average magnitude of all annual daytime and nighttime HW events	°C decade ⁻¹
HWA	Amplitude of the hottest annual daytime and nighttime HW event	°C decade ⁻¹
HWO	Annual onset date of the first daytime and nighttime HW event	Days decade ⁻¹
HWE	Annual end date of the last daytime and nighttime HW event	Days decade ⁻¹

the first (last) day/night with daily T_{\max}/T_{\min} is greater than T_2 during the daytime/nighttime HW event. It is worth mentioning that these indices have been used for the first time to study the daytime and nighttime HW characteristics over the CEPC region.

3.3 Trend estimation and statistical significance test

The non-parametric Theil–Sen's (TS) and modified Mann–Kendall (m-MK) tests were employed to determine the slope and the significance of the trend in HWs time series, respectively (Sen 1968; Hamed and Rao 1998). Both the TS estimator and m-MK techniques are not required normality of data and are highly effective against data oddness, and missing numbers in a time series (Zhang et al. 2014; Panda et al. 2017; Salman et al. 2017). Furthermore, the least square method and student t-test techniques were applied to calculate and determine the significant linear trend in HW behaviors, respectively. To check the significance of the probabilistic distribution of time series, the chi-square goodness-of-fit test was employed at the 95% confidence level. In recent years, these statistical methods have been extensively used by different investigators to calculate and detect the significant trends in hydrological and climatological datasets (Zhou et al. 2016; Ahmed et al. 2017; Khan et al. 2018a, b; Lin et al. 2018; Ullah et al. 2018a).

4 Results

4.1 Long-term summer climatology of the study region

Figure 2 shows the spatial distribution of the summer T_{mean} and the monthly mean of T_{\max} and T_{\min} of the summer months (i.e., May–September) in the study region. The spatial pattern of summer T_{mean} exhibits a significant spatial variability at latitudes (longitudes) with a clear contrast between northern and southern (western and eastern) parts of Pakistan (Fig. 2a). The results depict that both the northwestern mountainous region is characterized by a humid climate with a seasonal T_{mean} of 15–25 °C in the summer months. The southwestern and coastal belts exhibit continental to a tropical climate with summer T_{mean} ranging from 25 to 35 °C. Moreover, the northern, central, and southeastern zones are dominated by a hot climate with seasonal T_{mean} ranging from 30 to 40 °C during the summer months. Furthermore, the monthly mean analysis indicates that the long-term mean of T_{\max} (T_{\min}) of the summer months is higher than 35 (22) °C (Fig. 2b) and thus the study region experiences high temperatures with frequent HW events in this season. According to the long-term analysis of monthly T_{\max} , June is the hottest

month, followed by July, May, August, and September with a mean T_{\max} of 37.22, 36.81, 35.23, 34.99, and 33.21 °C, respectively. In contrast, the long-term monthly analysis of T_{\min} shows that July is the hottest month, followed by June, August, May, and September with mean T_{\min} of 23.88, 23.16, 22.95, 20.40, and 20.13 °C, respectively. It has been stated that the deviations of summer T_{\max} and T_{\min} in terms of heat accumulation are highly influenced by the tropical climate, which may affect the variability of HWs and related extremes in the region (Iqbal et al. 2016).

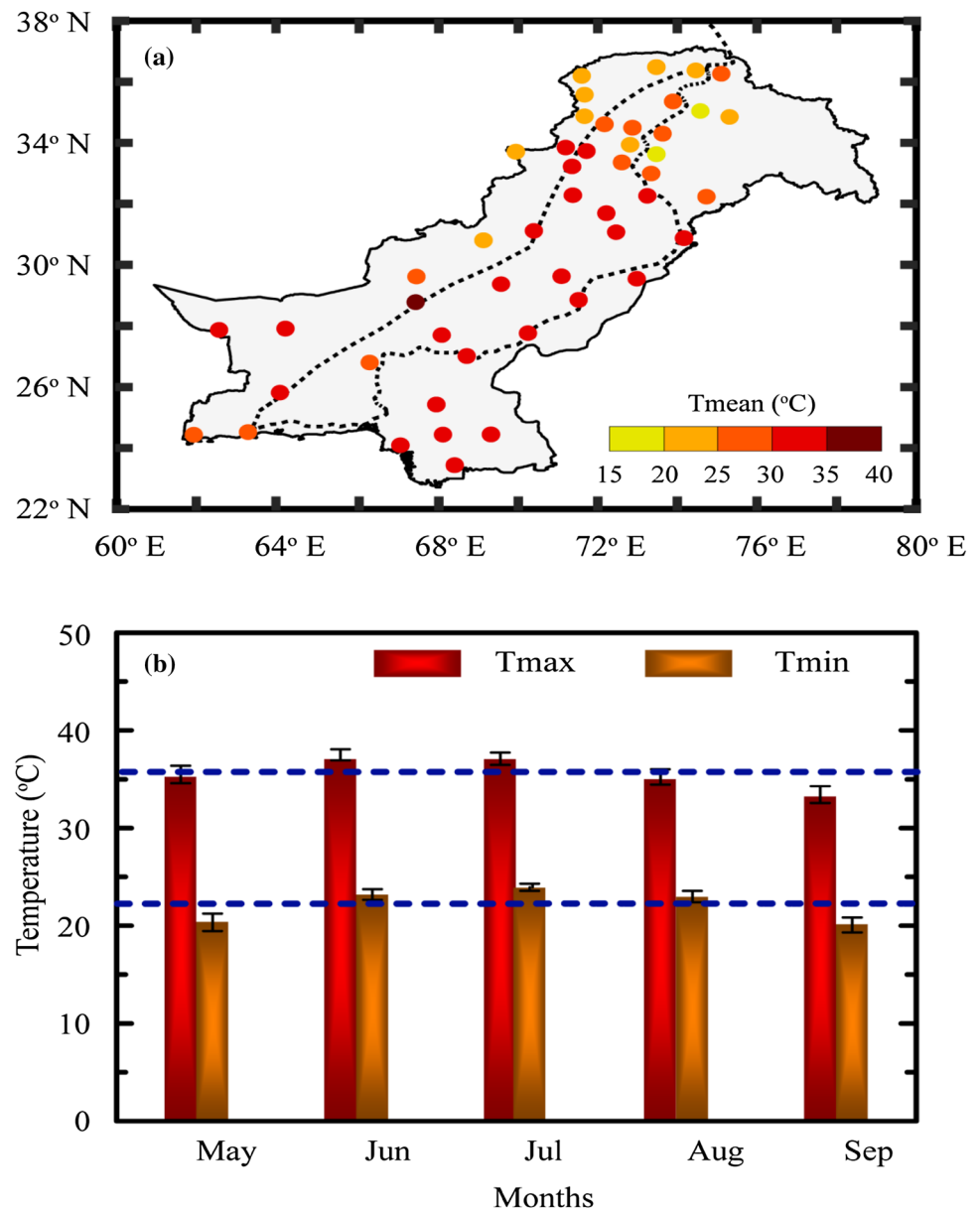
4.2 Probability distribution functions of summer daily T_{\max} and T_{\min}

Figure 3 shows the probability distribution functions (PDFs) of summer daily T_{\max} and T_{\min} in different epochs of the study period. The analysis was conducted on 4 epochs i.e., (a) first epoch; 1980–1990, (b) second epoch; 1991–2000, (c) third epoch; 2001–2010, and (d) fourth epoch; 2011–2016. The overall distribution of the summer T_{\max} (T_{\min}) shows a significant move towards the right (left) side during the study period; however, in the second and third (third and fourth) decades, the daily T_{\max} (T_{\min}) exhibits a slight shift towards the right side, which indicates an increase in the daily T_{\max} (T_{\min}) during the corresponding epochs. On the other hand, the skewness of the summer T_{\max} (T_{\min}) is passive (active) in all epochs of the study period; however, their frequencies vary from decade to decade. It has been noticed that the skewness of the third and fourth (second and fourth) decades exhibited positive changes in summer daily T_{\max} (T_{\min}), which imply that high temperatures with sustained HW events were evident during these time periods. The findings suggest that the intensifying trends of various HW activities in different epochs of the study period are mostly associated with positive changes both in the distribution and skewness of the summer daily T_{\max} and T_{\min} . These positive shifts in distribution and skewness may affect the frequency, intensity, strength, duration, and timing of the HWs in the study region.

4.3 Temporal trends in HW characteristics

Figure 4 represents the annual mean time series of daytime HW behaviors and their linear trends. The results show that all characteristics of HW show significant positive trends except HWO during 1980–2016. The annual number of daytime HW events (HWN) and the annual sum of participating HW days (HWP) have been significantly increased over the CPEC region at the rate of 0.78 events decade⁻¹ and 10 days decade⁻¹, respectively (Fig. 4a, b). The temporal trend of daytime HWN shows a linear increased after 1993 with a maximum number of events (6 HW events) during 2009–2016 (Fig. 4a). Moreover, the trend of day HWP

Fig. 2 Climatological summer mean of daily T_{mean} and monthly mean of daily T_{max} and T_{min} of the target region during 1980–2016: **a** summer daily T_{mean} , **b** monthly mean of T_{max} and T_{min} . Dashed horizontal line denotes monthly mean of T_{max} (35.49 °C) and T_{min} (22.10 °C). The standard deviations of the corresponding temperatures are shown by vertical bars



moves upward during the study period with a maximum number of hot days in the years of 2000, 2001, 2009, 2011, 2012, 2013, and 2015 at the rates of 63, 65, 76, 62, 65, 60, and 62 days, respectively (Fig. 4b). This obvious upward trend indicates that the country has experienced frequent HW events with an increased number of hot days during the study period. Similarly, the average length of annual daytime HW events (HWL) and duration of the longest annual daytime HW event (HWD) exhibit significant positive trends at the rate of 2 and 2.16 days decade⁻¹, respectively (Fig. 4c, d). The overall tendency of daytime HWL exhibits a significant positive trend with a maximum length of days in the years 2001, 2009, 2012, 2014, 2015, and 2016 at the rates of 12.20, 11.60, 12.60, 11.20, 12.00, and 11.20 days (Fig. 4c). In addition, HWD of daytime events, displays a

significant increasing trend with a maximum duration during 1997 (24 days), 2001 (28 days), 2002 (32 days), 2004 (24 days), 2005 (32 days), 2015 (25 days), and 2016 (24) (Fig. 4d). The results show that the trend of daytime HWL and HWD is higher than nighttime HWL and HWD, which indicates that the length and duration of daytime HWs have been increased during 1980–2016. Similarly, HWL has a slight upward trend than HWD in the daytime HWs, which employ that the average length of the yearly HW events (HWL) became more extended than HWD during the study period. The average magnitude of all annual daytime HW events (HWM) and amplitude of the hottest annual daytime HW event (HWA) show a significant rising trend with 0.40 and 0.24 °C decade⁻¹, respectively (Fig. 4e, f). The annual mean time series of daytime HWM shows a significantly

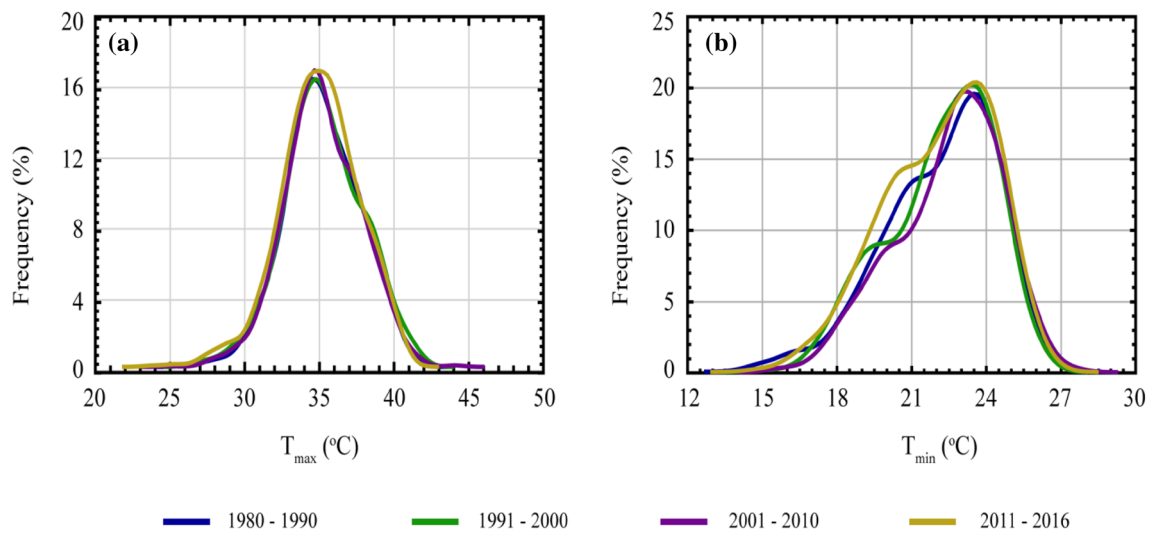


Fig. 3 Frequency distribution of summer daily T_{max} and T_{min} for different time periods (11 year for 1980–1990, and 6 year for 2011–2016) during 1980–2016: **a** daily T_{max} , **b** daily T_{min}

increasing trend with maximum temperature magnitudes in the years of 2002, 2012, 2014, 2015, and 2016 at the rates of 41.70, 41.11, 41.16, 41.05, and 41.02 °C, respectively (Fig. 4e). Similarly, the tendency of daytime HWA was significantly increased over the study period with maximum temperature magnitude during 2005 (42.11 °C), 2012 (42.16 °C), 2013 (42.16 °C), 2014 (42.16 °C), 2015 (42.18 °C), and 2016 (42.20 °C) (Fig. 4f). This noticeable severity of HWM and HWA suggests that both the average magnitude and amplitude of HW events have been substantial during the study period. With respect to the timing of the daytime HW events, it has been found that the onset date of the yearly first daytime HW event (HWO) [ending date of yearly last daytime HW event (HWE)] shows significant decreasing (increasing) trend with -5.71 (12.29) days decade⁻¹ (Fig. 4g, h). The annual time series of daytime HWO (HWE) exhibited a significant decreasing (increasing) shift in the onset (end) day of HWs with earliest (latest) days of May (August) during 2006, 2009, 2011, 2012, 2013, 2014, 2015, and 2016 (2009, 2011, 2012, and 2013, 2014, 2015, and 2016) (Fig. 4g, h). These findings imply that the daytime HW events are starting earlier and ending later in the calendar year due to which HW season is becoming larger in the study region.

The annual mean time series of nighttime HW behaviors and their linear trends are shown in Fig. 5. The results show that all the aspects of nighttime HWs exhibit a positive linear trend except HWO during the study period. The monotonic trend indicates that the annual number of nighttime HW events (HWN) and the annual sum of participating HW nights (HWP) have been significantly increased over the CPEC region at the rate of 1.43 events decade⁻¹ and 11.82 days decade⁻¹, respectively (Fig. 5a,

b). The linear trend of nighttime HWN shows an increasing trend after 1997 with the highest number of events (7 HW events) in 2007, 2008 and 2016 (Fig. 5a). Similarly, the nighttime HWP showed an increasing trend during 1997–2002, and 2013–2016 with the highest number of HW days in 2000, 2002, 2013, 2015 and 2016 at the rate of 50, 53, 56, 52, and 53 days, respectively (Fig. 5b). The evident increasing trend of nighttime HWN and HWP indicates that the study region has witnessed frequent nighttime HWs with an increased number of hot nights during 1980–2016. Compared to daytime HWN and HWP, nighttime HWN and HWP are slightly increased, which suggest that night HWs are becoming more frequent and stronger than daytime HWs in the region. Similarly, the average length of annual nighttime HW events (HWL) and duration of the longest annual nighttime HW event (HWD) exhibit significant positive trends at the rate of 1.74 days and 1.52 days decade⁻¹, respectively (Fig. 5c, d). In nighttime HWL, a significant positive trend has been found in 1997 and onward with a maximum length in 2001, 2008 and 2015 at the rate of 8.50, 8.17 and 8.5 days, respectively (Fig. 5c). The annual time series of nighttime HWD shows that the length of the longest HW event moves upward during 1997–1999 and 2012–2016 with a maximum length of 19, 18, 17, 18, 18, and 23 days in 1997, 1998, 1999, 2012, 2015, and 2016, respectively (Fig. 5d). In addition, the average magnitude of all annual nighttime HW events (HWM) and amplitude of the hottest annual nighttime HW event (HWA) show a significant rising trend with 0.59 °C and 0.73 °C decade⁻¹, respectively (Fig. 5e, f). The annual mean time series indicates that the average magnitude (HWM) (amplitude (HWA)) of nighttime HW has been linearly increased over the target

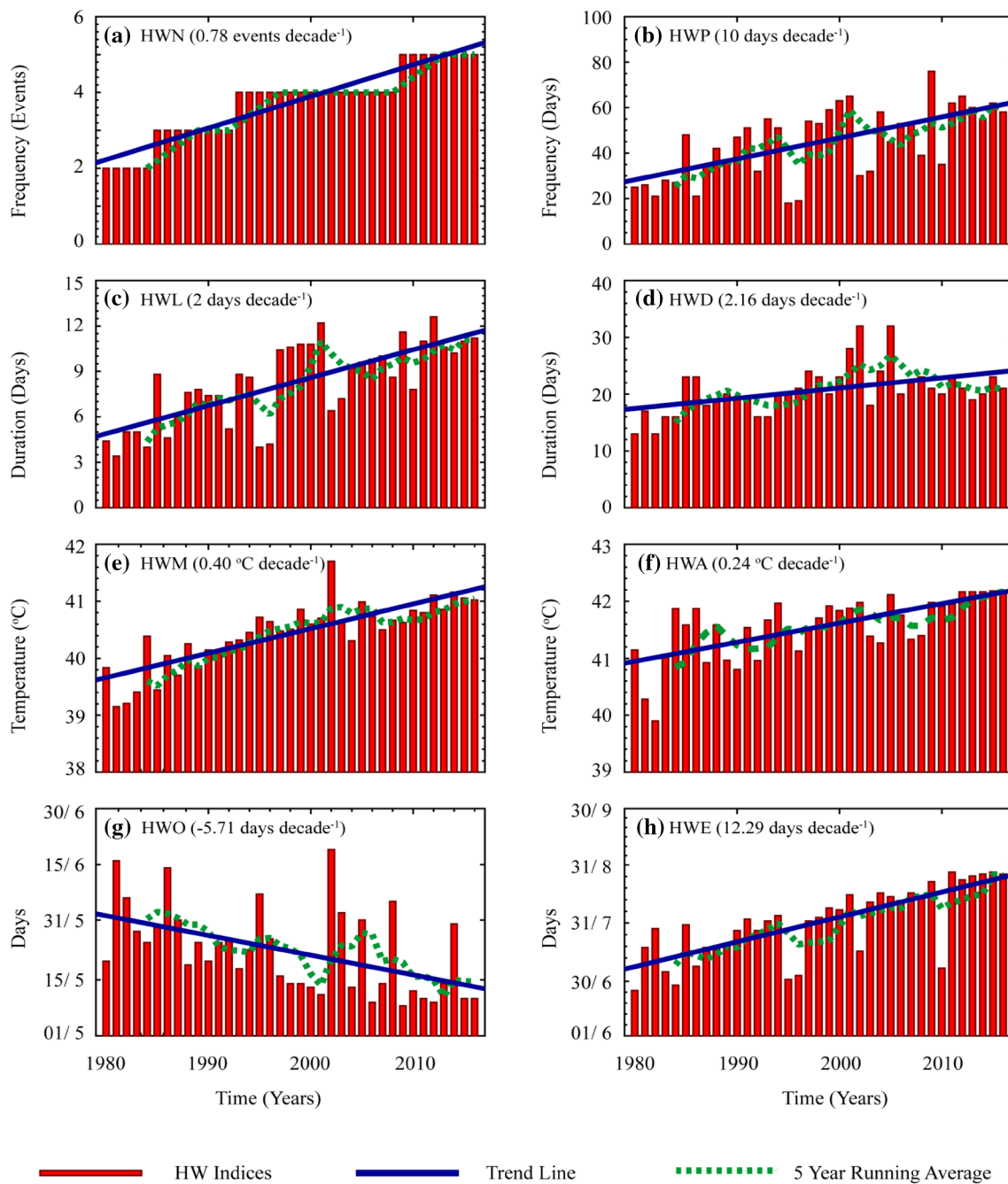


Fig. 4 Annual mean time series of daytime HW indices and their linear trends over the target region during 1980–2016. The values in each panel represent the monotonic trends of the corresponding daytime HW indices

period with extreme intensity of temperature in the years of 2011, 2012, 2013, 2014, 2015, and 2016 (2000, 2012, 2013, 2014, 2015, and 2016) at the rates of 27.33, 27.51, 27.62, 28.15, 28.14, and 28.03 (27.92, 28.18, 28.45, 28.59, 28.88, and 28.69) °C, respectively (Fig. 5e, f). The obvious increase in the intensity of HWM and HWA of hot nights suggests that both the average magnitude and amplitude of nighttime HWs have been considerable

over the study period. Moreover, it has been noticed that the intensity of nighttime HWM and HWA is higher than daytime HWM and HWA, which indicates that the nighttime HWs are becoming more severe and intense over the study region. Corresponding to the timing of the nighttime HW events, it has been found that the onset date of the yearly first nighttime HW event (HWO) (the ending date of yearly last nighttime HW event (HWE) shows

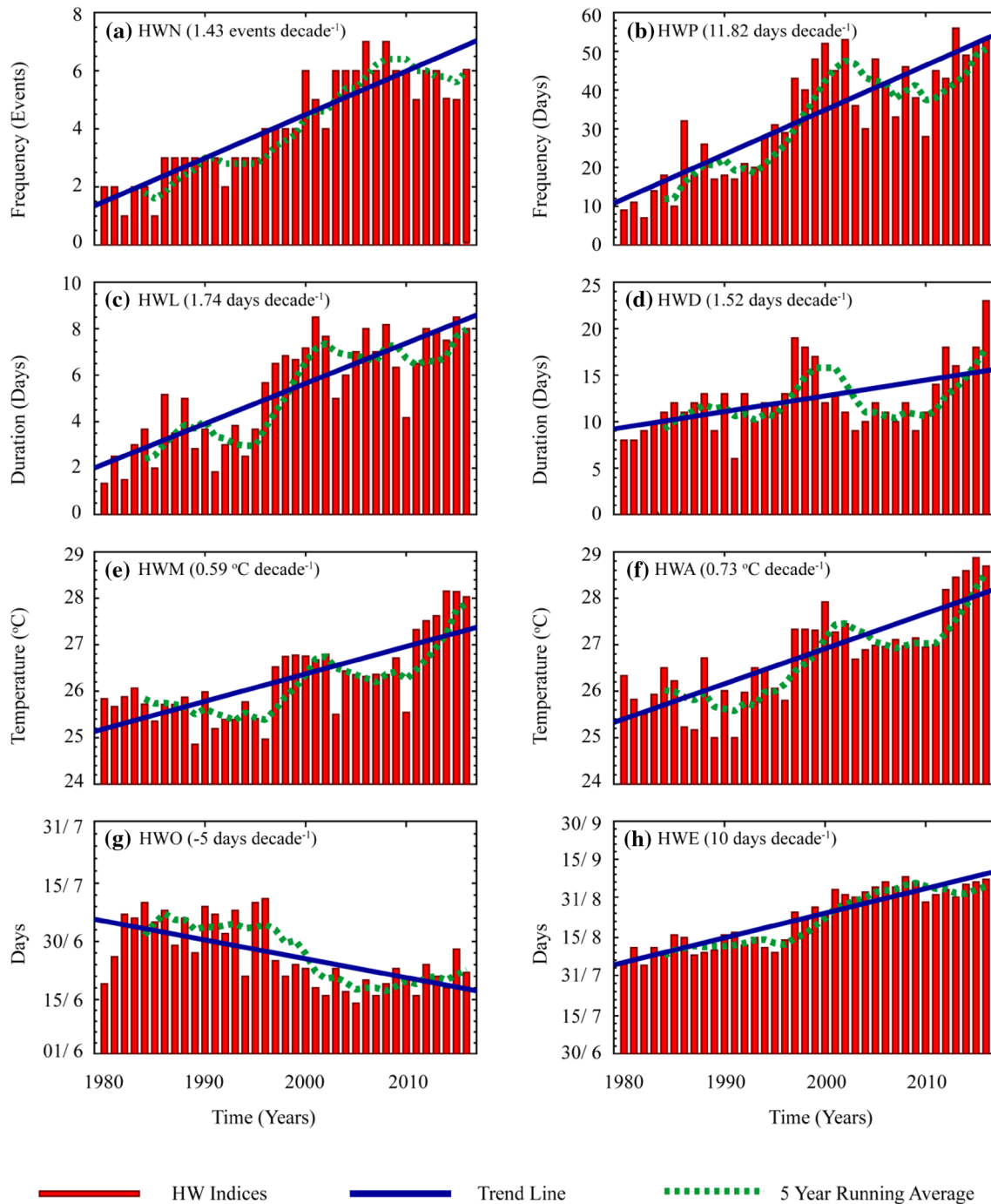


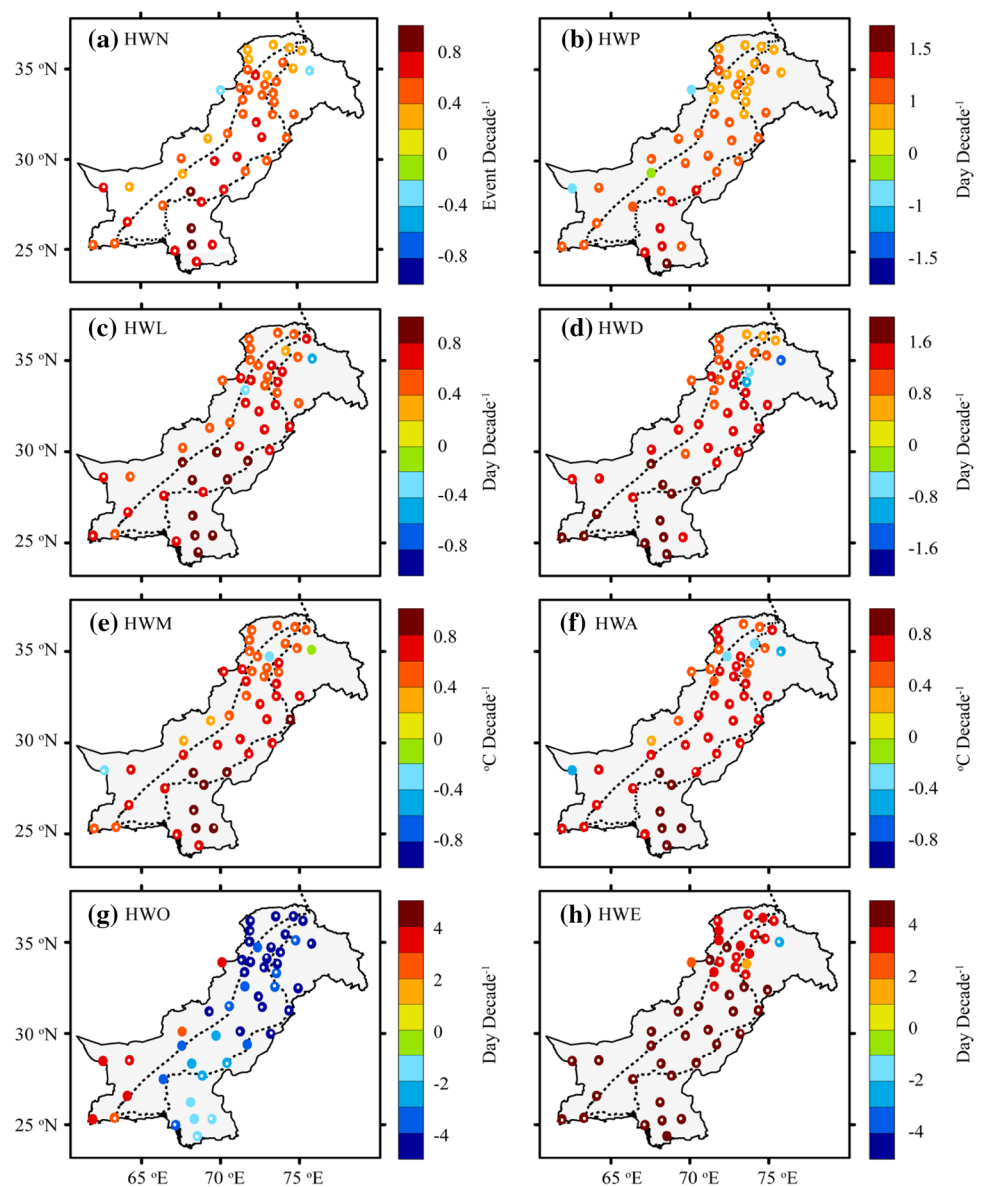
Fig. 5 Similar to Fig. 4, but for nighttime HW indices

significant negative (positive) trend with -5.00 (10.00) days decade $^{-1}$ (Fig. 5g, h). Moreover, the time series of nighttime HWO (HWE) exhibits a decreasing (increasing) trend in the onset (end) day of nighttime HWs with mid (earlier) days of June (August) during 2002, 2005, 2007, and 2011 (2006, 2008, 2009, and 2015) (Fig. 5g, h).

4.4 Spatial pattern of trends in HW characteristics

The spatial distribution of trend in daytime HWs and related characteristics over the CPEC region is shown in Fig. 6. The overall analysis showed a warming tendency of day-time HWs throughout the country. The central, eastern, and

Fig. 6 Spatial pattern of trend in daytime HW indices over the target region during 1980–2016. The white dots denote statistically significant trends at the 0.05 significance level



southern regions were dominated by a positive trend of HW activities. Interestingly, the northern mountainous region showed a high spatial variability in terms of daytime HW behaviors over the selected stations. The analysis showed significant increasing trend in daytime HWN over the whole study region (Fig. 6a). The central and southeastern parts showed a positive trend of daytime HWN with maximum positive trends at Hyderabad (1 event decade⁻¹), Jacobabad (0.80 event decade⁻¹), and Shaheed Benazirabad (0.95 event decade⁻¹) stations. Irrespectively, Parachinar and Skardu were the two stations, which showed a negative trend in daytime HWN at the rate of -0.38 and -0.34 events decade⁻¹, respectively. Moreover, the spatial analysis of daytime HWP shows that the whole country was characterized by a significant increasing trend with a maximum positive trend at the Badin station (2 days decade⁻¹) (Fig. 6b). Interestingly,

Nokkundi, Parachinar and Sibbi stations exhibited a negative, but non-significant trend of daytime HWP with -0.60 , -0.53 and -0.36 day decade⁻¹, respectively. These findings suggest that the country has experienced frequent daytime HWs and hot days during the study period and are expected to increase in the future. Similarly, the spatial distribution of daytime HWL (HWD) indicated a significant increasing trend in the whole region with the maximum increasing trend in the central and southeastern regions. The stations with the maximum positive trend of daytime HWL (HWD) were Badin, Bahawalpur, Barkhan, Chhor, Hyderabad, Jacobabad, Shaheed Benazirabad, and Sibbi (Badin, Hyderabad, Jacobabad, Jiwani, Karachi, Khanpur, Panjgur, Pasni, Rohri, Shaheed Benazirabad, and Sibbi) with 0.95, 0.93, 0.97, 0.90, 0.94, 0.91, 1, and 0.87 (2, 2, 1.92, 1.89, 2, 1.61, 2, 1.67, 1.84, 2, and 1.67) days decade⁻¹, respectively (Fig. 6c, d).

Regardless of the whole country, Kohat and Skardu (Murree, Muzaffarabad, and Skardu) stations exhibited a significant negative trend in daytime HWL (HWD) at the rate of -0.27 and -0.58 (-0.91 , -0.77 , and -1.40) days decade $^{-1}$, respectively. The findings indicate that that the study region was dominated by long-lasting HWs events during the study period, which could be expected in the future with more prolonged duration.

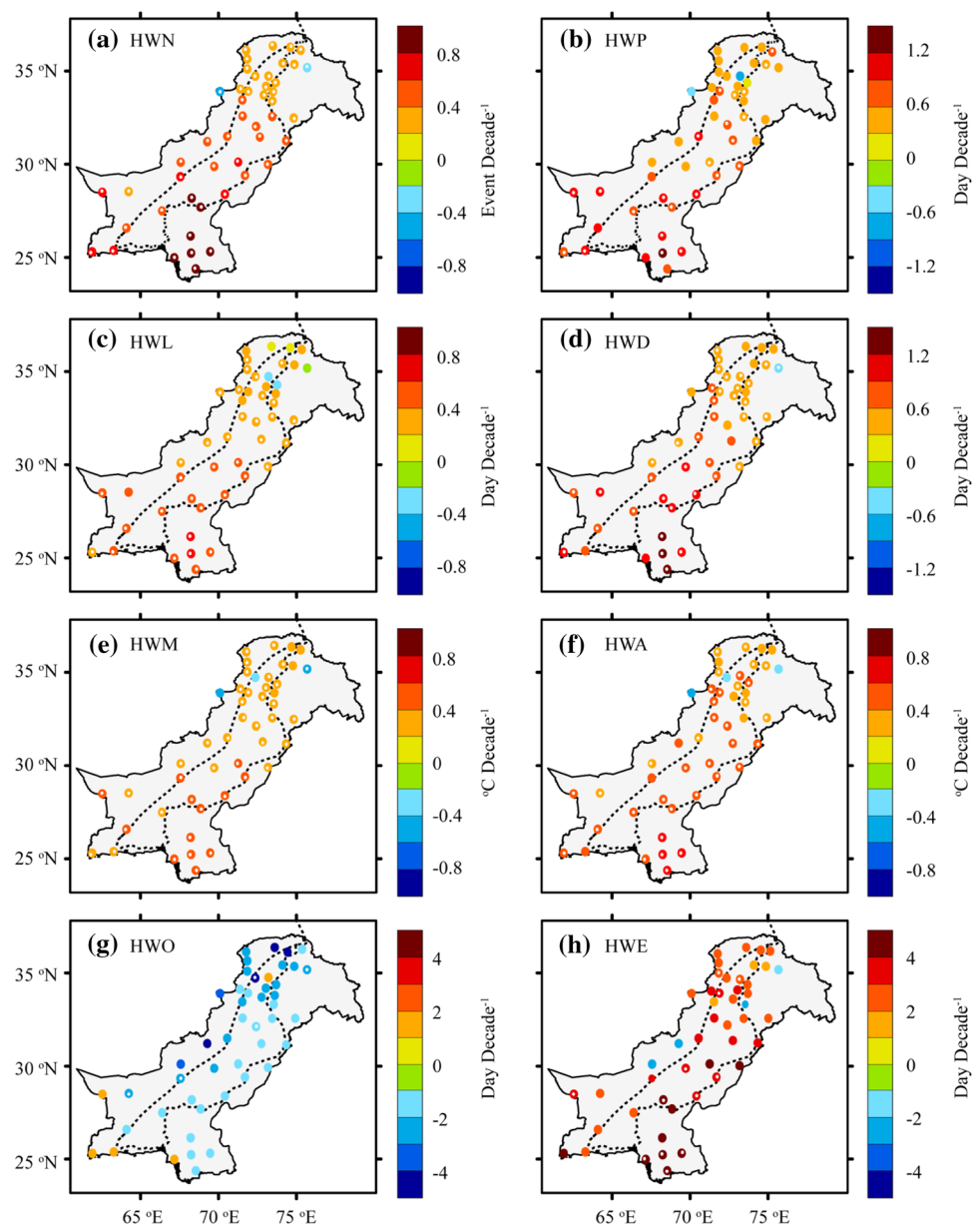
The spatial analysis of daytime HWM (HWA) shows that the entire country experienced a prominent increase in HWs activities with more intense HWs over the central and southeastern regions during 1980–2016. The analysis illustrates that the maximum trend values of daytime HWM (HWA) were detected at Chhor, Hyderabad, Jacobabad, Khanpur, Lahore, Rohri, and Shaheed Benazirabad (Badin, Chhor, Hyderabad, Jacobabad, Rohri, and Shaheed Benazirabad) stations at the rate of 0.94, 0.93, 0.86, 0.89, 0.81, 0.88, and 0.92 (0.83, 0.85, 0.85, 0.97, 0.90, and 0.94) °C decade $^{-1}$, respectively (Fig. 6e, f). Based on m-MK test results, the trend of HWM (HWA) was statistically significant at all locations except Balakot and Skardu (Chilas, Kohat, Murree, Nokkundi, and Saidu Sharif) stations. The rising trends of daytime HWM and HWA suggest that the study region has experienced intense and strong HWs during the study period. It can be concluded that the increasing tendency of temperature under the global warming scenario may trigger the intensity of HWs in the near future over the CPEC region. Moreover, the spatial distribution of daytime HWO (HWE) indicates that the onset (end) timing of daytime HWs exhibited a negative (positive) trend over the CPEC region. The highest negative (positive) values for daytime HWO (HWE) were found in the northern (central and southern) zones (Fig. 6g, h). Irrespectively, the target stations in the southwestern region displayed a positive trend of daytime HWO, which reflects delay arrival of daytime HWs during the study period. The m-MK technique showed that the trend of daytime HWO (HWE) was statistically significant at 34 (39) stations. Among these, 32 (38) stations were negatively significant and 2 (1) were positively significant. The overall analysis shows that both daytime and nighttime HWs arrived (terminate) earlier (latter), indicating an extended season of HWs in the target region.

Figure 7 shows the spatial pattern of the trend in nighttime HWs and their behaviors over the CPEC region. The overall results indicated that the entire country was dominated by a warming pattern of nighttime HWs with prominent and consistent warming tendency of HW behaviors in the central and southern regions. On the other hand, the spatial variability of nighttime HW activities was highly dynamic over the northern hilly areas and the trend magnitudes vary from station to station. The analysis shows that the trend of nighttime HWN (HWP) has significantly increased over the whole country (Fig. 7a, b). The central, southern and southeastern (eastern

and southern) regions of the country were dominated by an obvious increasing trend of nighttime HWN (HWP). The maximum positive trend of nighttime HWN (HWP) was noticed at Chhor, Hyderabad, Jacobabad, Jiwani, Karachi, Rohri, and Shaheed Benazirabad (Chhor, Hyderabad, Karachi, Nokkundi, and Shaheed Benazirabad) stations with 0.91, 0.94, 0.86, 0.81, 0.81, 0.87, and 0.91 event decade $^{-1}$ (1.11, 1.43, 1.10, 1, and 1 days decade $^{-1}$), respectively. Irrespective of the whole region, the trend of nighttime HWN (HWP) was found significantly positive (negative) trend at Parachinar and Skardu (Balakot and Parachinar) stations with -0.43 and -0.37 events decade $^{-1}$ (-0.71 and -0.36 days decade $^{-1}$), respectively. The m-MK test results exhibited that the positive trend of nighttime HWN (HWP) was statistically significant at all (23) stations. The findings of the study suggest that the region has experienced frequent and severe nighttime HWs during the study period. It can be stated that the sharp rise in temperature may result in more severe and frequent nighttime HW events in the future over the CPEC region. The spatial trend of nighttime HWL/HWD is shown in Fig. 7c/9d. The results illustrate that the trend of nighttime HWL (HWD) moved upward over the entire region with a maximum positive tendency in the southern and eastern (central, southern and southeastern) parts. The maximum positive trend of nighttime HWL (HWD) was reported at Hyderabad and Shaheed Benazirabad (Badin, Hyderabad, and Shaheed Benazirabad) stations with 0.63 (1.67, 1.54, and 1.25) days decade $^{-1}$. Moreover, a negative trend of HWL (HWD) was also detected at 3 (1) stations situated in the northern mountainous region. These stations include; Balakot, Muzaffarabad, and Skardu (Skardu) stations with -0.30 , -0.32 , and -0.19 (0.33 days decade $^{-1}$) days decade $^{-1}$, respectively. The results of the m-MK test show that 35 (37) stations displayed a significant positive trend of nighttime HWL (HWD). The positive trend of nighttime HWL and HWD suggests that the CPEC region has experienced extended and long-lasting nighttime HW events during 1980–2016, which might occur with lengthier periods in the future.

Similarly, the spatial analysis of nighttime HWM (HWA) indicates that the average magnitude (amplitude) of HW events has been increased throughout the country with an extreme tendency in the southern and eastern (southern, central and eastern) parts (Fig. 7e, f). The highest positive values were observed at Jacobabad, Karachi, Khanpur, Rohri, and Shaheed Benazirabad (Badin, Chhor, Hyderabad, and Shaheed Benazirabad) stations at the rate of 0.59, 0.56, 0.55, 0.52, and 0.53 (0.67, 0.66, 0.67, and 0.61) °C decade $^{-1}$, respectively. Interestingly, 3/3 stations were detected with a negative trend of nighttime HWM/HWA. The stations include: Parachinar ($-0.56/-0.49$ °C decade $^{-1}$), Saidu Sharif ($-0.24/-0.35$ °C decade $^{-1}$) and Skardu ($-0.46/-0.33$ °C decade $^{-1}$). Overall, the trend of

Fig. 7 Similar to Fig. 6, but for nighttime HW indices



nighttime HWM (HWA) was significant at 42 (36) stations. Among these, 41 (35) stations exhibited significant positive trends and 1 (1) station exhibited significant negative trends at the 95% confidence level. The rapid increase in nighttime HWM and HWA suggests that the study region was dominated by severe nighttime HW events during the study period, which could be expected in the future with more severity. The spatial distribution of nighttime HWO (HWE) demonstrated that the long-term trend has been decreased (increased) over the entire country during 1980–2016 (Fig. 7g, h). The prominent decrease (increase) was found in the northern and southwestern hilly (central, eastern and southern) regions. In HWO (HWE), the maximum negative (positive) shift was recorded at Gilgit, Gupis, Saidu Sharif,

and Zhob (Badin, Bahawalnagar, Hyderabad, Jacobabad, Jiwani, Karachi, Multan, Rohri, and Shaheed Benazirabad) stations with -4.84 , -4.55 , -4.29 , and -4.44 (4.74 , 4.68 , 4.39 , 4.41 , 4.44 , 4.23 , 4.39 , 4.04 , and 5) days decade $^{-1}$, respectively. Despite all, a limited number of stations in the coastal (northern and southwestern mountainous) zone were detected with an increasing (decreasing) but a non-significant trend of nighttime HWO (HWE). The stations include: Balakot, Jiwani, Karachi, Nokkundi, and Pasni (Kotli, Quetta, Skardu, and Zhob) at the rate of 1.74 , 1.02 , 1.61 , 1.40 , and 1.88 (-2.00 , -2.38 , -1.13 , and -2.35) days decade $^{-1}$, respectively. The m-MK test results showed that the negative (positive) trend of nighttime HWO (HWE) was significant at 4 (12) stations at the 0.05 significance level.

The decreasing (increasing) trend of nighttime HWO (HWE) indicates that the length of the hot season is becoming larger over the CPEC region, which may pose serious threats to local people in the near future.

5 Discussion

Recent studies have reported that the global mean temperature has been raised by 0.14–0.18 °C during 1979–2010, which has resulted in severe HW events over different regions of the world (Rahmstorf and Coumou 2011; Stefanon et al. 2012; IPCC 2013; Perkins 2015). According to Meehl and Tebaldi (2004); Schubert et al. (2014); Tomczyk and Bednorz (2016); Ahmadalipour and Moradkhani (2018); Li et al. (2018), climate change has significantly increased the number of daytime and nighttime HW events with high spatial and temporal variability across the globe. Recently, an increasing trend has been reported in the number of HW events over East Asia (Gu et al. 2012; Li et al. 2018; Luo and Lau 2019), Africa (Lelieveld et al. 2016; Waha et al. 2017; Barry et al. 2018), Europe (Stefanon et al. 2012; Ward et al. 2016; Hoy et al. 2017), South Asia (Sheikh et al. 2015; Im et al. 2017), Australia (Hansen et al. 2008; Cowan et al. 2014), and the Arab region (Almazroui et al. 2014; Donat et al. 2014). The rising trend of temperature in Pakistan is consistent with the global and regional temperature trends (Khan et al. 2018a; Waqas and Athar 2018a; Ullah et al. 2019b), which indicates a rising tendency of HW activities over different parts of Pakistan. Recent studies reported a pronounced rising trend in T_{\max} and T_{\min} and related extremes over the target region (Abbas 2013; Sun et al. 2017; You et al. 2017b; Ullah et al. 2018a). According to Nasim et al. (2018); Saeed et al. (2017), Pakistan is highly vulnerable to HWs and will face more frequent and severe HWs in the near future due to an obvious increase in T_{\max} and T_{\min} .

The results of this study show that the country has experienced frequent and severe daytime and nighttime HWs during the study period; however, the frequency, intensity, and duration of the daytime and nighttime HW indices were relatively high in two epochs of the study period i.e., 1997–2002 and 2011–2016. The analysis indicates an obvious warming trend with a slight shift in the onset (end) time of day and night HWs over the CPEC region. These results support the findings of previous studies conducted in the study region. According to Xie et al. (2013); Rahman and Dawood (2017), the country suffered a hot and dry phase of drought during 1997–2002, which could be one of the reasons for frequent and severe HWs during this period. Moreover, a sharp increase has been reported in summer T_{\min} after 2010 by various studies in the region (Khan et al. 2018a; Waqas and Athar 2018a; Ullah et al. 2019b). This obvious increase in

summer T_{\max} and T_{\min} could be one of the possible factors to trigger the frequency and intensity of daytime and nighttime HW activities in the study region. These results affirm the findings of recent studies conducted over the target area (You et al. 2017a; Khan et al. 2018b). They found an upward shift in HW events in China and Pakistan after 1990 and 2000, respectively. Recently, several studies have projected a sharp rise in T_{\max} and T_{\min} due to climate change, which may intensify the likelihood of temperature extremes and HWs in the region (Islam et al. 2009; Trenberth and Fasullo 2012; Mahmood and Babel 2014).

Moreover, the study found an increasing trend in the daytime and nighttime HWN and HWP over the CPEC region. Similar results were reported by regional and global studies in the recent past (Rahmstorf and Coumou 2011; You et al. 2011; Perkins 2015; Im et al. 2017; Rauf et al. 2017). According to Khan et al. (2018b), HWN and HWP have been increased at the rate of 0.71 events decade⁻¹ and 0.95 days decade⁻¹ over different climatic regions of Pakistan. The results also affirm the findings of Zahid and Rasul (2012). They reported positive trends in 5, 7, and 10 consecutive hot days with temperatures ≥ 40 °C and ≥ 45 °C over different parts of Pakistan. Similar results were found by previous studies (Abbas 2013; Ullah et al. 2018a). They revealed severe temperature extremes with an increased number of hot days and hot nights in the southeastern and southwestern parts of Pakistan. Moreover, Panda et al. (2017); Ratnam et al. (2016), also detected an upward shift in HWs and hot days in western India, bordering Pakistan. According to Ding et al. (2010), HWN and HWP have been increased at the rates of 1.5 events decade⁻¹ and 4 days decade⁻¹ over western China, a neighboring province of Pakistan. Recently, Wang et al. (2017a), has detected a significant positive trend in HWN with 0.27 events decade⁻¹ over China during 1987–2013. Similarly, Luo and Lau (2019), indicated an increasing trend of 0.32 events decade⁻¹ and 3.37 days decade⁻¹ in nighttime HWN and HWP over the Indochina Peninsula during 1961–2014. Wu et al. (2012) stated that the frequency of HWs and participating hot days are significantly increased within the range of 7–11 days decade⁻¹ over different parts of Northern America. Furthermore, several studies based on climate models have anticipated frequent HW events with maximum hot days and nights in the region (Russo et al. 2017; Nasim et al. 2018).

The results indicated that the average length of all annual daytime and nighttime HW events (HWL) and length of the longest annual daytime and nighttime HW event (HWD) exhibited a positive trend during 1980–2016. However, the trend of HWL was slightly upward than HWD implying that the average length of the yearly HW events became more prolonged and extended than an individual HW event. Overall, these results confirm the findings of recent studies (Meehl and Tebaldi 2004; Schär et al. 2004; Nasim et al.

2018). Related studies stated that climate change has significantly prolonged the length and duration of daytime and nighttime HWs in different regions of the globe (Perkins and Alexander 2013; Fischer 2014). Similarly, Khan et al. (2018b), have reported an upward trend in the length and duration of successive hot days in southern and eastern Pakistan. According to Rohini et al. (2016), the length and duration of HW events were significantly increased over the central and northwestern parts of India adjoining Pakistan during 1961–2013. Moreover, Lin et al. (2018), found a rising trend in nighttime HWL and HWD at the rate of 1.73 and 8.75 days decade⁻¹, respectively over the Fujian province of China. In addition, Luo and Lau (2017), reported a positive trend in nighttime HWL (0.57 days decade⁻¹) and HWD (2.43 days decade⁻¹) in southern China during 1979–2010. Recently, Wang et al. (2017a), found a rising trend in the HWD at the rates of 0.48 days decade⁻¹ over China for the period of 1987–2013. Similarly, an increasing trend has been reported in HWD and HWL over different parts of the United States (Rahmstorf and Coumou 2011; Bumbaco et al. 2013; Deng et al. 2018). Recent studies stated that global warming may intensify the tendency of HWL and HWD both in daytime and nighttime in the future with more frequent and intense HW events in the region (Islam et al. 2009; IPCC 2013; Saeed et al. 2017).

In addition, the study found a significant rising trend in the daytime and nighttime HWM and HWA over the CPEC region. The increasing trend of HWM and HWA suggests that the intensity of summer temperature has been moved upward during the study period. Since 1880, the global mean temperature has been raised by 0.89 °C, which may intensify the rate and severity of temperature extremes disproportionately over different regions of the world (IPCC 2013; Perkins 2015). It has been found that summer T_{\max} and T_{\min} are increasing faster than T_{mean} , indicating that the warming tendency of temperature extremes is high across the globe (Shahid et al. 2012; Iqbal et al. 2016; Sun et al. 2017; Waqas and Athar 2018b). Recently, a sharp increase has been noticed in summer T_{\max} and T_{\min} by several studies over the study region (Rauf et al. 2016; Waqas and Athar 2018a; Ullah et al. 2019b). This positive trend has resulted in pronounced warming of various temperature indices over different climatic zones of Pakistan (Khan et al. 2018a; Ullah et al. 2018a). Similarly, Abbas (2013); Sheikh et al. (2015), noticed a warming shift in the magnitude of summer T_{\max} and T_{\min} related extremes over the eastern and southern parts of Pakistan. Our results also affirm the findings of Sun et al. (2017); Zahid et al. (2017); Zahid and Rasul (2012), who revealed that southern and eastern parts of Pakistan are among the hottest parts of the Hindu Kush Himalayan (HKH) region with a maximum intensity of summer temperature. The results of this study are also consistent with the findings reported at regional and global scales. According to

Luo and Lau (2018), Indochina Peninsula has experienced a significant increase in the intensity of HWM and HWA at the rate of 0.05 and 0.17 °C decade⁻¹, respectively. Similarly, Luo and Lau (2017) revealed that HWM and HWA indices exhibited a positive trend in different parts of China with 0.14 and 0.21 °C decade⁻¹, respectively. Panda et al. (2017) revealed an increasing trend of HWM and HWA in India at the rate of 0.51 and 0.70 °C decade⁻¹, respectively. In addition, Wang et al. (2017a), reported a sharp rising trend in the HWM (0.17 °C decade⁻¹) over different parts of China during 1987–2013. Lin et al. (2018) found that the Fujian province of China (urban/rural area) has experienced an increasing trend in nighttime HWM and HWA at the rate of 0.05 and 0.21 (0.48 and 0.65/0.04 and 0.12) °C decade⁻¹ during 1971–2014. Moreover, climate models also projected a noticeable increase in the magnitude and amplitude of future HWs in the country and region (Im et al. 2017; Saeed et al. 2017; Nasim et al. 2018; Zhang et al. 2018).

Regarding the arrival and the end timing of HWs, the study found a significant negative (positive) trend during the daytime and nighttime HWO (HWE), which suggests that the onset (end) timing of the daytime and nighttime HWs was earlier (later) over the target region. The early arrival (delay termination) of HWs indicates that the country has experienced prolonged HWs seasons during the study period. Though determining the onset and the end timings of HWs can play a major role in the mitigation of HWs impacts still, very few studies have assessed the onset and end times of HW events around the globe. Interestingly, our results confirm the findings reported by previous studies (Schubert et al. 2014; Russo et al. 2017). Lin et al. (2018), have observed a significant positive (negative) trend in nighttime HWO (HWE) at the rate of 3.55 (8.80) days decade⁻¹ over the Fujian province of China. Moreover, they also detected a significant negative (positive) trend in the daytime HWO (HWE) at the rate of -1.79 (3.87)/-0.42 (2.48) days decade⁻¹ over the urban/rural area of Fujian province China. The climate model studies have also supported these findings and anticipated an evident decrease (increase) in the onset (end) timing of HWs around the world (Lau and Nath 2014; Lorenzo and Mantua 2016; Russo et al. 2017; Li et al. 2018).

The results show that both daytime and nighttime HW events dominated the target region during the study period. It is noteworthy that daytime and nighttime HWs exhibited asymmetrical characteristics with maximum variations in the last decade of the study period. The number of nighttime HWs was higher than daytime HWs with the highest number of events in the latter years of the study period. Based on the daily T_{\max} (T_{\min}), a total of 138 (155) daytime (nighttime) HW events have been identified, which indicate that the nighttime HWs occurred more frequently than daytime HWs. The frequent occurrence of nighttime HWs

could be the result of hot temperature and high humidity at nighttime, which poses more heat stress (Russo et al. 2017; Liao et al. 2018; Khan et al. 2019). Recent studies stated that successive hot nights with extreme heat stress can increase the number of deaths and casualties (Hansen et al. 2008; Mueller et al. 2014; Masood et al. 2015). Thus, the dynamic and complex nature makes nighttime HWs more dangerous than daytime HWs (Li et al. 2018; Lin et al. 2018; Ye et al. 2018). Similarly, the length and duration of both daytime and nighttime HWs have been increased simultaneously suggesting that the study region has experienced long-lasting HW activities during 1980–2016. The length and duration of daytime HWs exhibited a higher increase than nighttime HWs, which indicates that the daytime HWs were more extended and lengthy than nighttime. In recent years, several studies indicated that climate change can increase the number and length of hot days and nights in the future, which may prolong the length and duration of HWs in Pakistan (Saeed et al. 2017; Nasim et al. 2018; Khan et al. 2019).

Corresponding to the pertinent temperatures, the region has experienced severe daytime and nighttime HWs with maximum severity in the latter years of the study period. Interestingly, the magnitude and amplitude of nighttime HWs were higher than daytime HWs suggesting that the region experienced severe and intense nighttime HWs during 1980–2016. Moreover, nighttime HWs exhibited consistency in the high magnitude and amplitude, suggesting that the nighttime HW events were more severe than daytime HWs events. The persistent occurrence of consecutive hot nights could exacerbate vulnerability and poses potential risks to the human body (Nairn and Fawcett 2014; Mora et al. 2017). It has been reported that T_{min} is rising at a higher rate than T_{max} in the study region (Iqbal et al. 2016; Khan et al. 2018a; Ullah et al. 2019a), which can amplify the intensity of HWs in the future. In terms of timing, both daytime and nighttime HWs exhibited dynamic behaviors during the study period. The results show that the study region has experienced frequent, severe, strong, and extended HW events in day and night timings. It has been noticed that both daytime and nighttime HWs were commenced earlier and ended later, implying that the HWs season became larger over the target region. Generally, the daytime HWs commenced in mid-May and end in early-September, while nighttime HWs usually commenced in mid-June and ended in mid-September. The daytime HWs started (ended) one month (1 week) earlier than nighttime HWs, which indicates that the average difference between the onset (end) of daytime and nighttime HWs was relatively large (small). Related studies reported that climate change will largely affect the onset and end time of HWs, which will have substantial effects on human well-being (Mazdiyasnani et al. 2017; Li et al. 2018; Luo and Lau 2018).

Pakistan is located in a climatically warm geographical region, which is highly vulnerable to climate extremes such as HWs, drought, and floods (Khan et al. 2018a; Ullah et al. 2018a). The region experiences a higher increase in temperature than the global temperature (Iqbal et al. 2016; Ullah et al. 2019a). The sharp rise in temperature has intensified the melting of glaciers and snow covers in the Hindu Kush Himalayan region, which may amplify the risk of floods and drought in Pakistan (Kääb et al. 2012; Bocchiola and Diolaiuti 2013; Ragetti et al. 2016; Ullah et al. 2018a). Similarly, rapid heat accumulation has increased the intensity, duration, and frequency of HWs in Pakistan, which have disastrous impacts on human activities, natural and built systems (Khan et al. 2019). Furthermore, these hydro-meteorological disasters could cause serious threats to agriculture, water, and energy sector of the country. According to the Global Climate Risk Index 2014, Pakistan is the third most affected country by climate change. The extended hot period poses potential risks to the local people in the form of heat strokes, death, casualties, and health diseases due to the accumulation of heat stress (Masood et al. 2015; Rauf et al. 2017). Recent studies reported that climate change induced HWs and drought have significantly reduced crop yields of wheat, rice, cotton, and sugar cane in Pakistan, which may result in potential food insecurity in the near future (Ali et al. 2017; Ullah et al. 2018c). Moreover, climate change has intensified the rate of mortality and heat-related diseases in livestock (Shafiq and Kakar 2007; Nasim et al. 2018). In recent decades, the substantial impacts of HWs and drought have forced rural people of Pakistan to migrate to urban areas and seek alternate livelihood sources (Mueller et al. 2014; Saeed et al. 2016; Im et al. 2017). It is anticipated that urban heat island effect would intensify the impacts of HWs in the future (Anjum et al. 2017; Ye et al. 2018).

Since its independence, Pakistan has experienced prevalent HWs, which caused substantial human and socio-economic losses (Saeed et al. 2017; Khan et al. 2018b). So far, the June 2015 HW is the only event documented in the peer-reviewed literature. During 17th to 24th June 2015, the southeastern parts of Pakistan were dominated by connective hot days with high relative humidity resulted in unbearable perilous condition (Chaudhry et al. 2015; Ghumman and Horney 2016). Moreover, the unavailability of electricity and water contributed to the intensification of HW effects in the target regions (Rauf et al. 2017; Saleem et al. 2017). This catastrophic HW event caused an estimated death toll of 1200 people with the highest number of mortalities in the megacity of Karachi (Masood et al. 2015; Wehner et al. 2016). The majority of the deaths was reported among old aged, children, women, and disabled people in the affected cities (Ghumman and Horney 2016; Saleem et al. 2017). The event was prevailed by the highest temperature since 1979 (Khan et al. 2018b), and was considered the fifth deadliest

HW in global history (Im et al. 2017). It has been stated that climate change may exacerbate the intensity and frequency of future HWs in the southeastern parts of Pakistan, which would affect a large proportion of the country's population.

The spatiotemporal variability of surface variables is usually influenced by atmospheric elements such as relative humidity, air temperature, cloud cover, wind speed and direction, solar radiation, and specific humidity, etc., (Sayemuzzaman et al. 2015; Guo et al. 2016; Yan et al. 2016; Li et al. 2017, 2018). The direct or indirect interactions of these elements develop a positive and negative feedback mechanism, which ultimately affect the large-scale atmospheric circulation and climate processes of a region (Duan et al. 2013; Ahmad et al. 2014; Wan et al. 2017; Wang et al. 2017b). Among these, relative humidity is one of the key factors, influencing the surface temperature and HW activities at regional and local scales (Stefanon et al. 2012; Miralles et al. 2014; Ratnam et al. 2016; Park et al. 2017; Zhang et al. 2018). Recent studies reported that the combination of high relative humidity and extremely high temperature causes exponential humid HW events (Lau and Kim 2012; Priya et al. 2015; Yamada et al. 2016; Luo and Lau 2019). Over the past few decades, an increasing trend has been reported in high humid HWs across the globe (Barriopedro et al. 2011; Rahmstorf and Coumou 2011; Scocci-marro et al. 2013; Liao et al. 2018). The present study found that the entire country has experienced severe HW activities with a maximum trend in the northern and southeastern regions. It can be suggested that the increasing trend of HWs and related characteristics over the said regions could be the results of high relative humidity and temperature (Sun et al. 2017; Khan et al. 2019; Ullah et al. 2019a; You et al. 2019).

Similarly, the coupling of high air temperature and high solar radiation increases evapotranspiration, which may result in cloudy and humid condition. It has been reported that the presence of cloud cover with the humid condition can amplify HW activities (Schubert et al. 2014; Ali et al. 2017; Luo and Lau 2017). Several studies suggested that the effects of HWs are more severe under cloudy condition than clear-sky, due to the trapping capability of the cloud (Wu et al. 2012; Waqas and Athar 2018a). The cloud trap heat and moisture generating humid condition and heat stress (Fang et al. 2016; Luo and Lau 2019), posing potential risks to human well-being (Mora et al. 2017; Liao et al. 2018; Luo and Lau 2018). This study found severe HWs in the northern and central parts of the study region, which could be the possible reason for the said condition. Moreover, the speed and direction of wind coupling with water vapors affect the behaviors of HWs in the coastal and adjacent regions (Pathak et al. 2017a; Priya et al. 2017). During the summer season, strong winds from the Indian Ocean are moving towards the coastal parts of Pakistan containing water vapors (Priya et al. 2015; Pathak et al. 2017b). In this study,

we found that the southern and eastern parts of Pakistan experienced an increasing trend in HW activities during the study period, which could be linked to hot temperature, high humidity, wind speed, and direction.

Besides these, Pakistan experiences HWs as a result of manifold anthropogenic factors such as high population, extended urbanization, industrialization, and rapid deforestation (Malik et al. 2012; Saeed et al. 2016). These factors play a key role in rising regional and local temperature, which may result in intense and frequent HW activities (Lin et al. 2018; Luo and Lau 2018; Ye et al. 2018). Furthermore, several cities of Pakistan have been transformed into metropolitan cities due to rapid industrialization and migration of rural people for better job opportunities and improved life, health and education facilities (Ilyas et al. 2010; Rauf et al. 2017). The large inflow of people to urban areas has resulted in a shortage of civic transport such as buses, rail, taxi, and auto rickshaws (Anjum et al. 2017; Ullah et al. 2018a). In response, a sharp increase has been noticed in personnel transport facilities (i.e., cars, motorbikes, and scooter) (Ilyas et al. 2010; Abbas et al. 2018). The rapid urbanization, extensive industrialization, and excessive utilization of individual vehicles may amplify the emission of greenhouse gasses, which eventually increase the local warming pattern and temperature extremes (IPCC 2013; Rauf et al. 2017; Khan et al. 2019). It can be concluded that the exponential increase of HWs in Pakistan could be the result of the above-mentioned anthropogenic factors. Recently, many studies reported a sharp rise in urban heat stress and HW activities over different regions of the world (Herring et al. 2015; Liao et al. 2018; Luo and Lau 2018). Similarly, several agricultural practices such as increased irrigation and open canal system have substantial effects on temperature and associated extremes in the target region (Roy et al. 2007; Ullah et al. 2018a). Although, Pakistan is an agricultural country and most of its arable land is located in the Indus River Basin with open canal and irrigation system (Iqbal et al. 2016; Ali et al. 2017; Ullah et al. 2019a). The persistence of high temperature under clear-sky may increase the process of evaporation from the open canal system and irrigated land, which may induce cloudy and humid condition at the local scale. Hence, it can be concluded that the agricultural practices adopted by the local farmers cannot be ignored in intensifying the trend of long-term temperature, which may also increase HW activities in the study region.

6 Conclusion

The present study aims to assess the spatiotemporal variability of HW characteristics based on multiple indices over the CPEC region. The daily occurrence of daytime (night-time) HWs indicates that HWs are becoming more frequent,

stronger, severe, and longer during 1980–2016. The temporal analysis of HW behaviors shows that the daytime (nighttime) HWN and HWP are significantly increased, which suggest that the country has experienced frequent HWs and hot days during the study period. Similarly, daytime (nighttime) HWL and HWD exhibited a significant increasing trend, which indicates that the average length of the yearly HW events have become lengthier over the CPEC region. In addition, daytime (nighttime) HWM and HWA have shown a significant rising trend during the study period, implying that the region has suffered intense and severe daytime (nighttime) HW events over the recent past few decades. Moreover, daytime (nighttime) HWO/HWE exhibited a significant decreasing/increasing trend during 1980–2016, which suggests that the HW events are starting earlier and ending later in the calendar year due to which HW season is becoming larger in the study region. The spatial distribution of trend indicates that the central, eastern and southern areas of the country displayed a prominent and consistent warming tendency, while the northwestern mountainous regions showed a high spatial variability both in the daytime and nighttime HWs and related characteristics. Despite all, some of the stations located in the northwestern regions displayed decreasing trends in different indices of day and nighttime HWs. Though this study analyzed the spatiotemporal changes in daytime and nighttime HW characteristics, but for deep understanding, the present study recommends a comprehensive assessment of both natural and human factors responsible for variations in the trend of daytime and nighttime HWs characteristics over the CEPC region. Moreover, this study suggests a thorough investigation of the HWs mechanism and their connection with large-scale atmospheric circulation in the region.

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