Heat Waves Assessment and Their Future Projections over Pakistan

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Abstract

With the rising of global temperature, heat waves have gained regional and global concern and interest as a growing social and health issue due to its various impacts on living beings. To cope with the devastating effects of extreme heat great efforts are made in developed countries and still in progress in under developing countries. For the purpose to investigate and assists future heat waves in Pakistan, we select four major heat waves hitting sites i-e Karachi, Lahore, Multan and Peshawar. In this study we followed three different heat waves calculating concepts. We have defined heat waves from daily maximum (HW_TX90p) and minimum (HW_TN90p) temperatures and from mean (HW_EHF) of daily maximum and minimum temperature. The threshold used in this study is the 90th percentile of daily maximum, minimum and mean temperature. The purpose of 90th percentile to use as a threshold for measurement of heat waves lie in its suitability of an "adequate" population of measurable events. The minimum period for a heat wave event to exists is three at least days. Because for extreme heat three days are quite enough to negatively affects a living body. Results show an overall significant increase in amplitude, number, duration, and frequency the heat waves for the study locations. Heat wave number shows greater increase in Peshawar for HW_TX90p and Lahore for both HW_TN90p and HW_EHF respectively. However, among the cities in Karachi individual heat wave events are observed longer in duration for both HW_TN90p and HW_EHF. Corresponding heat wave frequencies in between the methodologies is higher for minimum (HW_TN90p) temperature in all the sites. However in Karachi it has the highest increase.

1. Introduction

Heat waves have gained regional and global concern and interest as a growing social and health issue due to its various impacts. Heat waves are periods of extremely high surface air temperatures consistence for several days. These higher temperatures results in heat stress and higher proportion of morbidity and mortality in the lack of appropriate adaptation strategies. Temperature extremes show widespread changes in response to global warming, that results in more frequent, longer and high intensity temperature related hazards (Meehl and Tebaldi 2004; Kharin et al., 2013; Collins et al., 2013), consistent to experienced evolution in the past decades (Donat et al., 2013). In developed countries great efforts are made in order to cope with the devastating effects of extreme heat on society, economy, and environment. For instance, just after the European theatrical event of 2003 (Schär and Jendritzky 2004; GarcíaHerrera et al., 2010). However, in developing countries especially in Pakistan heat waves are still understudied where mean climate is warm and have relatively low adaptation capacities. Heat waves are correlated with higher excess heat illnesses and health problems such as cardiovascular and respiratory diseases, and life-threatening crises (Wilker E. H et al.,2012; S. Hajat, R et al.,2007). Excess mortalities associated with heat waves are also justified from the global heat wave events that results in thousands of deaths. European heat wave of 2003 affects major part of western Europe, breaking the record of temperature and deaths tall about seventy thousands (Poumadere et al., 2005). In the 2nd severe heat event of Europe (France) in 2006, around 2,065deaths were recorded due to extreme temperatures (Fouillet A et al.,2008).The California extreme heat event in 2006 with around 600 deaths (Ostro et al., 2009), the 2007 heat wave of Greek (Founda and Giannakopoulos, 2009) and many deaths related to heat wave have been recorded in Australia (Mason et al., 2010;Loughnan et al., 2010;Tong et al., 2010). The 2011 heat wave of Texan (Rupp et al.,2012) and the heat waves of United States (Zanobetti and Schwartz, 2008; Peterson et al., 2013) results in damage to lives where temperatures were highly unusual than normal climate. Similarly, a severe heat wave event during 2010 in Russia results nearly 11,000 mortalities (Shaposhnikov et al., 2014). Numerous studies predict more intense and frequent heat waves (Schiermeier, 2011;Perkins and Alexander, 2013; Murari KK et al., 2014). Approximately 9.0% of the global population (seven hundred million people) will have exposure towards extreme heat in each upcoming 20 years under 1.5°C comparing to a 2°C warming 28.2% population (additional 2 billion people) (Dosio A et al., 2018). A significant increase in the magnitude of heat waves is expectable over South America, Africa and Southeast Asia under 1.5°C and at 2°C degree warming the frequency will be double across major parts of the Globe (Dosio A et al., 2018). In Pakistan, one third of total population (188 million) depends on sensitive sectors to climate for their survival (Saeed et al.,2017), climate change related hazards are flattering as a major concern of extreme importance. Previous studies over Pakistan examines the past and future trends of extreme events and have shown the robust positive tendencies towards maximum and minimum temperatures, frequently related with recurrent warm extremes of heat (Zahid and Rasul et al.,2011; Ali et al.,2015). Over the twenty first century, such trends of maximum and minimum warm extremes have been predicted mostly found in arid and semiarid regions globally (Collins et al., 2013; Roehrig et al.,2013; Russo et al.,2016).Unfortunately, issues related to heat waves across Pakistan has been discussed by few studies along with adaptive measures. Several studies examine past and future heat wave trends over Pakistan (Zahid and Rasul ,2012;Saeed et al., 2017; Khan et al.,2018).

The average predicted increase in warm spells is projected to be 350 days in 2100 from 150 days since 1990 at high emissions scenario. But if the emissions are decreased rapidly, the average increase in heat waves and warm spells could be limited nearly to 185 days. By 2080 at such high scenario the heat deaths in elders above 65 years will lie to about 63 deaths per total of 100,000 as compared to estimations (10 deaths per 100,000) from baseline (WHO 2015).

One of the studies examines different adaptation measures in different sites of Faisalabad through questionnaires. The adaptive means during extreme heats in such localities includes green sheets in houses, uses of water and liquid fluids, regular baths, avoidance of sunlight through head caps and umbrellas (Bakhsh K et al.,2018). Under the circumstances of extreme heat conditions it is of utmost importance for health professionals to understand the configuration of effects on health during such events and then to afford guidance to stakeholders and decision makers for their decision-makings and service guidelines.

To figure out reliable predictions and cope suitable mitigation and adaptation strategies documentation of characteristics and assessment of associated physical mechanisms of heat waves are highly needed for Pakistan.

2. Impacts of Heat Waves

Heat waves and stress impacts that put high stress on biological systems, on human beings are greatly related to the existing conditions which are exacerbate by high temperatures and their developing capacity to such impacts. Individuals with poor thermoregulation especially among the sick and the elderly are more susceptible to the heat wave impacts. Children and pregnant women exposed to extreme heats are also at higher dangers. In countries with low and middle incomes and among the vulnerable populations the heat wave impacts are more significant (Watts et al., 2017). Heat waves can acutely impact large populations for short periods of time, often trigger public health emergencies, and result in excess mortality, and cascading socioeconomic impacts (e.g. lost work capacity and labor productivity). Though the human body can adapt effectively to environmental conditions but when the body is exposed to extreme heat waves, where it reaches its core internal temperature to 40°C , this results in internal injuries to cellular components. These internal injuries initiates a flow of reactions that led to organs damage and fatality (Becker and Stewart, 2011;Basarin et al., 2016). The negative response of human body system to effectively react to extreme heat could led to various ill conditions such as acute cerebrovascular damage, aggravation of chronic pulmonary and cardiac disorders, kidney failure, hyperthermia and even heat stroke, and many other illnesses (WHO, 2006; Basarin et al., 2016).

Neurological co-morbidities of heat stroke results in around 20 to 30% of patients (Bouchama and Knochel 2002). Among other causes of heat deaths hyperthermia was considered a major contributing cause of exceeds 54% deaths in United States in between 1999 to 2003 (CDC, 2006).

Heat waves can also cause loss of health service delivery capacity, where power shortages which often accompany heat waves disrupt health facilities, transport, and water infrastructure. Additionally, extreme heat impacts also lead to socio-economic disruption and triggered intensive discussions on the field of livestock and crops as well, environment, agriculture and marine life (Zahid and Rasul ,2012;Nairn and Fawcett, 2013).

Awareness remains insufficient of the health risks posed by heat waves and prolonged exposure to increased temperatures. Health professionals must adjust their planning and interventions to account for increasing temperatures and heat waves. Practical, feasible, and often low-cost interventions at the individual, community, organizational, governmental and societal levels, can save lives.

3. Study Area

Pakistan (latitudes 23.5°-40°N and longitudes 60°-80°E), situated in South Asia with occupied land zone of 796,095 km^2 has high topographical and physiographic changes. The Northern part of it is characterized by highlands of Himalaya-Karakoram-Hindukush region with various highest peaks in the region of Gilgit-Baltistan, Azad Kashmir and Northern Khyber PakhtunKhwa. In addition locating Southern part, Sindh and Punjab is categorized by coastal parts, semiarid, arid, hyper-arid along the latitudinal belt (Saeed et al.,2017). Four different topographic sites from the country are selected for the assessment for heat waves namely Karachi, Lahore, Multan and Peshawar (Figure 1). The assessment of heat waves across Karachi through the same methods is submitted for publication.

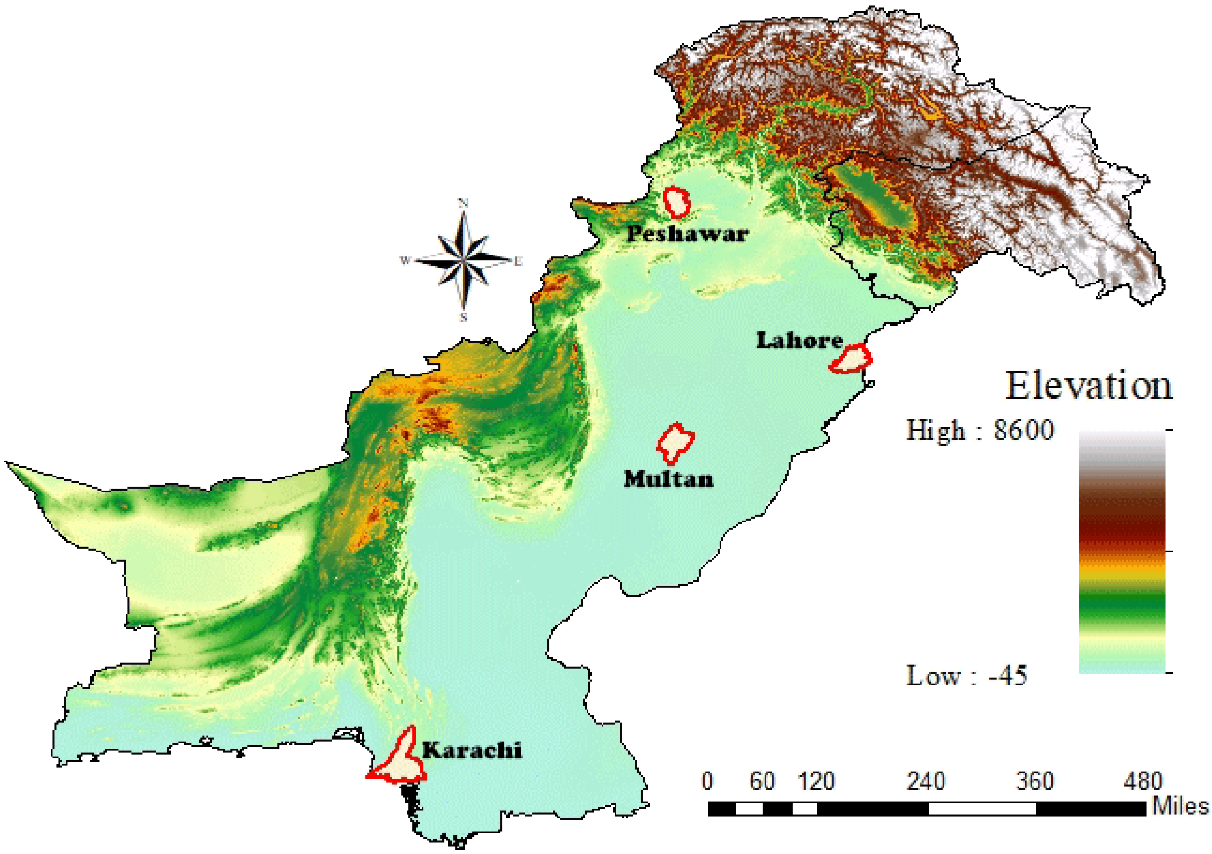

Figure 1: Topographic representation of Pakistan with red polygon indicating the study sites (Peshawar, Lahore, Multan and Karachi).

4. Heat wave definitions For Pakistan

Definition of heat wave event is sector such as human health, agriculture and transport energies dependent and relative to locality. Heat waves can be defined from meteorological parameters likely daily maximum and minimum temperatures (e.g., Beniston et al., 2007) and extreme heat posing life-threatening stressful indices as well (e.g., Fischer and Schär, 2010) that significantly accounts for impacts on humans wellbeing resultant from heat. Generally it can be defined as a period of unusually daily extreme temperature weather above their normal maximum range for at several days usually two to three (Stefanon, D'Andrea, & Drobinski, 2012). Both daytime and nocturnal temperatures, as well as humidity could reach to high values beyond their long-term mean during period of heat wave event (NOAA, 2016). Heat waves are generally relative to regional climate, for instance the same meteorological data and their intensity that mean heat wave in a location could not be considered substantially as heat wave for another region.

In Pakistan, heat waves are defined from daily maximum and minimum temperatures using different approaches over several number of duration. For instance Zahid and Rasul (2012) defined heat wave as an event where temperature reaches beyond 40°C and 45°C for successive duration of 5 and 7 days respectively. Saeed et al (2017) uses two different approaches (fixed and relative) for future heat waves over Pakistan one that define heat wave when maximum temperature could exceeds 45°C for consistent several number of days applicable as a fixed threshold to southern areas and a relative approach for heat waves over northern areas where when the daily maximum temperature rises by 5°C or more from average maximum temperature for more than five consecutive number of days. Nasim et al. (2018) characterized heat wave relative to topography, the rise of 5°C to 6°C above average daily extreme temperature for succeeding 8 days. Khan et al (2018) define heat wave over Pakistan when maximum temperature exceeds 95th percentile for consecutive 5 days. Our study define heat wave using 90th percentile as a threshold for daily minimum, maximum and mean temperature separately. Extremely high dew point temperatures lead to extremely warm nights therefore minimum temperature based heat wave assessment is important which results to high-impact heat waves. Further, minimum temperature assessment is also beneficial for agricultural sectors. Each 1°C rise in daily minimum temperature extreme during growth seasons would result in a decrease about 10% in production of rice grain (Peng et al., 2004). So, this study defines heat waves based on both daily maximum and minimum temperature and mean of both that is comprised in a different concept.

5. Data

14 General Circulation Models (GCMs) of Coupled Model Intercomparison Project Phase 5 (CMIP5) with Representative Concentration Pathways with RCP8.5 were used after bias correction downscaling by spatial disaggregation and quantile delta mapping (SDQDM) method. Daily Maximum temperature, minimum temperature, and precipitation data of observed meteorological stations daily were acquired from Pakistan Meteorological Department (PMD) for the period of 1976-2005.

6. Methodology

The identification and determination of heat waves over the study area is achieved using the computation of three different heat wave phenomena that resultant from maximum and minimum daily temperatures. The minimum temperature is of great importance because high minimum temperature values intensify the heat wave conditions, also increasing the degree of heat stress (Nairn et al.,2009; Trigo et al.,2005). The basis of the study is 90th percentile being used as a threshold for three consecutive days for daily maximum, minimum and mean temperature, widely used for other regions (Perkins and Alexander, 2012;2013). The present study selects a percentile threshold rather than absolute as it is highly recommended for heat wave metrics to accomplish the locality measures (Perkins and Alexander, 2013). The purpose of 90th percentile to use as a threshold for measurement of heat waves lie in its suitability of an "adequate" population of measurable events. For each day of the year daily 90th percentile is calculated using a 15 day running window and then the TX, TN and TM (EHF) of each day is matched to the threshold value (percentile) of the corresponding calendar day. The percentile values are calculated from the baseline, so there is a different value for each day. The three consecutive days criteria is selected based on human behavior response to extremely hot conditions that rise the mortality rate significantly (Nairn and Fawcett, 2015).

We defined heat waves according to the methodologies as;

- **TX > 90th percentile of TX**

  Based on the maximum temperature a heat wave event is defined as when the maximum daily temperature exceeds the 90th percentile of maximum daily temperature for at least three consecutive days.

- **TN > 90th percentile TN**

  Based on the minimum temperature a heat wave event is defined as a when the minimum daily temperature exceeds the 90th percentile of minimum daily temperature for at least three consecutive days.

  - **Excess Heat Factor (EHF)**

    The EHF index is a combination of two sub excess heat indices (EHI), one that represents the acclimatization to heat and other that represent climatological significance. It incorporates both daily temperatures (maximum and minimum) and provides a measure of the environmental heat load.

So, according to EHF, heat wave conditions are present when the EHF is being positive. For detail see appendix A.

Table 1: Indices used in the study for the assessment of heat waves.

Index	Definition	Unit
HWN(EHF/Tx90/Tn90)	Number of individual heat waves	events
HWA(EHF/Tx90/Tn90)	Hottest day of the hottest heat wave	°C (°C^2 for EHF)
HWD(EHF/Tx90/Tn90)	Length of the longest heat wave	days
HWF(EHF/Tx90/Tn90)	Total number of days that contribute to individual heat waves	days

7. Results

This section explains the time series and projected changes in heat wave conditions over the study area for the baseline (1976-2005) and future (2006-2030, 2041-2070 and 2071-2099). The results shows an overall significant increase in heat waves conditions for the different approaches utilized over the study sites with their relative changes in the frequency and intensity of heat events. The same results of heat waves across Karachi are already submitted for publication.

Heat wave Amplitude

Climatologist of the heat wave amplitude (HWA) derived from the formulation of EHF, TX90p and TN90p are described in this section. Figure (2) shows the results for HWA in the time period 1976-2099. The results show an increase in amplitude of heat wave events over the entire study area for the followed methodologies. The total average increase in the amplitude of heat event is seen to be 45°C, 34°C and 21.3°C^2 for TX90p, TN90p and EHF respectively. Lahore is subjected to have an average increase of 51°C, 36.87°C and 37.2°C^2 for TX90p, TN90p and EHF respectively. Multan revealed a total of 52.62°C, 37.6°C and 36.72°C^2 increase in the heat wave amplitude for TX90p, TN90p and EHF respectively. Peshawar indicates an increase of 51.3°C derived from TX90p. Respectively for TN90p and EHF it possess 35.7°C and 41.82°C^2.

Projections

Table (2) show the changes in projection of amplitude to Heat wave events across the study area. The projection in HWA from TX90, TN90p and EHF show more increase during the last period (2071-2099). Across all the stations the increase in amplitude of heat events were more during 2071-2099 in the used methodologies, however for EHF the changes are more pronounced.

Heat waves Number

The number of heat wave event (HWN) derived from the used methods have been discussed in this division. The location and temperature (i-e TX,TN or Mean) specific heat wave methodologies utilized forms a standard for the characteristics of heat wave events across study area that could be used as useful means for further quantification. Figure (3) shows the results for HWN in the time period 1976-2099. The results show an increase in the individually summer heat wave events over the entire study area for the three heat wave methodologies. The average increase in the number of heat wave across Karachi is 8.53, 4.65 and 5.21 events for TX90p, TN90p and EHF respectively. Lahore is subjected to have an average increase of 9.5, 8.05 and 7.27 events for TX90p, TN90p and EHF respectively. Multan revealed a total of 9.631, 7.21 and 6.85 increase in the heat wave events for TX90p, TN90p and EHF respectively. Peshawar indicates the highest mean increase of 10.5 events derived from TX90p. Respectively for TN90p and EHF it possess occurrence of 7.75 and 7.1 events.

Projections

Table (3) show the relative changes in projection of Heat wave number across the study area for the baseline and future. The projection in HWN from EHF and TN90p show more increase during 2041-2070 across Lahore, Multan and Peshawar. While for TX90p they showed more increase during the last period (2071-2099). In the case of Karachi, it show more increase during 2041-2070 for EHF, 2006-2035 for TN90p and 2071-2099 for TX90p, which indicates fluctuations in temperature. Overall the highest increase in the heat wave events exists in case of maximum temperature (TX90p) with highest increase in Peshawar among all locations.

Heat Wave Duration

Figure (4) shows the descried results in heat wave duration (HWD) for EHF, TX90p and TN90p in the time period 1976-2099. The results show an increase in duration of heat wave events over the entire study area for the followed methodologies. The average increase in the duration of heat event over Karachi is 38.52, 116.98 and 79.67 days for TX90p, TN90p and EHF respectively. Among the stations Karachi possesses longer heat wave events for TN90p and EHF.

Lahore is subjected to have an average increase of 40.67, 66.97 and 68.62 days for TX90p, TN90p and EHF respectively. Multan revealed a total of 42.26, 77.58 and 75.83 days increase in the heat wave duration for TX90p, TN90p and EHF respectively. Peshawar indicates an increase of 38.37 days derived from TX90p. Respectively for TN90p and EHF it possess 69.50 and 71.90 days.

Projections

Table (4) show the changes in projection of Heat wave days across the study area for the baseline (1976-2005) and future (2006-2030, 2041-2070 and 2071-2099). The projection in HWD from TX90, TN90p and EHF show more increase during the last period (2071-2099). Across the stations according to TN90p the heat waves duration show highest increase followed by EHF and less increase for TX90p.

Heat wave Frequency

Heat wave Frequency (HWF) derived from the formulation of EHF, TX90p and TN90p are described in this section. Figure (5) shows the results for HWF in the time period 1976-2099. The results show an increase in Frequency of heat wave events over the entire study area for the followed methodologies. The average increase in the frequency of heat event is 101.56, 180.22 and 153.35 days for TX90p, TN90p and EHF respectively over Karachi. Lahore is subjected to have an average increase of 117.17, 150.15 and 147.73 days for TX90p, TN90p and EHF respectively. Multan revealed a total of 118.96, 160.1 and 153.60 days increase in the heat wave frequency for TX90p, TN90p and EHF respectively. Peshawar indicates an increase of 120.54 days derived from TX90p. Respectively for TN90p and EHF it possess

148.81 and 129.92 days. Among the different heat wave methodologies all the stations possesses more frequent heat wave events for TN90p followed by EHF.

Projections

Table (5) show the changes in projection of total contributing days to Heat wave events across the study area for the baseline(1976-2005) and future (2006-2030, 2041-2070 and 2071-2099). The projection in HWF from TX90, TN90p and EHF show more increase during the last period (2071-2099). Across all the stations the increase in frequency of heat events was more during 2071-2099 in the used methodologies.

8. Summary

Daily temperatures both minimum and maximum have been implemented as a means of calculating heat waves across Karachi Lahore Multan and Peshawar cities of Pakistan. Three different methodologies are utilized for the analysis of heat waves. The one presented as HW_TX90p is based on daily maximum temperature when it exceeds the 90th percentile of daily maximum temperature. The appliance of heat waves derived from minimum temperature (HW_TN90p) is same as for maximum temperature (HW_TX90p). However, heat waves for mean temperature incorporated in EHF utilized a different technique (for detail see appendix A). Heat wave indices (HWN, HWD, HWF and HWA) are used for all the methods. The results show an increase in heat wave conditions over the study locations. Heat wave number is seen to be greater in Peshawar for HW_TX90p and Lahore for both HW_TN90p and HW_EHF respectively. However, among the cities in Karachi individual heat wave events are observed longer in duration for both HW_TN90p and HW_EHF. Corresponding heat wave frequencies which is the total contribution of days to heat wave events in between the methodologies is higher for HW_TN90p in all the sites. However in Karachi it has the highest increase. While for HWF_EHF, Karachi and Multan show higher increase. HWA, the daily peak value in the hottest heat event show more total increase in Multan over the cities for HWA_TX90 but the rate of increase in amplitude over Lahore(8°C) were greater than Multan(7.2°C). Since the wide range of divesting effects of extreme heat across many different health and other sectors, the definition of heat waves will always be comprehensive and ambiguous. Adding to, the concepts (maximum, minimum and mean) used in the study should be utilized as a measure of impact studies relative to location. For instance the importance of minimum temperature is significant for agriculture purposes.

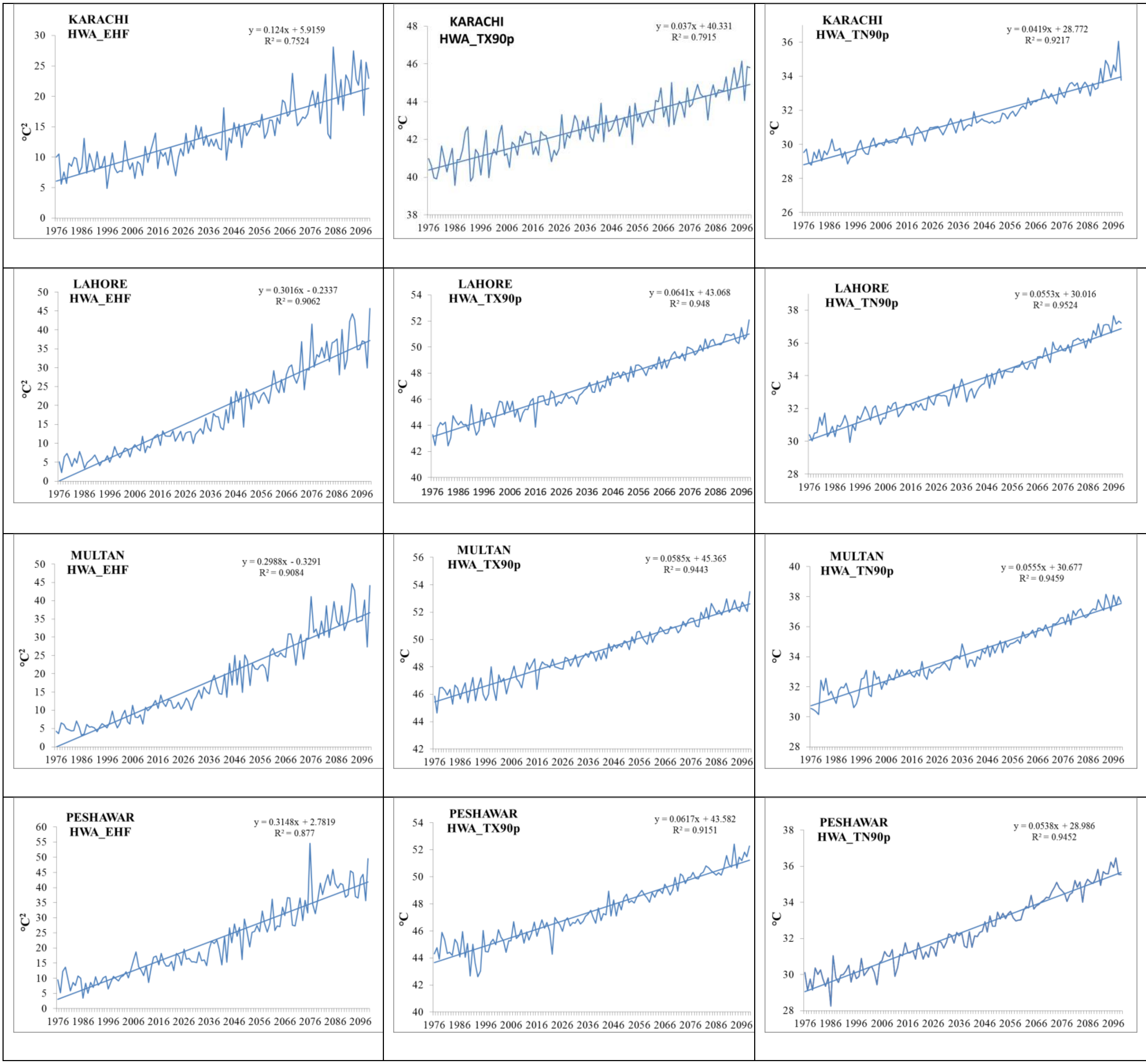

Figure 2: Time series plots of heat wave amplitude over the period 1976-2099. Straight line represents linear regression.

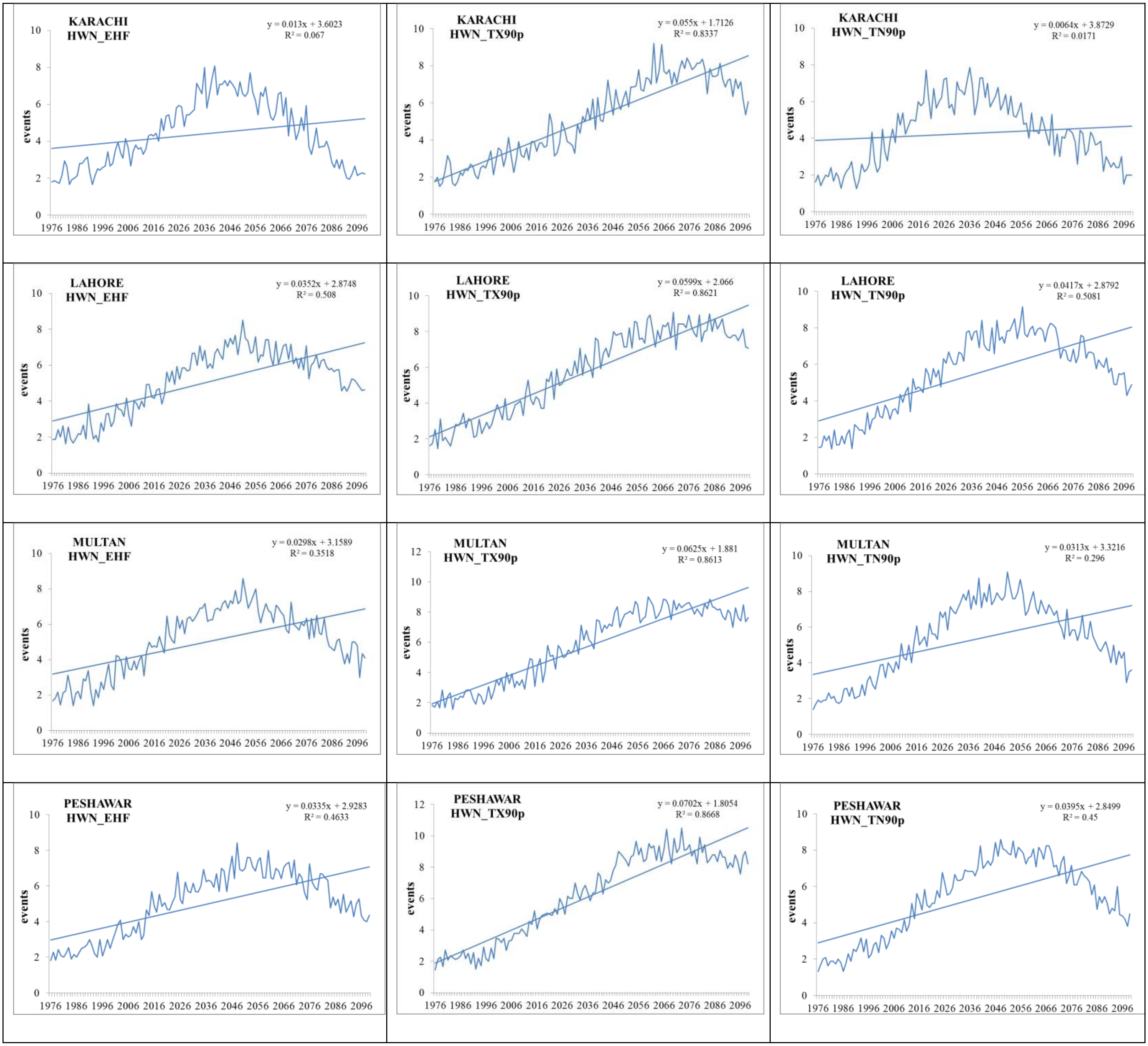

Figure 3: Time series plots of heat wave number over the period 1976-2099. Straight line represents linear regression.

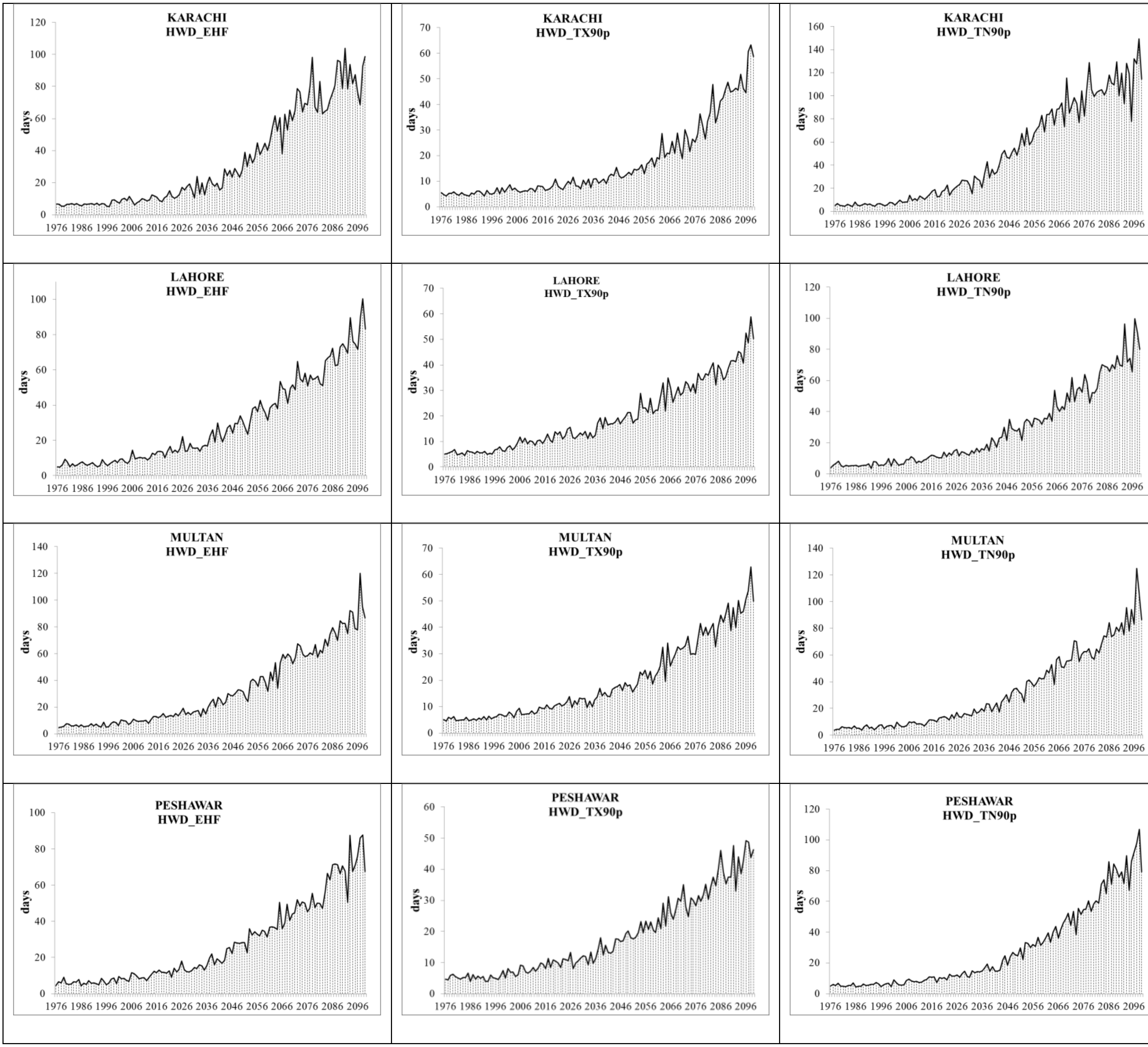

Figure 4: Time series plots of heat wave duration over the period 1976-2099.

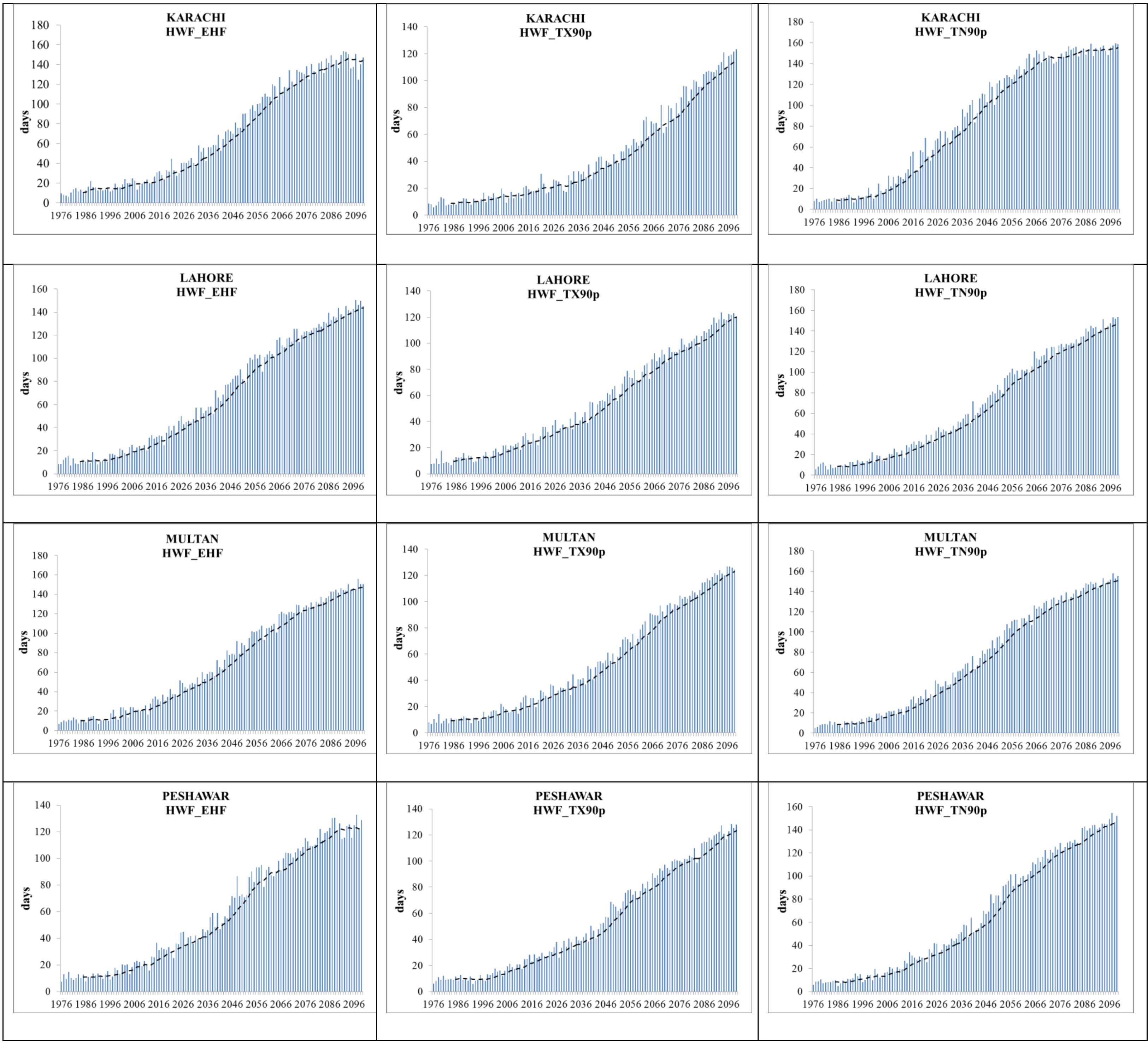

Figure 5: Time series plots of heat wave frequency over the period 1976-2099. The dash line represents 10 years moving average.

Table 2: Relative changes in amplitude of heat waves derived from EHF, TN90p and TX90p. Units are represented in "°C²"for EHF and "°C" for TN90p and TX90p. Bold digits show higher increase.

	HWA_EHF				**HWA_TN90p**				**HWA_TX90p**			
Period	1976-2005	2006-2035	2041-2070	2071-2099	1976-2005	2006-2035	2041-2070	2071-2099	1976-2005	2006-2035	2041-2070	2071-2099
Karachi	8.76	2.03	6.62	**11.44**	29.58	1.04	2.32	**4.01**	41.05	0.88	2.09	**3.48**
Lahore	6.12	5.50	16.72	**28.76**	31.10	1.24	3.17	**5.22**	44.27	1.47	3.90	**5.99**
Multan	5.79	5.85	16.64	**28.57**	31.70	1.40	3.25	**5.27**	46.31	1.69	3.66	**5.60**
Peshawar	9.15	6.18	17.45	**30.38**	29.95	1.38	3.23	**5.15**	44.70	1.51	3.69	**5.90**

Table 3: Relative changes in heat wave number derived from EHF, TN90p and TX90p. Units are represented in "events". Bold digits show higher increase.

	HWN_EHF				HWN_TN90p				HWN_TX90p			
Period	1976-2005	2006-2035	2041-2070	2071-2099	1976-2005	2006-2035	2041-2070	2071-2099	1976-2005	2006-2035	2041-2070	2071-2099
Karachi	2.58	2.22	**3.83**	0.79	2.33	**3.46**	2.95	0.90	2.48	1.38	4.39	**4.91**
Lahore	2.57	2.40	**4.41**	3.05	2.45	2.93	**5.29**	3.57	2.66	2.10	5.08	**5.38**
Multan	2.57	2.60	**4.42**	2.54	2.44	3.18	**5.07**	2.65	2.49	2.16	5.41	**5.60**
Peshawar	2.56	2.37	**4.41**	2.87	2.32	2.91	**5.43**	3.37	2.42	2.64	6.14	**6.36**

Table 4: Relative changes in duration of heat waves derived from EHF, TN90p and TX90p. Units are represented in "days". Bold digits show higher increase.

	HWD_EHF				HWD_TN90p				HWD_TX90p			
Period	1976-2005	2006-2035	2041-2070	1971-2099	1976-2005	2006-2035	2041-2070	2071-2099	1976-2005	2006-2035	2041-2070	2071-2099
Karachi	7.14	5.12	32.10	**71.78**	6.17	12.05	61.74	**101.86**	5.64	2.22	11.15	**33.84**
Lahore	6.93	6.67	28.49	**59.63**	6.03	5.62	27.04	**59.96**	6.15	5.45	16.80	**32.70**
Multan	6.75	6.60	31.84	**66.88**	5.94	6.90	33.23	**69.23**	5.80	4.26	16.02	**35.64**
Peshawar	6.54	5.44	25.55	**55.07**	5.75	4.89	25.54	**63.94**	5.46	4.26	15.73	**31.47**

Table 5: Relative changes in frequency of heat waves derived from EHF, TN90p and TX90p. Units are represented in "days". Bold digits show higher increase.

	HWF_EHF				HWF_TN90p				HWF_TX90p			
Period	1976-2005	2006-2035	2041-2070	2071-2099	1976-2005	2006-2035	2041-2070	2071-2099	1976-2005	2006-2035	2041-2070	2071-2099
Karachi	14.55	18.49	81.74	**124.45**	11.91	40.74	114.51	**140.02**	10.85	9.16	40.55	**88.52**
Lahore	13.35	23.30	80.92	**119.18**	11.81	22.72	80.96	**123.70**	12.43	17.94	58.99	**94.93**
Multan	13.14	23.83	83.79	**124.75**	11.49	26.42	90.44	**130.52**	11.38	15.78	57.76	**99.31**
Peshawar	12.89	19.61	69.08	**104.60**	10.75	21.01	78.80	**124.84**	10.78	17.82	61.05	**100.21**

Appendix A

EHF:

EHF is the combination of two Excess heat sub-indices;

EHI(sig.) = $[(TM_i + TM_{i-1} + TM_{i-2})/3] – TM90_i$

EHI(accl.) = $[(TM_i + TM_{i-1} + TM_{i-2})/3] – [(TM_{i-3} + \ldots + TM_{i-32})/30]$

EHI(sig.), significant excess heat index is the amount of Excess heat load that does not discharges sufficiently during overnight because of unusually high night temperature which results from high temperature during the day time. This factor is calculated over a average of daily mean temperature for a three day period and directly compared against the 90^{th} percentile of the daily mean. For day_i the daily mean temperature represents as TM_i(average of TX and TN of day i) and 90^{th} percentile of TM for day_i represents as $TM90_i$ using a 15 day running window is derived for each calendar day of the reference period.

Every system has natural ability that depends on diurnal variation in temperature, to recover itself from extreme environmental heat load. Heat load discharges due to a sufficient drop from the maximum temperature to the following minimum temperature. However higher minimum temperatures results in an accumulation of loaded heat. For the same purpose daily mean temperature is useful to calculate excess heat.

EHI(accl.), is acclimatization to excess heat. Acclimatization is a feature of human physical adaptation to unusual high temperatures that takes almost 2-6 weeks with the involvement of physiological adjustments endocrine, renal and cardiovascular systems (Knochel and Reed,1994; Guyton and Hall, 2000).

EHI(accl.) is derived for the same 3 day average temperature (EHIsig) and compared with the previous 30 days temperature. It assists the human body to adapt to its local climate conditions in term of air temperature. For acclimatization 30 days are considered sufficiently enough (Nairn and Fawcett,2013).

So EHF is derived by combining equation (1) and (2);

EHF = max [1, EHIaccl] × EHIsig

The combined effect (excess heat and stress) comprised as an EHF provides a relative measures of intensity, load, duration and spatial distribution of a heat wave event. Heat wave conditions persist when values for EHF are positive. So according to EHF, heat wave conditions must exists for at least three days to identify heat wave event for day i where there is positive EHF value (meaning that a heat wave is in progress). The units of EHF are °C2.

References

Ali, S., Li, D., Congbin, F., & Khan, F. (2015). Twenty first century climatic and hydrological changes over Upper Indus Basin of Himalayan region of Pakistan. Environmental Research Letters, 10(1), 014007.

Basarin, B., Lukić, T., & Matzarakis, A. (2016). Quantification and assessment of heat and cold waves in Novi Sad, Northern Serbia. International journal of biometeorology, 60(1), 139-150.

Bakhsh, K., Rauf, S., & Zulfiqar, F. (2018). Adaptation strategies for minimizing heat wave induced morbidity and its determinants. Sustainable Cities and Society, 41, 95-103.

Becker, J. A., & Stewart, L. K. (2011). Heat-related illness. American family physician, 83(11).

Beniston, M., Stephenson, D. B., Christensen, O. B., Ferro, C. A., Frei, C., Goyette, S., ... & Palutikof, J. (2007). Future extreme events in European climate: an exploration of regional climate model projections. Climatic change, 81(1), 71-95.

Bi, P., Williams, S., Loughnan, M., Lloyd, G., Hansen, A., Kjellstrom, T., ... & Saniotis, A. (2011). The effects of extreme heat on human mortality and morbidity in Australia: implications for public health. Asia Pacific Journal of Public Health, 23(2_suppl), 27S-36S.

Bouchama, A., & Knochel, J. P. (2002). Heat stroke. New England journal of medicine, 346(25), 1978-1988.

Centers for Disease Control and Prevention. (2006). Heat-Related Deaths--United States, 1999-2003. MMWR: Morbidity and mortality weekly report, 55(29), 796-798.

Climate and Health Country Profile – 2015: Pakistan, WHO,2015 available at apps.who.int/iris/bitstream/10665/246150/1/WHO-FWC-PHE-EPE-15.28-eng.pdf

Collins, M., Knutti, R., Arblaster, J., Dufresne, J. L., Fichefet, T., Friedlingstein, P., ... & Shongwe, M. (2013). Long-term climate change: projections, commitments and irreversibility.

Donat, M. G., Alexander, L. V., Yang, H., Durre, I., Vose, R., Dunn, R. J. H., ... & Hewitson, B. (2013). Updated analyses of temperature and precipitation extreme indices since the beginning of the twentieth century: The HadEX2 dataset. Journal of Geophysical Research: Atmospheres, 118(5), 2098-2118.

Dosio, A., Mentaschi, L., Fischer, E. M., & Wyser, K. (2018). Extreme heat waves under 1.5° C and 2° C global warming. Environmental Research Letters, 13(5), 054006.

Fischer, E. M., & Schär, C. (2010). Consistent geographical patterns of changes in high-impact European heatwaves. Nature Geoscience, 3(6), 398.

Fouillet, A., Rey, G., Wagner, V., Laaidi, K., Empereur-Bissonnet, P., Le Tertre, A., ... & Jougla, E. (2008). Has the impact of heat waves on mortality changed in France since the European heat wave of summer 2003? A study of the 2006 heat wave. International journal of Epidemiology, 37(2), 309-317.

Founda, D., & Giannakopoulos, C. (2009). The exceptionally hot summer of 2007 in Athens, Greece—a typical summer in the future climate?. Global and planetary change, 67(3-4), 227-236.

García-Herrera, R., Díaz, J., Trigo, R. M., Luterbacher, J., & Fischer, E. M. (2010). A review of the European summer heat wave of 2003. Critical Reviews in Environmental Science and Technology, 40(4), 267-306.

Guyton, A.C. and Hall, J.E. 2000. Textbook of medical physiology 10th ed. Philadelphia, PA: W.B. Saunders Company.

Global climate report,2016, available at https://www.ncdc.noaa.gov/sotc/global/2016

Hajat, S., Kovats, R. S., & Lachowycz, K. (2007). Heat-related and cold-related deaths in England and Wales: who is at risk?. Occupational and environmental medicine, 64(2), 93-100.

Khan, N., Shahid, S., Ismail, T., Ahmed, K., & Nawaz, N. (2018). Trends in heat wave related indices in Pakistan. Stochastic Environmental Research and Risk Assessment, 1-16.

Knochel, J.P., Reed, D. editors. Disorders of heat regulation. 5th ed. New York, NY: McGrawHiII; 1994.

Mason, K., Nairn, J., Herbst, J., & Felgate, P. (2010, September). Heatwave—the Adelaide experience. In Proceedings of The 20th International Symposium on the Forensic Sciences, Sydney, Australia (pp. 5-9).

Meehl, G. A., & Tebaldi, C. (2004). More intense, more frequent, and longer lasting heat waves in the 21st century. Science, 305(5686), 994-997.

Murari, K. K., Ghosh, S., Patwardhan, A., Daly, E., & Salvi, K. (2015). Intensification of future severe heat waves in India and their effect on heat stress and mortality. Regional Environmental Change, 15(4), 569-579.

Nairn, J., Fawcett, R., & Ray, D. (2009, November). Defining and predicting excessive heat events, a national system. In Modelling and understanding high impact weather: extended abstracts of the third CAWCR Modelling Workshop (Vol. 30, pp. 83-86).

Nairn, J. R., & Fawcett, R. J. (2014). The excess heat factor: a metric for heatwave intensity and its use in classifying heatwave severity. International journal of environmental research and public health, 12(1), 227-253.

Nasim, W., Amin, A., Fahad, S., Awais, M., Khan, N., Mubeen, M., ... & Ahmad, S. (2018). Future risk assessment by estimating historical heat wave trends with projected heat accumulation using SimCLIM climate model in Pakistan. Atmospheric Research, 205, 118-133.

Ostro, B. D., Roth, L. A., Green, R. S., & Basu, R. (2009). Estimating the mortality effect of the July 2006 California heat wave. Environmental Research, 109(5), 614-619.

Peng, S., Huang, J., Sheehy, J. E., Laza, R. C., Visperas, R. M., Zhong, X., ... & Cassman, K. G. (2004). Rice yields decline with higher night temperature from global warming. Proceedings of the National Academy of Sciences, 101(27), 9971-9975.

Perkins, S. E., Alexander, L. V., & Nairn, J. R. (2012). Increasing frequency, intensity and duration of observed global heatwaves and warm spells. Geophysical Research Letters, 39(20).

Perkins, S. E., & Alexander, L. V. (2013). On the measurement of heat waves. Journal of Climate, 26(13), 4500-4517.

Peterson, T. C., Heim Jr, R. R., Hirsch, R., Kaiser, D. P., Brooks, H., Diffenbaugh, N. S., ... & Katz, R. W. (2013). Monitoring and understanding changes in heat waves, cold waves, floods, and droughts in the United States: state of knowledge. Bulletin of the American Meteorological Society, 94(6), 821-834.

Poumadere, M., Mays, C., Le Mer, S., & Blong, R. (2005). The 2003 heat wave in France: dangerous climate change here and now. Risk Analysis: an International Journal, 25(6), 1483-1494.

Roehrig, R., Bouniol, D., Guichard, F., Hourdin, F., & Redelsperger, J. L. (2013). The present and future of the West African monsoon: A process-oriented assessment of CMIP5 simulations along the AMMA transect. Journal of Climate, 26(17), 6471-6505.

Rupp, D. E., Mote, P. W., Massey, N., Rye, C. J., Jones, R., & Allen, M. R. (2012). Did human influence on climate make the 2011 Texas drought more probable. Bulletin of the American Meteorological Society, 93(7), 1052-1054.

Russo, S., Marchese, A. F., Sillmann, J., & Immé, G. (2016). When will unusual heat waves become normal in a warming Africa?. Environmental Research Letters, 11(5), 054016.

Saeed, F., Almazroui, M., Islam, N., & Khan, M. S. (2017). Intensification of future heat waves in Pakistan: a study using CORDEX regional climate models ensemble. Natural Hazards, 87(3), 1635-1647.

Schär, C., & Jendritzky, G. (2004). Climate change: Hot news from summer 2003. Nature, 432(7017), 559.

Schiermeier, Q. (2011). Climate and weather: Extreme measures. Nature News, 477(7363), 148-149.

Shaposhnikov, D., Revich, B., Bellander, T., Bedada, G. B., Bottai, M., Kharkova, T., ... & Pershagen, G. (2014). Mortality related to air pollution with the Moscow heat wave and wildfire of 2010. Epidemiology (Cambridge, Mass.), 25(3), 359.

Sillmann, J., Kharin, V. V., Zwiers, F. W., Zhang, X., & Bronaugh, D. (2013). Climate extremes indices in the CMIP5 multimodel ensemble: Part 2. Future climate projections. Journal of Geophysical Research: Atmospheres, 118(6), 2473-2493.

Stefanon, M., D'Andrea, F., & Drobinski, P. (2012). Heatwave classification over Europe and the Mediterranean region. Environmental Research Letters, 7(1), 014023.

Tong, S., Ren, C., & Becker, N. (2010). Excess deaths during the 2004 heatwave in Brisbane, Australia. International journal of biometeorology, 54(4), 393-400.

Trigo, R. M., García-Herrera, R., Díaz, J., Trigo, I. F., & Valente, M. A. (2005). How exceptional was the early August 2003 heatwave in France?. Geophysical research letters, 32(10).

Watts, N., Amann, M., Ayeb-Karlsson, S., Belesova, K., Bouley, T., Boykoff, M., ... & Cox, P. M. (2017). The Lancet Countdown on health and climate change: from 25 years of inaction to a global transformation for public health. The Lancet.

World Health Organization (WHO. (2006). Preventing harmful health effects of heat-waves. World Health Organization (WHO).

Wilker, E. H., Yeh, G., Wellenius, G. A., Davis, R. B., Phillips, R. S., & Mittleman, M. A. (2012). Ambient temperature and biomarkers of heart failure: a repeated measures analysis. Environmental health perspectives, 120(8), 1083.

Zanobetti, A., & Schwartz, J. (2008). Temperature and mortality in nine US cities. Epidemiology (Cambridge, Mass.), 19(4), 563.

Zahid, M., & Rasul, G. (2011). Thermal classification of Pakistan. Atmospheric and Climate Sciences, 1(04), 206.

Zahid, M., & Rasul, G. (2012). Changing trends of thermal extremes in Pakistan. Climatic change, 113(3-4), 883-896.