Characteristics of human thermal stress in South Asia during 1981–2019

Safi Ullah, Qinglong You, Guojie Wang, Waheed Ullah, D A Sachindra, Yechao Yan, Asher Samuel Bhatti, Adnan Abbas and Mushtaq Ahmad Jan

1 Department of Atmospheric and Oceanic Sciences/Institute of Atmospheric Sciences, Fudan University, Shanghai 200438, People’s Republic of China
2 Innovation Center of Ocean and Atmosphere System, Zhuhai Fudan Innovation Research Institute, Zhuhai 518057, People’s Republic of China
3 School of Geographical Sciences, Nanjing University of Information Science and Technology (NUIST), Nanjing 210044, People’s Republic of China
4 Department of Hydrology and Climatology, Faculty of Earth Sciences and Spatial Management, Maria Curie-Sklodowska University, al. Krasinski 2a, 20-718, Lublin, Poland
5 Department of Geology, Bacha Khan University Charsadda, Khyber Pakhtunkhwa Pakistan, P.O. Box 20, Charsadda 24420, Pakistan
6 Land Science Research Center, Nanjing University of Information Science and Technology (NUIST), Nanjing 210044, People’s Republic of China
7 Centre for Disaster Preparedness and Management, University of Peshawar, Peshawar 25000, Pakistan

∗ Author to whom any correspondence should be addressed.
E-mail: yqingl@126.com

Keywords: UTCI, Human thermal stress, ENSO, ERA5, HITiSEA, South Asia

Abstract
Climate change has significantly increased the frequency and intensity of human thermal stress, with relatively more severe impacts than those of pure temperature extremes. Despite its major threats to public health, limited studies have assessed spatiotemporal changes in human thermal stress in densely populated regions, like South Asia (SAS). The present study assessed spatiotemporal changes in human thermal stress characteristics in SAS, based on daily minimum, maximum, and mean Universal Thermal Climate Indices (i.e. UTCI\textsubscript{\text{min}}, UTCI\textsubscript{\text{max}}, and UTCI\textsubscript{\text{mean}}) using the newly developed high-spatial-resolution database of the thermal-stress Indices over South and East Asia for the period 1981–2019. This study is the first of its kind to assess spatiotemporal changes in UTCI indices over the whole of SAS. The study also carried out extreme events analysis of the UTCI indices and explored their nexus with El Niño-Southern Oscillation (ENSO) index. Results revealed a significant increase in heat stress in SAS, with the highest human thermal stress in western Afghanistan, the Indo-Gangetic Plain, and southeastern and central parts. The extreme event analysis showed that the study region is likely to observe more frequent and intense heat extremes in the coming decades. The correlation of UTCI indices with ENSO exhibited a robust positive coherence in southeastern and central India, southern Pakistan, and northwestern Afghanistan. The findings of the study are critical in understanding human thermal stress and adopting effective risk reduction strategies against heat extremes in SAS. To better understand the dynamic mechanism of thermal extremes, the study recommends a detailed investigation of the underlying drivers of UTCI variability in SAS.

1. Introduction
Climate change, characterized by anthropogenic global warming, has increased the intensity, frequency, duration, and spatial extent of thermal extremes across the globe (Vicedo-Cabrera et al 2021, Wang et al 2020, IPCC 2021). According to Li et al (2018), Raymond et al (2020), and Yan et al (2021), the level of human thermal stress or human thermal discomfort is determined by the
combination of multiple bio-meteorological factors. Due to their complex nature, the stress caused by thermal extremes has relatively more severe impacts on public health than pure high-temperature events (Coffel et al 2018, Russo et al 2019, Li et al 2020). Extreme heat accompanied by other meteorological factors affects the human body's function via thermophysiological processes (Mueller et al 2014, Roshan et al 2018, Mishra et al 2020). The asymmetric heat exchange between the human body and the biothermal environment results in human thermal discomfort (Napoli et al 2018, Luo and Lau 2019, Blażejczyk 2021), which has catastrophic impacts on human health, vulnerable demographic groups, and marginal socioeconomic classes (Mora et al 2017, Li et al 2020, Yan et al 2021). Besides public health, the stress caused by thermal extremes also decreases labor productivity (Dunne et al 2013, Kumar and Mishra 2020). In recent years, the increasing prevalence of human thermal discomfort due to heat extremes has attracted the attention of the scientific community, still the robust assessment and quantification of the thermophysiological effects of the atmospheric environment are the key challenges in bioclimatic research.

More than 100 different indices and procedures have been developed to study and quantify human thermal stress in response to thermophysiological effects (Blázejczyk et al 2012, de Freitas and Grigorieva 2015, Yan et al 2021). The Universal Thermal Climate Index (UTCI) was developed in 1999 by a group of multidisciplinary experts (thermophysiology, occupational medicine, environmental sciences, physics, biometeorology, and climatology), recommended by the International Society of Biometeorology and later by the European Cooperation in Science and Technical Action 730 (Coccolo et al 2016, Napoli et al 2018, Blażejczyk 2021). The UTCI is a state-of-the-art thermal index that determines the physiological comfort of the human body under specific meteorological conditions (Jendritzky et al 2012, Seo and Honjo 2021, Yan et al 2021). The UTCI is defined as the air temperature of the reference condition, causing the same thermal stress as actual conditions under the background of the related factors (de Freitas and Grigorieva 2015, Coccolo et al 2016, Jacobs et al 2019). It takes into account the effects of both meteorological factors (the ambient temperature, relative humidity, solar and thermal radiation, and wind speed) and human factors (adaptive clothing behavior and physical activity level and type) (Blázejczyk et al 2012, Fiala et al 2012, Havenith et al 2012).

Since its introduction, the UTCI has been widely used to thoroughly assess and quantify human thermal stress in different parts of the world. In Europe, it has been applied to analyze the spatiotemporal conditions of bioclimatic factors (Németh 2011, Novak 2013, Bleta et al 2014, Matzarakis et al 2014, Krzyżewska et al 2021). At the same time, the UTCI has been used to assess the effects of heat stress on mortality and morbidity (Nastos and Matzarakis 2012, Urban and Kyselý 2014, Burkart et al 2016, Blażejczyk et al 2018). Moreover, the UTCI has also been used in Brazil, Canada, the Republic of Korea, Iran, Japan, Russia, and China (Bröde et al 2012b, Zeng and Dong 2015, Park et al 2017, Roshan et al 2018, Seo and Honjo 2021, Vinogradova 2021).

Despite its extensive use worldwide, very few studies have applied the UTCI in South Asia (SAS). Recently, Zeng et al (2020) investigated the observed spatiotemporal changes in UTCI over the China-Pakistan Economic Corridor and found a general increasing trend of 0.33 °C/decade during the period 1979–2018. In another study, Jacobs et al (2019) assessed the spatiotemporal pattern of exposure to thermal stress in three major cities in SAS: Delhi (India), Dhaka (Bangladesh), and Faisalabad (Pakistan). Their results revealed the occurrence of extremely high temperatures and heat stress over prolonged periods in these cities. The above studies have assessed thermal stress based on the mean UTCI (UTCI$_{\text{mean}}$), while did not consider the minimum (UTCI$_{\text{min}}$) and maximum (UTCI$_{\text{max}}$) indices and their thermal stress categories, which are very important indicators of thermal discomfort. Moreover, previous studies have targeted small specific geographical parts of SAS and did not consider the whole of SAS.

To overcome these limitations, the present study assessed spatiotemporal changes in UTCI$_{\text{min}}$, UTCI$_{\text{max}}$, and UTCI$_{\text{mean}}$ as well as their characteristics over the whole of SAS. The study also explored the relationship of UTCI indices with the El Niño–Southern Oscillation (ENSO) index during the study period. We preferred the UTCI over other thermal indices as it considers the effects of multiple meteorological and anthropogenic factors in quantifying human thermal discomfort. More importantly, the present study is the first of its kind to thoroughly assess the spatiotemporal changes in UTCI indices and their characteristics over the whole of SAS from a newly developed high-resolution database of thermal stress indices. The comprehensive assessment of the UTCI-based thermal stress helps to better understand and quantify the resultant human thermal discomfort in densely populated regions, like SAS. Moreover, the outcomes of such assessment are critical in meaningful planning and risk management strategies for ongoing and future human thermal discomfort in SAS.

2. Study area, data, and methods

2.1. Study area

SAS is located in the southern part of the Asian continent (figure 1), with geographical coordinates of 5°–40°N latitudes and 60°–100°E longitudes (Ullah et al 2020). The region has an estimated land area of 5134613 km$^2$, with a complex topography having the
world’s highest mountains ‘Karakoram–Hindukush–Himalayan (HKH) ranges’ in the north, the Indian Ocean in the south, and drylands in the central parts (You et al. 2017, Xu et al. 2020). SAS is one of the world’s most populous regions, with an estimated population of 1.5 billion (Xu et al. 2020, Ullah et al. 2022). The region is among the top ten vulnerable regions to climate extremes (Eckstein and Kt 2020, IPCC 2021). During the past few decades, SAS has experienced several hot extremes, including the extreme heat in 1991, 2006, 2014, 2015, 2017, and 2022, which caused extensive human and socio-economic losses in the region (Wehner et al. 2016, Mazdiyasni et al. 2017, Ullah et al. 2019b, Saeed et al. 2021). The accumulation of heat stress during these extreme events has posed potential risks to the local people in the form of heat strokes, death, casualties, and health diseases (Saleem et al. 2017). It is argued that the sharp increase in temperature coupled with fragile socioeconomic conditions and low adaptive capacity could greatly aggravate the vulnerability of people to hot extremes in SAS (Im et al. 2017, Kotharkar and Ghosh 2021, Ullah et al. 2022).

2.2. Datasets
The study used the daily UTCI min, UTCI max, and UTCI mean indices from the newly developed high-spatial-resolution database of the Thermal-stress Indices over South and East Asia (HiTiSEA) for the period 1981–2019 (Yan et al. 2021). The HiTiSEA database is computed from multiple key meteorological variables of the European Centre for Medium-Range Weather Forecasts (ECMWFs) ERA5-Land and ERA5 reanalysis, including air temperature, humidity, wind speed, direct solar radiation, and shortwave and longwave radiation fluxes. Compared to the existing spatial-resolution (0.25° × 0.25°) ERA5-HEAT (Human thErmAl comforT) data of the ECMWF (Napoli et al. 2021), the HiTiSEA database has new features in terms of higher spatial resolution (0.1° × 0.1°), with a comprehensive validation based on thousands of weather stations over South and East Asia (including bias and root mean square error for each index at each station released as part of the dataset). The HiTiSEA developers stated that the finer spatial resolution coupled with wider applicability to stress conditions make this dataset a valuable resource for health authorities and researchers to study the evolution of the thermal environment and identify high-risk areas to potential heat or cold stress. Policymakers can also use the dataset to assess and estimate the costs of extreme thermal stress on the economy through reduced labor productivity and high energy demand, especially in Bangladesh, India, and Pakistan. More details about the processing and computational procedures of the HiTiSEA data are provided by Yan et al. (2021). The study also used the ENSO4.0 index to assess its effects on thermal stress distribution and correlation with the UTCI indices in SAS. The monthly time series of the ENSO4.0 index is obtained from the National Center for Atmospheric Research for the period 1981–2019 (https://psl.noaa.gov/data/climateindices/list).

2.3. Calculation of UTCI
Generally, UTCI is calculated in terms of an equivalent ambient temperature (°C) and physiological response in reference and actual environmental
conditions, respectively. The calculation of physiological response to meteorological inputs is based on thermoregulation and adaptive clothing models, which consider behavioral changes in clothing insulation related to the actual thermal environment. Moreover, the reference environment refers to the given conditions: (a) calm air with a 10 m wind speed of 0.5 m s\(^{-1}\), (b) mean radiant temperature (MRT) equals the air temperature \(T_a\), (c) 50% relative humidity (RH) for \(T_a \leq 29 \, ^\circ\text{C}\), and (d) water vapor pressure \(e = 20 \text{ hPa}\) for \(T_a > 29 \, ^\circ\text{C}\), where an average person walks at the speed of 4 km h\(^{-1}\) and generates a metabolic rate of 135 W m\(^{-2}\). The mathematical equation of UTCI is as follows (equation (1)):

\[
\text{UTCI} = T_a + f(T_a, V_a, e, \text{MRT} - T_a).
\]  (1)

In equation (1), \(T_a\) is the 2 m air temperature, \(V_a\) is the 10 m wind speed (m s\(^{-1}\)), \(e\) is the water vapor pressure (hPa), and MRT is the mean radiant temperature (\(^\circ\text{C}\)).

### 2.4. UTCI stress classes

According to the thermal physiological response of the human body that corresponds to the comfort standard of the model, the values of the UTCI are generally divided into ten thermal stress categories (Blazejczyk et al. 2012, Napoli et al. 2018, Zeng et al. 2020). Further details of the UTCI stress categories and their corresponding physiological conditions are provided by Bröde et al. (2012a). Given the hot tropical climate over the major part of SAS and substantial warming in recent decades (Panda et al. 2017, Jacobs et al. 2019, Ullah et al. 2019b, Islam et al. 2021), this study considered only six thermal stress categories, which mainly represent the hot conditions. Table 1 presents the selected stress categories and their respective physiological conditions.

### 2.5. Statistical analyses

The study used the nonparametric Sen’s slope estimator (SSE) (Sen 1968) and modified Mann-Kendall (m-MK) (Hamed and Rao 1998) tests to determine the magnitude and the significance level of the trend in UTCI indices and their stress categories during the study period, respectively. The SSE and m-MK tests are simple and robust against the outliers, spikes, and missing values in a time series (Ullah et al. 2019a, Ali et al. 2020). Further, these tests are less sensitive to abrupt breaks in a time series and do not require data normalization (Khan et al. 2018, Ahmed et al. 2019). To estimate the return period of UTCI indices, we employed the Generalized Extreme Value approach, suggested by Kharin et al. (2013) and Sun et al. (2019). A return value for a specified probability \(P\) is the value that is exceeded by an annual extreme with a return period, i.e. \(T = 1/P\). This study estimated the extreme values of UTCI indices for 5-, 10-, 20-, 50-, 75-, 100-, 150-, 200-, 300-, 400-, and 500-years return periods. A nonparametric Kolmogorov–Smirnov (K–S) test was applied with a 95% confidence level to determine the significance probability of return values and their distributions. In addition, the Pearson’s correlation test was applied to estimate the relationship between ENSO and UTCIs, while the two-tailed student t-test was used to determine the significant correlation at the 95% significance level.

### 3. Results and discussion

#### 3.1. Spatiotemporal changes in UTCI indices

Figure 2 shows the long-term spatiotemporal changes and trends in UTCI\(_\text{min}\), UTCI\(_\text{max}\), and UTCI\(_\text{mean}\) over SAS during 1981–2019. The spatial distribution of daily climatological means of UTCI indices exhibits a significant variability in SAS (figures 2(a)–(c)), with the highest magnitude \((10 \, ^\circ\text{C}–40 \, ^\circ\text{C})\) in the Indo-Gangetic Plain (IGP), central, southern, and eastern parts, while the lowest magnitude \((−25 \, ^\circ\text{C}–10 \, ^\circ\text{C})\) in the northwestern mountainous region. Recently, several studies reported similar patterns of heat conditions in SAS (Joshi et al. 2020, Mishra et al. 2020). The larger spatial variability of UTCI in SAS can be attributed to its complex topographic and climatic conditions (Ullah et al. 2019b). The results of long-term climatology indicate that the observed means of UTCI\(_\text{min}\), UTCI\(_\text{max}\), and UTCI\(_\text{mean}\) over SAS were 2.40 \(^\circ\text{C}\), 24.99 \(^\circ\text{C}\), and 12.61 \(^\circ\text{C}\), respectively (figure 2(d)).

In monthly analysis, June had the warmest thermal conditions followed by May and July with observed intensities of 34.43 \(^\circ\text{C}\), 34.40 \(^\circ\text{C}\), and 32.71 \(^\circ\text{C}\), respectively. In contrast, January had the coldest thermal conditions followed by December and February with the lowest intensities of −5.26 \(^\circ\text{C}\), −3.42 \(^\circ\text{C}\), and −3.16 \(^\circ\text{C}\), respectively. The countrywise statistics show that all SAS countries had the
The coldest thermal conditions in January followed by December (table SM1). However, in terms of hot conditions, Bangladesh and India experienced the warmest thermal conditions in May, while Afghanistan and Bhutan experienced the warmest thermal conditions in July. Interestingly, Nepal and Pakistan followed the regional pattern of hot thermal conditions and experienced the warmest thermal conditions in June (table SM3). The results are in agreement with the findings of Kumar and Sharma (2022) and Jacobs et al. (2019). The dynamic variations in heat accumulation of monthly UTCI indices are highly influenced by complex climatology and multiple atmospheric and oceanic factors (Miralles et al. 2014, Nasim et al. 2018, Ullah et al. 2021a, Singh et al. 2022).

The spatial distribution of trends in UTCI indices shows a significant increase in thermal stress during the study period (figures 3(a)–(c)). The highest trend (0.5 °C–0.7 °C/decade) of all UTCI indices can be seen in the northwestern and southwestern mountainous parts of SAS. The sharp increasing trend of thermal stress in these areas can be attributed to elevation-dependent warming (Pepin et al. 2015, You et al. 2020). The central parts have also experienced an increase in all UTCI indices, ranging from 0.25 °C to 0.45 °C/decade. Overall, the magnitude and spatial extent of the warming tendency are larger in UTCI$_{\text{min}}$, followed by UTCI$_{\text{mean}}$ and UTCI$_{\text{max}}$. The asymmetric trend in UTCI indices can be attributed to the sharp increase in daily minimum temperature than those of maximum and mean temperatures in SAS (You et al. 2017).

The long-term temporal trends in annual anomalies of UTCI indices showed a linear increase during the study period (figure 3(d)). The temporal distribution reveals an anomalous increase from 1997 and onward, highlighting the tipping points of climate warming and the occurrence of severe heat extremes in the study region (Roshan et al. 2018, Jacobs et al. 2019). In terms of monotonic trend, the highest increasing trend was found in...
UTCImin (0.27 °C/decade), followed by UTCImean (0.25 °C/decade) and UTCImax (0.18 °C/decade). During 1997–2002, most parts of SAS witnessed an extended dry–hot period (Ullah et al 2019a, 2021b), which resulted in extensive socioeconomic losses in the region. This catastrophic dry-hot episode has forced millions of rural people to migrate to urban areas and seek alternate livelihood sources in SAS (Xie et al 2013).

Moreover, the last two decades (2001–2020) were reported as the hottest decades of the world’s history by the World Meteorological Organization (WMO 2021, Shen et al 2022). Recently, the study region has experienced multiple hot extremes, particularly in the years 2006, 2014, 2015, 2017, and 2022 (Wehner et al 2016, Ullah et al 2019b, Saeed et al 2021). Among those extremes, the 2015-heatwave was the deadliest, which killed more than 4000 people in SAS (Im et al 2017, Mazdiyasni et al 2017, Saeed et al 2021), with the highest number of mortalities and morbidities in the metropolitan coastal cities (Chaudhry et al 2015, Masood et al 2015, Saleem et al 2017). Interestingly, the majority of the deaths were reported among old-aged, children, women, and disabled people in the affected cities. During the 2015-heatwave event, the central plains of SAS were struck with >45 °C temperature and high humidity for several consecutive days, which resulted in extremely humid-hot conditions (Wehner et al 2016, Im et al 2017). The extended humid-hot period posed potential risks to the local people in the form of heat strokes and health diseases due to the accumulation of heat stress. The above extremes and their catastrophic impacts on the local population confirm the findings of this study.

3.2. Spatiotemporal changes in UTCI stress categories

The spatial trend pattern in the frequency of UTCI stress categories over SAS is shown in figure 4.
The overall results indicate a rise in human thermal discomfort in SAS, due to an increase in the number of heat stress days. The highest significant increase in heat stress days can be found in the western parts of Afghanistan, the Pak–Afghan border, IGP, and central India. Among all UTCI\text{max}-based stress categories, the observed trend (6–8 d/decade) and spatial extent of very strong heat stress days are the highest. This suggests that a large proportion of the population in SAS likely experience periods of strong thermal discomfort (Im et al 2017, Jacobs et al 2019, Kotharkar and Ghosh 2021). Moreover, the highest trend and spatial extent were observed in moderate stress and strong heat stress days under UTCI\text{min} and UTCI\text{mean}, respectively. On the other hand, the higher thermal stress categories (i.e. very strong and extreme heat stress days) based on UTCI\text{min} and UTCI\text{mean} did not show any trend, which can be attributed to their low intensities observed in SAS, which could not exceed their thermal ranges.

The spatial distribution of trends in the intensity of UTCI categories over SAS is presented in figure 5. The overall results indicate an increasing trend in the intensity of human thermal discomfort. The highest increase (0.2 °C–0.8 °C/decade) in thermal stress intensity can be found in western Afghanistan, IGP, southeastern coastal, and central parts of SAS. The increasing intensity of heat stress in the western parts of Afghanistan and IGP can be linked to elevation-dependent warming (You et al 2020, Shen et al 2021) since these parts are located in the HKH region, which experiences relatively more warming than those of the low-lying areas in SAS. Similarly, the southeastern parts of SAS have a hot climate and are located in the proximity of the Indian Ocean and the Bay of Bengal, which acts as a major source of moisture and water vapor (Pathak et al 2017a, Ullah et al 2021b). The movement of moisture and water vapor contents from these sources to the land results in a hot-humid climate over the southeastern coastal belt of SAS (Wehner et al 2016, Pathak et al 2017a, Ullah et al 2021b), which induced significant heat stress in the local population.

The persistent occurrence of extreme heat stress poses potential heat-related risks to humans in SAS, particularly to the elderly, children, women, the disabled, laborers, and other marginalized groups. Such health-related risks include heat stroke, sunstroke, dehydration, and excess morbidity and mortality in affected areas due to cardiovascular and respiratory diseases (Napoli et al 2018, Luo and Lau 2019, Blazejczyk 2021). In addition, the rising trend of human thermal discomfort coupled with fragile socioeconomic conditions and limited adaptive capacity could further exaggerate the exposure of the local population to extreme heat stress in SAS (Im et al 2017, Kotharkar and Ghosh 2021). Given the UTCI\text{min} and UTCI\text{mean} indices, some of the higher stress categories did not show any trend, which can be attributed to their low intensities in SAS, which could not exceed their thermal ranges.

Figure 6 illustrates the temporal patterns of annual anomalies and linear trends in the frequency and intensity of UTCI stress categories over SAS during the period 1981–2019. In terms of frequency, the number of days with heat stress increased during the study period. The temporal distribution of annual anomalies reveals a sharp increase in the number of

Figure 4. Spatial trends in the frequency of UTCI stress categories over SAS during 1981–2019; (a)–(f) UTCI\text{min}, (g)–(l) UTCI\text{max}, and (m)–(r) UTCI\text{mean}. The black dots indicate that the trend is statistically significant at the 0.05 significance level.
Figure 5. Spatial trends in the intensity of UTCI stress categories over SAS during 1981–2019; (a)–(f) UTCI$_{\text{min}}$, (g)–(l) UTCI$_{\text{max}}$, and (m)–(r) UTCI$_{\text{mean}}$. The black dots indicate that the trend is statistically significant at the 0.05 significance level.

Figure 6. Temporal trends in the frequency and intensity of UTCI stress categories over SAS during 1981–2019; (a)–(c) frequency, (d)–(f) intensity. The dotted lines in different colors indicate the linear trends of the respective UTCI stress categories.
thermal stress days during 1997 and onward, indicating a shift towards a hotter climate for a prolonged period in the study region. In terms of monotonic trend (table 2), the number of slight cold stress and no thermal stress days has decreased in the range of −0.55 to −0.06 and −0.87 to −0.03 d/decade, respectively. Whereas the frequency with moderate, strong heat stress, very strong heat stress, and extreme days has increased in the range of 0.36–0.70, 0.01–0.66, 0.03–0.87, and 0.06 d/decade, respectively. The sharp increase in heat stress days highlights the persistent and prolonged occurrence of hot extremes in SAS (Rohini et al 2016, Panda et al 2017), which could have exacerbated the discomfort level of the local population during the study period (Jacobs et al 2019, Yan et al 2021).

In terms of intensity, most of the stress categories exhibited an increasing trend, confirming that the study region has predominantly experienced significant heat stress during the study period. The temporal pattern of annual anomalies shows that the intensity of heat stress categories experienced a sharp rise in the study’s late period. A set of the literature revealed that the major parts of South Asia have witnessed several episodes of extreme heat during the last two decades (Rohini et al 2016, Im et al 2017, Ullah et al 2019b), which confirms the findings of the current study. Given the monotonic trend (table 2), the intensity of the slight cold and no thermal stress days has decreased at the rates of −0.03 and −0.06 °C/decade, respectively. Whereas the intensities of moderate heat stress and strong heat stress classes have increased at the rates of 0.01–0.37 and 0.02 °C–0.03 °C/decade, respectively, confirming their evolution into higher stress categories with stronger thermal discomfort.

### 3.3. Extreme events analysis of the UTCIs’ frequency and intensity

Figures 7(a)–(c) and table 3 illustrate the return period of the UTCI indices in SAS using extreme event analysis (Kim et al 2020, Shi et al 2020). The results show that the estimated frequencies of 5–500 year return periods of all UTCI indices in SAS are gradually decreasing, while their respective intensities are increasing, leading to more frequent and intense thermal extremes, which would have catastrophic impacts on human health. Climate extremes with relatively stronger magnitudes have greater adverse effects over a larger spatial extent than those with low magnitudes extremes (Karl and Knight 1997, Frias et al 2012, Zahid et al 2017, Sun et al 2019). The analyses revealed that the estimated magnitude of UTCI\_min, UTCI\_max, and UTCI\_mean in the selected return periods (5–500 year) could be 21.84 °C–25.56 °C, 38.95 °C–44.80 °C, and 29.41 °C–33.78 °C, respectively.

Figures 7(d)–(f) shows the histogram of daily observed UTCI indices in SAS during 1981–2019. The UTCI\_min and UTCI\_mean histograms exhibit a positively skewed bimodal distribution, with higher frequencies of 12–14 and 10–13 and maximum observed densities of 22 °C–24 °C and 27 °C–31 °C, respectively (figures 7(d) and 6(f)). The bimodal distribution of UTCI\_min and UTCI\_mean indices infer an increase in winter UTCI, exposing more population to mild to moderate heat stress. As the bimodal distribution has two peaks on the right and left sides of the UTCI\_min and UTCI\_mean time series, indicating positive shifts in their frequencies and intensities. These positive shifts further confirm the frequent and intense occurrence of heat stress in SAS during the study period. The results can also be confirmed from the spatial distribution of UTCI\_min and UTCI\_mean indices, which exhibited the lowest climatological values (−25 °C–10 °C) with maximum spatial extents during the study period. The histogram of UTCI\_max exhibits a normal pattern with the highest density of 35 °C–38 °C (figure 7(e)), indicating the frequent occurrence of thermal stress days in this range.

From the ECDFs’ pattern (figures 7(g)–(i)), it can be seen that the extreme value distribution fits the observed data of all UTCI indices significantly. The UTCI\_min observed and fitted lines indicate a significant similarity with a moderate overestimation of 5 °C–17 °C and an evident underestimation of 18 °C–24 °C (figure 7(g)). In terms of UTCI\_max (figure 7(h)), the observed and fitted lines are distributed significantly, indicating a close pattern of both time series. The UTCI\_mean demonstrates a similar pattern to that of the UTCI\_min, with overall significant distribution and overestimation at 16 °C–24 °C and underestimation at 25 °C–28 °C (figure 7(i)).
3.4. Effects of ENSO on UTCIs’ amplification

To determine the effects of ENSO on UTCIs’ amplification, we assessed the spatial correlation between ENSO and UTCI indices. ENSO is one of the key atmospheric drivers of the global climate system, having significant implications on large-scale climate anomalies (Lewis and Karoly 2013, Luo and Lau 2018, Luo and Lau 2020). The variability of ENSO can greatly affect temperature distribution and its associated climate extremes in SAS and the Western Pacific regions (Del Río et al 2013, Duan et al 2017, Saleem et al 2021). As seen in figure 8, the correlation between ENSO and UTCIs has a dipole pattern, with a robust and significant positive correlation (>0.6) over southeastern parts of India, while a mild to moderate (0.1–0.4) non-significant correlation over central India, southern Pakistan, and northwestern Afghanistan. The southeastern parts of India and Pakistan are located along the coast of the Indian Ocean and are influenced by the ocean–atmosphere interactions (Del Río et al 2013, Pathak et al 2017b).

Several studies have reported that high sea surface temperature intensified the evaporation of moisture and water vapor contents from the ocean, which move towards the coastal belt of SAS (Pathak et al 2017a, Ullah et al 2021b). The movement of moisture-rich winds results in warming surface temperature, which evolves into hot-humid conditions in the coastal areas (Trenberth and Fasullo 2012, Wehner et al 2016, Pathak et al 2017b). The Asian monsoon precipitation regional variability could be another driver of the UTCI variability that is directly sensitive to ocean–atmosphere interactions (Ullah et al 2021a, Singh et al 2022).

Moreover, northern SAS, covering the northwestern parts of Pakistan and India, and most parts of Nepal and Bhutan, exhibited a negative correlation pattern (−0.3 to −0.6) between ENSO and UTCI indices. These parts of SAS are located in the jurisdiction of the HKH region and are influenced by two key global weather systems, i.e. western disturbance and monsoon (Ullah et al 2021b, Abbas et al 2022).
The negative correlation between ENSO and UTCI indices in northwestern parts of SAS could be attributed to the atmospheric dynamics of westerly and monsoon weather systems, which have strong effects on the local and regional climates in SAS (Niranjan Kumar et al 2013, Joshi and Kar 2018, Hong et al 2019, Hussain et al 2021). It should be noted that both these weather systems bring a significant amount of precipitation to northwestern parts of SAS (Abbas et al 2022), which could have significant impacts on the distribution of temperature, humidity, cloud cover, solar radiation, and wind at the local scales.

4. Conclusions

The present study assessed spatiotemporal changes in UTCI indices over SAS during 1981–2019. For the first time, this study comprehensively assessed observed changes in characteristics of human thermal stress over the whole of SAS using a newly developed high-resolution database of thermal stress indices called HiTiSEA. Results of the study revealed a significant increase in human thermal stress, with the highest increasing trend in western Afghanistan, IGP, and southeastern and central parts of SAS. The temporal characteristics of UTCI indices and their stress categories have experienced a relatively dynamic and increasing trend in the late 1990s and onward, indicating more human thermal stress during this period. In terms of the return period, the study region is likely to observe more frequent and intense thermal extremes with significant adverse impacts on human health, particularly the elderly, children, women, disabled, labor, and other marginalized groups. Moreover, the spatial correlation of UTCI indices with ENSO exhibited a dipole pattern, with a positive correlation in southeastern and central India, southern Pakistan, and northwestern Afghanistan, while a negative correlation in northwestern Pakistan and India, and most parts of Nepal and Bhutan. This dipole pattern could be monsoon and westerly driven, as both weather systems are sensitive to the oceanic forcing but ENSO is a major driver of the regional climate warming. Further causal attribution and detection analyses are recommended, which will further explore and complement this pattern. Overall, the findings of the study provide potential implications for policy-makers to design climate change adaptation and mitigation strategies in the region.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://doi.org/10.6084/m9.figshare.c.5196296.

Acknowledgments

This study is supported by the Research Fund for International Young Scientists of the National Natural Science Foundation of China (42150410381) and the National Natural Science Foundation of China (41971072 and 41771069). We are grateful to Fudan University-Tibet University Joint Laboratory For Biodiversity and Global Change. The first author acknowledges the Shanghai Local (Municipal) Government for providing financial assistance under the Shanghai Super Postdoctoral Fellowship Program.

Conflict of interest

The authors declare no conflicts of interest relevant to this study.
References

Abbas A et al 2022 Evaluation and projection of precipitation in Pakistan using the coupled model intercomparison project phase 6 model simulations Int. J. Climatol. 42 1–20

Ahmed K, Shahid S, Wang X, Nawaz N and Khan N 2019 Spatiotemporal changes in aridity of Pakistan during 1901–2016 Hydrol. Earth Syst. Sci. 23 3081–96

Ali G, Bao Y, Ullah W, Ullah S, Guan Q, Liu X, Li L, Lei Y, Li G and Ma J 2020 Spatiotemporal trends of aerosols over urban regions in Pakistan and their possible links to meteorological parameters Atmosphere 11 1–28

Blazieczyk A, Blazieczyk K, Baranowski J and Kuchick M 2018 Heat stress mortality and desired adaptation responses of healthcare system in Poland Int. J. Biometeorol. 62 307–18

Blazieczyk K 2021 UTCI—10 years of applications Int. J. Biometeorol. 65 1461–2

Blazieczyk K, Epstein Y, Jendritzky G, Staiger H and Tinz B 2012 Comparison of UTCI to selected thermal indices Int. J. Biometeorol. 56 515–35

Bleta A, Nastos P T and Matzarakis K 2014 Assessment of bioclimatic conditions on Crete Island, Greece Reg. Environ. Change 14 1967–81

Bröde P, Fiala D, Blazieczyk K, Holmér J, Jendritzky G, Kampmann B, Tinz B and Havenith G 2012a Deriving the operational procedure for the Universal thermal climate index (UTCI) Int. J. Biometeorol. 56 481–94

Bröde P, Krüger E L, Rossi F A and Fiala D 2012b Predicting urban outdoor thermal comfort by the Universal thermal climate index UTCI-a case study in Southern Brazil Int. J. Biometeorol. 56 471–80

Burkart K, Meier F, Schneider A, Breitner S, Canário P and Alcacerdo M J 2016 Modification of heat-related mortality in an elderly urban population by vegetation (urban green) and proximity to water (urban blue): evidence from Lisbon, Portugal Environ. Health Perspect. 124 927–34

Chaudhry Q Z, Rasul G, Kamal A, Mangrio M A and Mahmood S 2015 Technical Report on Karachi Heat Wave June 2015 (National Disaster Management Authority (NDMA), Ministry of Climate Change, Government of Pakistan)

Coccolo S, Kempf J, Scartezzini J L and Pearlmutter D 2016 Outdoor human comfort and thermal stress: a comprehensive review on models and standards Urban Clim. 18 33–57

Coffel E D, Horton R M and De Sherbinin A 2018 Temperature and humidity based projections of a rapid rise in global heat stress exposure during the 21st century Environ. Res. Lett. 13 1–10

de Freitas C R and Grigorieva E A 2015 A comprehensive catalogue and classification of human thermal climate indices Int. J. Biometeorol. 59 109–20

Del Rio S, Anjum Iqbal M, Cano-Ortiz A, Herrero L, Hassan A and Penas A 2013 Recent mean temperature trends in Pakistan and links with teleconnection patterns Int. J. Climatol. 33 277–90

Duan A, Sun R and He J 2017 Impact of surface sensible heating over the Tibetan Plateau on the western Pacific subtropical high: a land–air–sea interaction perspective Adv. Atmos. Sci. 34 157–68

Dunne J P, Stouffer R J and John J G 2013 Reductions in labour capacity from heat stress under climate warming Nat. Clim. Change 3 563–6

Eckstein D and Kreft S 2020 Global climate risk index 2021 Who Suffers Most From Extreme Weather Events?

Fiala D, Havenith G, Bröde P, Kampmann B and Jendritzky G 2012 UTCI-Fiala multi-node model of human heat transfer and temperature regulation Int. J. Biometeorol. 56 429–41

Frias M D, Mínguez R, Gutiérrez J M and Méndez F J 2012 Future regional projections of extreme temperatures in Europe: a nonstationary seasonal approach Clim. Change 113 371–92

Hamed K H and Rao R A 1998 A modified Mann–Kendall trend test for autocorrelated data J. Hydrol. 204 182–96

Havenith G, Fiala D, Blazieczyk K, Richards M, Bröde P, Holmér I, Rintamaki H, Benshabat Y and Jendritzky G 2012 The UTCI-clothing model Int. J. Biometeorol. 56 641–70

Hong B, Rabassa J, Uchida M, Hong Y, Peng H and Ding H 2019 Response and feedback of the Indian summer monsoon and the Southern Westernly winds to a temperature contrast between the hemispheres during the last glacial—interglacial transitional period Earth-Sci. Rev. 197 102917

Hussain A, Cao J, Hussain I, Begum S, Akhtar M, Wu X, Guan Y and Zhou J 2021 Observed trends and variability of temperature and precipitation and their global teleconnections in the upper indus basin, Hindukush-Karakoram-Himalaya Atmosphere 12 1–22

Im E S, Pal J S and Eltahir E A B 2017 Deadly heat waves projected in the densely populated agricultural regions of South Asia Sci. Adv. 3 1–8

IPCC 2021 Climate change 2021: the physical science basis Working Group I Contribution to the Sixth Assessment Report (Cambridge University Press)

Islam A R M T, Islam H M T, Shahid S, Khattun M K, Ali M M, Rahman M S, Ibrahim S M and Almoajel A M 2021 Spatiotemporal nexus between vegetation change and extreme climatic indices and their possible causes of change J. Environ. Manage. 289 112505

Jacobs C, Singh T, Gotti G, Ilíkhar U, Saeed S, Syed A, Abbas F, Ahmad B, Bhadwal S and Siderius C 2019 Patterns of outdoor exposure to heat in three South Asian cities Sci. Total Environ. 674 264–78

Jendritzky G, de Dear R and Havenith G 2012 UTCI-Why another thermal index? Int. J. Biometeorol. 56 421–8

Joshi M K, Rai A, Kulkarni A and Kucharski F 2020 Assessing changes in characteristics of hot extremes over India in a warming environment and their driving mechanisms Sci. Rep. 10 1–14

Joshi S and Kar S C 2018 Mechanism of ENSO influence on the South Asian monsoon rainfall in global model simulations Theor. Appl. Climatol. 131 1449–64

Karl T R and Knight R W 1997 The 1995 Chicago heat wave: how likely is a recurrence? Bull. Am. Meteorol. Soc. 78 1107–19

Khan N, Shahid S, Ismail T, Ahmed K and Nawaz N 2018 Trends in heat wave related indices in Pakistan Stoch. Environ. Res. Risk Assess. 2 1–16

Kharin V V, Zwiers F W, Zhang X and Wehner M 2013 Changes in temperature and precipitation extremes in the CMIP5 ensemble Clim. Change 119 345–57

Kim Y H, Min S K, Zhang X, Sillmann J and Sandstad M 2020 Evaluation of the CMIP6 multi-model ensemble for climate extreme indices Weather Clim. Extremes 29 1–15

Kothar A R and Ghosh A 2021 Review of heat wave studies and related urban policies in South Asia Urban Clim. 36 1–18

Krzyszewska A, Wereski S and Dobeck M 2021 Summer UTCI variability in Poland in the twenty-first century Int. J. Biometeorol. 65 1497–513

Kumar P and Sharma A 2022 Assessing the monthly heat stress risk to society using thermal comfort indices in the hot semi-arid climate of India Mater. Today 61 132–7

Kumar P and Mishra V 2020 Increase in population exposure due to dry and wet extremes in India under a warming climate Earth’s Future 8 1–14

Lewis S C and Karoly D J 2013 Anthropogenic contributions to Australia’s record summer temperatures of 2013 Geophys. Res. Lett. 40 5708–9
Li D, Yuan J and Kopp R E 2020 Escalating global exposure to compound heat-humidity extremes with warming Environ. Res. Lett. 15 1–12
Li J, Chen Y D, Gan T Y and Lau N C 2018 Elevated increases in human-perceived temperature under climate warming Nat. Clim. Change 8 43–47
Luo M and Lau N C 2018 Amplifying effect of ENSO on heat waves in China Clim. Dyn. 27 1–13
Luo M and Lau N C 2019 Characteristics of summer heat stress in China during 1979–2014: climatology and long-term trends Clim. Dyn. 53 5375–88
Luo M and Lau N C 2020 Summer heat extremes in northern continents linked to developing ENSO events Environ. Res. Lett. 15 1–13
Masood I, Majid Z, Sohail S, Zia A and Raza S 2015 The deadly heat wave of Pakistan, June 2015 Int. J. Occup. Environ. Med. 6 247–50
Matzarakis A, Mathers S and Rutzf C 2014 Application and comparison of UTCI and pet in temperate climate conditions Finisterra 49 21–31
Mazdiyasni O et al 2017 Increasing probability of mortality during Indian heat waves Sci. Adv. 3 1–6
Miralles D G, Teuling A J, van Heerwaarden C C and Arellano D J V-G 2014 Mega-heatwave temperatures due to combined soil desiccation and atmospheric heat accumulation Nat. Geosci. 7 345–9
Mishra V, Ambika A K, Asoka A, Adharr S, Buzan J, Kumar R and Huber M 2020 Moist heat stress extremes in India enhanced by irrigation Nat. Geosci. 13 722–8
Mora C et al 2017 Global risk of deadly heat Nat. Clim. Change 7 501–6
Mueller V, Gray C and Kosic K 2014 Heat stress increases long-term human migration in rural Pakistan Nat. Clim. Change 4 182–5
Napoli D C, Barnard C, Prudhomme C, Cloke H L and Pappenberger F 2021 ERA5-HEAT: a global gridded historical dataset of human thermal comfort indices from climate reanalysis Geosci. Data J. 8 2–10
Napoli D C, Pappenberger F and Cloke H L 2018 Assessing heat-related health risk in Europe via the Universal Thermal Climate Index (UTCI) Int. J. Biometeorol. 62 1155–65
Nasim W et al 2018 Future risk assessment by estimating historical heat waves trend with projected heat accumulation using SimCLIM climate model in Pakistan Atmos. Res. 205 118–33
Nastos P T and Matzarakis A 2012 The effect of air temperature and human thermal indices on mortality in Athens, Greece Theor. Appl. Climatol. 108 591–9
Németh A 2011 Changing thermal bioclimate in some Hungarian cities Acta Climatol. Chron. 44–45 93–101
Niranjan Kumar K, Rajeevan M, Pai D S, Srivastava A K and Preethi B 2013 On the observed variability of monsoon droughts over India Weather Clim. Extremes 1 42–50
Novak M 2013 Use of the UTCI in the Czech Republic Geogr. Pol. 86 21–28
Panda D K, Agkarakouk A and Ambast S K 2017 Increasing heat waves and warm spells in India, observed from a multisaspect framework J. Geophys. Res. 122 3857–58
Park J, Kim Y and Oh I 2017 Factors affecting heat-related diseases in outdoor workers exposed to extreme heat Occup. Environ. Med. 29 4–9
Pathak A, Ghosh S, Alejandro Martinez I, Dominguez F and Kumar P 2017 A role of oceanic and land moisture sources and transport in the seasonal and interannual variability of summer monsoon in India J. Clim. 30 1839–59
Pathak A, Ghosh S, Kumar P and Murttugudde R 2017b Role of oceanic and terrestrial atmospheric moisture sources in intraseasonal variability of Indian summer monsoon rainfall Sci. Rep. 7 1–11
Pepin N et al 2015 Elevation-dependent warming in mountain regions of the world Nat. Clim. Change 5 242–30
Raymond C, Matthews T and Horton R M 2020 The emergence of heat and humidity too severe for human tolerance Sci. Adv. 6 1–8
Rohini P, Rajeevan M and Srivastava A K 2016 On the variability and increasing trends of heat waves over India Sci. Rep. 6 1–9
Roshan G R, Ghaghhermeh A A and Kong Q 2018 Spatial and temporal analysis of outdoor human thermal comfort during heat and cold waves in Iran Weather Clim. Extremes 19 58–67
Russo S, Sillmann J, Sippel S, Baricikowska M J, Ghisetti C, Smid M and O’Neill B 2019 Half a degree and rapid socioeconomic development matter for heatwave risk Nat. Commun. 10 1–9
Sacred F, Schlesener C F and Ashraf M 2021 Deadly heat stress to become commonplace across South Asia already at 1.5 ◦C of global warming Geophys. Res. Lett. 48 1–11
Saleem F, Zeng X, Hina S and Omer A 2021 Regional changes in extreme temperature records over Pakistan and their relation to Pacific variability Atmos. Res. 250 105407
Saleem S G, Ansari T, Ali A, Fatima S and Rizvi H 2017 Risk factors for heat related deaths during the June 2015 heat wave in Karachi, Pakistan J. Ayub Med. Coll. Abbottabad 29 320–42
Sen P K 1968 Estimates of the regression coefficient based on Kendall’s Tau J. Am. Stat. Assoc. 63 1379–89
Seo Y and Honjo T 2021 Thermal stress in Tokyo and Sapporo during the 2020 Olympics period J. Environ. Inf. Sci. 2021 29–36
Shen L, Wen J, Zhang Y, Ullah S, Cheng J and Merg X 2022 Changes in population exposure to extreme precipitation in the Yangtze River Delta, China Clim. Ser. 27 100037
Shen L, Zhang Y, Ullah S, Peprin N and Ma Q 2021 Changes in snow depth under elevation-dependent warming over the Tibet Plateau Atmos. Sci. Lett. 22 1–12
Shi C, Jiang Z H, Zhu I H, Zhang X, Yao Y V and Li L 2020 Risks of temperature extremes over China under 1.5 ◦C and 2 ◦C global warming Adv. Clim. Change Res. 11 172–85
Singh J, Ashraf M, Skinner C B, Anderson W B, Mishra V and Singh D 2022 Enhanced risk of concurrent regional droughts with increased ENSO variability and warming Nat. Clim. Change 12 163–70
Sun C, Jiang Z, Li W, Hou Q and Li L 2019 Changes in extreme temperature over China when global warming stabilized at 1.5 ◦C and 2.0 ◦C Sci. Rep. 9 1–11
Trenberth K E and Fasullo J T 2012 Climate extremes and climate change: the Russian heat wave and other climate extremes of 2010 J. Geophys. Res. 117 1–12
Ullah S et al 2020 Evaluation of CMIP5 models and projected changes in temperatures over South Asia under global warming of 1.5 ◦C, 2 ◦C and 3 ◦C Atmos. Res. 246 1–18
Ullah S, You Q, Ali A, Ullah W, Jan M A, Zhang Y, Xie W and Xie V 2019a Observed changes in maximum and minimum temperature extremes over China under 1.5 ◦C of global warming during the 2020 Olympics period Atmos. Res. 216 37–51
Ullah S, You Q, Chen D, Sachindra D A, Aghakoouchak A, Kang S, Li M, Zhai P and Ullah W 2022 Future population exposure to daytime and nighttime heat waves in South Asia Earth’s Future 10 1–16
Ullah S, You Q, Ullah W, Hagan D F T, Ali A, Ali G, Zhang Y, Jan M A, Bhatti A S and Xie W 2019b Daytime and nighttime heat wave characteristics based on multiple indices over the China–Pakistan economic corridor during 1980–2016 Atmos. Res. 216 37–51
Ullah W, Guojie W, Gao Z, Hagan D F T, Bhatti A S and Zhua C 2021a Observed linkage between Tibetan plateau soil moisture and South Asian summer precipitation and the possible mechanism J. Clim. 34 361–77
Ullah W, Guojie W, Lu D, Ullah S, Bhatti A S, Ullah S, Karim A, Hagan D F T and Ali G 2021b Large-scale atmospheric circulation patterns associated with extreme monsoon precipitation in Pakistan during 1981–2018 Atmos. Res. 253 1–14
Urban A and Kyselý J 2014 Comparison of UTCI with other thermal indices in the assessment of heat and cold effects on cardiovascular mortality in the Czech Republic Int. J. Environ. Res. Public Health 11 952–67
Vicedo-Cabrera A M et al 2021 The burden of heat-related mortality attributable to recent human-induced climate change Nat. Clim. Change 11 492–500

Vinogradova V 2021 Using the Universal Thermal Climate Index (UTCI) for the assessment of bioclimatic conditions in Russia Int. J. Biometeorol. 65 1473–83

Wang J, Chen Y, Tett S F B, Yan Z, Zhai P, Feng J and Xia J 2020 Anthropogenically-driven increases in the risks of summertime compound hot extremes Nat. Commun. 11 1–11

Wehner M, Stone D, Krishnan H, Achutarao K and Castillo F 2016 The deadly combination of heat and humidity in India and Pakistan in summer 2015 Bull. Am. Meteorol. Soc. 97 S81–6

WMO 2021 State of the global climate 2020

Xie H, Ringler C, Zhu T and Waqas A 2013 Droughts in Pakistan: a spatiotemporal variability analysis using the Standardized Precipitation Index Water Int. 38 620–31

Xu Y, Wu X, Kumar R, Barth M, Diao C, Gao M, Lin L, Jones B and Meehl G A 2020 Substantial increase in the joint occurrence and human exposure of heatwave and high-PM hazards over South Asia in the Mid-21st Century AGU Adv. 1 1–19

Yan Y, Xu Y and Yue S 2021 A high-spatial-resolution dataset of human thermal stress indices over South and East Asia Sci. Data 8 1–14

You Q, Chen D, Wu F, Pepin N, Cai Z, Ahrens B, Jiang Z, Wu Z, Kang S and AghaKouchak A 2020 Elevation dependent warming over the Tibetan Plateau: patterns, mechanisms and perspectives Earth-Sci. Rev. 210 1–19

You Q, Ren G, Zhang Y, Ren Y, Sun X, Zhan Y, Shrestha A B and Krishnan R 2017 An overview of studies of observed climate change in the Hindu Kush Himalayan (HKH) region Adv. Clim. Change Res. 8 141–7

Zahid M, Richard B, Valerio I and Bramati M C 2017 Return levels of temperature extremes in Southern Pakistan Earth Syst. Dyn. 8 1263–78

Zeng D, Wu J, Mu Y, Deng M, Wei Y and Sun W 2020 Spatial-temporal pattern changes of UTCI in the China-Pakistan economic corridor in recent 40 years Atmosphere 11 1–17

Zeng Y L and Dong L 2015 Thermal human biometeorological conditions and subjective thermal sensation in pedestrian streets in Chengdu, China Int. J. Biometeorol. 59 99–108