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Changes in extreme temperature events over the Hindu Kush Himalaya during 1961−2015

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Abstract

This study uses the CMA (China Meteorological Administration) global land-surface daily air temperature dataset V1.0 (GLSATD V1.0) to analyze long-term changes in extreme temperature events over the Hindu Kush Himalaya (HKH) during 1961−2015. Results show there was a significant decrease in the number of extreme cold events (cold nights, cold days, and frost days) but a significant increase in the number of extreme warm events (warm nights, warm days, and summer days) over the entire HKH during 1961−2015. For percentile-based indices, trends of extreme events related to minimum temperature (Tmin) were greater in magnitude than those related to maximum temperature (Tmax). For absolute-value based indices, maximum Tmax, minimum Tmin, and summer days all show increasing trends, while frost days and the diurnal temperature range (DTR) show significant decreasing trends. In addition, there was a decrease in extreme cold events in most parts of east HKH, particularly in Southwest China and the Tibetan Plateau, while there was a general increase in extreme warm events over the entire HKH. Finally, the change in extreme cold events in the HKH appears to be more sensitive to elevation (with cold nights and cold days decreasing with elevation), whereas the change in warm extremes (warm nights, warm days, and maximum Tmax) shows no detectable relationship with elevation. Frost days and minimum Tmin also have a good relationship with elevation, and the trend in frost days decreases with an increase in elevation while the trend in minimum Tmin increases with an increase in elevation.

Keywords: Climate change; Extreme temperature events; HKH; Land-surface air temperature; Elevation-dependent warming

1. Introduction

Previous studies have indicated that the socio-economy and natural systems are more sensitive to changes in extreme events than to changes in climate means (Katz and Brown, 1992; Karl et al., 1999; Easterling et al., 2000; Meehl et al., 2010; Stocker et al., 2013). In recent years, the impacts of extreme climate have been reported to be damaging to societal infrastructure and agricultural production; in addition, they increase energy consumption, increase the risk to human health and lives, increase the risk of species extinctions, and cause an increase in water resource management related problems (Karl and Easterling, 1999; Easterling et al., 2000).

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In recent decades, the temporal and spatial characteristics of extreme temperature changes have attracted considerable attention on both global and regional scales (Easterling et al., 2000; Zhai and Pan, 2003; Domonkos et al., 2003; Alexander et al., 2006; Vincent and Mekis, 2006). For example, Alexander et al. (2006) indicated that most global continents showed significant changes in temperature extremes during 1951−2003, especially for those indices related to daily minimum temperature. Based on an analysis using the CMIP3 and CMIP5 simulation data, Sillmann et al. (2013) also showed that over 70% of global lands experienced a significant decrease in the annual occurrence of cold nights and a significant increase in the annual occurrence of warm nights. However, results on a regional scale differ from region to region (Easterling et al., 2000). For example, the Hindu Kush Himalaya (HKH) is vulnerable to climate change and variability, and as such concerns climate scientists from countries such as China, India, Nepal, and Pakistan (Liu et al., 2006; You et al., 2008a; Singh et al., 2011; Eriksson et al., 2009; Zahid and Rasul, 2011).

Almost all extreme temperature indices on the Tibetan Plateau (TP) show statistically significant trends over the past half century, and stations in the northwestern, southwestern, and southeastern TP have larger trend magnitudes (Zhai and Pan, 2003; Liu et al., 2006; You et al., 2008a; Zhou and Ren, 2011; Yan and Liu, 2014). In Pakistan, Zahid and Rasul (2011) analyzed absolute extreme temperature events and showed that the frequency of extreme maximum (minimum) temperature events exhibited increasing (decreasing) trends throughout Pakistan, and a marked increase (decrease) occurred in northern Pakistan, southern Punjab, Sindh, and Baluchistan during 1965−2009. In northern India, Kothawale et al. (2010) found a significant decreasing trend in the frequency of cold days over the western Himalayas but a significant increasing trend in the frequency of warm nights in northwestern India during 1970−2005. In Nepal, Baidya et al. (2008) indicated that most of the temperature extreme indices experienced consistent changes but that there were relatively higher trends in mountainous regions during 1971−2006. Shrestha et al. (2016) conducted a study of the Koshi River Basin and the transboundary basin between China, Nepal, and India and found an increase in the daily maximum and minimum temperatures and number of warm nights in the basin. However, most extreme temperature indices showed a consistently different pattern in the mountains than on the Indo-Gangetic plains. Researchers from other countries such as Iran (Rahimzadeh et al., 2009), Myanmar, Vietnam, and Laos (Manton et al., 2001) have also studied the HKH. Panday et al. (2014) indicated a significant decreasing trend in frost days and a significant increasing trend in warm nights in the east HKH during 1960−2000. Their study also analyzed CMIP3 and CMIP5 simulation data and indicated that the change characteristics observed in past decades would continue in the future. In general, the warming trends in minimum temperature (Tmin) indices for the HKH are of greater magnitude than those of maximum temperature (Tmax), although the magnitude differs from region to region, which is consistent with the results of previous studies (Alexander et al., 2006).

The HKH is monitored by an observation station network that covers an elevation ranging from low-lying plains to mountains and plateaus at nearly 5000 m a.s.l (Revadekar et al., 2013). Some studies have found a possible elevation-dependent warming (EDW) in the HKH that could have a significant impact on mountain ecosystems, hydrological regimes, and biodiversity (Chen et al., 2003; Liu et al., 2009; Yan and Liu, 2014; Yan et al., 2016; Pepin et al., 2015; Shrestha et al., 1999; Shrestha, 2008). Giorgi et al. (1996) analyzed EDW in the Alps using a regional model, and results suggested that significant warming or cooling at high elevations could be used as an early detection tool for global warming, especially in northern winters and spring. Yan and Liu (2014) recently investigated the warming trends at 139 stations on the TP and determined that the TP is a region that is very sensitive to global warming. Pepin et al. (2015) investigated EDW over the TP and found that the vertical change in the annual and winter warming rates was a reflection of more rapid warming at higher altitudes. However, these previous studies mainly focused on mean temperature changes and did not aim to examine EDW phenomenon in terms of extreme temperature events. However, in India and its neighboring countries, Revadekar et al. (2013) analyzed the impact of elevation and latitude on changes in temperature extremes and determined that stations at high elevations recorded more obvious absolute trends in extreme temperature indices.

Previous analyses have been mostly limited to individual countries and an overall analysis of the HKH as a whole is lacking, both for changes in extreme temperature events and for EDW in terms of extreme temperature. Therefore, one of the objectives of this paper is to provide a comprehensive analysis of temperature extreme changes over the entire HKH. The other objective is to analyze the possible impact of elevation on long-term trends of temperature extreme indices. In this respect, a new multi-source dataset is used in this paper to analyze changes in extreme temperature events over the HKH during 1961−2015.

This paper is organized as follows. Section 2 describes the study region, data sources, extreme indices, and statistical methods. Results are presented in Section 3; the temporal and spatial characteristics of extreme temperature changes in the HKH are analyzed in Section 3.1, and the possible impact of elevation on changes in extreme temperature events is analyzed in Section 3.2. Section 4 then presents a discussion of results and conclusions are given in Section 5.

2. Study region, data sources, extreme indices, and statistical methods

The HKH (20−40°N, 60−105°E) spans six entire countries (Nepal, Pakistan, Afghanistan, Bhutan, Burma, Bangladesh), parts of nine other countries (China, India, Iran, Turkmenistan, Uzbekistan, Tajikistan, Kazakhstan, Vietnam and Laos), and has an elevation range between sea level and more than 8000 m a.s.l. (Fig. 1).

The available daily temperature measurement used in current analysis is the global land-surface daily air temperature dataset V1.0 (GLSATD V1.0) (Xu et al., 2014) developed by China Meteorological Administration (CMA). This temperature dataset has been quality controlled and includes daily Tmax and Tmin. A 55-year period (1961—2015) is used in analysis; however, as lengths of available records vary between stations, certain prerequisites for inclusion were determined as follows. Stations included in analysis had to provide at least 30-year records within the entire period and at least 15-year records during the 1961—1990 reference period. In addition, they had to provide at least 10-month valid records within each year. And the end-year of record must be after the year 2000. In this respect, a total of 478 stations were used; the spatial distribution and record length of each station is shown in Fig. 1, and the data sources and number of stations are shown in Table 1.

Time series were constructed by area-weighted averaging all grids with data using cosines of the central latitudes of grid boxes as weight coefficients and by referring to the method of Jones and Moberg (2003). The method involved is as follows. Firstly, each station is assigned to a regular 2.5° × 2.5° latitude—longitude grid box. Grid boxes that contain at least one station are used in calculating regional averages and grid box temperature anomalies are then calculated by averaging anomalies for all the stations within grid boxes. Finally, the HKH average temperature and Tmax and Tmin anomalies are calculated by the area-weighted (using cosines of mid-grid latitude as weights) average of all grid box anomalies.

The period 1961—1990 is chosen as the reference period, mainly because there is a better spatial coverage of records during this period. Annual mean values are calculated by averaging all 12 monthly values, and linear trends are calculated by the least squares method. The significance of linear trends is determined using the 2-tailed simple t-test method.

Nine temperature-related indices are used in this paper. These include four percentile-based indices and five absolute-value based indices out of the 27 extreme climate events indices recommended by the Expert Team for Climate Change Detection Indices. Definitions of indices can be found in Table 2.

Table 1
Daily data sources and number of stations during 1961—2015.

Source	CMA	GHCND	GSOD	ECA	MONRE	Total
Number	388	55	27	6	2	478
Percentage (%)	81.2	11.5	5.6	1.3	0.4	100

Note: China Meteorological Administration (CMA), Global Historical Climatology Network-Daily (GHCND), Global Summary of the Day (GSOD), European Climate Assessment (ECA), Ministry of Natural Resources and Environment, Vietnam (MONRE).

3. Results

3.1. Changes in extreme temperature over the HKH

Annual mean anomaly time series of the percentile-based (Fig. 2 a—d) and absolute (Fig. 2 e—h) temperature extreme indices for the whole HKH, based on the CMA GLSATDV1.0 dataset, are shown. The percentile-based temperature indices are calculated using percentages and units are then converted into days for easy understanding, as suggested by Alexander et al. (2006). There was a significant decrease in extreme cold events for the entire HKH during 1961—2015 (Fig. 2 a, b) but a significant increase in extreme warm events (Fig. 2 c, d). However, the trends in warm events are larger in magnitude than those of cold events (Table 2), and there was a dramatic increase after the early-1990s especially for warm nights (Tn90p). In addition, the trends in extreme events related to Tmin are greater in magnitude than those related to Tmax.

In general, there was also a generally significant change in the extreme values and frequencies of absolute-temperature based indices. The extreme values of both TXx and the TNn showed increasing trends in the HKH, and the rising rate of

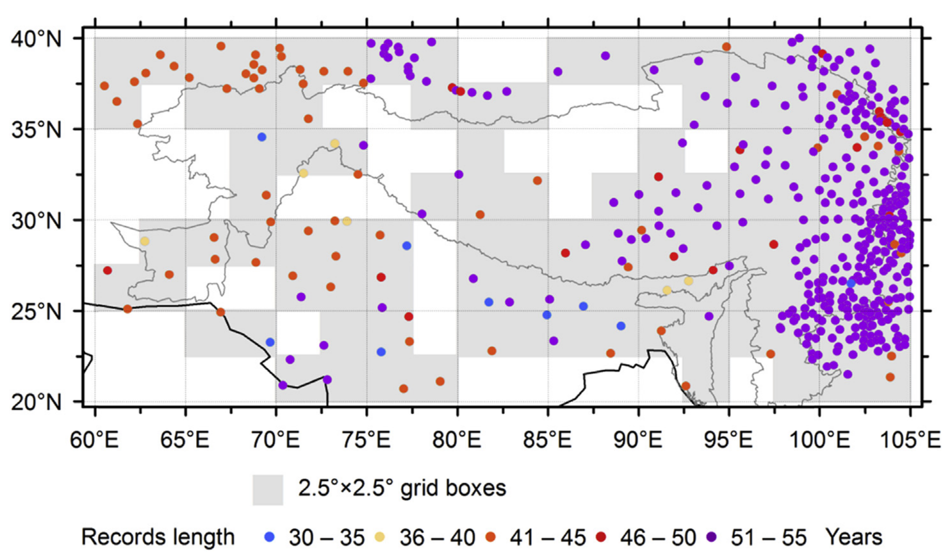

Fig. 1. Maps of study region, location of 478 stations in HKH (colors represent length of records in years and grid boxes with a spatial resolution of 2.5° × 2.5° are used for estimating regional averages and are shown by gray areas).

Table 2
Trends of extreme temperature indices over HKH in 1961–2015.

Indicator name	ID	Definition	Trend	Trend unit
Cold nights	TN10p	Days when Tmin <10th percentile	−0.977*	d per decade
Cold days	TX10p	Days when Tmax <10th percentile	−0.511*	d per decade
Warm nights	TN90p	Days when Tmin >90th percentile	1.695*	d per decade
Warm days	TX90p	Days when Tmax >90th percentile	1.239*	d per decade
Max Tmax	TXx	Monthly maximum of daily maximum temperature	0.282*	°C per decade
Min Tmin	TNn	Monthly minimum of daily minimum temperature	0.419*	°C per decade
Frost days	FD	Annual count when Tmin <0 °C	−3.636*	d per decade
Summer days	SU	Annual count when Tmax >25 °C	6.741*	d per decade
Diurnal temperature range	DTR	Monthly mean difference between Tmax and Tmin	−0.108*	°C per decade

Note: * denotes the trend is statistically significant at the 0.05 confidence level.

TNn was more than double that of TXx (Table 2). In addition, the rising rate of TNn was dominated by large positive anomalies after 1990s (Fig. 2e). There was also an increasing trend (6.74 d per decade) in the frequency of summer days (SU), which was related to dramatic positive anomalies after 1990 (Fig. 2h). However, summer days increased by about 20 d during 1989 and 1998, which is a much larger amount than the average rising rate of the whole period. The frequency of frost days (FD) showed a decreasing trend of −3.63 d per decade (Fig. 2g). Throughout the entire HKH, the annual mean DTR anomalies showed an obvious decreasing trend before the 1980s, but DTR shown a slight increased trend after the mid-1980s (Fig. 2i). The overall decline was mainly because of the much larger increase in annual mean Tmin rather than that of annual mean Tmax. This result is agreement with Makowski et al. (2008), who found that the DTR over Europe showed a reversed trend from the mid-1980s.

Fig. 3 shows the spatial distribution of linear trends for extreme temperature indicators of every grid in the HKH. There was an evident decrease in the frequency of cold nights and cold days (TN10p and TX10p) in most parts of east HKH particularly in Southwest China and the TP, while a few grid boxes in western HKH showed an upward trend (Fig. 2a and b). There was an evident increase in the frequency of warm nights and warm days (TN90p and TX90p) in the whole HKH (Fig. 2c and d).

For absolute-value based indices, there was a decreasing trend in frost days in most parts of the HKH, except parts of western India and western HKH (Fig. 2e). There was a large increasing trend in summer days between 60°E and 80°E, but a lower rate of increase on the TP (Fig. 2f). The TXx and TNn showed increasing trends over the whole HKH, but TNn showed a larger increase on the TP (Fig. 2g–h). There was an increasing trend in DTR along the Himalayan belt, while most of the other regions experienced a significant decreasing trend, with the downward trend especially large in the TP (Fig. 2i). In general, the absolute-value based extreme temperature indices showed obvious changes throughout the HKH.

3.2. Impact of elevation on changes in extreme temperature events

Section 3.1 shows that there are spatial differences in the trends of several extreme temperature indices between the mountainous belt and areas of low elevation. The objective of this section is to analyze the possible impact of elevation on changes in temperature extremes.

Fig. 4 shows the relationship between station elevation and trends in extreme temperature indices. Stations are divided into 10 groups by 500 m altitudes. However, as more than 95% of stations are located below 4000 m the results from stations above 4000 m are likely to be accompanied by a great degree of uncertainty. For percentile-based indices of cold events, the absolute values of negative trends in extreme cold events are found to increase with increasing elevation, indicating a larger decreasing rate at higher altitudes. In addition, the impact of elevation is greater on cold nights than on cold days. However, the relationship between elevation and the trends of warm events is not always obvious. For the absolute-value based indices, frost days and TNn have a good relationship with elevation and the trend in frost days decreases with an increase in elevation, while the trend in TNn increases with an increase in elevation. As stations above 4500 m are not included in Tmin/Tmax (records above 0 °C/25 °C), the number of frost days and summer days could not be considered in analysis. The absolute values of the DTR trend increase with an increase in elevation, although they increase slowly below 4000 m but show an obvious increase above 4000 m. Changes for the trends in nine temperature-related extreme indices with elevation are also shown in Table 3. In general, changes in extreme cold events throughout the HKH are more sensitive to elevation, whereas changes in extreme warm events show no obvious relationship with elevation.

4. Discussion

Major uncertainties relating to estimates of extreme temperature trends are due to systematic biases in the historical temperature data series with respect to the effect of urbanization. Urbanization exerts a large effect on the long-term trends of both mean surface air temperature and on the extreme temperature indices in sub-continental regions, such as mainland China (Zhou and Ren, 2011; Ren and Zhou, 2014; Sun et al., 2016; Ren et al., 2012). However, this effect has not yet been corrected within the annual and seasonal extreme temperature indices in the TP or HKH regions. Nevertheless, even when this effect is considered, background warming over the TP and the HKH, which is probably caused by global and

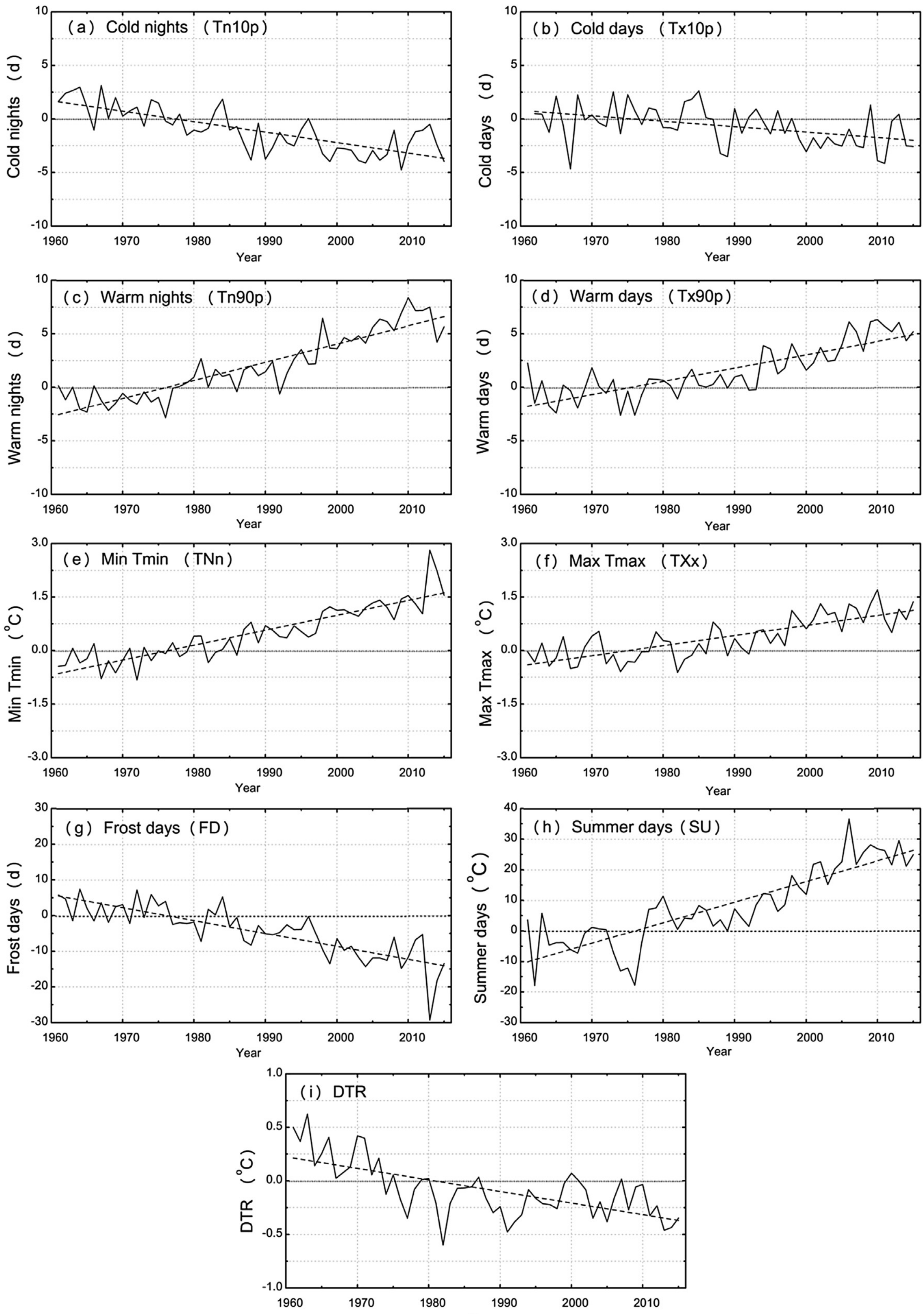

Fig. 2. Annual mean anomalies of extreme temperature indices over HKH during 1961−2015 for (a) cold nights (TN10p), (b) cold days (TX10p), (c) warm nights (TN90p), (d) warm days (TX90p), (e) maximum Tmax (TXx), (f) minimum Tmin (TNn), (g) frost days (FD), (h) summer days (SU), and (i) diurnal temperature range (DTR) (relative to 1961−1990 means). Dashed lines indicate the linear trends.

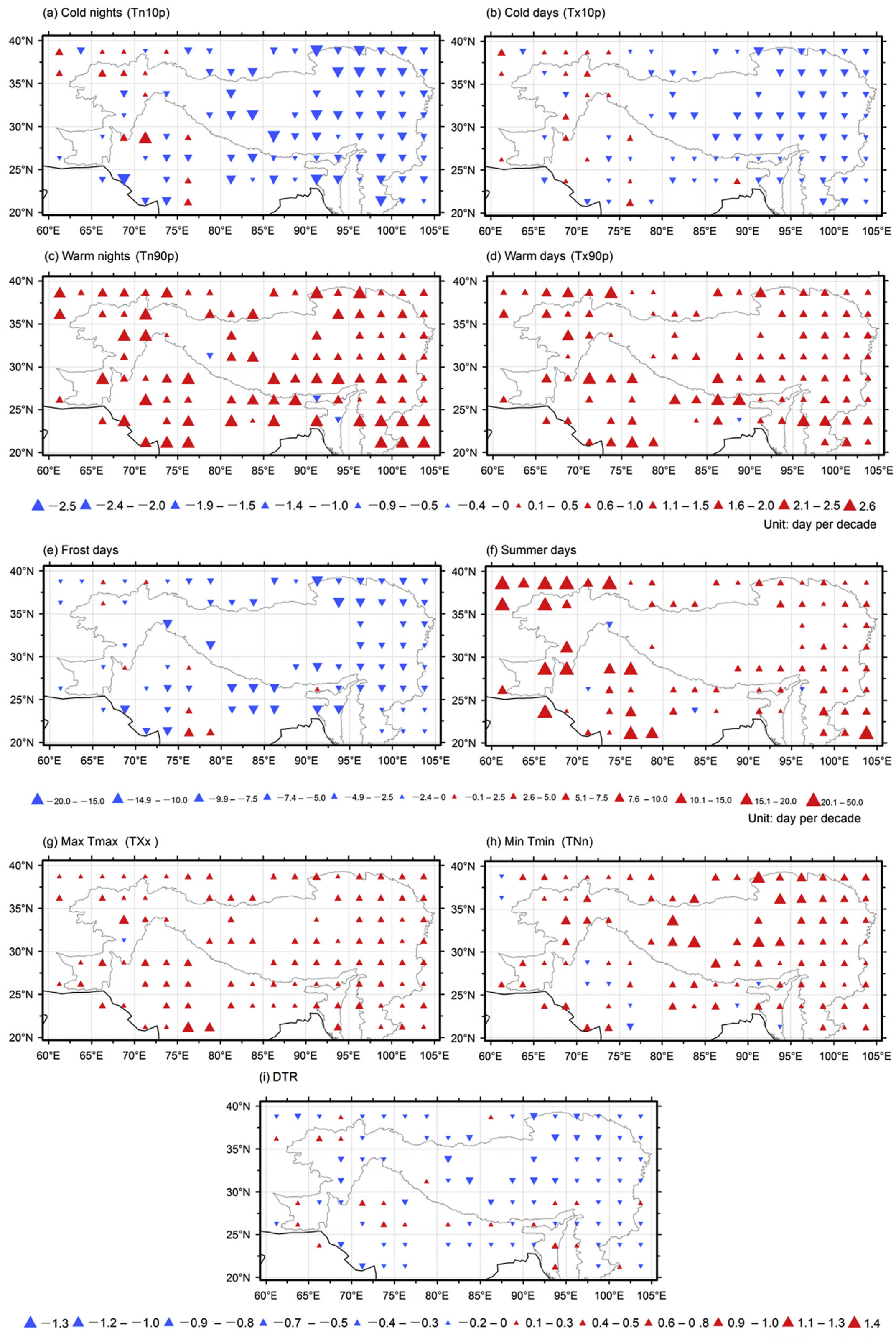

Fig. 3. Trends in temperature-related indices over the HKH during 1961−2015.

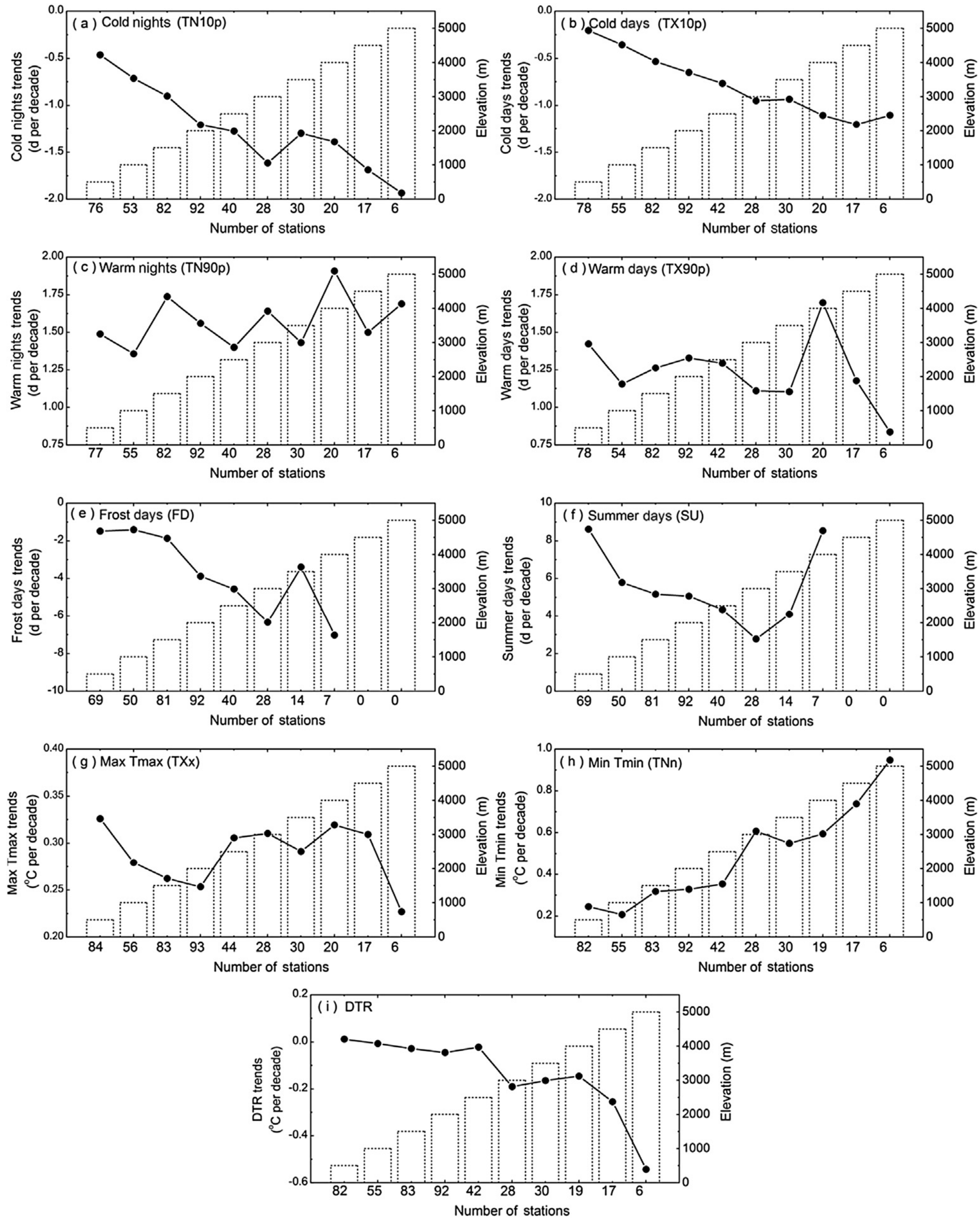

Fig. 4. Elevation-dependent trends of extreme temperature indices over the HKH during 1961–2015 (bars indicate elevations; lines indicate trends of extreme temperature indices).

regional drivers including anthropogenic-related increases in atmospheric CO_2 concentration, is still likely to be significant.

Another source of uncertainty is related to the gaps in observations throughout the HKH, especially in Afghanistan, northern India, Bhutan, and the northwestern part of the TP. In this paper, the coverage rate of grid boxes is ~74% over the HKH; therefore, the sparseness of observational data is one of the major sources of uncertainties in estimates of long-term trends therein. In addition, station relocation, the different observation practices used, and instrumentation changes could cause data to be inhomogeneous, and could also cause the trend analysis to be less reliable in certain places (Peterson et al., 1998). Therefore, to determine whether or not spatial differences in data between eastern and western HKH effect results, different resolution gridding average methods ($1° \times 1°$, $2.5° \times 2.5°$, and $5° \times 5°$) were used to evaluate the magnitude of influences. Using cold nights (TN10p) as an example, a comparison shows that the influences are about an order of magnitude smaller than trend estimation results (Table 4); therefore the method of using different resolution gridding averages does not substantially affect the final result over the whole region. However, it is considered necessary to conduct further future studies to assess influences, using high resolution observation data or satellite data. The multi-source stations dataset used in this paper has not yet been examined for temporal inhomogeneities, which may be one of the main sources of uncertainty, and thus detecting and adjusting these inhomogeneities in the data series needs to be performed in future studies. However, it is considered that the influence of data being homogenized would be generally small for a large

Table 3
Elevation-dependent trends for extreme temperature indices over the HKH during 1961–2015.

Index	Elevation range (m)	Number of stations	Classification of events	Elevation-dependent trend (trend unit $(500\ m)^{-1}$)
Cold nights	0–5000	444	Cold event	−0.140
Cold days	0–5000	450	Cold event	−0.109
Warm nights	0–5000	447	Warm event	+0.021
Warm days	0–5000	449	Warm event	−0.023
Max Tmax	0–5000	461	Warm event	−0.002
Min Tmin	0–5000	454	Cold event	+0.075
Frost days	0–4000	381	Cold event	−0.747
Summer days	0–4000	381	Warm event	−0.201
DTR	0–5000	454	Other	−0.047

Note: Trend unit $(500\ m)^{-1}$: day per decade $(500\ m)^{-1}$for cold (warm) days (nights), frost days and summer days, and °C per decade $(500\ m)^{-1}$ for Max (min)Tmax (Tmin) and DTR.

Table 4
Trends of cold nights (TN10p) based on different gridding average methods.

Item	Cold nights (TN10p)/461 stations		
Grid resolution	1° × 1°	2.5° × 2.5°	5° × 5°
Number of grids	232	96	35
Trend (d per decade)	−0.964	−0.977	−1.061

domain like the HKH, and thus results of extreme temperature changes obtained in this analysis are considered to be robust.

It is believed that the HKH is one of the most sensitive areas globally to climate change (Xu et al., 2009); Table 5 shows the percentage of significant annual trends for global land and for the HKH. It is evident from the comparison that the percentage of significant trends in the HKH region is consistently lower than that of global land, except for trends of TXx and TNn. The significant positive trends of TXx and TNn are more than 50%, which is evidently larger than that globally. However, the positive and negative trends of all extreme indices in the HKH region overall are approximately consistent with global land averages.

Several previous studies have investigated the EDW phenomenon on the TP and have determined a more pronounced warming at high elevations compared to the surrounding regions (Liu and Chen, 2000; Chen et al., 2003; Liu et al., 2009; Yan and Liu, 2014; Yan et al., 2016; Pepin et al., 2015), although the magnitude of EDW has been shown to be different among the various research groups. However, using temperature trend magnitudes at 71 surface stations at elevations above 2000 m on eastern and central TP, You et al. (2008b) failed to find an elevation dependency in the trends of temperature extremes in the eastern and central TP. In contrast, our analysis finds that changes in extreme cold events in the HKH are more sensitive to elevation, but changes in extreme warm events show no obvious relationship to elevation. Therefore, the results presented here show certain differences to those of previous studies (Liu and Chen, 2000; Chen et al., 2003; Liu et al., 2009; Yan and Liu, 2014; Yan et al., 2016; Pepin et al., 2015). However, according to a previous study (Kang et al., 2010), the varied conclusions obtained in analyses are probably due to the differing datasets, periods of analysis, and lowland stations used in making comparisons.

Table 5
Percentage of significant annual trends globally and for HKH (solid numbers represent HKH).

Index	Global land (1951–2003)/**HKH (1961–2015)**		
	Grid boxes/**Stations**	Significant positive trend (%)	Significant negative trend (%)
Cold nights	1306/**461**	0.1/**1.5**	74.0/**51.4**
Cold days	1321/**462**	0.5/**0.7**	46.0/**11.9**
Warm nights	1404/**459**	73.1/**54.2**	0.1/**0.2**
Warm days	1275/**461**	41.0/**36.9**	0.9/**0.2**
Max Tmax	1028/**471**	11.6/**52.4**	2.7/**0.2**
Min Tmin	1379/**467**	45.0/**62.1**	1.9/**0.2**
Frost days	1039/**395**	0.2/**1.0**	40.6/**36.5**
Summer days	957/**395**	23.4/**33.2**	3.7/**0.3**
DTR	1024/**467**	4.2/**3.6**	39.3/**18.0**

5. Conclusions

A new multi-source dataset is used in this paper to analyze changes in extreme temperature events over the HKH region during 1961–2015. The main conclusions are as follows:

(1) There was a significant decrease in the number of extreme cold events but a significant increase in the number of extreme warm events over the whole HKH during 1961–2015. For percentile-based indices, trends of extreme events related to Tmin are greater in magnitude than those related to Tmax. For absolute-value based indices, TXx, TNn, and summer days show an increasing trend, and the rising rate of TNn is more than double that of TXx. Frost days and DTR show a decreasing trend.

(2) For the percentile-based indices, there was an obvious decrease in the number of extreme cold events in most parts of eastern HKH, particularly in Southwest China and the TP, while there was a general increase in extreme warm events over the whole HKH. For absolute-value based indices, frost days (summer days) show an obvious decreasing (increasing) trend on the TP. TXx and TNn show increasing trends over the whole HKH, and DTR shows an increasing trend along the Himalayan belt.

(3) The change in extreme cold events in the HKH is more sensitive to elevation (with cold nights, cold days decreasing with elevation) but the change in extreme warm events (warm nights, warm days, and TXx) shows no obvious relationship with the elevation. For the absolute-value based indices, frost days and TNn have a good relationship with elevation and the trend in frost days decreases with an increase in elevation, while the trend in TNn increases with an increase in elevation.

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