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• Review •

Recent Progress in Studies on the Influences of Human Activity on Regional Climate over China※

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ABSTRACT

The influences of human activity on regional climate over China have been widely reported and drawn great attention from both the scientific community and governments. This paper reviews the evidence of the anthropogenic influence on regional climate over China from the perspectives of surface air temperature (SAT), precipitation, droughts, and surface wind speed, based on studies published since 2018. The reviewed evidence indicates that human activities, including greenhouse gas and anthropogenic aerosol emissions, land use and cover change, urbanization, and anthropogenic heat release, have contributed to changes in the SAT trend and the likelihood of regional record-breaking extreme high/low temperature events over China. The anthropogenically forced SAT signal can be detected back to the 1870s in the southeastern Tibetan Plateau region. Although the anthropogenic signal of summer precipitation over China is detectable and anthropogenic forcing has contributed to an increased likelihood of regional record-breaking heavy/low precipitation events, the anthropogenic precipitation signal over China is relatively obscure. Moreover, human activities have also contributed to a decline in surface wind speed, weakening of monsoon precipitation, and an increase in the frequency of droughts and compound extreme climate/weather events over China in recent decades. This review can serve as a reference both for further understanding the causes of regional climate changes over China and for sound decision-making on regional climate mitigation and adaptation. Additionally, a few key or challenging scientific issues associated with the human influence on regional climate changes are discussed in the context of future research.

Key words: human activity, regional climate, China

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Article Highlights:

- Recent evidence of the human influences on regional climate over China is reviewed based on studies published since 2018.
- Human activity has contributed to changes in SAT, wind speed, precipitation, droughts, and compound extreme climate/weather events.
- Anthropogenic forcing of regional climate changes can be climatic factor-, region-, period-, and event-dependent.

1. Introduction

In addition to natural climate variations, human activity has induced prominent influences on regional climate over China in recent decades (Zhai et al., 2018; Sun et al., 2022), and the anthropogenic signal on temperature seasonality has been tracked back to the late 19th century in the Tibetan

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Plateau (TP) region (Duan et al., 2019; Yin e al., 2022). Human activities are characterized mainly by the emissions of industrialization-induced greenhouse gas (GHG) and anthropogenic aerosols (AA), land use and cover change (LUCC), urbanization, and some other aspects (e.g., anthropogenic heat release, AHR) (Fig. 1). The emissions of GHG and AA have altered atmospheric components and influenced radiative forcing, ultimately affecting the global or regional climate, while LUCC and urbanization have changed the physical properties of the underlying surfaces, induced land–atmosphere interactions, and ultimately influenced the regional climate. It is unequivocal that the human influence has greatly warmed the atmosphere, ocean and land (IPCC, 2021). However, the anthropogenic forcing effect can differ regionally. For example, some regions suffer more from global warming (Xie et al., 2019), and the regional climate responses to anthropogenic forcing also differ (Li et al., 2022a). Typically, SAT changes over China seem more sensitive to external forcing than those over the United States owing to the stronger climate memory, and this has led to substantially different warming trends between China and the United States (Li et al., 2022a). Therefore, a systematic review of the evidence of anthropogenic influences on regional climate can not only deepen our understanding of the regional anthropogenic climate effect, but can also serve as a reference for regional climate mitigation and adaptation.

China has the largest population in the world and has experienced rapid economic development and industrialization in recent decades; the anthropogenic influences on the regional climate of China have drawn great attention. Many studies have indicated that anthropogenic forcing has contributed to both the rapid increase in SAT trends and the increased frequency and intensity of SAT extremes over China during recent decades (Chen et al., 2019a, Chen et al., 2021, Li et al., 2022a; Sun et al., 2022). Although the anthropogenic signal of regional precipitation might be obscured by the strong internal variability, some studies have revealed an effect of anthropogenic warming on the mean and extreme precipitation trends via enhancing the water cycle over China in recent decades (Zhai et al., 2018; Li et al., 2021c). Moreover, anthropogenic forcing has triggered droughts, weakened monsoon precipitation, and surface wind speed (SWS) changes over China (Fig. 1). These changes resulting from human activity, especially for extreme event changes, have brought potential or direct threats to human societies in China (Wang et al., 2018b; Yuan et al., 2019; Li et al., 2021b). Sound regional- or national-level decision-making for disaster prevention and mitigation depends on the reliable detection of anthropogenic forcings of mean and extreme climate changes.

Human activity–induced regional climate changes may cover many aspects. In this paper, we mainly review the anthropogenic effects on regional SAT, precipitation, drought, SWS, and monsoon-related precipitation changes over China (Fig. 1). According to the journal's requirement that this paper should focus on progress mainly over the last five years, the evidence reviewed is derived from references published since 2018.

2. Methods employed in detection and attribution studies

Before reviewing the research progress on the anthropogenic influences on regional climate changes over China, the key methods used for detection and attribution studies are first summarized. For the detection and attribution of trends in climate changes, multivariate analysis and Bayesian inference are used most. The optimal fingerprinting method, the most popular method in detection and attribution studies, is a multivariate analysis method, while Bayesian inference methods can integrate multiple sources of data for attribution (Zhai et al., 2018).

The so-called "fingerprint" is the climate system that generates unique responses to various external forcings, just as every person has a unique fingerprint (Hasselmann, 1993, Allen and Tett, 1999). These responses can be obtained from simple physical arguments based on the forcing pattern or the mean response to a particular forcing scenario among an ensemble of climate model runs (Allen and Tett, 1999). Generalized linear regression is usually utilized to achieve the optimal fingerprinting method (Allen and Tett, 1999; Allen and Stott, 2003; Stott et al., 2003).

With the development of attribution methods, regularized optimal fingerprinting (ROF) was developed to obtain more objective and accurate implementation in the area of detection and attribution (Ribes et al., 2013). The main difference of ROF from the classical optimal fingerprinting method is that ROF uses a regularized estimate of the internal variability covariance matrix to improve the estimation of residuals (Ribes et al., 2013).

The most commonly used climate event attribution method is calculating an event's probability related to anthropogenic forcing. The core idea of this probability approach is the "control variable method". For example, based on the distribution of climate variables or of an index characterizing the corresponding extreme events in two sets of simulations (one containing all forcings, and the other containing only the natural forcing), the contribution of the human influence to the risk of change in a certain extreme event can be calculated. The probability of a certain extreme event simulated with all forcings is denoted as P1, and the probability of the same event under only the natural forcing is denoted as P0. Then, the ratio P1/P0 is the risk ratio, and (1 − P1/P0) is the fraction of attributable risk, which is used to measure the extent of human influence on the extreme event (Otto, 2017; Zhai et al., 2018). The other method of event attribution is the "storyline approach" (Shepherd, 2016), which mainly deduces the event of interest. In summary, experiments should be designed with possible physical influencing factors, and some of them are taken as preconditions (mostly large-scale circulations), and the question of to what extent climate change has altered the magnitude of this specific event is finally answered deterministically (Shepherd, 2016).

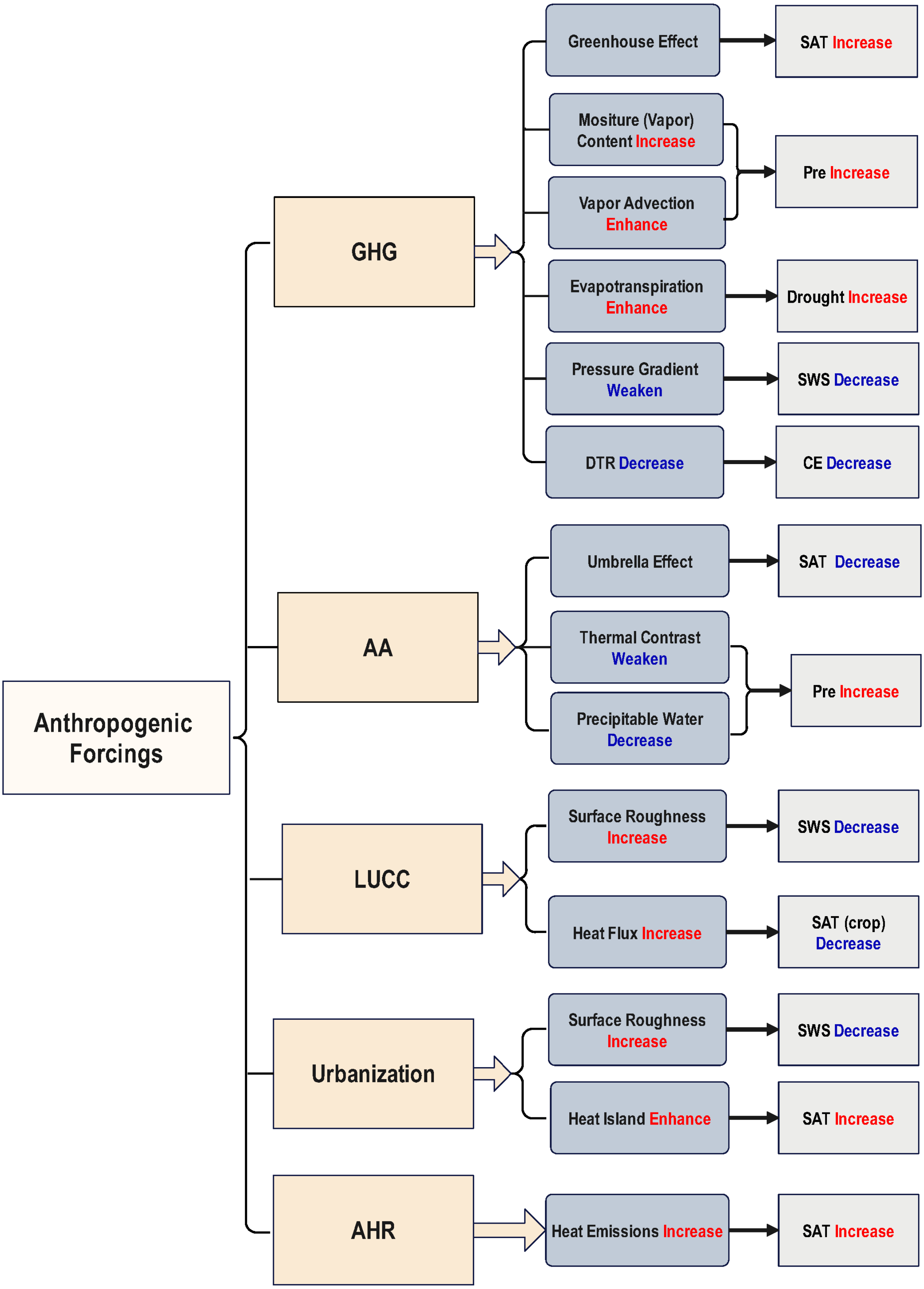

Fig. 1. Schematic of the influence of human activities on regional climate changes over China. Among the physical mechanisms, the pressure gradient refers to the atmospheric pressure difference between the high- and mid-latitude zone. The umbrella effect, representing the direct effect of aerosols, refers to aerosol particles that weaken surface solar radiation by reflecting and absorbing solar radiation. GHG, greenhouse gas; AA, anthropogenic aerosols; LUCC, land use cover change; AHR, anthropogenic heat release; SAT, surface air temperature; Pre, precipitation; SWS, surface wind speed; CE, compound events; DTR, diurnal temperature range.

Most of the following reviewed studies used the optimal fingerprinting or ROF method and an event probability method for detection and attribution in trends of climate changes and extreme climate events, respectively.

3. Anthropogenic influences on SAT trends and extremes over China

3.1. *Anthropogenic influences on SAT trends over China*

Anthropogenic forcing has been identified as the dominant factor for the rapid SAT increase over China in recent decades (Allabakash and Lim, 2022; Sun et al., 2022) (Table 1). During the period 1961–2005, the SAT over China increased by 0.78°C ± 0.27°C, with warming of 0.25°C (10 yr)$^{-1}$ and 0.17°C (10 yr)$^{-1}$ resulting from GHG emissions and other anthropogenic factors, respectively (Allabakash and Lim, 2022). Compared to other parts of China, the TP has shown a greater warming rate in recent decades (1.23°C from 1961–2005) (Zhou and Zhang, 2021), and GHG forcing has contributed an increase of 1.37°C according to best estimates (Zhou and Zhang, 2021). GHG forcing was the major contributor to the increased warming, and AA induced a cooling effect and offset part of the warming resulting from the GHG effect over the whole of China and in a few subregions (Jia et al., 2020;; Zhou and Zhang, 2021) (Fig. 2). In addition to GHG and AA, LUCC and urbanization also influenced the local or regional SAT trends over China (Du et al., 2019; Jin et al., 2021; Yang et al., 2021; Zhang et al., 2022a) (Fig. 2). LUCC has generally induced significant SAT decreases in cropland areas and significant SAT increases in urbanized areas over China (Jin et al., 2021; Yang et al., 2021). Urbanization contributed to an increase of 0.49°C in the annual SAT over the whole of China from 1961 to 2013 (Sun et al., 2022). Urbanization also contributed to the diurnal temperature range trends by more than 25% in both winter and summer, and positively affected the surface sunshine duration by approximately 29.4% in winter and 11.9% in summer, over China from 1951 to 2020 (Zhang et al., 2022a). Moreover, the urban drying island effect in recent periods over eastern China, resulting from the decreased cloud cover, induced a mitigation effect on the urban heat island effect (Du et al., 2019).

Apart from the increased SAT, human activity has also contributed to a significant weakening of the SAT seasonality on the TP (Duan et al., 2017, 2019) and over China (Qian and Zhang, 2015). This mainly features a significant reduction in the winter–summer SAT difference, driven by the combined effect of increased GHGs and AAs with a meridional difference (Duan et al., 2019). In particular, anthropogenic forcing–induced SAT seasonality weakening has been tracked back to the 1870s on the TP (Duan et al., 2019). A detection and attribution study (Duan et al., 2019) using tree ring–based reconstructions of the summer–winter temperature difference indicates that the anthropogenic signal is detectable since the 1870s and can be supported by natural climate proxy evidence (Fig. 3).

3.2. *Anthropogenic influences on SAT extremes over China*

Anthropogenic forcing has influenced the intensity, frequency and occurrence likelihood of extreme temperature events in many regions of China (Chen et al., 2019a; Yin et al., 2019; Lu et al., 2020b; Liu et al., 2022). In view of the whole of China, both intensity and frequency indices of extreme temperature showed continuous warming from 1951 to 2018, and more intense and more frequent warm extremes and less intense and less frequent cold extremes were observed in most regions (Hu and Sun, 2022). GHG forcing accounted for approximately 1.6 (1.1 to 2) times the observed warming reflected in the changes in most indices, while AA offset approximately 35% (10%–60%) of GHG-induced warming for warm extremes, and land use and ozone may have made very small positive contributions to extreme temperatures (the effect of ozone was separated from the GHG effect) (Hu and Sun, 2022). Anthropogenic forcing is also a critical factor affecting the observed decadal changes in temperature extremes over China since the mid-1990s (Chen and Dong, 2019) and has contributed to the increased frequency, intensity, and spatial extent of regional daytime and nighttime heatwaves (HWs) over China in recent decades (Lu et al., 2018; Wang et al., 2018b; Yin and Sun, 2018; Su and Dong, 2019; Wang et al., 2022b). These changes were driven both directly by the strengthened greenhouse effect and indirectly by the related land–atmosphere and circulation feedbacks (Su and Dong, 2019). Estimations have indicated that the increased probability of the hottest day occurring over more than 75% of the observed areas in China could be attributed to anthropogenic forcing (Chen et al., 2021), and the GHG effect changed the frequencies of summer days and tropical nights by +3.48 ± 1.45 d (10 yr)$^{-1}$ and +2.99 ± 1.35 d (10 yr)$^{-1}$ over eastern China from 1960 to 2012, respectively (Wang et al., 2018b). Nevertheless, local AA emissions may be a factor affecting the spatially heterogeneous extreme temperature trends in China (Chen and Dong, 2019).

Many case-based quantitative attribution studies have also demonstrated that anthropogenic forcing was the dominant factor affecting the increased frequency and intensity of extreme high-temperature events over China in recent decades (Fig. 4, Table 2). Anthropogenic forcing explained approximately 42% of the SAT warming and 60% (40%) of the increases in maximum (minimum) temperature, respectively, corresponding to extreme summer heat in western China in 2015 (Chen et al., 2019a). Simulation-based attribution results show that, given the external forcing at the 1961–2015 level and regardless of the sea surface boundary conditions, there is a 21-fold increase in the likelihood of 2015-like heat events in Northwest China due to anthropogenic forcing (Zhang et al., 2022d). Anthropogenic forcing has made the occurrence likelihood of July 2017–like HW events over eastern China increase by a factor of 4.8 (Sparrow

Table 1. Quantitative contributions of anthropogenic forcings to regional climate changes over China obtained from references published since 2018. See Table 3 for abbreviation definitions.

Climatic/ environmental factor	Region (site)	Period	Season	Quantitative contribution (forcing factor)	Reference
SAT trend	Whole of China	1961–2013	Annual	↑0.49°C (urbanization)	Sun et al. (2022)
	TP	1961–2005	Annual	↑1.37°C (GHG)	Zhou and Zhang (2021)
	WC	1958–2015	Annual	↑ (GHG)	Wang et al. (2018)
	WC (WBGT)	1961–2010	Summer	↑1.178°C (ANT)	Li et al. (2020a)
	EC (WBGT)	1961–2010	Summer	↑0.708°C (ANT)	Li et al. (2020a)
Precipitation trend	Whole of China (trend in extreme)	1961–1990	Annual	↑ (GHG); ↓ (AA); hard to separate from NAT	Dong et al. (2022)
	Whole of China	1961–2012	Summer	↑ (GHG)	Lu et al. (2020a)
	SEC	1961–2014	Summer	↑ (GHG); ↓ (AA)	Guo et al. (2023)
	NWC	1961–2014	Summer	↑ (AA)	Guo et al. (2023)
	NEC	1961–2014	Summer	↓ (ANT)	Guo et al. (2023)
	SWC	1961–2014	Summer	↓ (AA)	Guo et al. (2023)
	NSTP	1961–2013	Summer	↑ (ANT)	Zhao et al. (2022)
	STP	1961–2013	Summer	↓ (ANT)	Zhao et al. (2022)
	NC	1994–2011	Summer	↑ (GHG); ↓ (AA)	Zhang et al. (2020a)
	SC	1994–2011	Summer	↑ (GHG)	Zhang et al. (2020a)
	SWC	1993–2007	Autumn	↓ (AA)	Huo et al. (2021)
	EC	1956–2003	Annual	↑ (GHG); ↓ (AA)	Ma et al. (2017b)
	TCZ	1951–2005	Late summer	↓ (AA)	Zhao et al. (2021)
	SC/Shenzhen (rural)	1979–2020	Annual	↑ (urbanization)	Zhang et al. (2020d)
	CP-SFND	1961–2013	Annual	↑ (ANT)	Zhou et al. (2021a)
Drought trend	Whole of China (flash drought)	1959–2005	Annual	↑77 ± 26% (GHG)	Yuan et al. (2019)
	NC/YRB	1960–2010	Annual	↑ (reservoir operation)	Omer et al. (2020)
	SEPTP	1959–2015	Autumn	↑ (anthropogenic warming)	Ma et al. (2017a)
	WC/YlRB	1961–2017	Annual	↑ (reservoir impoundment)	Liang et al. (2021)
	NC	1961–1015	Autumn	↑ (anthropogenic warming)	Zhang et al. (2022e)
	SC	1961–1015	Autumn	↑ (rainfall change by anthropogenic factors)	Zhang et al. (2022e)
	NC/BTH (VPD)	1951–2017	Annual	↑ ⩾ 30% (urbanization)	Wang et al. (2022a)
	EC/YRD (VPD)	1951–2017	Annual	↑ ⩾ 30% (urbanization)	Wang et al. (2022a)
	SC/PRD (VPD)	1951–2017	Annual	↑ ⩾ 30% (urbanization)	Wang et al. (2022a)
	WC/SCB (VPD)	1951–2017	Annual	↑ ⩾ 30% (urbanization)	Wang et al. (2022a)
SWS	Whole of China	1981–2021	Annual	↓ (GHG; LUCC)	Zha et al. (2021)
	EC	1991–2015	Annual	↓ (LUCC)	Li et al. (2018c)
	NWC	1980–2012	Annual	↓ (ANT)	Zheng et al. (2018)
	NC/BTH	1980–2018	Annual	↓ 0.37 m s^{-1} yr^{-1} (urbanization)	Wang et al. (2020a)
CE	SWC	1967–2010	Summer	↑ (ANT)	Wu et al. (2022)
	NEC	1951–2014	Summer	↑ (ANT; GHG)	Li et al. (2022b)
	EC	1961–2018	Summer	↑ (GHG); ↓ (urbanization)	Yu and Zhai (2020)
	EC	1965–2014	Summer	↑ (GHG)	Wang e al. (2022b)

et al., 2018) and the frequency of July 2017–like HWs in central eastern China become approximately 1 in 5 years under current climate conditions (Chen et al., 2019b). Due to the combined influences of anthropogenically forced warming (~78%) and urbanization (~17%), July and August 2018–like HW events in Northeast China have become a one-in-60-year event in urban regions and a one-in-80-year event in rural regions (Zhou et al., 2020). Simultaneously, anthropogenic warming has made 30-day persistent nighttime HWs like the event of summer 2018 in Northeast China become about a one-in-60-year event (compared to about a one-in-a-500-year event naturally) (Ren et al., 2020). Moreover, anthropogenic forcing has also contributed to extreme warm events in spring, such as the 2018 event that occurred over eastern China, and has increased the chance of this event occurring by tenfold (Lu et al., 2020b). Aside from GHG-induced warming, urbanization, the effects of energy consumption (i.e., AHR) and urban development have also

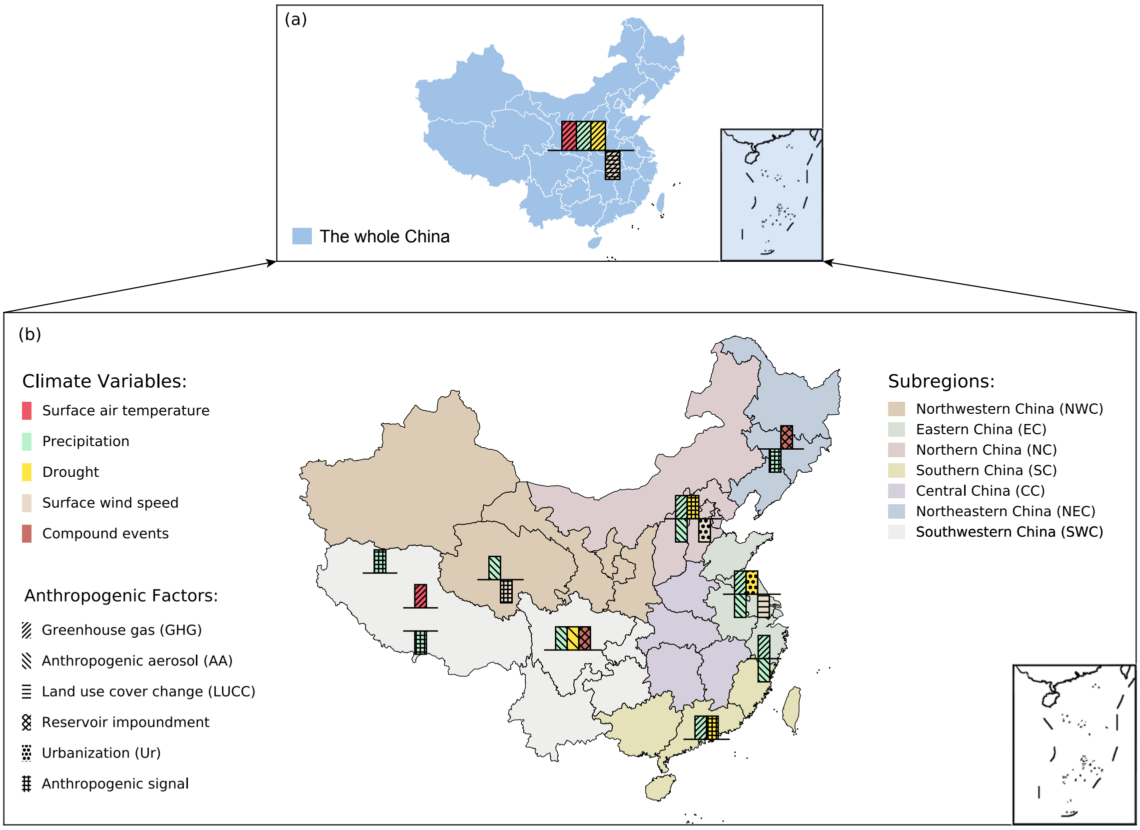

Fig. 2. The dominant anthropogenic factors influencing the trend of regional climate changes (including a few climatic parameters) over (a) the whole of China and (b) in a few subregions of China based on study results obtained from references published since 2018. The upward/downward histograms indicate uptrends/downtrends. For the quantitative contributions and further detailed information, please see Table 1. Panel (a) highlights the influences of different anthropogenic factors [legend provided in the lower-left corner of panel (b)] on different climate variables [legend provided in the upper-left corner of panel (b)] over the whole of China (i.e., the nationwide scale). Panel (b) highlights the influences of different anthropogenic factors [legend in the lower-left of panel (b)] on different climate variables [legend in the upper-left of panel (b)] over the subregions [legend in the upper-right of panel (b)].

contributed to hot extremes over China (Chen and Dong, 2019; Sun et al., 2019; Yang et al., 2019, 2021; Liu et al., 2021; Wang et al., 2021a). Urbanization has contributed about 30%–40% of the nighttime high temperature extremes since 1960 over eastern China (Sun et al., 2019). AHR can drastically aggravate urban heat stress (Yang et al., 2021), and has contributed an annual increase of 0.02–0.19 days of extreme heat events in Beijing city center (Liu et al., 2021). It was revealed that urban development increased the total thermal discomfort hours by 27% in the urban areas of the Yangtze River Delta during the period 2009–2013, with AHR and urban land use contributing nearly equal amounts (Yang et al., 2019). The mean contributions of urbanization to the maximum daily maximum temperature, high-temperature days, and hot-night days were 68%, 45% and 27%, respectively, in Beijing, Tianjin and Shijiazhuang (Wang et al., 2021c).

Simultaneously, anthropogenic forcing has significantly decreased regional extreme low-temperature events over China (Table 2). Although the reduced trend of cold events in southeastern China cannot be attributed with high confidence to any anthropogenic signal alone (Freychet et al., 2021), human influence can clearly be detected in the changes in cold spell durations (Lu et al., 2018), icy days, and frosty nights at the whole-China scale (Wang et al., 2018b; Yin and Sun, 2018). Due to anthropogenic-induced warming, the likelihoods of 2019-like early spring cold events occurring over the southeastern TP (Duan et al., 2021) and of April 2020–like cold events occurring over Northeast China (Yu et al., 2022) have reduced by about 80%. For the record-breaking three-day cold events since 1961 that occurred in January 2021 across eastern China, human activities have reduced the likelihood of such events by about 50% (Liu et al., 2020). Moreover, anthropogenically induced warming also partly contributed to the rapid switches between warm and cold extremes in winter (volatile winters) in China, leading to increased volatile winters in Northeast, Northwest, Southwest, Southeast China, and the Yangtze River Valley after 1980 (Chen et al., 2019c).

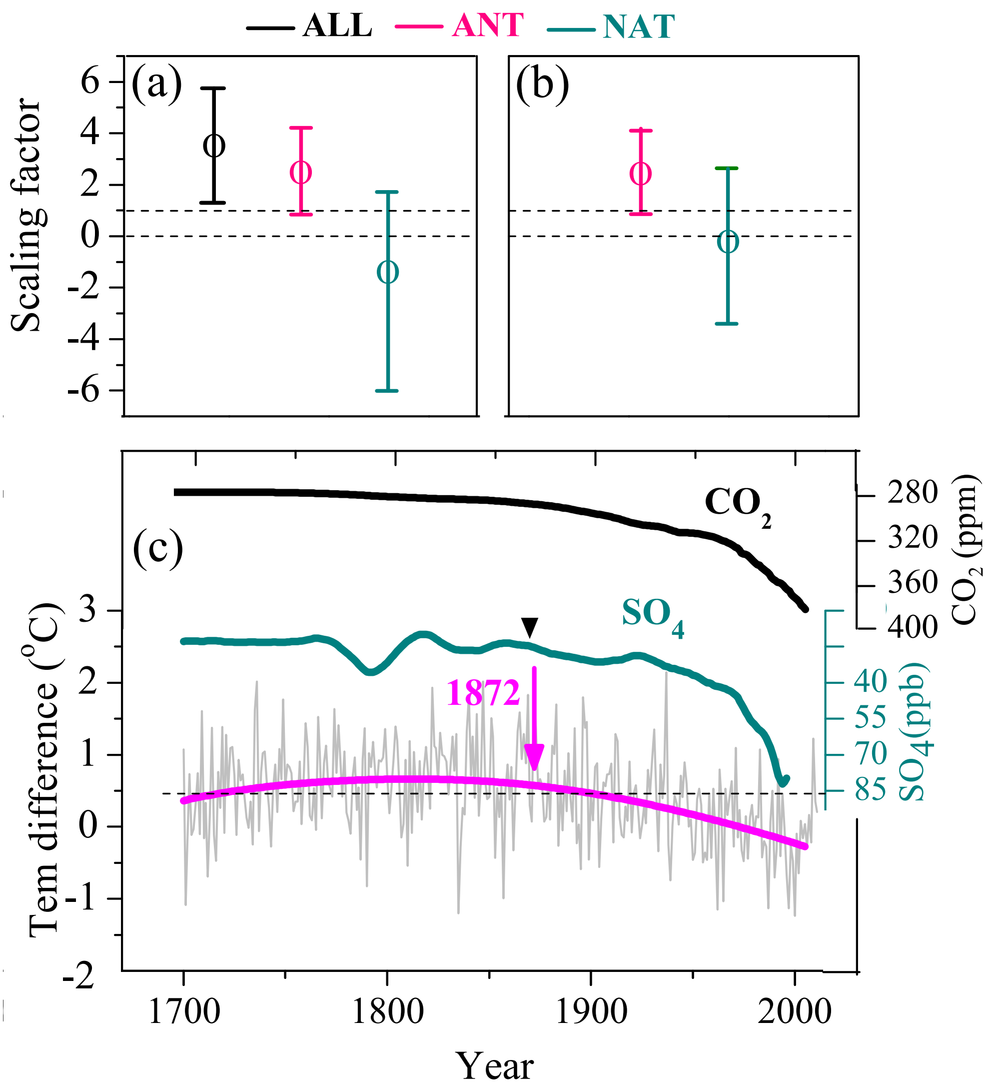

Fig. 3. The (a, b) detectable anthropogenic signal and (c) natural evidence for the influence of anthropogenic forcing on temperature seasonality in the TP region since the 1870s. ALL, ANT and NAT mean all forcing, anthropogenic forcing and natural forcing, respectively. Panels (a) and (b) are the scaling factors and corresponding 90% confidence intervals derived from one-signal and two-signal detection and attribution analysis, respectively. The data used in (a, b) are derived from Fig. 4 of Duan et al. (2019). "Tem difference" (grey line) in (c) means the summer minus winter temperature difference, and the pink line is its 50-year Gaussian smoothing. CO_2 (thick black line) and sulfate (dark cyan) concentrations are increasing downwards. The black triangle and the pink arrow in (c) indicate the corresponding turning points. The data used in (c) are derived from Fig. 2 of Duan et al. (2019).

4. Anthropogenic influences on regional precipitation and droughts over China

4.1. *Anthropogenic influences on precipitation trends over China*

The signal of anthropogenic forcing of precipitation over China might be region-, season-, period- or intensity-dependent. The anthropogenic signal can be detected in the observed changes in summer precipitation over China and in heavy precipitation over eastern China/the whole of China in recent decades, while external forcings cannot be detected for moderate or light precipitation individually (Lu et al., 2020a) (Fig. 2, Table 1). Anthropogenic signals also cannot be detected in the trends of either the annual mean or the annual extreme precipitation over China from 1961 to 2010 (Li et al., 2021c). Moreover, it is difficult to separate the contributions of anthropogenic and natural forcings of annual extreme precipitation in northern and southern China in the period 1961–2020 and decompose the anthropogenic component into specific components (e.g., GHG) driving changes in Chinese precipitation (Dong et al., 2022). Regionally, an anthropogenic signal was detected in the changes in

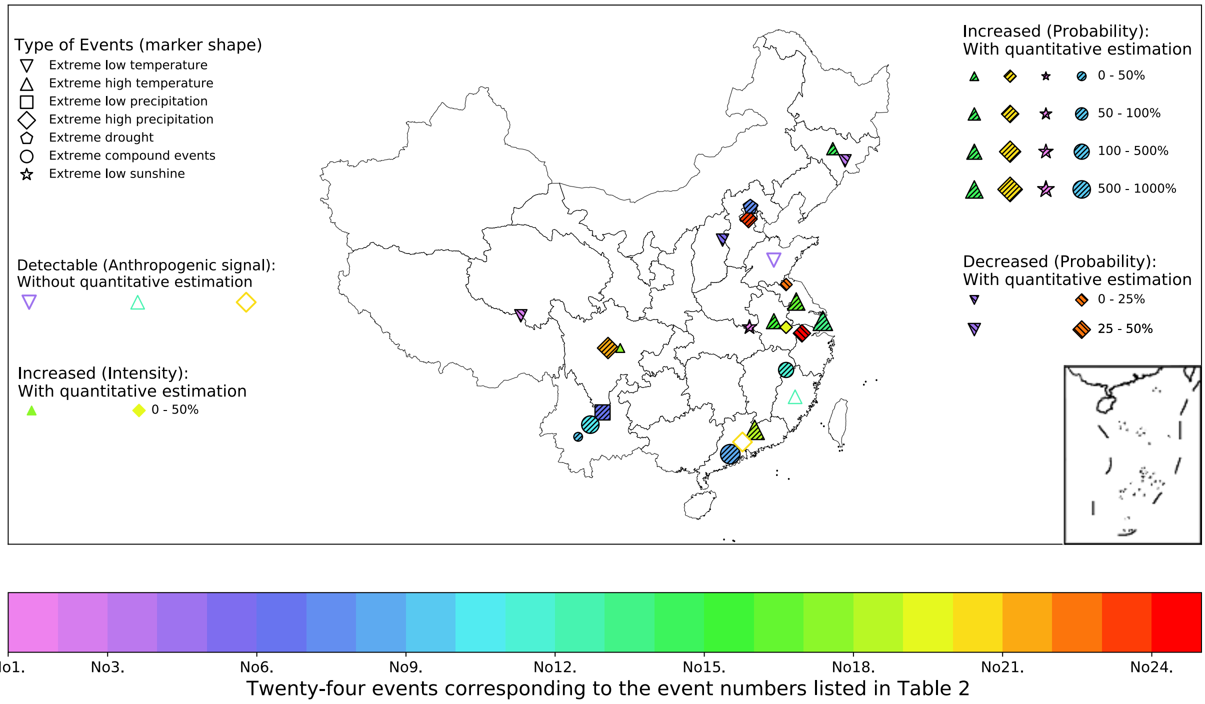

Fig. 4. Anthropogenic forcing–induced changes in the occurrence likelihoods of record-breaking climate/weather events that occurred in China in recent years from study results published since 2018. The marker shape in the top-left denotes the type of event, and the open markers in the middle-left indicate detectable anthropogenic signals without quantitative estimations. The solid markers in the bottom-left, upper-right and middle-right indicate detectable anthropogenic signals with quantitative estimations of increased intensity, increased probability, and decreased probability, respectively. The different colors denote the different events listed in Table 2. The color bar shows 24 events corresponding to the event numbers listed in Table 2.

summer precipitation trends over the northern TP, while the change over the southern TP was controlled mainly by internal variability (Zhao et al., 2022). GHGs were identified as the critical factor affecting the increased precipitation frequencies over southern and northeastern China, while AA contributed to the decreased precipitation frequency over northern China (Zhang et al., 2020a). AA also contributed significantly to the decreasing autumn precipitation trends over Southwest China from 1961 to 2007 and over Southeast China in 2020 (Huo et al., 2021; Tan et al., 2022), as well as the reduction in decadal changes in summer rainfall over the northern IndoChina Peninsula since the mid-1990s (Luo et al., 2019). Moreover, anthropogenic forcing has altered the occurrences of daily circulation patterns governing precipitation over eastern China and contributed to shaping the contrasting north– south precipitation trends (Zhou et al., 2021a).

4.2. *Anthropogenic influences on precipitation extremes over China*

In addition to the effects of anthropogenic forcing on the trend and spatial patterns of precipitation over China, human activity has also affected precipitation extremes over China (Zhai et al., 2018, Duan et al., 2022; Sun et al., 2022). GHG forcing plays an important role in affecting the upward trend of intensified precipitation extremes over China, and AA forcing partly offsets the GHG effect (Xu et al., 2022). In Southeast and Northwest China, GHG and AA forcings have contributed to the increase in summer extreme precipitation through different processes (Guo et al., 2023). Moreover, anthropogenic forcing positively influenced the temporal inequality of precipitation extremes over China, especially in southern China, during the period 1961–2005 (Duan et al., 2022). Anthropogenic forcing has already decreased the occurrence probability of snowfall relative to natural forcing in some parts of China in recent decades (Chen et al., 2020). At relatively small spatial scales, anthropogenic forcing has likely played a role in increasing the risk of extreme rainfall north of the Yangtze by a factor of 1.64 (Li et al., 2018a) and caused a greater variance in precipitation extremes in the period 1986–2012 than 1960–1985 in the provinces of Zhejiang and Guangdong (Gao et al., 2018, Liu et al., 2020). When the relative humidity (RH) is less than 80% or greater than 85%, increased AA emissions tend to inhibit or enhance precipitation in the middle reaches of the Yangtze River (Bai et al., 2020). However, when RH is between 80% and 85%, AA has little influence on the change in precipitation. A record-breaking (since 1961) heavy rainstorm occurred in Beijing on 19–20 July 2016 (Luo et al., 2020). Although the pattern of synoptic systems (western Pacific subtropical high and cold vortex) has been identified as the key cause of this event, AA also influenced mixed-phase microphysical processes contributing to the heavy rainstorm (Guo et al., 2019). AA also tends to delay and prolong the period with the highest frequency of precipitation start times in the northern China Plain,

Table 2. Quantitative contributions of anthropogenic forcings to regional record-breaking climate/weather events over China obtained from references published since 2018. See Table 3 for abbreviation definitions.

Number	Extreme event(s)	Region (site)	Duration	Quantitative contribution (forcing factor)	Reference
1	extreme low sunshine	YRD	Jan–Feb 2019	↑ 3.1 times; ↑ 1.3 times (probability) (AA; GHG)	He et al. (2021)
2	extreme low temperature	TP	Feb–Mar 2019	↓ 80% (probability) (human activity)	Duan et al. (2021)
3	extreme low temperature	NEC	19–25 Apr 2022	↓ 80% (probability) (human activity)	Yu et al. (2022)
4	extreme low temperature	NC	21–25 Jan 2016	↓ 89% (probability) (human activity)	Sun et al. (2018)
5	extreme low temperature	EC	6–8 Jan 2021	detectable (human activity)	Liu et al. (2022)
6	extreme low precipitation	SWC	Apr–Jun 2019	↑ ~6 times (probability) (human activity)	Lu et al. (2021)
7	extreme drought	NC/Beijing	Winter 2017	↑ 1.29 times (probability) (human activity)	Du et al. (2020)
8	extreme compound events	SC	Apr–May 2018	↑ 17 times (probability) (human activity)	Zhang et al. (2020b)
9	extreme compound events	SWC/Yunnan	Spring–early summer 2019	↑ 43% (probability) (human activity)	Wang et al. (2021b)
10	extreme compound events	SWC	May–Jun 2019	↑ 7.21 times (probability) (anthropogenic warming)	Du et al. (2021)
11	extreme compound events (wet–dry)	SC	Summer 2020	↑ 3.51 times (probability) (anthropogenic warming)	Du et al. (2022)
12	extreme high temperature (warming winter)	NC/SEC	Winter 2016	↓ detectable (water vapor / aerosols)	Zhang et al. (2022b)
13	extreme high temperature	EC/Shanghai	Jul 2017	↑ ⩾10 times (probability) (anthropogenic warming)	Chen et al. (2019b)
14	extreme high temperature	NEC	Jul–Aug 2018	↑ 78% (probability) (anthropogenic)	Zhou et al. (2020)
15	extreme high temperature	CEC	21–25 Jul 2017	↑ 4.8 times (probability) (human activity)	Sparrow et al. (2018)
16	extreme high temperature	EC	Spring 2018	↑ 10 times (probability) (human activity)	Lu et al. (2020b)
17	extreme high temperature	WC	Summer 2015	↑ 42% (intensity) (GHG)	Chen and Dong (2018)
18	extreme high temperature	SC	Sep 2021	↑ 50 times (probability) (anthropogenic warming)	Wang and Sun (2022)
19	extreme high precipitation	EC/Yangtze River	Dec 2018–Feb 2019	↓ 19% (intensity) (anthropogenic warming)	Hu et al. (2021)
20	extreme high precipitation	SC/Guangdong	14–16 Dec 2013	↑ detectable (AA)	Liu et al. (2021)
21	extreme high precipitation	SWC/Sichuan	11–20 Aug 2020	↑ 2 times (probability) (human activity)	Qian et al. (2022)
22	extreme high precipitation	EC	Summer 2020	↓ 46% (probability) (human activity)	Zhou et al. (2021b)
23	extreme high precipitation	NC/Beijing	Winter 2020	↑ 52.9% (probability) (human activity)	Pei et al. (2022)
24	extreme high precipitation	YRB	June, July 2020	↓ 54% (probability) (human activity)	Lu et al. (2022)

Yangtze River Delta, and Pearl River Delta regions (Sun and Zhao, 2021). AA also influenced the warm rain and mixed-phase microphysical processes contributing to the heavy rainstorm that occurred in Beijing on 19–20 July 2016 (Guo et al., 2019).

Anthropogenic signals have also been detected in regional precipitation over China in many case-based quantitative detection and attribution studies (Fig. 4, Table 2). Anthropogenic forcing has increased the likelihood of April to June 2019–like precipitation deficit events in southwestern China by 10% by increasing the probability of anomalous high pressure in southwestern China (Lu et al., 2021). However, anthropogenic forcing reduced the likelihood of March to July 2019–like heavy precipitation events in southern China by about 60% (Li et al., 2021b) and reduced the likelihood of the rainfall amount in the extended rainy winter of 2018/19 over the middle and lower reaches of the Yangtze River of China by ~19% (Hu et al., 2021). Anthropogenic forcing has reduced the probability of summer persistent heavy rainfall in central western China similar to 2018 by ~47% but increased that of daily rainfall extremes by ~1.5 times (Zhang et al., 2020c). An anthropogenic signal is detectable in the more water vapor pattern (increase by ~100%) that contributed to the high precipitation event that

Table 3. Abbreviations used in Tables 1 and 2.

Abbreviation	Full name	Abbreviation	Full name
BTH	Beijing–Tianjin–Hebei	SEC	Southeastern China
CE	Compound Events	SEPTP	Southeastern Periphery of the Tibetan Plateau
CP/SFND	circulation patterns /southern flood–northern drought	STP	Southern Tibetan Plateau
EC	Eastern China	SWC	Southwestern China
NC	Northern China	TCZ	transitional climate zone
NEC	Northeastern China	TP	Tibetan Plateau
N/STP	North/South Tibetan Plateau	VPD	Vapor Deficit
NWC	Northwestern China	WBGT	Wet Bulb Globe Temperature Index
PRD	Pearl River Delta	WC	Western China
SAT	Surface Air Temperature	YlRB	Yalong River Basin
SC	Southern China	YeRB	Yellow River Basin
SCB	Sichuan Basin	YRD	Yangtze river delta

occurred in North China in February 2020 (Pei et al., 2022), and in the intensified daily and subdaily precipitation extremes observed in eastern China since 1970 (Chen et al., 2021). Anthropogenically forced climate change doubled the occurrence probability of 11 to 20 August 2020–like record-breaking persistent heavy rainfall events in southwestern China (Qian et al., 2022). Moreover, extensive urbanization exerted thermal and dynamic influences on precipitation in China, decreasing the total precipitation over and downwind of Beijing city by 11% in summer during 2005–2012 (Wang et al., 2018a) and significantly increasing the hourly precipitation intensity over the Pearl River Delta during 1994–2016 compared to that during 1971–1993 (Wu et al., 2019). The enhanced local AHR combined with global warming (Wen et al., 2020) led to an ~20% to more than 100% increase in the probability of hourly precipitation with a magnitude of 20–100 mm h^{-1} occurring over urban locations in China (Fung et al., 2021). Additionally, another study indicated that the anthropogenic influence cannot be significantly detected over China in the observational record or simulations from 1961 to 2012 based on field significance tests (Li et al., 2018b). The above evidence from references published since 2018 indicates that the anthropogenic signal in regional precipitation over China is obscure compared to the signal in the regional SAT, and can be region-, season-, period-, intensity- or model-dependent; the influencing mechanisms are also highly complex.

4.3. *Anthropogenic influences on monsoon-related precipitation over China*

In addition to the direct influence of human activity on regional precipitation over China, anthropogenic forcing also affects Chinese precipitation indirectly by influencing monsoons. Model simulations have indicated that anthropogenic forcing, especially AA, played a dominant role in the weakened monsoon circulation and the observed decrease in interdecadal precipitation over the South China Sea in the late 20th century (Lin et al., 2020). AA-induced tropospheric cooling over Asian land regions led to anomalous descending motion between 20° and 40°N and reduced the land–sea thermal contrast, resulting in weakened East Asian summer monsoon (EASM) precipitation over eastern China observed in recent decades (Wang et al., 2019; Zhao et al., 2021). AA forcing significantly exacerbated the weakening of the EASM (Wang et al., 2020b), and the aerosol-induced fast atmospheric response dominated the weakening of the EASM and the decreased precipitation over eastern China (Mu and Wang, 2021). In contrast, GHG forcing led to a wetting trend in the transitional climate zone by inducing southerly wind anomalies, thereby offsetting the effect of AA forcing (Zhao et al., 2021). Black carbon aerosol emissions from different sectors resulted in a regional warming effect over China, leading to an enhanced summer monsoon circulation and a subsequent decrease/increase in rainfall over northeastern/southern China (Zhuang et al., 2019).

4.4. *Anthropogenic effects on regional droughts over China*

Due to the effects of anthropogenic forcing on SAT and precipitation over China, anthropogenic activities have also contributed to drought events, including meteorological and hydrological droughts, over China (Fig. 4, Tables 1 and 2). The effects of human activity on droughts over China are mainly in the form of GHG-induced warming, increased AA emissions, urbanization, and human water use (Ma et al., 2019; Jiao et al., 2020; Huang et al., 2022). Anthropogenic warming was found to be conducive to the robust increases in the dry and warm meteorological conditions of the autumn drought event over the southeastern periphery of the TP in 2009 (Ma et al., 2017a) and severe droughts in Northwestern China (Ma et al., 2019). Anthropogenic climate change has increased the probability of the 2020 extreme SPEI (Standardized Precipitation Evapotranspiration Index) occurring over the southern coastal regions of China by 3.51 times and explained 71.5% of the attributable risk (Du et al., 2021). Increased GHGs accounted for 77% ± 26% of the upward trend in the flash drought frequency from 1961 to 2005 over China (Yuan et al., 2019). Furthermore, anthropogenic forcing–triggered droughts have increased the fire risk over China. For example, anthropogenic warming has increased the likelihood of the extreme FWI (fire weather index) over Southwest China in 2019 by 7.21 times (Du et al., 2021).

Although AA has caused humidification over many parts of the globe, a notable aridification effect resulting from AA has occurred over a large part of China (Zhang et al., 2018). Moreover, urbanization has intensified droughts over China. An estimation showed that urbanization has contributed more than 30% to the total increase in atmospheric aridity in Chinese urban core areas (Wang et al., 2022a). However, in the Yangtze River Basin (YaRB), urbanization seems to have alleviated extreme drought conditions (1.14%) while increasing the drought duration and severity (9.02%) (Huang et al., 2022; Wang et al., 2022a). On the other hand, human activities, mainly referring to water management, industrial water usage and reservoir regulation, have exerted a substantial effect on hydrological drought over China (Jiao et al., 2020), but the effects of human activities vary with location. Due to the large amount of irrigation water and high evapotranspiration, human activities have induced a change from a positive correlation to a negative correlation between meteorological and hydrological droughts in the midstream region of the Heihe River basin, especially during the warm and irrigation seasons (Ma et al., 2019). In the YaRB and the Yellow River Basin (YeRB), human activities have exerted positive and negative effects on the spatiotemporal characteristics of hydrological droughts, respectively (Jiao et al., 2020; Omer et al., 2020). Specifically, reservoir operations decreased the multiyear monthly discharge but increased the low flow in severe drought years in the middle and lower sub-basins of the YaRB (Jiao et al., 2020). Similarly, in the YeRB, agricultural practices and afforestation intensified soil-moisture drought, while grassland restoration had a positive impact on the agricultural drought severity (Omer et al., 2020). In the Yalong River basin (YlRB), anthropogenic disturbances, mainly referring to the construction of large reservoirs, have led to a dramatic decrease in RH in the past decade, far beyond its previous periodic amplitude range (Liang et al., 2021).

5. Influences of anthropogenic forcing on compound extreme weather/climate events over China

Anthropogenic forcing has contributed to compound extreme events, especially compound dry and hot events (CDHEs) and compound daytime and nighttime HWs over China (Fig. 4, Tables 1, 2). Over most regions of China, especially southwestern and northeastern China, anthropogenic forcings, mainly GHG emissions, have increased the likelihood or severity of CDHEs in recent decades (Li et al., Li et al., 2020b, 2022b; Wu et al., 2022). GHG-induced warming increased the likelihood of the CDHEs that occurred in spring to early summer 2019 in Yunnan Province by about 140% (123%–157%) (Wang et al., 2021b). GHG forcing has also produced prominent impacts in terms of an increased frequency, intensity and spatial extent of compound daytime and nighttime HWs over China, while AA forcing has influenced HWs mainly during the daytime (Wang et al., 2022b; Wang et al., 2018b; Su and Dong, 2019). In addition, urbanization has played an important role in compound maximum daily maximum temperature and minimum daily minimum temperature events in a few regions of China, with contributions ranging from 11% to 41% and 14% to 29%, respectively (Yang et al., 2022). Urban compound daytime and nighttime hot extremes across eastern China increased by 1.76 d (10 yr)$^{-1}$ from 1961 to 2014, and the attributable fractions were estimated as 0.51 (urbanization), 1.63 (GHGs) and 0.54 (other anthropogenic forcings) d (10 yr)$^{-1}$ (Wang et al., 2021a). Urbanization has also moderated the changes in CDHEs in eastern China (Yu and Zhai, 2020; Yang et al., 2022).

6. Influence of human activities on SWS over China

In addition to affecting the SAT, precipitation and drought, human activities have also resulted in changes in SWS over China (Fig. 2, Table 1). Some studies have demonstrated that human activity has been an important factor contributing to regional near-surface wind speed declines over China in recent decades (Bian et al., 2018; Li et al., 2018c; Ao et al., 2020; Wang et al., 2020a, Zhang et al., 2021). The mechanisms by which human activities contribute to the decline in SWS over China may include the following: (1) the high-latitude rapid warming in recent decades weakened the annual and seasonal meridional air temperature gradients and then resulted in slowed SWSs in northern China (Zhang et al., 2021); (2) LUCC led to an increased surface roughness, contributing to a reduction in near-surface wind speeds over China (Zha et al., 2021), especially in urban areas. Related to anthropogenically induced warming, the SWS showed a significant declining trend of −0.103 m s^{-1} (10 yr)$^{-1}$ annually, and showed similar seasonal changes in the central and eastern parts of northern China, from 1961 to 2016 (Zhang et al., 2021). In Northwest China, human activities also contributed to the annual and seasonal (except winter) SWS decreases observed during 1980–2012 (Zheng et al., 2018). Urbanization contributed to an annual SWS decline of approximately −0.37 m s^{-1}, with the largest declines exceeding −1.0 m s^{-1} in some highly urbanized areas in the Beijing–Tianjin–Hebei region over the period 1980–2018 (Wang et al., 2020a). Urbanization induced an annual SWS decline of −0.13 m s^{-1} (10 yr)$^{-1}$ during the period 1972–2012 at Shijiazhuang Station, contributing 86.0% of the total SWS decline at the station (Bian et al., 2018). Additionally, urbanization has contributed approximately 73.3% to the annual and seasonal SWS declines observed in Liaoning Province over the past 40 years (Ao et al., 2020).

7. Summary and future research

Based on the evidence obtained from studies published since 2018, some achievements are summarized as follows. Human activities, including GHG and AA emissions, urbanization, LUCC, and AHR, have contributed significantly to the SAT trend and extreme changes over China, and the anthropogenic signal can be tracked back to the 1870s in the TP region. The anthropogenic signal affecting precipitation over China is relatively obscure and can be dependent on the period, season, event intensity, spatial scope, or even model simulation. Anthropogenic forcing has also weakened monsoon precipitation, triggered regional droughts, and contributed to the decline in SWS over China. Moreover, anthropogenic forcing, especially GHG-induced warming, has intensified regional compound extreme climate/weather events (e.g., compound dry and hot events and compound daytime and nighttime HWs) over China in recent decades.

While the achievements mentioned above constitute great advancements, further studies have also covered the following points that, whilst challenging, should be considered in future research:

(1) In addition to the significant contribution of anthropogenic forcing to regional climate changes over China, decadal- and multidecadal-scale climate fluctuations may also contribute to those changes simultaneously. Quantitatively attributing regional climate changes to anthropogenic forcing and decadal or multidecadal climate fluctuations is still challenging because sometimes superimposed or counteracting effects occur between these factors.

(2) Many attribution studies have provided quantitative, confirming, and distinct evidence that anthropogenic forcing has influenced the regional climate over China in recent decades, while evidence for earlier periods is relatively rare due to the limited length of observational records. In view of the multitude of climate proxy data available over the TP and eastern China, such as tree rings, ice cores, and historical documents, the detection and attribution of anthropogenic signals based on the combined use of observations, climate proxy data and model simulations could provide further understanding or confirmational evidence regarding the influences of human activity on regional climate changes over China.

(3) To achieve the target of carbon neutrality, clean energy (e.g., hydropower) might be utilized more widely in the future, and this would induce very strong local human activities (e.g., to develop hydropower by building large reservoirs). Specifically, large dams (e.g., the Three Gorges Dam) have significantly influenced the regional climate (e.g., SAT, precipitation and moisture) and atmospheric circulation (Li et al., 2019; 2021a, 2021d, Chen et al., 2022). Apart from hydropower, solar energy is also a promising application (Yang et al., 2018). Solar energy exerts a significant influence, especially through changes in LUCC, on local climate (e.g., surface temperature and albedo) (Hua et al., 2022; Xia et al., 2022; Yang et al., 2022). Such strong local human activity certainly induces a great effect on the regional climate. Assessing and quantifying the influence of human activities on regional climate conditions is a popular and challenging scientific issue.

(4) Compared to general extreme climate/weather events, studies on the influence of human activity on compound extreme climate/weather events are still scarce. China, with the largest population worldwide, is highly vulnerable to meteorological disasters under climate change (IPCC AR6). In view of the great effect of compound extreme climate/weather events on human health/life and crops/plants (Wang et al., 2021a; Zhang et al., 2022c), further studies on the effects of human activity in terms of compound extreme climate/weather events might be a key scientific issue in the future.

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