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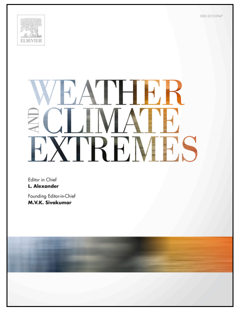

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Impact of urbanization on regional extreme precipitation trends observed at China national station network

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Abstract

An enhanced extreme precipitation (EXP) in or near cities compared to rural areas has been widely observed and verified in individual urban sites. However, at a sufficiently large region, the robustness of evidence for the urbanization contribution to the estimate of EXP trends is still lack. Here, we present clear evidence from observational records of a dense national station network that a significant urbanization-induced increase in annual EXP changes across mainland China (p<0.01), which is detectable through urban–rural comparative analysis. This urbanization effect accounts for approximately one-third of the observed EXP trends from 1960 to 2018. The results also indicate that urbanization significantly influences the frequency of EXP change. The positive effect is especially noticeable in the humid climate zones of the southeastern China monsoon region, except coastal zones. Our analysis shows that the observed increase in regional EXP is more complex, and the observational data bias related to urbanization has to be considered in the large-scale detection and attribution of extreme precipitation changes.

Keywords: urbanization; extreme precipitation; observational dataset; long-term trend; mainland China;

MAIN TEXT

1. Introduction

Extreme weather has a devastating effect on the urban environment and society, thereby seriously threatening human safety as more than half of the global population lives in urban areas. Based on observations and modelling approaches, studies have investigated the climatology (Yan et al. 2020; Zhang et al. 2019a) and cases (Luo et al. 2023; Yang et al. 2019) of urban heavy precipitation or extreme precipitation events in selected cities or urban agglomerations. The Intergovernmental Panel on Climate Change (IPCC) indicated that urbanization intensifies precipitation extremes, especially in the afternoon and early evening, over the urban area and its downwind region (*medium confidence*) in the Synthesis Report for the Sixth Assessment Report (IPCC 2021).

There are three hypotheses (Changnon et al. 1981; Han et al. 2014; Huff and Changnon 1973; Liu and Niyogi 2019; Oke et al. 2017; Qian et al. 2022; Shepherd 2005; Zhang 2020) regarding the influence of urbanization on extreme precipitation events: *i*) Modification of moisture and thermodynamic processes: urban-induced heating not only enhances atmospheric instability by increasing the depth of the urban planetary boundary layer but also leads to perturbations in the wind field arising from thermally induced gravity waves that, in turn, result in a zone of upwards motion downstream of urban areas. The subsequent increase in atmospheric humidity is caused by horizontal convergence. *ii*) Modification of microphysical processes: urban aerosols increase condensation but reduce solar energy that reaches the ground. The effect of aerosols on precipitation processes depends on their size and concentration. *iii*) Modification of dynamical processes: the “blocking” effect of urban structures could impede atmospheric movement and change the current direction. Moreover, the roughness of surfaces can also enhance airflow convergence over and downwind of cities. However, particular combinations of synoptic weather conditions (Li et al. 2021; Wang et al. 2021), topography (Freitag et al. 2018; Yang et al. 2019) and aerosol characteristics (Guo et al. 2016) lead to different urban precipitation outcomes (Zhang 2020). The enlarged atmospheric water holding capacity could result in stronger precipitation in urban areas, when the conditions for large-scale moisture transport and moisture convergence are met.

Urban areas have experienced dramatic expansion in mainland China during the past several decades. Yang et al. (2017) showed a strong association between the urbanization process and short-term intense precipitation events in Beijing urban areas, based on hourly precipitation dataset of high-density weather station network. Studies have also revealed that urbanization over three urban agglomerations, including the Pearl River Delta (Su et al. 2019; Wu et al. 2019; Yan et al. 2020; Zhang et al. 2019a), Yangtze River Delta (Jiang et al. 2020; Liang and Ding 2017; Lu et al. 2019; Yu et al. 2022), and Beijing-Tianjin-Hebei region (Fu et al. 2019; Zhang et al. 2019b), has amplified the changes in the days and intensity of EXP for the past few decades. Yu et al. (2022) proposed that approximately 26% of the increasing heavy precipitation (>90th percentile) could be attributed to urbanization over the Yangtze River Delta region. Lin et al (2020) demonstrated a significant urbanization effect on the trend of EXP events in 20 major urban agglomerations across mainland China. In particular, the urbanization effect and its contribution to the annual EXP ratio change reach 1.21/decade and 63.9%, respectively. The method of urban-rural comparison is utilized in the climatological statistical analysis involved in the urbanization effect on precipitation and its change.

Previous studies have attempted to detect and attribute changes in precipitation extreme in observations. They revealed that greenhouse gas concentration-induced anthropogenic climate change may have increased precipitation extremes at subcontinental-continental (Dong et al. 2020; Kirchmeier-Young and Zhang 2020), and hemispheric and global scales (Min et al. 2011; Westra et al. 2013; Zhang et al. 2013). In addition, at the city level, studies have also shown that rapid urbanization has affected the observed EXP trend around the globe (Kishtawal et al. 2010; Li et al. 2020; Liang and Ding 2017; Marelle et al. 2020; Rahimpour Golroudbary et al. 2017; Wu et al. 2019). Obviously, the local anthropogenic effect from urbanization is quite different from the possible influence of the human-induced increase in atmospheric CO_2 concentration on large-scale extreme precipitation change, and the former one has to be identified in the observations before any detection and attribution of global and regional climate change can be made.

The analyses of individual cases cannot rule out the influence of local and accidental factors, such as geographical location and the non-standard selection of reference stations used for detecting the urbanization effect. On the other hand, at the regional to subcontinental scales, a gap still exists in our understanding of the urbanization contribution to the estimates of long-term observed EXP trend at all stations in mainland China. A recent study by Singh et al. (2020) raised the concern that urbanization may have been one of the local influences related to regional changes in precipitation extremes across the contiguous United States, and these types of studies have been performed in Europe (Trusilova et al. 2008) and India (Shastri et al. 2015).

By using the method of target-reference comparison (see the Section **Methods**), a quantitative analysis is performed here on the contribution of urbanization to the estimated trends of EXP on a frequently applied dataset, which is from the observation network of all national stations in mainland China. Five EXP indices are examined, including the day, amount and intensity of the precipitation exceeding the 99th percentiles of all wet-day precipitation (abbreviated as DEXP, AEXP, and IEXP, respectively), the contribution of the AEXP to total precipitation (EXPTOT), and also the maximum 1-day precipitation (RX1D).

2. Methods

21. Data

The rain gauge-based daily precipitation and mean surface air temperature data (1960-2018) used are from the “China National Surface Meteorological Station Homogenization Precipitation Daily Dataset (V1.0)” and “China National Surface Meteorological Station Homogenization Temperature Daily Dataset (V1.0)", respectively. These datasets are provided by the National Meteorological Information Center, China Meteorological Administration (http://www.gov.cn/gzdt/2013-12/25/content_2554132.htm). It has certain integrity and reliability since it has undergone rigorous quality controls, including testing of climatological limit, internal consistency, and spatial consistency. The standard normal method was further used to detect and adjust the inhomogeneity of the precipitation time series, which is mainly caused by the relocation of stations and the replacement of observation instruments. As the highest spatial density observation network with 2419 national stations in mainland China (**Fig. 1a**), the datasets have been widely used in previous climatological and climate change studies (Xiong 2017; Ye et al. 2004; Yu et al. 2007).

2.2 Methods

i. Definition of EXP indices

In this study, the EXP is determined when the wet-day precipitation (>0.1mm/day) is higher than the 99th percentile of annual or warm seasonal wet-day precipitation during the study period (1960–2018). The definition follows the guidelines for climate change indices, which are established by the Expert Team on Climate Change Detection and Indices (ETCCDI) (https://etccdi.pacificclimate.org/list_27_indices.shtml). Based on the relative thresholds recommended by the ETCCDI, the extreme precipitation indices are defined as the precipitation greater than 99th and 95th percentile of wet-day precipitation, respectively. We find that urbanization effects estimated in this study are insensitive to the choice of the threshold, whether it is the 90th, 95th or 99th percentile of wet-day precipitation (see **Fig. 4**). The precipitation greater than 99th percentile represents a more intense extreme daily precipitation. Five types of EXP are defined as follows: DEXP, the count of EXP; AEXP, total precipitation amount of EXP; IEXP, the ratio of AEXP to DEXP; EXPTOT, the fraction of AEXP in total wet-day precipitation; and RX1D, the highest 1-day precipitation amount within a year or the warm season.

ii. Calculation methods

The annual and warm seasonal EXP are the average or sum of EXP indices during January to December and April to October, respectively. Specifically, taking the annual scale as an example, the annual DEXP/AEXP is calculated as the total DEXP/AEXP during the corresponding time scale; the annual IEXP is the ratio of the annual DEXP to AEXP; the annual EXPTOT is the ratio of the annual AEXP to the total wet-day precipitation; and the annual RX1D is the maximum 1-day precipitation in a year or warm season. In addition, all calculations of the EXP time series are based on their standardized anomalies. The standardized anomaly is defined as the ratio of the EXP anomaly to the standard deviation. The EXP anomaly is the departure of EXP from its mean during the study period (1960-2018).

The difference of trends between the target (all/urban) and reference (rural) stations is defined as the urbanization effect on the time series at the target station (Hinkel and Nelson 2007; Ren and Ren 2011; Tayanç et al. 1997). The percent proportion of the urbanization effect on the overall trend is defined as the urbanization contribution. The contribution is only calculated when the urbanization effect is statistically significant at a 95% confidence level. The urbanization effect (*UE*) and its contribution (*UC*) are defined as follows:

$$UE = T_n - T_r \quad (1)$$

$$UC = \left|\frac{T_n - T_r}{T_n}\right| \times 100\% \quad (2)$$

where T_n and T_r are the linear trends of the time series at the target and reference stations, respectively.

In order to examine the statistical significance, the applied procedure is to calculate the difference of the EXP indices between target and reference stations, and obtain the difference time series. The linear trend of the difference time series is equivalent to the difference of trends between the target and reference stations. The linear trend and its significance are estimated by the ordinary least squares' method and Student's t-test, respectively. The trend and correlation are considered statistically significant if they pass the 95% confidence level.

iii. Definition of the different networks

In this study, target-reference comparison is employed to examine the trend differences between target (all/urban) stations and nearby reference (rural) stations, with the assumption that the linear trends of any two observational stations within a grid cell (1.0°×1.0°, latitude×longitude) are the same under the influence of other factors, especially large-scale (global and regional) drivers. In our previous study (Tysa et al. 2019), the proportion of urban land use in each of the buffer circles of a 1-16km radius at approximately 2419 all stations was extracted and defined as the urbanization indicator. It means that the possible impact of urban land use/urbanization on the observed variables at the stations is considered spatially from the micro to medium scale. All stations are further divided into six categories of stations that are differently affected by urbanization processes, based on the maximum and area-weighted average urban land use ratio in the 16 buffer circles around the stations. The classification assumed that the first category of all stations (abbreviated as U1 station) is nearly unaffected by urbanization, since the maximum and area-weighted average urban land use ratio in each of the 16 buffer circles around the U1 stations are less than 5% and 1%, respectively. The other national stations are defined as being affected by lower (U2 station), low (U3 station), medium (U4 station), high (U5 station), and higher (U6 station) levels of urbanization (See Tysa et al. (Tysa et al. 2019) for details).

The U1 stations are further grouped into 1.0° latitude×1.0° longitude grid cell to form the network of rural stations. Since the networks were established by assigning at least one rural station within each grid cell over mainland China, U2 and U3 stations are further selected as rural stations over eastern China as a supplement, where is the most rapid urbanization over the last decades with no U1 stations. So, the highest urbanization level of the rural stations is U3 stations, and the numbers of U1, U2, and U3 stations are 262, 265, and 324 in the network of rural stations, respectively. The remaining stations in each grid cell were identified as urban stations (**Fig. 1b**), so the urban and rural stations are the subsets of all stations.

The main purpose of using recent land use data for classifying stations is to guarantee a more objective determination of reference (rural) stations, and to provide a more complete estimate of the urbanization effect in the extreme precipitation data series of urban and all stations. If the reference stations are located in rural areas at present, then they must have been there since their establishment when no relocation ever occurred. In this case, we do not need to consider the dynamic process of the land use and cover in the selection process of the reference stations. For urban stations, we do not need to have the change series of land use for a period either, and the observational precipitation data series contains the urbanization effect which is the objective of our analysis.

Thus, the observation networks of all, urban, and rural stations are composed of all, urban, and rural stations in mainland China, respectively. Based on target–reference comparison, the network of rural station applied as reference to detect the urbanization effect in the EXP data series at the network of target (all and urban) stations. In our previous study, the reference network with spatial resolutions of 2.0°×2.0° and 1.0°×1.0° (latitude×longitude) have been set to estimate the urbanization effect on the regional surface air temperature (Tysa et al. 2019) and light precipitation (Tysa and Ren 2022) changes at the target network, respectively. Since precipitation shows a well-known spatial variability, especially EXP, the reference network with spatial resolutions of 1.0°×1.0° is applied in this study, as shown in **Figure 1c-d**. It should also be emphasized that the identification of reference stations is a crucial issue when applying the method of target-reference comparison to evaluate the urbanization effect on the observed variables. The reference station used in our study is the station with the lowest level of urbanization in each grid cell. Nevertheless, most of them are likely to be influenced to some extent by urbanization, as they are located in or near small cities or towns (Tysa et al. 2019). In order to ensure that there is at least one reference station in a grid cell, the standard of the reference station has to be lowered to include some stations of U3 category which are usually of small city stations. Therefore, the estimates of urbanization effect on EXP trends shown in this paper should be regarded as conservative values.

To derive the gridded precipitation indices from all, urban, and rural stations, the indices at the corresponding stations within the grid cell are arithmetically averaged. Furthermore, the gridded precipitation indices in the study areas are constructed by area-averaging corresponding indices in all grid cells. In this study, more than four adjacent grid cells with significantly positive urbanization effects on each EXP index change are defined as the key region. The key region is further masked in the figures related to spatial distribution.

3. Results

A significantly increasing trend in annual EXP is assessed in mainland China over the six decades (p<0.01), except for IEXP (**Fig. 2**). In particular, DEXP, AEXP, and RX1D all present linear trends exceeding 0.04 /decade. Although EXP follows a similar pattern of change at the three networks, the changes at the network of urban/rural stations are greater/less than those of all stations. As urbanization levels increase, the linear trend in DEXP increases from 0.03/decade at rural stations to 0.04/decade at urban stations during the period of 1960-2018. Such urban–rural disparity in long-term observed EXP change is also exhibited during the warm season (**Fig. S1**), with a more pronounced effect on EXPTOT changes compared to the annual scale.

The difference time series of annual EXP between all (target) stations and rural (reference) stations exhibit a significantly upward trend, except for IEXP (**Fig. 3**). Or, a positive urbanization effect on the EXP change is detectable at the observational network of all stations, at rates ranging from 0.011 to 0.014/decade. From the early 1990s, a rapid enhancement is observed in the difference time series of EXP indices, but the shift point for annual RX1D occurs earlier (**Fig. S2**). Intriguingly, a greater positive urbanization effect is estimated as EXP levels increase, when comparing it on the trends of annual precipitation greater than the 90th, 95th, and 99th percentiles of all wet-day precipitation during the study period (**Fig. 4a**), except for IEXP. There is a significantly positive effect on the IEXP changes when the precipitation exceeds the 90th and 95th percentiles. Additionally, the positive effect increases with urbanization level, as shown by comparing urbanization effects on the EXP changes at U4, U5, and U6 stations (in order of enhancement of urbanization level, see Section **Methods**) across mainland China during the period (**Fig. 5**). A positive urbanization effect on EXP changes is also evident during the warm season (**Fig. S3**). Compared with the annual scale, more obviously positive effects on the EXPTOT and RX1D changes are observed during the warm season. Additionally, an evident positive urbanization effect on the change in frequency and amount appears from April to June, but it is slightly greater from June to August on RX1D change (**Fig. 6a**).

Approximately 60% of the grid cells show a positive urbanization effect on EXP changes, except the IEXP, and over 30% show significant effects (p<0.05). EXP changes have experienced an evidently positive urbanization effect in Eastern China, but mainly in inland areas (**Fig. 7**). Specifically, the inland portion of Southeastern China exhibits a prominently positive effect on the EXP changes, while a less organized distribution is observed for IEXP changes over Central and Southwestern China. A similar spatial distribution of the urbanization effect on the warm seasonal EXP changes is observed (**Fig. S4**). However, fewer grid cells show a positive effect on IEXP changes during the warm season are observed compared to the annual scale.

Urbanization contributes approximately 26-29% of the long-term observed annual EXP changes at all stations in mainland China during the period of 1960-2018, with slightly higher contributions to frequency changes (**Fig. 8**). Nevertheless, the urbanization contribution to IEXP change is not calculated, due to statistically insignificant effects. The contribution of urbanization to EXP change is also proportional to the EXP level, with only 16-18% of the changes registered in precipitation greater than the 90^{th} and 95^{th} percentiles (**Fig. 4b**). However, it is notable that 40% of annual IEXP changes is contributed by urbanization when EXP is defined as precipitation exceeding the 95^{th} percentile. Urbanization even contributes 30-34% of the EXP changes from April to June, when a greater urbanization effect appears (**Fig. 6b**). Nevertheless, it contributes a significant portion of 29% to the RX1D change from July to December. Although no apparent spatial differences are exhibited in urbanization contribution to annual EXP trends (**Fig. S5**), contributions are larger than 30% in more than half of the grid cells over all key regions (see the definition in Section **Methods**), where urbanization effects are statistically significant. In addition, greater contributions to IEXP changes are observed in grid cells with significant positive urbanization effects.

4. Discussion

On the subcontinental scale, this analysis provided the observed evidence and understanding of urbanization-induced regional extreme precipitation changes at observational network of all stations in mainland China. A few of findings revealed in the analysis and their significance are discussed as follows:

4.1 Significant urbanization bias in the currently observed daily and extreme precipitation data series

With regard to large-scale climate change, the results shown in this study highlight a systematic bias in observed precipitation data at stations (Ren and Zhou 2014; Ren et al. 2016). For most EXP indices, the urbanization effects or the absolute biases are significant statistically, and the annual mean urbanization contributions or the relative biases to the estimated trends up to 1/3 in mainland China. It is widely accepted that the EXP frequency and intensity have increased in many regions over recent decades. In mainland China and most land areas with reliable observational coverage, the observed rise in EXP events, especially those of short-duration, has been dominantly caused by the anthropogenic global warming (Min et al. 2011). The physical explanation is straightforward: human-induced global warming intensifies oceanic surface evaporation and land evapotranspiration, leading to a rise in atmospheric water vapour content, which, in turn, results in an increase in intense precipitation. Additionally, our findings reveal that the observed increase in regional EXP events can be partly caused by urbanization surrounding observational stations. This urbanization-induced increasing bias leads to an overestimate of large-scale intensification of precipitation in mainland China. Thus, the actual rise in EXP frequency and amount in mainland China, and probably in other land regions of the world, would be significantly smaller than those shown by using observational data and climate models. Obviously, both data and models currently used in studies of large-scale climate change are defective, and they need to be adjusted or improved.

In terms of urban climate change, however, urbanization-induced extreme precipitation increases around the meteorological stations in China, which is actually the manifestation of urban climate change near the national stations. These insights are crucial for understanding and mitigating risks associated with locally anthropogenic climate changes. Most previous studies focused on smaller area, used limited sample (fewer stations), and were unable to obtain a robust conclusion for sufficiently large regions, often overlooking spatial difference. Thus, the novelty of this study lies in its demonstration of a significant urbanization effect or bias in the observed extreme precipitation data series for a subcontinental region, and it also indicates the same significant urban-induced change in extreme precipitation near the thousands of national stations in the country which is actually one of the urban climate changes as conceptualized in Ren et al (2015).

It is worth noting that the spatial distribution of all/national stations is uneven, with most stations concentrated in Eastern China (**Fig.1a**). In Western China, most grid cells contain only one national station, which is further classified as either an urban or rural station. In this case, the urbanization effects in these grid cells are not calculated. Therefore, the urbanization effect on, and its contribution to, the estimated extreme precipitation trends in mainland China primarily reflect the results in the Eastern China monsoon region in this study. Considering the fact that the reference station network includes some small city stations (U3 stations), our results show an at least 26-29% urbanization bias in the trend of long-time daily EXP data series of mainland China, which can be regarded as the prescribed minimum of the data biases. Further investigation is needed to fix the real bias, and, if the bias does not reach 100%, to quantify the respective contributions of global warming, multi-decadal variability and locally anthropogenic influence on the residual increase in EXP events at global and regional scales. In addition, other local factors around the observational stations have potentially contributed to the difference in climate variable between urban and rural stations in one grid cell, such as water bodies, terrains, vegetation and cultivated land, if they also experienced a change over the period analyzed.

4.2 Urbanization-induced precipitation extreme changes are more pronounced in EXP frequency and more extreme EXP events

Our analysis indicates that the EXP frequency change is more greatly affected by urbanization than the EXP intensity. At a subcontinental scale, the result adds new supporting evidence to the findings from the recent studies by Marelle (2020) and Jiang (2020), which reached similar conclusions at local scale. Nevertheless, to better understand the mechanisms underlying urban rainfall climatology and urban climate change, further study is needed to investigate how urbanization affects different EXP metrics. Additionally, our study also shows that the urbanization effect on EXP trends increases with the EXP level rising, which means that urbanization has a generally stronger effect on most extreme daily precipitation events recorded at national stations. This indicates that urbanization is causing the rarer extreme precipitation events to increase in frequency and rainfall amount. Since the urban environment is extremely vulnerable to the rare extreme precipitation events, our findings underscore the urgent need to enhance monitoring and forecasting the most extreme precipitation in urban areas.

The urbanization-induced precipitation extreme change is estimated on the annual scale in this analysis. This is different from most of the previous studies which were only focused on the warm or wet season only (Huang et al. 2022; Su et al. 2019; Yan et al. 2020; Yeung et al. 2015; Zhang et al. 2014). Although the urbanization signal is often more detectable during the warm season, the annual-scale analysis reveals the significant influence of urbanization on EXP changes over larger spatial scales (e.g., mainland China) or by applying a bigger set of observational network.

4.3 Influence of local background climate on urbanization-induced precipitation extremes

Except for the coastal zone, the wet climate areas of the Eastern China monsoon region exhibit prominently positive urbanization effects on precipitation extreme changes in this study. The urbanization process is more rapid in the Eastern China monsoon region than the non-monsoon region of Western China over the last decades, and this might have been a major factor affecting the EXP changes at national stations. Specifically, the expansion of urban underlying surface is more pronounced in north potion of Eastern China, as estimated from urban land use data around the stations (Huang et al. 2022). As indicated in a recent study (Huang et al. 2022), urbanization amplifies the intensification of hourly extreme precipitation in South China, affecting not only in metropolitan areas and also in smaller cities. In contrast, less precipitation is received in urban than surrounding areas over North China (Huang et al. 2022; Li et al. 2015; Zhang et al. 2009). More water vapour could be carried into the urban atmosphere by local convergence over wet regions compared to insufficient water vapour conditions in arid zones. Hence, our observational results indicate that, as a local to regional background climate, the amount of precipitable water and its supply might have also contributed to urban-induced precipitation extreme change. Since precipitation extremes certainly contribute to total precipitation over China monsoon region (Sun et al. 2017), the contributions of urbanization to incremental regional total rainfall are worth further discussion.

On the other hand, the development of urban precipitation extremes must involve the interactions of urbanization-induced circulation and external forces, such as mesoscale organization, cloud microphysics (Fan et al. 2020), and synoptic scale process. In contrast to other regions of Southeastern China, the tropical cyclone is one of the main weather types that produces precipitation in long southeast coastal zones (Luo et al. 2016). By exploring the influence of urbanization on different extreme precipitation events in the Guangdong-Hong Kong-Macau Greater Bay Area, China, a recent study indicated that urbanization-induced convectional rainfall is obvious, while the impact on frontal and typhoon rainfall is not detectable (Li et al. 2021). The large-scale and strong synoptic background, such as monsoon and typhoon-related precipitation, would weaken local wind convergence and strengthen advection, thereby diminishing urban heat island circulation and other urbanization-induced processes (Wang et al. 2021). Hence, our study has not ruled out the possibility that the synoptic scale might play a certain role in regulating the development of urban-induced extreme precipitation events occurring at the national stations.

4.4 The connections between the urbanization effect on RX1D trend and the urban heat island intensity change

An apparently positive urbanization effect is detected in the estimation of the annual mean surface air temperature (SAT) anomaly trend in mainland China during the period of 1960-2018 (**Fig. S6**), which is consistent with our previous analysis (Tysa et al. 2019). Furthermore, a positive relationship between the urbanization effect on the annual EXP and SAT change is shown when the effect on the annual SAT change is a function of the effect on the annual EXP change (**Fig. 9**). However, it is only statistically significant at the 95% confidence level for the annual RX1D, although the effect on the changes in EXP indices shows a consistently positive effect in the whole study area, except for the IEXP.

The impact of urban heat island (UHI)-induced thermodynamic processes on urban EXP changes is always pronounced as the major contributor (Liang and Ding 2017; Liu and Niyogi 2019). Nevertheless, Marelle (2020) recently indicated a proportionally large role of anthropogenic heat emissions on urbanization-induced precipitation extremes, although the difference in the influence of urbanization on EXP between selected case cities can be partly explained by the magnitude of the UHI change in their study. The precipitation enhanced by the urban sensible heat occurs through increasing vertical motion and water vapour convergence over the city (Kusaka et al. 2014; Marelle et al. 2020; Zhong et al. 2017), and the increasing anthropogenic heat emissions could enhance sensible heat without reducing surface specific humidity over urban areas (Marelle et al. 2020). The influence of dynamic processes accompanying urbanization would be also important, which might result in a low-layer flows converging over the urban areas, and also a stagnated movement of small to meso-scale weather systems, due to the increased roughness of the underlying surface. Hence, under the difference climate background, future efforts on the separate contributions of various dynamical and thermodynamic process to change in precipitation extremes are needed.

5. Conclusions

In this study, the urbanization effect on, and its contribution to, the estimation of regional observed EXP trend at the observation network of all station in mainland China for the past six decades are assessed. The following conclusions can be drawn: The observed increase in regional EXP is partially caused by urbanization around the observational stations for the past six decades, and the urbanization contributes approximately one-third of the long-term observed EXP changes (p<0.01). The positive urbanization effect and its contribution increase with the EXP level (from 90^{th} and 95^{th} to 99^{th} percentiles). The EXP frequency change is more greatly affected by urbanization than the EXP intensity. From the spatial-temporal variation of the urbanization effect, the positive effect is concentrated in inland areas of the Southeastern China monsoon region. And it even contributes 30-34% of the EXP frequency and amount changes from April to June, when a greater effect appears. A significantly positive relationship is only detected between the urbanization effect on the long-term maximum 1-day precipitation trend and surface air temperature trend (p<0.05).

Therefore, there is an at least 26-29% urbanization bias in the estimated trends of the currently used daily precipitation data. The bias has led to an overestimate of the upward trends in EXP events (days and amount) during the last almost six decades in mainland China. Hence, at the sub-continental scale, the background increase in EXP events is actually smaller than previously thought.

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Competing interests

Authors declare that they have no competing interests.

Figures and Tables

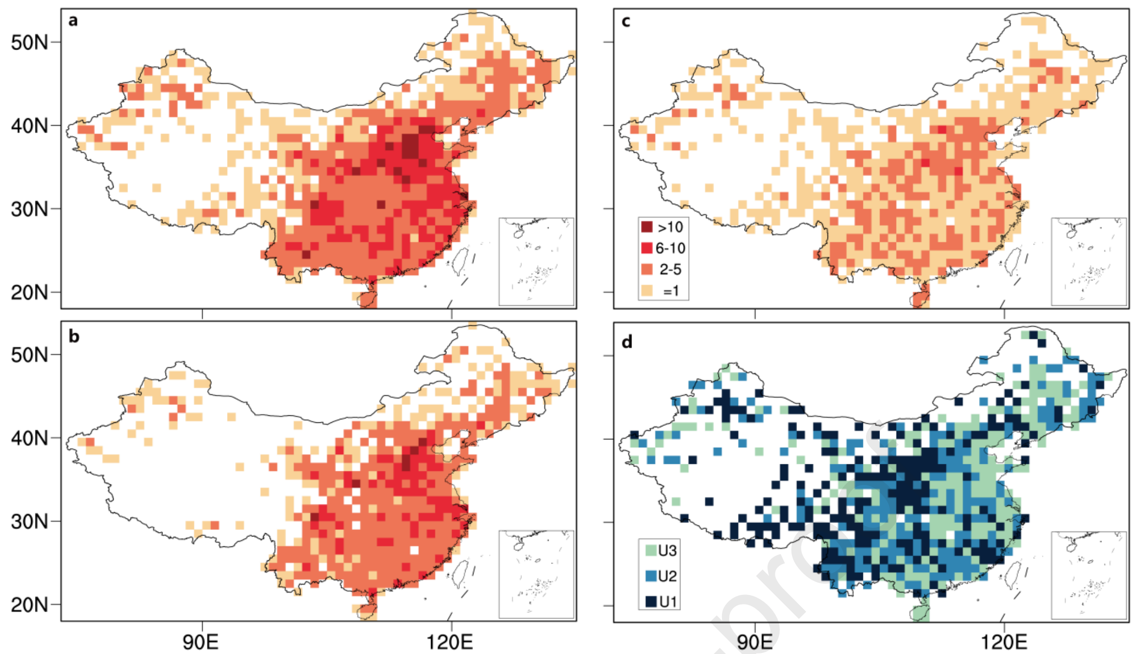

Figure 1. Spatial distribution of all/national, rural and urban stations. (**a-c**) The grid cells with the number of all national stations (urban + rural stations), urban stations, and rural stations in mainland China, respectively. (**d**) The grid cells with the urbanization levels of rural stations, including U1, U2, and U3 stations (in order of enhancement of urbanization level). Grid size: 1.0°*1.0° (latitude*longitude).

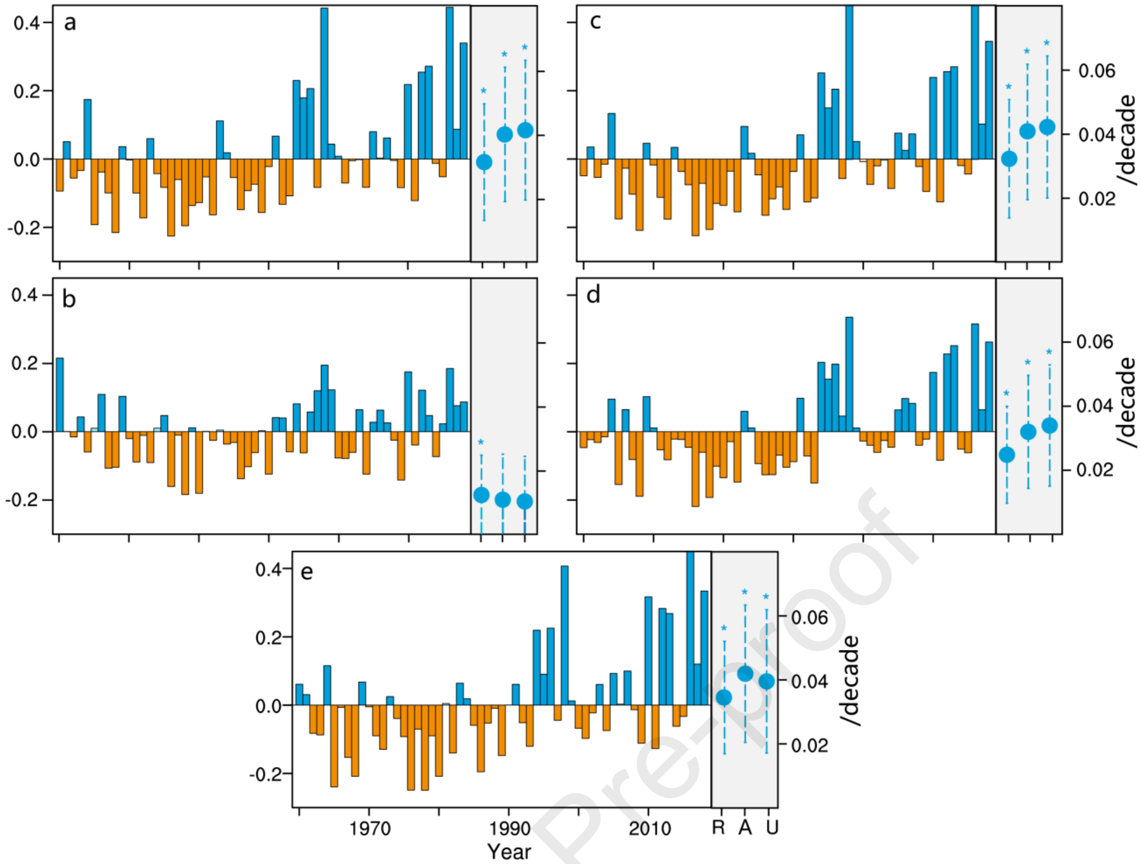

Figure 2. Comparison of the changes in observed EXP for different networks. (Left of each panel) The time series of the standardized anomalies of the annual EXP (**a-e**: total DEXP, mean IEXP, total AEXP, EXPTOT, and RX1D) at all stations in mainland China during the period of 1960-2018. (Right of each panel) The linear trend of the annual EXP (**a-e**: total DEXP, total AEXP, mean IEXP, EXPTOT, and RX1D) at the rural stations (R), all stations (A), and urban stations (U), with 2.5% and 97.5% regression coefficient confidence intervals. Asterisks indicate a statistically significant trend (**p*<0.01), and the unit is /decade.

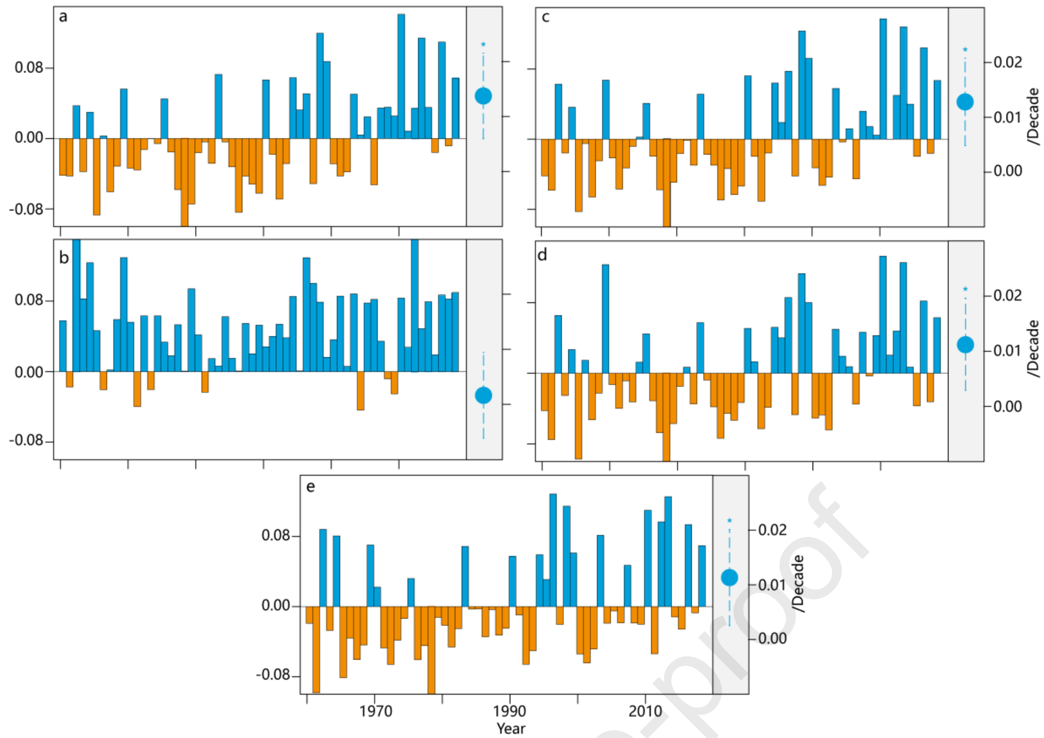

Figure 3. Estimation of the urbanization effect on the EXP change for national station network. (Left of each panel) Difference time series of the standardized anomalies of the annual EXP (**a-e**: total DEXP, mean IEXP, total AEXP, EXPTOT, and RX1D) between all stations and rural stations in mainland China during the period of 1960-2018. (Right of each panel) The linear trend of the annual EXP (**a-e**: total DEXP, mean IEXP, total AEXP, EXPTOT, and RX1D) between all stations and rural stations, with 2.5% and 97.5% regression coefficient confidence intervals. Asterisks indicate a statistically significant trend (**p*<0.01), and the unit is /decade.

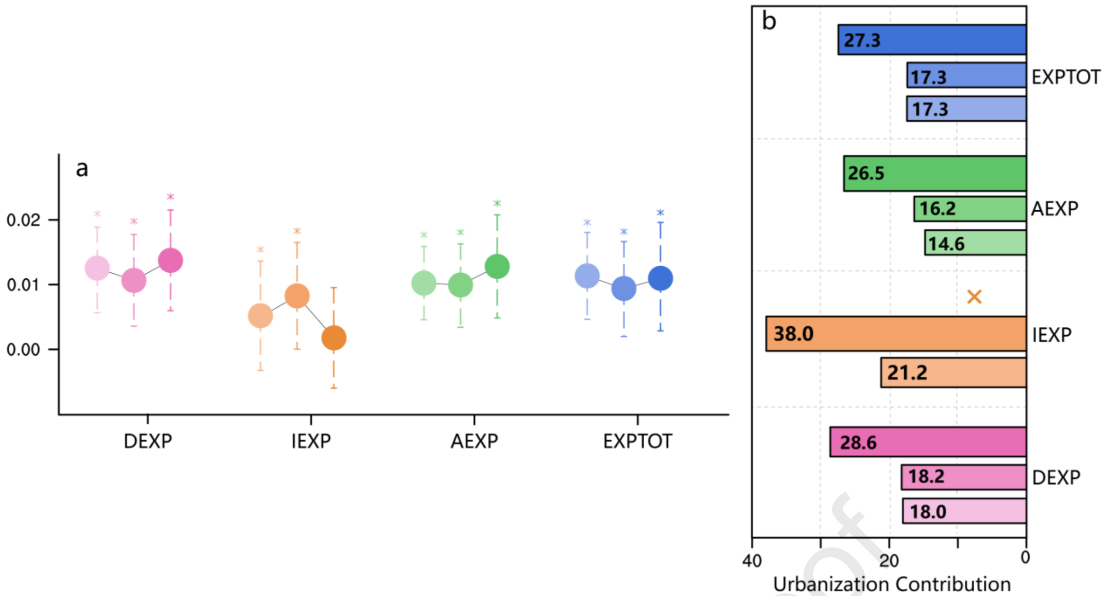

Figure 4. Comparison of the urbanization effect and its contribution to different EXP changes. The urbanization effect (**a**) and its contribution (**b**) to the standardized anomalies of the annual EXP (total DEXP, mean IEXP, total AEXP, and EXPTOT) changes at all stations in mainland China during the period of 1960-2018, when EXP is defined as precipitation greater than the 90th, 95th, and 99th percentiles (from light to dark colour) of all wet-day precipitation during the period. Asterisks indicate a statistically significant effect (*p<0.05).

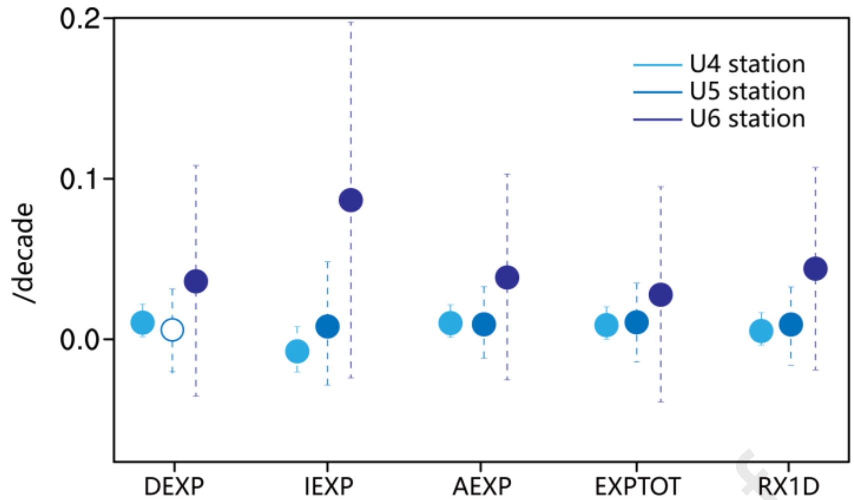

Figure 5. Comparison of the urbanization effect on the EXP change at different urban stations. The urbanization effect on the standardized anomalies of the annual EXP (total DEXP, mean IEXP, total AEXP, EXPTOT, and RX1D) changes at the U4, U5, and U6 stations (in order of enhancement of urbanization level) in mainland China during the period of 1960-2018. Hollow circles indicate a statistically non-significant effect (p>0.05), and the unit is /decade.

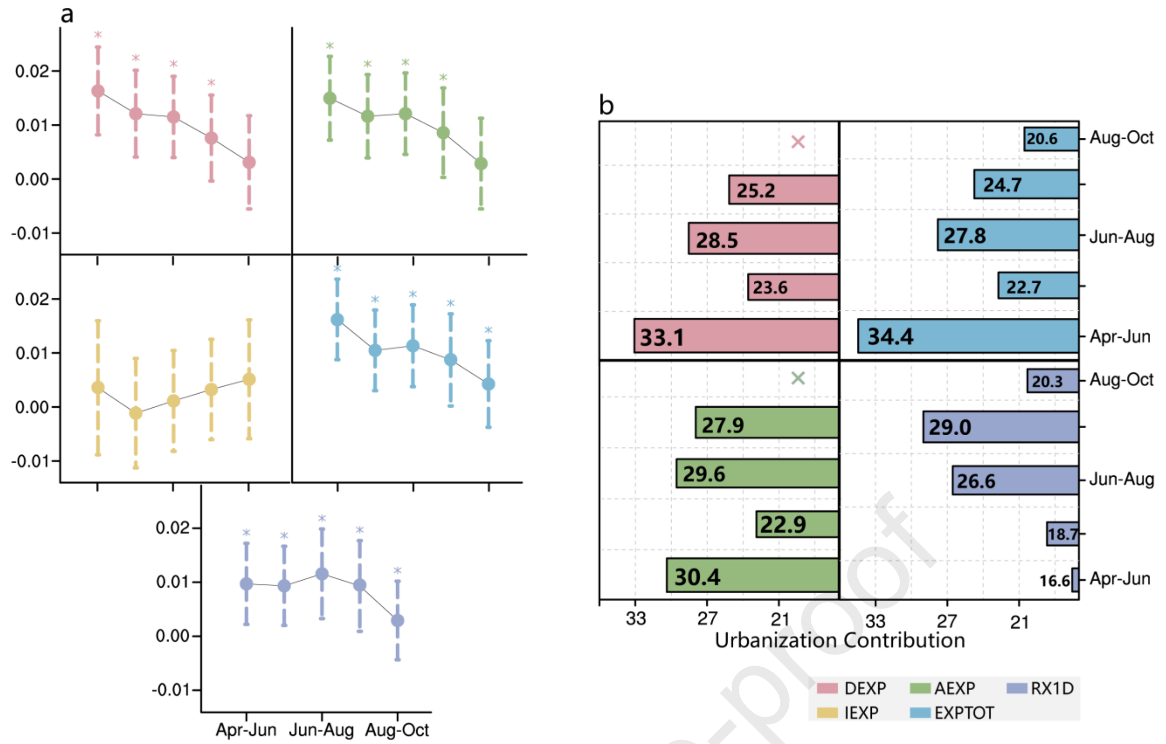

Figure 6. The seasonal variation of the urbanization effect and its contribution on EXP change. The urbanization effect (**a**) and its contribution (**b**) to the standardized anomalies of the 3-month EXP (total DEXP, mean IEXP, total AEXP, EXPTOT, and RX1D) changes at all stations in mainland China during the warm season of the period of 1960-2018. The units are /decade and %, respectively. Asterisks indicate a statistically significant effect (*p<0.05).

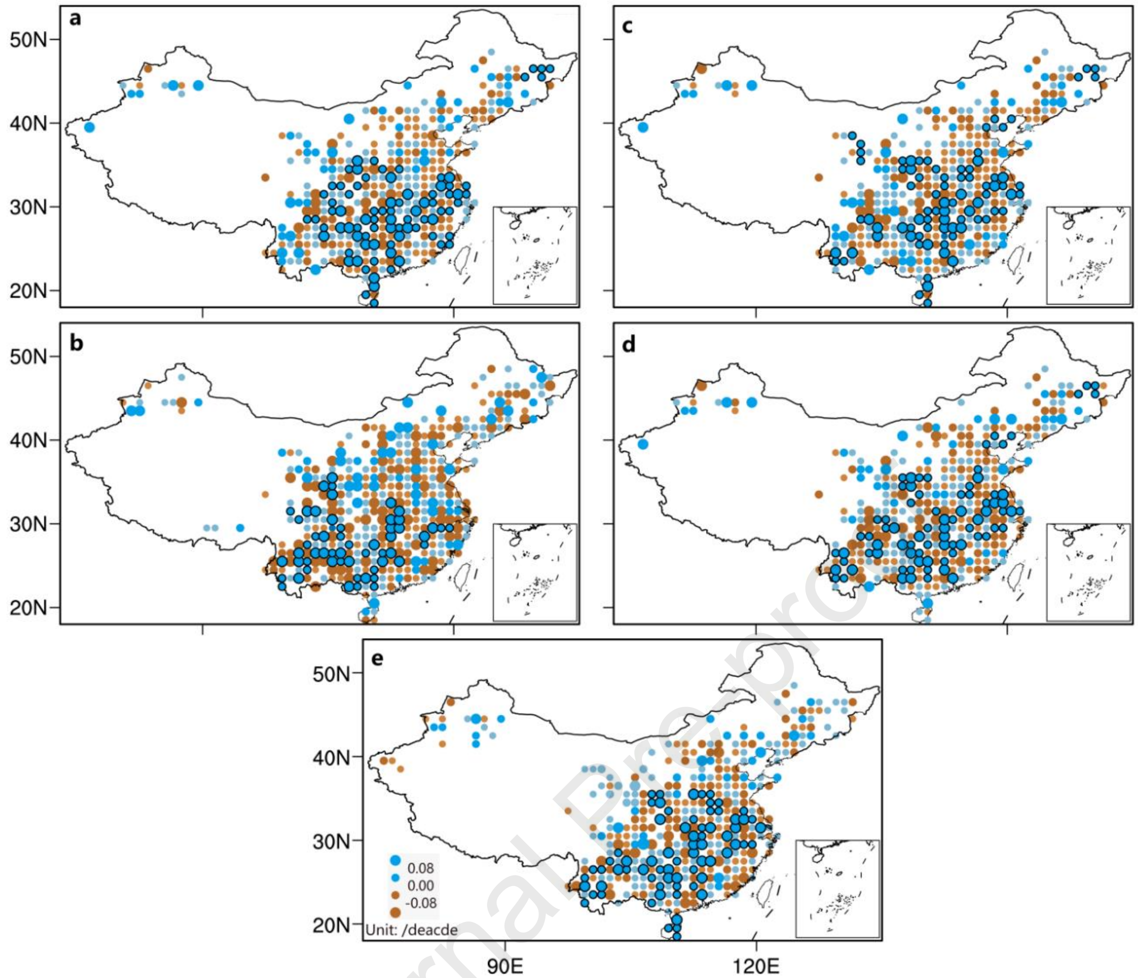

Figure 7. Spatial distribution of the urbanization effect on the EXP change. The spatial distribution of the urbanization effect on the standardized anomalies of the annual EXP (**a-e**: total DEXP, mean IEXP, total AEXP, EXPTOT, and RX1D) changes in mainland China during the period of 1960-2018. The dark blue/brown indicates statistically significant positive/negative urbanization effects (p<0.05), more than four adjacent grid cells with significantly positive urbanization effects on each EXP index change are marked by black ring, and the unit is /decade.

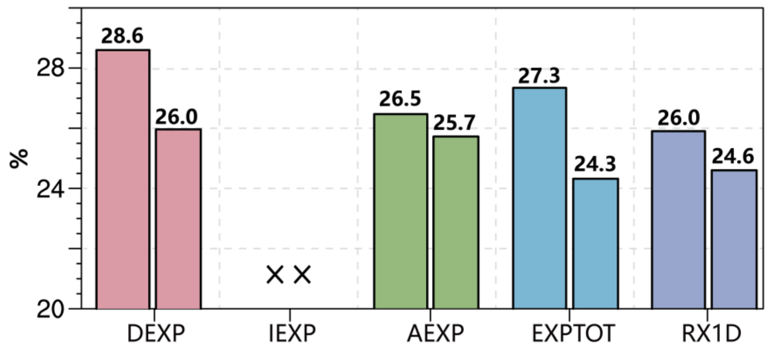

Figure 8. Urbanization contribution to the EXP change for national station network. The urbanization contribution to the trends of standardized anomalies of the (right) annual and (left) warm seasonal EXP (total DEXP, mean IEXP, total AEXP, EXPTOT, and RX1D) at all stations in mainland China during the period of 1960-2018. The unit is %.

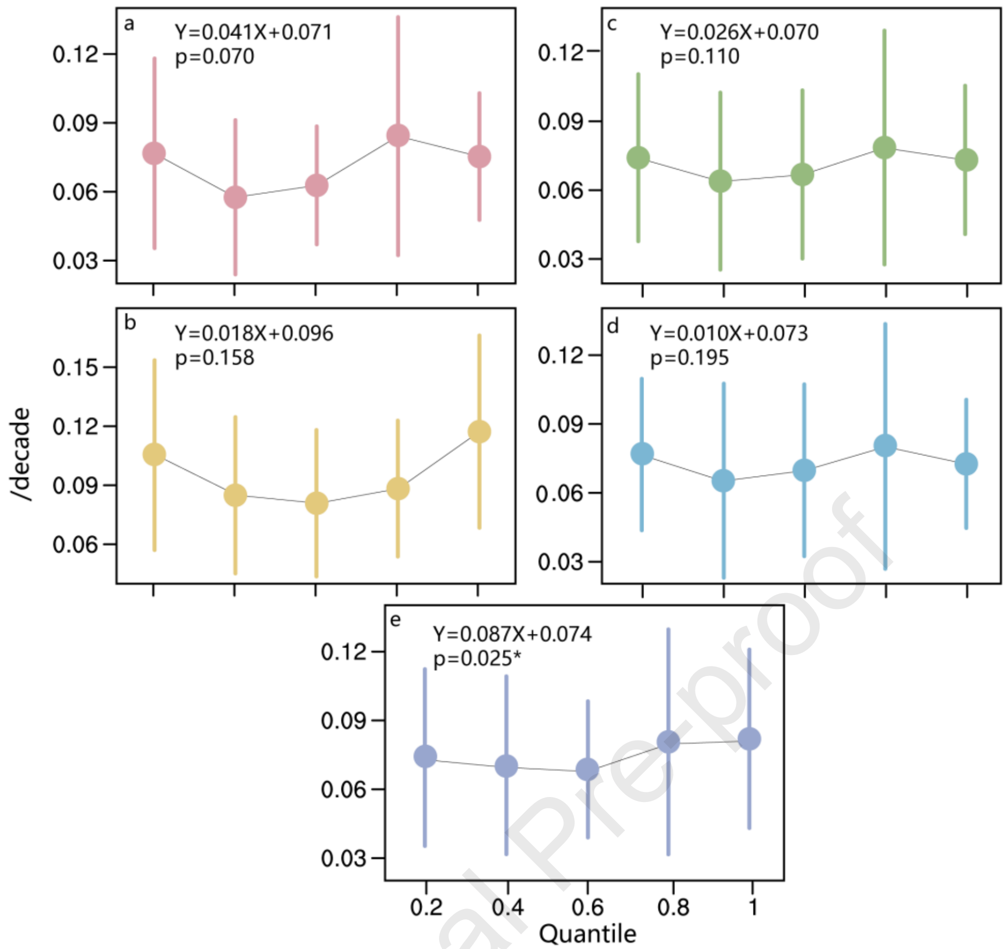

Figure 9. The relationship between urbanization effect on the EXP and SAT changes. The urbanization effect on the standardized anomalies of the annual EXP (**a-e**: total DEXP, mean IEXP, total AEXP, EXPTOT, and RX1D) changes for the different quantiles (0-0.2, 0.2-0.4, ..., 0.8-1) of the urbanization effect on the annual mean SAT anomaly change. The box-and-whisker plot shows the average±SD (top, bottom) and average (medium), and the unit is /decade. Asterisks indicate statistical significance (*p<0.05).

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: