Urbanization altered atmospheric humidity diurnally and seasonally through ecohydrological processes in five urban agglomerations in China

Xiaolin Huang, Kailun Jin, Dongxu Chen, Qingzhou Zheng and Lu Hao

1 Collaborative Innovation Center on Forecast and Evaluation of Meteorological Disasters (CIC-FEMD)/Jiangsu Key Laboratory of Agricultural Meteorology, Nanjing University of Information Science and Technology, Nanjing, People’s Republic of China
2 Qingdao Joint Institute of Marine Meteorology, Chinese Academy of Meteorological Sciences, Qingdao, People’s Republic of China
3 Chongqing Meteorology Bureau, Chongqing, People’s Republic of China
* Author to whom any correspondence should be addressed.
E-mail: haolu@nuist.edu.cn

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Abstract

The large-scale conversion of vegetated land to urban use leads to a significant reduction in evapotranspiration (ET) due to the lack of vegetation, which may aggravate urban dry island (UDI) effect. Analysis of diurnal and seasonal (e.g. growing season) variations in UDI can help us to better identify the role of ET in processes of UDI. We compared six-hourly weather observation data (1980–2017) from 140 paired urban-rural stations across a large climatic gradient in China to explore how near-surface atmospheric dryness changed both diurnally and seasonally, and its relationship with urbanization-associated ecohydrological processes. We showed that the difference in atmospheric dryness (i.e. UDI intensity) between urban and rural areas, as measured by specific humidity \( \Delta q \), is more pronounced during the daytime and growing seasons. The nighttime urban wet island (UWI, \( \Delta q > 0 \)) effect partially offset daily UDI effect, which has made the latter underestimated. Intensified nighttime urban heat island (UHI) reduced the diurnal temperature range (DTR) in cities and thus enhanced nighttime UWI effect from 2000 to 2010. However, after 2010, nighttime UWI effect weakened or disappeared, whereas nighttime UDI intensified in humid cities, resulting in a significant increase in daily UDI. Intensified UHI and UDI are often closely coupled (synchronous occurrence) through latent heat (LE) or ET processes, especially after 2010. Our results indicate that the conversion of vegetated lands to urban impervious surface, especially in humid regions, leads to the reduction in transportation during daytime and evaporation at night in urban cores, which alters the relationships between near-surface air temperature, atmospheric moisture, and ET. The present diurnal and seasonal variations in UDI were delineated in detail to explicate the patterns and interconnections of local urban climate and surface ecohydrological processes, which are critical for ecosystem services in urban landscape design.

1. Introduction

Large-scale urbanization leads to a significant reduction in vegetation, which are likely to alter the surface energy and water balance and exacerbate the urban heat island (UHI) (Fischer and Schar 2010, Zhou et al 2016, Oke et al 2017, Sarangi et al 2021, Shi et al 2021, Zhao et al 2021) and urban dry island (UDI) effects (Hao et al 2018, Huang et al 2022, Meili et al 2022). Understanding the influence of urbanization on near-surface air temperature and atmospheric humidity is important to better monitor the urban climate, inform urban planning, and assess ecosystems (i.e. urban forests) and human health under environmental change (Betts et al 1996, Holt et al 2006, Seager et al 2015, Du et al 2019, Li et al 2020a, 2020b, Zhang et al 2021, 2022). Individual studies suggested that the UDI effect has been enhanced by rapid urban-land expansion in some countries (Chow 1994, Lokoshchenko 2017). It is generally
agreed that, in terms of atmospheric humidity differences, cities tend to be dry during most months of the year. Some studies have shown large diurnal changes in humidity differences in cities (Lee et al 1991, Deosthali 2000, Moriwaki et al 2013, Wang et al 2017), particularly during the warm season (Ackerman 1971, Hage 1975). Chow (1994) found that Shanghai City was moist at night and dry by day relative to the surrounding countryside, and called it urban wet islands (UWIs) and UDI effects, respectively. Ackerman (1971) and Chow (1994) provided comprehensive surveys of urban effects on air moisture and attributed high city moisture at night during warm season to dewfall in the country. Nevertheless, recent study often focused on daily atmospheric humidity (i.e. UDI effects) and neglected nighttime UWI effect (Hao et al 2018, Luo and Lai 2019, Lin et al 2020), which leads us to underestimate UDI effect. The UDI/UWI also have seasonal differences, reflected in the emergence of UWI in winter and UDI in other seasons (Moriwaki et al 2013, Yang et al 2017). However, the patterns of hourly and seasonal differences in atmospheric humidity are complex and contain some unexplained anomalies (Hage 1975). Therefore, a variety of temporal and spatial scales is required to fully understand the causality and nature of UDI for a given region.

Previous studies related to UDI have discussed humidity changes under increasing air temperature due to global warming and increasing UHI (Chow 1994, Lokoshchenko 2017), or ambient wind speed, cloud cover, and moisture stratification in the atmospheric boundary layer (Ackerman 1987). The linkages between land surface ecohydrological processes and the UHI and UDI also have been discussed (Hao et al 2018, Huang et al 2022). Exploring UDI process and its interrelationship with UHI can improve our understanding of the integrity of urban physical process of hydrothermal coupling (Roy and Singh 2015, Wang et al 2017, Dong et al 2022). Therefore, UHI and UDI should be collectively addressed in urban adaptive strategy development and global change assessment (Hao et al 2018).

Evapotranspiration (ET) plays a central role in climate stabilization by offsetting air temperature and moisture fluctuations and therefore essential in management decisions-making related to mitigating UHI (Peters et al 2011, Lee et al 2011, Hao et al 2015, Sun et al 2016, 2017, Li et al 2019, Venter et al 2021) and UDI effects (Hao et al 2018). Terrestrial plant transpiration is one of three important sources (i.e. antecedent atmospheric water vapor, lateral convective water vapor source, and local ET) of atmospheric moisture (Pielke 2005). Urban vegetation plays an important role in modulating urban radiation, heat fluxes, and the hydrological cycle. However, the interactions between urban hydrology and vegetation and the feedbacks to urban weather and climate are still simplified or underestimated in current urban climate/weather models, which could lead to uncertainties in modeling (Qian et al 2022).

Due to the relatively small amount of ET at night, previous studies have often paid less attention to nighttime ET (i.e. between sunset and sunrise) (Groh et al 2019). Current evidence suggests that nighttime water loss could have a greater impact on total ET than current changes in ET due to global warming (de Dios et al 2015). However, little is known about the environmental factors that affect nighttime water loss (Zeppel et al 2014). Analysis of diurnal variation in UDI and its relationship with urbanization-associated ecohydrological processes can help us better identify the role of ET in the processes of UDI effects.

This study aimed to identify the role of vegetation and its potential ecohydrological drivers in the processes of UDI by examining the long-term changes in UDI diurnally and seasonally and its relationship with UHI and ET across a large physiographic gradient in China (figure 1). The importance of vegetation differentials between urban and rural areas in spatiotemporal variability was also detected.

2. Materials and methods

The UDI/UWI effect is a phenomenon whereby cities experience lower/higher atmospheric humidity than the surrounding countryside. In this study, we defined UDI/UWI and UHI intensity specifically referring to the difference between the humidity and temperature of the air contained in the urban canopy layer and the corresponding height in the near-surface layer of the countryside (Oke et al 2017) which is more associated with urban land use change and relevant to public health (Venter et al 2021).

Taking into account the representativeness of urbanization and climate regions, five urban agglomerations span a large climatic gradient from humid to arid zone, the Pearl River Delta (PRD), Yangtze River Delta (YRD), Chengdu–Chongqing, Beijing–Tianjin–Hebei zone, and Northern Tianshan (TSB), were chosen as our study areas (Fang 2020) (figures 1 and S1). We selected 140 paired urban vs. rural meteorological stations (table S1) considering their history, geographic location, data record length, and imperious surface area (ISA) (Zhao et al 2014, Ren et al 2015, Gong et al 2019) in five urban agglomerations. We used six-hourly near-surface (measured at 1.5 m) meteorological data to calculate specific humidity ($q$), vapor pressure deficit (VPD), and potential ET (PET) using Hamon’s method (Hamon 1961). The diurnal and seasonal changes of UDI ($\Delta q < 0$ or $\Delta VPD > 0$)/UWI ($\Delta q > 0$ or $\Delta VPD < 0$) intensity and UHI intensity (air temperature $\Delta T_a$) during different urbanization stages (figure 1(b)) were detected, respectively.

Pearson correlations between $\Delta VPD$ and six biophysical drivers, $\Delta q$, $\Delta T_a$, $\Delta$LAI (leaf area index)
Figure 1. (a) Land use and land cover (LULC) (2018) distribution and location of five urban agglomerations across four climate zones in China. (b) Urban expansion rates (U-rate, calculated based on impervious surface area) for the five urban agglomerations from 1980 to 2017. The grey thick lines in (a) mark the boundary of four climate zones (humid, semi-humid, semi-arid, and arid from south to north), which is defined by the ratio of annual potential evapotranspiration and annual precipitation (PET/P), i.e. humid climate (PET/P $\leq 0.9$), semi-humid climate (0.9 $< \text{PET/P} \leq 1.3$), semi-arid climate (1.3 $< \text{PET/P} \leq 2.5$), and arid climate (PET/P $> 2.5$). The red thick lines mark five urban agglomerations including the Pearl River Delta (PRD), the Yangtze River Delta (YRD), Chengdu–Chongqing (CY), Beijing–Tianjin–Hebei (JJJ), and the Northern Tianshan cities (TSB). The black circles and cross marks are the urban-rural paired sites. Five lines and shading areas in (b) illustrate the mean and SD of urbanization ratio across five urban agglomerations.

(Xiao et al 2016), $\Delta$ET (Senay et al 2013), $\Delta$ISA, $\Delta$wind (wind speed) and AI (PET/Precipitation), were used to explain the magnitude of UDI (i.e. $\Delta$VPD $> 0$) (Snee 1983). We also used Geographical Detector Model for spatial stratified heterogeneity analysis (Wang et al 2010, 2016). The Weather Research and Forecasting (WRF) model coupled with a single-layer and multi-layer (Krayenhoff et al 2020) Urban Canopy Model were respectively used to simulate the vertical distributions of humidity in urban and rural areas across the YRD. More details about data set, flowchart (figure S2), Geographical Detector Model, and WRF configuration (figure S3, table S2) and validation (figures S4–S6) are provided in SI appendix.

3. Results and discussion

3.1. Intensified UDI effects at daytime and nighttime

Atmospheric dryness changed diurnally and seasonally across multiple large city clusters over time (figure 2). During 1980–2000 (pre-urbanization period), except for YRD, UDI ($\Delta q < 0$) rarely appeared in other arid or humid regions, even during the daytime. After 2000 (post-urbanization period), $q$ in urban was generally lower than that in rural areas during both daytime and nighttime, that is, UDI effects ($\Delta q < 0$) occurred (figures 2(a) and (b)). The UDI effect mainly occurred during daytime but was also observed at nighttime in YRD and PRD during 2001–2017 (figures 2(c) and (d)). After 2010, even though local climate became wetter (figure S7) compared to previous period of 2000–2010, UDI effect was more pronounced. The urban drying effect showed strong seasonality at both daytime and nighttime (figure 2(a)). Daytime $\Delta q$ was significantly greater than nighttime $\Delta q$ in growing season (i.e. summer and fall), especially after 2000 (figures 2(a) and (b)). However, the change of $\Delta$VPD in growing season is opposite to that of $\Delta q$, which is different from Wang et al (2017) that $\Delta$VPD at daytime is higher than that at night in Boston during the growing season. Unlike $q$, VPD varies with air temperature, so we suppose that one possible reason for higher nighttime $\Delta$VPD in this study is intensified nighttime UHI (figure 2(c)).

The intensity of diurnal UDI was more pronounced in growing season and in humid PRD and semi-humid YRD regions (figures 2(a) and (b)) owing to greater losses of vegetation in urban areas. Even if there is ‘Oasis Wet Islands’ effect in arid zone
3.2. Nighttime UWI effect offset daily UDI effect

The nighttime UWI ($\Delta q > 0$) was also found in urban cores across multiple large city clusters during the two periods of 1980–2000 (pre-urbanization period) and 2001–2010 (initial urbanization period) (figure 2). The UWI affects at night in both humid and arid areas partially offset the daily UDI effects (figure 2). If nighttime UWI is not considered, the daily UDI effect will be significantly underestimated. Generally speaking, at night, when weather in rural areas is fine and stable without low clouds, as well as low wind speed, water vapor often condenses into dew near the ground due to rapid cooling, which greatly reduces the water vapor pressure (Ackerman 1971, Landsberg 1981). On the contrary, due to slow cooling and higher air temperatures, combined with higher emissions of heat storage and long-wave radiation at night (Lee 1991, Peng et al 2013), there is much less condensation at night in urban than that in rural areas. In addition, a relatively stable atmospheric layer structure and weaker turbulence at night in urban (Mahrt and Vickers 2006, Banta et al 2007) also lead to less water vapor being transported to upper layer, which makes near-surface water vapor pressure higher than that in rural areas, plus human-made water vapor supplementation (e.g. burning fossil fuels), the UWI occurs (Chow 1994). Generally, cooling condensation is the most common cause of UWI and is accompanied by UHIs (Lee 1991, Chow 1994).

In this study, the DTR$_{14-02}$ in rural areas was larger than that in urban areas across multiple large city clusters (figures 3(a) and (b)), which is a prerequisite for the occurrence of urban condensation wet islands, and leads to higher $q$ at night in urban areas than in rural areas (figure 2). From 2000 to 2010, in humid and semi-humid areas, the nighttime UHI (blue lines in figure 3(b)) intensified, and the negative differences in DTR$_{14-02}$ between urban and rural areas (orange lines in figure 3(b)) increased, resulting in the intensification of nighttime UWI (figures 3(a) and (b)). Our results are consistent with those of previous studies. Hage (1975) found that the time synchronization between maximum cooling rates and maximum humidity in rural areas may indicate that moisture is an important factor in UHI development. Chow (1994) found that condensation UWI is conducive to the maintenance and intensification of UHI. However, this is not supported by observations in arid or semi-arid areas.

3.3. Nighttime UWI effect weakened in humid areas

From 2000 to 2010, the intensified night UHI reduced DTR in humid and semi-humid cities and enhanced nighttime UWI effect (figure 3(b)). However, after 2010, nighttime UHI and DTR did not weaken in these cities, while nighttime UWI disappeared and nighttime UDI occurred (figures 2(c), (d) and 4(d)), which is reflected in the significant increase in daily UDI. This suggests that there may be other factors affecting nighttime atmospheric humidity in addition to DTR. This can be supported by the fact that $q$ at night (02:00) and DTR$_{14-02}$ in both rural and urban areas had a negative correlation during 1980–2017, however, the correlation was significant only in urban areas during 1980–2000 (figures 3(c) and (d)).

We suppose that one possible reason for the weakening of nighttime UWI is increase in haze days in urban areas. Wu et al (2016) and Liu et al (2018) found that haze days were significantly negatively correlated with the relative humidity in southern China, such as YRD. Another possible reason may be the increasing urban-rural nighttime ET differences, especially in subtropical humid areas (e.g. PRD and YRD) dominated by natural and artificial wetlands (e.g. rice paddy fields). In wetlands, nighttime ET is significantly higher than that in farmlands and
is closely related to water temperature (Eichelmann et al 2018), which is mainly attributed to the additional contribution of standing water evaporation. Plant transpiration occurs during daylight (Photosynthesis) and night (CO₂ respiration). Evaporation from land and water bodies also occurs day and night (Sun et al 2005, 2006). Some studies have shown that nighttime ET accounts for about 10%–20% of daytime ET (Sugita and Brutseta 1991, Novick et al 2009, Wang and Dickinson 2012). Moreover, under conditions of high vegetation coverage, adequate soil moisture, high wind speed, warm temperature and high VPD, nighttime ET will increase (Martilli 2002, Tolk et al 2006, Dawson et al 2007, Novick et al 2009, Paschalis et al 2021). Our previous observations using weighing lysimeters (Fang et al 2020) and eddy-covariance (Liu et al 2020, Zheng et al 2020) in paddy fields in YRD showed that nighttime ET accounts for approximately 7% of daytime ET in growing season. Liu et al (2017) measured evaporation and transportation using mini-lysimeter and eddy covariance during paddy rice growing season in YRD, and found that the main contribution of daytime ET is transportation, whereas nighttime ET is largely related to evaporation (mainly from water, wet soil, and the canopy surface). This indicates that the contribution of nighttime evaporation of rice paddy fields to total ET cannot be ignored. After 2010, the nighttime air temperature rise caused by climate warming in this region also promoted nighttime evaporation in rural areas. In this case, the lower atmospheric humidity at night in urban areas due to the reduction in evaporation may overwhelm condensation UWI effect, resulting in nighttime UDI effect.

3.4. UHI and UDI are coupled diurnally and seasonally

Considering that \( q \) does not vary with temperature or pressure, we used \( \Delta q < 0 \) to identify UDI for comparative analysis with UHI. Results showed that UHI and UDI processes were gradually coupled (synchronous occurrence) in humid and semi-humid areas (figures 4(a)–(c)). During 1980–2000 and 2001–2010, only a few coupled UHI and UDI were observed at 20:00 in all seasons except winter, while during 2011–2017, more coupled UHI and UDI with higher intensity were observed at four times in all seasons, especially at 14:00 and 20:00 in the growing season (summer and autumn).

Our study also found that in humid and semi-humid regions, \( \Delta T_a \) and \( \Delta q \) changed asynchronously from 8:00 to 14:00, especially during the growing season, with changes in \( \Delta q \) generally preceding changes in \( \Delta T_a \). This is consistent with Wang et al (2017) showing that \( \Delta VPD \) generally precedes changes in \( \Delta T_a \) in the early morning. In humid and semi-humid areas (PRD and YRD), during the first period of 1980–2000, from 08:00 to 14:00, urbanization led to drying in the lower atmosphere (UDI) due to the reduction in ET caused by the loss of vegetation.
Figure 4. Diurnal change of UHI (Δ\(T_a\)) and UDI (Δ\(q\)) at 02:00, 08:00, 14:00 and 20:00 (BJT, UTC/GMT + 8:00) in four seasons across humid (PRD) and semi humid regions (YRD) during three periods (a) 1980–2000 (pre-urbanization period), (b) 2001–2010 (initial urbanization period), and (c) 2011–2017 (accelerated urbanization period), respectively. Colored dots represent the UDI and UHI intensities at four times, and the dotted lines with arrow represent the chronological order. H, D, HD or N means UHI occurred only, UDI only, coupled UHI and UDI (synchronous occurrence, i.e. Δ\(T_a\) > 0 and Δ\(q\) < 0), or no UHI/UDI (i.e. Δ\(T_a\) ≤ 0 and Δ\(q\) ≥ 0), respectively. (d) Specific humidity (\(q\)) in urban (orange bars) and rural areas (green bars) at four times during three periods of (1) 1980–2000, (2) 2001–2010, and (3) 2011–2017, respectively.

From 14:00 to 02:00, the UHI effect gradually intensified, whereas the UDI effect weakened (decoupled) (figure 4(a)). This is consistent with Chow and Chang (1984) showing that UDI in Shanghai city is most prominent at 14:00. However, during the second period (2001–2010), the UDI and UHI effects intensified synchronously (coupled) from 14:00 to 20:00; that is, the UDI effect did not weaken in the afternoon (figure 4(b)). After 2010 (the third period), the UHI intensity was similar to that during the second period with significantly enhanced UDI. That is to say, the intensified UDI and UHI effects were closely coupled (figure 4(c)).

A strong UHI effect often leads to a significant increase in air temperature near the urban surface. In addition, higher urban surface roughness enhances convergence in the lower atmosphere, and thus promotes convective movement. This is conducive to water vapor transportation from the lower layer to the upper layer, which leads to lower surface atmospheric humidity (figure 5). Therefore, significantly stronger UHI effect at 14:00–20:00 during the second period (2001–2010) than that during the first period (1980–2000) (figure 4(b)) caused an enhanced UDI (figure 4(b)).

However, for the third period (2011–2017), UDI intensified significantly, although UHI effect was not strengthened compared with the second period (figure 2(c)). Different from previous two periods when UDI only appeared at 14:00 and 20:00, after 2010, UDI appeared at four times (figures 4(a)–(c)). UHI effect is insufficient to explain significantly intensified UDI. In addition to intense vertical moisture transport from lower layer to upper level caused by UHI, another possible cause for the lack of surface water vapor is significant reduction of vegetation and thus decreased ET (or LE flux at surface) in urban cores (figure 6(a)). Consequently, the urban lower atmosphere is drier than ever before (figure 4(d)).

3.5. Relationship between UHI, UDI, and ET

The WRF simulation coupled with a single-layer (figure 5(a)) Urban Canopy Model to a typical process from 2013-7-1 to 7-8 in the YRD both showed
Figure 5. WRF coupled with single-layer urban canopy model simulating results (averaged from 2013–7–3 to 7–8) in Yangtze River Delta. (a) Specific humidity \( q \) at 14:00 (BJT), (b) \( q \) at 02:00 (BJT), (c) vertical distributions of \( q \) at 14:00 (BJT) in urban area and rural area, (d) upward heat flux at the surface, (e) upward moisture flux at the surface, and (f) latent heat flux at the surface. Urban and rural areas are defined same as in figure 1.

Figure 6. (a) Differences in annual mean evapotranspiration of 2011–2017 and 2003–2010 across China. Spatial correlation of (b) ET vs. \( T_a \) and (c) ET vs. \( q \) (\( T_a \) and \( q \) are observations at daytime 14:00) from 2003 to 2017 in five urban agglomerations. The significance level for the correlation of 'SIG positive' or 'SIG negative' is 0.01. The five urban agglomerations across from humid to arid zone, including the Pearl River Delta (PRD) in humid zone, the Yangtze River Delta (YRD) in semi-humid zone, Chengdu–Chongqing (CY) in semi-humid zone, Beijing–Tianjin–Hebei (JJJ) in semi-arid zone, and the Northern Tianshan cities (TSB) in arid zone.

There was UDI occurred at daytime (figure 5(a)) and UWI at nighttime (figure 5(b)) in three megacities of Shanghai, Nanjing, and Hangzhou, which also observed at paired weather stations. The simulated vertical distributions of \( q \) at 14:00 Beijing time in YRD support our hypothesis that atmospheric moisture differences between urban and rural areas are opposite at lower and upper layers, that is, the atmosphere below 1000 m in urban is drier than that in rural areas but wetter above 1000 m, especially from 1000 m to 2500 m (figure 5(c)). The low-layer drier condition over urban areas (i.e. UDI) is partially due to strong
Figure 7. A summary of the relationships across climatic gradient from humid to arid zones for six biophysical drivers versus $\Delta$VPD at (a) daytime (14:00) and (c) nighttime (02:00) during 2003–2010 (initial urbanization period), and (b) daytime (14:00) and (d) nighttime (02:00) during 2011–2017 (accelerated urbanization period) to explain the causes of six biophysical factors affecting magnitude of UDI. Only data that had $\Delta$VPD > 0 (UDI occurred) were pooled. $\Delta$LAI, $\Delta$ET, $\Delta$ISA, $\Delta$Ta, $\Delta$VPD, $\Delta$q, and $\Delta$wind represents urban-rural difference in annual mean leaf area index, evapotranspiration, proportion of impervious surface area, near-surface air temperature, atmospheric vapor pressure deficit, atmospheric specific humidity, and wind speed, respectively. $\Delta$Ta, $\Delta$VPD, $\Delta$q and $\Delta$wind was calculated for daytime and nighttime, respectively. AI is the aridity index, the ratio of annual potential ET and precipitation (PET/P). Confidence levels are denoted by * $P < 0.01$ and ** $P < 0.001$.

Ascent motion and intense vertical moisture transport from lower layer to upper level. Large-scale conversion of vegetated lands to urban uses altered surface energy balance and thus likely led to more upward heat flux (figure 5(d)), as well as a significant reduction in moisture flux at the surface (figure 5(e)) and LE or ET (figure 5(f)) in three urban cores than that in rural areas, especially at afternoon (14:00) compared with full-day average (figure S8). WRF scenario simulations (figure S9) also showed that upward moisture flux (figure S9(c)), LE/ET (figure S9(f)), and $q$ (figure S9(a)) all decreased after the conversion of irrigated cropland to impervious surface. The WRF simulation coupled with multi-layer Urban Canopy Model showed similar urban-rural patterns (figure S10).

The remote sensing annual ET generally decreased during 2011–2017 compared with 2003–2010 in most urban cores except TSB (figure 6(a)). Overall, $T_a$ had significant negative correlations with ET ($P < 0.01$) in most urban cores in 2003–2017 (figure 6(b)). In humid vegetated areas, such as south of the YRD, ET was positively correlated with $T_a$, indicating that ET increased with higher air temperature (figure 6(b)). However, in urban cores, ET decreased (figure 6(a)) and was mainly negatively correlated with $T_a$ ($P < 0.01$) (figure 6(b)), which indicated that the loss of vegetation as a result of urbanization led to a reduction in ET (less LE consumption), which is conducive to UHI effect.

The strong relationship between ET and $q$ during 2003–2017 (figure 6(c)) also confirmed our hypothesis that urbanization greatly reduced water vapor source as a result of decreased vegetation ET. In the surrounding areas with relatively slow urbanization and more vegetation coverage, for example, south of the YRD, ET is generally positively correlated with $q$ (figure 6(c)), i.e. the increase of ET (figure 6(a)) is conductive to atmospheric water vapor content. In urban cores, ET and $q$ were also positively correlated, but the mechanisms were different. Most urban cores are also ET reduction areas (figure 6(a)), and the positive correlation indicates that the reduction in ET as a result of urbanization reduced the content of water vapor in the atmosphere (figure 6(c)). Some coastal areas showed a negative correlation, which may be related to water vapor transport from ocean. Generally, loss of vegetation in cities alters the relationship between $T_a$, $q$, and ET. The change in sign indicates the increasing role of ET in affecting $q$.

Correlations between $\Delta$VPD and biophysical variables (figure 7) suggested that the magnitude of atmospheric humidity was controlled by local
background climate (PET/P) and vegetation characteristics diurnally and seasonally. During the daytime, the main factor affecting ∆VPD is ∆q (except for TSB), while ∆Tₐ at nighttime. The Geographical Detector Model also support the Pearson correlations results (figures S11 and S12). The partial correlations between nighttime ∆q and ∆ET during the accelerated urbanization period of 2011–2017 is different from previous initial urbanization period, that is, the previous significant negative partial correlation (P < 0.01 or P < 0.10) becomes insignificant (PRD), or even becomes significant positive correlation (YRD) (P < 0.10) (figure 8).

Generally, daytime UHI intensity showed associations with urban-rural difference in vegetation cover, while the nighttime values was correlated with urban-rural difference in shortwave reflectivity (or albedo) and night light (Qian et al. 2022). Recent research found that enhanced nighttime UHI partly arise due to ET reduction (Zhao et al. 2018, Mazrooei et al. 2021). Due to relative lack of evaporative water on urban impervious surface and the closure of plant stomata at night, soil evaporative in rural areas contributes greatly to urban-rural difference in nighttime ET, which aggravates the intensity of nighttime UHI and UDI in humid and semi-humid climate (figure 7(d)). In arid climate, ET contribution to the nighttime UHI and UDI is small (figure 7(d)).

Both of the above suggested that the impact of ET on nighttime urban-rural atmospheric humidity differences should not be ignored, especially during the accelerated urbanization period (2011–2017) (figure 7). This, again, supports our hypothesis that the increasing urban–rural nighttime ET difference is one of potential reasons for the occurrence of UDI (∆q < 0) and weakening of UWI (∆q > 0) at night in humid and semi-humid areas (figures 2(c), (d) and 4(d)). Previous studies have shown that urban-rural vegetation differences modulate near-surface UDI intensity via differential ET (Huang et al. 2022). This study further confirmed that urban-rural ET differences affected the variability of surface atmospheric humidity at both daytime and nighttime.

3.6. Limitations
This study has some limitations. First, we used ‘paired’ urban–rural method to detect the sole effect of urbanization due to change in land surface conditions and ecohydrology (i.e. reduction in vegetation thus local ET) on UDI intensity. However, due to the lack of observed ET data from urban–rural paired EC flux measurements, we used remote-sensing-based ET products and WRF simulated ET. Unlike with homogeneous natural vegetation, EC flux measurements, we used remote-sensing-based ET products and WRF simulated ET. This study further confirmed that urban-rural ET differences affected the variability of surface atmospheric humidity at both daytime and nighttime.
The effect of air pollutants on atmospheric humidity should also be investigated. Future research should adopt multiple approaches to explicitly quantify relative contributions of various biophysical factors that control urban atmospheric environment diurnally and seasonally, considering spatial heterogeneity of urban landscapes and urban agglomerations effects.

4. Conclusions and implications

This study detected diurnal and seasonal variations in UDI and revealed a connection between UDI, UHI, and vegetation changes across a large climatic gradient. Our investigation suggests that the UDI effects were significantly enhanced and more pronounced during daytime and growing seasons. Although nighttime UWI partially offset the daily UDI effect and made daily UDI underestimated during 2000–2010, after 2010, it weakened or disappeared in humid and semi-humid areas, resulting in a significant increase in daily UDI. Not all five urban agglomerations had distinct UDIs, and the UDI characteristics and UDI intensity depended strongly on local background climate. Nevertheless, urbanization has magnified the effects of climate change on city air temperature and atmospheric humidity diurnally and seasonally.

All evidence about the linkages between ET, LAI, and $T_u/q$ in this study suggests that ecohydrological processes contribute to UHI and UDI both diurnally and seasonally. Less ET in cities leads to less LE consumption, which is conducive to urban warming and causes UHI effect. The occurrence of the UHI strengthens the vertical thermal turbulence, which is conducive to the transportation of near-surface water vapor to the upper layer, resulting in the reduction of the near-surface water vapor pressure and strengthening of the UDI effect at daytime. We concluded that the conversion of vegetated lands to urban uses, especially in humid and semi humid regions, leads to the reduction in transportation during daytime and evaporation at nighttime in urban cores, which may partly control the long-term diurnal and seasonal variability of near-surface atmospheric humidity.

The present study provides new insights into the possible mechanism of the impact of urbanization on atmospheric humidity and highlight the modulate role of ET in the processes of UDI effects diurnally and seasonally. Our investigation have broad implications for ecosystem services in urban planning and illustrates that more attention should be paid to water fluxes from the land surface into atmosphere during both daytime and nighttime in urban ecosystem.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://doi.org/10.5281/zenodo.6342673 (Huang 2022).

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Conflict of interest

The authors declare no competing financial interests.

ORCID iDs

Xiaolin Huang https://orcid.org/0000-0002-9770-9870
Lu Hao https://orcid.org/0000-0002-2947-1901

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Urbanization increases the rate of urban heat island formation and affects local climate. Urbanization alters the balance of urban and rural climates, leading to changes in temperature, humidity, and precipitation patterns. These changes are critical for understanding the impacts of urbanization on local and regional climate systems. This topic is relevant for urban planning, climate change mitigation, and adaptation strategies.

Urbanization and climate change are closely interlinked. Urbanization results in increased greenhouse gas emissions, which contribute to global warming. At the same time, climate change alters the urban climate, leading to more extreme heat waves, droughts, and flooding events. Understanding these interactions is crucial for developing effective strategies to address climate change and improve urban resilience.

Urbanization is a major driver of climate change, with implications for global warming and local climate. The impacts of urbanization on climate are complex and multifaceted, involving changes in energy balance, hydrological processes, and atmospheric dynamics. This topic is important for understanding the role of cities in the global climate system and for developing sustainable urban development strategies.
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