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Geophysical Research Letters

RESEARCH LETTER

10.1029/2021GL095709

Urbanization Aggravates Effects of Global Warming on Local Atmospheric Drying

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Key Points:

- 'Urban Dry Islands' (UDI) effects are detected across a large climatic gradient
- Urbanization exacerbates global warming and UHI effects on UDI through reducing evapotranspiration and water vapor availability
- The magnitude and frequency of UDI are more pronounced in humid regions than arid regions due to differences in vegetation and climate

Supporting Information:

Supporting Information may be found in the online version of this article.

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Citation:

Huang, X., Hao, L., Sun, G., Yang, Z.-L., Li, W., & Chen, D. (2022). Urbanization aggravates effects of global warming on local atmospheric drying. *Geophysical Research Letters*, *49*, e2021GL095709. https://doi.org/10.1029/2021GL095709

Received 18 AUG 2021
Accepted 17 DEC 2021

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Abstract

Urbanization is known to cause 'Urban Heat Island' (UHI) and elevate storm runoff. However, how urbanization influences local atmospheric moisture under global warming is not well-understood. By examining 140 paired urban-rural weather station data (1980–2018), this study finds significant declines in atmospheric humidity or the 'Urban Dry Island' (UDI) in multiple large city clusters across a large climatic gradient in China. Global warming, UHI, and reduction in local evapotranspiration and water vapor supplies all contribute to the observed UDI. The magnitude and frequency of UDI are more pronounced in humid regions than arid regions due to differences in background climate and vegetation characteristics that affect both energy and water balances at land surfaces. Mitigating the negative effects of UDI and UHI should focus on restoring the evapotranspiration power of urban ecosystems. The present empirical analyses provide new evidence and mechanistic understanding of environmental change in urban ecosystems.

Plain Language Summary

More than half of the world's population live in cities and the Earth is increasingly urbanized. Understanding near-ground atmospheric humidity is important to better monitor urban climate, inform urban planning, and assess ecosystem (i.e., urban forests) and human health under environmental change. This study shows that urban cores have become drier, the so-called 'Urban Dry Island' (UDI) effect, across a large climatic gradient in China, which has experienced dramatic urbanization in the past three decades. This atmospheric drying (UDI) effect is attributed to both global warming and 'Urban Heat Island' (UHI), but it is significantly exacerbated by urban sprawls due to the loss of vegetation and associated reduction in evapotranspiration and water vapor supply. This study offers insights into the ecohydrologic role of urban ecosystems in mitigating the negative effect of the UHI and UDI. Such knowledge would help design 'Low-Impact Development' and 'Nature-based Solutions' to address urban environmental problems.

1. Introduction

Urbanization permanently alters land surface hydrological and thermal properties, which, in turn, causes changes in land surface energy and water balances (Bonan et al., 2011). The 'Urban Heat Island' (UHI) effect, which refers to the fact that cities have a higher 2-m air temperature than surrounding rural areas (Akbari et al., 1992; Georgescu et al., 2013; Oke, 1973), exemplifies how land cover change can dramatically alter near-ground air temperature. UHI effects have been well-documented in China (Li et al., 2014, 2016; Zhou et al., 2004; Zhou, Li, et al., 2016; Zhou, Zhao, et al., 2016;) and elsewhere (Mora et al., 2017; Zhao et al., 2014). Similarly, urbanization is known to elevate storm runoff and flood risks (Boggs & Sun, 2011) due to increases in land imperviousness and reduction in latent heat and evapotranspiration (ET) (Hao et al., 2015; Li, Sun, Caldwell, 2020; Li, Sun, Cohen, 2020; Sun & Lockaby, 2012).

Urbanization also causes differences in near-surface atmospheric moisture between urban and rural areas. The atmospheric drying or the 'Urban Dry Island' (UDI) hypothesis has existed since the 1970s (Budyko, 1974; Chow & Chang, 1984; Hage, 1975). Since then, considerable progress has been made to understand the effects of urbanization on both the heat and moisture budgets in the lower atmosphere (Hao et al., 2018; Li et al., 2019; Lokoshchenko, 2017; Luo & Lau, 2019; Manoli et al., 2019; Pielke, 2001, 2005; X. Li et al., 2021; Zhao et al., 2014). However, debates remain regarding the relative contributions of various natural and anthropogenic factors that control urban climate change and theoretical models are rarely validated with field data (Hass et al., 2016; Hu et al., 2015; Z. Wang et al., 2021). In particular, there is no consensus on how urban land cover, ecohydrology, and atmospheric humidity and temperature interact during urbanization (Moriwaki et al., 2013; Paschalis et al., 2021; Sakakibara, 1995, 2001; Weaver & Avissar, 2001; Willett et al., 2007). Understanding such interactions is important for projecting future climate change in urban areas, especially in humid regions (Meili et al., 2020; Nice et al., 2018; X. Li et al., 2021).

Indeed, changes in atmospheric dryness related to urbanization, have important implications to climate change projection and impact assessment (Betts et al.,). For example, changes in air humidity affect cloud formation (Du et al., 2019), rainfall intensity (Betts et al., ; Holt et al., 2006), human thermal comfort (Zhao et al., 2021), and wildland fires at the 'urban-forest interface' (Pyne, 2009; Seager, et al., 2015). Recent studies highlighted the importance of vapor pressure deficit (VPD) rather than soil moisture and precipitation in controlling plant photosynthesis and ecosystem productivity, and carbon sequestration (Fletcher et al., 2007; Madani et al., 2020; Novick et al., 2016; Yuan et al., 2019;). The mechanisms behind effects of global warming on VPD have been well studied (IPCC, 2013), but how urbanization modifies VPD has been investigated only recently (Hao et al., 2018; Luo & Lau, 2019; X. Li et al., 2021).

The goal of this study is to improve our understanding of the UDI processes amid climatic warming and urbanization across a large geographic gradient. This work extends our previous studies on climatic and hydrologic consequences of urbanization that focused on land surface evapotranspiration processes (Fang et al., 2020; Hao et al., 2015, 2018; Li, Sun, Caldwell, 2020; Li, Sun, Cohen, 2020; Qin et al., 2019; Sun & Lockaby, 2012; Zhou et al., 2014; Zhou, Li, 2016; Zhou, Zhao, 2016). By examining the five major city clusters including the Pearl River Delta (PRD), the Yangtze River Delta (YRD), Chengdu-Chongqing (CY), the Beijing-Tianjin-Hebei zone (JJJ), and the Northern Tianshan (TSB) (Figure S1 in the Supporting Information S1) across a large physiographic gradient, we establish a broad casual linkage between the reduction in vegetation and the decline of atmospheric humidity.

2. Materials and Methods

2.1. Selection of Paired Urban-Rural Weather Stations

This study focused on the meteorological differences between urban and rural areas under the same regional climate. We assembled long term (1980–2018) daily climate data from 580 weather stations that represent the core meteorological monitoring stations in the five urban agglomerations in China and cover a large climatic gradient (Figure S1, Table S1 in the Supporting Information S1). Using the Paired Urban-Rural Classification method (Ren et al., 2015; Zhao et al., 2014), we selected 140 paired urban versus rural meteorological stations and grouped these stations in the five urban agglomerations in four distinct climatic zones across China. The climates of the five city clusters were determined by the long term ratio of annual potential ET (PET) and annual precipitation (P) (defined as aridity index, AI = PET/P) (Figure S1 in the Supporting Information S1). PET was estimated using the Hamon's method (Hamon, 1961). Two key variables, specific humidity (q) and vapor pressure deficit, were used to examine variations of atmospheric moisture over time, that is, the UDI phenomena (*SI Appendix*).

We used following key criteria and rationales (Ren et al., 2015; Zhao et al., 2014) to select 140 pair weather stations for this analysis: (a) station history, length with valid records, and relocation times, (b) the urban stations must remained in the urban core for the entire data records, (c) the paired urban-rural sites should locate in the same climate zone, (d) because the impervious surface area (ISAs) are quite different for the five urban agglomerations, the urban core site was selected with ISAs ≥0.5 in three city clusters, PRD, YRD, and JJJ, and ISAs ≥0.3 for the other city clusters, CY and TSB, and (e) to avoid rural sites with large elevation and latitude differences relative to the urban core, we selected the nearest adjacent paired rural sites with ISAs <0.3 in PRD, YRD and JJJ and ISAs < 0.1 in CY and TSB (Figure S1 in the Supporting Information S1).

By the updated definition of UHI (Oke, et al., 2017; Stewart, 2011), UHI has four types: Surface heat island (UHI_{Surf}), canopy layer heat island (UHI_{UCL}), boundary layer heat island (UHI_{UBL}), and subsurface heat island (UHI_{Sub}). In this study, we focused on UHI_{Surf} and surface urban dry island (UDI_{Surf}), that is, temperature or humidity differences at the interface of the outdoor atmosphere with the solid materials of the city and equivalent rural air to ground interface (Oke, et al., 2017). The UHI_{Surf} and UDI_{Surf} is hereinafter referred to as UHI and UDI, respectively.

2.2. Determination of Turning Points in Urbanization

We found that years 2000 and 2010 were two most obvious urbanization turning points due to their significantly higher ISAs portion (Figure S2a in the Supporting Information S1) (Gong et al., 2019). Accordingly, we separated the entire datasets (1980–2018) into two periods, the 'pre-urbanization period' 1980–2000 and the 'post urbanization period' 2001–2018 to detect change in the differences in q and VPD between the paired stations over time. Since ET and leaf area index (LAI) data are only available during 2003–2017, further correlation analysis compared the 'initial urbanization period' 2003–2010 and the 'accelerated urbanization period' 2011–2017 (More details see *SI Appendix* Text S3 in the Supporting Information S1).

2.3. Datasets for Understanding Factors Controlling UDI

To establish the causal linkage between the UDI and ecohydrological processes, we acquired ET data derived from the Operational Simplified Surface Energy Balance (SSEBop) model (Senay et al., 2013). The SSEBop data set includes ET estimates at a spatial scale of 1 km over urban areas in contrast to the raw MODIS ET products (i.e., MOD16A2) that exclude urban areas (Mazrooei et al., 2021). The Global Land Surface Satellite (GLASS) LAI data sets (version 3.0) generated from MODIS products with a resolution of 1 × 1 km (Xiao et al., 2016). Other affiliated datasets are in *SI Appendix* Text S2 and Table S2 in the Supporting Information S1.

2.4. Attribution Analysis of Factors Controlling ΔVPD

To quantify the relative contributions of urbanization-induced changes in near-surface air temperature ($\boldsymbol{\Delta T_a}$), atmospheric humidity (Δq), and air pressure (Δp) to the observed change in ΔVPD (VPD $_{\text{Urban}}$–VPD $_{\text{Rural}}$), we proposed an attribution method following Diao et al. (2014) and J. A. Wang et al. (2017):

$$\Delta \text{VPD} \approx \Delta e_s(T_a) - p/\varepsilon \cdot \Delta q - q/\varepsilon \cdot \Delta p \tag{1}$$

where, $e_s\ (T_a)$ is saturation vapor pressure (hPa). ε is the ratio of molar mass of water vapor M_v and molar mass of dry air M_d ($\varepsilon = M_v/M_d = 0.622$). The three terms on the right-hand side of Equation 1 represent contributions from ΔT_a, Δq, and Δp on urbanization-induced ΔVPD, respectively. The plus or minus signs before each item indicates positive or negative contribution, respectively (see *SI Appendix*).

The Pearson correlations between the annual mean ΔVPD and six biophysical drivers, that is, Δq, ΔT_a, ΔLAI, ΔET, ΔISAs, and AI (PET/P) were used to explain the magnitude of UDI (i.e., ΔVPD > 0) (see *SI Appendix*). In this study, a p-value less than 0.01 was considered to be statistically significant.

3. Results and Discussion

3.1. Observed Warming and Drying Trends Due to Urbanization Across All Climatic Regimes

Differences in VPD increased only slightly during 1980–2000, but increased more obviously for the period of 2001–2018 in all five urban agglomerations (Figure 1). Similarly, changes in air temperature ΔT_a ($T_{a\ \text{Urban}}$–$T_{a\ \text{Rural}}$) (or UHI intensity) and humidity Δq (q_{Urban}–q_{Rural}) (or UDI intensity) were also significant at various degrees. Interestingly, Δq was mostly positive with a slight decrease trend prior to 2005, but became negative and decreased much strongly afterwards. Prior to 2005, ΔVPD fluctuated with ΔT_a, but followed more closely with Δq after 2005 (Figure 1). The number of years (i.e., frequency) show both ΔVPD > 0 and UHI ($\Delta T_a > 0$) increased with intensification of urbanization over time. The frequency of the UDI ($\Delta q < 0$) was relatively stable initially, but increased much strongly afterwards (Figure S3 in the Supporting Information S1).

Overall, the humid PRD and semi-humid YRD showed the most pronounced UDI (ΔVPD = 0.7 ± 0.04 and 0.4 ± 0.06 hPa, respectively) (Figure 1; Table S3 in the Supporting Information S1) during the post urbanization period, except for TSB, which had the largest ΔVPD due to extremely high ΔT_a. Similar to ΔVPD, Δq was most pronounced in humid and semi-humid areas (Figure 1, Figure S4 and Table S3 in the Supporting Information S1). For the semi-humid CY and the arid TSB, Δq was positive for both 1980–2000 (0.03 ± 0.007 and 0.19 ± 0.009 g/kg, respectively) and 2001–2018 (−0.00 ± 0.04 and 0.04 ± 0.02 g/kg, respectively). However, the magnitude of Δq decreased by 0.03 g/kg (CY) and 0.15 g/kg (TSB), respectively after 2000, indicating water vapor was also

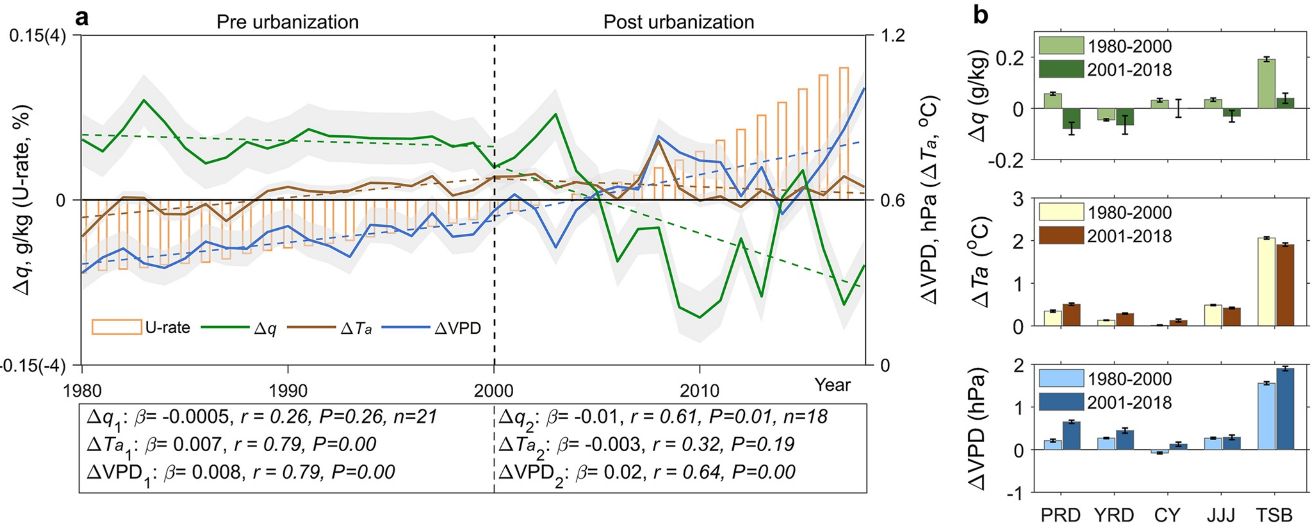

Figure 1. Anomalies of urbanization ratio (proportion of impervious surface area) and difference in near-surface air temperature (T_a), atmospheric humidity (q), and Vapor Pressure Deficit (VPD) for (a) annual mean across all for the five urban agglomerations over time from 1980 to 2018 and (b) mean by time periods and regions. The surface urban heat island intensity (ΔT_a, °C), Urban Dry Island (UDI) intensity ($\Delta q < 0$, g/kg), and ΔVPD (hPa) were the differences in near-surface air temperature, atmospheric specific humidity, and vapor pressure deficit between the urban and the adjacent rural land and were calculated based on 140 urban-rural paired sites. The five urban agglomerations span a large climatic gradient from humid to arid zone, including the Pearl River Delta , the Yangtze River Delta, Chengdu-Chongqing , Beijing-Tianjin-Hebei, and the Northern Tianshan cities. Orange bars in (a) are anomalies of average impervious surface area (i.e., urbanization ratio, U-rate) across the five urban agglomerations in China. Anomalies are relative to the mean of 1980–2018. Three lines and shading areas illustrate the mean and SD of Δq, ΔT_a and ΔVPD. Error bounds are ±1 s.e. β denotes the slope of the multiple linear regression.

declining in these two regions. Notably, TSB that represented as an 'Oasis Wet Islands' in an arid zone appeared to become drier during 2005–2012.

During 1980–2018, T_a and VPD in both urban and rural areas showed increasing trends over time (Figure S2 in the Supporting Information S1) consistent with the global warming trend. Importantly, ΔT_a and ΔVPD were mostly positive and Δq were negative after 2000, suggesting that urban core areas were hotter and drier than the rural counterpart (Figure 1). Meanwhile, ΔVPD and negative Δq values increased over time as well (Figure 1). Therefore, this study indicated that urbanization aggravated effects of climate warming on local atmospheric drying (ΔVPD > 0 and $\Delta q < 0$). The intensity of UDI also increased over time (i.e., the magnitude of ΔVPD and Δq increased over time during 1980–2018).

3.2. Atmospheric Drying Caused by Both Rise in Air Temperature and Loss in Water Vapor Source

It came no surprise that the increase in T_a due to global warming and/or UHI corresponded to an increase in VPD in urban areas because warmer air can hold more water vapor. However, attribution analysis found that the rise of ΔT_a alone was not sufficient to explain the observed increase in ΔVPD for the period of 2001–2018 (post urbanization period) (*SI Appendix*; Figure 2).

Both Δq and ΔT_a significantly contributed to ΔVPD during the entire study period (Figure 2). However, the overall contribution of ΔT_a to ΔVPD was much greater during the first period of 1980–2000 (73%) than that during the later period 2001–2018 (56%) (Figure 2a), while the overall contribution of Δq to ΔVPD was much greater during the later period 2001–2018 (43%) than that during the first period of 1980–2000 (24%) (Figure 2b). For both periods, the contribution of atmospheric pressure (Δp) was negligible (Figures 2a and 2b). The individual contributions of ΔT_a and Δq to ΔVPD varied by climatic region (Figure 2c; Figure S5 in the Supporting Information S1). Different from dry regions (represented by JJJ and TSB), contributions of Δq increased from the first period (1980–2000) in all three humid or semi-humid regions. In the humid YRD, humidity (Δq) effects even exceeded that of ΔT_a during the second period (post 2000), and more than 63% of the observed change in VPD could be explained by the differences in Δq (Figure 2c; Figure S5 in the Supporting Information S1).

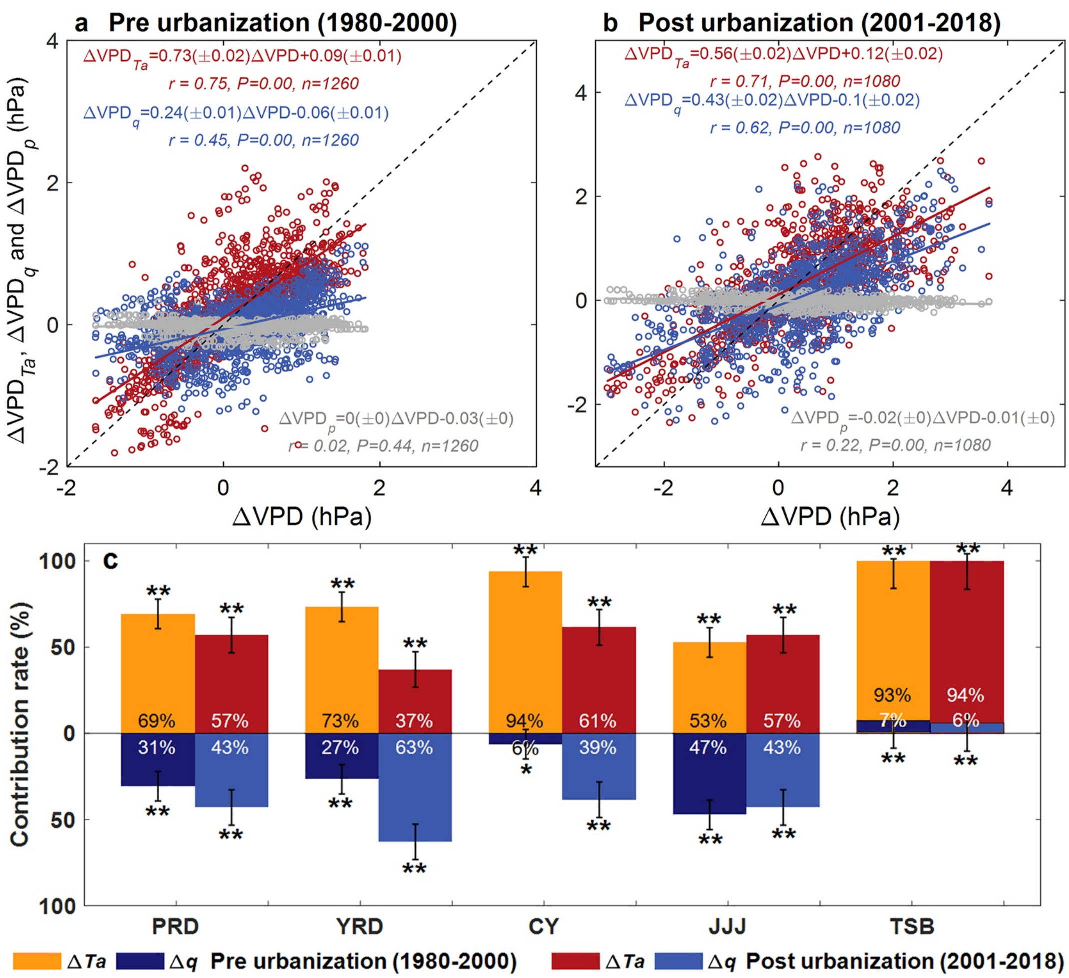

Figure 2. Contributions from Δq (ΔVPD$_q$), ΔT_a (ΔVPD$_{Ta}$), and Δp (ΔVPD$_p$), to annual mean ΔVPD individually during periods of (a) 1980–2000 (pre urbanization period) and (b) 2001–2018 (post urbanization period), and (c) Relative individual contributions of Δq, ΔT_a, to annual mean ΔVPD in the five urban agglomerations across China. ΔVPD (hPa), ΔT_a (°C), Δq (g/kg), and Δp (hPa) represents urban-rural differences in annual mean vapor pressure deficit, near-surface air temperature, atmospheric specific humidity, and atmospheric pressure respectively. In (a) and (b), all year-site data except TSB (arid region) were pooled. Lines are linear regression with regression statistics noted. Errors on the regression parameters are 95% confidence bounds. In (c), contribution (%) of ΔT_a are shown in the upper panel and contribution rate of Δq in the lower panels. Error bars are ±1 s.e. Confidence levels are denoted by $*P < 0.01$ and $**P < 0.001$.

The variable relationships between ΔT_a, Δq and ΔVPD over time offered additional evidence that climate and stage of urbanization affected UDI characteristics (Figures S6 and S7in the Supporting Information S1). The intensification of UDI ($\Delta q < 0$ and inter-decadal variation of Δq, $\Delta\Delta q < 0$) and the UHI ($\Delta T_a > 0$ and $\Delta\Delta T_a > 0$) (Figure 2; Table S3 and S4 in the Supporting Information S1) were coupled, and both contributed to the increase in urban atmospheric dryness (ΔVPD >0 and $\Delta\Delta$VPD >0) in recent two decades (2000–2018).

Because specific humidity (q) does not vary with temperature or pressure, the decrease in q (negative Δq) over time was likely the result of loss in local water vapor source and ecohydrological change. Given the attribution analysis by both region and time of urbanization progression (Figure 2; Figure S5 in the Supporting Information S1), and close correlations between Δq and ΔVPD in the recent time period (Figures S6 and S7 in the Supporting Information S1), it is reasonable to conclude that loss of water vapor due to urbanization aggravated atmospheric drying (ΔVPD > 0).

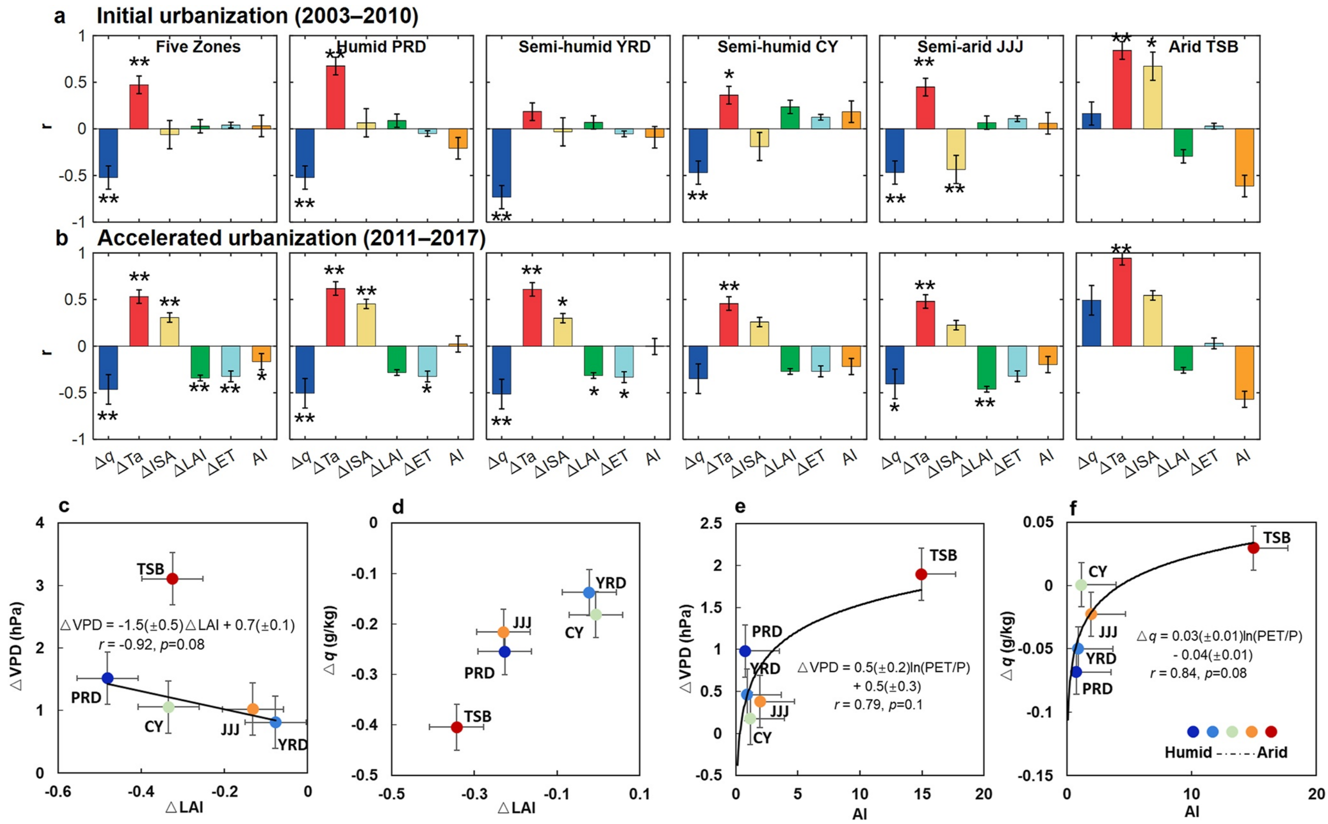

Figure 3. A summary of the relationships across climatic gradient from humid to arid zones for (a) ΔVPD versus six biophysical drivers during 2003–2010 (initial urbanization period) and (b) ΔVPD versus six biophysical drivers during 2011–2017 (accelerated urbanization period) to explain the causes of six biophysical factors affecting magnitude of UDI, and (c) ΔLAI versus ΔVPD, (d) ΔLAI versus Δq, (e) AI versus ΔVPD, and (f) AI versus Δq for post urbanization periods of 2001–2017 to show variable atmospheric moisture response to urbanization due to background climatic differences. Only data that had ΔVPD > 0 and $\Delta q < 0$ (UDI occurred) were pooled in (a–d) ΔVPD, ΔLAI, ΔET, Δq, ΔT_a, and ΔISA represents urban-rural difference in annual mean vapor pressure deficit, leaf area index, evapotranspiration, atmospheric specific humidity, near-surface air temperature, and ISAs (proportion of impervious surface area), respectively. AI is the aridity index, the ratio of annual potential evapotranspiration and precipitation (PET/P). Confidence levels are denoted by $*P < 0.01$ and $**P < 0.001$. Error bars are ±1 s.e. Lines are linear regression with regression statistics noted. Errors for the parameters in the regression models represent 95% confidence bounds (regression line in **d** not plotted, $p > 0.1$).

3.3. Magnitude of UDI Controlled by Local Background Climate and Vegetation Characteristics

Correlations between annual mean ΔVPD and Δq and change in common biophysical variables confirmed that ecohydrological processes such as land cover change-induced change in ET contributed to UDI (Figures 3a and 3b, Figures S8 and S9 in the Supporting Information S1). Overall, ΔT_a, ΔISAs, and Δq had significant correlations with ΔVPD ($P < 0.001$) during both periods of 2003–2010 (Figure 3a) and 2011–2017 (Figure 3b), suggesting consistent influence of T_a, ISAs, and q on VPD at all stages of urbanization.

The correlation between ΔLAI and ΔVPD generally changed from positive in the first period (2003–2010) to negative in the second period (2011–2017). This was especially true when UDI (ΔVPD > 0 or $\Delta q < 0$) occurred (Figures 3a and 3b; Figures S8 and S9 in the Supporting Information S1). However, the correlation between ΔLAI and ΔVPD is insignificant in some regions (Figure 3b). This indicates that ΔT_a and Δq still dominated local atmospheric drying, while changes in vegetation, impervious surface and ET exerted additional influences on VPD under intensified urbanization conditions, especially in humid areas. Another reason that the correlation between ΔLAI and ΔVPD in some regions was not significant may be due to the low resolution (1 × 1 km) of LAI and ET data used in this study that could bring some uncertainties. In addition, the variability of ΔLAI might be too small within one urban-rural cluster pairs to have a strong statistical relationship with ΔVPD. We found that ET decreased significantly in the five urban cores from 2003 to 2017 (Figure S10 in the Supporting Information S1). Overall, ΔET was negatively correlated with ΔVPD during the accelerated urbanization period (Figure 3b). All evidence about the linkages between ET and VPD further suggested that ecohydrological processes contributed to UDI.

When vegetation and climate data for the five climatic zones were pooled, a general pattern emerged. Except for the arid TSB, ΔLAI was negatively correlated with ΔVPD ($r = -0.92$, $P = 0.08$) during 2001–2017 (Figure 3c). For all five climate zones, mean ΔVPD became significantly negatively correlated with ΔLAI ($r = -0.45$, $P = 0.00$) during accelerated urbanization period of 2011–2017 (Figures S8a and S9 in the Supporting Information S1) in contrast to the initial urbanization period of 2001–2010 ($r = -0.04$, $P = 0.79$). Across climate gradient, ΔVPD (or Δq) was also found to follow with ΔLAI more closely after 2010 (Figure S11 in the Supporting Information S1). Correlations between Δq and ΔLAI ($r = 0.85$, $P = 0.15$) (except TSB) were weaker during 2001–2017 across climate gradient comparing to the ΔVPD and ΔLAI relationship (Figures 3c and 3d). Both ΔVPD and Δq showed significantly positive correlations with aridity index (PET/P) during 2001–2017 (Figures 3e and 3f; Figure S11 in the Supporting Information S1).

Urbanization was more likely to cause ‘Oasis Wet Islands’ ($\Delta q > 0$) effects in the arid zone (e.g., the TSB area), while urbanization was more likely to trigger the ‘Urban Dry Island’ ($\Delta q < 0$) effects in the humid regions (Figure 1; Tables S3 and S4 in the Supporting Information S1). The arid zone (TSB) became drier with increased VPD as those in other humid regions, but the drying trend was mostly caused by global climate warming and localized UHI effects (Figures 1 and 2; Figure S5 in the Supporting Information S1). However, in humid ‘energy limited’ regions where soil water does not limit ET, biophysical factors such as leaf biomass that directly affects ET becomes more important. In addition to global warming and localized UHI effects, the loss of vegetation cover (i.e., forests, natural and man-made wetlands such as rice paddies) can result in loss of ET and water vapor sources, thus jointly caused the increases in VPD and decline in q in urban areas in humid regions.

It should be noted that some of the six biophysical drivers are likely correlated with each other in certain climates. For example, ET and LAI are known to positively correlate in most ecosystems (Sun et al., 2011). Urbanization does not necessarily mean a decrease in LAI in arid regions where artificial greening using irrigated plants is common. In this case, like the TSB region in this study, ‘Oasis Wet Islands’ occur. Nevertheless, our results identified a few understandable and quantifiable drivers that help to explain the UDI effects.

4. Implications for Urban Environmental Change

Our data show that UHI and UDI processes are coupled through latent heat or the ET processes (Figure S12 in the Supporting Information S1). The linkages between land surface ecohydrological processes and UHI and UDI found in this study have important implications for understanding regional climate change, urban environmental threats, and land planning and management. Our findings are consistent with previous statement that ET is one of the important atmospheric moisture sources (Trenberth, 1999; Trenberth et al., 2003; Wei et al., 2016) that plays a central role in climate stabilization by offsetting air temperature and moisture fluctuations (Lee et al., 2011; Pielke, 2005). Large-scale conversion of vegetated lands to urban uses leads to a significant reduction in ET, which reduces ‘air conditioning’ functions of ecosystems (Hao et al., 2015; Sun et al., 2017) and may be sufficient to alter the precipitation, latent heating, and thus atmospheric circulation and moisture transport (Trenberth, 1999). Thus, the role of vegetation in slowing down the effect of UHI and UDI and maintaining regional climatic and hydrological stability should be considered as nature's ecosystem services (Kalnay & Cai, 2003; Vose et al., 2011). Unfortunately, we know little about how land cover change (i.e., leaf area index, LAI), ecohydrology (i.e., ET) and meteorological (i.e., air temperature and humidity) interact during urbanization. For example, there are few flux measurements in urban environments globally. Current remote sensing-based ecohydrological measurements (e.g., ET, ecosystem productivity) and land surface modeling efforts often exclude urban areas, and we have rather limited knowledge of urban ecosystem functions (Fisher et al., 2020; Senay et al., 2013; Zhao et al., 2021). The biophysical variables identified by this study may help the modeling and remote sensing efforts that aim at quantifying urban environmental changes and their broad effects on the global climate.

One of the many Nature-based Solutions (International Union for Conservation of Nature (IUCN) 2009) to mitigate detrimental urbanization effects is urban forestry-tree planting or installing other green infrastructure (i.e., wetlands, afforestation) within or around city areas (Li, Sun, Caldwell, 2020; Li, Sun, Cohen, 2020; Sun et al., 2011). However, recent synthesis of global climate datasets found a sharp increase in VPD since the late 1990s and highlighted the importance of VPD in ecosystem functions (Yuan et al., 2019). A large increase in VPD under a drier and hotter climate is likely to cause an increase in tree water use and drought stress, threatening the health of urban forest ecosystems (e.g., productivity and vulnerability to insect and disease attacks) (Novick et al., 2016; Vose et al., 2012). In many regions, the number of wildland fires and burning areas at the urban-rural interface are on the rise partially due to global warming and atmospheric drought (i.e., increase in VPD) (Mueller et al., 2020; Sedano & Randerson, 2014). Urban planners should carefully design landscape and evaluate introduced plants about their ability in adapting to novel urban climatic environments (i.e., temperature, VPD, aridity, wind, and pollution levels).

Our findings highlight the importance of vegetation in affecting local atmospheric moisture and temperature, and for developing mitigation and adaptation strategies in response to climate change. Maintaining forest vegetation and wetlands, thus the evapotranspiration power of nature, should be a core element of 'Low-Impact Development' and 'Nature-based Solutions'. These strategies represent modern integrated watershed management options to mitigate the negative environmental impacts of urbanization. Measures that mitigate impacts of urbanization on UHI and UDI likely benefit ecosystems as well as human health in an increasingly urbanized world.

5. Conclusions

Based on empirical data, this study revealed a plausible connection between land-use change and an urban atmospheric moisture drying phenomenon, or the UDI effect across a large climatic gradient. We showed that the five large urban agglomerations in China have experienced aggravated atmospheric drying during the past 30 years. We concluded that global warming, the UHI effects, the loss of vegetation and the associated decrease in evapotranspiration have all contributed to the UDI effects. With the acceleration of worldwide urbanization and a drying trend of atmospheric humidity (i.e., increased VPD) due to climate warming, the UDI effects may become more pronounced and more common in the future.

This study provided new insights into the likely mechanisms of urbanization impacts on atmospheric humidity by linking land surface ET processes and near surface air moisture and temperature. However, other physical processes such as anthropogenic vapor injection due to combustion and artificial irrigation, convective flux of heat and moisture via entrainment, and advection moisture from surrounding areas that contribute to the UDI are not explicitly examined. Essentially, our attribution analysis represents the 'net effects' of environmental change (i.e., global warming, land use/cover change, lateral mass flows etc.) on the UDI.

Future studies are needed to explicitly link energy/water balance and temperature and humidity change in rural and urban systems by employing paired flux measurements combined with high-resolution remote sensing monitoring and modeling. Such process-based studies are essential for understanding how temperature and humidity change affects the UHI and UDI that occur for surface, atmospheric, and subsurface environments. Further analysis of diurnal and seasonal variations of the UDI are also needed to better identify the role of vegetation at fine temporal scales in UDI. Such an integrated endeavor is likely to result in a unified analytical framework to quantify UDI processes and the impacts of UDI on the urban ecosystems.

Conflict of Interest

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

Data Availability Statement

The weather observation data are available online (http://data.cma.cn/en); the Global Land Surface Satellite (GLASS) LAI data sets (version 3.0) are free available online (http://www.glass.umd.edu/Download.html); Impervious surface data set are free available online (http://data.ess.tsinghua.edu.cn/gaia.html); and USGS FEWS NET SSEBop Actual Evapotranspiration Products (Version 5.0) are free available online (https://earlywarning.usgs.gov/fews/product/458). The raw data used in this study are free available via https://doi.org/10.5281/zenodo.5768800.

Acknowledgments

This research was supported by National Key Research and Development Program of China (grant 2019YFC1510202) and the National Natural Science Foundation of China (grants 41877151, 42061144004, and 41977409). Partial support was also from the Southern Research Station, United States Department of Agriculture Forest Service.

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