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Key Points:

- Proposed urban dry island (UDI) to characterize urbanization effects on reducing atmospheric humidity and elevating vapor pressure deficit
- Enhanced UDI effects are explained by feedback of the ecohydrological cycle to urban land cover change
- Urban heat island and UDI effects are coupled and should be collectively addressed in urban planning and climate change assessment

Supporting Information:

- Supporting Information S1

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Ecohydrological Processes Explain Urban Dry Island Effects in a Wet Region, Southern China

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Abstract Conversion of agricultural lands to urban uses affects regional and global climate not only through the release of greenhouse gases but also through altering land surface physical processes such as energy and water balances. Most existing studies on the meteorological impacts of urbanization focus on urban heat island effects with little attention on its impacts of atmospheric humidity, a key variable in hydrometeorology and climate science. We define the influences of urbanization on reducing atmospheric humidity and elevating vapor pressure deficit as urban dry island (UDI) effects. We conduct a case study in the Yangtze River Delta, a typical humid area in southern China that is under rapid urbanization. We examine spatiotemporal characteristics of UDI and identify potential drivers during 2001–2014. Relationships and interactions between variations of air temperature, atmospheric humidity, evapotranspiration, and leaf area index of different land cover were determined using correlation and attribution analyses at both station and regional levels. We show that atmospheric humidity decreased dramatically and vapor pressure deficit increased sharply in the urban core, resulting in enhanced UDI. In addition to global warming and localized urban heat island, UDI is closely related to the loss of vegetation cover (i.e., natural wetlands and paddies). Reduction of evapotranspiration or latent heat is another important factor contributing to UDI effects. We conclude that the role of vegetated land cover and associated ecohydrological processes in moderating UDI and maintaining a stable climate and environment should be considered in massive urban planning and global change impact assessment in southern China.

1. Introduction

Land use and land cover (LULC) change reflects important interactions between natural ecosystems and human activities (Mooney et al., 2013; Sterling et al., 2012). The first-order effects of LULC change on climate have been well studied at multiple scales (Hansen et al., 2005; Huber et al., 2014; Pielke, 2001). LULC due to urbanization alters terrestrial ecosystem structure and functioning permanently, inevitably leading to profound impacts on the water and energy balances by influencing surface evapotranspiration (ET; Foley et al., 2005; Hao et al., 2015). Urbanization increases the surface temperature by enhancing sensible heat flux and soil heat flux at the expense of latent heat flux, which leads to the well-known urban heat island (UHI) effect (Arnfield, 2003; Howard, 1833; Oke, 1982; Zhao et al., 2014; Zhou, Li et al., 2016; Zhou, Zhang et al., 2016). These feedback between LULC change and the ecohydrological cycle are particularly evident in subtropical humid areas dominated by rice paddy fields (Hao et al., 2015; Sun et al., 2017). Although water vapor is one of the most important greenhouse gases (Kiehl & Trenberth, 1997), and the water vapor condensation process in the lower troposphere is the key to quantify atmospheric latent heat transmission (Trenberth & Stepaniak, 2003), little is known about how urbanization affects atmospheric humidity, that is, the urban dry island (UDI) phenomenon (Akinbode et al., 2008; Lokoshchenko, 2017; Moriwaki et al., 2013; Sakakibara, 2001; Yang et al., 2016).

Literature on UDI, the drying of climate in cities is limited. Very few attempts have been made to link UDI to ecohydrological cycle feedback to urbanization-associated land cover change. Early studies have recognized the UDI phenomenon (Ackerman, 1987; Hage, 1975; Chow & Chang, 1984; Sakakibara, 2001), but only recent efforts start to explore the underlying processes (Chhetri et al., 2017; Lokoshchenko, 2017; Moriwaki et al.,

2013) and refine the concept. Ackerman (1987) and Hage (1975) compared dew-point temperature in urban and rural areas and analyzed the effects of urbanization on relative humidity (RH) and absolute humidity, respectively. Sakakibara (1985), Sakakibara (2001), and Moriwaki et al. (2013) concluded that UDI effects existed and there were significant differences in water vapor between rural and urban areas in Japan. Chhetri et al. (2017) standardized the UHI and UDI effects by focusing on the local climate zones in the Matsuyama plain of Japan.

Most previous process-based studies related to UDI have focused on humidity change 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). Research relating LULC change (i.e., leaf area index [LAI]) to the coupling of hydrological (i.e., ET) and meteorological (i.e., air temperature and humidity) processes is limited (Foley et al., 2005), especially in the subtropical humid region (Sun et al., 2017). A limited number of studies indicated that the role of land cover in slowing down the effect of UHI and UDI and maintaining regional climatic and hydrological stability should not be ignored (Kalnay & Cai, 2003; Pielke et al., 2011; Vose et al., 2011).

It is well known that vegetated lands consume a large amount of energy on ET, thus reducing sensible heat and cooling the surrounding atmosphere (Hao et al., 2015; Peng et al., 2014; Sun et al., 2005). Kalnay and Cai (2003) found that the surface temperature doubled due to urbanization and conversion of agriculture land when compared to urbanization effect alone during 1950 to 1999 over the United States. Trees and wetlands are more beneficial for alleviating UHI (Ellison et al., 2017; Shastri et al., 2017) and UDI (Wang & Gong, 2010) effects than urban land cover, dryland, bare land, or grasslands. The cooling effects of increased latent heat flux from agricultural irrigation may have explained the differences between global circulation models and ground observations in the massive irrigated region in Central America (Brunsell et al., 2010). Similarly, converting wetlands (e.g., rice paddy field) with high ET to urban uses leads to a sharp decrease in ET and thus UHIs (Sun et al., 2017; Zhou, Li et al., 2016) in humid regions in China.

Previous studies have recognized the interactions between vegetation, hydrology, climate, and UHI and UDI (Pielke et al., 2011; Vose et al., 2011; Lawrence & Chase, 2010). Nevertheless, the existing studies mainly focused on the phenomenon description of the UHI and UDI effects (Chhetri et al., 2017; Lee et al., 2011; Zhou, Li et al., 2016). Little is known about the interactions of ecohydrological processes and regional climate feedback in highly urbanized regions. The environmental effects of vegetation (i.e., wetlands/rice paddies) cover conversions may have been severely underestimated (Hao et al., 2015).

Ecohydrological research in the past decades shows that ET or latent heat flux is a key hydrometeorological variable, which uniquely connects water, energy, and carbon cycles (Fall et al., 2010; Pielke, 2005; Sun et al., 2011; Vose et al., 2011). Fisher et al. (2017) suggested that changes in ET can be used as an indicator of climate variability and change (Dai et al., 2004; Greve et al., 2014; Mao et al., 2015; Prudhomme et al., 2014; Sheffield et al., 2012). ET plays an important role in driving local weather patterns, affecting turbulence, cloud formation, and convection (Fisher et al., 2017; Zhang et al., 2002). The role of ET in affecting local hydrology and climate is especially pronounced in humid regions where precipitation is relatively high and growing season is long (Zhou et al., 2014). However, few studies have linked hydrological change such as ET reduction due to urbanization to local climatic change, atmospheric humidity in particular (Fisher et al., 2017; Hao et al., 2015).

The Yangtze River Delta (YRD) region with high population density is the most industrialized part of the subtropical region in China, representing one of the largest urban agglomeration. Rapid urbanization in this region has resulted in obvious UHI (Zhou, Zhang et al., 2016) and associated environmental and human health concerns. However, most existing studies focus on the meteorological impacts of urbanization such as UHI, with little attention on UDI effects (Chow & Chang, 1984; Gu et al., 2009; Zhou, Li et al., 2016). The overall goal of this study was to present evidence of UDI development and to identify its potential ecohydrological drivers. We determined the spatial and temporal relationships between atmospheric humidity and LAI, ET, and atmospheric temperature at both station and regional levels using a series of correlation and attribution analyses. We hypothesized that the large-scale urbanization with conversion of paddy fields to urban use in this wet region altered the ecohydrological processes, therefore, also the energy partitioning, potentially resulting in an enhanced UDI effect through the combined impacts of global warming and UHI.

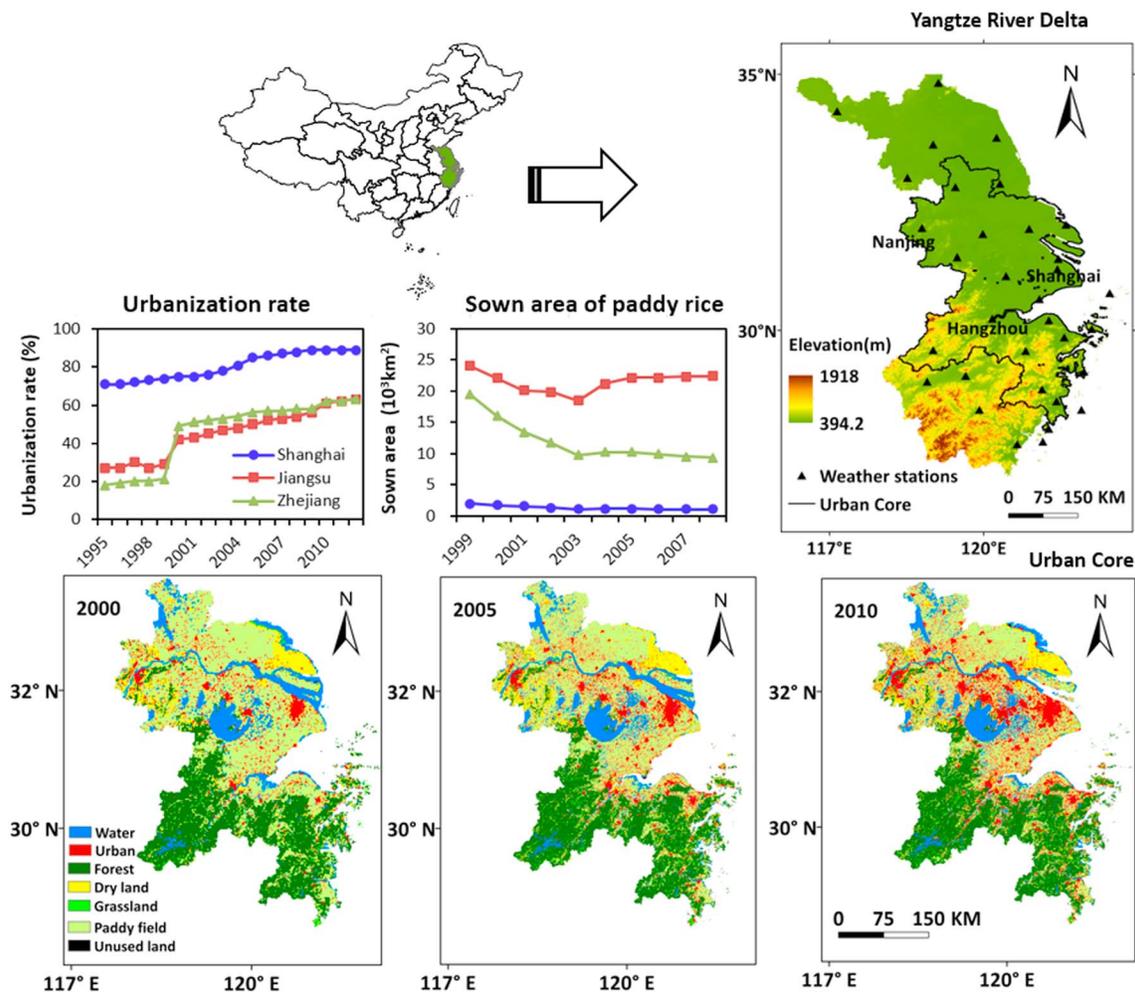


Figure 1. Location and land use and land cover (LULC) change patterns in 2000, 2005 and 2010 in the Yangtze River Delta. The inserts are urbanization rate and sown area of paddy rice, respectively.

2. Data and Methods

2.1. Study Area

The study region (YRD) covers Shanghai, one of the world's largest cities; Nanjing, and Hangzhou, which are the respective capitals of Jiangsu and Zhejiang provinces. The urbanization rates of these three large cities are about 89, 67, and 66%, respectively (Figure 1). The total land area of YRD is about 210,700 km² with a population over 159 million in 2015, of which 111 million are in urban. The region, representing 1% of China's land area, generated over 20% of China's total gross domestic product in 2016.

The local climate in the YRD is influenced by the East Asia summer monsoon (Wang et al., 2008). The long-term annual precipitation has a great seasonal variability in this region, varying from 1,000 mm/year inland to 1,400 mm/year near the coast, and almost 40% of the total annual precipitation occurs from June to August. The multiyear average air temperature is 14–18 °C. Generally, the atmospheric humidity increases from the west to the east and decreases from the south to the north, but the air temperature gradient is conversed (see supporting information Figure S1). Given the fertile alluvial soils, the hot and wet summer climate, and rich water resources, agriculture is intensive with abundant products of grain, cotton, hemp, and tea.

The region has seen dramatic land use change during the past decade. The dominant land cover type in the northern part of the YRD region in 2000s is crop lands, while the southern area is covered by forests. The central core area located in the southeast of Jiangsu Province, Shanghai, and the northern part of Zhejiang

Table 1
The Conversion Matrix for Land Cover Change during 2000–2010 in the Central Core of the Yangtze River Delta

| 2,000 (km ²) | 2,010 (km ²) | | | | | | | Total |
|---------------------------|--------------------------|----------------|--------|-----------|--------|--------|--------|---------|
| | Paddy | Dry crop lands | Forest | Grassland | Water | Urban | Unused | |
| Paddy | 41,001 | 86 | 388 | 13 | 1,202 | 6,420 | 14 | 49,125 |
| Dry crop lands | 83 | 6,585 | 61 | 3 | 100 | 720 | 12 | 7,562 |
| Forest | 146 | 80 | 30,579 | 105 | 104 | 401 | 36 | 31,451 |
| Grassland | 10 | 23 | 75 | 1,098 | 132 | 74 | 18 | 1,430 |
| Water | 144 | 67 | 33 | 14 | 10,522 | 319 | 1 | 11,101 |
| Urban | 200 | 21 | 21 | 1 | 117 | 9,754 | 11 | 10,124 |
| Unused | 0 | 12 | 2 | 0 | 0 | 9 | 20 | 44 |
| Total | 41,584 | 6,874 | 31,159 | 1,234 | 12,177 | 17,696 | 113 | 110,837 |
| Change (km ²) | −7,541 | −689 | −291 | −195 | 1,076 | 7,572 | 68 | − |
| Change (%) | −15 | −9 | −1 | −14 | 10 | 75 | 154 | − |

Province is dominated by paddy fields and urban areas (Figure 1). Over the past 10 years, the land conversion of paddy rice fields to urban use mainly occurred in the central area. The land cover change matrix in the central core indicated that from 2000 to 2010, the urban areas increased 7,572 km² or 75% at the expense of paddy fields (reduced 7,541 km², or 15%), drylands (reduced 689 km², or 9%), forest lands (reduced 291 km², or 1%), and grasslands (reduced 195 km², or 14%) (Figure 1 and Table 1). The detected decrease in cropland is mainly caused by the reduction in paddy rice fields.

2.2. The Conceptual Model

In general, the land-air exchanges of water and heat mainly depend on two factors: the vertical exchange rate through turbulence and differences in humidity or temperature between the ground surface and the atmosphere above. Based on previous studies in East Asia (Hao et al., 2015; Kim et al., 2014; Liu et al., 2013), we hypothesized that converting wetlands to “dry” urban impervious surfaces was bound to alter the land-air exchanges of water and heat, and thus the hydrological and meteorological processes. Processes and variables associated with the water and energy exchange between vegetation and the atmosphere and regional climate feedback include soil heat capacity, vegetation leaf area, surface albedo, aerodynamic roughness, and net radiation, which alters latent heat transfer (i.e., ET) and sensible heat transfer. This conceptual framework was used as a guide to examine how urbanization affects atmospheric humidity or UDI (Figure 2).

2.3. Regional LAI, ET, and LULC

The Global Land Surface Satellite (GLASS) LAI data sets (version 3.0; Xiao et al., 2016) generated from Moderate Resolution Imaging Spectroradiometer (MODIS) surface reflectance data at an 8-day and 1-km resolution were used to assess vegetation change during 2001 to 2014. The accuracy of estimated LAI dynamics was extensively validated for the study period (Xiao et al., 2016). The improved MOD16 data sets provide global actual ET estimates with a resolution of 8 days and 1 km (Mu et al., 2011). The LULC data for three key years, 2000, 2005, and 2010, were derived from Landsat TM/ETM+ images with a resolution of 30 m (www.geodata.cn). Based on ground observations, LULC can be classified into seven categories including water bodies, built-up land, forest, dryland, paddy field, grassland, and unused land. Both estimation stability and accuracy of data set were acceptable, and the overall classification accuracy is 94.3% (Yao et al., 2017). The urbanization rate and sown area data were obtained from government records (Joint research center of the Yangtze River Delta (JCYRD), 1996; Ministry of Agriculture of the People’s Republic of China (MAC), 2009).

2.4. Climate Data

The daily meteorological data were acquired from 33 standard weather stations across the YRD for the period 1961–2014. Meteorological data were obtained from the China Meteorological Administration and were used to calculate atmospheric humid indicators (i.e., specific humidity) and estimate potential ET (PET). The data set includes RH (%), wind speed (m/s), sunshine hours (h), and daily maximum and minimum atmospheric temperature (T_{\max} , T_{\min} , and °C). The Australian National University Splines (ANUSPLIN) model

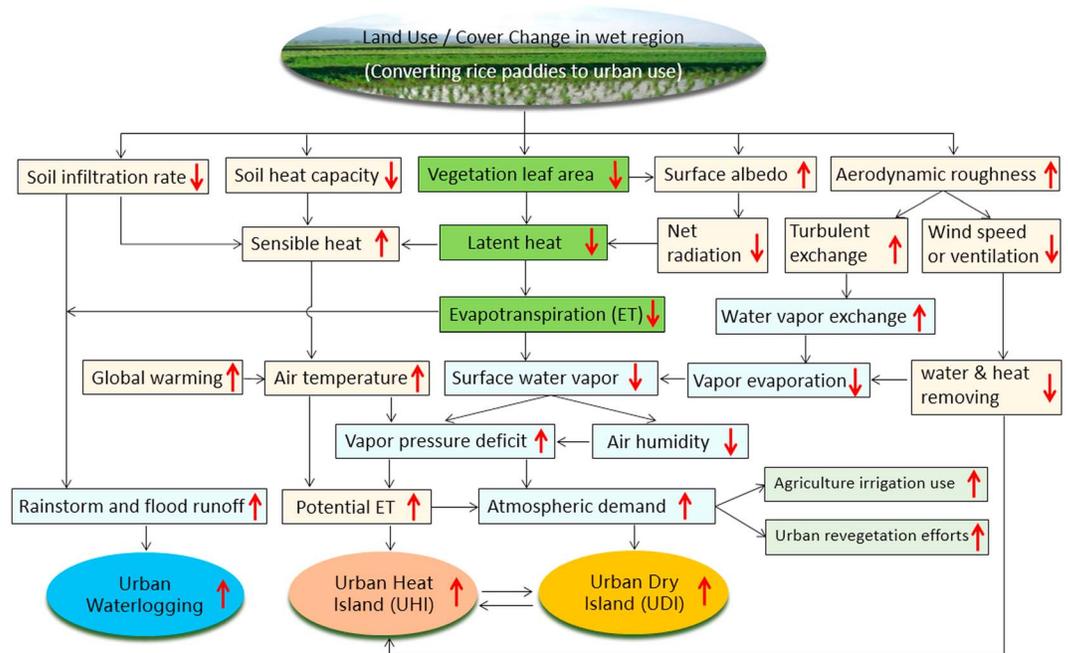


Figure 2. A conceptual model illustrating the potential climatic and environmental impacts of urbanization-associated land cover change in the Yangtze River Delta region. Arrows represent directions of change.

provides a powerful tool to optimize thin plate smoothing splines that can be fitted to data sets with any number of individual climate stations (Hutchinson, 2001). In this study, it was applied to interpolate the meteorological grid data with a 1-km spatial resolution. We used the partial thin-plate splines with a linear dependency on elevation, which was generated from digital elevation model with a 1-km resolution (www.geodata.cn).

2.5. Humidity Indicators

Literature suggests that none of the humidity variables is perfect for comparisons among physical locations. Given the functional sensitivity of RH and vapor pressure to temperature, specific humidity was preferred for investigating moisture differences among sites. In this study, RH, atmospheric water vapor pressure (e_a), specific humidity (q), and vapor pressure deficit (VPD) were examined. The description and calculation of humidity indicators were presented in supporting information (S1).

2.6. Sensitivity Coefficients and Contributions to PET

The “Sensitivity Coefficient” (Beven, 1979; Hupet & Vanclooster, 2001; McCuen, 1974) was adopted to compare the sensitivity of PET to changes in a number of climatic variables. We first examined partial derivatives to PET, and then PET trends were attributed by applying the “Contributions” method (Yin et al., 2010) by comparing the responding changes of PET to different meteorological variables during a 14-year period (2001–2014). As far as multivariable models is concerned (e.g., the Penman-Monteith method), each variable has a variety of dimensions and ranges of value, which make it not easy to make comparison of the sensitivity using a partial derivative. Therefore, a nondimensional form of the partial derivative is converted (Beven, 1979):

$$S_c = \lim_{X \rightarrow 0} \frac{\Delta \text{PET} / \text{PET}}{\Delta X / X} = \frac{\partial \text{PET}}{\partial X} \cdot \frac{X}{\text{PET}} \quad (1)$$

S_c is sensitivity coefficient, and X is the i th meteorological variable. McCuen (1974) adopted the transformation of “nondimensional relative S_c ” (hereinafter referred to as “ S_c ”) for the first time, which has been widely used at present (e.g., Beven, 1979; Hupet & Vanclooster, 2001). Generally speaking, a positive (or negative) S_c of a meteorological variable means that PET will be enhanced (or declined) as the meteorological variable

increases. For example, a S_c of 0.3 for a variable indicates that the variable increases by 10%, while all other variables remain unchanged, which may increase PET by 3%. The larger the S_c is, the higher a meteorological variable's contribution to PET is.

A meteorological variable's contributions (G_x) to PET trends were calculated by multiplying the relative change R_c ($R_c = \Delta X/X$) by the variable's sensitivity coefficient, S_c (Yin et al., 2010). The meteorological variable with the largest absolute value of G_x is considered as the dominant factor influencing PET trend in the corresponding time period. Meteorological variables examined include daily RH, daily air temperature, daily wind speed at a 2 m height, and shortwave radiation during a 14-year period. PET was estimated by the FAO-56 Penman-Monteith method (Allen et al., 1998).

2.7. Trend and Correlation Analysis

The nonparametric Mann-Kendall test (Kendall, 1975; Mann, 1945; see supporting information S1) was performed to detect the parameter trends. Five types of trend, "Significant increase," "Increase," "No change," "Decrease," and "Significant decrease" for each of the pixels within the YRD, were determined according to their Z values.

A correlation analysis was made for key variables at the pixel level including the pairs of ET and LAI, RH and ET, and LAI and VPD. Three types of correlation of "Significantly negative correlation" with $p < 0.1$, "Significantly positive correlation" with $p < 0.1$, and "Nonsignificant correlation" with $p > 0.1$ for each of the pixels were detected.

The relationships between air humidity and climatic factors and other factors are more complex because autocorrelations between these factors exist. In this case, the partial correlation method (De La Fuente et al., 2004) was applied to isolate how air temperature and ET influence air humidity individually.

3. Results and Discussion

3.1. Regional UDI Patterns

The regional RH trend suggested that the central urban core of the YRD was significantly drier compared to other rural areas in the southern and northern regions that had no significant change in RH (Figure 3a). The station-level RH data also showed a significant decreasing trend after 1991 in three mega cities of Shanghai, Nanjing, and Hangzhou, while the nonsignificant trends in three rural areas were found (Figure 3b).

Our study results agreed with the early studies on urbanization effects due to converting forests on atmospheric humidity by Ackerman (1987) and Hage (1975) in the U.S, Sakakibara (2001) and Moriwaki et al. (2013) in Japan, and Lokoshchenko (2017) in Moscow. In our study, the three parameters RH, water vapor pressure (e_a), and specific humidity (q) all indicated significant downward trends in the urban core during a 14-year period (Figures 3, 4). In addition, with the acceleration of large-scale urbanization, land cover change has increased dramatically in the urban-rural interfaces. Small- and medium-sized cities around mega-cities in the recent decade have formed a dry island cluster (Figure 3a), rather than isolated dry islands as reported by previous studies (Chow & Chang, 1984; Gu et al., 2009).

Although the mean surface air temperatures in the urban core did not increase significantly during 2001–2014 (Figure 5a), the differences of mean, minimum, and maximum surface air temperature between the urban core and surrounding areas have changed from negative (−0.2, −0.3, and −0.1 °C, respectively, during 1961–1970) to positive value (0.2, 0.1, and 0.2 °C, respectively, during 2001–2014), respectively. These change patterns suggested that the UHI effects have been enhanced due to local urbanization (Table 2). At the same time, the differences of RH, vapor pressure, and specific humidity between the urban core and the surrounding areas have changed from positive (2.5%, 0.34 hPa, and 0.14 g/kg, respectively, during 1961–1970) to negative values (−0.8 °C, −0.01 hPa, and −0.07 g/kg, respectively, during 2001–2014), suggesting an enhanced UDI as well.

3.2. Atmospheric Humidity Change Not Explained by Change in Air Temperature in the Urban Core

Over most of the southern region dominated by forest covers, RH and e_a decreased significantly but not specific humidity, q ($p > 0.1$; Figure 3a, 4) when temperature increased significantly ($p < 0.1$; Figure 5a), suggesting that air temperature was the potential dominant factor for the reduction of atmospheric humidity in the

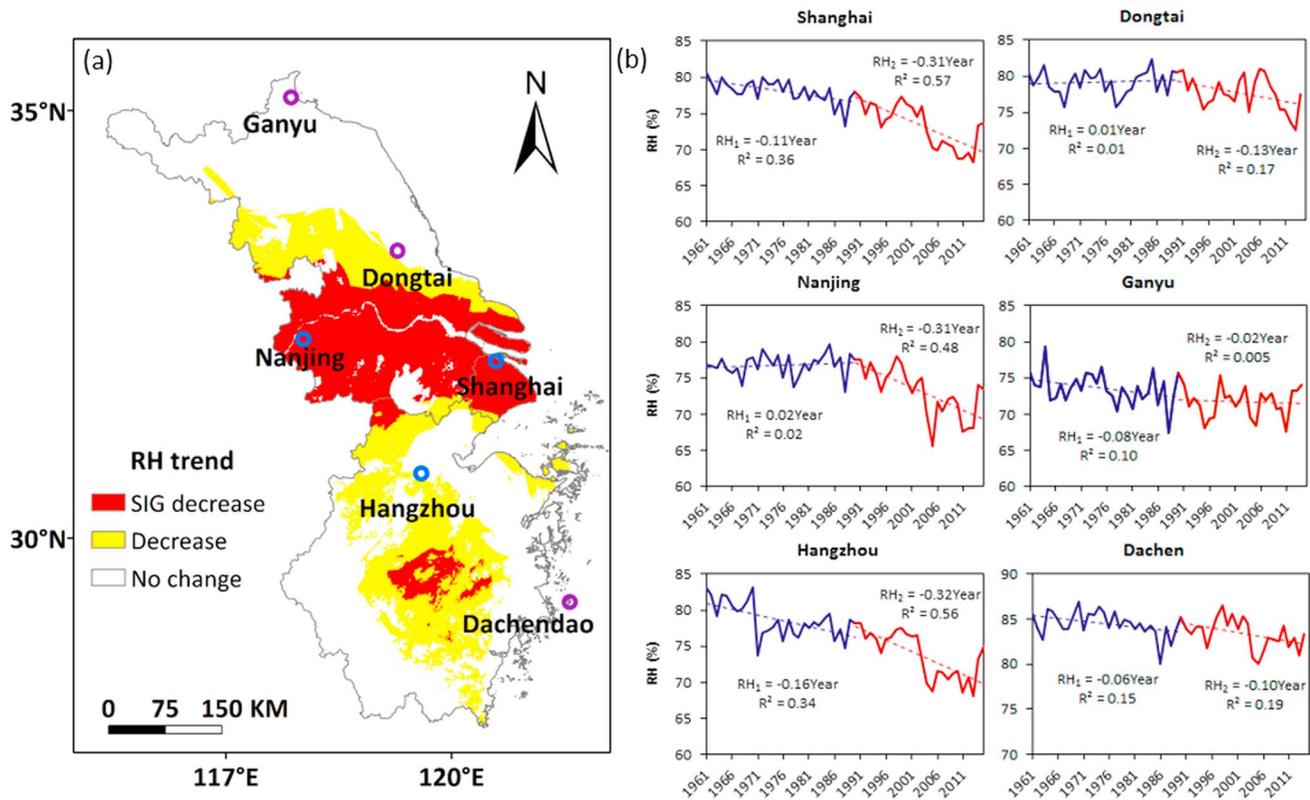


Figure 3. (a) Regional relative humidity trend (2001–2014) across the Yangtze River Delta and (b) observed relative humidity change in mega cities (blue circles in Figure 3a, left in Figure 3b) and rural areas (purple circles in Figure 3a, right in Figure 3b; 1961–2014).

southern region. The negative correlation (Figure 5b) between RH and air temperature in most of this area also confirmed this pattern. In the central urban core, however, RH decreased significantly ($p < 0.05$; Figure 3a), while air temperature had no significant change ($p > 0.1$; Figure 5a), and positive relationships

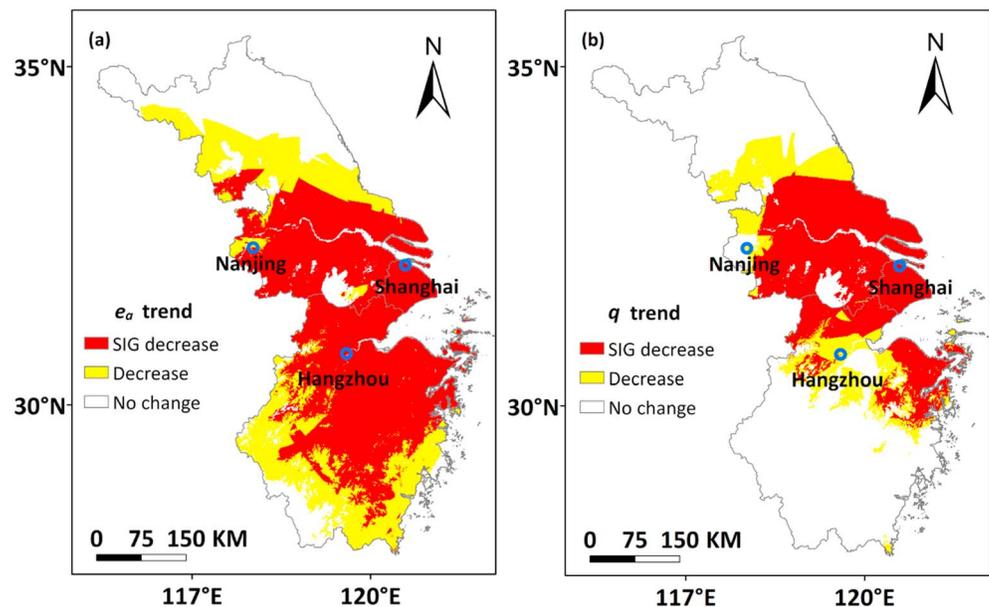


Figure 4. Trends of (a) vapor pressure (e_a) and (b) specific humidity (q) (2001–2014).

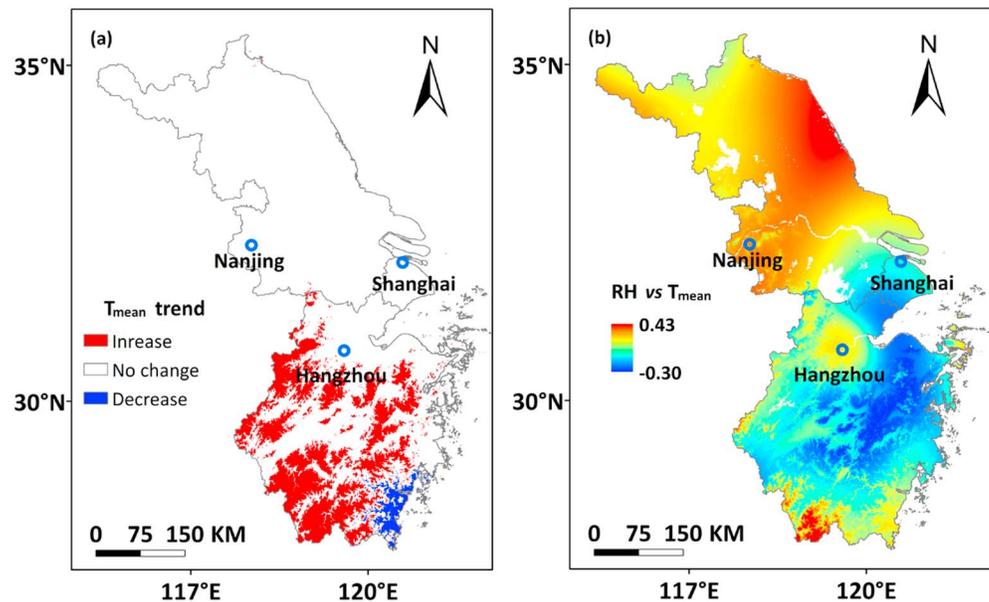


Figure 5. (a) The annual mean air temperature trend and (b) correlation of annual mean air temperature (T_{mean}) with annual mean relative humidity (RH) with no significant pattern observed across the Yangtze River Delta (2001–2014).

between RH and air temperature insignificant ($p > 0.1$; Figure 5b), suggesting that air temperature was not the dominant factor for the reduction of RH in this region.

3.3. Enhanced Urban Dry Island Explained by the Decreases in LAI and ET

Mean annual regional level LAI declined significantly ($p < 0.05$) in the central urban core, while LAI increased significantly ($p < 0.05$) in the southern area dominated by forest vegetation, and stable in the northern area (Figure 6a). Because the major decreased land cover type was paddy rice field (Table 1), the decrease of LAI was mainly a result of urbanization-associated land use change of rice paddy field to urban land (Figure 6a insert bars). In the central urban core, the decreased trend of annual mean ET followed a similar pattern to annual mean LAI (Figure 6b) with a significant positive relationship ($p < 0.1$; Figure 6c). ET did not correlate significantly with PET ($p > 0.1$) and did not follow a similar temporal pattern as PET in most regions (Figure 6d) during 2001–2014.

Converting croplands to urban use reduces vegetation leaf area, rooting depth, and surface roughness, thus reduces ecosystem ET rates (Sampaio et al., 2007). In humid, energy-limited regions in southern China, LAI is a major dominant factor for ET, especially during the growing season (Liu et al., 2013; Sun et al., 2011; Sun & Lockaby, 2012). In this study, a decreasing trend of the RH in most of the YRD was observed in a 14-year period. This decrease of RH is not surprising when the climate is warming up in theory. However, it appears the sharper decrease in RH in the urban core when compared with rural areas (Figure 3) was related to the decrease ET, thus the ecohydrological processes. We argued that the ET reduction reduced water vapor

Table 2
Differences in Temperature and Humidity Between the Urban Core^a and Surrounding Area^b in Five Periods

| Periods | T_{mean} (°C) | T_{min} (°C) | T_{max} (°C) | RH ^c (%) | e_a ^d (hPa) | q^e (g/kg) |
|-----------|------------------------|-----------------------|-----------------------|---------------------|--------------------------|--------------|
| 1961–1970 | −0.2 | −0.3 | −0.1 | 2.5 | 0.34 | 0.14 |
| 1971–1980 | −0.2 | −0.3 | −0.2 | 1.8 | 0.20 | 0.07 |
| 1981–1990 | −0.2 | −0.3 | −0.2 | 1.2 | 0.12 | 0.02 |
| 1991–2000 | −0.1 | −0.2 | −0.1 | 0.4 | 0.01 | −0.06 |
| 2001–2014 | 0.2 | 0.1 | 0.2 | −0.8 | −0.01 | −0.07 |

Note. The locations of the 33 weather stations can be found in Figure 1.

^aThe urban core includes 14 weather stations. ^bThe surrounding area includes 19 weather stations. ^cRH is relative humidity. ^d e_a is vapor pressure. ^e q is specific humidity.

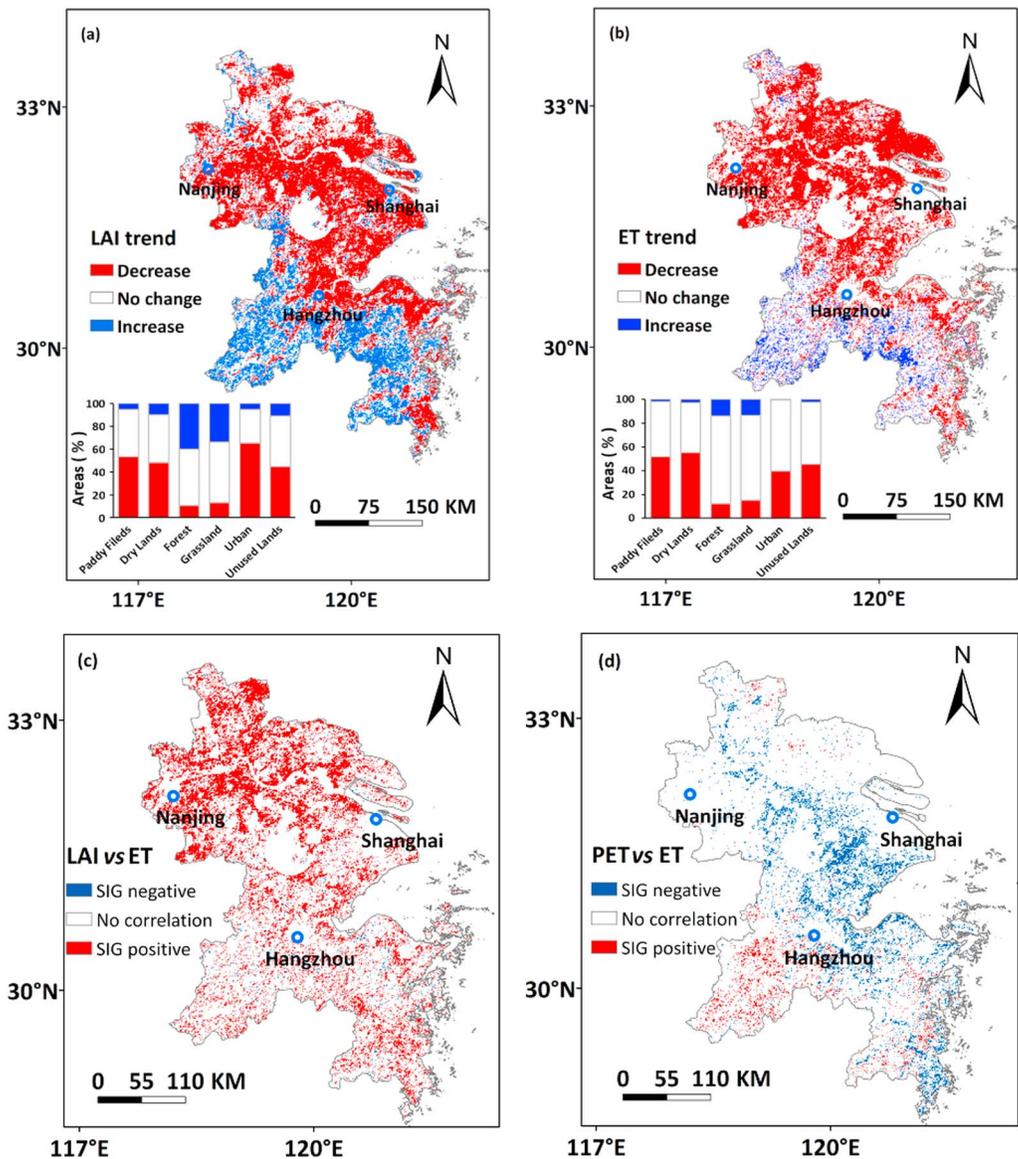


Figure 6. Temporal trend of annual mean (a) leaf area index (LAI), (b) evapotranspiration (ET), and correlation of (c) LAI versus ET and (d) observed potential ET (PET) versus ET (2001–2014). The insert bars are the proportions of three trends with different land cover types.

during urbanization. The strong relationships between atmospheric humidity and LAI/ET in the urban core at both station and regional levels (Figures 6–8 and supporting information Table S1) also confirmed our hypothesis that urbanization reduced ET greatly as a result of the decrease of LAI. The chain reaction of land use change might explain the observed decrease in water vapor in urban core. The atmospheric humidity showed drying patterns in both southern and urban cores (Figures 3, 4). However, potential drivers for the decreasing humidity trends in different regions differed, that is, rising temperature and intensive urbanization, respectively (Figure 5–7).

3.4. Changes in PET Trend and Dominant Influence Factors

We found that mean PET decreased first from 1960 to 1989 and then increased from 1990 to 2014 across the whole YRD. The sensitivity of PET to the meteorological variables was from large to small: RH, solar radiation, air temperature, and wind speed. During the PET decline period from 1960 to 1989, the contribution of air temperature, wind speed, RH, and solar radiation to the PET change were -0.8 , -1.8 , 0.7 , and -4.6% ,

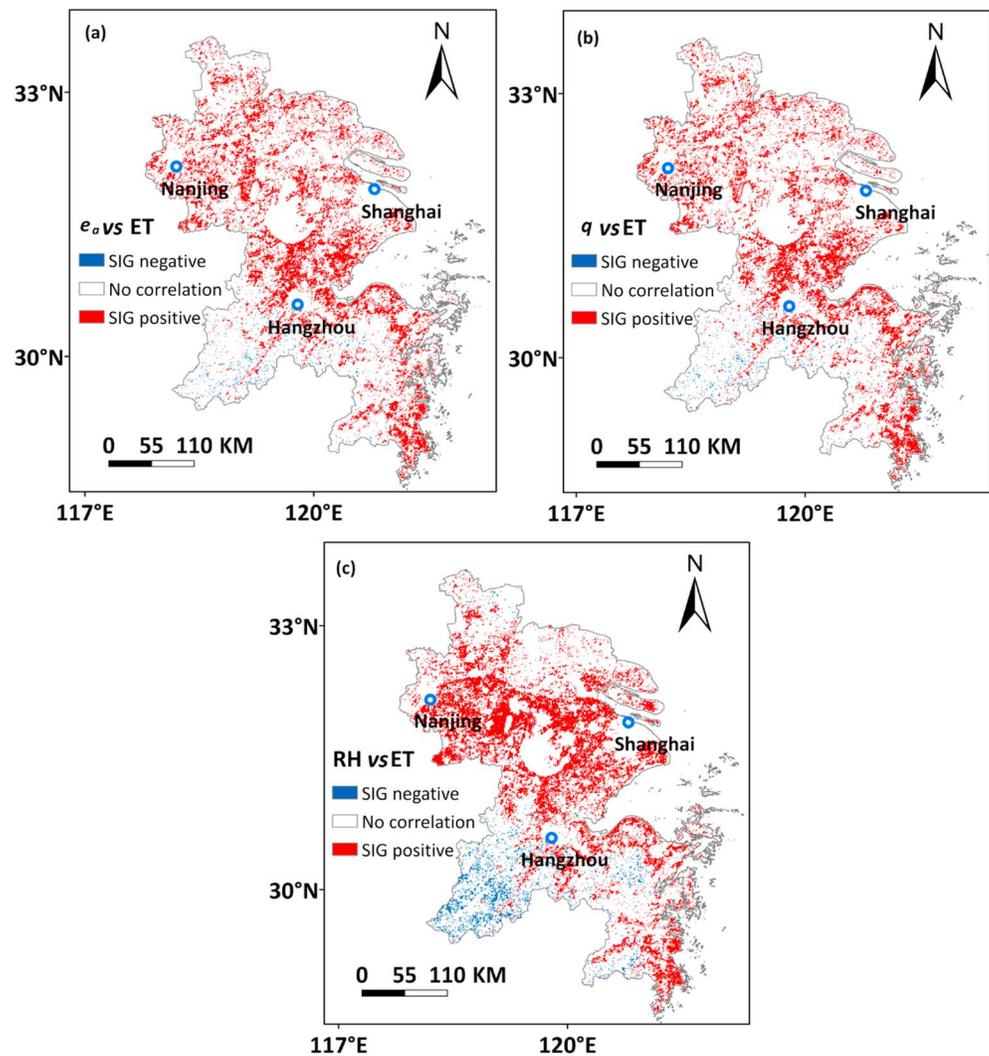


Figure 7. Correlations of (a) vapor pressure (e_a) versus evapotranspiration (ET) and (b) specific humidity (q) versus ET and (c) relative humidity (RH) versus ET (2001–2014).

respectively. Only RH affected the PET increase. Reduced incoming shortwave radiation was the dominant factor for PET decrease. During the PET rising period from 1990 to 2014, the contribution of air temperature, wind speed, RH, and solar radiation to PET change were 3.7, -2.2 , 9.7, and 1.3%, respectively. RH appeared to be the dominant factor for PET increase (Table 3). The gradual reduction in air temperature's dominance indicated that global climate warming does not consequentially result in an increase in atmospheric evaporative demand. This is consistent with the observations across China (Fan & Thomas, 2018).

3.5. Changes in VPD Linked to Changes in Vegetation LAI

In the urban core area, increased VPD (Figure 9a) correlated well with the reduction in vegetation LAI and ET spatially and temporally (Figures 9b and 9c). This observational result indicated that the increased VPD in the urban area was related to the conversion of paddy wetlands to urban uses. VPD had a significant positive correlation with PET ($p < 0.1$) across the whole YRD (Figure 9e). In addition to rising temperatures, the decreased atmospheric humidity (q or RH) is closely related to the rise of VPD (Figures 8d and 9f) and PET (Table 3). This is in agreement with our previous results that the atmospheric demand (i.e., VPD), instead of surface air temperature alone, is a dominant factor on PET in the Qinhuai River Basin, a typical urbanization watershed in the YRD (Qin et al., 2017). Similar to Pielke et al. (2007,

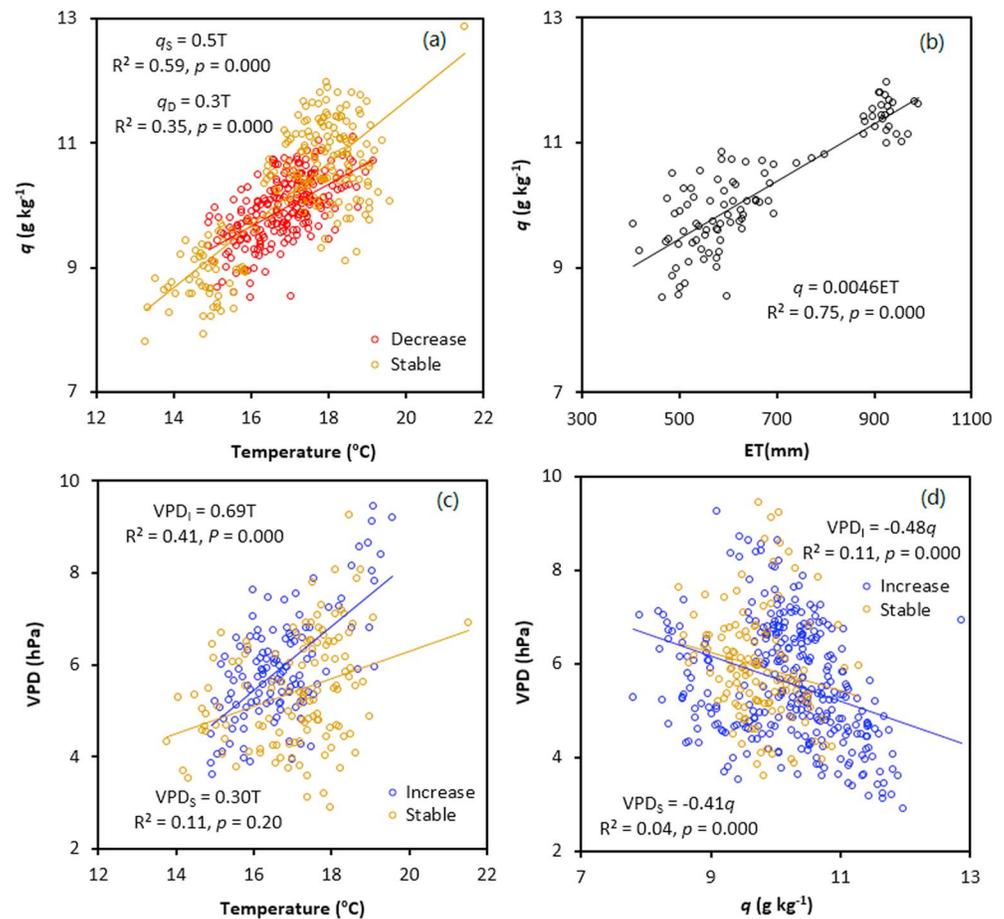


Figure 8. Comparing relationships of annual mean (a) q versus Temp, (b) q versus evapotranspiration (ET), (c) vapor pressure deficit (VPD) versus Temp, and (d) VPD versus q for three trend areas (Increased, Stable, and Decreased for q and VPD, respectively) at 33 observation stations (location of the stations see Figure 2) and corresponding pixel data of Moderate Resolution Imaging Spectroradiometer (MODIS) ET across the Yangtze River Delta (2001–2014).

Table 3

Sensitivity of Potential Evapotranspiration (PET) to Meteorological Variables and Their Contributions in Two Periods of 1960–1989 and 1990–2014 in the Yangtze River Delta

| Meteorological factors | Sensitivity coefficients and contributions | 1960–1989 | 1990–2014 |
|---|--|-----------|-----------|
| Air temperature ($^{\circ}\text{C}$) | R_c^a (%) | −1.7 | 8.1 |
| | S_c^b | 0.5 | 0.5 |
| | G_X^c (%) | −0.8 | 3.7 |
| Wind Speed at 2 m height (m/s) | R_c (%) | −16.0 | −16.0 |
| | S_c | 0.1 | 0.1 |
| | G_X (%) | −1.8 | −2.2 |
| Relative humidity (%) | R_c (%) | −0.6 | −9.8 |
| | S_c | −1.3 | −1.0 |
| | G_X (%) | 0.7 | 9.7 |
| Shortwave radiation ($\text{MJ} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$) | R_c (%) | −7.1 | 2.0 |
| | S_c | 0.7 | 0.6 |
| | G_X (%) | −4.6 | 1.3 |
| PET (mm) | R_d^d (%) | −6.6 | 11.7 |
| | R_s^e (%) | −6.4 | 12.4 |

^a R_c is the relative change of meteorological variables. ^b S_c is the sensitivity coefficients. ^c G_X is the contributions. ^d R_d is the relative change of actual PET. ^e R_s is the relative change of PET calculated by sensitivity coefficients.

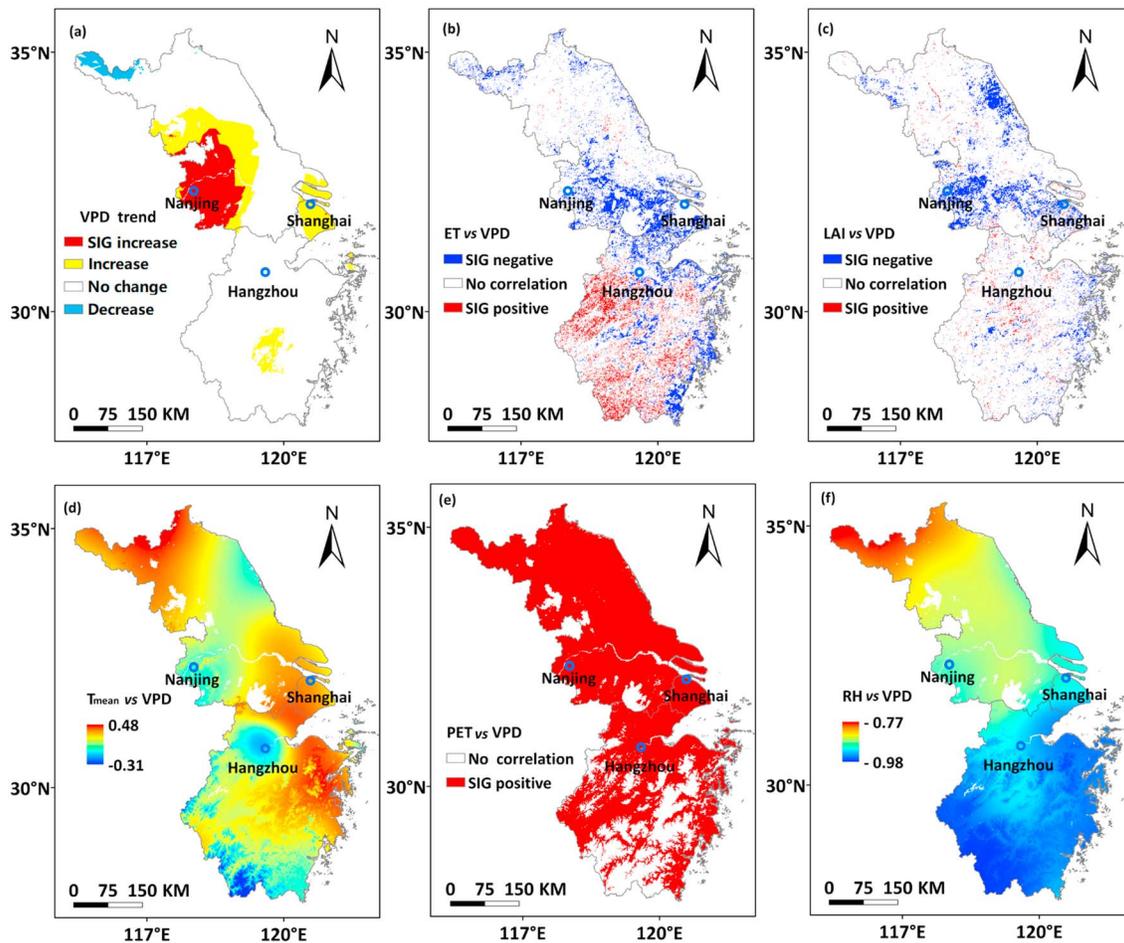


Figure 9. The annual mean (a) vapor pressure deficit (VPD) trend and correlation of (b) evapotranspiration (ET) versus VPD, (c) leaf area index (LAI) versus VPD, (d) air temperature (T_{mean}) versus VPD, (e) potential ET (PET) versus VPD, and (f) relative humidity (RH) VPD with all significant pattern observed ($p < 0.1$) across the Yangtze River Delta (2001–2014).

2011), we concluded that analyses must include water vapor trends in order to better understand climatic change. These studies suggested that surface air temperature itself may not fully capture the true dynamics of the Earth system’s surface air heat content. For better defining “global warming,” we must consider the moisture content of the surface air (Pielke et al., 2007). However, our findings in VPD trend contrasted a recent report by Lokoshchenko (2017). This study found that mean annual water vapor pressure did not show systematic changes in Moscow during a 146-year time period, while mean annual RH had a sharp decrease from 81% in the 1870s to nearly 72% in recent years. Lokoshchenko (2017) concluded that the UDI was closely connected with the UHI.

The UDI effects, characterized as declining atmospheric humidity and rising VPD in the wet region, have important implications to local environments. The rise of VPD will pose additional challenges for water availability, especially in the humid regions where paddy field is the dominated land cover and actual loss of water is mainly regulated by atmospheric demand (i.e., PET; Qin et al., 2017). Recent studies suggest that VPD is vitally important for carbon and water cycles in ecosystems (Novick et al., 2016; Pan et al., 2011). The atmospheric demand for water has direct relationship with VPD, which also influences the surface conductance and thereby ET (Novick et al., 2016). The role of VPD in controlling plant growth and ecosystem productivity is often underestimated especially in humid areas with a large terrestrial carbon sink (Sun et al., 2017). An increasingly drier climate and atmospheric demand due to increasing VPD also has implications to the health of human and ecosystems that have adapted to a humid climate. VPD is highly sensitive to changes in air temperature and is thus expected to be enhanced (Greve et al., 2014; Mao et al., 2017; McDowell & Allen, 2015) with the combined impacts of future global warming and UHI (Zhou, Li et al., 2016; Zhou, Zhang et al., 2016).

4. Conclusions

This study presents empirical evidence of an UDI phenomenon in a humid region in southern China. In addition to global climate warming and UHI, urbanization-associated land cover change is connected to UDIs. Our analysis showed that the atmospheric RH declined dramatically and VPD increased sharply in the urban core during 2001–2014, resulting in enhanced UDI. The change in atmospheric humidity in the urban core cannot be explained by the air temperature change alone. UDI is closely related to the loss of vegetation (i.e., wetlands/rice paddies) covers, and thus, this shift of ET or latent heat processes is another important cause for UDI. The dramatically reduced water vapor also enhanced VPD, a major driver of the watershed hydrology in a humid environment.

We conclude that UDI has been developing rapidly in the wet study region as a result of urbanization. In addition to UHI, UDI imposed additional challenges on water availability for agriculture irrigation use and urban revegetation efforts. The potential role of vegetated land cover in moderating UDI and maintaining a stable climate should be considered in massive urban planning in southern China. UHI effects may also be aggravated in the study region with an enhanced UDI from reduction of ET. UHI and UDI phenomena are coupled and should be collectively addressed in landscape design, urban adaptive strategies development, and global change assessment.

This study improves the understanding of regional processes underlining the mechanisms of water-energy coupling and offers insights into the climatic and hydrological consequences of converting crop lands (i.e., rice paddy) or natural wetlands to urban uses in the context of global climate change. The results have broad implications for quantifying feedback of urban climate to urbanization and climate change. Future study should explore process-based approaches or models on how land cover conversions affect water and energy balances by feedback of the ecohydrological cycle. An integrated approaches including paired flux observations, remote sensing, and coupled regional hydrometeorological models need to be adopted to further confirm our observations in other regions in China and to better understand the coupled UHI and UDI effects at multiple scales.

Conflicts of Interest

The authors declare no conflict of interest.

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