Impacts of the Decadal Urbanization on Thermally Induced Circulations in Eastern China*

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ABSTRACT

Significant urbanization has occurred in the Yangtze River Delta region of eastern China, which exerts important effects on the local thermally induced circulations through regulating the heat flux and thermal structure. Previous studies lack a correct representation of the seasonal vegetation phenology associated with urban expansion, and therefore it is difficult to accurately describe the land–atmosphere coupling. In this study, high-resolution Moderate Resolution Imaging Spectroradiometer (MODIS) observations are used to describe the changes in land surface characteristics, including land-cover type, green vegetation fraction, and leaf area index with the Weather Research and Forecasting Model. The use of MODIS satellite observations provides a clear improvement in model performance when compared with ground-based measurements. A typical urban heat island is generated around Shanghai, Wuxi–Suzhou–Yangzhou, and cities along the Yangtze River and Hangzhou Bay, which subsequently modifies the local thermal circulations. The sea breeze is significantly enhanced over the north bank of Hangzhou Bay because of the increased land–sea temperature contrast. Several surface convergent zones are generated along the Shanghai–Suzhou–Wuxi city belt as a result of the combined effects of the urban heat island, the enhanced sea breeze, and the lake breeze at Lake Tai.

1. Introduction

Rapid urbanization has been recognized as one of the most important aspects of global land-use and land-cover

changes, particularly in the most rapidly developing countries (Lambin et al. 2003; Liu et al. 2005; Liu and Tian 2010). Since the economic and political reforms of the late 1970s, China has been developing at an unprecedented growth rate, with an annual gross domestic product (GDP) growth at approximately 10%. In 2010, China's GDP surpassed 4 trillion yuan, making it the world's second largest economy next to the United States. As a consequence of the rapid economic expansion, China experienced an unrivalled growth in urban area and population. From 1980 to 2005, the urban area expanded by 35.7% (Liu and Tian 2010) and the total urban population doubled from 20% to 43% (National

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Bureau of Statistics of China; available online at <http://www.stats.gov.cn/>). China's urbanization level is projected to reach 48%–50% by 2020, and the proportion of urban populations is expected to exceed 60% by 2030 (Chen 2007).

Urbanization could lead to a massive loss of vegetation, which produces great environmental impacts, ranging from extensive modifications of Earth's ecosystems (Foley et al. 2005) to threats to food security (Chen 2007) and changes in atmospheric composition (Heald et al. 2008). More important, the changes of surface physical properties (e.g., albedo, emissivity, stomatal resistance, and roughness) are important in modulating the land–atmosphere heat and moisture exchanges, which in turn result in perceivable alterations of the temperature structure (de Foy et al. 2006), boundary layer evolution (Fan et al. 2011), wind flow field or circulation (Li et al. 2014), and cloud formation or precipitation (Wan et al. 2013) through land–atmosphere coupling.

Many researchers have focused on the effects of urbanized levels on urban climate and boundary layer dynamics in China. The urban heat island (UHI) phenomenon, which is characterized by an elevated temperature contrast between a city and its surroundings, has been observed through long-term weather records or satellite observations in many Chinese megacities, such as Beijing (Chu and Ren 2005; Jiang et al. 2006), Guangzhou (Chen et al. 2006; Qian et al. 2006), and Shanghai (Du et al. 2007). Ren et al. (2008) analyzed the observational data from 282 national basic meteorological stations in northern China and estimated that urban warming caused a $0.11^{\circ}\text{C} (10 \text{ yr})^{-1}$ increase in the annual mean temperature from 1961 to 2000, which contributed to 38% of the total temperature change. Jones et al. (2008) assessed the urban influences for eastern China using sea surface temperature datasets and showed a $0.1^{\circ}\text{C} (10 \text{ yr})^{-1}$ urban warming over the period from 1951 to 2004, with true climatic warming accounting for 0.81°C . Yu et al. (2012) and Wang (2009) explored the impacts of urbanization on local meteorological conditions by incorporating a new land-cover map into a numerical weather model and suggested a typical warm island and increased boundary layer height in China's three largest metropolitan agglomerations: the Beijing–Tianjin–Hebei region, the Yangtze River Delta (YRD) region, and the Pearl River Delta (PRD) region.

Changes in local atmospheric circulations that are mainly driven by the surface heterogeneity of thermal effects have been regarded as another important consequence of urbanization. Under calm weather conditions, the horizontal urban–rural temperature difference can induce the UHI circulation, which is characterized

by low-level convergent flow toward the city and divergent flow in the upper boundary layer. Fan et al. (2011) revealed clear discrepancies in the lower-tropospheric wind regimes and thermodynamic structures among various sites in southern China that are due to urban expansion and the UHI circulation. In a highly urbanized coastal area, such as the YRD and PRD regions in China, the interactions between urbanization and local sea–land/lake–land–breeze circulations have also been the focus of many researchers. Numerical modeling coupled with continuous satellite remote sensing provides an important tool for understanding the role of urbanization in thermally induced circulations (Li et al. 2014; Li et al. 2003; Li et al. 2011; Lo et al. 2006, 2007; Lu et al. 2010; Zhang et al. 2011). For example, by incorporating a new urban map into the mesoscale model, Lo et al. (2006) and Lu et al. (2010) suggested that increased urbanization on the eastern coast of the Pearl River estuary could enhance the sea breeze and surface convergent zones.

As one of the six world-class city groups and one of China's three main city clusters, the YRD region has the highest city density and urbanization level in China. The YRD city belt is composed of the megacity Shanghai and another 22 cities in the well-industrialized Jiangsu, Zhejiang, and Anhui provinces. It is located on the eastern coast of the Yangtze plain and faces the East China Sea. The YRD is influenced by a more complex wind regime that comprises apparent interactions among the UHI circulation (Tang and Miao 1998), sea–land–breeze circulation (Li et al. 2011; Tang and Miao 1998), and land–lake–breeze circulation (Li et al. 2003; Zhang et al. 2011), which have also been documented in many numerical studies. With the continuous increase of urbanization in eastern China, the UHI and its influence on thermally induced circulations are receiving more and more attention in this region.

Past studies in eastern China did not pay enough attention to the correct representation of seasonal vegetation phenology in the urban regions. Sailor (1995) found that the increment of vegetative coverage fraction tended to lower the urban temperature or weaken the heat-island intensity and the local circulation in response to temperature change. Deardorff (1978) also noted that evapotranspiration could increase twofold as the amount of vegetation cover increased, along with a corresponding decrease of sensible heat flux. Our previous work (Li et al. 2014) in the PRD metropolitan area suggested that precise estimates for all of the urban surface parameters are critical to capture the major features of UHI effect and local circulations in the mesoscale model; similar studies are lacking in the YRD region of eastern China, however.

FIG. 1. (a) Two-nested WRF modeling domains, and (b) locations of the meteorological stations (red dots) in the inner domain. The shaded contour represents topography height (m), the black labels represent the major provinces, and the blue labels represent the names of the observational sites.

Therefore, this study aims to explore the impacts of urbanization on thermally induced circulations in the YRD region with the Weather Research and Forecasting (WRF) Model. High-resolution Moderate Resolution Imaging Spectroradiometer (MODIS) observations are used to describe the changes of land-cover type, green vegetation fraction (GVF), and leaf area index (LAI). Descriptions of the numerical model, experimental designs, and land surface changes are provided in the second part. The model evaluations, urban heat island, and local circulations are examined in section 3. Section 4 discusses the conclusions and uncertainties of this study.

2. Methods and data

a. WRF Model

The meteorological model used in this study is the National Center for Atmospheric Research Advanced Research configuration of the WRF Model. WRF is a sophisticated three-dimensional compressible and nonhydrostatic numerical weather simulation and prediction model (Skamarock et al. 2008). It is widely used for numerical weather prediction, hydrological studies, and air-quality studies.

In this study, a two-way-interacting, two-nested grid system is established (Fig. 1) that is centered at 31.3°N and 119.5°E . The outermost domain covers the eastern and central part of China's mainland, the Yellow Sea, and the East China Sea to capture the synoptic-scale

features. It has a horizontal grid spacing of 12 km and 120×104 grid points. The innermost domain focuses on the YRD region; it is designed to resolve the local-scale circulation features and has a grid spacing of 4 km and 124×109 grid points in the horizontal direction. Both domains have 28 vertical layers that extend from the surface to 5 hPa. The 6-h National Centers for Environmental Prediction global final analysis (FNL) data at $1^{\circ} \times 1^{\circ}$ resolution are used as the initial and boundary meteorological conditions. A 12-h spinup time is allowed to minimize the influence of initial conditions for each WRF run that covered 3.5 days. Hourly model outputs from the WRF simulations are used for analysis in the following sections.

In this study, the main physical-parameterization schemes contain the Noah land surface scheme to describe the detailed thermodynamic and hydrological processes of land-atmosphere interactions (Chen et al. 2006; Ek et al. 2003), the Lin microphysics scheme (Lin et al. 1983) coupled with the Kain-Fritsch cumulus parameterization (Kain 2004) to describe the cloud and precipitation processes (for the 4-km inner domain, no explicit cumulus parameterization scheme is considered), the Yonsei University boundary layer scheme (Noh et al. 2003), the Goddard shortwave radiation scheme (Chou and Suarez 1999), the Rapid Radiative Transfer Model longwave radiation scheme (Gallus and Bresch 2006), and the Monin-Obukhov surface similarity scheme (Monin and Obukhov 1954).

FIG. 2. Land-cover maps for the (a) PRE-URBAN and (b) URBAN experiments.

b. Experiment designs

Two parallel WRF experiments that are designated as “PRE-URBAN” and “URBAN” are conducted, with identical physical-parameterization configurations, initial meteorological conditions, and lateral boundary conditions (as described in section 2a). The two simulations have different representations for the land surface characteristics, however. In the PRE-URBAN experiment, the static geographical field is set to default values that are representative of the urban distribution as of the early 1990s. The modified case (URBAN) is conducted with updated land cover, GVF, and LAI, which are all produced from MODIS observations in 2006 (as will be described in section 2c). The remaining secondary surface parameters (e.g., albedo and roughness length) in WRF are assigned by tabulated values in the same way according to land-cover type, GVF, and soil index.

The YRD region is located in a typical subtropical monsoon region, with warm and humid conditions in summer and cold and dry weather in winter. To investigate the urbanization-induced effects under different synoptic conditions, WRF simulations are run for six typical episodes (15–20 April, 3–8 August, 11–16 August, 19–25 September, 3–9 October, and 11–16 October) that span spring, summer, and autumn for 2006 and all of which are characterized by clear sky, no precipitation, and long sunshine duration. Here, no wintertime cases (December–February) are chosen because of the weak UHI and frequent invasion of cold air, which tends to cause large uncertainties in the model results. Numerous observations of the interannual and seasonal variability of the UHI intensity (Du et al. 2007; Wang et al. 1990; Zhang et al. 2013) also indicated that a stronger UHI was frequently observed in summer and

autumn, when clear and warm skies are common in the YRD. In particular, during the 11–16 August episode continuous hot weather was reported to be induced by a subtropical high and continental warm high ridge, and the observed maximum temperature reached 38°C. During the 3–9 October episode, eastern China was under the influence of northerly winds and was not affected by a strong synoptic system. Thus, weak synoptic forcing, calm conditions, and clear skies are typical for this region during both episodes, which provided optimal conditions for the surface heat budget to influence local meteorological behavior and for the development of strong thermal circulation.

In the following sections, statistical evaluations of model results will be discussed for all six episodes. Detailed results of the UHI effect and local thermal circulation will be presented in this paper for the two main cases (11–16 August and 3–9 October), and simplified analyses for the other four episodes are provided in the online supplemental material (see text S1).

c. Satellite land surface parameters

1) LAND-COVER TYPE

Two commonly used land-cover datasets, respectively derived from Advanced Very High Resolution Radiometer (AVHRR) and MODIS satellite observations, are used to represent the land-cover type before and after urbanization. In WRF, the land cover is described by two parameters: the dominant land-cover type (“LU_INDEX”) and the proportion of the grid occupied by each land-cover type (“LANDUSEF”). By default, WRF uses the 24-category U.S. Geological Survey (USGS) global 1-km land-cover map (Fig. 2a) derived from monthly AVHRR normalized difference vegetation

FIG. 3. Comparisons of (a) GVF and (b) LAI for PRE-URBAN [left panels in (a) and (b)] and URBAN [right panels in (a) and (b)] in (top) August and (bottom) October.

index (NDVI) observations from April 1992 to March 1993 (Loveland et al. 2000). To represent the current surface features, a new land-cover map is constructed by combining MODIS land-use data (“MCD12Q1”) for 2006 and water-mask data (“MOD44W”) for 2000, both of which have a 500-m resolution (Justice et al. 2002). The 17-category MODIS International Geosphere–Biosphere Programme classes are then translated into the 24-category USGS categories (Li et al. 2014). The coverage fraction of each land-cover type (LANDUSEF in WRF) is also recalculated on the basis of the newly constructed land-cover map.

Comparisons in Fig. 2 reveal significant changes in the land-cover patterns. During the early 1990s, the YRD region was characterized by substantial amounts of cropland in the northern and central portions and mixed natural vegetation in the south (Fig. 2a). The main cities, such as Shanghai, Nanjing, Zhenjiang, and Yangzhou, are scattered along the Yangtze River (Fig. 2a). By comparison, in 2006 the MODIS land-cover designated over 8 times as much urban area as the AVHRR did, along with a massive loss of cultivated land. Several city belts are formed in the YRD, including Shanghai, Suzhou–Wuxi–Changzhou in mid-YRD, Nanjing–Zhenjiang–Yangzhou along the Yangtze River, and Hangzhou–Ningbo lying along the Hangzhou Bay (Fig. 2b).

2) GVF

Green vegetation fraction is defined as the fraction of a grid cell in which midday downward insolation is

intercepted by the photosynthetically active green canopy (Chen and Dudhia 2001b). In the land surface model, the spatially and temporally varying GVF is used to determine the surface energy partition separately over fractional vegetated and bare ground; it has a large impact on the latent heat flux by controlling plant evapotranspiration (Chen and Dudhia 2001a).

In the WRF Model, the monthly AVHRR NDVI collected from 1985 through 1990 is used to represent the GVF, with a resolution of 20 km (Gutman and Ignatov 1998). In this study, the monthly 1-km NDVI product (“MOD13A2”) for 2006, which is produced from visible and near-infrared data acquired by the MODIS sensor, is used to estimate the current fractional distribution of green vegetation (Justice et al. 2002; Purevdorj et al. 1998).

The two GVF datasets have large differences, as presented in Fig. 3a. The comparison suggests that the default GVF fails to capture the complex spatial patterns and is likely too low over much of the YRD rural region (below 0.6, Fig. 3a). The MODIS GVF composite (Fig. 3a) has more mixed spatial structure and agrees well with the land-cover map (Fig. 2b), with high vegetation fractions of more than 0.7 throughout the forested regions. A large amount of vegetation was lost as cities developed, leading to vegetation cover as low as 0.1 or below.

3) LAI

Leaf area index is defined as the one-sided green leaf area per unit of ground area ($\text{m}^2 \text{m}^{-2}$). It is the basic

TABLE 1. Meteorological statistical analyses at each site for URBAN and PRE-URBAN (in parentheses) during 11–16 Aug and 3–9 Oct.

Variable	Index	Nanjing	Pudong	Wuhu	Liyang	Baoshan	Xujiahui	Huangshan	Hangzhou	Dinghai	Chengzhou	All sites
Episode: 11–16 Aug												
2-m temperature (°C)	MB	−0.03 (−0.58)	−0.75 (−1.41)	−0.60 (−0.64)	−0.24 (−1.23)	0.01 (−2.30)	0.03 (−1.53)	3.82 (3.73)	0.10 (−0.10)	0.18 (−0.87)	−0.92 (−1.61)	0.01 (−0.79)
	ME	1.20 (1.32)	0.96 (1.52)	1.17 (1.24)	1.14 (1.57)	0.71 (2.32)	0.88 (1.99)	3.82 (3.73)	1.03 (0.98)	0.65 (1.85)	1.40 (1.61)	1.15 (1.61)
	RMSE	1.72 (1.69)	1.17 (1.77)	1.50 (1.64)	1.54 (1.94)	0.89 (2.53)	1.21 (2.27)	4.12 (4.05)	1.45 (1.34)	0.83 (1.30)	1.60 (2.16)	1.63 (2.02)
	IOA	0.93 (0.93)	0.93 (0.85)	0.95 (0.95)	0.95 (0.92)	0.97 (0.80)	0.96 (0.88)	0.51 (0.52)	0.95 (0.95)	0.97 (0.94)	0.96 (0.92)	0.95 (0.93)
2-m relative humidity (%)	MB	−2.29 (2.42)	7.39 (12.61)	−1.17 (0.94)	−3.38 (4.55)	0.81 (17.05)	0.23 (10.94)	−3.29 (−2.54)	−0.87 (0.63)	2.41 (8.97)	7.50 (11.40)	0.94 (6.77)
	ME	6.81 (6.16)	8.54 (12.69)	6.57 (6.76)	7.41 (6.42)	6.57 (17.18)	8.50 (14.11)	6.26 (5.68)	5.83 (5.60)	5.68 (10.48)	9.36 (12.04)	7.27 (9.74)
	RMSE	8.98 (8.02)	9.86 (13.71)	7.70 (7.98)	9.06 (8.47)	8.18 (18.77)	10.64 (16.33)	8.60 (7.73)	7.56 (7.58)	7.03 (11.41)	11.79 (14.83)	9.17 (12.13)
	IOA	0.91 (0.92)	0.81 (0.66)	0.94 (0.93)	0.89 (0.90)	0.88 (0.62)	0.88 (0.76)	0.70 (0.72)	0.92 (0.92)	0.93 (0.82)	0.88 (0.82)	0.91 (0.84)
10-m wind speed (m s ^{−1})	MB	0.67 (0.50)	−0.97 (−1.1)	1.02 (0.82)	0.68 (0.52)	−0.28 (−0.14)	−0.44 (−0.12)	−1.02 (−0.74)	0.04 (0.17)	0.14 (0.05)	0.23 (0.15)	−0.08 (−0.07)
	ME	1.21 (1.27)	1.32 (1.68)	1.32 (1.52)	1.47 (1.89)	0.82 (1.24)	0.85 (1.38)	1.70 (2.02)	1.03 (1.39)	0.92 (1.19)	0.94 (1.29)	1.13 (1.19)
	RMSE	1.65 (1.74)	1.59 (1.68)	1.73 (1.52)	1.83 (1.89)	1.07 (1.24)	1.10 (1.38)	2.10 (2.02)	1.39 (1.39)	1.14 (1.19)	1.25 (1.29)	1.48 (1.55)
	IOA	0.78 (0.75)	0.78 (0.76)	0.80 (0.84)	0.70 (0.70)	0.85 (0.84)	0.85 (0.81)	0.79 (0.82)	0.70 (0.70)	0.82 (0.83)	0.83 (0.82)	0.80 (0.79)
10-m wind direction (°)	MB	−8.52 (−8.37)	−11.66 (−7.51)	−1.72 (8.13)	19.15 (30.05)	2.59 (7.84)	−1.50 (−4.52)	2.39 (5.62)	24.09 (7.02)	11.71 (10.54)	−28.62 (−23.59)	0.18 (−0.29)
	ME	73.74 (73.60)	34.62 (32.58)	67.79 (54.77)	93.23 (87.47)	35.59 (43.85)	32.71 (34.44)	52.99 (43.67)	74.48 (57.24)	73.53 (72.51)	71.05 (80.72)	60.94 (57.33)
Episode: 3–9 Oct												
2-m temperature (°C)	MB	0.02 (−0.20)	−0.56 (−0.94)	−0.22 (−1.06)	−0.37 (−0.97)	−0.05 (−1.86)	0.46 (−1.78)	3.34 (3.11)	−0.02 (−0.88)	0.18 (−1.05)	−0.73 (−1.55)	0.09 (−0.85)
	ME	0.99 (1.00)	0.84 (1.22)	1.42 (1.57)	1.39 (1.44)	0.66 (1.90)	1.26 (2.14)	3.34 (3.13)	1.23 (1.34)	0.69 (1.11)	1.34 (1.89)	1.19 (1.55)
	RMSE	1.26 (1.27)	1.10 (1.50)	1.72 (1.97)	1.68 (1.82)	0.80 (2.39)	1.51 (2.80)	3.73 (3.51)	1.55 (1.73)	0.97 (1.28)	1.66 (2.38)	1.58 (2.05)
	IOA	0.98 (0.98)	0.94 (0.88)	0.96 (0.94)	0.95 (0.94)	0.96 (0.77)	0.92 (0.83)	0.58 (0.59)	0.93 (0.92)	0.94 (0.93)	0.95 (0.91)	0.95 (0.92)
2-m relative humidity (%)	MB	−3.97 (−0.32)	2.08 (5.10)	−4.96 (2.38)	−2.19 (3.90)	0.74 (10.44)	−4.38 (6.04)	−5.07 (−2.13)	−6.02 (0.42)	−1.78 (5.33)	1.43 (7.78)	−2.28 (4.34)

TABLE 1. (Continued)

Variable	Index	Nanjing	Pudong	Wuhu	Liyang	Baoshan	Xujiahui	Huangshan	Hangzhou	Dinghai	Chengzhou	All sites
10-m wind speed (m s^{-1})	ME	5.24 (2.67)	5.47 (6.17)	5.30 (9.42)	4.80 (7.03)	6.53 (10.81)	7.88 (10.69)	11.25 (10.47)	7.97 (6.04)	5.23 (6.84)	4.94 (8.62)	7.05 (8.08)
	RMSE	10.78 (5.62)	6.39 (7.92)	7.26 (11.50)	6.48 (8.96)	7.91 (12.57)	9.92 (12.74)	13.63 (12.91)	10.20 (7.67)	6.82 (8.17)	6.34 (10.69)	9.02 (10.18)
	IOA	0.86 (0.87)	0.93 (0.86)	0.93 (0.85)	0.95 (0.94)	0.91 (0.78)	0.91 (0.87)	0.78 (0.78)	0.89 (0.94)	0.90 (0.86)	0.97 (0.91)	0.91 (0.88)
	MB	0.82 (0.80)	-0.39 (0.04)	0.47 (0.50)	0.95 (0.95)	0.50 (0.88)	-0.20 (0.14)	0.03 (0.36)	0.39 (0.55)	1.37 (1.57)	0.83 (0.87)	0.33 (0.53)
	ME	1.24 (1.22)	0.72 (0.91)	0.99 (1.12)	1.19 (1.40)	1.00 (1.37)	0.92 (1.20)	1.56 (2.28)	0.90 (1.17)	1.50 (1.97)	1.11 (1.59)	1.03 (1.08)
	RMSE	1.55 (1.52)	0.90 (0.91)	1.22 (1.12)	1.43 (1.40)	1.20 (1.37)	1.10 (1.20)	2.13 (2.28)	1.12 (1.17)	1.76 (1.97)	1.47 (1.59)	1.32 (1.38)
	IOA	0.45 (0.45)	0.90 (0.90)	0.63 (0.66)	0.60 (0.60)	0.68 (0.69)	0.82 (0.82)	0.76 (0.75)	0.71 (0.72)	0.69 (0.67)	0.68 (0.66)	0.80 (0.81)
	MB	-11.57 (-12.88)	-7.20 (-10.25)	5.14 (3.11)	10.79 (14.40)	0.99 (2.56)	-6.89 (-4.29)	-8.71 (-5.04)	4.00 (9.72)	-20.79 (-17.42)	-20.54 (3.97)	-5.70 (-3.33)
	ME	56.46 (57.28)	17.67 (20.08)	53.80 (51.48)	46.81 (45.84)	26.74 (27.36)	22.59 (22.55)	42.37 (39.52)	46.04 (45.93)	45.80 (44.78)	71.86 (69.93)	41.16 (40.93)
	10-m wind direction ($^{\circ}$)											

TABLE 2. Overall meteorological statistical analyses for the four supplemental cases.

Variable	Index	MB	ME	RMSE	IOA
Episode: 15–20 Apr					
2-m temperature (°C)	PRE-URBAN	−1.14	1.96	2.53	0.94
	URBAN	0.23	1.37	1.85	0.96
2-m relative humidity (%)	PRE-URBAN	6.25	11.09	13.71	0.88
	URBAN	−3.49	10.53	13.32	0.89
10-m wind speed (m s^{-1})	PRE-URBAN	0.36	1.30	1.70	0.81
	URBAN	0.16	1.24	1.65	0.80
10-m wind direction (°)	PRE-URBAN	3.62	46.44	—	—
	URBAN	2.99	48.12	—	—
Episode: 3–8 Aug					
2-m temperature (°C)	PRE-URBAN	−1.15	1.60	1.94	0.91
	URBAN	−0.39	1.12	1.52	0.95
2-m relative humidity (%)	PRE-URBAN	10.18	11.35	13.28	0.76
	URBAN	4.23	7.85	9.59	0.87
10-m wind speed (m s^{-1})	PRE-URBAN	0.15	1.30	1.65	0.74
	URBAN	−0.05	1.26	1.59	0.73
10-m wind direction (°)	PRE-URBAN	−7.55	44.12	—	—
	URBAN	−8.13	44.26	—	—
Episode: 19–25 Sep					
2-m temperature (°C)	PRE-URBAN	−0.77	1.39	1.83	0.93
	URBAN	0.29	1.05	1.43	0.96
2-m relative humidity (%)	PRE-URBAN	4.19	8.10	10.64	0.87
	URBAN	−2.37	7.34	9.75	0.89
10-m wind speed (m s^{-1})	PRE-URBAN	0.52	1.08	1.36	0.77
	URBAN	0.40	0.99	1.23	0.78
10-m wind direction (°)	PRE-URBAN	−7.44	45.40	—	—
	URBAN	−8.60	44.97	—	—
Episode: 11–16 Oct					
2-m temperature (°C)	PRE-URBAN	−0.55	1.63	2.06	0.91
	URBAN	0.29	1.19	1.62	0.94
2-m relative humidity (%)	PRE-URBAN	5.05	9.05	11.04	0.84
	URBAN	−0.46	7.10	9.14	0.89
10-m wind speed (m s^{-1})	PRE-URBAN	0.70	1.18	1.49	0.72
	URBAN	0.49	1.07	1.39	0.73
10-m wind direction (°)	PRE-URBAN	0.41	42.52	—	—
	URBAN	−2.91	41.28	—	—

parameter required in the Jarvis-type approach to calculate vegetation stomatal resistance (Jacquemin and Noilhan 1990; Jarvis 1976) and to determine plant evapotranspiration.

The LAI parameter is dependent on vegetation type and varies seasonally. By default, the varying LAI is determined on the basis of a tabulated method, in which a typical LAI value is assigned to each vegetation type and then is modified throughout the growing season on the basis of the GVF. In this study, the current LAI distribution is directly described with the 8-day MODIS satellite measurements (“MCD15A2”) in 2006 at 1-km resolution and is resampled on a monthly basis (Knyazikhin et al. 1998).

Comparisons indicate a generally reduced urban LAI to below 0.5–1.0 as a result of vegetation loss as detected by the MODIS sensor (Fig. 3b). An obvious overestimation of rural LAI in the north inferred from lookup

tables can also be seen, which is higher than MODIS measurements by roughly 1.0–2.0 (Fig. 3b).

3. Results and discussions

a. Comparisons with observations

Hourly or 3-h observations at 10 weather stations (Fig. 1) were obtained from the National Climatic Data Center. Four statistical metrics—mean bias (MB), mean error (ME), root-mean-square error (RMSE), and index of agreement (IOA) [Eq. (1)]—are used to evaluate the overall model performance for all six cases (Tables 1 and 2). The detailed statistical results at each meteorological station in the two main cases (11–16 August and 3–9 October) are also provided in Table 1. The statistics are defined as

$$\text{MB} = \frac{1}{N} \sum_{i=1}^N (\text{sim}_i - \text{obs}_i),$$

FIG. 4. Time series of 2-m temperature [$^{\circ}\text{C}$; top plot in (a)–(d)], relative humidity [%; top-middle plot in (a)–(d)], wind speed [m s^{-1} ; bottom-middle plot in (a)–(d)], and wind direction [$^{\circ}$; bottom plot in (a)–(d)] at four selected sites: (a) Baoshan, (b) Xujiahui, (c) Dinghai, and (d) Chengzhou [the left y axis represents the value scale of the August episode (leftmost six dates); the right y axis represents the value scale of the October episode (rightmost seven dates)].

$$\text{ME} = \frac{1}{N} \sum_{i=1}^N |\text{sim}_i - \text{obs}_i|,$$

$$\text{RMSE} = \left[\sum_{i=1}^N (\text{sim}_i - \text{obs}_i)^2 / N \right]^{1/2}, \quad \text{and}$$

$$\text{IOA} = 1 - \frac{N \times \text{RMSE}^2}{\sum_{i=1}^N (|\text{obs}_i - \overline{\text{obs}}| + |\text{sim}_i - \overline{\text{obs}}|)^2}, \quad (1)$$

where sim and obs refer to the simulated and observed meteorological values, respectively, and N represents the number of data pairs.

The overall statistical metrics for the two main cases (Table 1) and the other four supplemental cases (Table 2) demonstrate that the use of highly resolved land surface data acquired from MODIS could lead to remarkable model improvements in the near-surface

simulation. An obvious underestimation of 2-m air temperature is generated in PRE-URBAN when compared with the actual observations, leading to a domain-average cold bias ranging from -1.15° to -0.55°C and an RMSE of 1.83° – 2.53°C (Tables 1 and 2). After the inclusion of MODIS measurements, different degrees of model improvement are achieved in all six cases, leading to a sharply reduced mean bias from -0.39° to 0.29°C . In particular, from the site-by-site comparison (Table 1) it is noticed that the temperature underestimation in the PRE-URBAN case is more serious at several urban sites located in the metropolitan area. For example, at the Pudong, Baoshan, and Xujiahui sites in Shanghai, the temperature cold bias reaches levels from -1.41° to -2.30°C in the 11–16 August episode, which is sharply reduced to levels from -0.75° to 0.03°C in URBAN. For the typical rural sites—for example, Wuhu and Huangshan—the model improvement owing to satellite-derived land surface data is insignificant (Table 1). In terms of 2-m relative humidity, overall the PRE-URBAN case

FIG. 5. Comparisons of (a) ground heat flux (W m^{-2} ; from -33 to 0), (b) sensible heat flux (W m^{-2} ; from 0 to 130 in August and from -10 to 110 in October), and (c) latent heat flux (W m^{-2} ; from 50 to 210 in August and from 20 to 170 in October) for PRE-URBAN [left panels in (a)–(c)] and URBAN [right panels in (a)–(c)] during the August episode [top panels in (a)–(c)] and the October episode [bottom panels in (a)–(c)]. (d) The urban area (red color) in PRE-URBAN and URBAN.

produces high positive moist bias (4.19% – 10.18%), along with an RMSE of 10.18% – 13.71% (Tables 1 and 2). In the URBAN experiment, the simulated relative humidity is significantly improved in terms of MB (ranging from -3.49% to 4.23%), and the IOA reaches 0.84 – 0.89 . In a similar way, the reduction of moist bias is particularly significant at the major urban sites, with a maximum reduction of moist bias by over 10% (Table 1). A general overestimation of wind speed is observed in most cases over the inner regions by 0.15 –

0.70 m s^{-1} in PRE-URBAN. A reduction of the wind speed bias (now ranging from -0.05 to 0.49 m s^{-1}) is achieved by implementing the newly developed land surface parameters. For the simulation of wind directions, the differences between the two experiments were not very large.

Figure 4 provides the time-series comparisons for 11–16 August and 3–9 October at three representative sites that have changed from vegetation to metropolis [Baoshan (31.4°N , 121.5°E), Xujiahui (31.2°N , 121.4°E), and Dinghai

TABLE 3. Simulated average values and differences (diff) between the two experiments for each meteorological variable over the urban grids. The urban grids in the inner domain are classified on the basis of the MODIS land-cover map. The values are averaged over all of the urban grids in the inner domain and over the entire simulation period. Fluxes GRDFLX, HFX, and LH (W m^{-2}) and temperature LST ($^{\circ}\text{C}$) are defined in section 3b; T2 is air temperature at 2 m ($^{\circ}\text{C}$); Q2 is water vapor mixing ratio at 2 m (g kg^{-1}). Daytime lasts from 0800 to 1900 LT, and nighttime lasts from 2000 to 0700 LT.

Variable	Episode: 11–16 Aug			Episode: 3–9 Oct		
	PRE-URBAN	URBAN	Diff	PRE-URBAN	URBAN	Diff
All day						
GRDFLX	−12.2	−63.5	−51.3	−3.0	−25.4	−22.4
HFX	50.4	130.4	80	40.9	92.4	51.5
LH	134.4	2.0	−132.4	71.3	0.3	−71.0
LST	32.0	35.9	3.9	21.9	25.6	3.7
T2	29.8	31.4	1.6	20.6	22.6	2.0
Q2	20.2	18.8	−1.4	10.7	10.2	−0.5
Daytime						
GRDFLX	−42.2	−159.0	−116.8	−43.1	−117.5	−74.4
HFX	101.6	246.6	145	91.3	183.8	92.5
LH	258.2	3.0	−255.2	144.3	0.6	−143.7
LST	37.5	42.3	4.8	27.9	31.1	3.2
T2	32.7	34.1	1.4	23.9	25.1	1.2
Q2	20.1	18.0	−2.1	10.8	9.5	−1.3
Nighttime						
GRDFLX	17.7	32.0	14.3	37.0	66.7	29.7
HFX	−0.8	14.1	14.9	−9.5	1.0	10.5
LH	10.6	1.0	−9.6	−1.6	0.0	1.6
LST	26.5	29.5	3.0	15.9	20.1	4.2
T2	26.9	28.7	1.8	17.4	20.2	2.8
Q2	20.2	19.6	−0.6	10.6	10.9	0.3

(30.0°N, 122.1°E)] and at one site that has changed from cropland to grassland [Chengzhou (29.6°N, 120.8°E)]. The meteorological elements at all four stations are significantly influenced by land surface changes, and the model results show an obvious improvement, especially at the two urban sites in Shanghai (i.e., Baoshan and Xujiahu). The strong diurnal temperature patterns are captured in both experiments. The PRE-URBAN model tends to underpredict the afternoon and mid-night minimum values by 1°–3°C (Figs. 4a,b), however. In contrast, in the URBAN run, both the maximum and minimum temperature in the near-surface layer increase, causing a decrease of the diurnal temperature range and better agreement with the observations. The diurnal variations of 2-m relative humidity shows a minimum at midday (less than 60%) and a nocturnal maximum, which is opposite to that of temperature. A systematically positive humidity bias of 10%–20% is noted in the PRE-URBAN simulation at urban sites, and the URBAN simulation yields lower humidity and better uniformity. The distributions of wind speed/direction are very similar between the two simulations, and no systematic differences are identified. The wind speed is characterized by large diurnal fluctuations, with nocturnal minimums in both simulations. Both cases could successfully capture the prevailing southerly wind

in the summer modeling period and the northerly wind in the autumn modeling period.

b. Urban heat island

In the following sections, UHI effects and local thermal circulation will be discussed for the two main cases (11–16 August and 3–9 October). Brief analyses for the other four episodes are provided in the online supplemental material (see text S1).

At the land surface, the net incoming radiation is balanced by ground heat flux (GRDFLX), sensible heat flux (HFX), and latent heat flux (LH), which is an important influencing factor on local meteorological conditions. Comparisons of the modeled heat fluxes for the PRE-URBAN and URBAN runs in Fig. 5 reveal pronounced differences in the surface energy budgets that are due to urbanization. As the urban landscape develops, the higher soil thermal conductivity, low albedo, and soil moisture availability of urban surface, in combination with the absence of vegetation cover (Fig. 3), give rise to more energy transferred into ground heat flux (Fig. 5a) and sensible heat flux (Fig. 5b) over the cities (Fig. 5d), along with the suppression of latent heat exchange (Fig. 5c). On average, the urban GRDFLX could reach −63.5 and −25.4 W m^{-2} and the HFX reaches 130.4 and 92.4 W m^{-2} for the summer and autumn episodes, respectively (Table 3). Thus,

FIG. 6. Simulated land surface temperature ($^{\circ}\text{C}$; from 25° to 37° in August and from 14° to 27° in October) in (a),(d) PRE-URBAN and (b),(e) URBAN and the (c),(f) MODIS-derived land surface temperature ($^{\circ}\text{C}$; temperature increases from blue to red shades) during the (top) August and (bottom) October episodes.

more energy goes into heating the near-surface air and land rather than as latent heat for evaporation. The reduction of latent heat exchange acts to suppress the daytime hydrological cycle and dry the urban atmosphere by as much as 1.4 g kg^{-1} in summer (Table 3). In contrast, over the rural areas in the YRD, the latent heat exchange dominates because of the dense vegetation layer and enhanced evapotranspiration (Fig. 5).

The clear urban–rural energy balance differences at the land–atmosphere interface lead to the well-acknowledged UHI phenomenon. As displayed in Fig. 6, the distribution of land surface temperature (LST) averaged over the entire simulation period in URBAN shows a significantly different pattern from that of PRE-URBAN. This is consistent with the considerable shift from latent heat to sensible heat fluxes in the urban energy budget (Fig. 5). It is noticeable that multiple cities, such as Shanghai, Wuxi–Suzhou–Changzhou, Nanjing–Zhenjiang, and Hangzhou–Ningbo, act as hot islands with elevated land surface temperature (with a modeled average of 35.9°C in summer and 25.6°C in autumn) relative to the natural areas surrounding them (Figs. 6b,e). Further quantitative analysis reveals that

these newly urbanized regions have experienced a strong warming effect at an average of 3.8°C (Table 3) when compared with the PRE-URBAN simulation. A decrease of LST is observed in the northern cropland and the southern forest because of the synergistic cooling effects from shade and evaporation loss (Figs. 6b,e). The MODIS sensors aboard the *Terra* and *Aqua* satellites provide measurements of 1-km-resolution land surface temperature four times per day from the night and day passes (each satellite passes over once per night and day; Wan 2003). Daily averages of the four-time-per-day remote sensing are also provided in Figs. 6c and 6f. As shown by the MODIS observations, the high-value centers are distributed from the northwest to southeast in mid-YRD and along the Yangtze River and Hangzhou Bay, as the urban area spreads (Figs. 6c,f). By comparison with the MODIS satellite measurements, the URBAN case (Figs. 6b,e) could better represent the heat island and its greater spatial extent resulting from urban growth. Figure 7 provides the scatter diagram between the simulated LST in the URBAN experiment and satellite observations. As can be seen, in the October episode the model

FIG. 7. Scatterplot of the simulated land surface temperature (°C) against MODIS observations for the (a) August and (b) October episodes.

simulations agree well with satellite measurements, except with a 1°–2°C warm bias at the urban grids (Fig. 7b). During the August episode, however, the model simulations are overestimated by ~3°–4°C at both the urban and vegetated grids (Fig. 7a). A large simulation bias of land surface temperature has also been noted in previous studies in Mexico City (de Foy et al. 2006). The absence of gas/aerosol radiation feedback in the WRF Model, increased measurement inaccuracies in summer that are due to higher cloud cover (Wan 2003), and the time difference between satellite overpass and temperature simulation may partly explain the overestimation.

Similar to the modeling of land surface temperature, the reclassification of the land use to urban surface exerts a remarkable warming effect on the air temperature, which averages 1.6°C in the summer episode and 2.0°C in the autumn episode (Table 3). The positive forcing for air temperature is associated with the enhanced daytime surface heating via upward sensible heat flux (246.6 and 183.8 W m⁻²) over the warmer land surface within cities and the massive release of ground heat storage (–159.0 and –117.5 W m⁻²) overnight (Table 3). Such differences are more significant across central YRD and northern Zhejiang, where an increase

FIG. 8. Simulated differences of 2-m air temperature (°C) between URBAN and PRE-URBAN during the (a) August and (b) October episodes.

FIG. 9. Diurnal variation of (a),(c) urban/rural heat flux (W m^{-2}) and (b),(d) UHI intensity ($^{\circ}\text{C}$) for the (top) August and (bottom) October episodes.

of approximately $2^{\circ}\text{--}3^{\circ}\text{C}$ is found between the two land-use experiments (Fig. 8). Noticeable is that the warming effect is not restricted to the local urban regions but extends to the surrounding cropland to a lesser extent through background advective transport, with a rise within 1°C , especially during the summer episode (Figs. 8a,b).

The UHI is present day and night, but with varying intensity. The UHI intensity exhibits a marked diurnal variation as shown in Fig. 9, which ranges from 0.5° to 3.0°C in the summer episode (Fig. 9b) and from 0.7° to 4.0°C in the autumn episode (Fig. 9d). The diurnal variations of UHI intensity are similar for the two episodes, which are caused by the diverging urban–rural energy balance and the warming/cooling rate. The urban land surface has a larger soil thermal conductivity and heat capacity than does vegetation (Ek et al. 2003); therefore more energy is stored during the daytime and heat is released faster during the nocturnal hours. During the nocturnal hours, when the release of daytime energy storage assumes an important role in surface energy balance and the turbulent mixing is sharply

suppressed, the urban surface tends to maintain a warmer temperature. As a result, a stronger nocturnal UHI that averages 2.0° and 3.3°C is established for the summer and autumn episodes, respectively. The UHI intensity normally peaks around early evening [1800–2000 local time (LT)] because of the stronger cooling rate in the rural area. The strong UHI remains until around sunrise (at 0600 LT), when the UHI intensity drops sharply to approximately 0.5°C . As the mixed layer builds, a weak daytime UHI is gradually established via sensible heating.

c. Thermally induced circulation

The initiation and development of the local thermal circulations are modified according to the thermal structure associated with the distribution of urban land cover. In this section, the urbanization-induced changes in the average horizontal wind field will first be discussed for the two episodes (Figs. 10 and 11). Detailed discussions of the impacts of UHI on the thermally induced circulations, however, will focus on one specific day for each episode (Figs. 12–15).

FIG. 10. Simulated average surface wind (vectors) and temperature ($^{\circ}\text{C}$; shaded contours) in (a), (d) PRE-URBAN and (b), (e) URBAN and (c), (f) differences in the wind vector and temperature between URBAN and PRE-URBAN at (top) 1600 and (bottom) 1800 LT during 11–16 Aug. The dashed red lines enclose the areas with obvious wind changes.

1) URBAN-BREEZE CIRCULATION

Figures 10 and 11 present the simulated surface wind/temperature fields that are averaged over the entire simulation periods at specific times in both experiments and their differences. During the 11–16 August episode, a slightly increased urban breeze directed from the rural regions to northwestern Shanghai can be seen in the afternoon (1600 LT) in the contrast map (Fig. 10c); in the 3–9 October episode, however, no significant impacts on urban breeze can be found (Fig. 11c). Moreover, enhanced inflow by $1\text{--}2\text{ m s}^{-1}$ directed from Lake Tai to the coastal Suzhou city can also be found in both

episodes (Figs. 10c and 11c). As the UHI intensity increases and the background wind weakens, the urban breeze appears to be significantly strengthened in both episodes. Around the Shanghai metropolitan area, Suzhou city along Lake Tai, and their prevailing downwind regions, the increment of urban breeze can reach $\sim 1.5\text{ m s}^{-1}$ (Figs. 10d–f and 11d–f).

In the following discussion, two typical days (15 August and 7 October) that feature relatively weak background wind and strong UHI are chosen for further analyses. By noon (1200 LT), a weak surface convergent zone appeared downwind of Shanghai city in the PRE-URBAN simulation (Figs. 12a and 13a). In the

FIG. 11. As in Fig. 10, but for the 3–9 Oct episode.

URBAN simulation, however, the temperature slowly increases along the Shanghai–Suzhou urban belt (Figs. 12b and 13b); as a result of the increased urban forcing over the entire delta, the contrast map (Figs. 12c and 13c) shows a surface divergent wind directed from the old town to the expanded urban region in Shanghai. A clear lake-breeze divergent zone concurrently dominates Lake Tai in the afternoon; as the temperature/pressure gradient between Lake Tai and the coastal Suzhou city increases, the enhanced lake breeze and urban breeze converge around Suzhou in the August episode (Figs. 12b,e).

As a result of the strong daytime background wind and weak UHI (Fig. 9), no obvious urban convergent zones are produced in the afternoon (1200–1600 LT). Observations also indicated that the urban breeze in

Shanghai appears to be very weak, with a speed of less than $1\text{--}2\text{ m s}^{-1}$ and a duration of no more than 3 h (Zhou and Zheng 1991). Until around sunset (1800–2000 LT), when the UHI intensity reaches a maximum (Fig. 9) and calm wind conditions appeared, a strong urban convergence zone was observed on 15 August that runs from the Shanghai–Jiangsu border to Wuxi and Changzhou (Fig. 12h). On 7 October, the contrast map also demonstrates a pulse of cooler country air oriented toward Shanghai and Suzhou cities by $2\text{--}3\text{ m s}^{-1}$, but with a smaller spatial extent and intensity (Fig. 13i).

Figures 14 and 15 present the cross sections of the wind components for the two episodes along 31.25°N (the line AA' as marked in Fig. 8b), which cross the isolated urban centers at Shanghai ($121^\circ\text{--}121.7^\circ\text{E}$), Lake

FIG. 12. Simulated surface wind (vectors) and temperature ($^{\circ}\text{C}$; shaded contours) in (left) PRE-URBAN and (center) URBAN and (right) differences in the wind vector and temperature between URBAN and PRE-URBAN at (a)–(c) 1200, (d)–(f) 1600, and (g)–(i) 2000 LT 15 Aug. The dashed red lines in (c), (f), and (i) enclose the areas with obvious wind changes; the blue lines in (a), (b), (d), (e), and (h) mark the surface convergent zone and the sea breeze front.

FIG. 13. As in Fig. 12, but at (a)–(c) 1200, (d)–(f) 1600, and (g)–(i) 1800 LT 7 Oct. The blue lines in (a), (d), and (e) mark the surface convergent zone and the sea-breeze front.

FIG. 14. Cross sections of wind vectors and temperature ($^{\circ}\text{C}$; shaded contours) along 31.2°N (the line AA' in Fig. 8b) at (a),(b) 1200 and (c),(d) 1600 LT 15 Aug in (left) PRE-URBAN and (right) URBAN. The black shaded areas at the bottom of each panel represent the terrain; along the x axis the red bar represents the extent of the urban area, the blue bar represents extent of the ocean, and the green bar represents the extent of Lake Tai.

Tai (119.8° – 120.6°E), and the East China Sea. The influence of urban surface heating extends into the overlying atmosphere and gradually diminishes with height. By noon (1200 LT), the influence of urbanization on the boundary layer warming can reach as high as 1–1.2 km, where the urban air is warmer than the surrounding countryside by $\sim 1^{\circ}\text{C}$. In the vertical direction, associated with this urban warming zone are increased upward velocities near 120.8° – 121.6°E (Figs. 14b and 15b), which reach approximately 0.2 m s^{-1} by 2 km. In the summer episode, the UHI effect at Shanghai combines with the strong vertical descending motion ($\sim 0.3\text{ m s}^{-1}$) lying on the East China Sea and the coastal sea breeze to form a closed vertical circulation (121.3° – 122°E) in the URBAN experiment (Fig. 14b). The extension of this circulation zone can reach up to 60 km in the horizontal dimension and 1.2 km in the vertical dimension (Fig. 14b). On 7

October, however, the large-scale background north wind hinders the development of the sea breeze, and therefore no complete circulation could be formed (Fig. 15b). As the UHI develops, the enhanced urban updraft air continues over several main cities during the afternoon (Figs. 14c,d and 15c,d). The vertical extent of the nocturnal UHI is restricted below 100 m; afterward, the urban upward flow begins to dissipate, which is indicative of the weak mixing in the stable nocturnal boundary layer.

2) SEA-BREEZE CIRCULATION

The evolution of the sea breeze is also modified. Both experiments generate similar sea breezes dominating the Hangzhou Bay and, to some extent, the mouth of the Yangtze (Figs. 10, 11). From the average field, it is clear that in the afternoon (1600 LT), when

FIG. 15. As in Fig. 14, but for 7 Oct.

a well-developed sea breeze forms in the Hangzhou Bay, urbanization increased the land–sea temperature difference and accelerated the daytime sea breeze by $1\text{--}2\text{ m s}^{-1}$ in both episodes when compared with the PRE-URBAN scenario (Figs. 10a–c and 11a–c). Noticeable is that the enhancement of the sea breeze is more significant in the October episode and covers the entire coastlines of Shanghai and Hangzhou (Fig. 11c).

Specific analysis shows that by noon (1200 LT) the sea breeze starts to develop and a distinct divergent zone forms over Hangzhou Bay. Nevertheless, the land surface forcing is so weak that the sea breeze just influences the coastal portions of Shanghai, Hangzhou, and Ningbo and does not penetrate farther inland (Figs. 12a–c and 13a–c). In the afternoon (~ 1600 LT; Figs. 12d–f and 13d–f), the sea breeze is substantially enhanced by the increased land–sea temperature contrast, leading to a well-developed sea breeze from Hangzhou Bay that penetrates inland at quite a long

distance. Furthermore, with the presence of urban land cover in the URBAN case, the sea-breeze front typically moves northwest and can penetrate inland by nearly 70 km in summer (Fig. 12e) and 40 km in autumn (Fig. 13e) over a span of approximately 3–4 h. In contrast, in the PRE-URBAN case, the influence of the sea breeze can only reach the north of Zhejiang province because of the weak land surface forcing (Figs. 12d and 13d). In addition, driven by the homodromous background wind and increased urban surface forcing in summer, the strong sea breeze could reach Lake Tai and form a surface convergent zone with the lake breeze (Fig. 12e). In the vertical direction, a closed thermal circulation ($121.3^{\circ}\text{--}121.8^{\circ}\text{E}$) develops along the East China Sea and Shanghai urban area for both episodes (Figs. 14d and 15d), which are absent in the PRE-URBAN cases (Figs. 14c and 15c).

Afterward, the land surface quickly loses heat and the sea-breeze circulation gradually dissipates. Under the strong background wind field, however, the land-breeze

circulation is not evident during the nighttime and early morning; therefore, the influence of urbanization on land breeze is not discussed here.

4. Conclusions

This study investigates the impacts of urbanization on UHI effects and thermally induced circulation in the YRD region. The changes of urban land cover, along with GVF and LAI, are described using high-resolution MODIS observations.

Analysis shows that the assimilation of satellite-derived land surface parameters provides a better description of the land surface characteristics and reduces the near-surface meteorological bias. Changes in land-cover specification and associated vegetation parameters noticeably affect the surface heat balance, which resulted in perceivable alterations in the temperature and wind fields. As the urban size increases, a typical urban heat island is generated along Shanghai, Suzhou–Wuxi–Changzhou, and Hangzhou–Ningbo as a result of the urban–rural energy balance differences. The local wind field is modified by the complex interactions between the UHI and the sea–land or land–lake breeze. For example, several surface convergent zones are generated along Shanghai–Suzhou–Wuxi as a result of a combination of UHI effect, enhanced sea breeze, and lake breeze; the UHI effect significantly enhances the daytime sea breeze over Hangzhou Bay because of the increased land–sea temperature contrast.

Some issues still exist after this study, however. Complex urban canopy processes are involved in urban climates, including urban geometry, surface properties, the release of anthropogenic heat, and so on. Feng et al. (2014) investigated the impacts of anthropogenic heat release in three urban clusters in China and found a pronounced temperature increase by 0.5°–1°C. Wang (2009) compared the flow structures and turbulence characteristics of the UHI-induced circulation over ideal urban areas by large-eddy simulation and demonstrated that the urban size has obvious influence on wind flow and turbulence features. Other studies (Grossman-Clarke et al. 2005; Stefanov et al. 2001) used the Landsat Thematic Mapper data to describe the heterogeneity of the urban surface and found a significant impact on the turbulent heat flux and boundary layer evolution. All of these studies highlight a new use for advanced urban modules, but these factors were not considered in this study because of the lack of precise input data.

Moreover, intrinsic differences do exist between the two parallel experiments as a result of the discrepancies of the AVHRR and MODIS datasets in retrieval algorithm, resolution, classification method, definition of LAI, and so on. This problem is particularly visible for

the vegetated regions. For example, it is reported that the AVHRR dataset overestimates the cropland area in Shanghai and Jiangsu by 14.7% and 19.7%, respectively (Wu et al. 2009), because of the limited spectral channels and unsupervised classification method. By contrast, MODIS performs better in vegetation monitoring, with the deviation under 5% when compared with field surveys (Ran and Li 2006a,b). On the other hand, as seen in Fig. 3b, the tabulated LAI values show systematic overestimation over the northern vegetated regions. Despite the uncertainties stated above, this study is expected to provide meaningful information to the readers. Our previous work (Li et al. 2014) highlights that the patterns of a UHI and its effects on thermal circulations are determined by land-cover type, which is in turn modified by GVF and LAI. This study focuses on the urbanization-induced changes in thermal circulations; the application of AVHRR and MODIS satellite retrieval data could successfully capture the decadal urban expansion as stated in other studies (Chen et al. 2000; Haas and Ban 2014; Wang et al. 2012) (Fig. 2), as well as the reduction in urban vegetation cover and LAI (Fig. 3). Investigations also found good agreement (90% or more) between the NDVI values obtained from AVHRR and MODIS sensors for various land-cover types and composite intervals (Gallo et al. 2004, 2005; Gitelson and Kaufman 1998).

A few studies have addressed the impacts of urban land surface forcing and associated circulations on local meteorological conditions and air quality. Sarrat et al. (2006) demonstrated that enhanced turbulence resulting from the UHI effect in Paris, France, dilutes pollutants inside the deeper boundary layer. Increased ozone (O_3) mixing ratios in urbanized coastal areas have been observed and modeled in a number of studies, and it has been shown that the recirculation of pollutants by sea- and land-breeze circulations is largely responsible for the increased O_3 levels (Levy et al. 2008; Martins et al. 2012; Oh et al. 2006). Thus, this study may lay a foundation for further study on the impacts of urban-induced circulation on air quality.

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REFERENCES

- Chen, F., and J. Dudhia, 2001a: Coupling an advanced land surface–hydrology model with the Penn State–NCAR MM5 modeling system. Part I: Model implementation and sensitivity. *Mon. Wea. Rev.*, **129**, 569–585, doi:[10.1175/1520-0493\(2001\)129<0569:CAALSH>2.0.CO;2](https://doi.org/10.1175/1520-0493(2001)129<0569:CAALSH>2.0.CO;2).
- , and —, 2001b: Coupling an advanced land surface–hydrology model with the Penn State–NCAR MM5 modeling system. Part II: Preliminary model validation. *Mon. Wea. Rev.*, **129**, 587–604, doi:[10.1175/1520-0493\(2001\)129<0587:CAALSH>2.0.CO;2](https://doi.org/10.1175/1520-0493(2001)129<0587:CAALSH>2.0.CO;2).
- Chen, J., 2007: Rapid urbanization in China: A real challenge to soil protection and food security. *Catena*, **69**, 1–15, doi:[10.1016/j.catena.2006.04.019](https://doi.org/10.1016/j.catena.2006.04.019).
- Chen, S. P., S. Zeng, and C. G. Xie, 2000: Remote sensing and GIS for urban growth analysis in China. *Photogramm. Eng. Remote Sens.*, **66**, 593–598.
- Chen, X. L., H. M. Zhao, P. X. Li, and Z. Y. Yin, 2006: Remote sensing image-based analysis of the relationship between urban heat island and land use/cover changes. *Remote Sens. Environ.*, **104**, 133–146, doi:[10.1016/j.rse.2005.11.016](https://doi.org/10.1016/j.rse.2005.11.016).
- Chou, M.-D., and M. J. Suarez, 1999: A solar radiation parameterization for atmospheric studies. Tech. Rep. Series on Global Modeling and Data Assimilation, Vol. 15, M. J. Suarez, Ed., NASA Tech. Memo. NASA/TM-1999-104606, 40 pp. [Available online at <http://gmao.gsfc.nasa.gov/pubs/docs/Chou136.pdf>.]
- Chu, Z., and G. Ren, 2005: Change in urban heat island magnitude and its effect on mean air temperature record in Beijing region (in Chinese). *Acta Meteor. Sin.*, **63**, 534–540.
- Deardorff, J. W., 1978: Efficient prediction of ground surface temperature and moisture, with inclusion of a layer of vegetation. *J. Geophys. Res.*, **83**, 1889–1903, doi:[10.1029/JC083iC04p01889](https://doi.org/10.1029/JC083iC04p01889).
- de Foy, B., L. T. Molina, and M. J. Molina, 2006: Satellite-derived land surface parameters for mesoscale modelling of the Mexico City basin. *Atmos. Chem. Phys.*, **6**, 1315–1330, doi:[10.5194/acp-6-1315-2006](https://doi.org/10.5194/acp-6-1315-2006).
- Du, Y., Z. Q. Xie, Y. Zeng, Y. F. Shi, and J. G. Wu, 2007: Impact of urban expansion on regional temperature change in the Yangtze River Delta. *J. Geogr. Sci.*, **17**, 387–398, doi:[10.1007/s11442-007-0387-0](https://doi.org/10.1007/s11442-007-0387-0).
- Ek, M. B., K. E. Mitchell, Y. Lin, E. Rogers, P. Grunmann, V. Koren, G. Gayno, and J. D. Tarpley, 2003: Implementation of Noah land surface model advances in the National Centers for Environmental Prediction operational mesoscale Eta Model. *J. Geophys. Res.*, **108**, 8851, doi:[10.1029/2002JD003296](https://doi.org/10.1029/2002JD003296).
- Fan, S. J., Q. Fan, W. Yu, X. Y. Luo, B. M. Wang, L. L. Song, and K. L. Leong, 2011: Atmospheric boundary layer characteristics over the Pearl River Delta, China, during the summer of 2006: Measurement and model results. *Atmos. Chem. Phys.*, **11**, 6297–6310, doi:[10.5194/acp-11-6297-2011](https://doi.org/10.5194/acp-11-6297-2011).
- Feng, J. M., J. Wang, and Z. W. Yan, 2014: Impact of anthropogenic heat release on regional climate in three vast urban agglomerations in China. *Adv. Atmos. Sci.*, **31**, 363–373, doi:[10.1007/s00376-013-3041-z](https://doi.org/10.1007/s00376-013-3041-z).
- Foley, J. A., and Coauthors, 2005: Global consequences of land use. *Science*, **309**, 570–574, doi:[10.1126/science.1111772](https://doi.org/10.1126/science.1111772).
- Gallo, K., L. Ji, B. Reed, J. Dwyer, and J. Eidenshink, 2004: Comparison of MODIS and AVHRR 16-day normalized difference vegetation index composite data. *Geophys. Res. Lett.*, **31**, L07502, doi:[10.1029/2003GL019385](https://doi.org/10.1029/2003GL019385).
- , L. Li, B. Reed, J. Eidenshink, and J. Dwyer, 2005: Multiplatform comparisons of MODIS and AVHRR normalized difference vegetation index data. *Remote Sens. Environ.*, **99**, 221–231, doi:[10.1016/j.rse.2005.08.014](https://doi.org/10.1016/j.rse.2005.08.014).
- Gallus, W. A., and J. F. Bresch, 2006: Comparison of impacts of WRF dynamic core, physics package, and initial conditions on warm season rainfall forecasts. *Mon. Wea. Rev.*, **134**, 2632–2641, doi:[10.1175/MWR3198.1](https://doi.org/10.1175/MWR3198.1).
- Gitelson, A. A., and Y. J. Kaufman, 1998: MODIS NDVI optimization to fit the AVHRR data series spectral considerations. *Remote Sens. Environ.*, **66**, 343–350, doi:[10.1016/S0034-4257\(98\)00065-0](https://doi.org/10.1016/S0034-4257(98)00065-0).
- Grossman-Clarke, S., J. A. Zehnder, W. L. Stefanov, Y. B. Liu, and M. A. Zoldak, 2005: Urban modifications in a mesoscale meteorological model and the effects on near-surface variables in an arid metropolitan region. *J. Appl. Meteor.*, **44**, 1281–1297, doi:[10.1175/JAM2286.1](https://doi.org/10.1175/JAM2286.1).
- Gutman, G., and A. Ignatov, 1998: The derivation of the green vegetation fraction from NOAA/AVHRR data for use in numerical weather prediction models. *Int. J. Remote Sens.*, **19**, 1533–1543, doi:[10.1080/014311698215333](https://doi.org/10.1080/014311698215333).
- Haas, J., and Y. F. Ban, 2014: Urban growth and environmental impacts in Jing-Jin-Ji, the Yangtze River Delta and the Pearl River Delta. *Int. J. Appl. Earth Obs.*, **30**, 42–55, doi:[10.1016/j.jag.2013.12.012](https://doi.org/10.1016/j.jag.2013.12.012).
- Heald, C. L., and Coauthors, 2008: Predicted change in global secondary organic aerosol concentrations in response to future climate, emissions, and land use change. *J. Geophys. Res.*, **113**, D05211, doi:[10.1029/2007JD009092](https://doi.org/10.1029/2007JD009092).
- Jacquemin, B., and J. Noilhan, 1990: Sensitivity study and validation of a land surface parameterization using the HAPEX-Mobilhy data set. *Bound.-Layer Meteor.*, **52**, 93–134, doi:[10.1007/BF00123180](https://doi.org/10.1007/BF00123180).
- Jarvis, P. G., 1976: Interpretation of variations in leaf water potential and stomatal conductance found in canopies in field. *Philos. Trans. Roy. Soc.*, **B273**, 593–610, doi:[10.1098/rstb.1976.0035](https://doi.org/10.1098/rstb.1976.0035).
- Jiang, Z., Y. Chen, and Y. Li, 2006: Heat island effect of Beijing based on Landsat TM data (in Chinese). *Geomatics Inf. Sci. Wuhan Univ.*, **31**, 120–123.
- Jones, P. D., D. H. Lister, and Q. Li, 2008: Urbanization effects in large-scale temperature records, with an emphasis on China. *J. Geophys. Res.*, **113**, D16122, doi:[10.1029/2008JD009916](https://doi.org/10.1029/2008JD009916).
- Justice, C. O., J. R. G. Townshend, E. F. Vermote, E. Masuoka, R. E. Wolfe, N. Saleous, D. P. Roy, and J. T. Morisette, 2002: An overview of MODIS land data processing and product status. *Remote Sens. Environ.*, **83**, 3–15, doi:[10.1016/S0034-4257\(02\)00084-6](https://doi.org/10.1016/S0034-4257(02)00084-6).
- Kain, J. S., 2004: The Kain–Fritsch convective parameterization: An update. *J. Appl. Meteor.*, **43**, 170–181, doi:[10.1175/1520-0450\(2004\)043<0170:TKCPAU>2.0.CO;2](https://doi.org/10.1175/1520-0450(2004)043<0170:TKCPAU>2.0.CO;2).
- Knyazikhin, Y., J. V. Martonchik, R. B. Myneni, D. J. Diner, and S. W. Running, 1998: Synergistic algorithm for estimating vegetation canopy leaf area index and fraction of absorbed photosynthetically active radiation from MODIS and MISR data. *J. Geophys. Res.*, **103**, 32 257–32 275, doi:[10.1029/98JD02462](https://doi.org/10.1029/98JD02462).
- Lambin, E. F., H. J. Geist, and E. Lepers, 2003: Dynamics of land-use and land-cover change in tropical regions. *Annu. Rev. Environ. Resour.*, **28**, 205–241, doi:[10.1146/annurev.energy.28.050302.105459](https://doi.org/10.1146/annurev.energy.28.050302.105459).
- Levy, I., U. Dayan, and Y. Mahrer, 2008: A five-year study of coastal recirculation and its effect on air pollutants over the east Mediterranean region. *J. Geophys. Res.*, **113**, D16121, doi:[10.1029/2007JD009529](https://doi.org/10.1029/2007JD009529).

- Li, M. M., Y. Song, X. Huang, J. Li, Y. Mao, T. Zhu, X. Cai, and B. Liu, 2014: Improving mesoscale modeling using satellite-derived land surface parameters in the Pearl River Delta region, China. *J. Geophys. Res. Atmos.*, **119**, 6325–6346, doi:[10.1002/2014JD021871](https://doi.org/10.1002/2014JD021871).
- Li, W. L., H. L. Liu, X. J. Zhou, and Y. Qin, 2003: Analysis of the influence of Taihu Lake and the urban heat islands on the local circulation in the Yangtze Delta. *Sci. China*, **46D**, 405–415, doi:[10.1360/03yd9036](https://doi.org/10.1360/03yd9036).
- Li, X., X. Yang, J. Tang, X. Sun, and J. Fang, 2011: Multiple urban heat islands and surface energy balance during summer in Yangtze River Delta city cluster region simulated with WRF/NCAR. *J. Meteor. Sci.*, **31**, 441–450.
- Lin, Y. L., R. D. Farley, and H. D. Orville, 1983: Bulk parameterization of the snow field in a cloud model. *J. Climate Appl. Meteor.*, **22**, 1065–1092, doi:[10.1175/1520-0450\(1983\)022<1065:BPOTSF>2.0.CO;2](https://doi.org/10.1175/1520-0450(1983)022<1065:BPOTSF>2.0.CO;2).
- Liu, J. Y., H. Q. Tian, M. L. Liu, D. F. Zhuang, J. M. Melillo, and Z. X. Zhang, 2005: China's changing landscape during the 1990s: Large-scale land transformations estimated with satellite data. *Geophys. Res. Lett.*, **32**, L02405, doi:[10.1029/2004GL021649](https://doi.org/10.1029/2004GL021649).
- Liu, M. L., and H. Q. Tian, 2010: China's land cover and land use change from 1700 to 2005: Estimations from high-resolution satellite data and historical archives. *Global Biogeochem. Cycles*, **24**, GB3003, doi:[10.1029/2009GB003687](https://doi.org/10.1029/2009GB003687).
- Lo, J. C. F., A. K. H. Lau, J. C. H. Fung, and F. Chen, 2006: Investigation of enhanced cross-city transport and trapping of air pollutants by coastal and urban land-sea breeze circulations. *J. Geophys. Res.*, **111**, D14104, doi:[10.1029/2005JD006837](https://doi.org/10.1029/2005JD006837).
- , F. Chen, J. C. H. Fung, and K. K. M. Leung, 2007: Urban modification in a mesoscale model and the effects on the local circulation in the Pearl River Delta region. *J. Appl. Meteor. Climatol.*, **46**, 457–476, doi:[10.1175/JAM2477.1](https://doi.org/10.1175/JAM2477.1).
- Loveland, T. R., B. C. Reed, J. F. Brown, D. O. Ohlen, Z. Zhu, L. Yang, and J. W. Merchant, 2000: Development of a global land cover characteristics database and IGBP DISCover from 1 km AVHRR data. *Int. J. Remote Sens.*, **21**, 1303–1330, doi:[10.1080/014311600210191](https://doi.org/10.1080/014311600210191).
- Lu, X., K. C. Chow, T. Yao, A. K. H. Lau, and J. C. H. Fung, 2010: Effects of urbanization on the land sea breeze circulation over the Pearl River Delta region in winter. *Int. J. Climatol.*, **30**, 1089–1104, doi:[10.1002/joc.1947](https://doi.org/10.1002/joc.1947).
- Martins, D. K., R. M. Stauffer, A. M. Thompson, T. N. Knepp, and M. Pippin, 2012: Surface ozone at a coastal suburban site in 2009 and 2010: Relationships to chemical and meteorological processes. *J. Geophys. Res.*, **117**, D05306, doi:[10.1029/2011JD016828](https://doi.org/10.1029/2011JD016828).
- Monin, A. S., and A. M. Obukhov, 1954: Basic laws of turbulent mixing in the surface layer of the atmosphere. *Tr. Akad. Nauk SSSR Geophys. Inst.*, **24**, 163–187.
- Noh, Y., W. G. Cheon, S. Y. Hong, and S. Raasch, 2003: Improvement of the K-profile model for the planetary boundary layer based on large eddy simulation data. *Bound.-Layer Meteor.*, **107**, 401–427, doi:[10.1023/A:1022146015946](https://doi.org/10.1023/A:1022146015946).
- Oh, I. B., Y. K. Kim, H. W. Lee, and C. H. Kim, 2006: An observational and numerical study of the effects of the late sea breeze on ozone distributions in the Busan metropolitan area, Korea. *Atmos. Environ.*, **40**, 1284–1298, doi:[10.1016/j.atmosenv.2005.10.049](https://doi.org/10.1016/j.atmosenv.2005.10.049).
- Purevdorj, T., R. Tateishi, T. Ishiyama, and Y. Honda, 1998: Relationships between percent vegetation cover and vegetation indices. *Int. J. Remote Sens.*, **19**, 3519–3535, doi:[10.1080/014311698213795](https://doi.org/10.1080/014311698213795).
- Qian, L. X., H. S. Cui, and C. Jie, 2006: Impacts of land use and cover change on land surface temperature in the Zhujiang Delta. *Pedosphere*, **16**, 681–689, doi:[10.1016/S1002-0160\(06\)60103-3](https://doi.org/10.1016/S1002-0160(06)60103-3).
- Ran, Y. H., and X. Li, 2006a: The analysis report on the comparisons between four 1 km global land cover products (in Chinese). Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, Lanzhou, China, 23 pp.
- , and ———, 2006b: The production process of the WESTDC land cover product (in Chinese). Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, Lanzhou, China, 17 pp.
- Ren, G. Y., Y. Q. Zhou, Z. Y. Chu, J. X. Zhou, A. Y. Zhang, J. Guo, and X. F. Liu, 2008: Urbanization effects on observed surface air temperature trends in north China. *J. Climate*, **21**, 1333–1348, doi:[10.1175/2007JCLI1348.1](https://doi.org/10.1175/2007JCLI1348.1).
- Sailor, D. J., 1995: Simulated urban climate response to modifications in surface albedo and vegetative cover. *J. Appl. Meteor.*, **34**, 1694–1704, doi:[10.1175/1520-0450-34.7.1694](https://doi.org/10.1175/1520-0450-34.7.1694).
- Sarrat, C., A. Lemonsu, V. Masson, and D. Guedalia, 2006: Impact of urban heat island on regional atmospheric pollution. *Atmos. Environ.*, **40**, 1743–1758, doi:[10.1016/j.atmosenv.2005.11.037](https://doi.org/10.1016/j.atmosenv.2005.11.037).
- Skamarock, W. C., and Coauthors, 2008: A description of the Advanced Research WRF version 3. NCAR Tech. Note NCAR/TN-475+STR, 113 pp. [Available online at http://www.mmm.ucar.edu/wrf/users/docs/arw_v3_bw.pdf.]
- Stefanov, W. L., M. S. Ramsey, and P. R. Christensen, 2001: Monitoring urban land cover change: An expert system approach to land cover classification of semiarid to arid urban centers. *Remote Sens. Environ.*, **77**, 173–185, doi:[10.1016/S0034-4257\(01\)00204-8](https://doi.org/10.1016/S0034-4257(01)00204-8).
- Tang, Y., and M. Miao, 1998: Numerical studies on urban heat island associated with urbanization in Yangtze Delta region. *Adv. Atmos. Sci.*, **15**, 393–403, doi:[10.1007/s00376-998-0009-5](https://doi.org/10.1007/s00376-998-0009-5).
- Wan, H. C., Z. Zhong, X. Q. Yang, and X. Q. Li, 2013: Impact of city belt in Yangtze River Delta in China on a precipitation process in summer: A case study. *Atmos. Res.*, **125–126**, 63–75, doi:[10.1016/j.atmosres.2013.02.004](https://doi.org/10.1016/j.atmosres.2013.02.004).
- Wan, Z. M., 2003: Monitoring thermal status of ecosystems with MODIS land-surface temperature and vegetation index products. *Remote Sensing for Agriculture, Ecosystems, and Hydrology IV*, M. Owe, G. D'Urso, and L. Toullos, Eds., International Society for Optical Engineering (SPIE Proceedings, Vol. 4879), 280–288, doi:[10.1117/12.462411](https://doi.org/10.1117/12.462411).
- Wang, J., C. L. Fang, and Z. B. Wang, 2012: Advantages and dynamics of urban agglomeration development on Yangtze River Delta. *J. Geogr. Sci.*, **22**, 521–534, doi:[10.1007/s11442-012-0944-z](https://doi.org/10.1007/s11442-012-0944-z).
- Wang, W. C., Z. M. Zeng, and T. R. Karl, 1990: Urban heat islands in China. *Geophys. Res. Lett.*, **17**, 2377–2380, doi:[10.1029/GL017i013p02377](https://doi.org/10.1029/GL017i013p02377).
- Wang, W. G., 2009: The influence of thermally-induced mesoscale circulations on turbulence statistics over an idealized urban area under a zero background wind. *Bound.-Layer Meteor.*, **131**, 403–423, doi:[10.1007/s10546-009-9378-2](https://doi.org/10.1007/s10546-009-9378-2).

- Wu, W. P., L. Yang, H. Tang, Q. Zhou, and R. Shibasaki, 2009: Accuracy assessment of four global land cover datasets in China (in Chinese). *Trans. Chin. Soc. Agric. Eng.*, **25**, 167–173.
- Yu, M., G. R. Carmichael, T. Zhu, and Y. F. Cheng, 2012: Sensitivity of predicted pollutant levels to urbanization in China. *Atmos. Environ.*, **60**, 544–554, doi:[10.1016/j.atmosenv.2012.06.075](https://doi.org/10.1016/j.atmosenv.2012.06.075).
- Zhang, H., Z. F. Qi, X. Y. Ye, Y. B. Cai, W. C. Ma, and M. N. Chen, 2013: Analysis of land use/land cover change, population shift, and their effects on spatiotemporal patterns of urban heat islands in metropolitan Shanghai, China. *Appl. Geogr.*, **44**, 121–133, doi:[10.1016/j.apgeog.2013.07.021](https://doi.org/10.1016/j.apgeog.2013.07.021).
- Zhang, N., L. F. Zhu, and Y. Zhu, 2011: Urban heat island and boundary layer structures under hot weather synoptic conditions: A case study of Suzhou City, China. *Adv. Atmos. Sci.*, **28**, 855–865, doi:[10.1007/s00376-010-0040-1](https://doi.org/10.1007/s00376-010-0040-1).
- Zhou, S., and J. Zheng, 1991: The solar radiation at Shanghai city and its relation to the intensity of the urban heat island (in Chinese). *Acta Geogr. Sin.*, **46**, 207–212.