

Multi-scale remote sensing estimates of urban fractions and road widths for regional models

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Received: 11 February 2013 / Accepted: 15 March 2014 / Published online: 2 April 2014
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Abstract Landuse in East Asia has changed substantially during the last three decades, featured with expansion of urban built-up at unprecedented scale and speed. The fast expansion of urban areas could contribute to local and even regional climate change. However, current spatial datasets of urban fractions do not well represent the extent and expansion of urban areas in the regions, and that best available satellite data and remote sensing techniques have not been well applied to serve regional modeling of urbanization impacts on near surface temperature and other climate variables. Better estimates of localized urban fractions are badly needed. Here we use high and mid resolution satellite data to estimate urban fractions and road width at local and regional scales. With our fractional cover, data fusion, and differentiated threshold approaches, more spatial details of urban cover are demonstrated than previously reported in many global datasets. Many city clusters were merging into each other, with gradual blurring of boundaries and disappearance of gaps among member cities. Cities and towns were more connected with roads and commercial corridors, while wildland and urban green areas have become more isolated as patches among built-up areas. Average road width in commercial areas was 37.2 m in Beijing (north, temperate) and 24.2 m in Guangzhou (south, tropical), which are greater than these listed in model default values. Those new estimates could effectively improve climate simulation at local and regional scales in East Asia.

This article is part of a Special Issue on “Regional Earth System Modeling” edited by Zong-Liang Yang and Congbin Fu.

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1 Introduction

Climate change is highly heterogeneous over the globe, with strong regionality (Fu 2003; Jia et al. 2011). We need to better understand the timing and magnitude of regional climate change, the environmental and socio-economic consequences of climate change, and the implications for society and environment (Foley et al. 2005). Meanwhile, intensified human activities and rapid economic development will likely cause increased impacts on regional climate through modifying land surface and atmospheric chemistry (Fu 2003; Rosenfeld 2000). It is therefore an essential issue to examine the impacts of land use change such as urban expansion on regional climate (Seto et al. 2011; Turner et al. 2007).

Urban heat island (UHI) effect was widely considered as a local phenomenon, with minor impact on regional climate, although the phenomenon has been observed in cities in a wide range of locations, from temperate to tropical regions (Brown 1999; Crutzen 2004; Grossman-Clarke et al. 2005; Hu and Jia 2010). However, in large area of mega-cities with significant expansion of built-up in relatively short period, UHI could contribute to regional climate forcing (Seto et al. 2011; Han and Baik 2008). Urban morphology can influence land-atmospheric energy exchange, turbulence regime of atmospheric flow, and the microclimate, and can accordingly modify the boundary layer processes over urban canopy and downstream areas (Dupont et al. 2004; Grossman-Clarke et al. 2005). Direct climate effects of urban surface are driven by turbulence regime related heterogeneity of building distribution, hydro-meteorological regime related to impervious surfaces, and release of anthropogenic heat fluxes (Li and Avissar 1994; Feng et al. 2012). Meanwhile, human induced release of urban aerosols affects the transfer of radiation, cloud formation, and precipitation (Rosenfeld 2000; Sarrat et al. 2006).

Rapid urbanization in East Asia in past three decades is considered as a remarkable process that could contribute to sub-regional and regional climate change (Gao and Jia 2013), which may not be well represented by global scale data and parameters. Meanwhile, key model parameters such as urban extent, fractional urban cover, and morphology are often available as rough estimates over the globe (Oleson et al. 2008; Tewari et al. 2007). Lack of regional details and spatial heterogeneity of urban datasets could greatly compromise the performance of regional climate models in capturing critical climate effects over large and rapid expanded urban clusters, especially those in developing East Asia where urbanization was not only significant but also highly localized in terms of spatial patterns and structure in recent decades. Remotely sensed estimates of urban fractions and other parameters are promising, and have been used at global scale, however, those estimates are often problematic at regional scales.

The objective of this study is to demonstrate remotely sensed approaches for East Asia specified estimates of urban fractions and other parameters to be used for regional urban climate effect simulation. Here we use high and mid resolution satellite data, combined with intense field measurements along urban–rural transects to evaluate some key urban parameters, including urban fractions and road width, and to get better spatial estimates of those parameters for the region.

2 Data and methods

2.1 Data

Various available satellite derived land cover products were examined for their consistency and performance in the region, and some of them were integrated for better estimate urban extent

and expansion in recent decade. The data include China NLCD dataset, MODIS land cover products (MCD12Q1) Collection V, IGBP-DISCover datasets provided by USGS, and GLC2000 datasets derived from SPOT VGT images (Gao and Jia 2013) over East Asia. The National Land Cover Dataset (NLCD) of China for 2000 with urban category extracted was used as basic data for threshold validation (Table 1).

Cloud free Landsat TM and QuickBird images in selected urban areas were obtained from CAS Center for Earth Observation and Digital Earth, and were interpreted with supervised classification algorithm (modified maximum likelihood algorithm) to derive high resolution urban land information over sample areas for assessment of land cover products and for estimates of urban parameters. Landsat data were acquired over major urban clusters, and QuickBird data were acquired over selected areas of Beijing and Guangzhou.

Nighttime satellite imagery from the DMSP OLS provides a unique view of human activities at 1 km spatial resolution globally since 1992. The sensor has two bands: a panchromatic VNIR band and a thermal infrared band (Elvidge et al. 1998). It is composed of grid-based visible band digital numbers (DN) ranged from 0 to 63 with resolution of 30 arc-seconds (approximately 1 km at the equator and 0.8 km at 40°N). OLS data for the region was used to analyze urban pattern and expansion in recent decade, and to develop integrated spatial datasets.

2.2 Multi-sensor urban cover detection

The method involved three main steps. In the first step, modified maximum likelihood supervised classification (Guindon et al. 2004) was applied to all bands of the Landsat images, with higher weights of blue and SWIR bands, and spectral and spatial signals were combined to improve urban detection. Overall accuracy of our maximum likelihood classification is about 92.4 %, which is assessed over 6 selected urban clusters in the region. In the second step, the binary images obtained in the first step were employed to calculate the statistics of urban and built-up ratio within the zones of grids. The coarse resolution urban landuse classifications listed above were examined against reference Landsat based urban fractions for their consistency and accuracy over the region. Datasets with relatively greater consistency and accuracy were integrated for better estimate urban extent and expansion in recent decade (Fig. 1).

Table 1 Data used in urban cover detection and road width estimation

Data type	Data name	Spatial resolution	Time of data collection	Preprocessing steps	Purpose of data collection
Land use/cover products	USGS	1 km	1992.04–1993.03	Reprojection, resampling	Comparison
	MODIS	1 km	2001–2010	Mosaicking, reprojection, resampling	Comparison
	GLC2000	1 km	1999–2000	Resampling	Comparison
	NLCD	1 km	1999/2000	Aggregation	Adjustment
Satellite data	Landsat TM/ETM+	30 m	1990/2000/2009/2010	Geometric registration	Classification
	DMSP/OLS	Approximately 1 km	2000, 2009	Extraction, reprojection, resampling	Mapping urban area
	QuickBird	0.7/2.8 m	2009/2010	Orthorectification, fusion	Estimation of road width

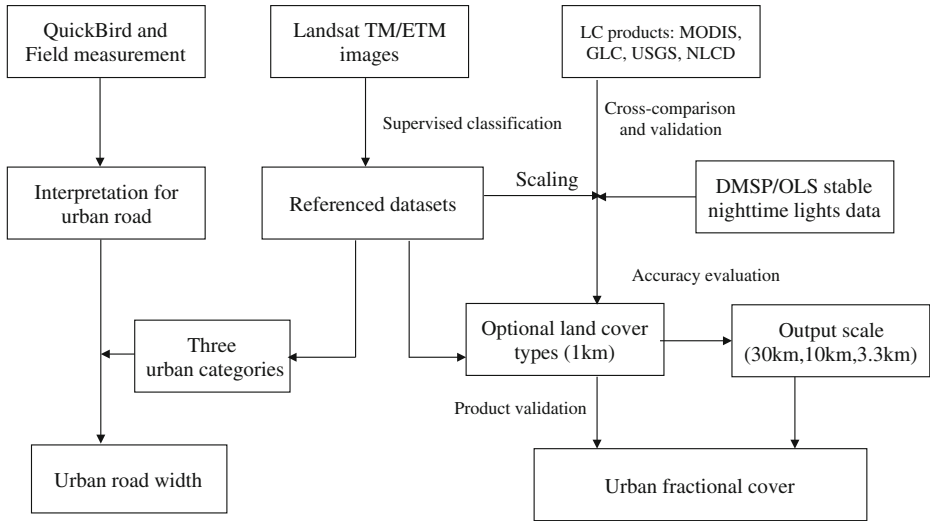


Fig. 1 Work flow of satellite based estimates of urban fraction and road width

According to the accuracy compared with reference data, data source in specific period were chosen and validated for fused urban land cover (Gao and Jia 2013; Hu and Jia 2010).

Urban area derived from night light datasets was validated with reference images of Landsat, and further combined with MODIS land cover datasets to improve small town and settlements estimation. The datasets that performed best in mapping urban land cover in the evaluation were chosen and combined as the data sources at 1 km resolution for fused land cover products. Fractional urban cover was then calculated in three specific spatial resolutions (3.3 km, 10 km, and 30 km) for nested climate modeling at local and regional scales.

We used high resolution satellite images in selected city clusters (e.g. Beijing, Shanghai, Guangzhou, Chengdu, Zhengzhou, and Kashi) to identify urban area, and tested various thresholds in fractional up-scaling. Different thresholds were applied over each city cluster to generate fractional urban cover dataset at 1 km resolution. The urban fraction reference data at same spatial scale were then applied to validate fused urban datasets.

2.3 Deriving urban fraction and road width

The urban canopy parameterization reflects thermodynamic effects in climate system caused by the presence of urban structures (Otte et al. 2004; Oleson et al. 2008). The primary urban parameters required by models include the fraction of the urban landscape that does not have natural vegetation (FRC_URB), and the urban road width (ROAD_WIDTH) for each urban category. It is preferable to use urban land use maps for climate models with following three urban categories (Tewari et al. 2007): Low intensity residential includes areas with a mixture of constructed materials and vegetation; High intensity residential includes highly developed areas where people reside in high numbers; Commercial includes all highly developed areas of city centers, business districts, warehouse, etc.

Considering urban areas are in different level of development among parts of the country, we divided the country into six regions with criteria of urban clusters. For each region, urban cover classifications derived above were up-scaled from its 30-m resolutions to the 1-km resolution by calculating gridded percentage of urban extent. The urban fractions of Landsat

and coarse resolution datasets were compared and scatter plots were used to examine their correlations for each region. We divided urban fraction at 1 km into three urban categories with differentiated thresholds (Fig. 2). To facilitate estimates and validation of satellite based urban fractions and road width, we conducted intense field measurements along urban–rural transects in 2012 and 2013 in greater Beijing and Guangzhou. During the field campaigns, we measured landuse fractions, land surface temperature, and road width at 100 randomly selected sample sites. Global positioning system unit (Trimble GeoXT) and Thermal Imager with fused visual imager (Fluke Ti32) were used as handheld and on top of vehicle to measure those parameters. Urban road widths were calculated from high resolution images of QuickBird and field measurements. 100 random samples were generated for both test sites over Beijing and Guangzhou. Maximal, mean, and minimal road widths were estimated at each sample, and then statistically analyzed in three urban categories respectively.

3 Results

3.1 Fractional urban extent over city clusters

At urban cluster scale, urban extent showed very identical spatial patterns in both north and south cases. With one single city center, built-up areas spread radially and formed mosaic with croplands and wildland in urban–rural fringe, until reaching natural barriers such as high mountains and water bodies (Fig. 2). Fractional built-up in each pixel gradually decreased from over 90 % in city core to 10–30 % in urban–rural fringe. In Beijing, very dense (built-up fraction) urban core was identified around its historical city center, with gradual declining of urban fractions approximately followed the extent of its six beltway system. Greater expansion

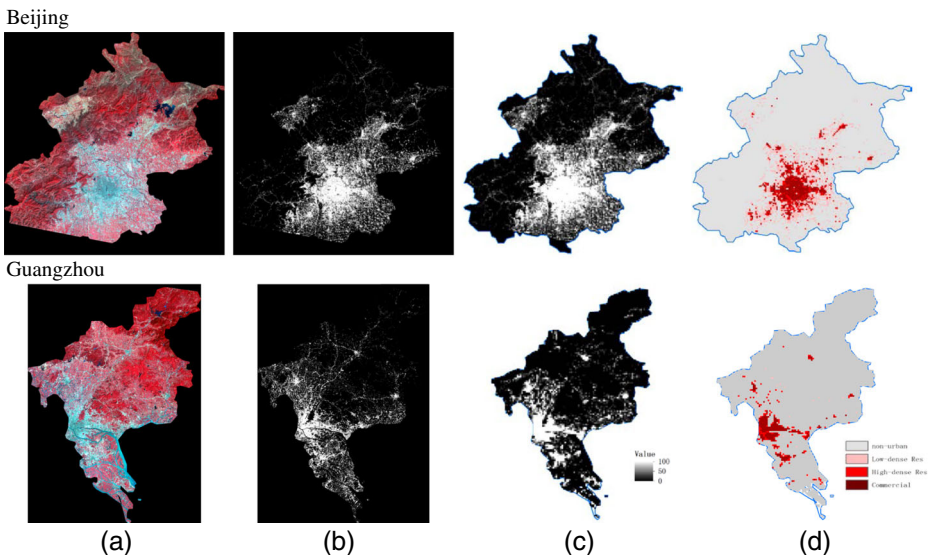


Fig. 2 Fractional built-up signals derived from high resolution satellite data. **a** the original Landsat images, **b** the binary images of the urban and built-up category, **c** the urban fraction at 1 km resolution and **d** the three categories of urban in UCM, the red color from deep to shallow represent commercial, high intensity residential and low intensity residential

occurred northwards than south with high fraction, while southern part is likely emerging for fast expansion in coming decade as municipal government launched its south development initiative in 2011. In Guangzhou, urban core is located in Pearl River Delta with high urban fraction, and spread into northeast areas. Built-up fractions were higher than Beijing, even in urban–rural fringe. Meanwhile, rapidly developed satellite towns with high urban fraction can be identified around both cities (Fig. 3). They spatially tend to connect with the main city areas, especially after many of them were upgraded to administrative municipal level in mid 2000s. Those satellite towns and high fraction urban–rural mosaic were largely ignored by current urban cover datasets used in land surface and climate models (Fig. 4), as fixed threshold of urban classes were applied to generate coarse resolution (10–60 km) grids from moderate resolution (1 km) data source. Fractional approach clearly captured those widely spread urban areas and kept the signals in up-scaled coarse resolution model input layers.

Urban canopy was further categorized into three classes, namely commercial, high density residence, and low density residence urban canopies, based on built-up fractions in each up-scaled pixel (Fig. 2). Major commercial or very high density canopies were identified in both historical city center and satellite towns in Beijing, while an almost continuous commercial canopies occurred in central Guangzhou. High density residence and low density residence radially located around the centers of main cities and satellite towns, with more low density residence canopies existed in urban–rural fringe. By comparing satellite derived urban extents between 2000 and 2009, the latter has substantially increased its density (built-up fraction) in

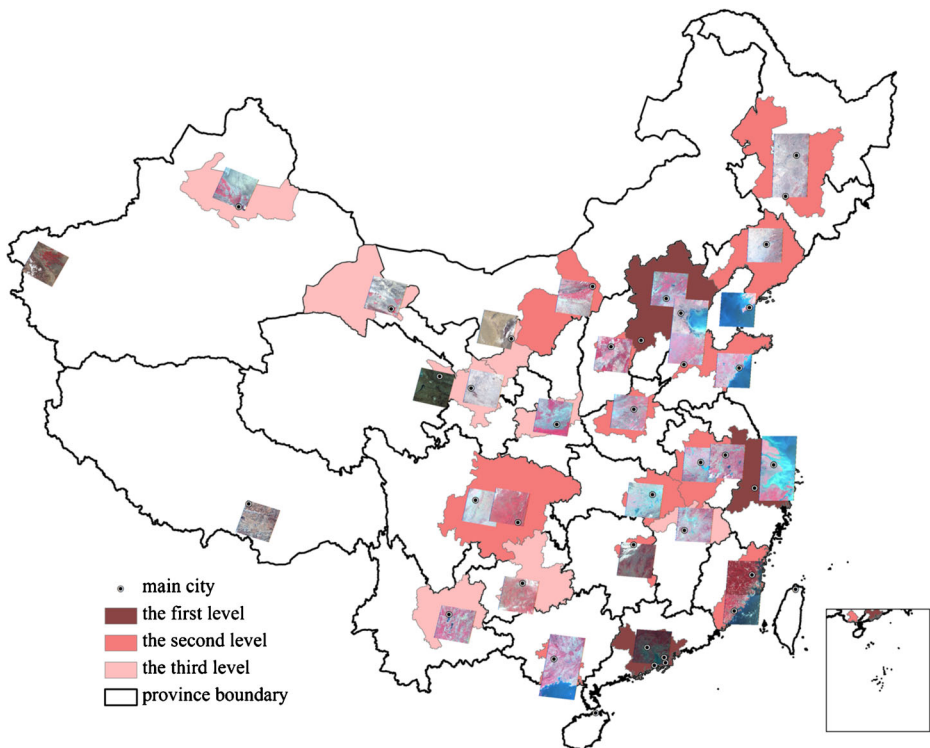


Fig. 3 Distribution of major urban clusters and fractions in China. The color-shaded areas represent major city clusters and the overlaid small images are Landsat data over sample areas, composed of bands 4, 3, 2

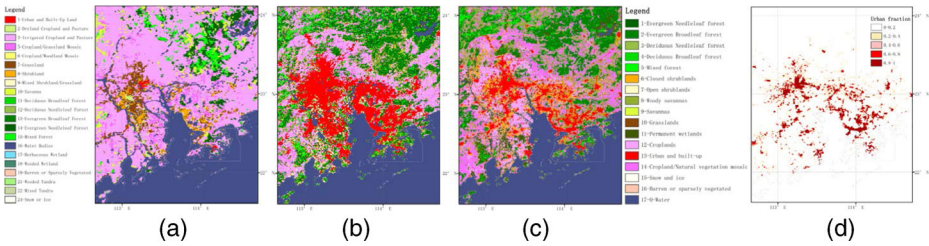


Fig. 4 Comparison of urban extents between the datasets from this study and those currently applied in land surface and climate models. **a** USGS 1992 derived from digital chart of world; **b** MODIS 2001 from census data; **c** MODIS 2006 derived from MODIS NDVI products; **d** Urban fraction derived from Landsat (this study). All images are scaled to 1 km spatial resolution

many cases, and could potentially develop into high density residence category in term of climate forcing in coming years as satellite town continue to develop and city center continue to expand. More importantly, most of those urban expansions followed vertical direction with prevailing wind, and therefore, could potentially lead to even stronger impacts on the monsoon system (Oke 2006; Feng et al. 2012).

Rapid urban development was detected in almost all temporal datasets except for MODIS based land cover products from 2001–2010, and urban expansion in fused urban fraction datasets and census data (Fang et al. 2011) were highly correlated ($r^2=0.73$, $p<0.01$). Meanwhile, fused urban cover captured the accelerated urban expansion by 6.7 % per year happened after 2000 that also reflected by those detected by night light and built-up datasets with increased rate 6.0 and 8.1 % respectively (Fang et al. 2011). Urban extent data from IGBP-DISCover land cover products was widely used in regional models to represent parameters in early 1990s (Wang et al. 2012), however, the extents were much smaller than Landsat derived ones in 1990, and even smaller than those in 1979. So, we consider it to represent urban extent before 1980 when urbanization was relatively minor in China.

3.2 Macro spatial structure of mega-cities

Major urban clusters are located in east coast areas, including greater Beijing, Yangzi River Delta centered by Shanghai, and Pearl River Delta centered by Guangzhou. Large scale, almost continuous urban areas cover those regions (Fig. 3). Meanwhile, twelve moderate scale urban clusters are located in both coastal and inland areas, along with eight emerging and rapid developing urban clusters in central and western part of the country (Fang et al. 2008). In most cases, those city clusters have single city center, and spread and often merged with nearby small cities and town during development. However, some cluster like Shandong Peninsula, Central Human, and Chengdu-Chongqing were spread from multiple centers and gradually connected into integrated urban districts. New districts and satellite towns are very common in those clusters, and they are connected or tend to be connected along economic corridors among them (Fig. 3). New district of a city are usually 10–30 km apart from historical city center (Fang et al. 2008; Hu and Jia 2010), and expansion of built-up can be clearly seen from fractional urban data. The key drivers are business opportunities along major highways and lower cost of land and labor along those corridors.

Many city clusters were merging into each other, with gradual blur boundaries and disappearing of gaps among member cities and towns. Cities and towns were more connected with roads and commercial corridors, while wildland and urban greens became more isolated as patches among built-up areas. Clearly, urban heat island effect tends to cover entire city

cluster without major gaps (Figs. 2 and 3). With traditional fixed threshold approaches, most of those emerging urban–rural mosaic and even some of the moderate–small scale urban areas were smoothed and ignored in coarse resolution land cover data layers applied in regional climate models (Feng et al. 2012). However, large patches of new districts and urban–rural fringe were categorized as low residence canopies in this study, and could potentially be developed into high density ones as member cities of an urban cluster continue to be interconnected and even merged (Fang et al. 2011).

3.3 Satellite based urban fractions and road width

Different thresholds of built-up fractions were applied to categorize urban canopy classes based on analysis of high resolution satellite data and field survey. The results showed that the urban fraction was 0.9, 0.75, and 0.5 for commercial, high intensity residential, and low intensity residential respectively in Beijing (north, temperate). The urban fraction for Guangzhou (south, tropical) was 0.95, 0.7, and 0.57 accordingly (Table 2, Fig. 5). The urban fraction for high intensity residential in both north and south of China are about 18 % lower than the default value in single-layer urban canopy model (UCM, Kusaka and Kimura 2004).

Meanwhile, average road width was 37.2, 34.7, and 25.6 m in Beijing for the above three urban categories, 24.2, 16.6, and 14.0 m in Guangzhou relevantly (Table 2). The average road widths for commercial and high intensity residential were slightly different in Beijing. While the average road widths in north were about 10 m greater when compared with southern China. All the average urban road widths were greater than those listed UCM.

4 Discussion

4.1 Scale and connectivity of city clusters

Typical pattern of urban climate effects is moderated by the structure of each city and the regional patterns of urban clusters (Loridan and Grimmond 2011). In earlier city clusters with different cores of high urban density, the effects are considered as multicellular, or act more like islands. In those cases, climate feedback of urban surface can be very limited at local scale, as urban green and natural vegetation dominate urban fringe (Grimm et al. 2000; Simon 2008). However, urban canopies are becoming huge single center as member cities gradually merged and connected to each other, and urban climate effect may no longer be a very local one, instead, it could go far beyond city limits into sub-regional and regional scales (Simon 2008; Seto et al. 2011). Spatial pattern and climate feedbacks may also be affected by the location of

Table 2 Statistical estimates of urban road width for three urban categories

	Urban categories	Sample numbers	Max [m]	Min [m]	AVG [m]	Values in WRF [m]
Beijing	Commercial	23	75.33	8.12	37.2	10.0
	High intensity residential	22	60.91	7.86	34.7	9.4
	Low intensity residential	31	47.97	7.55	25.6	8.3
Guangzhou	Commercial	49	52.90	6.78	24.2	10.0
	High intensity residential	21	30.50	6.68	16.6	9.4
	Low intensity residential	14	28.71	6.45	14.0	8.3

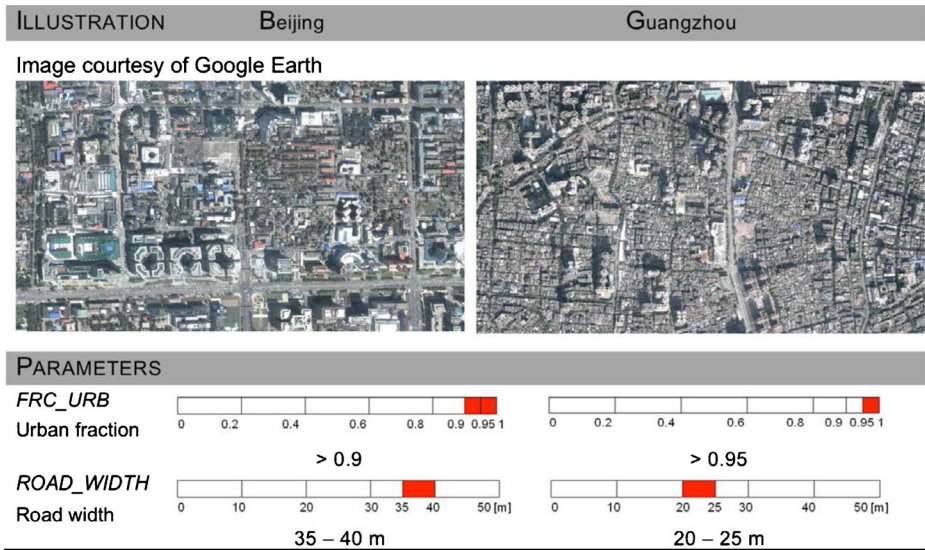


Fig. 5 An illustration of urban canopy parameters for commercial category in both Beijing and Guangzhou. Satellite urban view was provided by the Google Earth. The red color bars represent the average values of fractional urban cover and road width for each case

urban clusters. Inland cities often concentrated in oasis or valleys over background of vast grassland and desert, and climate effects may be more local. Meanwhile, coastal cities tend to widely spread and interconnected to each other over large areas, and make their climate effect go far beyond their physical boundaries (Brazel et al. 2000).

In China, almost continuous urban complex spread over east coast, from Beijing-Tianjin in the north, down to the Yangzi River Delta, all way to the Pearl River Delta in the south (see Fig. 2). Meanwhile, inland urban clusters such as those in Xinjiang, Inner Mongolia, and Sichuan are relatively isolated. The interconnection of member cities in urban clusters may greatly enhance mobility and regional economy, but in the same time expand spatial scale and intensity of urban climate effects. Such large scale climate effects of urban expansion was recently analyzed and simulated with regional climate models, major alteration of air temperature, precipitation, wind speed, and boundary layer height were found (Fu 2003; Feng et al. 2012) in East Asia.

4.2 Localized and heterogeneous urban parameters

Urban processes were traditionally ignored in coarse resolution (e.g., >30 km) climate models, because urban fractions in model grids were negligible and models were not sensitive enough to such weak urban signals (Oleson et al. 2008; Otte et al. 2004). With major enhancement in computing power and satellite based fine resolution datasets of key urban parameters in past decade or so, high resolution urban climate simulation became possible at local and regional scales (Dupont et al. 2004; Wang et al. 2012). As horizontal resolution of the land surface and climate models continues to increase, more realistic urban canopy parameters and datasets are required to improve model performance over heavily populated regions such as East Asia. This study indicated that concerned urban parameters in the region differ from default ones in models, and they also differ from north to south within region.

The urban parameterizations in regional models were established from urban field campaigns, statistical data, and general estimates, and focused on key variables that characterize the exchanges of energy between the urban surface and the atmosphere (Oleson et al. 2008; Martilli 2009). In most cases, urban areas are first categorized into high density residence, low density residence, and commercial areas, and then fixed values are set for each of parameters such as fractional vegetation cover, road width, and roof materials over each urban category (Masson 2006). Therefore, reasonable estimates of urban extent and expansion are critical for capturing key urban processes in regional climate modeling.

Most current urban parameterizations are based on coarse resolution global statistical datasets or field data from very limited sites in certain region, and therefore, often cannot represent key structures and processes of cities at regional scales. It is especially a concern in rapid and newly developed urban areas such as in East Asia where urban morphology and dynamics are quite different from Europe and North America from where most urban parameterizations were originated (Huang et al. 2007; Tewari et al. 2007). Our improved estimates of urban extent and canopy morphology over eastern China could potentially help better capture regional impacts of urbanization on seasonal and inter-annual climate variability, such as temperature, precipitation, wind speed, and air moisture with regional climate models (Wang et al. 2012), since most urban canopy parameters in regional models are linked primarily to spatial datasets of urban fractions or categories. Better estimates of urban fraction will improve our understanding of the following mechanisms: change of Bowen ratio due to replacement of green vegetation by wide-scale use of impervious materials for buildings and pavements, and heterogeneous surface emissivity and heat capacity along urban–rural fringe (Kusaka and Kimura 2004; Offerle et al. 2003; Oke 2006).

4.3 Impacts of urban landuse on near surface temperature

Spatial structure and size of urban canopy affect near surface temperature, and therefore, alter land-atmosphere energy exchange. The amount of energy radiated from urban surface is based on surface temperature of the object and emissivity of the materials (Kusaka and Kimura 2004). In our previous studies, we examined the temporal-spatial relationship between satellite derived land surface temperature and fractional land-use types (Hu and Jia 2010), and found that there were positive correlations between temperature and fractional cover of built-up and negative correlation between temperature and fractional cover of natural/cultivated vegetation. Meanwhile, strong urban heat island effects are evident from observations of air temperature over pairs of urban vs. suburban meteorological stations, indicating the climate effects of urbanization at least at local to regional scales (He and Jia 2012). They highlight the importance of localized urban parameters for regional land and climate modeling, and possible implications in urban climate adaptation and mitigation strategies.

5 Conclusions

Effects of urban processes to local and regional climate has been increasingly recognized, however, lack of reasonable estimates of urban areas is a critical issue in regional climate modeling in heavily populated areas such as East Asia. This study combines multi-sensor satellite data and field investigation to estimate fractional urban extent and expansion, spatial connection of urban clusters, and urban road width. Localized datasets for regional land surface and climate models were developed from the approaches, and they could potentially improve model performance over the region.

More details of urban fraction and spatial structure were demonstrated from this study than previously reported by many global datasets. Strong spatial connection and internal expansion were found in major city clusters, along with rapid external expansions that may not be clearly detected without fractional and scaling approaches as developed here. We would argue that in many cases in this region, urban are no longer “islands”, they are now “seas” in term of climate related urban canopy, because many historically isolated cities and towns are now highly connected and even merged with multiple roads and commercial corridors among them. Meanwhile, patches of wildland and urban greens in and around city clusters became highly fragmented and often isolated from each other. Urban greens such as parks and plantation were long recognized for their cooling effects that buffer the urban heat island effect (Oke 1988; Brazel et al. 2000), however, such cooling effects tend to be weakened as their patches became smaller and isolated, and over dominated by urban surfaces.

Acknowledgments This study was supported by CAS Strategic Research Program (XDA05090200) and China Basic Research Program (2009CB723904). We thank Dr. Weidong Liu for help facilitating our field investigation along urban–rural transects.

References

- Brazel AJ, Selover N, Vose R, Heisler G (2000) The tale of two climates: Baltimore and Phoenix LTER sites. *Clim Res* 15:123–135
- Brown MJ (1999) Urban parameterizations for mesoscale meteorological models. *Mesoscale Atmospheric Dispersion*. Edited by Z. Boybeyi, WIT Press, pp. 193–255, LA-UR-99-5329
- Crutzen P (2004) New directions: the growing urban heat and pollution ‘island’ effect—impact on chemistry and climate. *Atmos Environ* 38:3539–3540
- Dupont S, Otte TL, Ching JKS (2004) Simulation of meteorological fields within and above urban and rural canopies with a mesoscale model (MM5). *Bound-Layer Meteorol* 113:111–158
- Elvidge CD, Baugh K, Dietz JB, Bland T, Sutton PC, Kroehl H (1998) Radiance calibration of DMSP-OLS low-light imaging data of human settlements. *Remote Sens Environ* 68(1):77–88
- Fang C, Qi W, Song J (2008) Researches on comprehensive measurement of compactness of urban agglomerations in China. *Acta Geograph Sin* 63(10):1011–1021
- Fang C, Yao S, Liu S (2011) Development of major city clusters in China. Science Press, Beijing, pp 89–112
- Feng J, Wang Y, Ma Z, Liu Y (2012) Simulating the regional impacts of urbanization and anthropogenic heat release on climate across China. *J Clim* 25(20):7187–7203
- Foley JA et al (2005) Global consequences of land use. *Science* 309:570–574
- Fu CB (2003) Potential impacts of human-induced land cover change on East Asia monsoon. *Glob Planet Chang* 37:219–229
- Gao H, Jia G (2013) Assessing disagreement and tolerance of misclassification of satellite—derived land cover products used in WRF model applications. *Adv Atmos Sci* 30(1):125–141
- Grimm NB, Grove JM, Redman CL, Pickett SA (2000) Integrated approaches to long-term studies of urban ecological systems. *Bioscience* 70:571–584
- Grossman-Clarke S, Zehnder JA, Stefanov WL, Yubao L, Zoldak MA (2005) Urban modifications in a mesoscale meteorological model and the effects on near-surface variables in an arid metropolitan region. *J Appl Meteorol* 44:1281–1297
- Guindon B, Zhang Y, Dillabaugh C (2004) Landsat urban mapping based on a combined spectral–spatial methodology. *Remote Sens Environ* 92:218–232
- Han JY, Baik JJ (2008) A theoretical and numerical study of urban heat island-induced circulation and convection. *J Atmos Sci* 65:1859–1877
- He Y, Jia G (2012) A dynamic way to quantify natural warming in urban area. *Atmos Ocean Sci Lett* 5(5):408–413
- Hu Y, Jia G (2010) Influence of land use change on urban heat island derived from multi-sensor data. *Int J Climatol* 30:1382–1395
- Huang J, Lu X, Sellers JM (2007) A global comparative analysis of urban form: applying spatial metrics and remote sensing. *Landsc Urban Plan* 82:184–197

- Jia G, Fu C, Zhou Y, Li X (2011) Towards a sustainable Asia: environment and climate change. Springer-Verlag, 106 p. ISBN: 978-3-642-16671-6
- Kusaka H, Kimura F (2004) Thermal effects of urban canyon structure on the nocturnal heat island: Numerical experiment using a mesoscale model coupled with an urban canopy model. *J Appl Meteorol* 43:1899–1910
- Li B, Avissar R (1994) The impact of spatial variability of land-surface characteristics on land-surface heat fluxes. *J Climatol* 7:527–537
- Loridan T, Grimmond CSB (2011) Characterization of energy flux partitioning in urban environments: links with surface seasonal properties. *J Appl Meteorol Climatol* 51:219–241
- Martilli A (2009) On the derivation of input parameters for urban canopy models from urban morphological datasets. *Bound-Layer Meteorol* 130:301–306
- Masson V (2006) Urban surface modelling and the meso-scale impact of cities. *Theor Appl Climatol* 84:35–45
- Offerle B, Grimmond CSB, Oke TR (2003) Parameterization of net all-wave radiation for urban areas. *J Appl Meteorol* 42:1157–1173
- Oke TR (1988) Street design and urban canopy layer climate. *Energy Build* 11:103–113
- Oke TR (2006) Towards better communication in urban climate. *Theor Appl Climatol* 84:179–189
- Oleson KW, Bonan GB, Feddema J, Vertenstein M, Grimmond CSB (2008) An urban parameterization for a global climate model. Part I: formulation and evaluation for two cities. *J Appl Meteorol Climatol* 47:1038–1060
- Otte TL, Lacser A, Dupont S, Ching JKS (2004) Implementation of an urban canopy parameterization in a mesoscale meteorological model. *J Appl Meteorol* 43:1648–1665
- Rosenfeld D (2000) Suppression of rain and snow by urban and industrial air pollution. *Science* 287:1793–1796
- Sarrat C, Lemonsu A, Masson V, Guedalia G (2006) Impact of urban heat island on regional atmospheric pollution. *Atmos Environ* 40:1743–1758
- Seto KC, Fragkias M, Güneralp B, Reilly MK (2011) A meta-analysis of global urban land expansion. *PLoS ONE* 6:e23777
- Simon D (2008) Urban environments: issues on the peri-urban fringe. *Annu Rev Environ Resour* 33:167–185
- Tewari M, Chen F, Kusaka H (2007) Coupled WRF/Unified Noah/Urban-canopy modeling system, NCAR WRF Documentation, pp 1–20
- Turner BL II, Lambin EF, Reenberg A (2007) The emergence of land change science for global environmental change and sustainability. *Proc Natl Acad Sci* 104:20666–20671
- Wang J, Feng J, Yan Z, Hu Y, Jia G (2012) Nested high-resolution modeling of the impact of urbanization on regional climate in three vast urban agglomerations in China. *J Geophys Res* 117, D21103. doi:10.1029/2012JD018226