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Assessing the stability of annual temperatures for different urban functional zones

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A B S T R A C T

The urban functional zone (UFZ) is the basic unit of urban planning, which is defined as an area of similar social and economic functions. Despite the importance of UFZs, the stability of their annual temperature between winter and summer has seldom been investigated. With an understanding of the thermal impacts that planning decisions can have, it is essential to know how UFZs can be designed to regulate temperatures in the urban environment. 690 UFZs were identified using ALOS images in 2009 in Beijing. Land surface temperature (LST) was extracted from daytime Landsat TM (2002) and ASTER (2009) images. The regional LST variation of 31 district-sized sub-regions was correlated to the types of UFZs in the region and structural features of the region such as area, size, diversity, complexity and connectivity. Results showed that: (1) UFZ types, in order from highest to lowest LST variation, were commercial, campus, high density residential, water, recreational, low density residential, road, preservation, and agricultural zones; (2) the regional LST variation was positively correlated with the area of campus, commercial, high density residential, water, and road zones, but negatively correlated with the area of agricultural and low density residential zones; (3) increased connectivity and complexity decreased regional LST variations. The results indicated that the stability of annual temperatures was determined not only by the UFZ type and size but also by the connectivity and complexity. These results are clearly useful and essential pieces of information that can be applied in urban planning to improve climate adaptability.

1. Introduction

6.3 billion people are projected to be living in cities by 2050 and the negative impact of this urbanization is an increasing concern for people worldwide [1]. One potential negative impact is that of urbanization on the local climate of urban areas, such as elevated temperatures from urban heat island, which can affect the energy use of buildings as well as the health of ecosystems and people [2–6].

Many of the patterns, processes, and thermal fluxes that differentiate the local climate of artificial and natural landscapes are addressed in the decisions that planners make [7]. Studies reveal that water bodies and wetlands serve as cooling surfaces by absorbing radiation through high thermal capacity and releasing water vapor that cools the ambient environment [8,9]. Vegetation can decrease the near-surface air temperature by utilizing a relatively large proportion of the absorbed radiation in the evapotranspiration process and producing shade as well. The narrow arrangement of buildings along the city's streets forms urban canyons that inhibit the release of the reflected radiation to space from most of the three-dimensional urban surfaces. This radiation is ultimately absorbed by the building walls owing to their narrow arrangement and low thermal capacity, enhancing the UHI effect. Street trees and lawns have been used to mitigate UHI effects in big cities [10–13]. Green roofs and cool materials characterized by water retention or high solar reflectance values can also serve to cool the urban thermal environment [14–20]. The land surface temperature (LST) has been shown to be highly correlated with the near-surface air temperature [5,21]. The remotely sensed LST thus has thus often been used to assess the urban thermal environment due to its easy acquisition at a given moment and across broad areas [22,23]. Such studies attempt to reveal the effects and reasons of UHI by linking spatiotemporal variations in LST with land-cover and socio-economic indicators [23,24]. The proportion of landscape types, such as water, vegetated, and impervious areas, is found to

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Table 1
Weather conditions for each day of the acquisition of satellite images.

Image type	Date	Precipitation (mm)	Atmospheric pressure (hPa)	Wind speed (m/s)	Air temperature (°C)	Relative humidity (%)
Landsat TM	2002.05.22	0	1007.6	2.8	25.4	19
	2002.07.09	0	998.3	3	27.5	64
	2002.10.13	0	1014.6	2	12.3	42
	2002.11.14	0	1014.7	3	5	30
ASTER	2009.03.06	0	1020.3	4	4.6	21
	2009.08.08	0	1004.4	1.4	26.8	76
ALOS	2009.04.21	0	1003.8	4.3	18.1	19

have an essential impact on the spatial variations of the LST [11,25]. Recent studies reveal that the cooling effect of landscapes is correlated with the geometry and connectivity of landscape patches as well as the landscape types [9,26–28].

Increasingly, it has been recognized that urban landscape planning can be implemented to create additional energy savings and human comfort benefits [6,29–34]. However, few studies have been implemented to reveal how urban landscapes affect the land surface temperature difference between winter and summer. This difference is important if we evaluate the energy consumption for both heating and cooling a building over a year. Outdoor human comfort is also clearly affected by the temperature difference in winter and summer temperatures. Urban landscape planning includes a group of methods concerned with building locations, zoning, transportation, and how a town or city looks [35]. Urban functions are the largest concerns of landscape planning related directly to living, dwelling, education, industry, commerce, etc [36]. The urban functional zone (UFZ) is designated not only by its spectral characteristics but also by its social and economic functions in a city. The UFZ is usually organized by a specific function and therefore has a similar energy consumption and outdoor environment. Having information about the stability of annual temperatures for different UFZs enables urban planners and managers to rationalize the landscape planning sketches for an improvement of the urban thermal environment.

The urban thermal environment has attracted much attention in Beijing due to the city's rapid urban sprawl and population growth [37]. This study aims to: (1) assess the stability of annual temperatures for different UFZs inside the fifth ring-road of Beijing; and (2) quantify the relationship between regional LST variations and the UFZ structural features, including the area, size, diversity, complexity, and connectivity.

2. Study area and methods

2.1. Study area

Beijing is the capital of China, covering approximately 16,800 km^2 of land, and is a major international metropolis that has experienced rapid development in recent decades. Beijing is characterized by a warm temperature zone and has a typical continental monsoon climate with four distinct seasons. Rapid urbanization and city expansion started in the late 1980s, resulting in significant UHI effects [38,39]. Previous studies have found that the mean daily temperature in urban areas is 4.6° higher than the mean daily temperature in the suburbs [40]. The pattern of Beijing's development is a typical concentric expansion, showing a ring-shaped pattern with distance from the city center to the outskirts [36,37]. Our study area targeted the highly urbanized region inside the fifth ring-road of Beijing, with an area of 670 km^2, which accounts for 4% of the total area of Beijing.

2.2. UFZ and LST identification

Three types of satellite images were used to identify the urban functional zones and land surface temperatures in this study. The weather conditions from the satellite images acquisitions were collected from the National Meteorological Information Center, China Meteorological Administration (Table 1). Two cloud-free Advanced Land Observing Satellite (ALOS) images were used to retrieve detailed information on UFZ types and structural features inside the fifth ring-road of Beijing. The ALOS data were acquired on April 21st, 2009, with 2.5-m spatial resolution in a panchromatic band and 10-m spatial resolution in three visible and near-infrared bands. We identified the type and boundary of each UFZ manually according to the ALOS images. The 690 UFZs identified were classified into 10 major types based on our research objectivities (Table 2): high density residential zone (HDZ), low density residential zone (LDZ), campus zone (CPZ), industrial zone (IDZ), recreational zone (RAZ), commercial zone (CMZ), agricultural zone (AGZ), preservation zone (PVZ), road (ROD), and water (WTR) (Fig. 1).

Table 2
Classification of urban functional zones inside the fifth ring-road of Beijing.

Urban functional zone	Code	Areas (km^2)	Description
High density residential zone	HDZ	252.76	70–100% impervious, construction material; typically urban communities including multiple family houses and high buildings, and dense population in urban core areas.
Low density residential zone	LDZ	30.08	40–70% impervious, construction material; typically residential development including sparse population and low buildings and varying amounts of vegetation cover commonly found in housing divisions.
Campus zone	CPZ	34.76	Areas for schools, colleges, institutes, governments, hospitals, embassies, military bases, etc.
Industrial zone	IDZ	81.52	Stations for passenger-transport of buses and railways, airports, warehouses, graveyards, etc. Factories for manufacturing, electric power, food, gas, oil, water, etc.
Recreational zone	RAZ	59.28	Urban parks, golf courses, soccer fields, and other recreation areas.
Commercial zone	CMZ	110.00	Offices for finance organizations and headquarters, hotels, wholesale markets, etc.
Agricultural zone	AGZ	19.99	Crops, gardens, and other herbaceous vegetation.
Preservation zone	PVZ	17.96	Successional distribution of trees, shrubs, and brushes, such as shelter-forest, isolation belt, forest parks, etc. Natural and manmade grassland.
Road	ROD	54.30	Streets, roads, etc.
Water	WTR	8.31	All areas of open water, including rivers, reservoirs, and lakes.