This book showcases the different ways in which contemporary forms of data analysis are currently being used in urban planning and management. Including perspectives from across the globe, it's packed with examples of good practice and helps to demystify the process of using big and open data.

- Learn about different kinds of emergent data sources and how they are processed, visualised and presented.
- Understand how spatial analysis and GIS are used in city planning.
- See examples of how contemporary data analytics methods are being applied in a variety of contexts, such as 'smart' city management and megacities.

Highlighting the emerging possibilities that city-regional governance, technology and data have for better planning and urban management, this timely text is the perfect companion to enable you to apply data analytics approaches in your research.

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APPLIED DATA ANALYSIS FOR URBAN PLANNING AND MANAGEMENT

Rae • Wong

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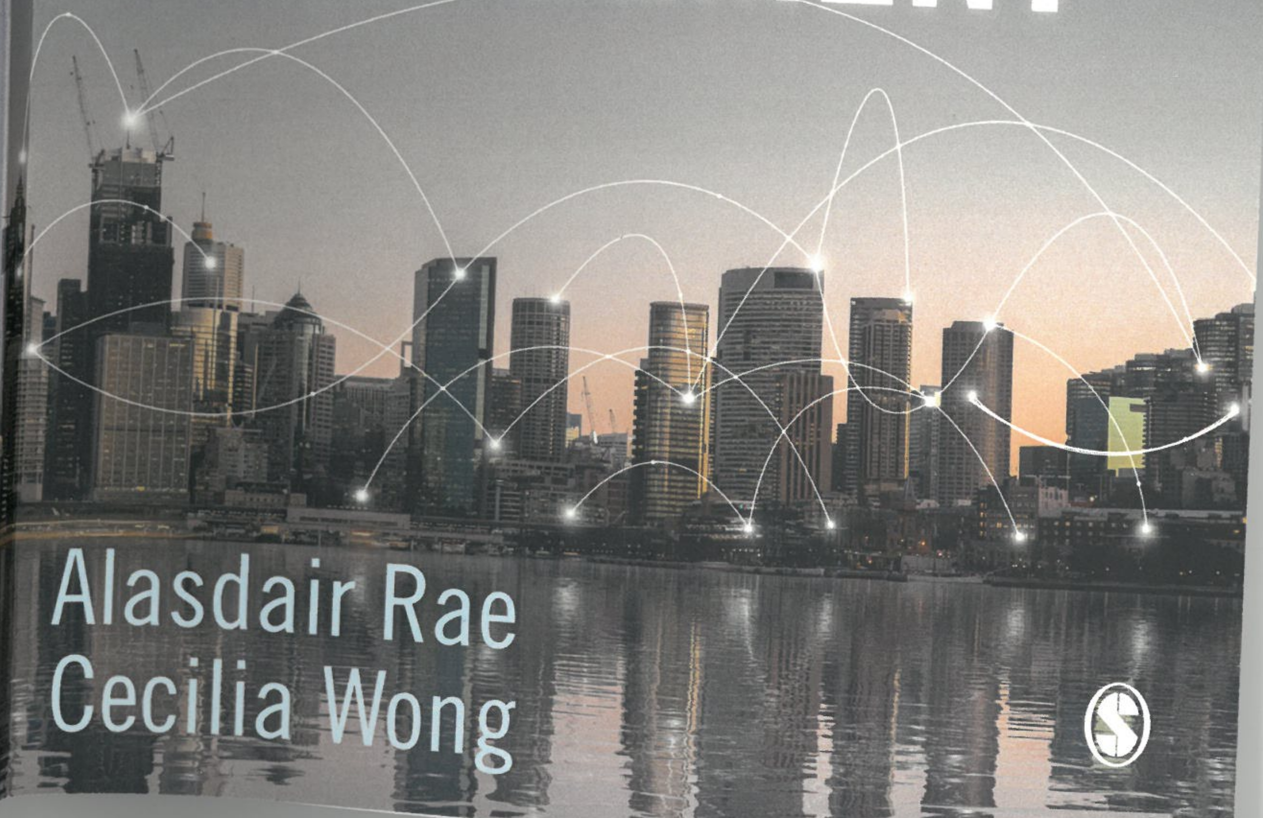

Alasdair Rae
Cecilia Wong

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DATA ANALYTICS, URBAN FORM AND CLIMATE CHANGE: THE URBAN CLIMATE MAP

Chao Ren, Edward Ng, Jason Wai Po Tse, Pak Shing Yeung, Jimmy Chi Hung Fung, Gerald Mills, Jason Ching, Benjamin Bechtel and Linda See

List of abbreviations

WUDAPT: World Urban Database and Access Portal Tools

SDGs: Sustainable Development Goals

IPCC: Intergovernmental Panel on Climate Change

WRF: Weather Research and Forecasting

PRD: Pearl River Delta

GE: Google Earth

LCZ: Local Climate Zone

UHI: urban heat island

Background and challenges

We are living in an urbanised world, yet we know very little about most cities on the planet, especially how they are built (urban form) and occupied (urban function). Urban residents are especially vulnerable to current and future climate hazards because of the concentration of people, infrastructure and social-economic activities in landscapes that are exposed to sea-level rise, river flooding, storms, heatwaves and so on (UN-Habitat, 2011; WHO and UN-Habitat, 2016; WMO, 2003, 2016). In addition, the character of urban development (e.g. extensive paving) and the attendant emissions of pollutants have profoundly altered the natural setting and exacerbated natural hazards. These changes have led to a series of urban environmental problems, such as the urban heat island effect, the pollution of rivers and seas, air pollutant effects and air quality degradation that directly impact urban citizens (Mills, 2007; UN-Habitat, 2016a).

Moreover, the emissions of greenhouse gases (GHG) globally are concentrated in cities; although less than 3% of global land-cover can be described as urban, over 75% of human-sourced CO_2 arises from these places. Thus, there is an increasing international focus on cities as a nexus for many global problems, including urban environmental conditions, living quality and human well-being, the challenges and risks for human population health in cities, and global climate change (Cleugh et al., 2009; Corburn, 2015; UN-Habitat, 2016b; WHO, 2010; WHO and UN-Habitat, 2016). The 2016 United Nation's HABITAT-III conference adopted the *New Urban Agenda* to focus on sustainable urban development. According to the Quito Declaration, the agenda focuses on 'Sustainable Cities and Human Settlements for All', and one of the main objectives is to create urban resilience (UN-Habitat, 2016b) to mitigate extreme weather events. Various models and simulations can be applied to understand the future urban environment and to review the effects of past urbanisation. The UN also calls for using data science and analytics to achieve 17 Sustainable Development Goals (SDGs) – especially for SDG 11 sustainable cities and communities and SDG 13 climate action – by using satellite imagery and remote sensing technology.

Most cities operate like management systems that respond by mitigating the actions that cause undesirable changes and then adapting the system to cope with environmental hazards. Since cities have different capacities to respond based on their political cultures, economic base, socio-cultural make-up and so on, there needs to be a common language to describe urban landscapes globally. Members of the scientific community (e.g. climatologists, geographers, ecologists, environmental engineers and technologists) are looking for more standardised information on the urban form and function of cities so that they can devise solutions to aid architects, designers, and municipal governments (i.e. City Planning Departments, Public Works Departments, Zoning Boards, Transportation Offices) in developing evidence-based design guidelines for best practices of mitigation and adaptation to climate change (Cleugh et al., 2009). However, a consistent database on global cites at scales suitable for scientific inquiry and policy formulation does not exist (see Table 7.1 and Figure 7.1). It is quite often left to researchers and the general public to find the issues of data availability, accessibility and standardisation. Whilst there are several well-established worldwide land use land cover databases such as AVHRR, MODIS, and ESA Globalcover, almost all of them only include one built-up or urban category in their classification, which cannot represent the intra-urban morphological variation and differences.

The World Urban Database and Access Portal Tools (WUDAPT, www.wudapt.org) project has grown out of the need for better information on the urban form and function of cities globally (Bechtel et al., 2019; Ching et al., 2018). Figure 7.1 shows the comparison among well-established land use land cover databases and the newly developed WUDAPT data, which can tell more details of urban morphological characteristics, especially the built environment at the city scale. The analysis of such data is critical as it represents the only way to solve cause-and-effect urban problems before they become crises (Mills, 2005). Even the most recent report from the Intergovernmental Panel on Climate Change (IPCC) notes the dearth of such information on urban areas (IPCC, 2014).

Table 7.1 Problems and needs of urban data

Problems & needs	Facts
Urban data availability & accessibility	Few or no data sets available globally on cities, especially for rapidly growing places in economically developing countries and regions
Climate relevant urban data	No consistency in existing urban databases on spatial and temporal resolution and the variables to characterise the urban landscape
Data standardisation & harmonization	No standard classification to represent land use and land cover of cities and surroundings landscapes (e.g. densities, heights, functions and natural coverage for distinction)
Modelling needs	Need a global database that offers multiple properties on urban morphologies and landscapes (e.g. morphologies, geometrics, thermal / physical information, surface cover…)
Application needs	Should be applicable globally and transferable to each city (e.g. transdisciplinarity for scientific research, urban planning, disaster & risk management, health impact analysis and response, etc.)

Source: Oke (2006a, 2006b); Stewart and Oke (2009)

The WUDAPT project started in 2011 and is still under development. The current stage focuses on urban data extraction and development. Some studies have explored the potential possibility of different applications of the WUDAPT data. Cities are described using Local Climate Zones (LCZ) (Stewart and Oke, 2009), which are associated with a range of key urban climate model parameters and thus can serve as inputs to high resolution urban climate models (Bechtel et al., 2019). The LCZ scheme has 17 standard types, including two subsets: 10 built types and 7 land cover types. The WUDAPT is designed to be universal, simple and objective, with the aim to be part of a global protocol to derive information about form and function of cities. It uses free satellite images and the free software of Google Earth (GE) and SAGA-GIS and applies globally available Landsat satellite images as input data in urban climate and climate change modelling (Cai et al., 2016).

The urban data gap

From a climate perspective, we need to capture urban information on the spatial character of aspects of urban form and function (Batty, 2009; Raven et al., 2017). The *form* of a city can be described in terms of:

1 **Land surface cover,** including vegetation, soil, water and impervious/paved surface cover. Surface cover is related to, e.g., the ability of the landscape to intercept, store and dispose of water.
2 **Construction materials,** including concrete, steel, brick, glass, asphalt, etc. used to build the city. These fabrics have distinctive properties related to their ability to absorb, store and release heat.
3 **Urban morphology,** including the dimensions of individual buildings and their position in relation to each other. Morphology creates a complex three-dimensional geometry that controls access to daylight and sunshine, modifies the flow of air and traps pollutants at street level.

The *function* of a city describes the residential, commercial, industrial activities and all that these entail (i.e. water, materials, food and energy requirements). Together these capture the metabolism of a city, that is, the throughput of resources and wastes needed to sustain its operations and maintain and extend its buildings and infrastructure (Batty, 2009; Mills, 2005). The form and functions of a city are strongly correlated, for example, international evidence indicates that cities that are more densely built and occupied have lower transportation costs (Betanzo, 2007; Jaillon and Poon, 2008; Ng, 2012; Smith, 1984). High-density cities such as Singapore and Hong Kong, through compact and mixed-land use design conserve valuable land resources, reduce people's daily transport distance, and thus, the energy needed (Ng, 2009). Ideally, information on the form and functions of cities should be collected and analysed at *multiple temporal and spatial scales* to meet different needs and to tackle cause-and-effect problems (Raven et al., 2017).

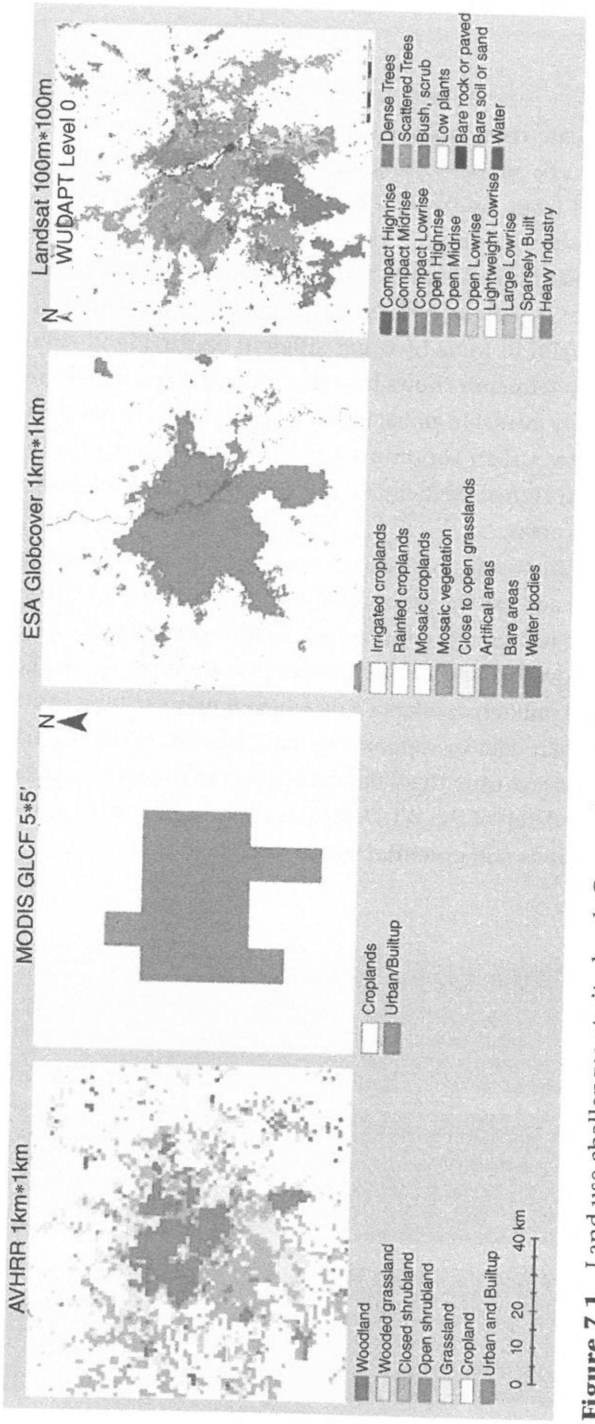


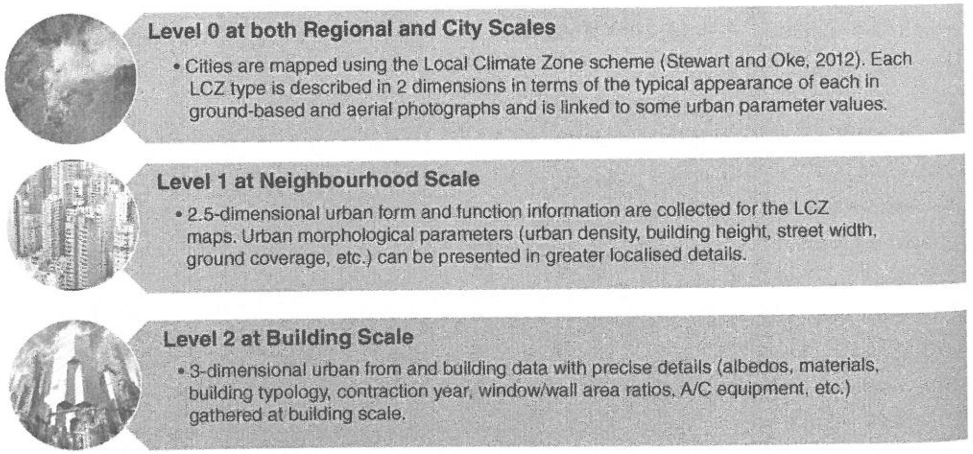
Figure 7.1 Land use challenges at city level. Currently available global scale data: Delhi, India

Source: ESA GlobCover 2009 project; Jackson et al. (2010)

World Urban Database and Access Portal Tools (WUDAPT)

The WUDAPT project seeks to acquire and store urban data using a common framework and to link these data to available methods for climate analysis and for current and what-if scenario development. Present global-scale urban data and land use at the city level is derived from global land cover data sets, e.g. AVHRR, MODIS GLCF, ESA GlobCover. Their resolutions mainly range from 1 km to 10 km and only have one land use category for urban/built-up areas, which may overestimate or underestimate urban forms and functions as well as not representing the actual situation of cities. Figure 1 shows the case of Delhi in India by using different existing land cover information and the final map in this sequence shows how the WUDAPT product improves spatial detail. There are other newly available global urban layers available from the German Aerospace Agency (DLR) (Global Urban Footprint) and the Joint Research Centre of the European Commission (Global Human Settlement Layer), but similarly, they show only one urban category of built-up areas.

The WUDAPT initiative is a global, bottom-up, self-organised effort that attempts to fill the data gaps to address the global challenges of sustainable cities and communities and to act as a guide to facilitate climate-based actions (Mills et al., 2015; See et al., 2015). It builds upon innovative approaches, employs community-based collaborations, and utilises existing and publicly available data where it exists (Ching et al., 2016). Given the urgent need for urban data to support climate research, WUDAPT has adopted a pragmatic approach to structuring these data according to the level of detail (see Figure 7.2). Table 7.2 shows the detail of the WUDAPT products, such as their coverage, data sources, resolution, applications and potential users.



Level 0 at both Regional and City Scales

- Cities are mapped using the Local Climate Zone scheme (Stewart and Oke, 2012). Each LCZ type is described in 2 dimensions in terms of the typical appearance of each in ground-based and aerial photographs and is linked to some urban parameter values.

Level 1 at Neighbourhood Scale

- 2.5-dimensional urban form and function information are collected for the LCZ maps. Urban morphological parameters (urban density, building height, street width, ground coverage, etc.) can be presented in greater localised details.

Level 2 at Building Scale

- 3-dimensional urban from and building data with precise details (albedos, materials, building typology, contraction year, window/wall area ratios, A/C equipment, etc.) gathered at building scale.

Figure 7.2 WUDAPT level 0, 1 and 2 products

Table 7.2 WUDAPT Levels 0, 1 and 2 data and their potential applications

WUDAPT data			
Product	**Level 0**	**Level 1**	**Level 2**
Coverage	Over 120 cities and regions	Data gathering methods testing based on building information	Any city by using our new 3-D mapping technology
Data source	Landsat + Google Earth	Landsat + Google Earth + local data & expert evaluation	World-view Stereo Data + Terra-SAR data
Resolution	100–500 m	100–500 m	2 m
Format	kml, tiff	GIS shapefiles	GIS shapefiles
Applications	Environment and Energy (Weather Research and Forecasting (WRF) modelling, urban heat island) Urban and Regional planning (population density)	• Environment and Energy (weather and climate, urban air flows, urban radiation, mean radiant temperature, urban energy consumption, air pollution, CO_2 and GHG emission) • Ecology (biodiversity) • Urban and Regional planning (master plan, land use plan, green master plan, new town plan)	• Environment and Energy (building energy cost) • Building and community design (visibility analysis, building development) • Disaster and risk management (flooding, heatwave) • Pedestrian and citizens' mobility (walkability, thermal comfort) • Public health (polluted areas)
Potential Users	Anyone Education institutions Researchers & Scientists	• Researchers & Scientists (Environment scientists, Climatologists, Meteorologists) • Engineering consultant companies and design firms • Education institutions • NGOs • Urban designers, town planners • City government (planning departments, transportation office, public works departments, zoning boards, etc.)	• Researchers & Scientists • Engineering consultant companies and design firms • NGOs • Education institutions • Architects, urban designers, town planners • City government (planning departments, transportation office, public works departments, zoning boards, infrastructure facilities, etc.)

An important component of WUDAPT is the development of portal tools which allow data to be extracted in formats suitable for climatic analysis. This includes sophisticated models such as the Weather Research and Forecasting (WRF) model (Skamarock et al., 2008), a widely employed community-based model that is capable of simulating all the parameters of climate and, depending on the setup, air quality and climate change scenarios (Ching et al., 2018). In fact, the major impediment to applying these models – which represent decades of research knowledge – is the lack of data.

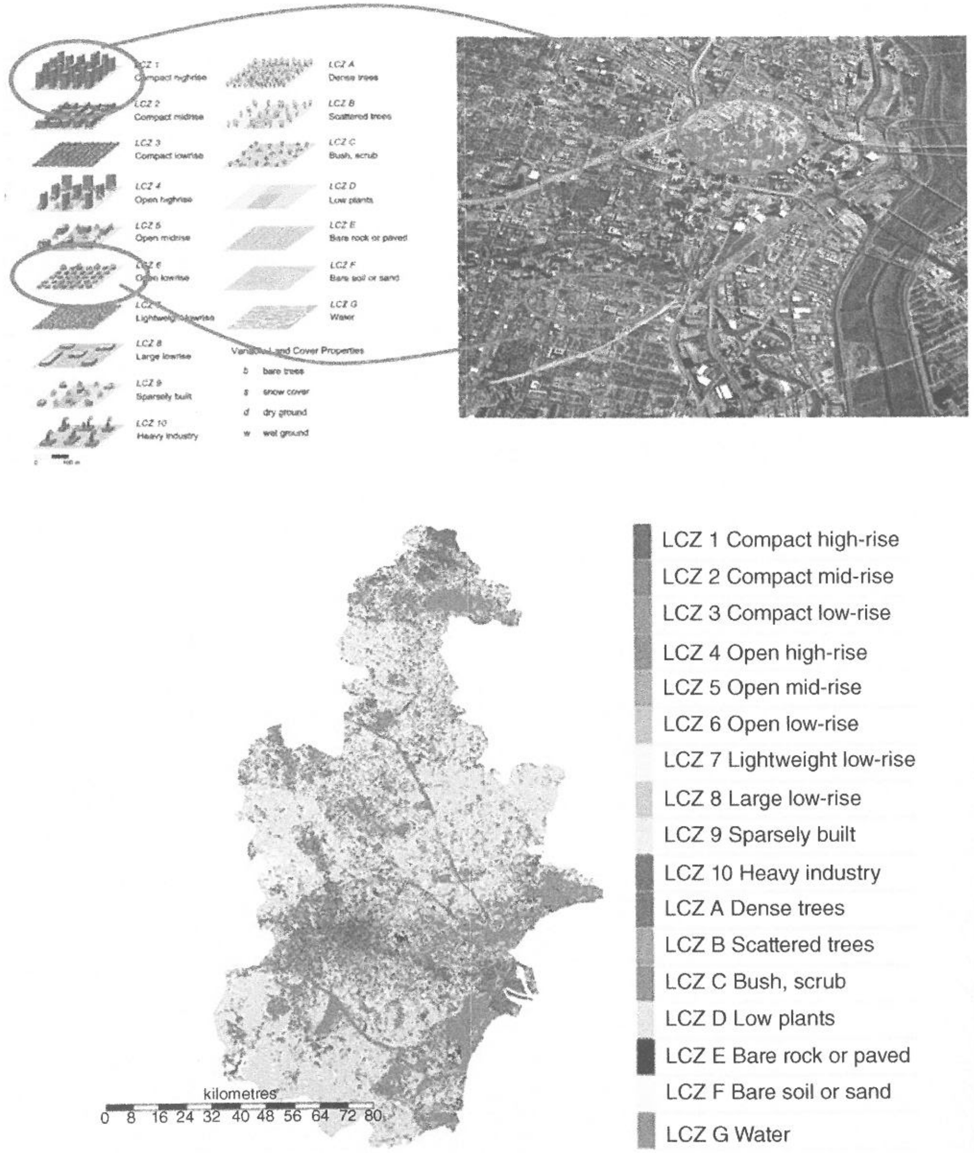


Figure 7.3 Generating L0 data. The top image shows how parts of the urban landscape are identified according to LCZ type. These data are used to automatically classify an entire urban region into common LCZ types (lower map)

The WUDAPT approach is underpinned by a community-based approach and relies on freely available data and tools. The lowest level of detail (L0) consists of decomposing urban (and surrounding landscapes) into common Local Climate Zone (LCZ) types using local expertise, Landsat remote sensing data and software tools (Figure 7.3) (Ching et al., 2018). The net result is an LCZ map of an urban region where each LCZ type is associated with a universal range of values that describe aspects of urban form and function. Currently, L0 data are available for more than 120 city regions across all continents. L0 data can be used as a sampling framework to gather more detailed information on cities (L1 data).

Level 2 (L2) data provide complete coverage of the urban landscape and include information on individual urban elements (e.g. buildings, trees), and Figure 7.4 provides an example of 3-dimentional urban morphology (Xu et al., 2017). Ideally, this information would be supplemented by information on the occupation patterns of buildings (commercial, residential, mixed use) and on their material composition. While the morphology can be acquired through remote sensing, other properties require a more holistic approach that may need traditional census data and crowd-sourced information.

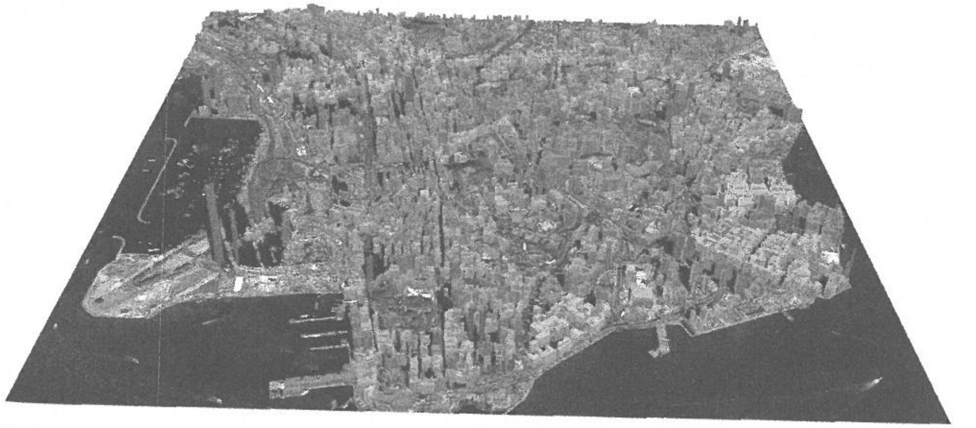


Figure 7.4 Level 2 product: 3D urban morphological data of Kowloon Peninsula, Hong Kong, based on innovative technology (under patent) which can extract and detect 3-dimensional urban morphological data by adopting multi-source satellite images. The overall accuracy of developed level 1 data can reach to 70–90%. This new technology has a low cost and a large spatial coverage, which can be updated efficiently

Collaboration and application: the Pearl River Delta (PRD) megalopolis project

Since its inception, the WUDAPT project has established working relationships with a number of organisations. We have a close association with the International Association for Urban Climate (IAUC), which has a diverse (e.g. architects, designers and planners, climatologists and meteorologists) and globally distributed membership with interests in urban environmental issues, weather/climate prediction, air pollution and risk management. Many of the local experts that we draw upon to provide city-specific information are IAUC members. In addition, WUDAPT has established strong collaborations with the Human Planet Initiative, the Global Carbon Project (GCP) and the Digital Belt and Road Initiative (DBAR). With funding from the Research Grant Council of Hong Kong, an extensive study of the Pearl River Delta has been undertaken using the WUDAPT methodology. Also, an informal collaboration with the World Meteorological Organization (WMO) is underway to provide supporting infrastructure to support their recent Urban Mandate for providing urban services.

The Greater Pearl River Delta (GPRD) includes the Hong Kong Special Administrative Region (HKSAR), the Macao Special Administrative Region and the Pearl River Delta (PRD) Economic Zone in Guangdong Province. The GPRD region is located at the mouth of the Pearl River estuary, where the river enters the South China Sea. The PRD Economic Zone, as specified by Guangdong Province, includes nine municipalities, namely Guangzhou, Shenzhen, Dongguan, Foshan, Jiangmen, Zhongshan, Zhuhai, and the urban areas of Huizhou and Zhaoqing (HK Government, 2015) (Figure 7.5). It is one of the most densely urbanised regions in the world. With China's remarkable economic growth since the beginning of the country's reform period in 1978, urbanised areas have increased by 8.47% annually, rising from 1,068.7 km² in 1979 to 4,617.16 km² in 2008. The rapidly expanding urban areas have emerged into one large region and formed a megaregion and urban agglomeration. Given these dramatic land use changes, it is not surprising that the GPRD has experienced noticeable regional climate changes. The Guangdong Meteorological Administration reported that the GPRD witnessed great temperature change of averaging +0.3 °C every 10 years (Guangdong Government, 2007). Guangzhou is located in the south of China with a total area of 7,434 km² (He et al., 2010). It is one of the most urbanised cities in GPRD and megacities not only in China, but also on earth. During its rapid urban expansion, the previously dispersed built-up areas have been integrated to a large extent and spread into the adjacent cities like Foshan and Dongguan (Mu et al., 2007). In addition, Guangzhou has a high people, of about 8.5 million people, greatly increasing the anthropogenic heat emissions (Xu, 2012). Therefore, the urban heat island (UHI) phenomenon is a significant, moreover immediate, problem of Guangzhou and the GPRD that requires research investigation.

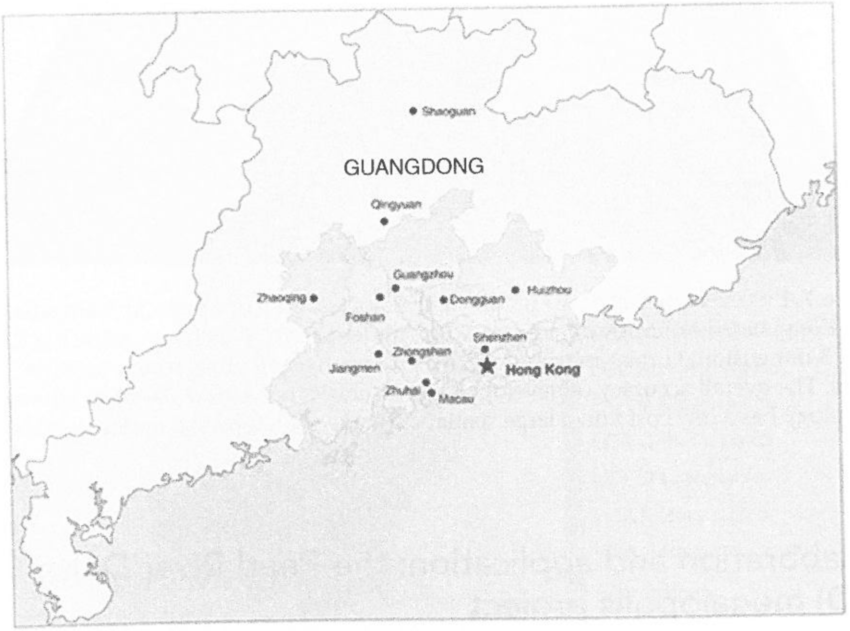


Figure 7.5 Map of the PRD region

Despite being the most densely populated and urbanised region in the world, urban expansion and intensive development in the PRD will continue according to *The PRD Region Reform and Development Plan (2008–2020)*. In the past urbanisation process, the whole region has created unique compact and dense urban morphological forms. Its local urban climatic conditions have also been inevitably and gradually changed. Thus, understanding the urban development impact on local urban climatic changes from the 1980s to the 2010s will allow planners to gain insights into the future.

Data

A proper land-surface model is particularly important in the simulation, especially because the objective of this study is to analyse meteorological changes due to rapid urbanisation in the PRD region. Landsat 8 Level 1 images of the PRD with the resolution of 30m were downloaded from the USGS (U.S. Geological Survey). Urban morphology information, including the building and land cover was derived from Google Earth (GE). Figure 7.6 shows the training samples in the PRD region. They are evenly distributed to get a better classification result. There are in total 17 categories defined for the LCZ classification and 10 represent urban categories; but the simulation model used in this study does not currently support the LCZ classification as input data, so it is necessary to remap these data in the USGS land-cover classification. However, the USGS land-cover classification has only one land use code to represent urban area, which is not representative in this study due to the heterogeneous nature of urban areas in the PRD region. As such, two more urban categories are defined to further differentiate urban areas into areas with low-rise, mid-rise, and high-rise buildings. After modifying the USGS land-cover classification, the categories in the LCZ classification are then remapped to follow the classification of USGS land-cover. The remapping results are shown in Figure 7.7 (only urban categories are shown). Moreover, a portion of the land use data was corrected manually via subjective analysis, especially when urban areas appeared on the sea. Such false classifications may occur due to poor data quality (Wang et al., 2018).

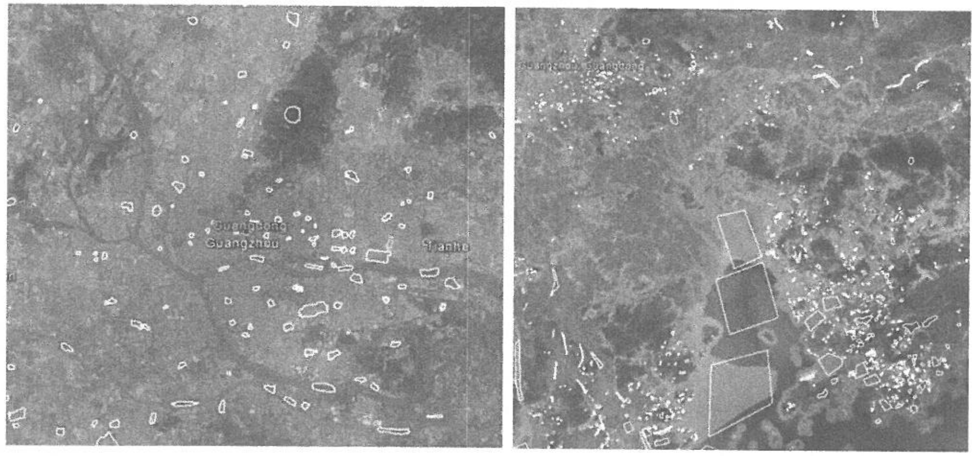


Figure 7.6 (a) Screenshots of training samples of Guangzhou from GE; (b) Screenshots of training samples of GPRD from GE

Source: Google Earth, Data collected on 16 August 2016

Main research steps

This study firstly collects historical Landsat images and detects land use land cover and urban morphological data representing the 1990s, 2000s and 2010s. This classification standard follows the guidelines of land use classification from WUDAPT (Bechtel et al., 2019). Secondly, referring to the USGS land use category, the WUDAPT level 0 product could be re-classified. For the urban category, three sub-categories of high-roughness, mid-roughness, and low-roughness are developed and their corresponding settings in the WRF simulation model are updated and redefined. Thirdly, the WRF simulation with the default setup for the year 2010 is run for the summer period and its results serve as the benchmark. Two new WRF simulations, using the WUDAPT products as input data, are conducted and their results are then compared with the first benchmark to establish the pure urbanisation (1980–2010) impact on local climate conditions in the summertime.

In this study, four simulation domains are configured (Figures 7.8a and 7.8b). The horizontal grid resolution for domains 1, 2, 3 and 4 are 27km, 9km, 3km and 1km, respectively. The fourth domain is the area of interest for this study, where there are numerous mountains with height ranging between 150m and 750m located at Jiangmen, Hong Kong, Shenzhen, and Huizhou respectively. The estuary of the Pearl River is a low lying plain. The asymmetric convective model (Pleim, 2007), which is a non-local planetary boundary layer scheme, was chosen as the physics scheme for the WRF model.

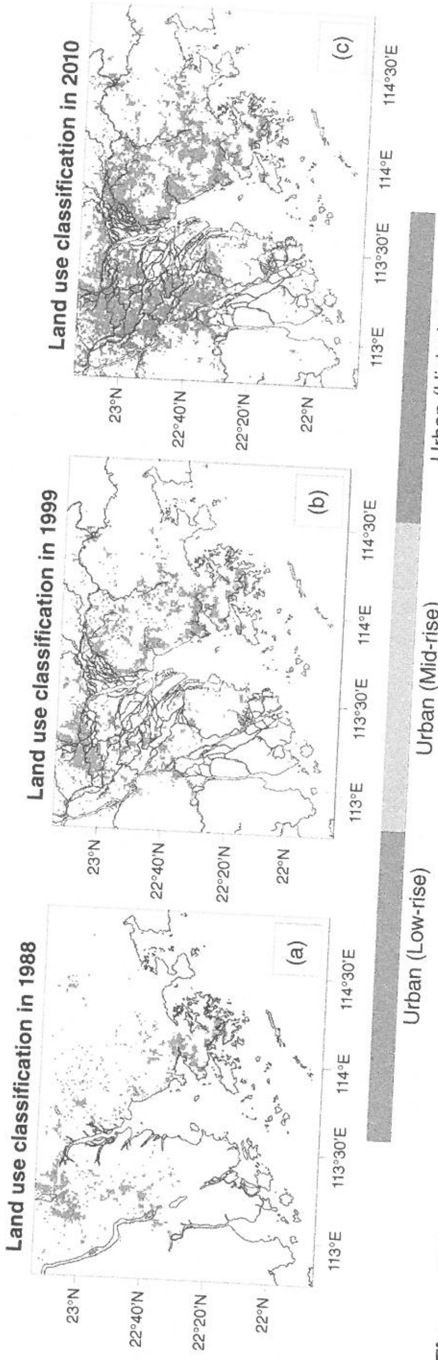


Figure 7.7 Classification of land use following USGS landcover classification in the PRD region (after manual correction; only urban categories are shown) in (a) 1988, (b) 1999, and (c) 2010

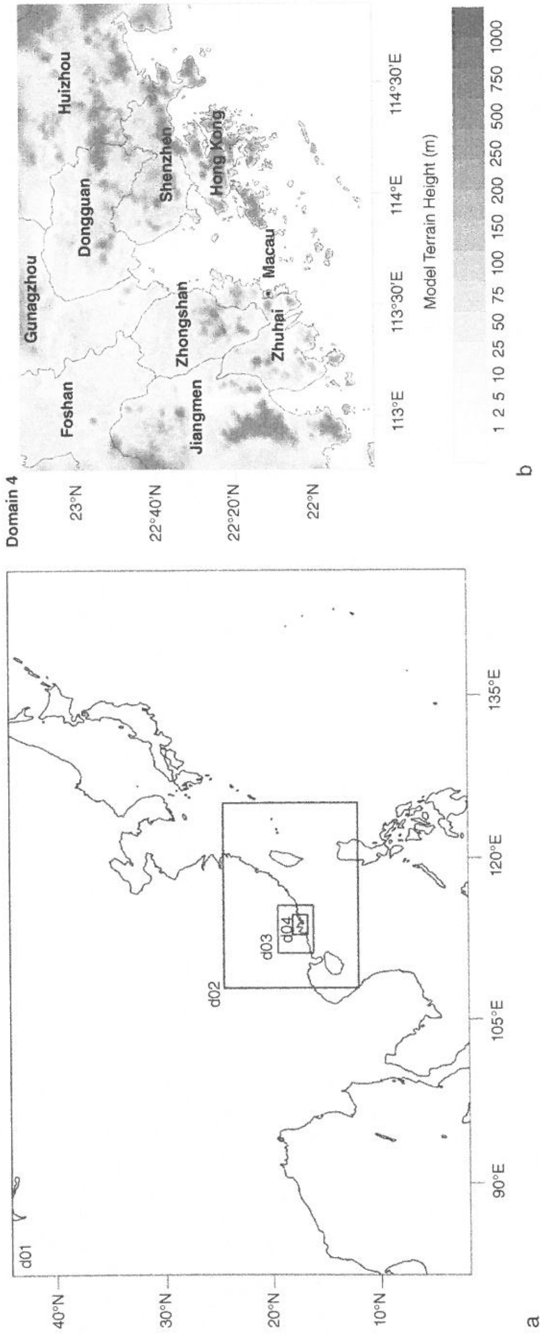


Figure 7.8 a) Four simulation domains set up in the WRF model; b) Fourth domain (PRD region) with major cities marked and contour plot of terrain height

In this study, the volumetric heat capacities and roughness lengths of the urban land uses are updated accordingly after changing the land-cover classification. The volumetric heat capacity of low-rise, mid-rise, and high-rise urban areas are consistent with the concrete materials used in buildings. Another changed parameter is the roughness length. The roughness lengths of the low-rise, mid-rise, and high-rise urban land use are set at 0.5m, 1.0m and 1.8m, respectively. These values refer to the study by Grimmond and Oke (1999) on the aerodynamic properties of urban areas. The techniques of changing urban parameters under the Noah-LSM have also been used to capture the urban effect (Liu et al., 2006).

Since the study period includes the summer season (June to August), to avoid deviation from the observation data due to the long simulation time, the simulation period is divided into four-day WRF simulations and the configuration from the first day of the simulation is used as the model spin-up time for initialisation. In the simulation, the initial and boundary conditions are provided for the WRF model from the National Centers for Environmental Prediction Final Operation Global Analysis data by the National Center for Atmospheric Research. Because the initial and boundary conditions for the different simulations with 1988, 1999 and 2010 land use data are all the same, the changes could be interpreted as purely the effects of urbanisation and its associated interaction with other physical parameters, such as the southern warm and moist oceanic air mass and solar irradiance, on the local climate.

Results and analysis

This section focuses on seasonal diurnal variation. For ease of analysis, 'day' and 'night' are defined as 1400 to 1600 local standard time (LST) (UTC + 8) and 0200 to 0400 LST, respectively, because urban effects such as the UHI effect are common at these times. The data presented in this section are averaged throughout the aforementioned time periods corresponding to the simulation years (1988, 1999 and 2010), with 1988 chosen as the reference year to evaluate changes since the beginning stages of urbanisation in the PRD region. Moreover, using the averaged data, three fundamental climatic variables were investigated: 2-m air temperature, 10-m wind speed, and the heat index developed by the U.S. National Weather Service.

Figures 7.9a and 7.10a show that parts of Guangzhou and Foshan were already the hottest areas in 1988 and became the warm centre because of pre-existing urban areas. In 1999 and 2010, more areas saw temperature increases from urbanisation, and some areas saw a 2 °C increase from 1988 (Figure 7.9e). The warm centre not only intensified, but also expanded and covered considerable areas in the western part of the PRD. Similar results were found for nighttime temperatures. Figures 7.10d and 7.10e also show that the urbanised areas experienced the greatest increase in temperature at night. Apart from the urbanised areas, their surrounding rural areas also experienced a slight temperature rise, which can be attributed to the heat diffused from urban areas.

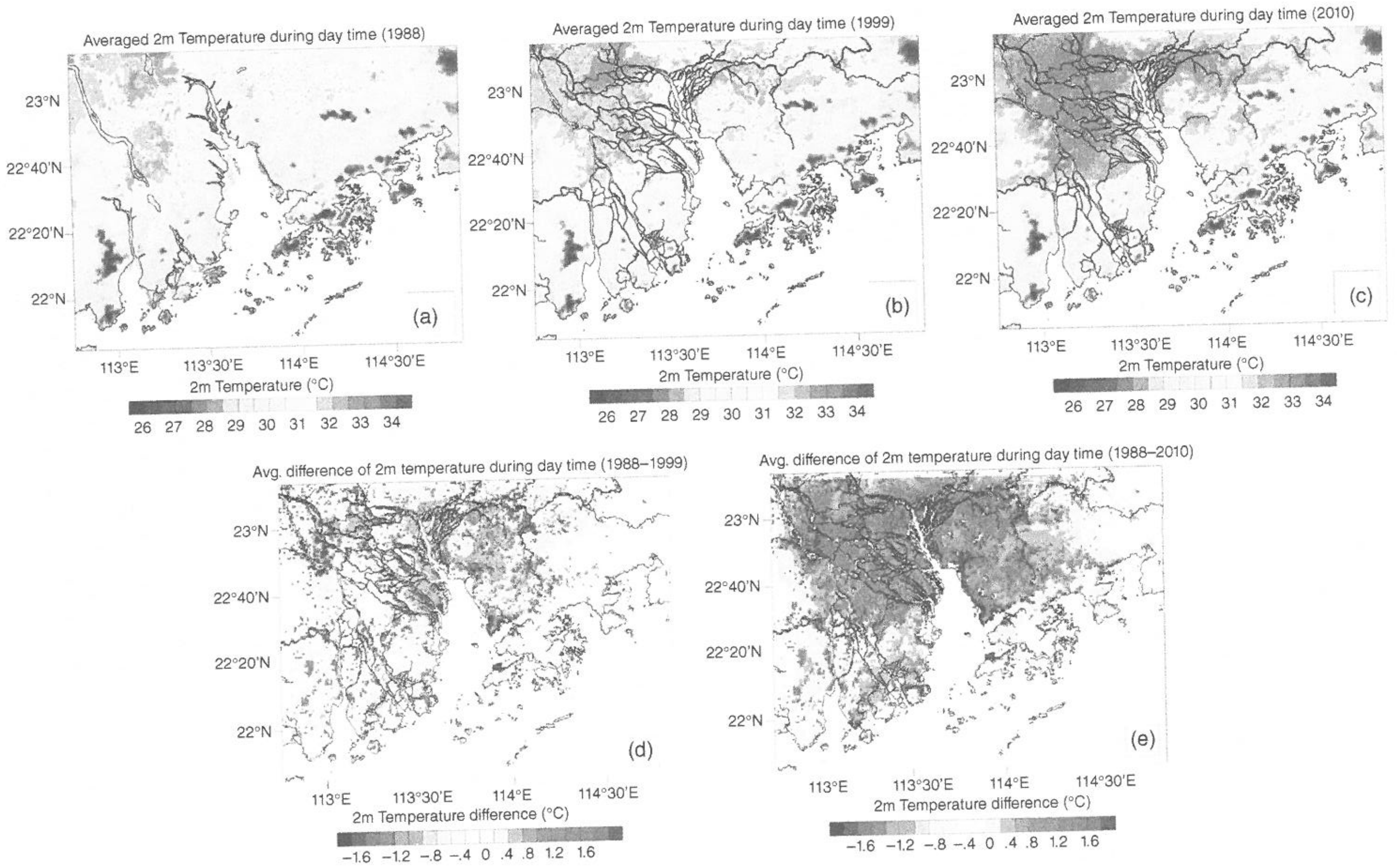


Figure 7.9 Average daytime 2m temperature over land in (a) 1988, (b) 1999, (c) and 2010 and (d–e) their difference

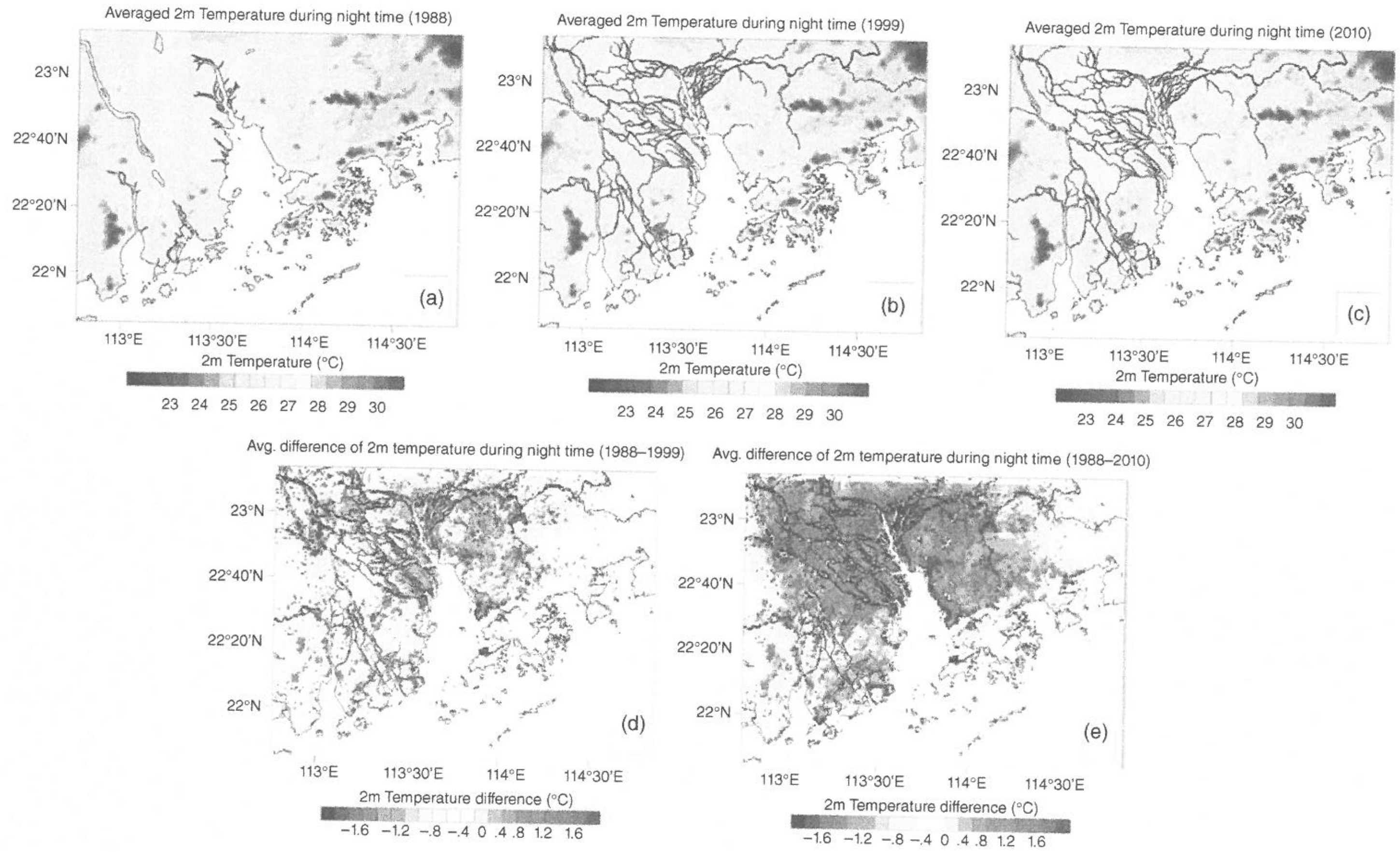


Figure 7.10 Average nighttime 2m temperature over land in (a) 1988, (b) 1999, (c) and 2010 and (d–e) their difference

The higher temperature in urban areas can be explained by the change of physical characteristics due to urbanisation. First, together with the reduced surface albedo due to urbanisation, buildings in urban areas allow a larger amount of energy to be absorbed during the day than those in rural areas. The absorbed energy is released at night, so higher temperatures are maintained throughout the night (Taha, 1997). Second, due to the reduction of soil moisture and vegetation in urban areas, there is a general increase in sensible heat flux and decrease in latent heat flux during the day to maintain the surface energy balance (Rizwan et al., 2008; Taha, 1997). When compared with the year 1988, most of the urbanised areas in 2010 have an increase of around 300Wm^{-2} in sensible heat flux and the same amount of decrease in latent heat flux; while there are no significant changes for most of the rural areas as they remain undeveloped. Overall, as the sensible heat flux in urban areas is strengthened, the temperature is also increased correspondingly.

The differences in the seasonal average of wind speed during the day and at night are generally weakened when compared to 1988, as seen in Figure 7.11. The result is consistent with the observation data from Hong Kong, which suggests that the wind speed in urban areas is declining due to urbanisation (HKO, 2016). As the urbanisation process will result in more buildings in urban areas, the corresponding surface roughness is increased. Consequently, the magnitude of wind speed is reduced.

The heat index aims to model the human-perceived equivalent temperature by accounting for various meteorological variables to evaluate the associated risks. The heat index model developed by the U.S. National Weather Service (Rothfusz, 1990) was chosen for this study. It uses an empirical formula associated with 2m relative humidity (R) and 2m air temperature (T) to determine the Human-perceived equivalent temperature in shaded areas and light wind conditions, which is shown below.

$$\text{Heat Index} = c_1 + c_2 T + c_3 R + c_4 TR + c_5 T^2 + c_6 R^2 + c_7 T^2R + c_8 TR^2 + c_9 T^2R^2 \qquad (7.1)$$

We adopted the above formula to estimate the potential heat stress on the human body which could be caused by the changing climate. In the formula, c is a constant for $1 \leq i \leq 9$. This formula is obtained by a multivariate fit to a model of the human body. The value calculated in the formula can be placed into four categories, as summarised in Table 7.3.

Because most areas in the PRD fall into the 'Extreme Caution' category (> 32 °C), the focus is on the comparison of the heat index. Figures 7.12a and 7.12b show that the increase in heat index is widespread during the day in both urban and rural areas near the coast, possibly because of intensified sea breezes and the widely urbanised area. The former facilitates the transportation of moisture from the sea to the coastal area and increases the relative humidity, whereas the latter increases the temperature. Both effects cause a significant increase in the heat index of coastal areas because the heat index depends on relative humidity and temperature. At night, however (Figures 7.12c and 7.12d), the difference in the heat index of coastal areas is insignificant because the sea breeze changes less near the coast (Figures 7.11c and 7.11d). In contrast to coastal areas, inland areas generally have a considerable increase in the heat index, which is enhanced at night. Some areas can even reach a 2.5 °C increase in the heat index, particularly the eastern part of Shenzhen and the northwestern part of the PRD (as shown in Figure 7.12d).

Table 7.3 Classification of heat index value

Classification	Range (°C)	Effect on the body
Caution	27 to 32	Fatigue possible with prolonged exposure and/or physical activity
Extreme caution	32 to 41	Heat stroke, heat cramps, or heat exhaustion possible with prolonged exposure and/or physical activity
Danger	41 to 54	Heat cramps or heat exhaustion likely, and heat stroke possible with prolonged exposure and/or physical activity
Extreme danger	Over 54	Heat stroke highly likely

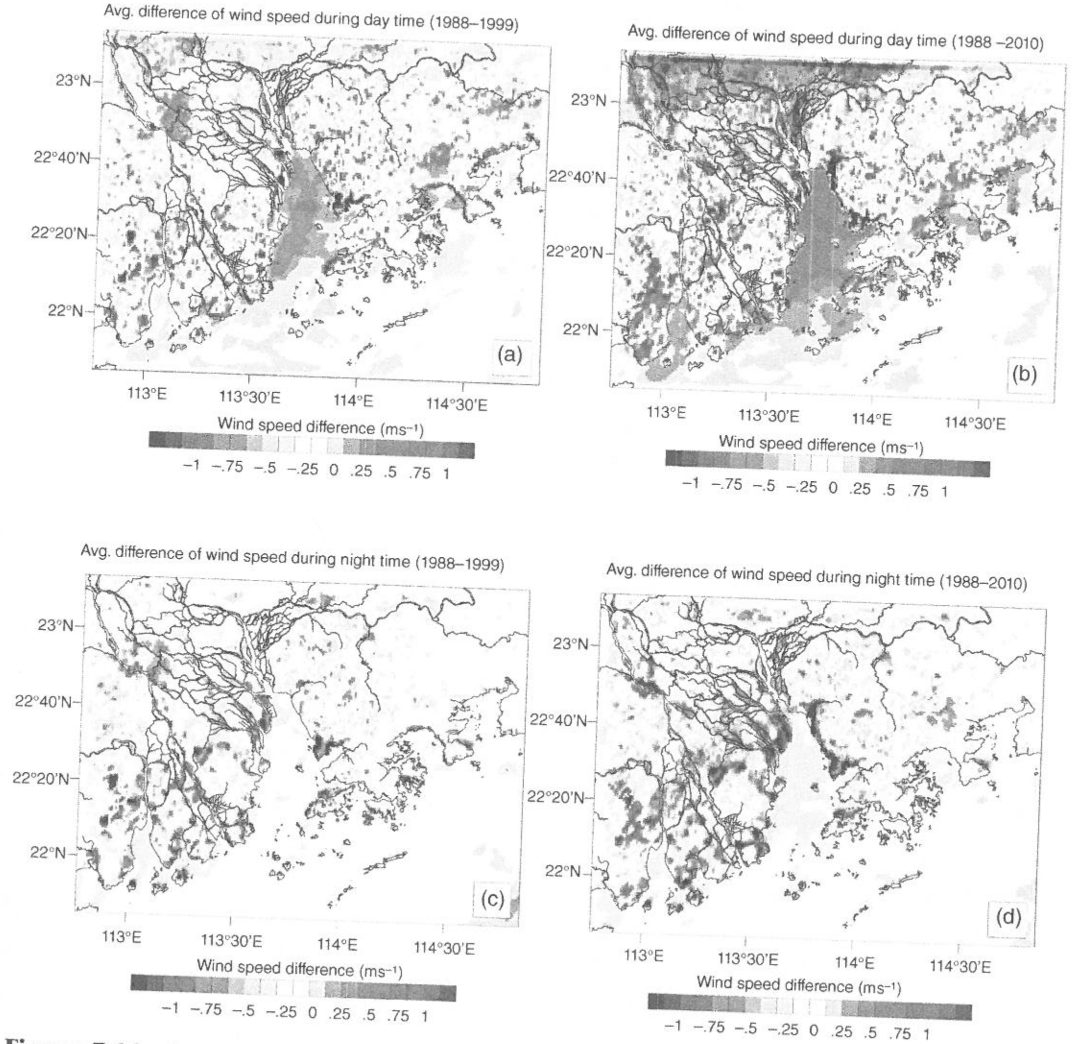


Figure 7.11 Average difference of 10m wind speed during day (a–b) and at night (c–d), respectively, in different years

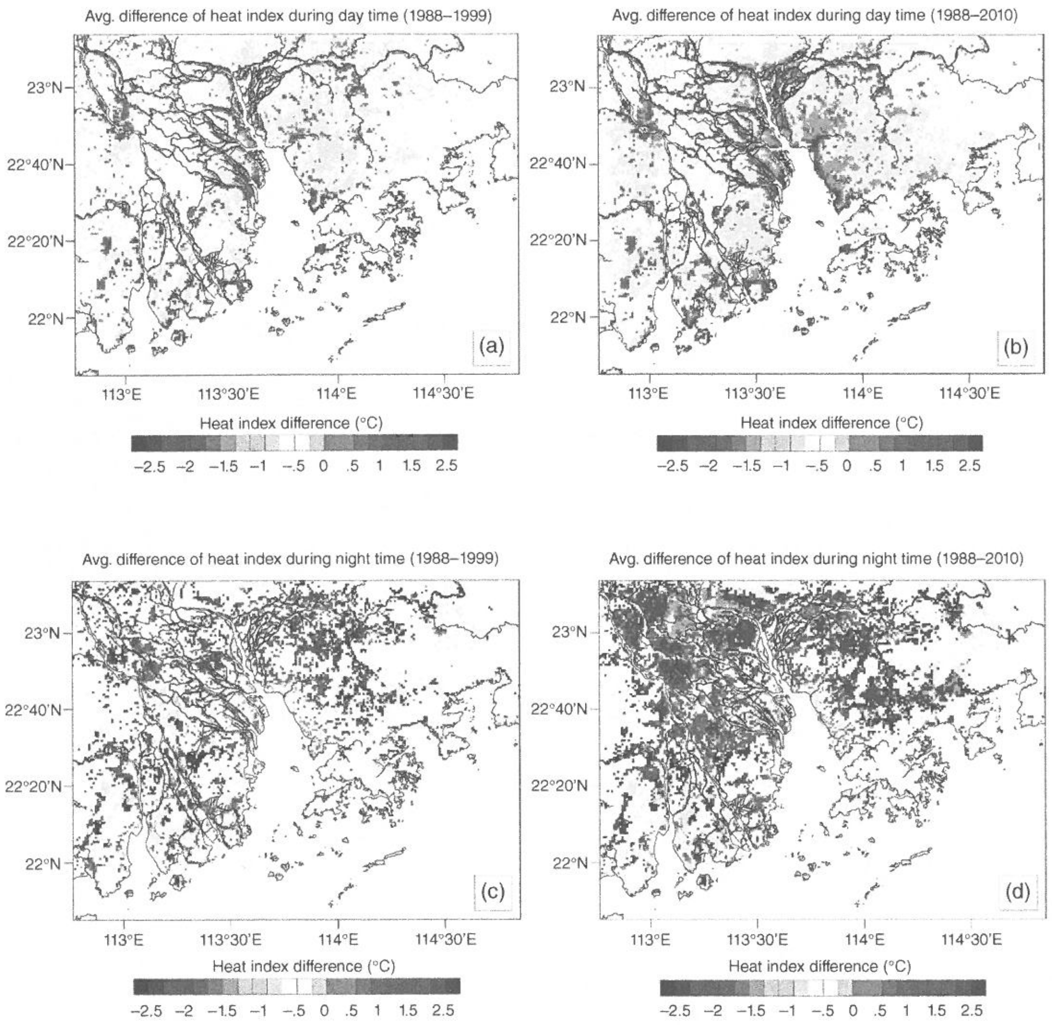


Figure 7.12 Average difference of heat index over land during day (a–b) and at night (c–d) in different years

Conclusion

The PRD region is the youngest and biggest mega urban region in the world. This study demonstrates the climatological changes caused by rapid urbanisation in the PRD region between 1988 and 2010. Land use data for different decades were created by applying machine learning techniques to classify the land use based on satellite images. The simulations were then performed with the WRF model with the corresponding land use data, while maintaining the same initial and boundary conditions to allow the changes to be investigated. After completion of the simulation, climatic variables like the 2m air temperature, 10m wind speed, and heat index were investigated through spatial cross-comparison and statistical analysis. It is expected that the results of this study could serve as a reference for the local planners, especially with the future development of the Guangzhou–Hong Kong–Macao bay area by the Chinese government. Through understanding of the impact of urbanisation, governors can plan correspondingly to alleviate its negative impact, for example, the UHI effect.

The lessons learned from this study can provide local policymakers and planners with a quantitative understanding of the urban development of the PRD region. It also can serve as a useful reference for developing countries in sub-tropical climate regions which are also facing fast urbanisation. By capturing detailed urban features and their impact with the help of WUDAPT data, the findings can inform documents such as *The environmental performance assessment guide of urban ecological development of China (Trial Version)* and *The PRD Region Reform and Development Plan (2008–2020)* (Guangdong Government, 2008).

The WUDAPT initiative has attracted a fast growing community to work together on urban data development and its application into urban climate and urban meteorology related studies. Now more than 150 cities' data are available online. This global initiative would not only develop a new set of standardised urban data, but also encourage cross-disciplinary collaborations on urban morphology, urban climatology and public health impact.

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8

DATA ANALYTICS AND MODELLING ACCESSIBILITY CHANGE OF HIGH-SPEED RAIL NETWORK DEVELOPMENT: A DOOR-TO-DOOR APPROACH

Lei Wang