Urban Microclimates and Urban Heat Island in Chongqing, China
Urban Microclimates and Urban Heat Island in Chongqing, China
A report for Royal Institution of Chartered Surveyors

Report written by:

Runming Yao
r.yao@reading.ac.uk
Zhiwen Luo
Lai Jiang
School of Construction Management and Engineering,
University of Reading, United Kingdom
Qing Luo
Yu Yang
Yafeng Gao
Faculty of Urban Construction and Environmental Engineering,
Chongqing University, China

RICS Research team

Dr. Clare Eriksson FRICS
Director of Global Research & Policy
ceriksson@rics.org
James Rowlands
Global Research & Policy Project Manager
jrowlands@rics.org
Amanprit Johal
Global Research & Policy Project Officer
ajohal@rics.org

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Chongqing is the largest directly-controlled municipality in China, which is now undergoing a rapid urbanization. The urbanization rate increased from 35.6% in 2000 to 48.3% in 2007, and it is estimated to reach at least 70% by 2020. The question remains open: What are the consequences of such rapid urbanization in Chongqing in terms of urban microclimate? Furthermore, Chongqing is located within the Three Gorges Reservoir (TGR) region and the upper Yangtze River, where the Three Gorges Reservoir (TGR) project started in 1993 and was completed in 2010. As one of the biggest construction projects in the world with a rising water level of 175m and water storage capacity of about 39.3 billion m³, it would be interesting to investigate how such a gigantic project impacts the surrounding micro-environment, especially in Chongqing.

Different research approaches are adopted in the study. Our literature review indicates present studies on the urban climate in Chongqing are mainly confined within the historical trend analysis of several weather stations operated by the Chongqing government, little is known about the spatial distribution of urban air temperature and how the local land cover influences the air temperature, especially when there are rivers running through the Chongqing urban area. To contribute to the present knowledge, a series of field measurement campaigns and numerical simulations were carried out. Two complementary types of field measurements are included: fixed weather stations and mobile transverse measurement. Numerical simulations using a house-developed program are able to predict the urban air temperature in Chongqing.

The main research findings are:

• An average rising trend of 0.10°/decade was found for the annual mean temperature from 1961-2010 in Chongqing. This number is much higher than the global rising trend of 0.074°/decade, indicating a higher degree of urban warming in Chongqing.

• More frequent and serious heat waves are also expected in Chongqing under the changing climates and increasing urbanization.

• Conflict exists on how the TGR influences surrounding microclimates. Some numerical simulations show that there are significant impacts on air temperature and precipitation, while recent high-resolution meso-scale simulation shows such influence to be insignificant.

• The urban microclimate is very sensitive to the local environment. A higher air temperature is always related to higher building density and population density.

• The urban heat island intensity in Chongqing is higher in the summer compared to autumn and winter. The maximum urban heat island intensity occurs at around 2400, and can be as high as 2.5°C. In the daytime, an urban cool island exists.

• Our mobile measurement shows that the local greenery has a great impact on the local thermal environment. Urban green spaces can help to reduce urban air temperatures and therefore mitigate the urban heat island.

• The cooling effect of an urban river is limited in Chongqing, as both sides of the river are the most developed areas, but the relative humidity is much higher near the river compared to places further away from the river.

• The numerical simulation and mapping is clearly influential in predicting the urban air temperature at an urban scale with its high resolution imagery. The prediction results agree with our onsite and mobile measurements. The urban air/surface temperature is very sensitive to the local land cover and anthropogenic activities. Moreover, the urban heat storage plays an important role in determining the temperature in the urban area. The urban fabric stores the heat and releases it later, which creates a profound urban heat island at night.
1.0 Background and the context

1.1 Urbanization in China and Chongqing

The proportion of the global population in urban areas has increased conspicuously from 29% in 1950 to 49% in 2005, and urbanization is projected to increase even further to 60% in 2030 (United Nations, 2005). The rural population has correspondingly reduced, see Figure 1.1, this is expected to decline from 3.1 billion in 2011 to 2.9 billion in 2050 according to the most updated UN report on urbanization (United Nations, 2011). However, cities are responsible for 75% global energy consumption and 80% greenhouse gas emissions (Ash et al., 2008).

There is a much higher urbanization rate and total population in developing countries (Figure 1.2), but China is among the highest. China now has 670 cities, up from 69 in 1947 and 223 in 1980. Of the 100 fastest growing cities with a population of more than 1 million (based on population growth between 1950 and 2000), 15 are in China (Normile, 2008). China now has 89 cities with a population of a million or more, 32 in India and 37 in the United States. By 2025, China will have 221 cities with one million-plus inhabitants—compared with 35 cities of this size in Europe today. Now, the government estimates that 44% of China’s population lives in cities, this figure will be 60% by 2020. Each year, about 12 million farmers move to cities. With rapid urbanization, China’s GDP grows dramatically, see Figure 1.3.

![Figure 1.1 Projection of urban/rural population](image1)

**Source:** Ash et al., 2008

![Figure 1.2 Distribution of the world urban population percentage by major area 1950, 2011, 2050](image2)

**Source:** UN, 2011
Chongqing became the largest directly-controlled municipality with 82,401 km² in China in 1997, where 42% of the area was classified as urban. It is located in the southwest part of China and the southeast edge of the Sichuan Basin between the Tibetan Plateau and the Yangtze Plain, shown in Figure 1.4(a). It is adjacent to Hubei, Hunan, Shaanxi, Sichuan and Guizhou provinces. The upstream area of the Yangtze River intersects the city. The Jialing and Wujiang Rivers join the Yangtze River from the north and the south respectively in this area. The city is generally surrounded by the Daba Mountain, the Wu Mountain, the Wulin Mountain and the Dalou Mountain. The main terrains of Chongqing are hills and mountains with many sloping fields.

Chongqing accommodated a population of 28,846,170 in 2010 (The Central People’s Government of P.R.C.). Over the last decade, the area has embraced rapid economic growth with an annual real GDP per capita growth of 15.98% between 1997 and 2006, accompanied by a rapid urbanization with the urban rate increasing from 35.6% in 2000 to 48.3% in 2007. Chongqing Municipal Government has established a master plan to increase Chongqing’s urbanization rate from its current level of just under 55% in 2012 to at least 70% by 2020 (Chongqing Statistical Yearbook, 2011). The question remains open: What are the consequences for energy and the environment in Chongqing of such rapid urbanization?
Figure 1.4a Location of Chongqing Municipal Area within China
Table 1.1 Urbanization rate, local GDP and energy consumption in Chongqing

<table>
<thead>
<tr>
<th>Year</th>
<th>Urbanization rate %</th>
<th>Local GDP billion yuan</th>
<th>Energy consumption 10 ktce</th>
</tr>
</thead>
<tbody>
<tr>
<td>1996</td>
<td>29.5</td>
<td>131.512</td>
<td>1871.09</td>
</tr>
<tr>
<td>2000</td>
<td>35.6</td>
<td>179.1</td>
<td>2410.82</td>
</tr>
<tr>
<td>2001</td>
<td>37.4</td>
<td>197.686</td>
<td>2573.68</td>
</tr>
<tr>
<td>2002</td>
<td>39.9</td>
<td>223.286</td>
<td>2823.05</td>
</tr>
<tr>
<td>2003</td>
<td>41.9</td>
<td>255.572</td>
<td>3137.90</td>
</tr>
<tr>
<td>2004</td>
<td>43.5</td>
<td>303.458</td>
<td>3668.41</td>
</tr>
<tr>
<td>2005</td>
<td>45.2</td>
<td>346.772</td>
<td>4464.58</td>
</tr>
<tr>
<td>2006</td>
<td>46.7</td>
<td>390.723</td>
<td>4881.63</td>
</tr>
<tr>
<td>2007</td>
<td>48.3</td>
<td>467.613</td>
<td>5512.44</td>
</tr>
<tr>
<td>2008</td>
<td>50.0</td>
<td>579.366</td>
<td>5895.10</td>
</tr>
<tr>
<td>2009</td>
<td>51.6</td>
<td>653.001</td>
<td>6431.63</td>
</tr>
<tr>
<td>2010</td>
<td>53.0</td>
<td>792.558</td>
<td>7117.41</td>
</tr>
</tbody>
</table>

Table 1.1 illustrates in broad terms the impact on energy consumption has had on the urbanization process during the 1996-2010 period. Urbanization has been the driving force behind local economic development. From 1996 to 2010, a 79.7% increase in the urban population coincided with an increase in local GDP of 661.04 billion Yuan (Chongqing Statistical Yearbook, 2011). However, energy consumption also rose rapidly with a 280% increase in 2010 since 1996. Along with such improvements in living conditions and higher income levels, inhabitants have begun to pay greater attention to indoor environmental quality. Air conditioners have become a necessity for most families in Chongqing because of the local adverse extremes of weather, both in summer and winter seasons.

The environmental consequences are mainly air pollution and urban heat island. To alleviate local air pollution, the local government has in recent times paid increasing attention to energy consumption, the reason being that the poor air quality is the result of the relatively high consumption levels of coal with high sulphur content. In the year 2000, the Chongqing government promulgated the ‘Clean Energy Movement’ in order to improve air quality. Considering local conditions and the rapid growth in the economy, a coal-centred energy consumption pattern is almost inevitable for the foreseeable future. That being the case, the main objectives of the ‘Movement’ have been focussed around developing clean coal technologies, controlling the direct consumption of high-sulphur content coal, developing alternative renewable energy sources and improving energy efficiency. However, very little has been done to address the problem of urban heat islands which is the main purpose of this research project.
1.2 Urban microclimates

This rapid urbanization brings about a series of environmental consequences. In one way, cities strongly contribute to the greenhouse gases emissions and consequently to global warming (IPCC, 2007), and also create a distinct urban climate at the city scale (Ash et al., 2008; Grimmond, 2007). An urban climate differs from its rural counterpart in its unique underlying surface characteristics and the anthropogenic activities within it (Oke, 1988). Urban infrastructures together with changes to the morphology and materials of the surface alter the energy and water exchange between surfaces and the adjacent atmosphere, as well as the airflows. All these are accompanied by direct anthropogenic emissions of heat, carbon dioxide and pollutants, which result in distinct urban climates (Belcher, 2005). In future decades, the complex interaction between the effects of global change at a regional scale and the evolution of cities themselves will probably lead to a deep change of urban climate. Consequences may vary, in terms of management of infrastructures, water resources, pollution, bioclimatic comfort, public health, energy demand and so on. A better scientific understanding of urban environmental physics can help optimize urban planning to achieve a sustainable city development (Bowler et al., 2010; Mills, 2007) and seek useful mitigation solutions to fight against climate change.

The urban heat island is one of the most important signatures for urban climate, it refers to an elevated temperature in the urban area compared with the rural outskirts, see Figure 1.5. It was first observed in London and thereby named by Luke Howard (Howard, 1883). Urban heat island intensity (UHII) is usually evaluated by means of the difference between urban and rural temperatures. There are basically three types of urban heat island depending on where the temperature is measured, i.e., surface UHI, urban canopy UHI and urban boundary UHI. UHI varies during the course of a day and is sensitive to meteorological conditions, especially wind speed and cloud cover. Therefore, UHIs tend to develop during calm and cloudless days. The main contributions to UHIs were summarized by Oke (1988) and Grimmond (2007) as follows:

- Decreased net long-wave loss due to smaller Sky View Factor (SVF) in street canyons,
- Higher short-wave absorption due to canyon geometry,
- Greater daytime heat storage (and nocturnal release) due to thermal properties of buildings and urban materials,
- More sensible heat flux into the adjacent atmosphere due to decreased evaporation resulting from removal of vegetation and surface ‘water proofing’,
- Convergence of sensible heat due to reduction of wind speed in the city,
- Generation of anthropogenic heat in the urban area.
1.3 The Three Gorges Reservoir (TGR) project

The Three Gorges Reservoir (TGR) project is one of the biggest construction projects in the world, which aims to generate hydropower. The construction period of the Three Gorges project lasted from 1993 to 2009 with the completion of the reservoir in October 2010; the water level has risen to 175m as originally designed. The water storage capacity of the reservoir is about 39.3 billion m³ and about 240m² of citrus orchards and farmland have been submerged (Zhang J., 2009).

The TGR area is located between latitudes 28°56'N-31°44'N and longitudes 106°E-111°28'E covering the lower section of the upper reaches of the Yangtze River, with an area of 58,000km² and a population of almost 20 million (Meng, 2005). It consists of Chongqing municipalities with 21 counties and Hubei province. The Yangtze River, especially its middle and upstream regions, is the key region for future economic development in the 21st century (Yang, 1999).

Chongqing located in the upstream Yangtze River, is the biggest municipality in terms of population (31.4 million) and area (82,300 km²). Over the past decade, Chongqing has experienced a great burden of migrants from the Three Gorges Reservoir region. The urbanization in the region has caused massive environmental impacts including urban microclimates and air/water pollution.

1.4 Rationale and significance of the study

Since the TGR covers a huge area geographically, it seems too ambitious to study its impact on the whole region. We take Chongqing as a case study site because:

1) It is located in the upper reaches of the Yangtze River and surrounded by the Yangtze and Jialin Rivers. Therefore the urban microclimates, including temperature and humidity, will be affected.

2) Chongqing is the biggest municipality with a large population, which will provide a good urban heat island case study.

3) Chongqing is experiencing rapid urbanization and construction, the urban planners need information on the local microclimate change in order to develop mitigation and adaptation strategies in the built environment.

Therefore, the main objectives for this research project will be:

• To review the most up-to-date research information about the environmental impact of the Three Gorges Dam construction project;
• To collect historical data on the local climate including temperature, humidity and wind speed;
• To monitor the urban microclimates including air temperature, humidity, wind speed, etc. in Chongqing;
• To compare the collected data with historical data and analyse the variation trends of the local climates;
• To study urban heat islands and mitigation and adaptation in building design and urban planning using a digital simulation method.
2.0 Research methodology

The objectives have been achieved through a well-structured research programme. The literature review and desktop studies have been carried out in conjunction with the experimental campaign.

1. Literature review.
   a) To carry out an in-depth literature review based on the local literature information previously collected by the research partner, Chongqing University, and collect new references from local and international journals;
   b) To identify key factors which affect the built environment by in-depth theoretical studies; the theory will include an energy balance model and statistical analysis;
   c) To collect historical local climate data including air temperature, wind speed, relative humidity (RH), solar radiation and precipitation in Chongqing.

2. Environmental data collection.
   a) To monitor the air temperature and humidity in Chongqing;
   b) Fixed weather station measurements to record long-term data;
   c) Mobile transverse campaign can provide a spatial distribution.

3. Data analysis.
   a) Local climate data collected from the measurements will be compared with historical data;
   b) An urban heat island simulation for Chongqing will be conducted.

Contribution to knowledge and impact of the research:

• This original project will fill the gaps in the information on microclimate changes due to the final completion of the Three Gorges Reservoir in October 2010 and urbanization in Chongqing;
• The research method is rigorous because the project combines experimental and theoretical studies;
• The impact is high because this is a timely and an internationally important project which will provide evidence-based information to the public, policymakers, environmental scientists and engineers, urban planners and building professionals.
3.0 Studies on the urban environment in Chongqing

3.1 Urban air temperature trends in Chongqing

3.1.1 Annual temperature trends

According to IPCC (IPCC, 2007), the global mean temperature ($T_{\text{mean}}$), averaged over land and ocean surfaces, increased by $0.76^\circ \text{C} \pm 0.19^\circ \text{C}$ respectively from 1850-1899, and $0.74^\circ \text{C} \pm 0.18^\circ \text{C}$ respectively over the last 100 years (1906-2005). This rising trend in temperature is one of the major indications of global warming and climate change.

Chongqing is relatively far from the sea and has a monsoon-influenced, humid, subtropical climate. In the summer, the climate of Chongqing is controlled by the southwest monsoon and in winter it is dominated by northeast monsoon. Because of the complicated hilly and mountainous terrain, the local area climates in different districts are varied. Also in the summer, the monsoon crosses the Yungui Plateau and the Dalou Mountain experiences a significant temperature increase from the descending draft. In the winter, the cold air from the north is blocked by the Qinling and Daba Mountain which makes the temperature in winter significantly higher than other areas on the same latitude. The climate in Chongqing is also affected by the Tibet Plateau. The warm and moist airflow from south of the Tibet Plateau meets the dry and chilly airflow from the north Tibet Plateau on the top of the east Sichuan Basin. This makes the weather rainy in Chongqing at the beginning of the summer and autumn (Chongqing Weather, 2013). The Chongqing government has operated 35 weather stations to monitor the local climate, as shown in Figure 3.1.

Figure 3.1 Distribution of weather stations in Chongqing

Source: Han et al., 2009
Zhang T. et al. (2009) analysed the data from 1961-2007, and found an average rising trend of 0.12°C/decade for the annual $T_{\text{mean}}$. Our data analysis from 1961 to 2010 shows the rising trend is 0.10°C/decade; see Figure 3.2. This number is much higher than the global rising trend of 0.074°C/decade, indicating a higher degree of urban warming in Chongqing. This rising trend is especially significant during the last 10 years (1997 to 2006), see Figure 3.2. This could be attributable to the rapid urbanization in Chongqing. Interestingly, there was a decreasing trend of -0.27°C/decade during 1961-1985 (especially in the summer, -0.43°C/decade and in spring, -0.43°C/decade), but it starts to rise from the 1980s, with a significant increase since 1997. The rising rate is as high as 0.34°C/decade from 1986-2007, with a 0.62°C/decade for spring and 0.61°C/decade for summer (Zhang T. et al.). It is not very clear why there was a decrease between 1961 and 1985, Zhao et al. (2008) argued that there was a distinctly different synoptic 100hpa circulation over the Sichuan basin during the 1960s compared to the 1980s, which contributed to a higher air temperature in the summer in the 1960s. Therefore the average temperature was higher in the 1960s compared with that in the 1980s. Zhang T. et al. also predicted the future climate in Chongqing under three scenarios: high emission (A2), middle emission (A1B) and low emission (B1) as shown in Table 3.1. $T_{\text{mean}}$ during 2011-2040 will increase as much as 1°C compared with the results from 1971-2000, 1.6-2.3°C during 2041-2070 and 2.2-3.7°C during 2071-2099. An increasingly warm climate will be expected for Chongqing in the future.

| Table 3.1 Predicted climate change based on different climate scenarios by IPCC (unit: °C) |
|---|---|---|---|---|
| Years | A2 | A1B | B1 | Average |
| 2011–2040 | 1 | 1 | 1 | 1 |
| 2041–2070 | 2.1 | 2.3 | 1.6 | 2 |
| 2071–2099 | 3.7 | 3.2 | 2.2 | 3 |

Figure 3.2 Annual average temperature trend in Chongqing

\[ y = 0.0097x + 18.112 \quad R^2 = 0.1086 \]
3.1.2 Urban extreme temperature trends

Urban heat waves (extremely high temperatures) have a strong impact on the population’s health. It is widely confirmed that there is a positive relationship between high temperature and mortality, especially for the elderly. Zhang et al. (2008) defined the heat wave days as the days with the daily maximum temperature higher than 95% of average annual maximum temperature. They analysed the data from 31 weather stations in Chongqing and found 21-26 heat wave days yearly. The heat wave days decreased before the 1980s, but thereafter significantly increased, however, overall, the trend is slightly decreasing from 1961-2006. Spatially, the yearly heat wave days increased in eastern Chongqing but decreased on the western side. The heat wave intensity increased linearly with an increasing rate of 0.05°C/decade, see Figure 3.3. The year 2006 exhibited the highest extreme temperature. Spatially, the heat wave intensity is higher in the southwest, the middle part along the river, but relatively lower in the southeast and farthest north, which is below 35°C (Zhang et al., 2008).

![Figure 3.3 Heat wave intensity variation from 1961-2007](source)

Source: Zhang et al., 2008

![Figure 3.4 Monthly heat waves during 1960–2006](source)

Source: Han et al., 2009
Han et al. (2010) applied a simple definition of heat wave days as the days with maximum temperature higher than 35°C. The heat wave days are further divided into three subgroups, i.e., high temperature days (a continuous 3 days with temperature higher than 35°C), severe temperature (24h-maximum temperature higher than 37°C but lower than 40°C), and extremely severe temperature (maximum temperature higher than 40°C). They also focused on the data from 33 weather stations in Chongqing. Figure 3.4 shows the distribution of monthly heat wave days. The heat wave days are concentrated during June, July, August, and September, which contribute 96.1% of the yearly total. August is the most vulnerable to heat wave days in Chongqing. Figure 3.5 depicts the yearly variation of heat wave days for different groups. It exhibits a typical ‘N’ trend, i.e., increases at the beginning, then gradually decreases, and finally increases again. Spatially, there are four heat wave areas: Wushan in the northeast, Wanzhou in the north, Fuling and Fengdu in the middle, and Wansheng in the southeast, see Figure 3.6.
Figure 3.6 Spatial distribution of heat wave days in Chongqing

(a) $35^\circ\text{C} \leq T \leq 37^\circ\text{C}$

(b) $37^\circ\text{C} \leq T \leq 40^\circ\text{C}$

(c) $T \geq 40^\circ\text{C}$

(d) $T \geq 35^\circ\text{C}$

Source: Han et al., 2009
3.2 The Chongqing urban heat island

The urban heat island studies in Chongqing are mainly due to remote sensing by satellite. Luo and Liu (2011) found that surface urban heat island intensity in Chongqing is quite profound and between 5-10°C using HJ-1B satellite remotely-sensed data, as shown in Figure 3.7. The surface temperatures in the urban area are between 30°C-39°C with an average of 33.6°C, while temperatures in rural areas are between 25°C-30°C, with an average of 27.3°C. The core of the urban heat island is not within the city centre; rather it is the industrial area in Dadukou and the airport, which are characterized by high urban population density and intense urban energy consumption. There is a relatively weak urban heat island near the water bodies such as the Yangzi and Jialing Rivers, indicating the mitigation effect from the river. Figure 3.8 shows that there is a negative relationship between NDVI (Normalized difference Vegetation Index) and UHI and a positive relationship between NDBI (Normalized Difference Built-up Index) and UHI. Liu and Su (2008) identified two major urban heat islands in Chongqing: the Yuzhong district with a population density of 31,338 persons/km², and also Dadukou. The urban area in Dadukou is around 2518.46 km², of which 40.5% (1018.8 km²) is developed into industrial projects.

Besides the satellite data, Zhao (2009) used the observed temperature data from the weather stations within the ‘One-hour Economic Circle’ to study urban heat islands. The ‘One-hour Economic Circle’ covers 17 weather stations, with 4 stations in the urban area and 13 located in rural areas. Figure 3.9 shows a higher temperature was expected in urban stations, such as Shapingba, compared with the two rural stations. As shown in Figure 3.10, there is a ‘cliff’ from the rural site to the urban area; a higher temperature gradient is expected. A ‘Plateau’ is found in the urban districts from Wansheng to city centre-Shapingba, the temperature gradient is mild. A ‘Peak’ will be reached at Shapingba where the urban population density and anthropogenic heat is the highest. All these are in accordance with the underlying land cover, for example, Shapingba is the Central Business District (CBD) which is highly urbanized and populated, and Nanchuan is a rural site characteristic by sparse, low-rise buildings and surrounding greenery. These are similar to the typical urban heat island profile observed in other cities.

Source: Luo and Liu, 2011
Figure 3.8 The relationship of urban heat island with NDVI and NDBI

(a) The NDVI distribution in Chongqing and its relationship with UHI

(b) The NDBI distribution in Chongqing and its relationship with UHI

Source: Luo and Liu, 2011
Figure 3.9 Urban vs. rural air temperature variations

Source: Zhao, 2009

Figure 3.10 Urban heat island profile from rural to urban

Source: Zhao, 2009
3.3 Urban wind speed in Chongqing

The urban wind speed in Chongqing changes profoundly over the past 50 years, characterised by a higher wind speed in spring and summer, but values are lower in autumn and winter, see Figure 3.11. As depicted in Figure 3.12, the wind speed increased till the maximum value of 1.15 m/s in 1976, and declined significantly to the minimum value of 0.8 m/s in 2000, and finally gradually increased again (Li et al., 2010). Spatially, a higher wind speed is expected in the northeast and southwest parts, compared to a lower wind speed in the middle.

**Figure 3.11** Seasonal variation of mean wind speed in Chongqing

**Figure 3.12** Yearly variation of mean wind speed in Chongqing
3.4 Solar radiation in Chongqing

Figure 3.13 shows the yearly variations in sunshine hours and corresponding average air temperature in Chongqing from 1951-2010. The sunshine hours decrease with time, especially there is a significant drop since 1980. This may be explained by the increasing pollution levels in Chongqing. With higher levels of pollutants in air, fewer sunshine hours would be expected. This trend correlates reasonably with the average air temperature in Chongqing, i.e., a lower air temperature is expected during a period of fewer sunshine hours. However, many other factors also contribute to this. Daily solar radiation in Chongqing in 2001 can be found in Figure 3.14. It is evident that intense solar radiation occurs in summer and is much weaker in winter. The maximum intensity of solar radiation can be as high as 27 MJ/m².

Source: Chongqing Statistical Book, 2011
3.5 Precipitation and relative humidity in Chongqing

We used the statistical data to obtain the yearly variation of precipitation and relative humidity (RH) in Chongqing (Chongqing Statistical Year Book, 2011). A slight increase in precipitation is observed in Chongqing over almost 60 years, see Figure 3.15. Many studies have revealed that the rapid urbanization is responsible for the increased amount of precipitation within the city (Mölders and Olson, 2004). The enhanced urban heat island circulation due to urbanization lifts the air mass over the city, and the higher level of human-induced aerosols contained in this rising urban air mass leads in turn to an increase in the number of condensation nuclei in the atmosphere. Therefore, more precipitation is expected within and downwind of the urban city. Another reason for the increase in precipitation is probably the influence of the Three Gorges Dam (TGD). Wu et al. (2006) found that the land use change associated with the TGD construction has increased the precipitation in the region between Daba and Qinling mountains after the TGD water level rose from 66 to 135m. In accordance with precipitation, the yearly averaged RH in Chongqing is also increasing, as shown in Figure 3.16. This may be also partly due to the increasing moisture released by human activities and partly due to the increased precipitation.

**Figure 3.15** Yearly variation of precipitation in Chongqing

![Yearly variation of precipitation in Chongqing](image)

\[ y = 1.0768x + 1061.2 \quad R^2 = 0.0119 \]

**Figure 3.16** Yearly variation of Relative Humidity (RH) in Chongqing

![Yearly variation of Relative Humidity (RH) in Chongqing](image)

\[ y = 1.0132 + 78.637 \quad R^2 = 0.0195 \]
3.6 Effect of the Three Gorges Reservoir (TGR) on the surrounding regions

How to evaluate the effect of the TGR on the micro-climate of the surrounding regions? It is not an easy task as it is extremely difficult to distinguish the TGR effect from other effects such as urbanization. Although some trial investigations have been done on the comparison of weather data before and after the TGR project, these studies are considered unconvincing. One possible approach would be numerical simulation with idealized scenarios. Miller et al. (2005) carried out two simulations to study how the land-use change influenced the local climate. The selected simulation period is 2 April – 16 May 1990. The simulation results show that the reservoir’s large evaporating surface decreases the surface temperature and cools the lower atmosphere thereby decreasing upward motion and increasing the mass of sinking air. The strong evaporation also supplies moisture to the atmosphere, suggesting an increase in precipitation. The study suggested that a more comprehensive, fine-scale set of multi-season simulations with additional observational data is needed for a more complete analysis.

Ma et al. (2010) used the fifth-generation Pennsylvania State University–NCAR Meso-scale Model (MM5) to simulate how the TGR influenced the surrounding micro-climate and found that the TGR increases the temperature in winter and decreases it in spring, but the temperature in summer can be higher or lower, i.e., higher at the downstream and lower at the upstream, shown in Figure 3.17. However, recent studies using high-resolution meso-scale simulation show that the TGR does not have a significant influence on the local climate over the area (Wu et al., 2012). The conflicting results strongly indicate that further studies are needed.
3.7 Further study needs

The above literature review shows that knowledge about the urban environment in Chongqing is incomplete, especially for the urban thermal environment. The satellite image can only provide the surface temperature; the spatial distribution of air temperature in Chongqing is still unknown. There are many open questions that still require answers. For example, there are major rivers running through Chongqing metropolitan area, how do they impact on the urban environment, especially the thermal environment? Is there any simulation tool to predict the urban air temperature for the purpose of urban planning and urban redevelopment? Our planned research hopes to shed some lights on these questions.
A field campaign to measure the urban thermal environment in the Chongqing area was conducted during June-December 2012. This field campaign consisted of two types of measurements: fixed station measurements and mobile transverse measurements. Fixed stations can be used for a long-term measurement, while mobile transverse measurements can give a full picture of the detailed, spatial distribution of temperature.

### 4.1 Fixed station measurements

Three fixed stations are set up for the field campaign: Huxi, Chongqing University (Cam A), and Xietaizi, see Figure 4.1. The selection of the weather stations is based on principles such as the distance to the TGR, and local environmental conditions etc. Cam A and Xiehezi are close to the area surrounding the TGR, with a distance to TGR of 700m and 2000m, respectively. Huxi is 14 km from the TGR region. This makes it possible to compare the different locations with different distances from TGR region. The local environmental conditions surrounding the three measuring stations are depicted in Figure 4.2. Huxi used to be an agriculture region before 2006, and has now become a low-density residential area (Figure 4.2a). The measurement was made at a height of 9m at the balcony of one residential building rather than at pedestrian level mainly for safety and security reasons. The stations at Cam A and Xietaizi are more urban and surrounded by residential buildings and lawns. The measurement height is 12m for both locations. But all the measurements at 12m are converted to a height of 3m by considering the vertical temperature gradient.

The major measuring parameters are air temperature and relative humidity. The instrument is a ZDR automatic data logger with the sensor inside and radiation shield outside. The data collection started in June 2012 and six months of data have been collected so far.
4.1.1 Characteristics of air temperature and humidity in June 2012

The measurements in June covered ten days, from June 21 to June 30, 2012. Figure 4-3 presents the air temperature and humidity distribution for three measurement stations in June. It is clear that the temperature in Cam A is highest among the three, followed by Xietaizi, while Huxi is the lowest. This is determined by the combined effects of local environments and population density. Huxi is newly developed and far from the CBD centre. The population density there is the lowest of the three sites. Cam A is located in the centre of Shapingba district, enjoying the highest population density. Xietaizi is somewhere in between. In terms of relative humidity, the location which is far from the TGR has a lower RH compared with the closer locations such as Cam A and Xietaizi. This shows the impacts of the TGR on increasing the RH in the nearby surrounding regions.

The local air temperature and RH will also be determined by large-scale meteorological weather conditions. Figure 4.4 shows two typical days in June, June 25 characterized by heavy rain, and June 28, a typical cloudy day. The air temperature and humidity present totally different patterns. On the rainy days, the temperature decreases with time and the differences between different stations are not significant, while during cloudy/sunny days, higher temperatures are expected in areas with higher population and building density.
Figure 4.3a  Air temperature for the three measurement stations in June 2012

Figure 4.3b  Humidity for the three measurement stations in June 2012
Figure 4.4a  Effect of meteorological conditions – Temperature on June 25 (rainy)

Figure 4.4b  Effect of meteorological conditions – Temperature on June 28 (cloudy)
**Figure 4.4c** Effect of meteorological conditions – RH on June 25 (rainy)

**Figure 4.4d** Effect of meteorological conditions – RH on June 28 (cloudy)
4.1.2 Characteristics of air temperature and humidity in July and August 2012

The air temperature and RH patterns in July and August are similar to those in June. Cam A has the highest air temperature and RH, especially during non-precipitation days. The detailed results are presented in Figure 4.5 to 4.8.
Figure 4.6a  Effect of meteorological conditions – Temperature on July 17 (rainy)

Figure 4.6b  Effect of meteorological conditions – Temperature on July 5 (cloudy)
Figure 4.6c  Effect of meteorological conditions – RH on July 17 (rainy)

Figure 4.6d  Effect of meteorological conditions – RH on July 5 (cloudy)
Figure 4.7a  Air temperature for the three measurement stations in August 2012

Figure 4.7b  Humidity for the three measurement stations in August 2012
Figure 4.8a Effect of meteorological conditions – Temperature on August 12 (sunny)

Figure 4.8b Effect of meteorological conditions – Temperature on August 25 (cloudy)
Figure 4.8c  Effect of meteorological conditions – RH on August 12 (sunny)

Figure 4.8d  Effect of meteorological conditions – RH on August 25 (cloudy)
4.1.3 Characteristics of air temperature and humidity in September and October 2012

The air temperature and RH patterns in the autumn period (September – October) are quite different from those in the previous summer time. We choose September as an example for illustration as shown in Figures 4.9 and 4.10. There is no much variation for air temperature for all three stations, but Huxi still exhibits the lowest RH among the three. In terms of the diurnal pattern, for a typical sunny day, Cam A and Xietizi still have a higher maximum temperature and a lag of the peak day temperature is also observed.
Figure 4.10a  Effect of meteorological conditions – Temperature on September 7 (sunny)

Figure 4.10b  Effect of meteorological conditions – Temperature on September 21 (low precipitation)
Figure 4.10c Effect of meteorological conditions – RH on September 7 (sunny)

Figure 4.10d Effect of meteorological conditions – RH on September 21 (low precipitation)
4.1.4 Characteristics of air temperature and humidity in November and December 2012

An obvious difference of air temperature between Huxi and Cam A starts to appear in November and reaches a significant level in December, see Figures 4.11 and 4.12. The trend for RH remains almost the same as for the other months.
Figure 4.12a  Effect of meteorological conditions – Temperature on December 5 (sunny)

Figure 4.12b  Effect of meteorological conditions – Temperature on December 11 (cloudy)
Figure 4.12c Effect of meteorological conditions – RH on December 5 (sunny)

Figure 4.12d Effect of meteorological conditions – RH on December 11 (cloudy)
4.1.5 Urban heat island intensity

The urban heat island intensity is expressed by the difference between urban air temperature and rural air temperature. In our analysis, it would be:

$$\Delta T = T_{\text{urban}} - T_{\text{rural}}$$

The monthly averaged urban heat island intensities between the two sites from July to December 2012 are calculated and shown in Figure 4.13. A typical ‘U’ shape is found for the diurnal pattern. An urban cool island is found around 12:00 p.m. in the daytime, which is also found elsewhere in the world. The urban air temperature is relatively lower compared with rural sites due to the shading effect of surrounding buildings. The maximum urban heat island occurs at around 1:00 a.m. but the magnitude is different from month to month. A lower urban heat island intensity, i.e., smaller than 1°C, is found during autumn (September, October and November). However, in the summer months, such as August, the maximum heat island intensity can be as high as 2.5°C, indicating that the urban heat island is more profound in summer in Chongqing. Memon et al (2009) reviewed the published papers addressing UHI intensity in different cities as shown in Table 4.1. In terms of air temperature, our result is in the middle. But it should be kept in mind the different measurement locations in different cities. For example, in Hong Kong, the measurement was taken at pedestrian level in a street canyon, which shows an extremely high temperature difference.

### Table 4.1

A summary of reported maximum UHI in different cities in the world Memon et al (2009)

<table>
<thead>
<tr>
<th>Study area</th>
<th>Reference Study</th>
<th>Approach</th>
<th>UHII (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atlanta, USA</td>
<td>Hafner and Kidder (1999)</td>
<td>Modelling</td>
<td>+1.2</td>
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<tr>
<td>NYC, USA</td>
<td>Holt and Pullen (2006)</td>
<td>Modelling</td>
<td>+2.2</td>
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<td>Pyongyong, N. Korea</td>
<td>Hung et al. (2005)</td>
<td>Satellite data</td>
<td>+4.0</td>
</tr>
<tr>
<td>Ho Chi Minh City, Vietnam</td>
<td>Hung et al. (2005)</td>
<td>Satellite data</td>
<td>+5.0</td>
</tr>
<tr>
<td>Hungary</td>
<td>Pongracz et al. (2006)</td>
<td>Satellite data</td>
<td>+6.0</td>
</tr>
<tr>
<td>Shanghai, China</td>
<td>Hung et al. (2005)</td>
<td>Satellite data</td>
<td>+7.0</td>
</tr>
<tr>
<td>Manila, Philippines</td>
<td>Hung et al. (2005)</td>
<td>Satellite data</td>
<td>+7.0</td>
</tr>
<tr>
<td>Tokyo, Japan</td>
<td>Saitoh et al. (1995)</td>
<td>Modelling</td>
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<tr>
<td>Seoul, S. Korea</td>
<td>Hung et al. (2005)</td>
<td>Satellite data</td>
<td>+8.0</td>
</tr>
<tr>
<td>Bangkok, Thailand</td>
<td>Hung et al. (2005)</td>
<td>Satellite data</td>
<td>+8.0</td>
</tr>
<tr>
<td>Beijing, China</td>
<td>Hung et al. (2005)</td>
<td>Satellite data</td>
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<td>Unger et al. (2001)</td>
<td>Site survey data</td>
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<tr>
<td>Seoul, S. Korea</td>
<td>Kim and Baik (2005)</td>
<td>Weather station data</td>
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<td>Hong Kong, China</td>
<td>Gridharen et al. (2007)</td>
<td>Site survey data</td>
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<tr>
<td>Rome, Italy</td>
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<td>Modelling</td>
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<td>Mexico city, Mexico</td>
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<td>Weather station data</td>
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<td>Hong Kong, China</td>
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<td>Granada, Nicaragua</td>
<td>Montavez et al. (2000)</td>
<td>Weather station data</td>
<td>-2.0</td>
</tr>
</tbody>
</table>

1 Surface-temperature based  2 Air temperature based  * Negative UHII  § Positive UHII

Figure 4.13 Comparing the urban heat island intensity between Xietaizi and Huxi

- Temperature Intensity (°C)
- Time (Hour)

- July
- August
- September
- October
- November
- December
4.2 Mobile transverse measurement

Mobile transverse measurement is a good way of compensating for fixed weather station measurement, as it can provide a spatial distribution. A weather station is installed on a car roof to measure air temperature and humidity at the same time when the car makes the transverse trips. GPS is used to record the transverse route. The transverse route is shown as Figure 4.14. Software Surfer can be used for post-processing for urban heat island mapping. Several field campaigns are made.
4.2.1 Campaign 1

The transverse measurement started at 14:11, 24 December 2012 and ended at 15:17, 24 December 2012. The whole measurement took 1 hour and 6 minutes. The weather was clear and sunny. The air temperature, relative humidity and location (latitude and longitude) are measured simultaneously. The sampling time is 10s. Figure 4.15 depicts the mapping of air temperature and humidity for this transverse measurement with detailed latitude and longitude information. It is evident that there is a much lower air temperature and higher RH near the Jialing River. There are several cool islands.

Further, some typical urban locations which are on the transverse route are selected to examine the relationship of air temperature and RH with the local environmental conditions including land cover, building/population density, greenery etc. As shown in Figure 4.16, a relatively high temperature is expected in locations such as Changjiangyilu, Eling etc., where a dense urban morphology and little greenery are found.

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**Figure 4.15a** Air temperature mapping for the mobile transverse route 1

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**Figure 4.15b** Humidity mapping for the mobile transverse route 1
Figure 4.16a
Air temperature at typical mobile points for transverse route 1

Figure 4.16b
Humidity at typical mobile points for transverse route 1
4.2.2 Campaign 2

The second transverse measurement took place at 14:05, 8 January 2013, and ended at 15:02 the same day. The duration was 57 minutes. The sky was cloudy during that period. The same transverse route was followed. The measurement results are presented in Figures 4.17 and 4.18. As with the first campaign, it was cool and humid near the river, but a much more well-defined cool island was found.

**Figure 4.17a** Air temperature mapping for the mobile transverse route 2

**Figure 4.17b** Humidity mapping for the mobile transverse route 2
Figure 4.18a  Air temperature at typical mobile points for transverse route 2

Temperature (°C)

Location

Figure 4.18b  Humidity at typical mobile points for transverse route 2

Humidity (%)

Location
4.2.2 Campaign 3 – across the river

Another two transverse measurements were made across the Jialing River. The mobile route is shown in Figure 4.19. The total length of the route was 2 Km. The first measurement started from 11:56, 18 January 2013 to 13:22 the same day. The sky was clear and sunny during that period. The ambient atmospheric pressure was 99500 Pa. The second campaign was from 12:58 to 14:00, 22 January 2013 on the same route. The sky was cloudy.

Temperature, RH and wind speed data were collected every 50m during the trip and presented in Figures 4.20 and 4.21. It is again evident that it is always cooler and more humid near the river, and the temperature is gradually increased but the RH decreased when travelling away from the river. The wind speed is also higher near the river.
Figure 4.20b  Humidity at the locations measured from the river for cross-river mobile transverse 1

Figure 4.20c  Wind speed at the locations measured from the river for cross-river mobile transverse 1
Figure 4.21a  Air temperature at the locations measured from the river for cross-river mobile transverse 2

Figure 4.21b  Humidity at the locations measured from the river for cross-river mobile transverse 2
Figure 4.21c Wind speed at the locations measured from the river for cross-river mobile transverse 2
5.1 The urban thermal simulation programme

Techniques for modelling urban microclimates and urban block surfaces temperatures are considered necessary by urban planners and architects for the early stages of strategic urban designs. We developed a simplified mathematical model for urban simulations (UMsim) including urban surfaces temperatures and microclimates (Yao et al., 2011). The nodal network model has been developed by integrating coupled thermal and airflow models. Direct solar radiation, diffuse radiation, reflected radiation, long-wave radiation, heat convection in air and heat transfer in the exterior walls and ground within the complex have been taken into account.

Modelling urban microclimates poses challenges because they are influenced by many factors including:

(1) **Weather data:**
These include air temperature and humidity, wind direction and velocity and solar radiation.

(2) **Urban forms and textures:**
These include building geometry and layout, the buildings’ heights, the thermal properties of building surfaces and the ground. Thermal behaviour within the blocks includes conductive heat transfer of surfaces, such as building facades and ground surfaces, radiant heat transfers from solar radiation, reflective radiation from other buildings and the ground and convective heat transfer due to the airflow.

The principle of the simplified mathematical model is to integrate the Digital Elevation Model (DEM) with the coupled thermal and airflow model in order to perform urban microclimate calculations simultaneously. Figure 5.1 shows the concept of the coupled thermal and airflow model integrated with DEM to simulate the urban microclimate.

From Figure 5.1 we can see that the basic urban complex information such as the buildings’ heights, geometry and layout, surface properties, etc. are stored in the DEM sub-model, which supplies input data to the sub-models of solar radiation, conductive heat transfer and airflow (including convective heat transfer). Together with the inputs of local weather data, the coupled thermal and airflow model will be able to perform a thermal simulation to produce numerical data as well as images of microclimates, including temperatures and solar radiation, within an urban complex. The coupled thermal and airflow model is developed and includes energy balance, mass balance and pressure balance within the urban blocks. To simplify the calculation, a nodal network method has been applied. The whole urban complex can be divided into a number of zones and the relevant equations for the mass, pressure and energy balance of each zone have thus been established. The detailed illustration of the model can be found in Yao et al. (2011).
Figure 5.1: The concept of the coupled thermal and airflow urban model

Source: Yao et al. 2011
5.2 Simulation results

Our self-developed simulation program was applied to the thermal environment of Chongqing. Figure 5.2 is the simulation domain, covering 8km×8km. The simulation period was 21 July 2012. The input parameter includes the DEM map of the city, meteorological weather conditions (solar radiation, wind speed, air temperature and RH in the rural site). The output results are surface and air temperatures at a height of 3 m, respectively. Figures 5.3 and 5.4 show the simulation results. The surface temperature gradually increases since the sun starts to rise at 6:00 a.m. The urban surface receives intense solar radiation, and reaches its maximum temperature as high as 44°C at around 14:00 due to the thermal storage effect. It then gradually decreases when the solar radiation reduces, and further decreases during the night due to the radiative loss to the sky. However, at night, the maximum surface temperature in the urban area can still be as high as 36°C in some regions, indicating a significant surface urban heat island phenomenon in Chongqing. The surface temperature reaches its minimum at around 6:00 a.m. just before sunrise. Spatially, the water temperature of the river is always lower than the urban surface, but this can be quite diverse within urban areas. Some cooling spots are observed within the urban districts, which is in accordance with the presence of urban greenery.

In terms of the air temperature distribution, quite similar patterns with surface temperature are found. The air is first heated up in the morning by the sun, and the temperature gradually increases due to the convective heat transported by the heated surface. The air temperature reaches its maximum at around 16:00 which is further behind the surface temperature. It is still very hot during the summer night time, the maximum air temperature can be as high as 34°C. In some regions within the urban area such as a park or lawn, a lower temperature is also expected. Under the cooling impact of the river, a lower air temperature is found near the river, which is consistent with our findings from the field campaign. The cooling effect of the water body within the city can never be ignored. Moreover, the highest temperature always corresponds with the highest population and building density.
Figure 5.3a  Surface temperature distribution
Figure 5.3b Surface temperature distribution
Figure 5.4a Air temperature distribution at a height of 3 m
Figure 5.4b Air temperature distribution at a height of 3 m

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6.0 Conclusions and future outlook
6.0 Conclusions and future outlook

This project investigated the urban microclimate in Chongqing by examining Chinese publications, undertaking a field measurement campaign and creating a numerical simulation against the background of the rapid urbanization in Chongqing and the construction of the TGR project. The comprehensive literature review of current Chinese publications strongly suggests that a further study on this topic is needed. Therefore, two types of field measurement campaigns were carried out, i.e., fixed-station measurement and mobile transverse measurement. For the urban surface/air temperature, an in-house-developed program is used to simulate the urban thermal environment in Chongqing. This provides a better tool for urban planners to study the effects of different urban planning scenarios. The major conclusions drawn from this project are:

- An average rising trend of 0.10°C/decade was found for the annual mean temperature from 1961–2010 in Chongqing. This number is much higher than the global rising trend of 0.074°C /decade, indicating a higher degree of urban warming in Chongqing.
- More frequent and serious heatwaves are also expected in Chongqing under the changing climate and increasing urbanization.
- Conflict exists on how the TGR influences surrounding micro-climates. Some numerical simulations show that there are significant impacts on air temperature and precipitation, while recent high-resolution, meso-scale simulation shows such influence to be insignificant.
- The urban microclimate is very sensitive to the local environment. A higher air temperature is always related to a higher building density and population density.
- The urban heat island intensity in Chongqing is higher in the summer compared to autumn and winter. The maximum urban heat island intensity occurs at around 2400 and can be as high as 2.5°C. In the daytime, an urban cool island exists.
- Our mobile measurements show that the local greenery has a great impact on the local thermal environment. Urban green spaces can help to reduce urban air temperature and therefore mitigate urban heat islands.
- The cooling effect of an urban river is limited in Chongqing, as both sides of the river are the most developed areas, but the relative humidity is much higher near the river compared to places further away from the river.
- Numerical simulation combined with digital elevation mapping is clearly influential in predicting the urban air temperature on an urban scale with its high resolution imagery. The prediction results agree with our onsite and mobile measurements. The urban air/surface temperature is very sensitive to the local land cover and anthropogenic activities. Also, the urban heat storage plays an important role in determining the temperatures in the urban area. The urban fabric stores the heat and releases it later, which creates a profound urban heat island at night.
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