Object-oriented tracking of thematic and spatial behaviors of urban heat islands

Rui Zhu[a,b], Éric Guilbert[c], Man Sing Wong[b,d,*]

[a] *Senseable City Laboratory, Singapore-MIT Alliance for Research and Technology, Singapore*
[b] *Department of Land Surveying and Geo-informatics, The Hong Kong Polytechnic University, Hong Kong, China*
[c] *Department of Geomatics Sciences, Laval University, Québec, Canada*
[d] *Research Institute for Sustainable Urban Development, The Hong Kong Polytechnic University, Hong Kong*

Abstract

Modeling thematic and spatial dynamic behaviors of Urban Heat Islands (UHIs) over time is important for understanding the evolution of this phenomenon to mitigate the warming effect in urban areas. Although previous studies conceptualized that a UHI only has a single life-cycle with spatial behaviors, a UHI can be detected to appear and to disappear several times periodically in terms of thematic and spatial integrated behaviors. Such multiple behaviors have not been illustrated with proof or evidence yet. This study conceptualizes a UHI as an object which has thematic and spatial behaviors simultaneously and proposes several graphs to depict periodic life-cycle transitions triggered by behaviors. The model has been implemented in an object-relational database management system and temperature readings collected numerous weather stations were interpolated as temperature images per hour. The results of this study indicate that the model could track the spatial and thematic evolution of UHIs continuously and reveal their periodical patterns and abnormal cases.

Keywords: Spatiotemporal data modeling; Object-oriented modeling; Urban heat islands

1. Introduction

An urban heat island (UHI) is an environmental phenomenon that air/land surface temperatures in urban areas are higher than that in surrounding rural areas. The existence of UHIs is a major problem in most metropolitan areas. They cause many adverse effects such as public health deterioration (Ding *et al.*, 2015; Kenney *et al.*, 2014; Morabito *et al.*, 2012), public security threats (Cohn and Rotton, 2000; Field, 1992; Rotton and Cohn, 2004), and increasing energy consumption (Fung *et al.*, 2006; Papakostas *et al.*, 2010). It is even a more serious problem in rapidly expanding cities given that the urbanization process is increasingly fast. An investigation into the adverse effects and exploring the causative factors of the phenomenon becomes urgent. Thus, it is needed to track evolutions of UHIs continuously in both thematic (i.e. temperature variations) and spatial (i.e. areal changes and topological transformations) dimensions over a long period.

Previous studies estimated land surface temperature (LST) in describing UHIs and analyzed its correlation with social indicators (Buyantuyev and Wu, 2010), environmental indices (Hu and Brunsell, 2015) and building impacts (Yuan and Ng, 2012; Wong and Nichol, 2013; Toparlar *et al.*, 2015; Wong *et al.*, 2016). Recent studies tend to analyze discrete pixels toward clustering UHIs as interactive objects extracted from thermal images. For example, object-based analysis clustered pixels of thermal infrared images as polygons of objects so that a strong correlation between spatial and thermal attributes (i.e. areal extent and LST) was revealed (Keramitsoglou *et al.*, 2011). However, these studies are incapable to track thematic and spatial changes of UHIs simultaneously over a long period. Although some empirical studies have been conducted by analyzing spatio-temporal variation patterns of UHIs based on the interpolation of air temperatures collected from meteorological

*Corresponding author
Email address: ls.charles@polyu.edu.hk (Man Sing Wong)

stations (Wu *et al.*, 2012; Kourtidis *et al.*, 2015), it is a challenge to describe instant changes at a fine temporal resolution over a long time period. Thus, a model using spatio-temporal data is needed for determining pixels of thermal images as UHI objects and tracking the changes of their dynamics through continuous time.

Many studies of modeling geographical phenomena as field objects have included variable boundaries determined by other properties (e.g. temporal and thematic properties) related to the field (Goodchild et al., 2007). Their dynamics could be represented in a hierarchical framework where a *sequence* was composed of consecutive *zones* and related together in *processes*, and *events* for observing their shape changes and spatial movements from a series of images (McIntosh and Yuan, 2005; Yuan and Hornsby, 2008). For instance, moving behaviors of each object were modeled as a set of semantic *events* such as *departure* and *arrival* and patterns were constructed from several sequences of the *events* (Hornsby and Cole, 2007). Other developed models conceptualized spatiotemporal dynamic phenomena as geo-entities in relationships and implemented data structures fitted for computations (Bothwell and Yuan, 2010; Pultar *et al.*, 2010; Li *et al.*, 2013). These approaches provide an appropriate strategy to model the dynamics of UHIs. For example, a series of zones of UHIs which expand continuously can correspond to a sequence.

However, UHI evolutions may involve a single object or several different objects that associate with topological relationships between zones of UHIs. For example, a UHI can contract, split into two parts and disappear. Oppositely, two UHIs can expand and merge into one. Claramunt and Thériault (1995) proposed a series of the topological process describing the behavior of a single object as an expansion or a contraction and behaviors between several objects as splits, unions, or re-allocations. Similar models were developed as such that objects disappear and reappear because of merging and splitting behaviors (Renolen, 2000; Nixon and Hornsby, 2010; Bothwell and Yuan, 2011). These studies provide an enlightening approach for modeling complex transformation of UHIs. However, they only focused on conceptual modeling and tracking UHIs needs logistical modeling incorporated into systematically conceptualized UHI behaviors. Furthermore, Del Mondo *et al.* (2013) depicted topological transformations in a *graph* composed of a set of nodes and several edges connecting the nodes with certain filiation relationships. Similarly, different graphs will be proposed to develop tracking dynamics of UHIs in our study.

A study has already proposed an object-oriented spatio-temporal framework in modeling the spatial behavior of UHIs (Zhu *et al.*, 2017a). Within this framework, a UHI was defined as a two-dimensional field object whose temperatures were equal to or higher than a reference rural temperature. A UHI may experience different sequences, each of which corresponds to a type of spatial behavior. The changes of UHI can be either internal with area changes or external involving topological transformations with one or several UHIs. In addition, spatial behaviors have been defined into two graphs; namely, a zone graph $\mathcal{G}_Z = (\mathcal{Z}, \mathcal{F}_z)$ which denotes a set of zones ($\mathcal{Z}$) as nodes and a set of filiations ($\mathcal{F}_z$) as edges (e.g., spatial behaviors of zones) associated with the zones; and a sequence graph $\mathcal{G}_S = (\mathcal{S}, \mathcal{E}_s)$ which represents a set of sequences ($\mathcal{S}$) that cover area changes or topological transformations ($\mathcal{E}_s$).

However, the aforementioned framework is lacking the capability to investigate temperature variations in the UHI extent, since the field was conceptualized and recorded as a homogeneous surface. Temperature distribution in a real situation within the UHI extent can vary significantly. For example, the temperature of a small area within a UHI may be steady, whereas the temperature of other areas in the same UHI may go up corresponding to a place with accumulated anthropogenic heat. The UHI may be considered as consisting of several small UHIs if the small areas are reckoned as UHIs with higher intensity. To have a better investigation into this phenomenon at different thematic intensities, a new definition of UHI will be introduced.

It was suggested that geographical phenomena may have a periodical process of state transitions between existence and non-existence (Hornsby and Egenhofer, 2000). As an object, a UHI may appear, disappear and reappear over time. In this consideration, the periodicity links a series of existences as a continuous process, in which the life span of UHIs can extend from a few hours to a couple of days. Thus, establishing the periodicity of UHIs for the investigation over long periods becomes very important for our study.

In addition, the above framework cannot track thematic changes of a UHI. This point is vital to clarify evolutionary trends of temperatures since they determine the spatial extent conclusively and influence its spatial behaviors consequently (Bothwell and Yuan, 2012). For example, an increase of the UHI temperature may lead to the expansion of its spatial extent at night-time but contraction during the daytime. Therefore, thematic tracking will also be modeled in our study to explore thematic-associated spatial behaviors.

To build a relationship between two zones at two consecutive time instants for computing the proposed spatial behaviors, the above framework only covered the relationship between the overlapping area and the zone in the prior time instant. This may cause a problem that two zones having no significant overlapping with each other are still determined as associated zones uncertainly, but UHI is a localized phenomenon having no significant displacement (Hua and Wang, 2012; Jalan and Sharma, 2014). To solve this problem, a refined method is also necessary.

In summary, this study has four originalities: (i) a new concept of UHI will be presented in considering of difference between urban and rural air temperatures; (ii) periodical process of UHIs with state transitions will be proposed to allow UHIs to have longer life spans; (iii) thematic behaviors as well as UHI graphs will be proposed and modeled to track the changes in a variety of aspects; and (iv) a refined and robust computational method will be developed.

The rest paper is organized into three sections. Section 2 presents a new conceptual model of UHIs viewed as dynamic objects and emphasizes on spatial and thematic behaviors with periodical transitions. Section 3, through an empirical evaluation in a developed spatial database management system, suggests the effectiveness of the proposed model. Finally, Section 4 draws the discussion and conclusion of this study.

2. Conceptual and logical modeling

2.1. UHIs as dynamic objects

During its lifetime, a UHI evolves through different stages. As shown in Figure 1, a UHI occurs at a given time and place if the temperature measured at this location is higher than a reference rural temperature. The *intensity* at a point is defined by this temperature difference (d). The UHI is characterized when the temperature difference is above a certain threshold, the *magnitude*.

As a temporal phenomenon, a UHI may expand, contract, or remain stable possibly because the intensity grows up, drops down, or remains constant over time. This variation in the extent and intensity of the UHI describes its behavior and can be summarized by a series of concepts represented in Figure 2. The behavior can describe a continuous process or a transformation. Continuous processes can be spatial (when they describe a variation of the UHI extent) or thematic (a variation of intensity).

UHIs also show periodical behavior. Since temperature varies periodically, with for example UHI episodes more intense at night or during the summer, UHI should be allowed to disappear and reappear periodically at the same location. This consideration is helpful to reveal thematic and spatial evolutionary trends of UHIs over longer periods (e.g., in months, seasons, or even years). In this regard, a UHI can go through several *active* and *inactive* periods (Figure 3). In this scenario, the *appearance* of a UHI indicates a *creation* if it is newly generated and *activation* if it existed before, and *disappearance* may lead to *death* if it disappears forever.

An active period can start from behaviors when zones appear and terminate at behaviors when zones disappear. However, termination of an *active period* followed by an *inactive period* means that the UHI is disappeared temporarily and it will appear again shortly. Therefore, this process requires some topological constraints:

- disappeared zones which will be activated cannot be made by *annexation* and *merging* since disappeared zones associated with the two behaviors are destructed forever; and
- activated zones which 118 have been created cannot come from *separation* and *splitting* because both behaviors generate entirely new objects.

2.2. Graph-based modeling of UHI behaviors

UHIs are observed from temperature data at given timestamps. At a timestamp t_i, a UHI u_n is observed by a zone z_n^i where the temperature is above the magnitude. A UHI will have a lifespan starting at t_i, when its first occurrence z_n^i is observed and ending at t_n^j when its last occurrence is observed. In between, the UHI goes through active and inactive periods and, in each active period, it goes through different sequences characterized by the behaviors of Figure 2. Hence, as Zhu *et al.* (2017a), sequences are defined by a series of zones and relationships between zones and sequences are defined by a graph. Furthermore, we add one level since a series of sequences form a period. In addition, we consider temperature to define trends in intensity variation.

In order to detect all behaviors, it firstly needs to have the set of all zones identified at all timestamps $\mathcal{Z}$. A sequence s_n^i is then a series of consecutive zones following the same spatial behavior. As Zhu *et al.* (2017a) proposed, two graphs are built to define the spatial behavior. The zone graph is noted $\mathcal{G}_Z = (\mathcal{Z}, \mathcal{F}_z)$ where $(\mathcal{F}_z)$ are edges connecting the zones and corresponding to some on-going process or transformation. The sequence graph $\mathcal{G}_S = (\mathcal{S}, \mathcal{E}_s)$ represents a set of sequences $(\mathcal{S})$ that have areal changes or topological transformations defining the set of edges $(\mathcal{E}_s)$ of $\mathcal{G}_S$.

Similarly, we define a graph storing variations in trends of intensity. The intensity of a UHI can increase, decrease or remain stationary. A *chain* is defined as a series of zones where the intensity evolves according to a constant trend (Figure 3). Hence, a *chain* can be noted $c_n = \{z_n^i, \ldots, z_n^j\}$ where for any k in $[i+1, j]$, variations between $I(z_n^{k-1})$ and $I(z_n^k)$ are of the same kind, where $I(z)$ is the intensity of zone z, equaling to the mean value of the temperature differences. Thus, a new graph of chains is introduced: $\mathcal{G}_C = (\mathcal{C}, \mathcal{F}_C)$ where $\mathcal{C}$ is the set of chains and $\mathcal{F}_C$ the filiations between consecutive chains. As with periods, transitions between chains can be defined by:

- if $c_n^{i_{j-1}}$ increases and $c_n^{i_j}$ decreases, u_n reaches a *peak* at the transition;
- if $c_n^{i_{j-1}}$ decreases and $c_n^{i_j}$ increases, u_n reaches a *low* at the transition;
- if $c_n^{i_{j-1}}$, $c_n^{i_j}$, and $c_n^{i_{j+1}}$ respectively increases, stays stationary and decreases, chain $c_n^{i_j}$ corresponds to a plateau. u_n is *reaching a plateau* and *leaving a plateau* during the transitions;
- if $c_n^{i_{j-1}}$ decreases, $c_n^{i_j}$ keeps stationary, and $c_n^{i_{j+1}}$ increases, chain $c_n^{i_j}$ is as a floor. u_n is *reaching a floor* and *leaving a floor* during the transitions; and
- if both $c_n^{i_{j-1}}$ and $c_n^{i_{j+1}}$ increase or decrease and $c_n^{i_j}$ is stationary, chain $c_n^{i_j}$ represents a pause for the thematic evolution. The two consecutive transitions are *stabilization* and *resumption.*

A series of consecutive sequences or chains starting with an appearance and a disappearance form an *active period.* Similarly, an *inactive period* contains an empty sequence and is denoted as p_n^b so that an *awakened* connects with an empty sequence and generates another practical sequence. Thereby, all the periods can be refined into a graph $\mathcal{G}_P = (\mathcal{P}, \mathcal{E}_p)$ where $\mathcal{P}$ is the set of nodes denoting periods and $\mathcal{E}_p$ is the set of edges representing the state transitions between the periods. When several UHIs have interactive evolution in the same urban area or spatial contiguous city clusters, a graph can be introduced as $\mathcal{G}_U = (\mathcal{U}, \mathcal{E}_u)$, where $\mathcal{U}$ is a set of UHIs that makes the graph nodes and $\mathcal{E}_u$ is the edges composed by topological transformations which lead the creation and destruction of the UHIs. In summary, three hierarchical graphs have been proposed (Figure 4). Thematic filiations construct the chain-graph $\mathcal{G}_C$. $\mathcal{G}_P$ records complete life-cycle of a UHI which may have several consecutive periods associated with some particular transformations. Ultimately, all of the UHIs evolution can be finally tracked in $\mathcal{G}_U$.

2.3. Extraction of UHI changes

The change of a UHI was built up by studying overlapping zones at consecutive time instants. If two zones share a similar position, they are most likely belonging to the same UHI. Let z^i and z^{i-1} be two zones at consecutive time instants t_i and t_{i-1}. Two irrelevant zones may be associated if only considering the relation between the intersection $z^i \cap z^{i-1}$ and z^{i-1}, because UHIs remain at the same location and do not have significant displacements. Thus, it is more convincing if related zones have a significant intersection $z^i \cap z^{i-1}$ for both z^i and z^{i-1}.

Given two zones z and z', we consider that z significantly overlaps z' and we note it $SO(z, z')$ if both zones overlap and the area of their intersection is large enough concerning the area of z'. If we note $0 < \varepsilon < \frac{1}{2}$ being a constant, significant overlap is defined by:

$$SO(z, z') \Leftrightarrow \frac{\text{area}(z \cap z')}{\text{area}(z')} > 1 - \varepsilon \tag{1}$$

Fixing $\varepsilon < \frac{1}{2}$ guaranties that for a given zone z', it is not possible to find two disjoint zones significantly overlapping z'. This relation is not symmetric and the relation $SO(z', z)$ may be false, if z is much larger than z'. If both relations are true, both zones significantly overlap and we note this relation $OO(z, z')$ as

$$OO(z, z') \Leftrightarrow SO(z, z') \wedge SO(z', z) \tag{2}$$

Although a zone cannot be significantly overlapped by two disjoint zones, it can significantly overlap several zones. For a given set of zones Z, the set of all zones significantly overlapped by z is given by

$$S_Z(z) = \{SO(z, z') | z' \in Z\} \tag{3}$$

For a given zone z, the number of zones in $S_Z(z)$ is given by $\#S_Z(z)$. If Z is the set of all zones $\mathcal{Z}_i$ at time i, we simply note $S_{\mathcal{Z}_i}$ as S^i and its cardinality $\#S^i$. As zones at a given time instant are supposed to be disjoint, we have

$$z \in \mathcal{Z}_i, z' \in \mathcal{Z}_i \Rightarrow z \cap z' = \varnothing \tag{4}$$

$$z_1^i \in \mathcal{Z}_i, z_2^i \in \mathcal{Z}_i, z^j \in \mathcal{Z}_j \Rightarrow \neg \left(SO(z_1^i, z^j) \wedge SO(z_2^i, z^j)\right) \tag{5}$$

The type of spatial behavior of a UHI can be determined by the number of zones with which it is associated by the type of filiation with these zones. The UHI has (i) area change if it associates with only one zone and without any topological transformations, (ii) appearance or disappearance if no overlapping or no association occurs, or (iii) transformations when overlapping and associating with several other zones. Thus, spatial behaviors can be conceptualized as *expansion*, *continuation*, and *contraction* if z^i significantly overlaps one zone at t_{i-1}, and the area of z^i is larger, equivalent and smaller, respectively. In addition, z^i can have topological transformations as *appearance* if z^i has no significant overlap between any zones at t_{i-1}, and as *disappearance* if z^i has no significant overlap between any zones at t_{i+1}. The other two transformations may occur when more zones are associated:

- *merge*: z^i overlaps several zones at t_{i-1} and each overlapping area is significant to its corresponding zone at t_{i-1}. If only one overlapping area is exclusively significant to the zone at t_i, the associated zone at t_{i-1} continues as z^i with an *annexation*. Otherwise, a *merging* happens;
- *split*: several zones at t_i overlap at z^{i-1} and each overlapping area is significant to its corresponding zone at t_i. If area of z^{i-1} equals to one particular zone at t_i, a *separation* is derived. Otherwise, a *splitting* occurs.

2.4. Modeling spatial behaviors

We now can redefine the transitions between zones from their relationships. If a UHI does not undergo any transformation between time t_{i-1} and time t_i, then $\#S^i(z^{i-1})$ and $\#S^{i-1}(z^i)$ cannot be greater than 1. If no change in an area occurs, both zones significantly overlap such that $OO(z^{i-1}, z^i)$ is true. Hence for two zones $z^{i-1} \in \mathcal{Z}_{i-1}$ and $z^i \in \mathcal{Z}_i$, continuation is defined by

$$\text{continuation}(z^{i-1}, z^i) \Leftrightarrow OO(z^{i-1}, z^i) \wedge \#S^i(z^{i-1}) = 1 \wedge \#S^{i-1}(z^i) = 1 \tag{6}$$

In a contraction, z^{i-1} is bigger than z^i hence only $SO(z^{i-1}, z^i)$ is true. As a continuous process, no other zone is involved in the process. Therefore, the contraction is defined by

$$\text{contraction}(z^{i-1}, z^i) \Leftrightarrow SO(z^{i-1}, z^i) \wedge \#S^i(z^{i-1}) = 0 \wedge \#S^{i-1}(z^i) = 1 \tag{7}$$

Similarly, the expansion is defined by

$$\text{expansion}(z^{i-1}, z^i) \Leftrightarrow SO(z^i, z^{i-1}) \wedge \#S^i(z^{i-1}) = 1 \wedge \#S^{i-1}(z^i) = 0 \tag{8}$$

Referring to Figure 2, a process (more specifically for an area change) is a relationship involving a limited number of zones. Anything that is not a process can then be defined as a transformation. The above three relationships correspond to processes where no topological change occurs. A more general relation can be defined relating two consecutive zones that are parts of a continuing process.

$$\text{process}(z^{i-1}, z^i) \Leftrightarrow \big(SO(z^{i-1}, z^i) \vee SO(z^i, z^{i-1})\big) \wedge \max\big(\#S^i(z^{i-1}), \#S^{i-1}(z^i)\big) = 1 \tag{9}$$

Transformations can involve several zones as different UHIs may be engaged. For example, a merge involves a set of zones $Z = \{z_1^{i-1}, \ldots, z_m^{i-1}\} \subset \mathcal{Z}_{i-1}$ and one zone $z^i \in \mathcal{Z}_i$. The zone z^i has to significantly overlap all the zones of Z. On the opposite, no zone of $\mathcal{Z}_{i-1}$ significantly overlaps z^i.

$$\text{merging}(Z, z^i) \Leftrightarrow \big(S^{i-1}(z^i)\big) \wedge \big(\forall z \in \mathcal{Z}_{i-1}, \neg SO(z, z^i)\big) \tag{10}$$

In the case where another zone $z_0^{i-1} \in \mathcal{Z}_{i-1}$ significantly overlaps z^i, we have an annexation instead of a merge.

$$\text{annexation}(z_0^{i-1}, Z, z^i) \Leftrightarrow \big(S^{i-1}(z^i)\big) \wedge \big(\forall z \in Z, \neg SO(z, z^i)\big) \wedge SO(z_0^{i-1}, z^i) \tag{11}$$

The other way around, one zone z^{i-1} at t_{i-1} overlapping a set of zones $Z = \{z_1^i, \ldots, z_m^i\} \subset \mathcal{Z}_i$ at t_i corresponds to a split. This requires that z^{i-1} significantly overlaps all the zones of Z while no zone overlaps z^{i-1} significantly.

$$\text{splitting}(z^{i-1}, Z) \Leftrightarrow \big(S^i(z^{i-1})\big) \wedge \big(\forall z \in \mathcal{Z}_i, \neg SO(z, z^{i-1})\big) \tag{12}$$

Instead, a separation occurs if one zone z_0^i significantly overlaps z^{i-1}.

$$\text{separation}(z^{i-1}, Z, z_0^i) \Leftrightarrow \big(S^i(z^{i-1})\big) \wedge \big(\forall z \in Z, \neg SO(z, z^{i-1})\big) \wedge SO(z_0^i, z^{i-1}) \tag{13}$$

Finally, a zone $z^i \in \mathcal{Z}_i$ can appear or disappear at time t_i. In the first case, it is not related to any zone in $\mathcal{Z}_{i-1}$, in the second case, it is not be related to any zone in $\mathcal{Z}_{i+1}$.

$$\text{appearance}(z^i) \Leftrightarrow \forall z \in \mathcal{Z}_{i-1}, \neg\big(SO(z, z^i) \vee SO(z^i, z)\big) \tag{14}$$

$$\text{disappearance}(z^i) \Leftrightarrow \forall z \in \mathcal{Z}_{i+1}, \neg\big(SO(z, z^i) \vee SO(z^i, z)\big) \tag{15}$$

Zones would have different spatial behaviors when their overlaps are in different scenarios. For example, if $SO(z_b, z_c)$ and $SO(z_b, z_a)$ are true, it's a merge. With a different epsilon $SO(z_b, z_c)$ and $SO(z_a, z_b)$, an annexation could be obtained (Figure 6). We may also have $SO(z_a, z_d)$, which leads to a split. In this case, z_a would have a special behavior, combining a split and a merge at the same time.

2.5. Modeling thematic behaviors

Studying thematic behaviors is done by measuring the evolution of intensity through time. From one instant to the next, it can *increase*, *decrease* or remain *stationary*. Indeed, if the intensity remains within a limited range, it reasonable to consider it is *stationary*.

$$\text{decrease}(z^{i-1}, z^i) \Leftrightarrow I(z^{i-1}) - I(z^i) > \varepsilon \tag{16}$$

$$\text{increase}(z^{i-1}, z^i) \Leftrightarrow I(z^i) - I(z^{i-1}) > \varepsilon \tag{17}$$

$$\text{stationary}(z^{i-1}, z^i) \Leftrightarrow |I(z^{i-1}) - I(z^i)| < \varepsilon \tag{18}$$

2.6. Modeling consecutive active-periods

Determination of two consecutive active periods connected by an inactive period is a necessity to construct a UHI. As conceptualized above, z^i could either derive a creation if it is newly generated or an activation if it has already existed. When z^i appears, a retrospective trace will check whether there was a disappeared z^{i-x} at the same location. Two active periods can be connected if (z^{i-x}, z^i) are spatially associated.

$$\text{consecutive}(p_n, p'_n) \Leftrightarrow \big(\text{process}(z^{i-x}, z^i) \wedge (x \geqslant 2)\big) \wedge \big(\neg\text{process}(z^{i-y}, z^i) \wedge (\forall y < x)\big) \tag{19}$$

3. Empirical evaluation

3.1. Study area and pre-processing

Guangzhou, located in the humid subtropical climate, is one of the most urbanized cities in China and has a population over 13 billion. It has high temperatures throughout the year. Since the model requires high temporal resolution of the data set to track changes of UHIs continuously, hourly updated near-surface (approximately 1.5 meters above land surface) air temperatures were measured in 216 automatic weather stations (Figure 5), 159 of which were located in the urban area of 3660 km^2 in size. Major stations in urban areas were on concrete surfaces besides roads and/or buildings. To analyze evolutionary trends of UHIs over a long time, data were collected during a long time in the year 2015 with an interval of 21 days between every two weeks, from July 31 to August 6, August 28 to September 3, September 25 to October 1, October 23 to October 29, November 20 to November 26, and December 18 to December 24.

To obtain a series of temperature images from the weather stations, an interpolation method of Universal Kriging was used as the method can highlight "hotspot" regions of UHIs supposing the input data set which contains an overriding trend (Chai *et al.*, 2011; Hofstra *et al.*, 2008; Irmak *et al.*, 2010; Stahl *et al.*, 2006). Since weekly-averaged root mean square errors of the six sequential weeks were 1.06 °C, 0.99 °C, 1.13 °C, 1.06 °C, 1.07 °C, and 1.03 °C, the magnitude m should be notably larger than 1 °C to extract zones of UHIs confidently. Temperatures observed as the red star symbol in Figure 5 were recorded in the Dajinfeng Eco-scenic Park which is a forestry area close to urban areas so they can represent as rural temperatures confidently to extract zones of UHIs and will not be affected by the heat dispersed from urban areas. Also, several other rural stations have lower temperatures so

SQL 1 FUNCTION ActivePeriod()

```
1 INSERT INTO period(pid, t_s, czid, pzid, spb, thb)
2 SELECT max(path) AS path, per.t_s, per.czid, per.pzid, per.spb, per.thb
3 FROM  (WITH RECURSIVE per_u(path, t_s, czid, pzid, spb, thb)
4        AS  (SELECT row_number() OVER (ORDER BY t_s) AS path, root.t_s,
5                    root.czid, root.pzid, root.spb, root.thb
6             FROM   behavior AS root UNION
7             SELECT leaf.path, root.t_s, root.czid, root.pzid, root.spb, root.thb
8             FROM   behavior AS root, per_u AS leaf
9             WHERE  root.czid = leaf.pzid
10            AND    leaf.pzid > 0 AND leaf.spat_beh <> 'separa_d_obj'
11            AND    root.spb <> 'annexa_d_obj'
12            AND    root.spb <> 'merging' AND root.spat_beh <> 'splitting')
13       SELECT * FROM per_u ORDER BY path, t_s) AS per
14 GROUP BY per.t_s, per.czid, per.pzid, per.spb, per.thb;
```

that rural areas may be included as part of a UHI if these stations are used. Therefore, only one rural station was used as the reference of rural temperatures to extract zones of UHIs.

3.2. System Implementation

The model has been implemented in PostgreSQL 10 to simulate behaviors and to track their changes during the complete life-cycles of UHIs. A UML model is presented in Figure 7, which summaries the classes as discrete records in tables and represents their associations. First, a time series of temperature images generated hourly from air temperatures are compiled in a set of `image` tables. Hence, all the zones are extracted from temperature images, and their spatial and thematic information is tabulated in the `zone` table. For example, each row records a unique zone identified by its ID (`zid`), which exists as a single polygon (`shape`) at a timestamp (`t_s`). Temperatures in the `shape` are at least with a magnitude (`m`) higher than the reference rural temperature (`rural_t`). Particularly, four types of thermal intensities are also summarized (`max_t`, `min_t`, `mea_t`, and `mod_t`). In order to determine filiation relations between zones, overlapping areas (`overlap_area`) of zones at the current instant (`czid`) and zones in the previous instant (`pzid`) should be calculated in advance. To avoid duplicate calculation, zones with area changes and topological transformations are classified into three tables (`merge`, `split`, and `area_change`) such that the `behavior` table can be built as the central domain to describe two types of behaviors (`spb` and `thb`) at each timestamp (`t_s`). Thus, UHIs (`oid`) can be constructed in the `uhi` table, and each UHI can have one or several periods (`pid`), and each period combines a time serial of spatial behaviors determined by thematic behaviors. Simultaneously, sequence and process descriptions for spatial behaviors (`spid`) and thematic behaviors (`cid`) are obtained, and their corresponding patterns (`spp` and `thp`) are finally shown.

It is necessary to identify topological relations associated with zones that can create and destroy an active period (SQL 1). It is also vital to connect active periods that belong to the same UHI by determining awakened zones that trigger new periods (SQL 2). In SQL 1, lines 4-6 generate serial numbers as candidates of period IDs and determine the first zone behavior (i.e. named as `root`) in the periods. Lines 7-12 build continual zone behaviors that extend from the roots (i.e. named as `leaf`). More specifically, line 9 connects the leaves to the root. Line 10 avoids endless loop computation by ensuring that the appearance and disappearance behaviors are included in the period, and generates new periods when zones are separated as different objects. Lines 11-12 cut off the extension of leaves when zones are destroyed. Lastly, lines 3-13 execute the recursive computation and lines 2-14 select the maximum value of path used as the final period ID. In SQL 2, lines 5-6 and 7-8 list zones having *appearance* as the head and *disappearance* as the tail respectively, where time interval between them is more than two hours but no longer than the maximum awakened time (lines 9-10). Thus, pairs

SQL 2 FUNCTION Awake(sleep_t, min_r, min_rein)

```
1 INSERT INTO awake(disappeared_zid, appeared_zid)
2 SELECT tail_seq.zid AS disap_z, head_seq.zid AS reapp_z,
3       (head_seq.t_s - tail_seq.t_s) AS dth_t,
4        ST_Area(ST_Intersection(head_seq.geom, tail_seq.geom)) AS i_a
5 FROM  (SELECT zone.* FROM zone, period
6        WHERE  spb = ‘appearance’ AND zone.zid = period.czid) AS head_seq,
7       (SELECT zone.* FROM zone, period
8        WHERE  spb = ‘disappearance’ AND zone.zid = period.pzid) AS tail_seq
9 WHERE  head_seq.t_s - tail_seq.t_s <= sleep_t * 3600 * ‘1 second’::INTERVAL
10 AND   head_seq.t_s - tail_seq.t_s >= 2 * 3600 * ‘1 second’::INTERVAL
11 AND   ST_Area(ST_Intersection(head_seq.geom, tail_seq.geom))/ST_Area(head_seq.geom) >= min_r
12 AND   ST_Area(ST_Intersection(head_seq.geom, tail_seq.geom))/ST_Area(tail_seq.geom) >= min_r
13 AND   ST_Area(ST_Intersection(head_seq.geom, tail_seq.geom))/ST_Area(head_seq.geom) >= min_rein;

14 INSERT INTO awake(disappeared_zid, appeared_zid)
15 SELECT cand.disap_z, cand.reapp_z
16 FROM   awakened_cand AS cand,
17       (SELECT cand.reapp_z, min(cand.dth_t) AS min_dth_t
18        FROM   awakened_cand AS cand,
19              (SELECT min(dth_t) AS min_dth_t, disap_z
20               FROM   awakened_cand GROUP BY disap_z) AS dth_cand,
21              (SELECT max(i_a) AS max_i_a, dth_t, disap_z
22               FROM   awakened_cand GROUP BY disap_z, dth_t) AS ints_cand
23        WHERE dth_cand.min_dth_t = cand.dth_t AND dth_cand.disap_z = cand.disap_z
24        AND   ints_cand.max_i_a = cand.i_a AND ints_cand.disap_z = cand.disap_z
25        AND   dth_cand.disap_z = ints_cand.disap_z GROUP BY cand.reapp_z) AS uhi_cand
26 WHERE  cand.reapp_z = uhi_cand.reapp_z
27 AND    cand.dth_t = uhi_cand.min_dth_t;
```

of the heads and tails that satisfy the awakened condition (lines 11-13) are selected as the awakened candidates (lines 2-3). However, several disappeared zones can map to the same appeared zone in the awakened candidates. On the basis of the candidates which have the minimum sleeping time (lines 19-20), zones having the maximum overlapping area are selected (lines 21-22) from the records of awakened candidates (lines 23-25). Finally, zones satisfying all the conditions are inserted into the awake table (lines 14-27).

3.3. Results

3.3.1. Dynamic behaviors of UHIs

Figure 8 presents seven consecutive days of the intensities (i.e. the mean value of temperature differences at each time instant) in five different magnitudes. Intensities (m = 1 °C) lasting almost all the time and suggesting that m = 1 °C cannot distinguish temperature difference effectively. It proves that zones of UHIs should be with m > 1 °C, as suggested in Section 3.1. Over seven days, intensities for each magnitude increased gradually accompanying the fact that reference rural temperature also increased from 27.6 °C to 29.2 °C. This reveals that air temperatures in urban areas increase faster than those of the reference rural temperature in this time period, suggesting a typical UHI phenomenon during the summer time. The figure also shows that intensities having a larger m were more stable and with shorter *active* period. For example, the highest peak of the intensities occurred in the mid-night on August 5 when m = 2 °C, while the peak was faded when m = 5 °C. This suggests that a small m would help to describe the overall evolutionary trend of UHIs while a large one could be able to locate stable heat sources of UHIs.

Based on the above statistics, Figure 9 draws UHIs in three magnitudes and presents behaviors of three UHIs queried in the `uhi` table, with object IDs (the `oid` column) equalling to 15 (m=2 °C), 17 (m=3 °C), and 10091 (m=4 °C). It shows that the UHI having the largest magnitude contracted insignificantly without any topological transformation and the intensity was stationary throughout the night. Since this UHI was located in the densest urban area of Guangzhou, it can be formed by many factors, such as heat exhaust of factories and vehicles, the release of household energy, and heat storage from building infrastructures, so that they can release the heat continuously and stably at night-time. Correspondingly, the UHI having a moderate magnitude contracted by separating several parts from its origin continuously and the intensity decreased gradually. New UHIs occurred from the separation simultaneously. It can be found that urban temperatures out of the downtown area decreased faster than that of the reference rural temperature, leading to a decrease of the intensity and contraction of the zone during the night from 2 am to 4 am. Then, the air started to accumulate heat at dawn from 5 am to 6 am so that air temperatures increased faster than that of the reference rural temperature, making expansion and merging. Lastly, UHIs contracted and disappeared when the sun rises at 7 am because the reference rural temperature has been increased faster and temperature differences have been smaller than m=3 °C. In contrast, the UHI having the smallest magnitude expanded gradually before dawn but contracted dramatically at dawn, and finally disappeared in the early morning. The intensity had a contrary evolutionary trend, which decreased and then increased following by the other decrease during the same corresponding time. It suggests that UHIs in different magnitudes have different evolutions.

Additionally, a UHI can exist throughout several periods (i.e. two active periods are connected by an inactive period in the `pid` column) as presented in Figure 9. It means that the UHI can either reappear in the next day (for the UHI with `oid`=15) or in several days (for the UHI with `oid`=17). This reveals that UHIs have periodicities and demonstrates that the proposed model can track evolutions of UHIs over a longer time compared with previous models, with the establishing of the periodicity.

3.3.2. Thematic evolution of UHIs

To find out evolutionary trends of UHIs over seasons, the study investigated into changes of UHIs in six weeks covering a continuous period of six months from July to December in 2015 (Figure 10). It shows that UHIs mostly happened and were the most significant at night. However, an entirely different phenomenon is found that UHIs were the most significant at noon on September 30, October 27 and November 25. This abnormal phenomenon always occurred with a dramatic decrease of the reference rural temperatures when it was sunny on the previous day and it was raining or cloudy on the current day. It can be explained that heat accumulated on the previous day could not disperse immediately at night because of the thermal insulation contributed by the urban canopy, i.e., rain-rich clouds obstructed the spread of heat. Thus, heat accumulated on the previous day gradually releases on the next day, and the UHI could become more obviously contributed by anthropogenic heat fluxes (e.g. heat emission from vehicles) in the daytime.

Some findings can also be revealed in Figure 10. UHIs usually occur at night and UHIs with larger magnitudes are more stable with a shorter active periods. However, intensities at dense urban areas (m=4 °C) can grow dramatically and reach up to 5.5 °C at dawn on September 25 and November 23, making them extremely significant. This phenomenon is always accompanied by clear sky at night followed by sunshine at dawn. This suggests that continuously clear sky would likely generate significant UHIs. It can be explained that dense urban areas can release a larger amount of heat speedily at night with a clear sky so that air temperatures in urban areas can increase much faster at dawn even though reference rural temperatures increase dramatically. Oppositely, UHIs were insignificant and even could not happen when amplitudes of the reference rural temperatures became much smaller between December 20 and December 23, caused by thick fogs all over the days. A similar phenomenon occurred between August 28 and September 3 that UHIs were short and insignificant over the whole week. However, the mechanism is different, because the heat was dispersed by a rainstorm lasting for the whole week and clouds obstructed absorption of solar radiation fluxes from the land surface. Moreover, continuous raining (e.g. days between August 28 and September 03) and fogs (e.g. days between December 20 and December 23) could obstruct the occurrence of UHIs. Apparently observed from these weathers, daily duration and intensities of UHIs were almost the same from summer to winter, disregarding the seasonal difference.

3.3.3. Relationship of UHIs in different magnitudes

According to the proposed UHI definition, a UHI in a small magnitude would be more likely to occur within a large zone, so that zones with a large magnitude can locate in the same zone with a small magnitude. Based on the evidence that small and dense urban areas can accumulate great amount of heat from solar heat fluxes (Nichol *et al.*, 2009) and anthropogenic heat fluxes (Zhu *et al.*, 2017b), there are reasons to believe that dense urban area could be the largest heat resource in a city. Thus, correlation analysis between areas of zones in the same instant but in different magnitudes would help to explore the relationship of UHIs in different magnitudes.

Total areas of UHIs in three magnitudes (m=2, 3, 4 °C) were computed through SQL queries and then correlations of the total areas between m=3, 4 °C (Figure 11) and between m=2, 4 °C (Figure 12) were computed respectively by using R^2. Overall, R^2=0.78 for m=3, 4 °C and R^2=0.59 for m=2, 4 °C for six weeks totally. Both cases show positive correlations. These two figures also represent that total area of UHIs were several times (for m=3 °C) to dozens of times (for m=2 °C) larger those that in a large magnitude (m=4 °C).

Particularly, all the values of R^2 for m=3, 4 °C were larger than 0.80 except for those during seven days between September 25 and October 01 (Figure 11). These values show strong and positive correlations. Two reasons can be discussed. First, dense urban areas determined the evolution of UHIs when m=4 °C, since the urban areas and zones of the UHIs had significant overlapping most of the time. Second, a great amount of the heat generated in small and dense urban areas could diffuse to large and low-density urban areas through air thermal diffusion. This process fundamentally affected thermal distribution in low-density urban areas and thus made merging and annexation between zones, as what has been obtained and presented in Figure 9. This reasoning can explain why strong and positive correlations could be shown between areas of zones. Therefore, UHIs in a large magnitude (m=4 °C) could overwhelmingly influence evolution of UHIs in a small magnitude (m=3 °C).

Additionally, the influence could extend across different seasons because $R^2 \geqslant$0.80 maintained from August to December basically. It is a weak and positive correlation (R^2=0.43) in the period between September 25 and October 01. Given the fact that the weather has been changing a lot during these days, i.e., fogs, clouds, and sunshine were mixed due to different meteorological conditions, it can be deduced that unstable weather can impede heat absorption and thermal diffusion notably, leading to the disappearance of UHIs.

Even though all the values of R^2 for m=2,4 °C (Figure 12) were smaller than those for m=3,4 °C (Figure 11), all of them show a positive correlation. Surprisingly, strong and positive correlations remained ($R^2 \geqslant$0.70) between July 31 and August 01, October 23 and October 29, and December 18 and December 24 for UHIs in m=2,4 °C. It can be explained that heat from small and dense urban areas still could influence the evolution of UHIs, spreading into much larger areas in mixed urban-and-rural regions.

4. Discussion and conclusion

This study established an object-oriented data model organized by graphing in three hierarchies. The model allows tracking of thematic and spatial behaviors of UHIs. Instead of focusing on numeric air temperatures of UHIs, this study proposed the concept of *intensity* as the statistics of temperature differences between urban temperatures and reference rural temperatures to build a model of different behaviors.

A UHI has a *magnitude* to maintain its significance and each one may experience several transitions between active and inactive periods, which breaks the traditional bondage of tracking UHIs in discrete days and allows a continuous tracking over days, weeks, and even seasons. UHIs at different magnitudes may build inclusive relationships with each other. It means that a large UHI may contain several small UHIs with a large magnitude. As such, the small UHIs would experience active and inactive transitions when the large UHI is active, while the disappearance of the large UHI would lead to the disappearance of all small ones.

A simple and effective criterion to test the reliability of the model is set on a concept that each zone has only one behavior at each time instant (no duplicate or undetermined behaviors). The model has been evaluated through a set of input parameters and a complete set of six-weeks data. Several technologies were used in the database management system to accelerate the computation, such as creating indices in spatial and non-spatial columns, tabulating intermediate data maintained in RAMs, and creating a new table to replace an existing one instead of making UPDATE queries. Through these optimizations, computing all the behaviors and establishing all the proposed graphs require about around three minutes.

This study has two limitations. First, the spatial density of the stations is not high enough so that micro-changes at the street-block level are difficult to be detected. Second, a UHI undergoes either topological transformation or areal change at each time instant. However, an existing UHI shall have both spatial and thematic properties all the time so that correlations between areas and temperatures for UHIs can be determined continuously. In this consideration, future work can allow a UHI to have areal change and topological transformation at a time instant if the UHI is still active. This study omitted displacements of UHIs as most of them are locationally static. Future work can incorporate this model into other geographical phenomena with obvious displacements, such as water pollutions. Hence, the model has to be improved in a more sophisticated scenario.

Four important findings in this study can be summarized, and they suggest the effectiveness of the model. Firstly, clear sky at night connecting sunshine at dawn can promote the occurence of UHIs of extremely high intensities at dawn. Secondly, UHIs in a specific magnitude could maintain their intensities during the daytime not only in summer but also across winter without the influence of rainy and foggy weather. Thirdly, UHIs normally occur at night across different seasons, while they can also be very significant at noon because of a sunny-to-rainy/cloudy weather in two consecutive days. Lastly, UHIs in a larger magnitude are more readily associated in locations with smaller spatial extents and shorter duration of active periods.

To sum up, two conclusions can be drawn. First, the model has four originalities: a new definition for investigating into UHIs in different significances, a new transition between active and inactive periods to extend the life span of UHIs, a new concept of UHI-graph to track dynamics of UHIs, and a new method to compute spatial behaviors confidently. Second, based on a well designed and implemented database management system, the empirical evaluation suggests that the proposed model can process a large set of images and can allow queries to explore evolutions and characteristics of UHIs effectively.

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References

Bothwell, J., & Yuan, M. (2010). Apply concepts of fluid kinematics to represent continuous space–time fields in temporal GIS. *Annals of GIS*, 16(1), 27–41.

Bothwell, J., & Yuan, M. (2011). A Kinematics-based GIS Methodology to Represent and Analyze Spatiotemporal Patterns of Precipitation Change in IPCC A2 Scenario. *ACM SIGSPATIAL GIS '11*, 152–161.

Bothwell, J., & Yuan, M. (2012). A Spatiotemporal GIS Framework Applied to the Analysis of Changes in Temperature Patterns. *Transactions in GIS*, 16(6), 901–919.

Buyantuyev, A., & Wu, J. (2010). Urban heat islands and landscape heterogeneity: linking spatiotemporal variations in surface temperatures to land-cover and socioeconomic patterns. *Landscape Ecology*, 25(1), 17–33.

Claramunt C., & Thériault M. (1995). Managing Time in GIS: An Event-Oriented Approach. *Proceedings of the International Workshop on Temporal Databases: Recent Advances in Temporal Databases*, 23–42.

Cohn, E. G., & Rotton, J. (2000). Weather, seasonal trends and property crimes in Minneapolis, 1987-1988. A moderator-variable time-series analysis of routine activities. *Journal of Environmental Psychology*, 20(3), 257–272.

Chai, H. X., Cheng, W. M., Zhou, C. Q., Chen, X., Ma, X. Y., & Zhao, S. M. (2011). Analysis and comparison of spatial interpolation methods for temperature data in Xinjiang Uygur Autonomous Region, China. *Natural Science*, 3(12), 999–1010.

Del Mondo, G., Rodríguez, M. A., Claramunt, C., Bravo, L., & Thibaud, R. (2013). Modelling Consistency of Spatio-temporal Graphs, *Data & Knowledge Engineering, Elsevier*, 84(1), 59–80.

Ding, Z., Guo, P., Xie, F., & et al. (2015). Impact of diurnal temperature range on mortality in a high plateau area in southwest China: A time series analysis. *Science of the Total Environment*, 526, 358–365.

Field, S. (1992). The effect of temperature on crime. *British Journal of Criminology*, 32(3), 340–351.

Fung, W. Y., Lam, K. S., Hung, W. T., Pang, S. W., & Lee, Y. L. (2006). Impact of urban temperature on energy consumption of Hong Kong. *Energy*, 31(14), 2623–2637.

Goodchild M. F., Yuan M., & Cova T. J. (2007). Towards a general theory of geographic representation in GIS. *International Journal of Geographical Information Science*, 21(3), 239–260.

Hua, L. and Wang, M., 2012. Temporal and spatial characteristics of urban heat island of an estuary city, China. Journal of Computers, 7(12), 3082–3087.

Hornsby K., & Egenhofer M. J. (2000). Identity-based change: a foundation for spatio-temporal knowledge representation. *International Journal of Geographical Information Science*, 14(3), 207–224.

Hornsby, K. S., & Cole, S. (2007). Modeling Moving Geospatial Objects from an Event-based Perspective. *Transactions in GIS*, 11(4), 555–573.

Hofstra, N., Haylock, M., New M., Jones, P., & Frei, C. (2008). Comparison of six methods for the interpolation of daily, European climate data. *Journal of Geographical Research*, 113, D21110. doi:10.1029/2008JD010100

Hu. L., & Brunsell, N. A. (2015). A new perspective to assess the urban heat island through remotely sensed atmospheric profiles. *Remote Sensing of Environment*, 158, 393–406.

Irmak, A., Ranade, P. K., Marx, D., Irmak, S., Hubbard, K. G., Meyer, G. E., & Martin, D. L. (2010). Spatial Interpolation of climate variables in Nebraska. *Transactions of the ASABE*, 53(6), 1759–1771.

Jalan, S. and Sharma, K., 2014. Spatio-temporal assessment of land use/land cover dynamics and urban heat island of Jaipur city using satellite data. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XL(8), 767–772.

Keramitsoglou, I., Kiranoudis, C. T., Ceriola, G., Weng, Q., & Rajasekar, U. (2011). Identification and analysis of urban surface temperature patterns in Greater Athens, Greece, using MODIS imagery. *Remote Sensing of Environment*, 115(12), 3080–3090.

Kenney, W. L., Craighead, D. H., & Alexander, L. M. (2014). Heat Waves, Aging, and Human Cardiovascular Health. *Medicine & Science in Sports & Exercise*, 46(10), 1891–1899.

Kourtidis, K., Georgoulias, A. K., Rapsomanikis, S., Amiridis, V., Keramitsoglou, I., Hooyberghs, H., Maiheu, B., & Melas, D. (2015). A study of the hourly variability of the urban heat island effect in the Greater Athens Area during summer. *Science of the Total Environment*, 517, 162–177.

Li, J., Liang, Y., & Wan, J. (2013). Geo-Ontology-Based Object-Oriented Spatiotemporal Data Modeling. *Lecture Notes in Computer Science*, 7719, 302–317.

McIntosh, J., & Yuan, M. (2005). Assessing Similarity of Geographic Processes and Events. *Transactions in GIS*, 9(2), 223–245.

Morabito, M., Crisci, A., & Moriondo, M. (2012). Air temperature-related human health outcomes: Current impact and estimations of future risks in Central Italy. *Science of the Total Environment*, 441, 28–40.

Nichol, J. E., Fung, W. Y., Lam K. S., & Wong, M. S. (2009). Urban heat island diagnosis using ASTER satellite images and 'in situ' air temperature. *Atmospheric Research*, 94(2), 276–284.

Nixon, V., & Hornsby, K. S. (2010). Using geolifespans to model dynamic geographic domains. *International Journal of Geographical Information Science*, 24(9), 1289–1308.

Pultar, E., Cova, T. J., Yuan, M., & Goodchild, M .F. (2010). EDGIS: a dynamic GIS based on space time points. *International Journal of Geographical Information Science*, 24(3), 329–346.

Papakostas, K., Mavromatis, T., & Kyriakis, N. (2010). Impact of the ambient temperature rise on the energy consumption for heating and cooling in residential buildings of Greece. *Renewable Energy*, 35(7), 1376–1379.

Renolen, A. (2000). Modelling the Real World: Conceptual Modelling in Spatiotemporal Information System Design. *Transactions in GIS*, 4(1), 23–42.

Rotton, J., & Cohn, E. G. (2004). Outdoor temperature, climate control, and criminal assault. *Environment and Behaivor*, 36(2), 276–306.

Stahl, K., Moore, R. D., Floyer, J. A., Asplin, M. G., & McKendry, I. G. (2006). Comparison of approaches for spatial interpolation of daily air temperature in a large region with complex topography and highly variable station density. *Agricultural and Forest Meteorology*, 139, 224–236.

Toparlar, Y., Blocken, B., Vos, P., Heijst, G. J. F., Janssen, W. D., Hooff, T., Montazeri, H., & Immermans, H. J. P. (2015). CFD simulation and validation of urban microclimate: A case study for Bergpolder Zuid, Rotterdam. *Building and Environment*, 83, 79–90.

Wong, M. S., & Nichol, J. E. (2013). Spatial variability of frontal area index and its relationship with urban heat island intensity. *International Journal of Remote Sensing*, 34(3), 885–896.

Wong, M. S., Zhu, R., Liu, Z., Lu, L., Peng, J., Tang, Z., Lo, C. H., & Chan, W. K. (2016). Estimation of Hong Kong's solar energy potential using GIS and remote sensing technologies. Renewable Energy, 99, 325–335.

Wu, F., Wang, X., Cai, Y., Yang, Z., & Li, C. (2012). Spatiotemporal analysis of temperature-variation patterns under climate change in the upper reach of Mekong River basin. *Science of the Total Environment*, 427-428, 208–218.

Yuan, M., & Hornsby, K. (2008). *Computation and Visualization for Understanding Dynamics in Geographic Domains*. CRC Press.

Yuan, C., & Ng. E. (2012). Building porosity for better urban ventilation in high-density cities - A computational parametric study. *Building and Environment*, 50, 176–189.

Zhou, B., Kropp, J., & Rybski, D. (2016). Assessing Seasonality in the Surface Urban Heat Island of London. *Journal of Applied Meteorology and Climatology*, 55, 493–505.

Zhu, R., Guilbert, E., & Wong, M.S. (2017a). Object-oriented tracking of the dynamic behavior of urban heat islands. *International Journal of Geographical Information Science*, 31(2), 405–424.

Zhu, R., Wong, M. S., Guilbert, E., & Chan, P. W. (2017b). Understanding heat patterns produced by vehicular flows in urban areas. *Scientific Reports*, 7, 16309.

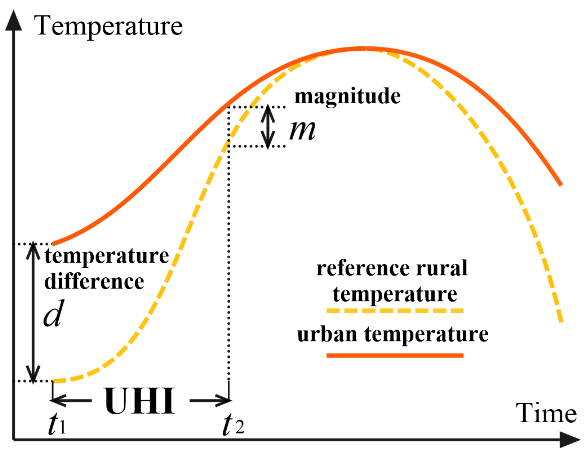


Figure 1: A UHI is with at least m degrees Celsius higher than the reference rural air temperature.

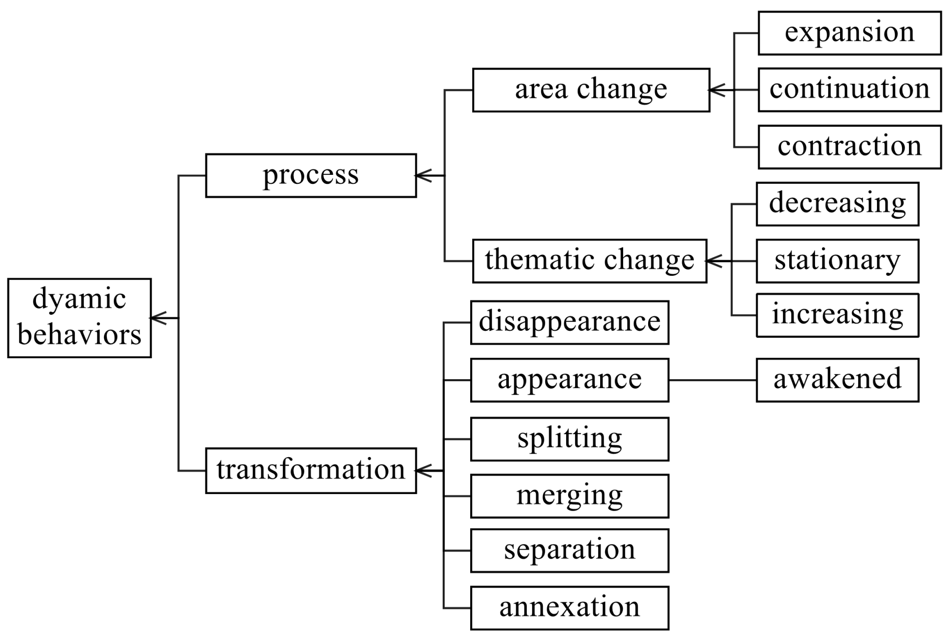


Figure 2: A hierarchical set of dynamic behaviors of UHIs.

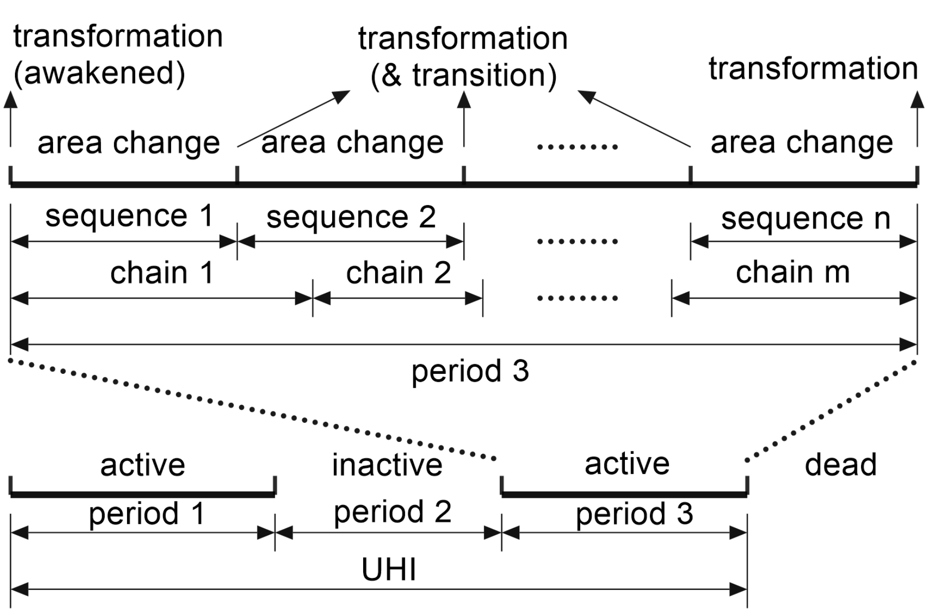


Figure 3: Complete life-cycle of a UHI. An active period contains a series of sequences and chains over a period, in which a sequence is made by a type of spatial behavior associated with transformations and chains correspond to thematic changes.

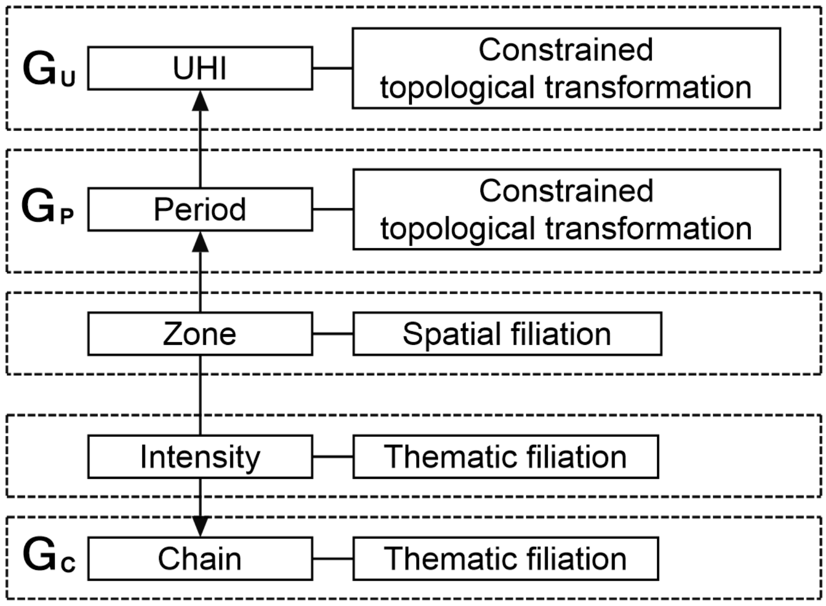


Figure 4: Three hierarchical graphs for UHIs.

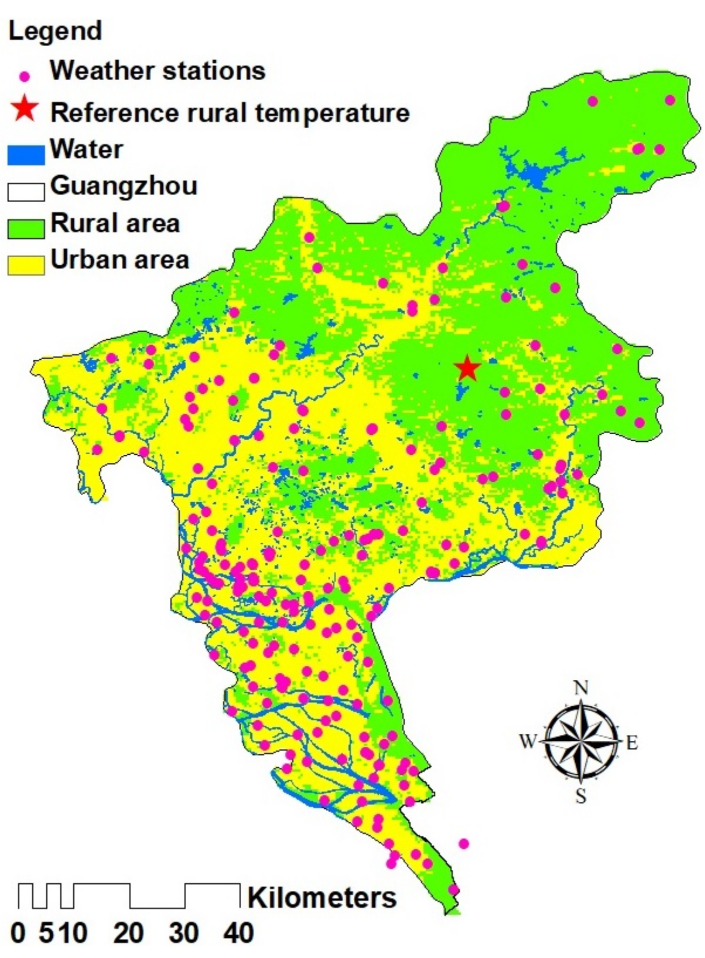


Figure 5: Weather stations are dominantly located in the urban areas of Guangzhou.

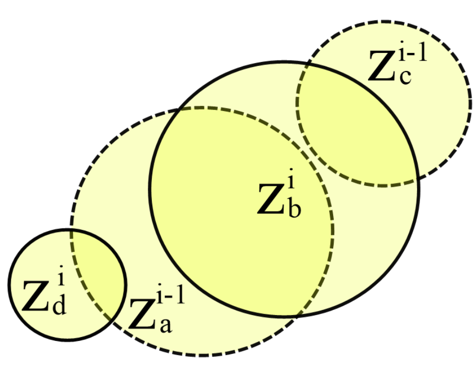


Figure 6: Different overlapping scenarios generate different spatial behaviors.

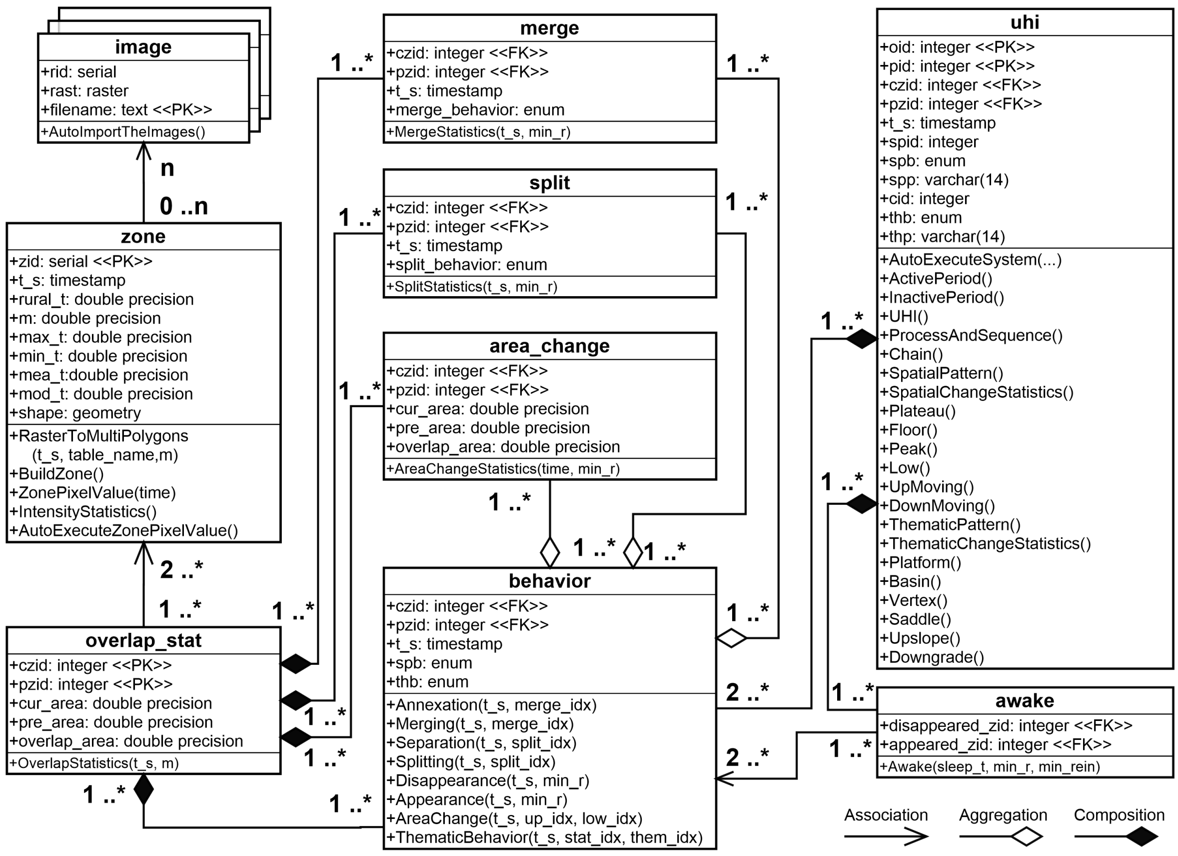


Figure 7: A UML model to present database tables, functions, and their associations and generations for tracking spatial and thematic behaviors of UHIs over time.

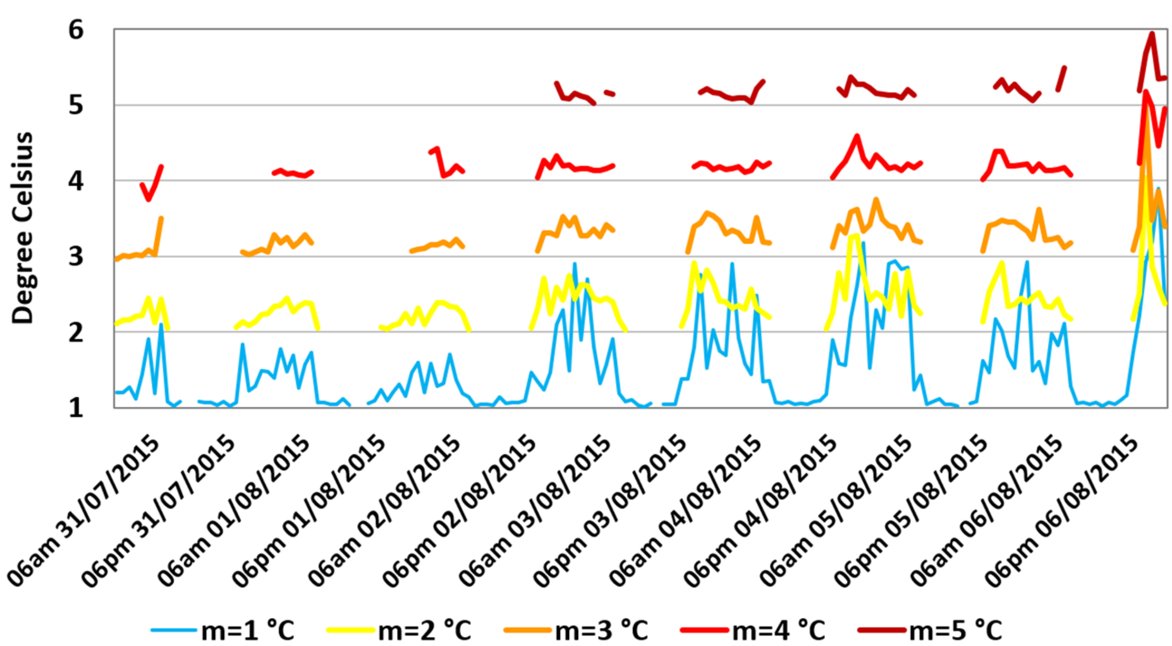
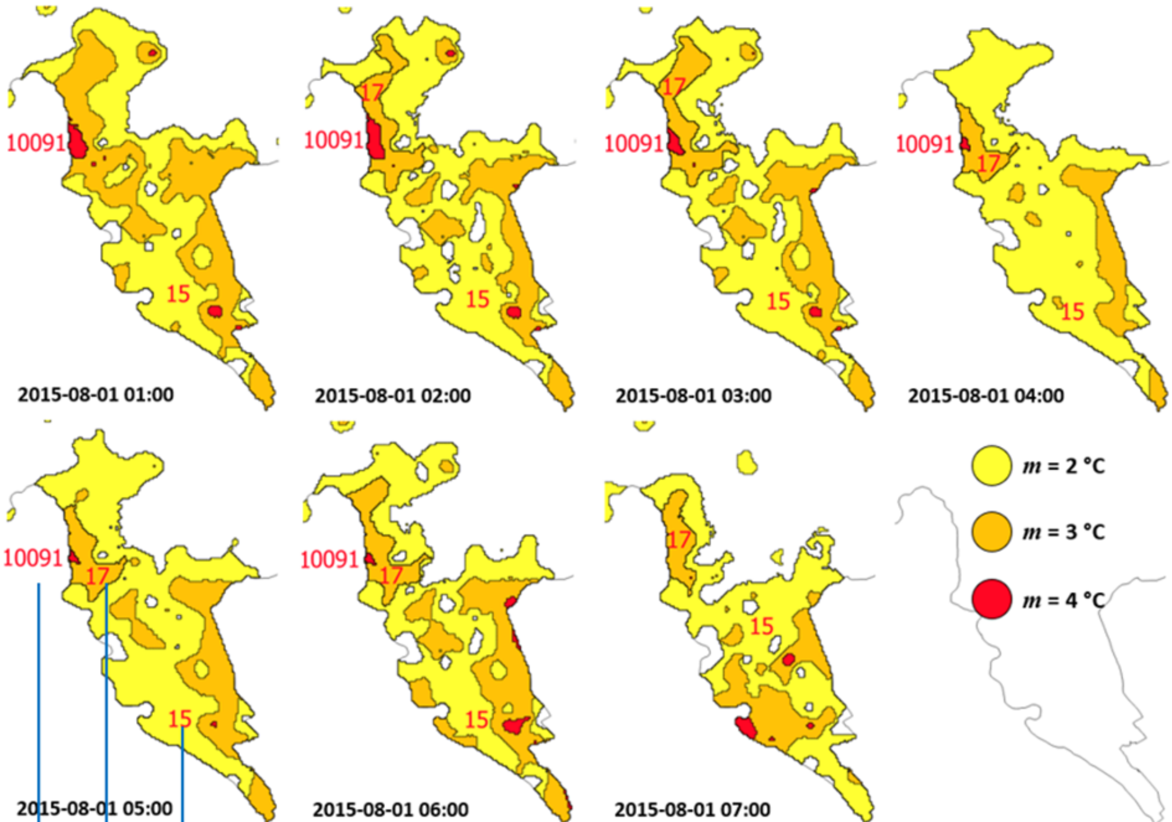


Figure 8: Intensities of UHIs in five different magnitudes for consecutive of seven days.



oid	pid	t_s	czid	pzid	spid	spb	spp	cid	thb	thp
15	315	31/7/2015 21:00	512	500	171	annex		159	stationary	
15	315	31/7/2015 22:00	41	512	171	annex		164	decreasing	re_low
15	315	31/7/2015 23:00	56	41	171	annex		186	increasing	le_low
15	315	1/8/2015 0:00	524	56	171	annex		186	increasing	le_low
15	315	1/8/2015 1:00	408	524	249	expan	re_peak	186	increasing	le_low
15	315	1/8/2015 2:00	414	408	250	contr	le_peak	213	decreasing	downgrade
15	315	1/8/2015 3:00	247	414	258	annex		217	stationary	stabilization
15	315	1/8/2015 4:00	533	247	266	contr		221	decreasing	downgrade
15	315	1/8/2015 5:00	537	533	272	annex		227	increasing	re_peak
15	315	1/8/2015 6:00	65	537	272	annex		227	increasing	re_peak
15	315	1/8/2015 7:00	542	65	272	annex		247	decreasing	le_peak
15	315	1/8/2015 8:00	403	542	295	contr		247	decreasing	le_peak
15	315	1/8/2015 9:00	0	403	300	disap		250	null	
15	316	1/8/2015 10:00								
15	316	1/8/2015 22:00								
15	431	1/8/2015 23:00	564	0	346	appea		294	null	
15	431	2/8/2015 0:00	593	564	360	expan		312	increasing	upslope
15	431	2/8/2015 1:00	583	593	360	expan		315	stationary	stabilization
15	431	2/8/2015 2:00	370	583	398	merge		335	increasing	upslope
17	289	1/8/2015 2:00	350	334	178	separ		171	increasing	re_peak
17	289	1/8/2015 3:00	361	350	209	annex		184	decreasing	le_peak
17	289	1/8/2015 4:00	304	361	213	separ		199	stationary	
17	289	1/8/2015 5:00	371	304	241	expan		199	stationary	
17	289	1/8/2015 6:00	384	371	254	annex		216	decreasing	
17	289	1/8/2015 7:00	387	384	272	contr		216	decreasing	
17	289	1/8/2015 8:00	0	387	283	disap		243	null	
17	290	1/8/2015 9:00								
17	290	6/8/2015 17:00								
17	1288	6/8/2015 18:00	627	0	1217	appea		1104	null	
17	1288	6/8/2015 19:00	826	627	1229	merge		1110	increasing	
10091	91	1/8/2015 1:00	112	0	55	appea		30	null	
10091	91	1/8/2015 2:00	121	112	64	annex		35	stationary	
10091	91	1/8/2015 3:00	71	121	67	contr	re_low	35	stationary	
10091	91	1/8/2015 4:00	72	71	67	contr	re_low	35	stationary	
10091	91	1/8/2015 5:00	74	72	67	contr	re_low	35	stationary	
10091	91	1/8/2015 6:00	80	74	84	expan	le_low	35	stationary	
10091	91	1/8/2015 7:00	0	80	90	disap		61	null	

Figure 9: Behaviors of UHIs in three magnitudes of 2, 3, and 4 degrees Celsius.

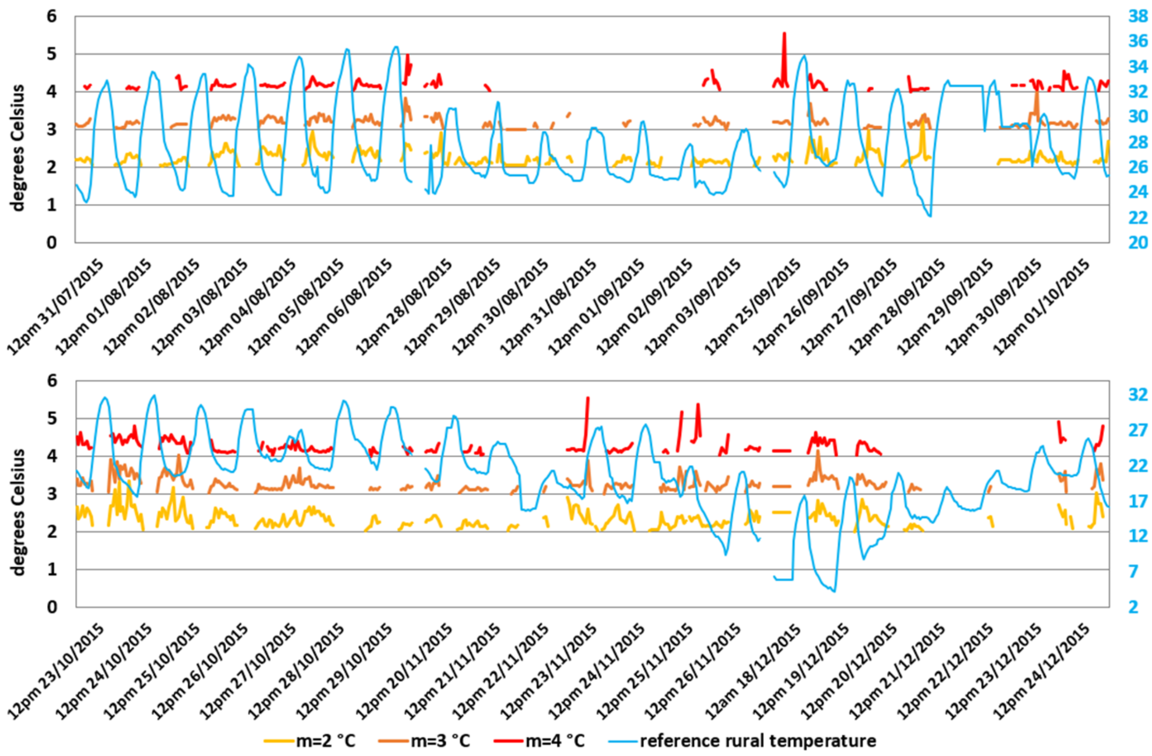


Figure 10: Intensities in three magnitudes over six weeks together with the reference rural temperatures.

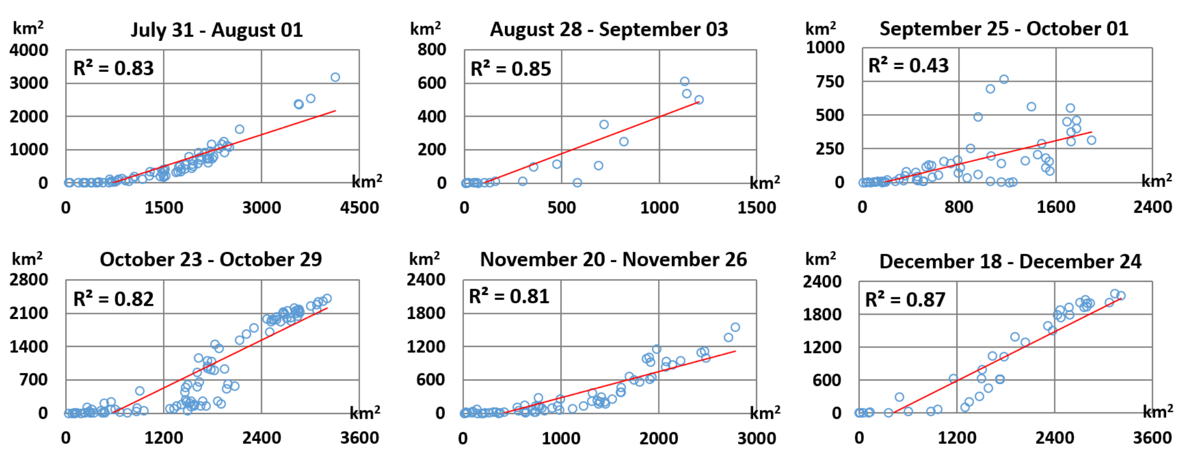


Figure 11: Correlation analysis between areas of UHIs in m=3 °C (x axis) and m=4 °C (y axis) over six weeks.

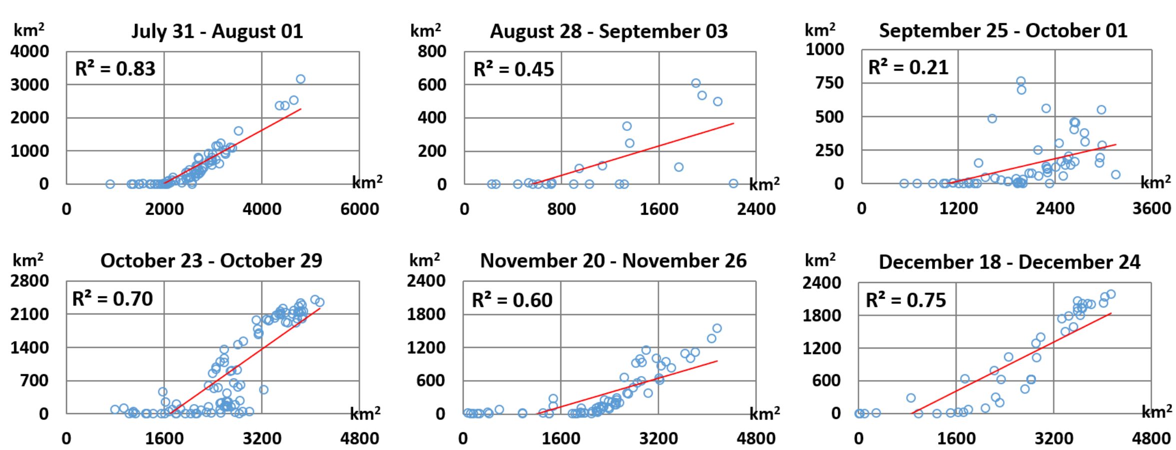


Figure 12: Correlation analysis between areas of UHIs in m=2 °C (x axis) and m=4 °C (y axis) over six weeks.