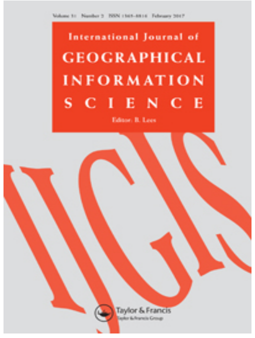

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Object-oriented tracking of the dynamic behavior of urban heat islands

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ABSTRACT

The urban heat island (UHI) phenomenon occurring within urban areas or city-clusters is increasingly becoming a severe problem in the urbanization process. Previous research mainly focusing on static UHI modeled at fixed time instants is not capable to track the evolutionary process of the UHIs in both time and space domains. This research designs an object-oriented dynamic model to reconstruct the evolutionary process of UHIs. Each UHI is modeled as a spatiotemporal field-object with its own life-cycle. The dynamic behavior of an UHI is defined by a series of filiations (e.g. expansion and contraction). The model was implemented in an object-relational database and applied to air temperature data collected from weather stations in hourly basis over 7 days. The behaviors of UHI were extracted from the data. Results suggest that the model can effectively identify different behaviors and status of UHIs, and reveal the spatiotemporal behavior of each of them.

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Spatiotemporal data modeling; object-oriented modeling; urban heat islands

1. Introduction

Urban Heat Island (UHI) is a phenomenon where temperature in urban areas is higher than in surrounding rural areas. With the increasing rate of urbanization process, many rural areas have gradually become urbanized areas; small and middle-sized cities expand to be metropolises, and mega cities split to several spatial contiguous city clusters, which significant impact on regional, city, and micro-scale climate, as well as UHI effect. Hence, much work has been done to study the causative factors and adverse effects of UHI from thermal images and from meteorological station records.

Most of the works in this direction consisted in correlating thermal intensity from static surface temperature images with environmental indicators such as the land cover (Lo *et al*. 1997, Dousset and Gourmelon 2003, Stathopoulou and Cartalis 2007) or social indicators (Buyantuyev and Wu 2010). Rajasekar and Weng (2009a) made use of data mining techniques to establish patterns between land cover and temperature. Recently, consideration has also been given to studying the dynamic evolution of UHI where UHI is defined as clusters of pixels, moving towards object-based analysis. For example,

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Rajasekar and Weng (2009b) estimated UHIs as Gaussian functions and Keramitsoglou *et al*. (2011) proposed an object-based image analysis to reveal thermal pattern that thermal intensities of hotspots are strongly correlated to their extent. In another direction, geographical information science (GIS) tools can be used to study and visualize UHI causative factors such as ventilation (Wong and Nichol 2013). However, conventional GIS data models and analytical tools lack capabilities to adequately handle massive multidimensional data (McIntosh and Yuan 2005). They also cannot provide qualitative information about the processes occurring within UHIs and trends that can take place over long periods of time. More in-depth study of UHI could be performed by extracting the dynamics of a UHI during its whole lifetime through the analysis of a set of images automatically. Such an approach requires the inclusion of the temporal dimension and thus the extension of the 2D raster model to a spatiotemporal model which can also support queries to retrieve data according to dynamic phenomena of interest.

In addition, the GIS community has studied data models to represent dynamic geographical phenomena. The objective of these models is to describe the spatiotemporal behavior of objects observed in sequences of images. Geographical phenomena can be defined as field objects corresponding to geo-objects with an internal structure defined by variations of field-like properties within the boundary of the object (Goodchild *et al*. 2007). Their dynamic is driven by their activities, events and processes, and can be observed through changes and movements (Yuan and Hornsby 2008). Such an approach works especially well with environmental phenomena such as UHI which can be seen as objects whose characteristics change over time.

The objective of this study is to provide a novel object-oriented model where UHIs are seen as spatiotemporal objects with their own thematic and field attributes and their relationships evolving through space and time. The purpose of this model is to extract spatiotemporal processes of UHIs in their life-cycle so as to provide a qualitative description of the UHI behavior. This approach can record the processes of UHI properties in a spatiotemporal database which allows the retrieval of UHI behavior through simple queries. Processes and events are stored and queried directly in the database which can allow further analysis of the relationships between UHI and their environment.

Spatiotemporal models were developed for different environmental phenomena such as precipitations (Yuan 2001). Data were originally represented on raster layers corresponding to different times, and entities were identified on each layer and models are event or process centered. Processes and events are spatiotemporal objects defined with time attributes (e.g. starting and ending time), thematic attributes and dynamic attributes describing movement (McIntosh and Yuan 2005) and are linked to entities involved in the events. The data model can indeed combine both raster and vector representations as thematic and kinematic data are computed from grid points inside the entities (Bothwell and Yuan 2010).

Event-based method models dynamic behaviors as event properties or relationships with spatiotemporal attributes (Peuquet and Duan 1995, Worboys 2005) which can be queried (Zaniolo 2009, Pultar *et al*. 2010). For instance, the dynamic behavior of a moving object can be modeled as semantic *events* (e.g. *departure, arrival*, or *unexpected destination*) and abstracted as patterns from the event sequences (Hornsby and Cole 2007). McIntosh and Yuan (2005) created a hierarchical framework where moving objects are described by four different states: (1) a *zone* is an area of spatial contiguous cells meeting a designated threshold in a snapshot; (2) a *sequence* is a set of zones meeting a threshold in consecutive snapshots; (3) a *process* is a set of sequences where the geographical objects are topologically related; and (4) an *event* is at least one type of process during a consecutive time interval.

Topological relationships between objects define topological transitions between two consecutive time steps. Claramunt and Thériault (1995) defined spatiotemporal topological process involving single and several entities. For instance, stability means the area remains unchanged; while, displacement indicates a polygon is moving without a change of area. A more complex taxonomy relating to topological change operations (e.g. reincarnation) based on three identified states (i.e. existence, non-existence, and transition) has been provided by Hornsby and Egenhofer (2000), which actually models each entity with its own life-cycle. Similarly, Renolen (2000) introduced a behavior modeling framework where each spatiotemporal object experiences its generic behavior as either alive or dead, and seven types of transition between two statuses: creation, alteration, destruction, reincarnation, annexation, deduction, and reallocation. Several studies applied this framework in specific applications (Guilbert and Lin 2007, Nixon and Hornsby 2010, Bothwell and Yuan 2011) where objects can merge or split leading to the creation and destruction of new objects. These transformations were more formally described by Del Mondo *et al*. (2013) who represent spatiotemporal relationships in a graph. Other transitions that affect the shape or thematic attribute of a field-object, growing or warming up that may be used for describing behavior of a UHI, are not systematically modeled but can be expressed to define relevant processes.

The rest of this paper is organized as follows. Section 2 presents the new conceptual model centered on UHI as spatiotemporal objects. Sections 3 and 4 evaluates the proposed method on a case study empirically. Finally, Section 5 concludes and points to future research.

2. Object modeling of UHIs

2.1. *UHI as a field-object*

A UHI is widely conceptualized as an environmental phenomenon where temperatures in urban areas are higher than in surrounding rural areas. Based on this perception, a UHI can be defined as a two-dimensional field where its areal extent can expand, contract, or remain stable when temperatures warm up, cool down, or keep constant through continuous time and space. Therefore, UHI can be seen as a variable field whose thematic attribute is the temperature intensity, which is the difference between the temperature measured in the urban area and a threshold temperature observed in the rural area at the same time. At this stage, other factors that influence temperature variation are not considered and thermal exchanges between different elevations are omitted. Only movements related to the areal extent are modeled for UHIs since several studies have indicated that UHI is a localized phenomenon which does not move away from its original location and the displacement is not obvious (Hua and Wang 2012, Jalan and Sharma 2014).

From the above conceptualization, a UHI can be integrated as a field-object having three components: a spatial component defined by a polygon delineating its extent, a temporal component allowing the description of its *life-cycle* in consecutive time instants and the thematic component which is the temperature intensity observed from the thermal image and defined as a field variable. On top of this, a UHI can go through spatiotemporal transformations describing a change of state or its relationships with other UHIs. For instance, a UHI may split itself in two or may disappear when the temperature intensity decreases. This shows that topological transformation determined by thematic characters can also trigger its state transition of the *life-cycle*.

As such, UHI can be characterized from series of thermal images obtained at regular time intervals. Following the definitions introduced by McIntosh and Yuan (2005), UHIs on a given image are identified by *zones* of high-temperature intensity inside urban areas. A *sequence* is a series of zones observed on consecutive images at a given location. Such a sequence corresponds to the observation over a time range of a UHI going through continuous change in shape and intensity. A *process* connects sequences together through a topological transformation such as a split or a merge. It occurs at a given time instant between two or more UHIs.

2.2. *Graph-based modeling of the UHI behavior*

Sequences and processes can be more formally defined by using a spatiotemporal graph approach as presented by Del Mondo *et al.* (2013). A UHI is identified through time as a series of zones which can be related together through spatiotemporal relationships. We note $G_Z = (Z, F_z)$ the graph where Z is the set of all zones and F_z is the set of filiation relationships connecting the zones. As zones are UHI components, each zone z_n^i can be identified by a time instant t_i and the UHI u_n it belongs to and a filiation can be noted as $\left(z_n^i, z_m^j\right) \in F_z$. Filiations between zones can be refined into several possible relationships:

- *continuation* between two zones z_n^{i-1} and z_n^i having a similar spatial extent;
- *expansion* from zone z_n^{i-1} to z_n^i where the geometry expands;
- *contraction* from zone z_n^{i-1} to z_n^i where the geometry contracts;
- *splitting* when one zone z_n^{i-1} splits into two zones z_m^i and z_p^i;
- *merging* when two zones z_m^{i-1} and z_n^{i-1} merge into one zone z_p^i;
- *separation* when one zone z_n^{i-1} is associated to two zones z_n^i and z_m^i;
- *annexation* when two zones z_n^{i-1} and z_m^{i-1} are associated to a third zone z_n^i.

Among these filiations, the first three are concerned with geometrical changes occurring within one UHI while the last four imply at least three zones and a topological transformation. The set of filiations can be partitioned into two sets $F_z = C_z \cup T_z$. defining the set of continuous relationships and the set of transformations, respectively. This study also extends T_z by adding two specific transformations as the following, and all different types of filiations are summarized in Figure 1.

- *appearance* if a zone z_n^i is not related to any zone at t_{i-1};
- *disappearance* if a zone z_n^{i-1} is not related to any zone at t_i.

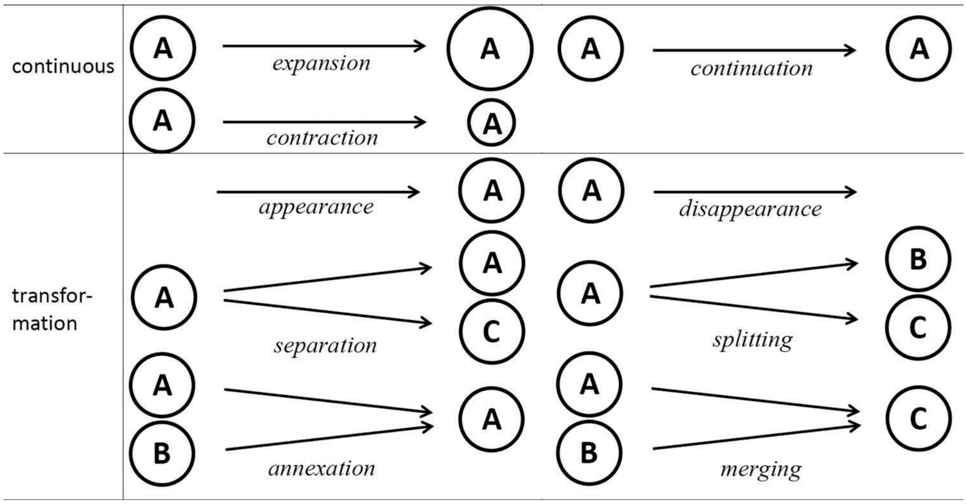

Figure 1. Filiations between zones. Above, filiations in C_z. Below, filiations in T_z.

A *sequence* is then defined by a series of zones over an interval $[t_i, t_j]$ such that all zones in the series are connected by the same continuous relationship. A consequence is that all zones must belong to the same UHI. Hence, a *sequence* s_n^i is a series of zones $\left\{z_n^i, \ldots, z_n^j\right\}$ such that $\forall k,\ i < k \leq j,\ \left(z_n^{k-1}, z_n^k\right) = \left(z_n^i, z_n^{i+1}\right) \in C_z$.

Furthermore, sequences can be gathered in a second graph $G_S = (S, E_s)$ where S is the set of sequences and E_s is the set of edges marking changes between the sequences. Each sequence can be characterized by one of the three relationships from C_z and edges can be characterized by the types of sequence they connect. Thus, E_s can be divided between a set C_s of continuous transitions where two consecutive sequences show an area change in the evolution of the UHI and a set P_s of processes where a transformation occurs. While processes have a similar meaning as transformations in T_z, continuous transitions can further describe the behavior of a UHI. Noting $s_n^{i_{j-1}}$, $s_n^{i_j}$, and $s_n^{i_{j+1}}$, three consecutive sequences connected by continuous transitions belonging to the same UHI u_n, the study associates edges $\left(s_n^{i_{j-1}}, s_n^{i_j}\right)$ and $\left(s_n^{i_j}, s_n^{i_{j+1}}\right)$ with an action describing u_n's behavior:

- if $s_n^{i_{j-1}}$ is an expansion and $s_n^{i_j}$ is a contraction, u_n *peaks* during the transition $s_n^{i_{j-1}}, s_n^{i_j}$;
- if $s_n^{i_{j-1}}$ is an expansion, $s_n^{i_j}$ is a continuation and $s_n^{i_{j+1}}$ is a contraction. Sequence $s_n^{i_j}$ is as a *plateau*. u_n *reaches a plateau* and *leaves a plateau* during the transitions;
- if $s_n^{i_{j-1}}$ is a contraction, $s_n^{i_j}$ is a continuation and $s_n^{i_{j+1}}$ is an expansion. Sequence $s_n^{i_j}$ is qualified as a *floor*. u_n *reaches to a floor* and *leaves a floor* during the transitions;
- if $s_n^{i_{j-1}}$ is a contraction and $s_n^{i_j}$ is an expansion, u_n reaches a *low* during the transition $s_n^{i_{j-1}}$, $s_n^{i_j}$;
- if $s_n^{i_{j-1}}$ and $s_n^{i_{j+1}}$ are both contractions or both expansions and $s_n^{i_j}$ is a continuation, $s_n^{i_j}$ corresponds to a pause in the evolution of the UHI. The first transition is a *stabilization* and the second a *resumption*.

2.3. *Conceptual modeling of UHI*

Hence, the *life-cycle* of a UHI can be described by a series of sequences where each sequence corresponds to a specific behavior. These sequences are connected by transitions and processes as shown in Figure 2. Eventually, each UHI can be defined as an object composed by a set of sequences. A UHI also goes through changes which can be internal (continuous transitions) or external (processes) and involve topological changes. In the object model, changes are also perceived as objects and can specialize into continuous transitions and processes. Continuous transitions are components of UHIs while processes are connected to one or more UHIs with three items of associations:

- a *process* can generate a UHI (appearance, separation, splitting, merging);
- a *process* can terminate a UHI (disappearance, splitting, annexation, merging);
- a *process* can modify the shape of a UHI (annexation, separation).

This conceptual model offers definitions that allow for the description of the qualitative behavior of a UHI as it can be described by the type of sequences and processes it goes through. Figure 3 presents the class diagram where UHIs are composed of sequences which are themselves composed of zones. Zones are delineated by a polygon extracted from the thermal images such that temperatures within the polygon are higher than the reference rural temperature, and zones also have continuous or transformation filiation. UHIs are composed by their continuous transitions and are associated to their processes. A transition is associated with two sequences while a process is associated with one to several sequences. Each transition and process class can be further specialized into subclasses corresponding to the behaviors described above. Essentially, continuous and transformation describing the filiation between zones differentiates process and transition depicting topological transformation between sequences. Contrary to McIntosh and Yuan (2005), processes do not include only split and merge but all topological transformation, allowing the description of a UHI *life-cycle* as a series of processes.

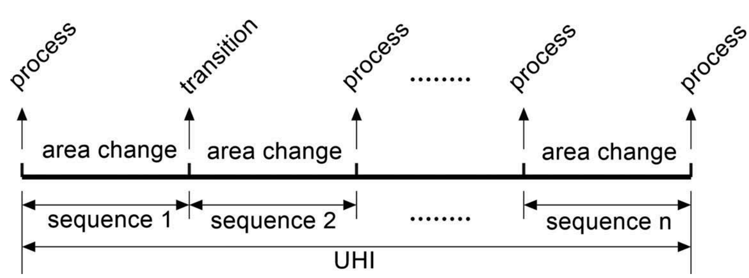

Figure 2. A UHI goes through a series of sequences related by transitions and processes in its life-cycle.

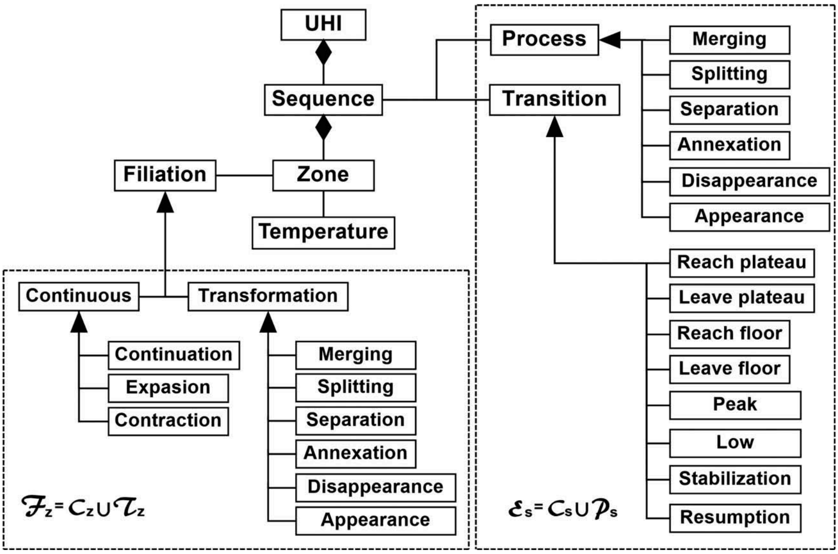

Figure 3. Class diagram of the UHI model.

3. Application to UHI tracking

3.1. *Study area*

The model is tested in Guangzhou city, which is the core area of urbanized city-clusters in the south of China with 13 million populations in total and 1700 population per square kilometer. UHI phenomenon in this city is significantly obvious with an annual average temperature of 22°C in the subtropical monsoon climate.

3.2. *Preprocessing*

Near-ground (approximately 1.5 m above the ground) air temperatures were collected in hourly basis from 1 am on 31 July 2015 to 12 pm on 6 August 2015 at 216 weather stations mainly located in the urban area as shown in Figure 4. Thereby, a series of near-ground thermal images are generated by interpolating hourly collected points as the input data of the model. Universal Kriging was used since it models the surface by assuming that an overriding trend exists in the data sets, which is beneficial for highlighting the hotspot character of UHIs (Stahl *et al*. 2006, Hofstra *et al*. 2008, Irmak *et al*. 2010, Chai *et al*. 2011).

3.3. *Extraction of UHI changes*

Hourly updated rural temperatures observed at the triangle in Figure 4 were used as the reference threshold temperature to extract zones of UHIs. UHI zones are defined by urban areas where the temperature is with a defined higher minimum difference from the reference temperature. Areal variations were computed at each time instant. If there is no overlapping area between two consecutive UHI polygons or if the proportion of

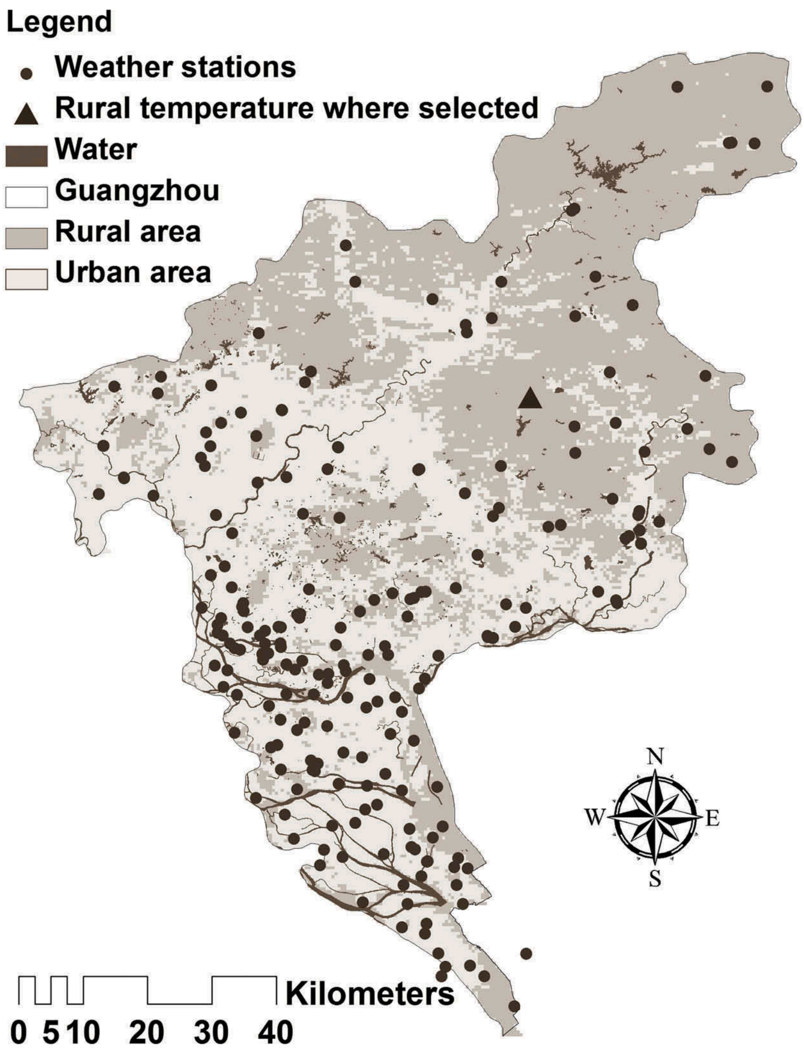

Figure 4. Automatic weather stations are located in Guangzhou city, China.

the overlapping area to either of the two polygons is small, it is reasonable to say that they have no relationship and belong to different UHIs. On the opposite, they can be considered as belonging to the same object if they overlap on a significant area as shown in Figure 5. Hence, changes at time t_i are more specifically defined as follows:

- *appearance*: the zone at time t_i has insignificant overlapping area or does not intersect with any zones at time t_{i-1};
- *disappearance*: the zone at time t_{i-1} has not significant overlapping area or does not intersect with any zone at time t_i;
- *expansion*: the UHI polygon significantly intersects with a UHI at time t_{i-1} and its area is bigger;

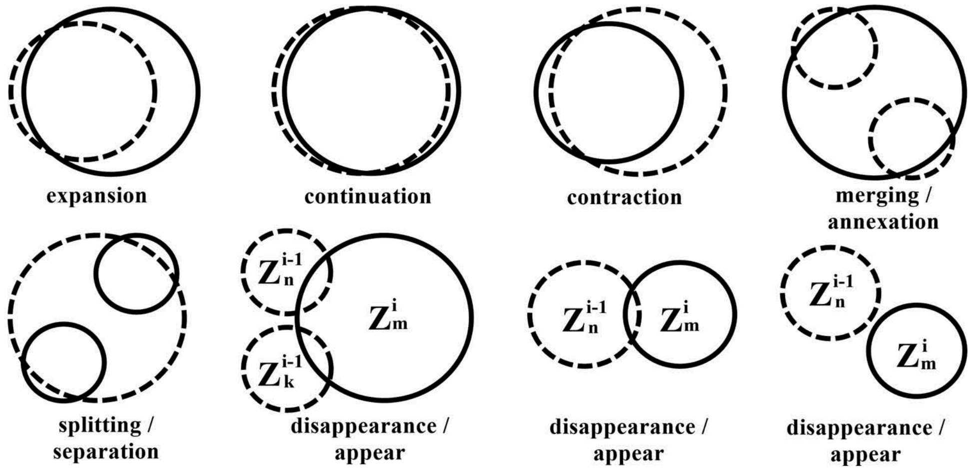

Figure 5. Overlapping instance of UHI zones in two consecutive time instants.

- *contraction*: the UHI polygon considerably intersects with a UHI at time t_{i-1} and its area is smaller;
- *continuation*: the UHI significantly overlaps with a UHI at time t_{i-1} and their areas are equivalent;
- *merge*: one UHI polygon at t_i overlaps with several UHIs at t_{i-1}. If one UHI at t_{i-1} is much bigger than the others and of an area close to the UHI at t_i, the UHI is supposed to be in the continuity of the big UHI and an annexation can be determined. If the new UHI cannot be associated to one specific UHI, it is considered as a new UHI and a *merging* is derived; and
- *split*: several UHI polygons at t_i overlap with one polygon at t_{i-1}. If the shape at t_i is similar to one specific polygon at t_{i-1}, it is a *separation* otherwise it is a *splitting*.

3.4. *Computation*

Several threshold parameters were defined to recognize different types of continuous and transformation filiations. First, in order to be related together, zones identified at two consecutive time instants need to overlap significantly. This is done by checking if the intersection of two zones takes significant area of the zone at t_{i-1}. Thus, a relative threshold $\varepsilon_{\text{related}}$ is defined for this (Equation 1).

$$\frac{\text{area}\left(z^i \cap z^{i-1}\right)}{\text{area}\left(z^{i-1}\right)} \geq \varepsilon_{\text{related}} \tag{1}$$

To facilitate the presentation, each type of filiation is named as an event. Then, the type of event that the UHI undergoes depends on the association relationship that has been determined above and the number of associations a zone has with other zones. If a zone is associated with one single zone, no transformation occurs and the UHI is changing. If no association can be determined with only one single overlapping or no overlapping, the UHI is appearing or disappearing. If several associations are made, a merge is taking place. Finally, a split occurs if there are several overlapping but has no association.

Two UHI zones are considered of same size if their relative area difference is smaller than a threshold ε_{area} (Equation 2). Hence, a UHI is considered to expand if its area has increased of ε_{area} between two consecutive time instants. Similarly, if the UHI area decreases by ε_{area}, the UHI is contracting.

$$\frac{\left|\text{area}\left(z^{i}\right)-\text{area}\left(z^{i-1}\right)\right|}{\text{area}\left(z^{i-1}\right)} \leq \varepsilon_{\text{area}} \tag{2}$$

A *merge* occurs when z_k^i is associated with several zones $\left\{z_j^{i-1}\right\}$ (j = 1,. . .,l). More distinctly, an *annexation* occurs if one of the zones at t_{i-1} significantly merges into the z_k^i. Hence, a UHI will undergo an *annexation* if it has the maximum overlapping area which also occupies significant area of z_k^i (Equation 3). Otherwise, all the older zones corresponding to the new zone have a *merging*.

$$\frac{\max\left(\left\{\text{area}\left(z_k^i \cap z_j^{i-1}\right)\right\}\right)}{\text{area}\left(z_k^i\right)} \geq \varepsilon_{\text{merge}} \quad (j = 1, \ldots, l) \tag{3}$$

In contrast, a split occurs when z_j^{i-1} overlaps but is not associated with several zones of $\left\{z_k^i\right\}$ (k = 1,. . .,l). A *separation* occurs if area of one of the zones z_k^i still notably splits from its origin. Thus, a UHI will experience a *separation* if it has the maximum overlapping area which also takes considerable area of the preceding zone (Equation 4). Otherwise, *splitting* will be derived for all the UHIs.

$$\varepsilon_{\text{split}} \leq \frac{\max\left(\left\{\text{area}\left(z_k^i \cap z_j^{i-1}\right)\right\}\right)}{\text{area}\left(z_j^{i-1}\right)} < \varepsilon_{\text{related}} \quad (k = 1, \ldots, l) \tag{4}$$

3.5. *System implementation*

A UML model for summarizing all the classes and their associations is represented in Figure 6. First, the `image` table stores all the thermal images interpolated from the absolute air temperatures observed each hour. Then, the `zone` table records all the zones of UHIs that have been extracted from images. Each zone is extracted as a single polygon and stored in the shape attribute, temperatures within which are with a given temperature (i.e. `temp`) higher than the rural temperature. To determine the event at each time instant, intersection area (i.e. `i_a`) of each pair of zones ⟨`p_oid`, `c_oid`⟩ respectively at t_{i-1} and t_i are stored in the `ints_st` table. To avoid duplicated calculation, zones which are to be merged or split are respectively listed in the `merge` and `split` tables in advance. Hence, a new table `event` can be added storing the event computed for each zone in order to build up *sequences* and *processes*. This table stores not only the continuous but also topological transformations of Figure 1. An `event` instance is composed of two attributes which are the current zones (i.e. `curTZoneID`) and preceding zones (i.e. `preTZoneID`). When the system has reconstructed all the events at each time, the `sequence` table is defined relating zones

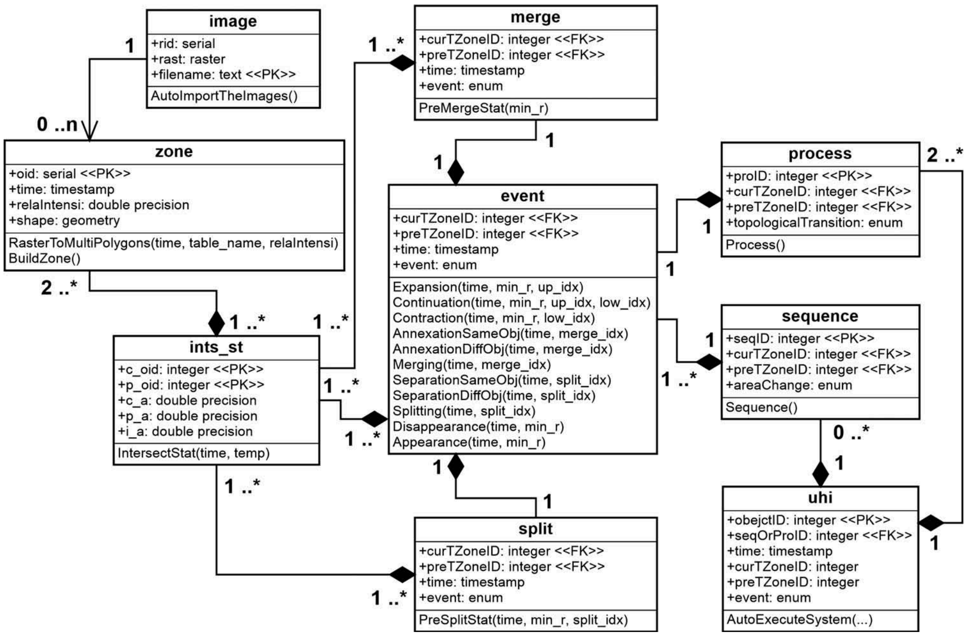

Figure 6. Classes association for the system implementation.

belonging to the same sequence. The table of `process` is defined by relating topological transformations. Finally, the table `uhi` is built from the series of processes and sequences.

The model was implemented in an object-relational DBMS PostgreSQL 9.3.4 to simulate the *events* and retrieve whole of the *life-cycle* of each UHI through SQL queries. SQL 1 computes all the zones that to be merged at each time instant. First, the number of zones ⟨`cnt,c_oid`⟩ which are related with ones at previous time instant are listed based on simple aggregations (Lines 2–4). Thus, all the pairs of zones ⟨`p_oid,c_oid`⟩ that each `c_oid` has more than one association are determined (Lines 1–6), suggesting which will be merged. Then, SQL 2 calculates each zone of `p_oid` that is disappeared absorbed by `c_oid`. Line 3 first lists the biggest intersection area for each zone ⟨`max_i_a,c_oid`⟩. Based on this clue, zones ⟨`p_oid,c_oid`⟩ that have the biggest intersection area are obtained (Lines 2–5). As an inverse, the function computes pairs of zones which only have the topological transformation when `p_oid` has no the biggest intersection area (Line 6). SQL 3 calculates zones which only have area changes (i.e. *expansion* more specifically). Based on the zones {`c_oid`} that are related with {`p_oid`} derived from one simple aggregation (Lines 2–3), the function further selects the only instance for `c_oid` (Line 4) that ⟨`p_oid,c_oid`⟩ are related (Line 5) and area of `c_oid` is bigger than p_oid (Line 6). Benefiting from the above achievements, SQL 4 computes appeared zones with a simple excluding method. First, line 2 lists zones that possibly are appeared ones in the current time instant. Second, the function queries all the zones of {`c_oid`} which have area changes (Lines 3–5), merges (Lines 6–7) and splits (Lines 8–9). Third, zones having *appearance* can be selected by excluding the above scenarios from derived {`potential_oid`} (Line 10).

4. Results

Temperature which is with a given temperature (i.e. relative intensity) above the referenced rural temperature was used as the threshold to extract zones from images. Based on the relative intensities that are between 1.5 and 5°C, accumulated number of UHIs summarized in unit of hour-of-day for 7 days is drawn in Figure 7. The figure represents that the numbers of UHIs with eight different relative intensities decrease dramatically from 8 am when the sun is raising, while there is no UHI during 11 am and 5 pm apart from the intensity of 1.5°C. After 5 pm, all the lines grow significantly in a whole trend with some variation between 7 pm and 9 pm. In general, this figure shows that the UHI phenomenon is much obvious during the night as this has been widely acknowledged.

To reveal the revolutionary trend of UHIs in the whole study area, a low relative intensity (1.5°C) was selected to simulate all the *events* and track all the life-cycles given the input parameters of $\varepsilon_{related}$, ε_{area}, ε_{merge}, and ε_{split} equaling to 0.53, 0.1, 0.65, and 0.5001, respectively. Table 1 lists a complete *life-cycle* of a UHI directly plotted from the `uhi` table. The table shows that this UHI exists from 9 pm to 8 am in the next day with several continuous processes of *annexation* and sequences of *continuation*. Simultaneously, change between sequences are also listed having the *plateau* and *leave a plateau* behaviors. To have an in-depth investigation of this UHI, Figure 8 draws part of its evolution interacting with other UHIs, which can be viewed as a graph G_S containing the vertices of *zones* connecting with the edges of several *events*.

SQL 1 FUNCTION PreMergeStat(min_r)

```
SELECT ints_st.c_oid, ints_st.p_oid, ints_st.c_a, ints_st.i_a
FROM (SELECT count(c_oid) AS cnt, c_oid
FROM (SELECT ints_st.c_oid FROM ints_st WHERE ints_st.i_a/ints_st.p_a ≥ min_r
AND p_a > 0) AS cur_g GROUP BY c_oid) AS cnt_cur_g, ints_st
WHERE cnt_cur_g.cnt > 1 AND cnt_cur_g.c_oid = ints_st.c_oid
AND ints_st.p_a > 0 AND ints_st.i_a/ints_st.p_a ≥ min_r;
```

SQL 2 FUNCTION AnnexationDiffObj(time, merge_idx)

```
SELECT time, merge.c_oid, merge.p_oid, annex_diff_obj
FROM (SELECT merge.c_oid, merge.p_oid
FROM (SELECT c_oid, max(i_a) AS max_i_a FROM merge GROUP BY c_oid) AS p_key, merge
WHERE merge.c_oid = p_key.c_oid AND merge.i_a = p_key.max_i_a
AND merge.c_a > 0 AND merge.i_a/merge.c_a ≥ inh_merge) AS inh_mer_obj, merge
WHERE inh_mer_obj.c_oid = merge.c_oid AND inh_mer_obj.p_oid <> merge.p_oid;
```

SQL 3 FUNCTION Expansion(time, min_r, up_idx)

```
SELECT time, ints_st.c_oid, ints_st.p_oid, expansion
FROM ints_st, (SELECT count(c_oid) AS cnt, c_oid FROM ints_st WHERE p_a > 0
AND i_a/p_a ≥ min_r GROUP BY c_oid) AS maintain_obj
WHERE maintain_obj.cnt = 1
AND ints_st.c_oid = maintain_obj.c_oid AND ints_st.i_a/ints_st.p_a ≥ min_r
AND ints_st.p_a > 0 AND ints_st.c_a/ints_st.p_a ≥ up_idx;
```

SQL 4 FUNCTION Appearance(time, min_r)

```
SELECT time, potential_oid.c_oid, appearance
FROM (SELECT c_oid FROM ints_st WHERE c_a > 0 GROUP BY c_oid) AS potential_oid
LEFT JOIN (SELECT c_oid FROM ints_st WHERE p_a > 0
AND i_a/p_a ≥ min_r GROUP BY c_oid) AS ints_oid
ON potential_oid.c_oid = ints_oid.c_oid
LEFT JOIN (SELECT c_oid FROM merge GROUP BY c_oid) AS merged_oid
ON potential_oid.c_oid = merged_oid.c_oid
LEFT JOIN (SELECT c_oid FROM split GROUP BY c_oid) AS split_oid
ON potential_oid.c_oid = split_oid.c_oid
WHERE ints_oid.c_oid IS NULL AND merged_oid.c_oid IS NULL AND split_oid.c_oid
  IS NULL;
```

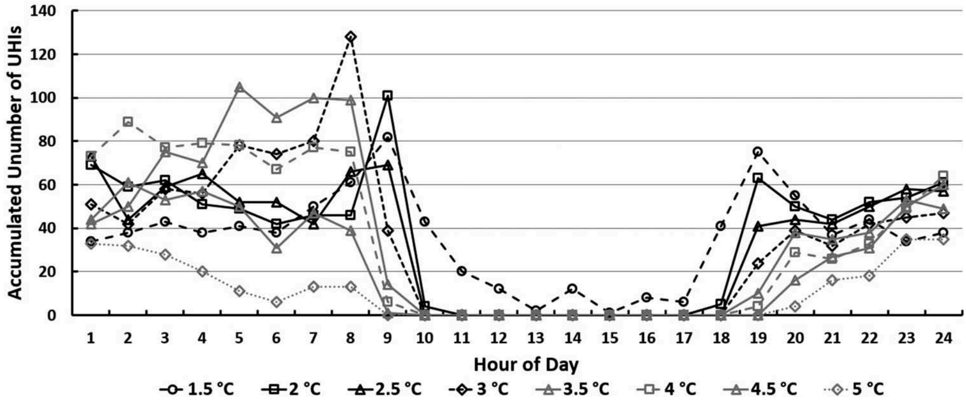

Figure 7. Accumulated number of UHIs with different relative intensities summarized by hour-of-day for 7 days.

Obviously, zone of `2626` absorbs zone of `2627` and becomes `2630` at 3 am. Then, this UHI is stabilized as zone of `2771` in a given range of area variation, and three new UHIs appear simultaneously. In the next hour, the zone `2771` merges the other two into its own body, and the newly appeared zone `2770` becomes `2774` contracting its areal extent in the meanwhile. Subsequently, the zone `2775` absorbs `2774` and becomes `167` at 6 am. Finally, the zone `167` contracts as `174` and splits as several new UHIs.

Figure 9 shows the spatial distribution of the above UHIs during six consecutive hours, which clearly represents that the UHI phenomenon is obvious and stable at night. More specifically, the large UHI covers the most urbanized urban areas all through the night with variations of appearing and disappearing of some small UHIs in the north-west. This is probably because of the thermal emission of the urban areas absorbed from the solar radiation and anthropologic heat flux during the day time. Then, area of the UHI decreases significantly in the early morning and continuously dissipates and splits into several pieces at 8 am, which corresponds to sunrise and a raising reference temperature. A similar phenomenon is revealed by Kourtidis *et al*. (2015) would also support the effectiveness of this model. Area change tracking of this UHI (i.e. `objID 251`) together with the other four in five different days is also drawn in Figure 10, which shows that all of them share the very similar area change trend, starting from stable

Table 1. A complete *life-cycle* for an urban heat island.

Time	curZoneID	preZoneID	objID	s/pID	Filiation	Change
15-07-31 21:00	67	51	251	152	annex_s_obj	annex_s_obj
15-07-31 22:00	70	67	251	152	annex_s_obj	annex_s_obj
15-07-31 23:00	74	70	251	174	continuation	plateau
15-08-31 00:00	2765	74	251	147	continuation	plateau
15-08-31 01:00	2694	2765	251	147	continuation	plateau
15-08-31 02:00	2626	2694	251	191	contraction	leave_plateau
15-08-31 03:00	2630	2626	251	196	annex_s_obj	annex_s_obj
15-08-31 04:00	2771	2630	251	199	continuation	NULL
15-08-31 05:00	2775	2771	251	205	annex_s_obj	annex_s_obj
15-08-31 06:00	167	2775	251	205	annex_s_obj	annex_s_obj
15-08-31 07:00	174	167	251	222	contraction	NULL
15-08-31 08:00	2776	174	251	229	splitting	splitting

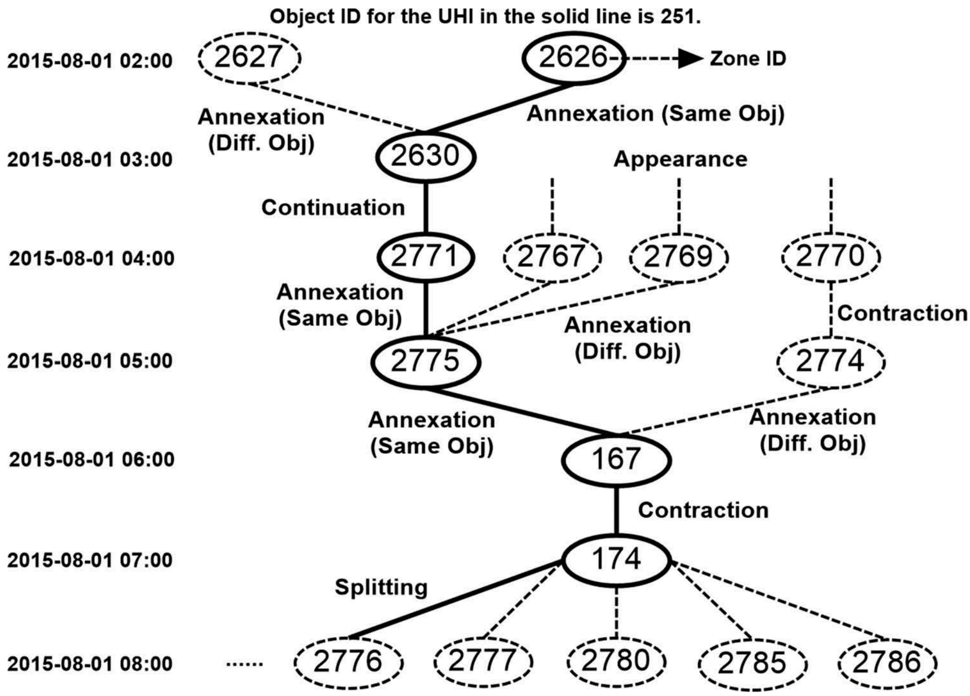

Figure 8. Evolutionary trajectory of a UHI drawn from part of its life-cycle.

increase followed by notable variation, and ending with dramatic decrease. More interestingly, all of these UHIs appear around 8 pm benefiting from *annexation* and disappears at 8 am caused by *splitting* or *disappearance*, which indicates an obvious periodical trend for them. Thus, this example explicitly suggests that the system can effectively track the dynamic behaviors of the UHIs in area changes and topological transformations.

Based on the simulation results as illustrated above, temporal evolution trend of UHIs can be revealed by accumulating the number of different events in unit of hour-of-day as shown in Figure 11. Obviously, the *appearance* and *merging* events mostly occur from 7 pm, which means the UHIs increasingly expand and merge together after the sunset. In contrast, the *splitting* and *disappearance* events dominantly happen at 9 am and 10 am, respectively, suggesting the fact that UHIs are splitted and disappeared rapidly most probably caused by the increase of referenced rural temperature after the sun raising. While, other three events are not observed frequently during the whole night. This indicates that only a few UHIs have independent evolution, while most UHIs interact with each other frequently due to the significant variation of air temperatures all the time.

Figure 12 shows that the total area of UHIs in the study area has an apparent periodical trend, which expands significantly around 8 pm, reaches to the largest amount around 1 pm, and contracts dramatically around 8 pm every day. To discover periodical trend of UHIs in spatial, zones of UHIs when disappeared and appeared are extracted from *processes* overlapping with the road networks (Figure 13). Obviously, occurrence of the disappeared and appeared zones of UHIs has almost the same spatial

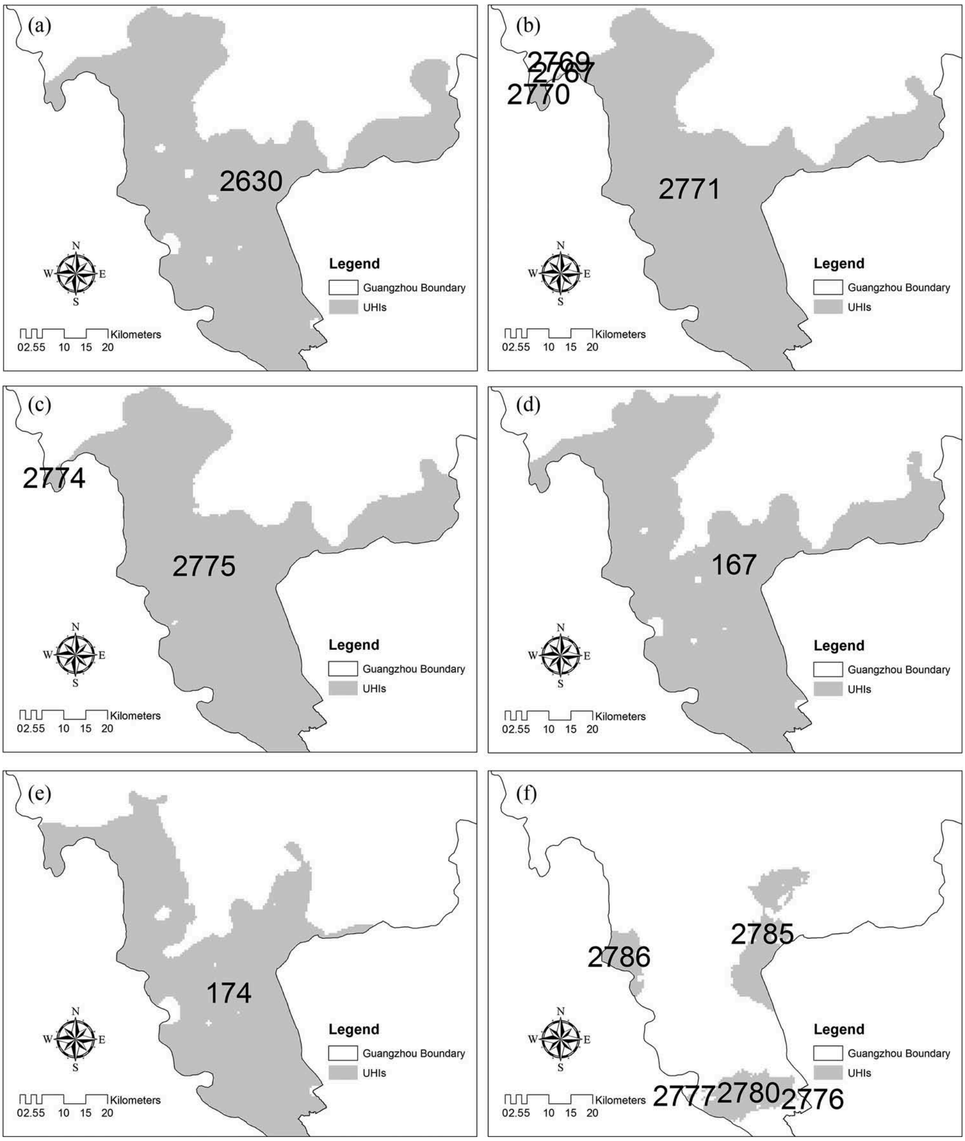

Figure 9. Area changes of UHIs at six consecutive time instants. (a) Two zones merge together as a single zone 2630 at 3 am. (b) Zone 2630 continues as 2771 and three new ones appear at 4 am. (c) Zone 2771 merges two others as 2775, and zone 2774 contracts at 5 am. (d) Zone 2775 grows and merges the other one as 167 at 6 am. (e) Zone 167 contracts as 174 at 7 am. (f) Zone 174 contracts and splits as five pieces at 8 am.

distribution indicating that they are most probably the same UHIs with periodical *life-cycle* trend. It also represents that the most frequently occurred disappeared and appeared zones are located in the less dense urban areas (i.e. north and east regions of the study area). Interestingly, several small and discrete areas in the core urbanized area with high density of road networks in the middle region of the study area also have the most frequent occurrences. This suggests that human activities (e.g. transportation)

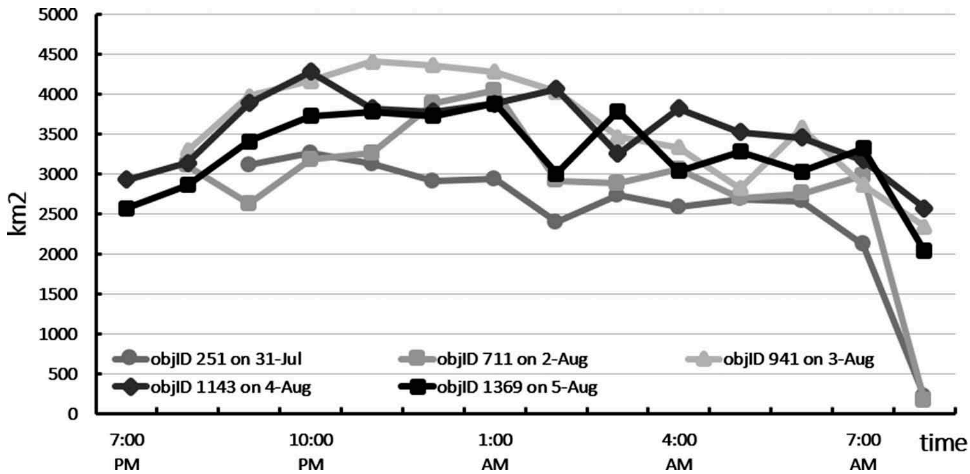

Figure 10. Area tracking of five UHIs in five different days.

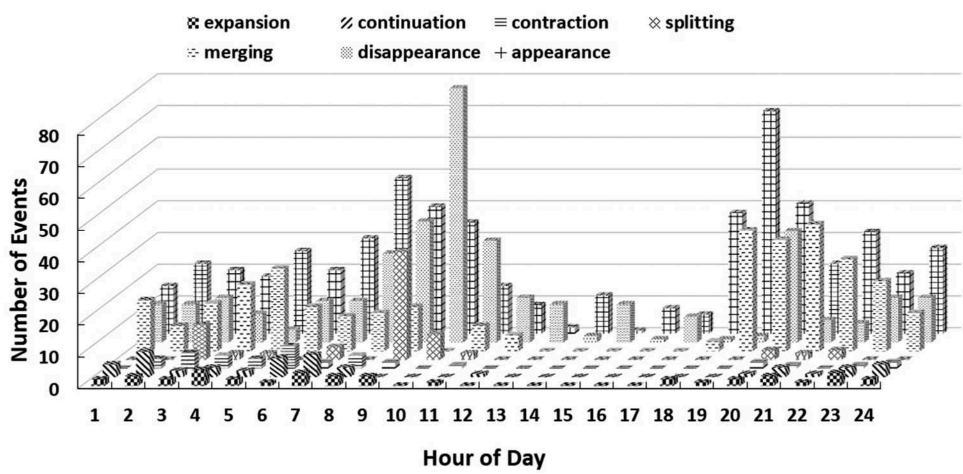

Figure 11. The number of different events accumulated by hour-of-day for 7 days.

may have considerable periodical influence to the UHI phenomenon as has been discussed in literature (Alonso *et al*. 2003, Srivanit and Hokao 2012). The southern part also has high frequent occurrence where a great number of factories are located; however, the density of road network is not high.

5. Discussion and conclusion

This study conceptualizes UHI as a two-dimensional field-object, proposes a novel model to describe the object-oriented dynamic behaviors of UHIs, and develops a system to evaluate the performance of the model. One graph G_z is proposed to describe the filiation relationships with zones, and the other one G_s is to record the transition of sequences. The model enables that each UHI has only one specific behavior for each

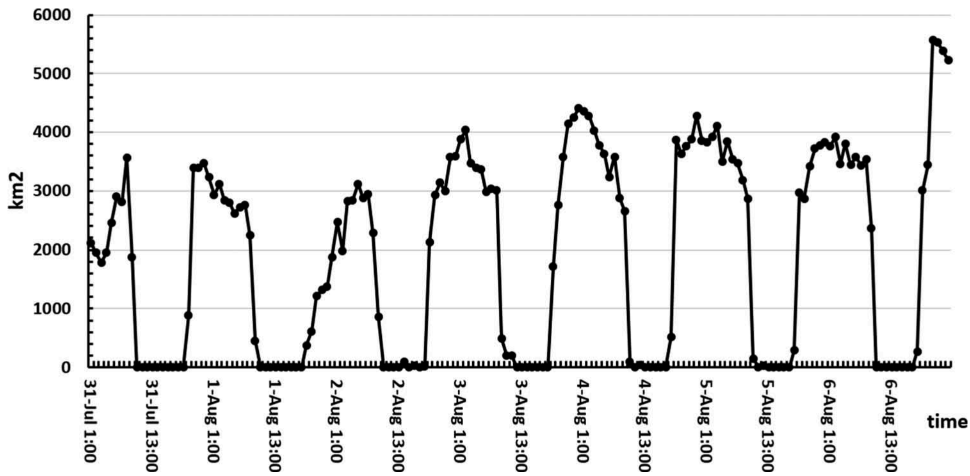

Figure 12. The total area of UHIs during 7 days in the whole study area.

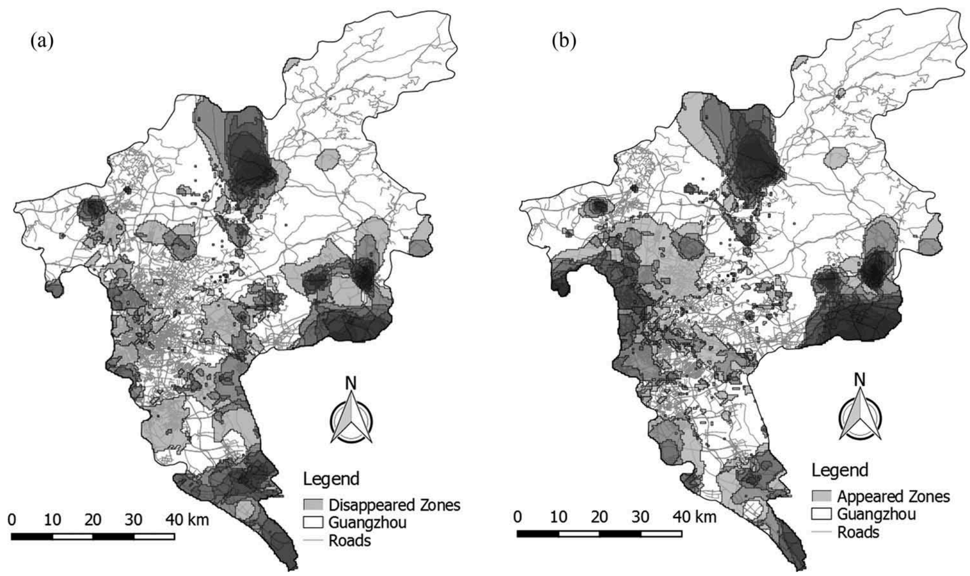

Figure 13. Roads are overlapped with disappeared and appeared zones of UHIs. (a) Disappeared zones of UHIs. (b) Appeared zones of UHIs.

time instant. For example, a UHI has been merged by another UHI cannot be split as several pieces at the same time.

The model considers UHI as localized phenomenon since many studies have suggested that thermal emissivity in the urban areas mainly comes from buildings, transportation, and human activities, all of which are very likely associated to fixed locations. Thus, current study only models extent movement of UHIs. The interpolated surface of near-ground air temperature is sufficient to construct UHIs covering the urban areas. In this work, threshold temperature to extract UHI is varying continuously, which is with a given temperature difference from an hourly updated rural temperature. In essential, this strategy excludes the impact of rural temperatures changes on the UHI boundary determination.

The model can incorporate different spatial and temporal scales in order to describe the UHI dynamic at different levels of detail. UHI behavior could be described spatially at city, district, or block level and temporally at daily, monthly, or yearly intervals. For instance, spatial scale is variable in shape from urban areas to city-clusters and temporal scale can be further expanded in time to a finite future time instant. More complicated behaviors can be modeled in new classes inheriting the event class. Also, interesting patterns can be predefined in cooperation with the direct association relationship with *sequence* and *process*. This model can be extended for tracking other environmental phenomena as well. For example, by continuously recording the wind speeds (i.e. directions and velocities) and incrementally summarizing the historical dynamic behaviors, this model can be used for predicting future revolutionary process of typical moving field-objects, for example, providing an early warning service for environmental and planning authorities.

A case study also demonstrates that the proposed model is able to reveal some particular revolutionary trends. As an overall trend, UHIs normally appear after the sunset, mostly grow and merge together before middle night, become stable and significant after the middle night, and finally split and disappear fast during the sun raising in the next morning. Moreover, location-associated hotspots of appeared zones and disappeared zones indicate a convincing periodical trend of UHIs. Specifically, these zones which perfectly coincident with each other are mostly small and discrete locating in the dense urban areas, which suggests that these UHIs probably have very stable status all through the time.

Future work is planned in three aspects. First, future work will extend this model by integrating thematic changes of UHIs. Thus, thematic and spatial behaviors of UHIs will be tracked simultaneously and their correlation relationship can be investigated deliberately. Second, it is helpful to model UHIs having several *active* and *dormant* periods since a UHI can appear and disappear periodically at a given place so that more significant periodical patterns can be revealed in the future. Third, future work will use this model to investigate UHI in a finer scale of an urban area such that underlying mechanism of the UHIs phenomenon may be revealed by synchronously tracking other hypothetical influential elements. For instance, a UHI may contract or expand periodically while its thematic intensity maintains at 33°C because it locates at a place where many air conditioning transformers are hanging on an outer wall.

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Disclosure statement

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