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Event-based Tracking of the Dynamic Behavior of Urban Heat Islands

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Introduction

UHIs are increasingly being a measurable influence in the weather and even regional climate evolution.

1. Phenomenon

Rural areas become urbanized areas
Small and middle-sized cities expend to be metropolises
Mega cities grow to be spatial contiguous city clusters

2. Demand

Tracking the evolutionary behaviors of the UHIs to reveal the mechanizes of the phenomena and to propose strategies for impairing its adverse effects are hence highlighted.

3. Problem

Current temporal GIS models particularly for the application of the UHI still limits to the static or preliminary dynamic modeling which cannot sufficiently simulate and track its evolutionary behaviors.

4. Objective

To establish a spatiotemporal model to track the dynamic behaviors of the UHIs.

Related Work

Toward more abstract representations

1. Field-based Data Modeling

Topological transformation operations for field-object are not systemically modeled (Nixon et al., 2010)

Required function to track topological transformation is not clearly stated (Kjenstad, 2006)

The method heavily relies on complex algorithms (Guilbert et al., 2007)

2. Event-based Data Modeling

Work does not establish spatiotemporal queries for knowledge discovery on processes and events (Yuan, M., 2001)

Behavior estimation model is not systematic (McIntosh et al., 2005)

3. Object-based Data Modeling

Do not provide direct guidance for the topological transformation of polygons (Li et al., 2013)

Conceptual Model of Urban Heat Islands

Traditionally, an UHI is simply conceptualized as an environmental phenomenon where temperatures in the urban area is considerably higher than its surrounding rural area.

1. Demands a Scale Free Model

In a ne geographical scale, this phenomenon may involve in many heat islands within an urban area.
In a larger geographical scale, this phenomenon may contain a set of heat islands among several cities.

2. Field Conceptualization

Temperatures can be modeled as a set of two-dimensional fields between different elevations.
Temperatures are able to warm up, cool down, or remain constant triggering the shape variation of each field.
UHI is a shape-variable field in a particular elevation determined by environmental temperatures.

3. Object Conceptualization

With the decreasing of temperatures in a continuous space and time, an existing UHI may be disappeared.
Model it as the death of its *life-cycle* from the *alive* state to the *dead* state.
With the decreasing of temperatures, this disappeared UHI may reappear again after a period of time, i.e., named as *apparent-death time*.
UHI is an object having its own life-cycle with three alterable states, i.e., *dead*, *reincarnation*, and *alive*.

Conceptual Model of Urban Heat Islands

4. Field-object Conceptualization

Model UHI as a field-object which has both spatial and temporal characteristics.
Model the spatiotemporal model of UHI with MADS since it is more expressive and complete in spatiotemporal data conceptual modeling.

Both UHI_A and UHI_B are respectively conceptualized as a two-dimensional field (i.e. SimpleSurface in MADS) associated with the continuous time.

Since temperatures are constantly changing in form of multiple fields (i.e. SimpleSurfaceBag in MADS) in a continuous space and time, UHI_A is transformed as UHI_B in terms of temperatures and shape.

Figure 1. Conceptual model of spatiotemporal urban heat island with MADS

Logical Model of Urban Heat Islands

1. Hypotheses

Hypothesis I.

Thermal interaction of air occurs in a horizontal two-dimensional surface in each particular elevation.

This means complex thermal exchange among different elevations is omitted in the current study.

Hypothesis II.

Variation of temperatures is the driving force that triggers operation of the whole UHI system.

Hypothesis III.

Each UHI is a field-object continuously representing its dynamic behaviors in form of topological transformation denoted by its own thematic attributes, which consequently triggers its state transitions of the *life-cycle*.

Hypothesis IV.

Location of an UHI is not likely moving in a significant long distance.

This indicates that an UHI viewed as an object most probably will stay at a given range of locations because confidential evidence has approved that thermal emissivity in the urban areas mainly comes from buildings (approx. 65%), transportation (approx. 30%), and human activities (approx. 5%), all of which are obviously location associated.

Logical Model of Urban Heat Islands

2. Event-based Dynamic Behaviors of Urban Heat Islands

In an abstraction level, an UHI would stay in the *dead* or *alive* state
or experiences a *reincarnation* state transiting from *dead* to *alive*.

born creates a new urban heat island.

disappear leads to the death or inexistence of an urban heat island in the next time instant.

In the alive state, each UHI may independently experience an evolution
triggered by three particular event-based dynamic behaviors
since temperatures are increased, constant, or decreased during two consecutive time instants.

grow enlarges the area of an urban heat island within a given range of area shifting.

stabilize maintains the area of an urban heat island within a given range of area shifting.

shrink compresses the area of an urban heat island within a given range of area shifting.

Logical Model of Urban Heat Islands

2. Event-based Dynamic Behaviors of Urban Heat Islands

Two or more UHIs may also interact with each other with more complex dynamic behaviors when temperatures are constantly changing.

inherited merge absorbs at least one urban heat island into the body of an originally existing one.

generated merge merges at least two urban heat islands together as a newborn urban heat island.

inherited split is an opposite process to the inherited merge that an urban heat island is still alive by inherited maintaining itself and splitting part of its body into other separated ones.

generated split is an opposite process to the generated merge that an urban heat island is dead by splitting itself into at least two newborn urban heat islands.

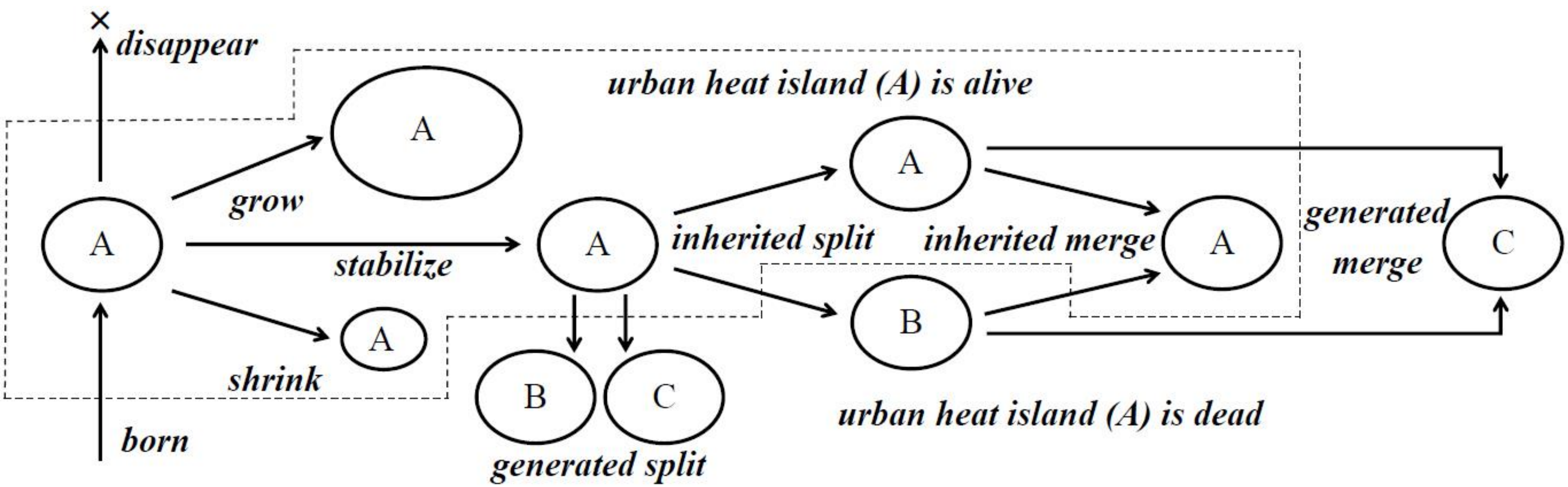


Figure 2. Event-based dynamic behaviors for an urban heat island (A)

Logical Model of Urban Heat Islands

2. Event-based Dynamic Behaviors of Urban Heat Islands

To track these dynamic behaviors and to reveal spatiotemporal distribution patterns of the UHIs, concepts about *sequence* and *pattern* are further proposed.

sequence is a set of time serial based events that an UHI experienced starting from three possible events, i.e., *born*, *generated merge*, or *generated split* and ending in three possible events, i.e., *disappear*, *generated merge*, or *generated split*.

sequence records the historical event-trajectory of an UHI such that its dynamic behaviors and characteristics are revealed during whole of its *life-cycle*.

pattern is a aggregation of sequences that UHIs share the same or similar sequence characteristics in the same spatiotemporal space.

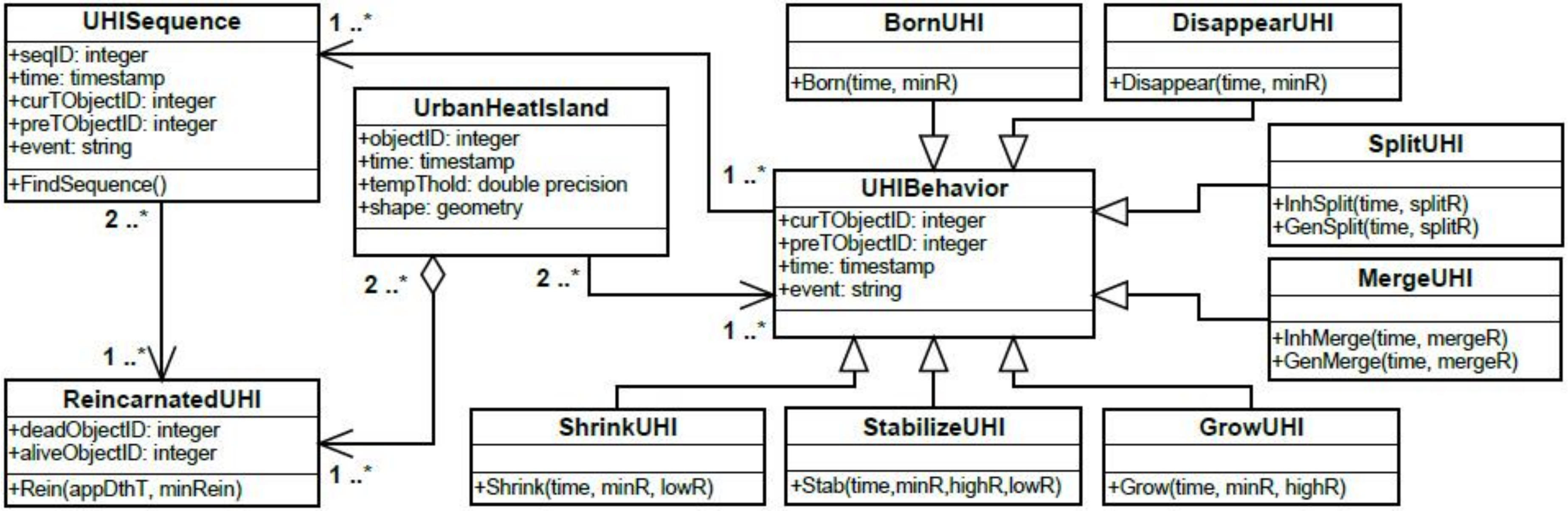


Figure 3. UML diagram for the logical model of urban heat islands

Implementation of the Model

1. System Environment

Object-relational database management system (DBMS) PostgreSQL 9.3.4 (to manage test data sets)

pgAdmin 1.18.1 (as an administrative and management tool)

Experiments for evaluating performance of the system have been conducted
in Windows 8 64-bit with Intel(R) Core(TM) i7-4770 CPU (4 cores, 8 processors, 3.4GHz, and 16.0 GB RAM)

2. Functionality and Table Structure of the System

Managing input data sets and constructing UHIs

Simulating and tracking event-based dynamic behaviors of the UHIs

Performing analysis to reveal their spatiotemporal distribution patterns

Implementation of the Model

2. Functionality and Table Structure of the System

Urban Heat Island Constructing, Event-based Dynamic Behavior Tracking, Spatiotemporal Patterns Discovering

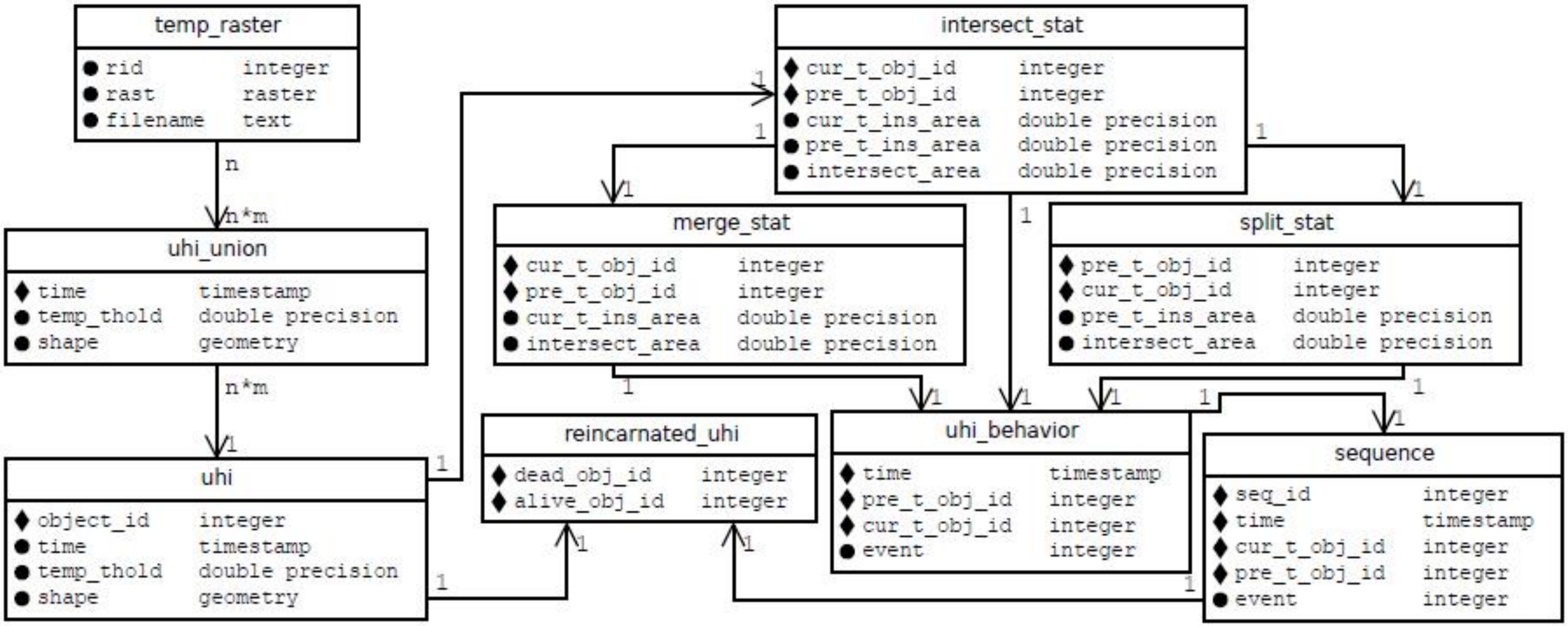


Figure 3. UML diagram for the logical model of urban heat islands

Table 1. Each number denotes one specific event for each two consecutive time instants

Int.	Event	Notation	Int.	Event	Notation	Int.	Event
1	grow		5	inherited merge	diff. objects	9	generated split
2	stabilize		6	generated merge		10	disappear
3	shrink		7	inherited split	same object	11	born
4	inherited merge	same object	8	inherited split	diff. objects		

Implementation of the Model

3. Tracking Algorithms

Definition Let ***S*** be a two-dimensional space and ***T*** be a given period of time starting from zero, and let ***p*** be the current timestamp with a constant time interval in ***T***.
Let ***Gp(c)*** denote an urban heat island in shape of ***G*** (i.e. a single polygon) at ***p*** existing in ***<T, S>***, in which the temperatures are equal or higher than a system-defined threshold ***c***.

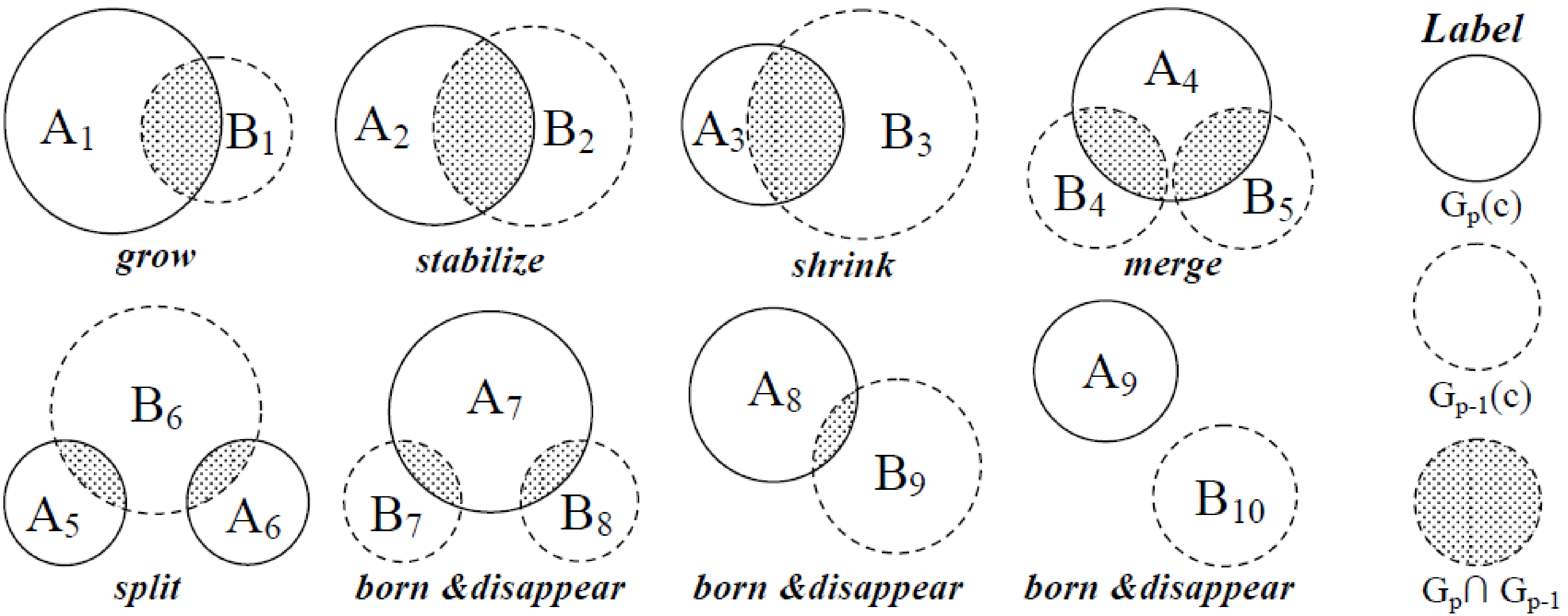


Figure 5. Event-based behaviors criteria for the Gp(S, c) heat island tracking

Implementation of the Model

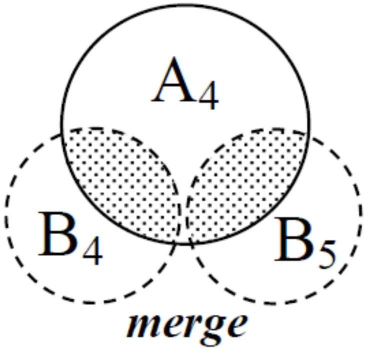
3. Tracking Algorithms

Let there be an UHI ***$G_p(c)$*** and a set of UHIs ***$\{G_{p-1}(c)\}$*** in the same ***<T, S>***. If the UHI ***$G_p(c)$*** clips the UHIs ***$\{G_{p-1}(c)\}$*** such that the number of clipped UHIs ***$\{G_{p-1}(c)\}$*** that satisfy the Equation 1 is equal or bigger than two, then the UHIs in ***$\{G_{p-1}(c)\}$*** satisfying the Equation 1 are merged into the UHI ***$G_p(c)$*** at the ***p***-th timestamp.

inherited merge when the maximum intersection area ***$\vee A(G_p \cap G_{p-1})$*** divided by the area ***$A(G_p)$*** is equal or bigger than the threshold *inhMerge* as it is presented in the Equation 2.

In particular, the UHI ***$G_{p-1}(c)$*** that has the maximum intersection area is still *alive* inherited by the UHI ***$G_p(c)$*** (i.e. both UHIs are the same object) while other UHIs are *dead*.

generated merge when the maximum intersection area ***$\vee A(G_p \cap G_{p-1})$*** divided by the area ***$A(G_p)$*** is smaller than the threshold *inhMerge* as it is presented in the Equation 3. In this scenario, all the UHIs ***$\{G_{p-1}(c)\}$*** are *dead* and the UHI ***$G_p(c)$*** is generated as a new object.



$$\frac{A(G_p \cap G_{p-1})}{A(G_{p-1})} \geqslant minRelated \tag{1}$$

$$\frac{\bigvee A(G_p \cap G_{p-1})}{A(G_p)} \geqslant inhMerge \tag{2}$$

$$\frac{\bigvee A(G_p \cap G_{p-1})}{A(G_p)} < inhMerge \tag{3}$$

Empirical Evaluation

1. Data Sets

Data sets of the near-land (approximately 3 meters above the ground) air temperature used in the current research is hourly updated provided by the Southeast Coastal Ocean Observing Regional Association.

Around 1600 sampling points are interpolated for each hour from 9.00 am of June 7, 2014 to 9.00 am of June 10, 2014 to create contiguous surfaces of near-land air temperature.

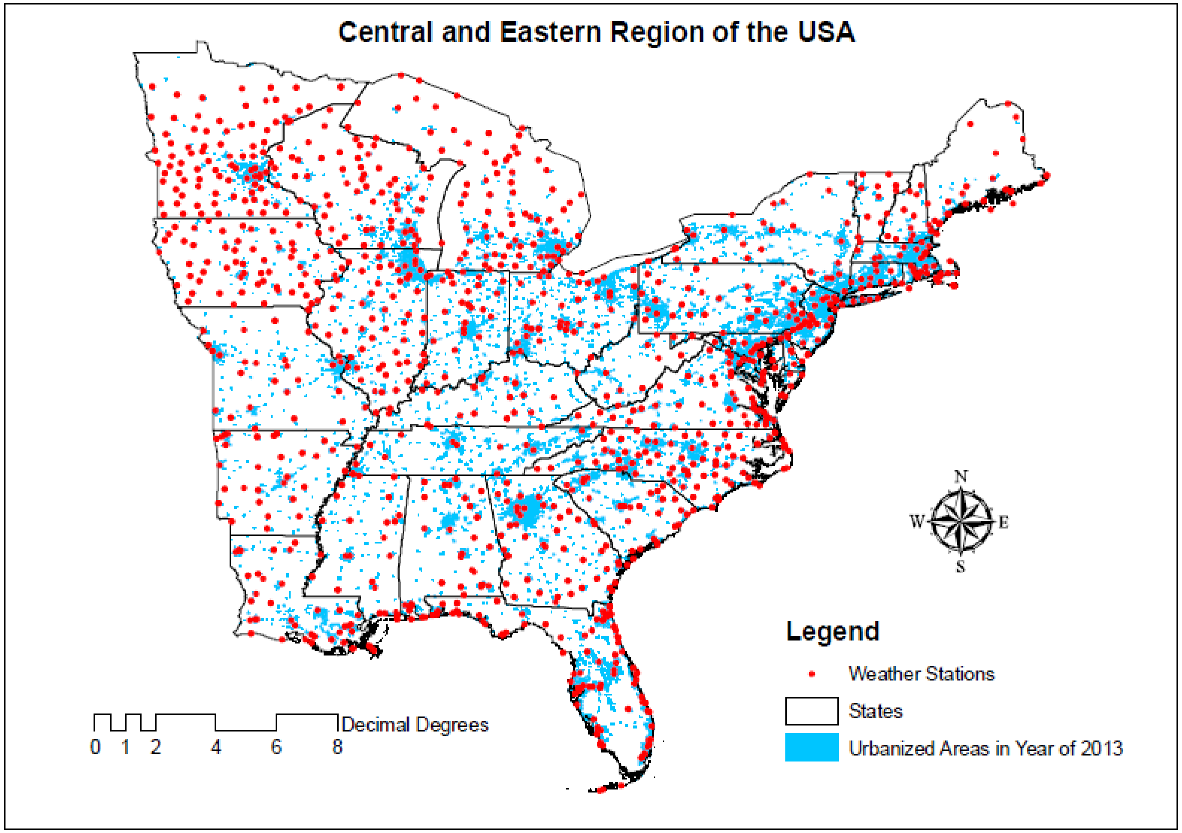


Figure 6. Location of 1600 weather stations in the central and eastern region of the USA

Empirical Evaluation

2. Evolutionary Trajectories of Urban Heat Islands

Input parameters: min_related = 0.65, inh_merge = 0.65, min_split = 0.2, inh_split = 0.5001, and min_rein = 0.5001

UHIs are constructed each hour for three continuous days and for each temperature threshold from 24 to 32 degrees Celsius with a constant of 1 degree Celsius interval.

This means there are 72 time instants, and for each time instant there are 9 layers of UHIs respectively in a set of temperature thresholds ranging from 24 to 32.

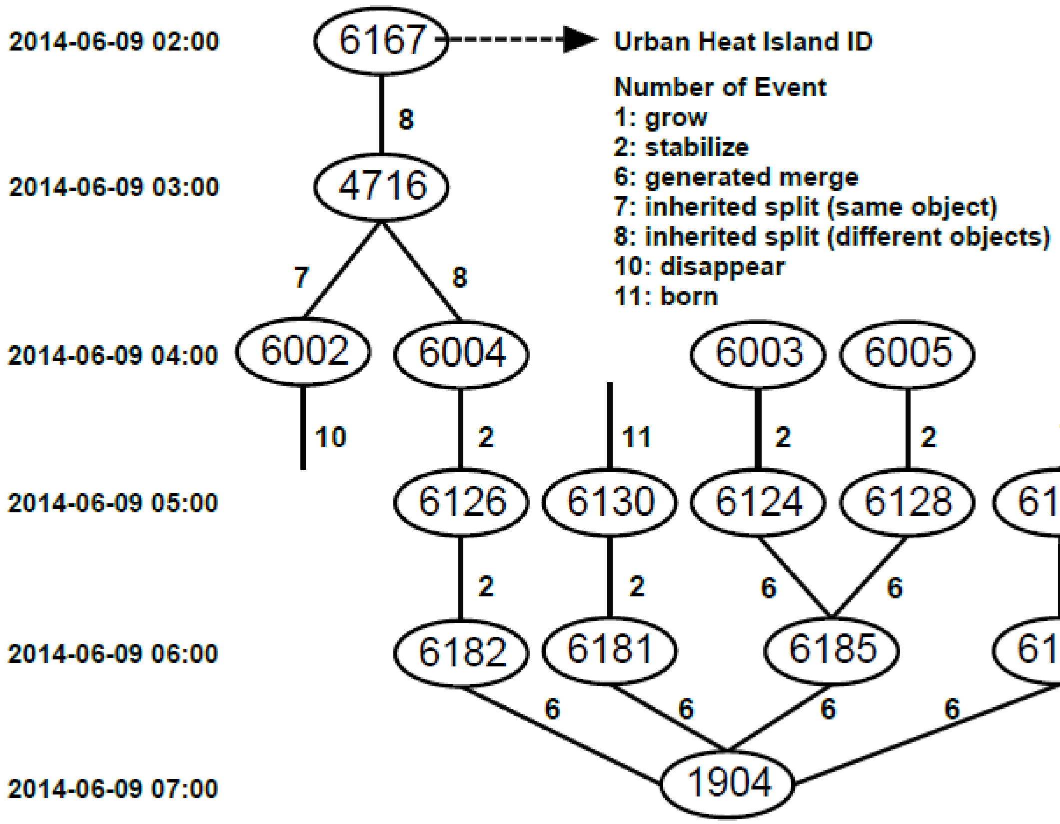
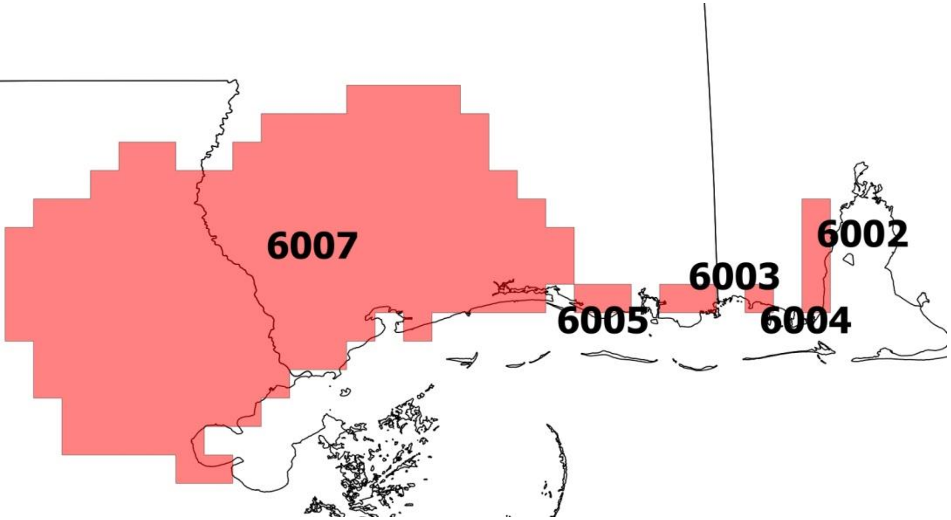


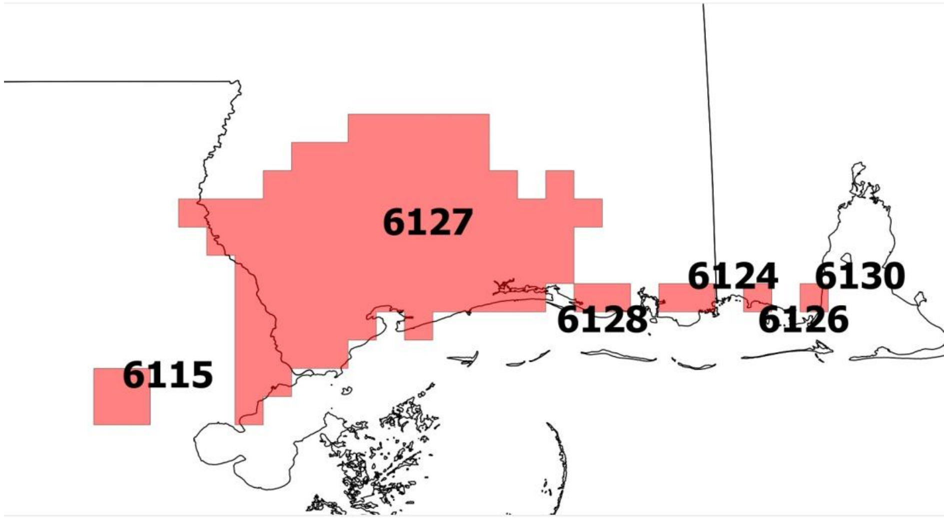
Figure 7. Evolutionary trajectories of urban heat islands drawn from part of the sequence table

Empirical Evaluation

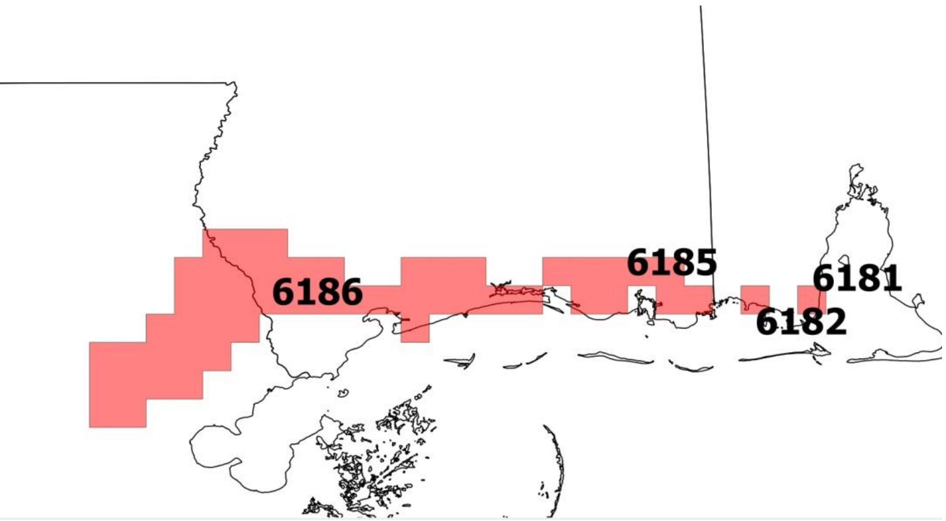
2. Evolutionary Trajectories of Urban Heat Islands



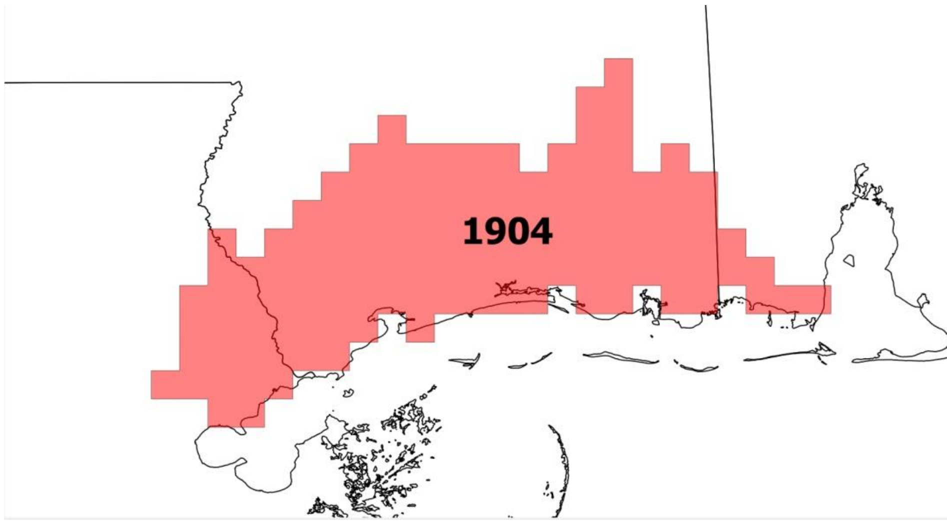
(a) UHIs are along the coastline at 4.00 am of June 9, 2014.



(b) UHIs are shrinked slightly at 5.00 am of June 9, 2014.



(c) UHIs are shrinked signicantly at 6.00 am of June 9, 2014.



(d) UHIs are merged as a big one at 7.00 am of June 9, 2014.

Figure 8. Shape evolution of urban heat islands at four consecutive time instants

Empirical Evaluation

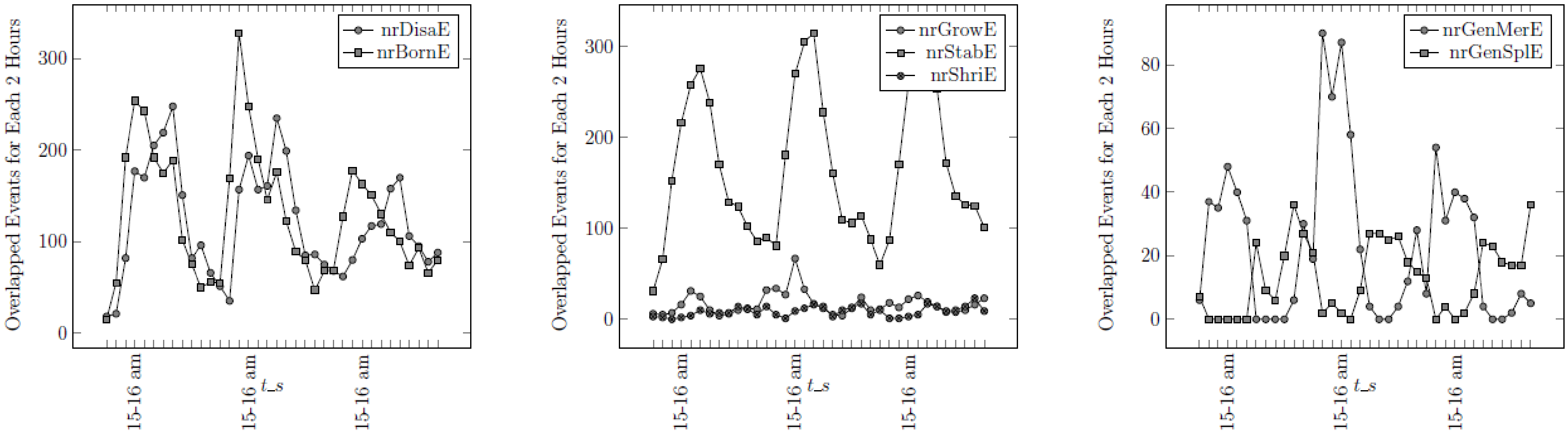
2. Evolutionary Trajectories of Urban Heat Islands

Table 2. Part of the sequence table showing the reincarnated urban heat islands

seq_id	time	cur_t_obj_id	pre_t_obj_id	event
8561	2014-06-08 14:00	7842	0	11
8561	2014-06-08 15:00	7946	7842	2
8561	2014-06-08 16:00	7981	7946	2
8561	2014-06-08 17:00	8000	7981	2
8561	2014-06-08 18:00	0	8000	10
14295	2014-06-09 14:00	8179	0	11
14295	2014-06-09 15:00	8145	8179	2
14295	2014-06-09 16:00	8187	7145	2
14295	2014-06-09 17:00	8184	8187	2
14295	2014-06-09 18:00	0	8184	10

The rein_uhi table records that UHIs with the cur_t_obj_id 8000 and 8179 are a pair of dead_obj_id and alive_obj_id, which means that UHI 8000 is reincarnated as UHI 8179 with an *apparent-death time* of 24 hours.

2. Evolutionary Trajectories of Urban Heat Islands



(a) *nrCreaE* is range from 15 to 330, and the curves for the number of *born* and *disappear* events are perioidcal with around 6 hours of peak displacement.

(b) *nrStabE* is periodical ranging from 30 to 310, but trend of curves for the number of *shrink* and *grow* events is not obvious.

(c) *nrGenMerE* ranges from 0 to 90, and the curves for the number of *generated merge* and *generated split* events are periodical with dislocational peak periods.

Figure 9. The number of the incremental summarized events for each two hours

The *born* curve is considerable because it reaches the second highest value around 9 pm as well during the first two days, which indicates that heating effect due to human activities can be essential during the night.

The *stabilize* curve reveals that a great number of generated UHIs are stable in the specific locations and incrementally accumulated during the day time.

The *generated merge* curve has a synchronized trend with the *born* event, which also most probably because of the temperature increasing.

Discussion and Conclusion

The logical model is extensible easily in different levels or scales if other tracking tasks are specified.

Complex DBMS aspects that deal with concepts such as granularity size is beyond the scope of current study.

The maximum area threshold used in the current research is set empirically after a number of prior experiments.

Parameter *minRelated* must be bigger than 0.5 because in the merge event an UHI $G_{p-1}(c)$ can be merged into only one of the UHIs $\{G_p(c)\}$ which requires that there is only one instance that $A(G_p \cap G_{p-1})$ divided by $A(G_{p-1})$ is equal or bigger than *minRelated* (*minRelated* > 0.5).

inhMerge and *inhSplit* are the same with the similar reason.

To deal with data sets that are with unequal time intervals
(e.g. a time serial of thermal remote sensing images from different satellites),
the concept of *maximum area changing ratio* determined by *time* may be integrated with *minRelated*
such that temperature layers (no matter in raster or in vector data type) with unequal time intervals still can be used for tracking the dynamic behaviors of UHIs.

Thank You ☺

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