SCOUTS: A Smart Community Centric Urban Heat Monitoring Framework

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ABSTRACT

Due to the rapid growth of buildings, depletion of green cover, and climate change, extreme heat events are posing an increasing threat to many urban communities around the world. To date, urban heat vulnerability research has mostly focused on generating coarse-grained heat maps of cities using satellite images with low spatio-temporal resolutions to quantify the heat hazard. While some recent works propose incorporating data from nearby static weather stations, they fail to reflect the spatial variations of air temperature in urban areas due to the limited availability of weather stations. In this paper, we present our vision for a multi-layer approach to tracking the actual heat experienced by individuals and communities with very high spatio-temporal resolution. The proposed framework, Smart Community-centric Urban Thermal Sensing (SCOUTS), seamlessly support a variety of human, and vehicle-borne sensors in conjunction with satellite and weather station data to accurately map the heat hazards of urban regions and communities.

CCS CONCEPTS

• **Information systems** → **Information systems Application**
→ **Spatial-temporal systems** → **Location based services**

KEYWORDS

Mobile Crowdsensing (MCS), Individually Experienced Temperature, Urban Heat Islands, Ambient Air Temperature

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1 INTRODUCTION

Extreme heat events increasingly pose a serious public health problem in the U.S. and around the world. Based on a report published in 2017 by the Centers for Disease Control and Prevention (CDC), an average of 618 people are killed each year in the U.S. by extreme heat events [1]. This phenomenon leads to many heat-related illnesses such as heat syncope, heat stroke and heat exhaustion which are preventable [2]. Even within a given urban area, the risk for heat-related morbidity and mortality varies among communities based on their physical exposure to heat as well as vulnerability factors such as age, health, and access to air conditioning.

To be able to devise effective strategies for protecting different groups of people from extreme heat-related hazards, it is imperative that we comprehensively track and understand the heat hazard risks of various at-risk communities. The poor, minorities, infants and seniors are at higher risk due to a combination of poor health, lack of access to air conditioning units and social resources to cope with the heat. Another vulnerable community is outdoor workers such as those involved in construction, sanitation, public works, and mail delivery [3]. Considering the warming climate trend, ambient heat exposure could be a prominent safety concern for employees in the near future [3].

The warming climate has exacerbated the Urban Heat Island (UHI) phenomenon which is the result of changes in urban climate compared with adjacent rural areas due to urbanization. Variables contributing to a city's UHI include increased surface area of buildings, decreased moisture and vegetation, greater

heat capacities of building material, and anthropogenic heat waste from vehicles and different types of machinery. The heat absorbed during the day is radiated out at night, which leads to an increase in the relative nighttime temperatures [4]. Therefore, this phenomenon has altered the urban climate not only during the daytime but also in the nighttime.

To monitor and analyze the heat exposure, current approaches which are mostly based on remote sensing fail to capture the highly dynamic nature of UHIs. For example, Landsat 8 satellite imagery with thermal bands has been widely used in the research community to generate heat maps, while images taken every few days at a fixed time of a day does not allow researchers to analyze the dynamicity of daytime and nighttime behavior of this phenomenon. These approaches are also subject to errors associated with atmospheric correction procedures to remove the scattering and absorption effects from the unstable atmosphere on the satellite images.

In this paper, we delineate our vision for a scalable cloud-based crowdsensing framework to monitor and analyze the heat exposure of individuals in different urban regions. This study explores the shortcomings of current methodologies and challenges associated with building a smart, accurate and agile thermal sensing framework. Towards addressing the challenges, we present a high-level architecture of our framework. The framework is unique in the sense that it is specifically designed to seamlessly integrate data from a variety of human and vehicle-borne sensors with traditional temperature data sources such as satellites and weather stations to capture and analyze heat stresses of urban regions and communities.

2 BACKGROUND AND RELATED WORK

In this section, we first discuss the limitations of current approaches to map the spatio-temporal variability of temperature. We also provide results from field studies to demonstrate the constraints of traditional sources of temperature data. We then discuss research studies that are geared towards crowdsourcing and explain their shortcomings.

There have been many research studies trying to locate and analyze variation in heat exposure in different cities, all of which have fundamental limitations associated with them. We can divide these studies into two categories: remote sensing-based methodologies and in situ-based methodologies.

In remote sensing techniques, researchers use satellite images with thermal infrared bands to derive heat maps. They use the emissivity of land surfaces, as a measure of effectiveness in emitting energy as thermal radiation, to calculate the land surface temperature. They also apply atmospheric correction methods to minimize the effects of the atmosphere on the images. Other than the instability of atmospheric conditions, the low spatio-temporal resolution is the main limitation of these techniques. For example, the thermal bands of Landsat 8 satellite images have a coarse spatial resolution of 100 meters. It also produces only one image every sixteen days from a given geographical area. ASTER and MODIS are two other satellite sensors with 90-meter and 1000-meter spatial resolution, and 16-days and daily temporal resolution, respectively.

In in-situ-based techniques, researchers rely on the readings from weather stations to measure the temperature of different areas. Spatial resolution of the network of weather stations is their main limitation. The study by Kuras et al. [4] suggests that heterogeneity in heat exposure exists even within an urban neighborhood. The experienced temperature can be affected by microclimate differences due to vegetation, buildings material, and street orientation. Consequently, a limited number of weather stations cannot capture the air temperature heterogeneity. In another study, Bernhard et al. [5] raised the same issue of the difference between readings from the nearest weather station and the experienced individual heat exposure.

In order to better understand the spatial variability of the ambient air temperature, we collected data on different dates using standard temperature sensors. For instance, we conducted an experiment on 10 July 2017 during which 25 temperature sensors (Kestrel DROP environmental data loggers with ± 0.5 °C accuracy) were installed in an area of about 0.16 km^2 of the University of Georgia (UGA) campus for 90 minutes in the morning between 9:45 AM and 11:15 AM. To measure the ambient air temperature, sensors were installed about one meter above the ground over different surfaces such as asphalt, grass, sand, and concrete. Fig. 1 illustrates the exact location of each sensor on the map.

Figure 1. Temperature Sensors Locations

Collected data shows the air temperature variations in this small area. On average, there was a 9.5 °C difference between the highest and the lowest recorded temperature at the same given points of time. We also compared the readings with the nearest weather station (1.75 km away from the study area), and we observed a 5 °C difference, on average, between the mean temperature recorded in the area and that of the weather station. These measurements represent the variation of ambient air temperature in response to different factors such as land cover or shading which is not obtainable by a limited number of weather stations.

However, it is impractical, at least in the near future, to have thousands of sensors installed on different parts of any given area because of the exorbitant cost it would impose. The proliferation of smart mobile phones, sensors, and GPS have made crowdsensing an attractive medium for gathering data at much richer spatio-temporal granularity in many geospatial domains. Michael Goodchild [6] introduced the term

Volunteered Geographic Information (VGI), as a particular case of the general phenomenon of user-generated contents. VGI is more prominent when analysis of highly dynamic features such as ambient air temperature is the primary concern.

We now discuss the related works trying to measure and analyze urban heat temperature through crowdsourcing. Overeem et al. [7] proposed a crowdsourcing method to measure air temperature using smartphone battery temperatures. They failed to take the fact into account that temperature of smartphone batteries can be impacted by many different factors including the phone's model, screen size, number of running applications and OS version. They assumed that phones are usually carried in pockets close to the user's body and came up with a heat transfer model. Their model is based on some certain assumptions which make it limited and non-scalable.

Recently, Chapman et al. [8] and Meier et al. [9] implemented two different case studies by using low-cost weather stations (i.e., Netatmo) to quantify the urban heat island of London and Berlin, respectively. These studies fail to capture the personalized individually experienced temperature and also community-centric heat exposure. More importantly, their approach is limited to a network of specific stationary sensors, which makes it non-scalable.

3 SCOUTS OVERVIEW

The overarching goal of this framework is to efficiently integrate and analyze data from multiple diverse sources such as human, and vehicle-borne sensors, satellites and weather stations for effective identification and tracking of heat stress risks of individuals and urban communities. Mobile Crowdsensing is an essential component of the SCOUTS as it helps us gather data at much finer spatio-temporal granularities compared to traditional sources. Since the framework has to support highly heterogeneous data sources seamlessly, it adopts the concept of data virtualization. The key strength of data virtualization is that it allows the users of the framework to retrieve and analyze data from diverse sources without needing to know the technical details about the data or its source.

The framework is composed of three layers, namely physical, virtualized data, and modeling/ notification layers. Fig. 2 shows the high-level architecture of this framework based on a multi-layer bottom-up model.

The physical layer is composed of the actual data sources such as temperature sensors, mobile devices, satellites, and weather stations. SCOUTS is designed to support a variety of small temperature and humidity data loggers (such as Kestrel DROP or iButton) which can be attached to clothing or backpacks. We have developed iOS and Android applications to communicate with the sensors and upload the data to the cloud. Weather stations are another data source providing us with readings of environmental features such as temperature and humidity. GPS information, temperature, and humidity are continuously uploaded to the virtualized data layer.

Virtualized data layer consists of cloud-based data stores and along with data analytics and data fusion tools. In conjunction with cloud storage which ensures data accessibility, data analysis

tools enable spatiotemporal data mining. Access to frequent arrays of geo-located and time-stamped data enables this layer to send quality-aware sensing feedbacks and calibration information to the physical layer. For instance, based on the heat hazard probability of a given area, configuration information will be sent to the physical layer to update the data collection frequency of sensors accordingly. Moreover, this layer integrates data streams coming from heterogeneous sources and perform anomaly detection techniques to assure the integrity of data.

The third layer is the modeling and notification layer, to which the analyzed and filtered data is fed. Data plotting and visualization are the two main tasks of this layer which yields urban heat maps, individual, and community-centric heat exposure maps with high spatio-temporal granularities. It also generates heat hazard notifications, sending alerts to individuals or communities who are at the risk of extreme heat events.

Figure 2. High level architecture of the SCOUTS framework

There are some research challenges associated with the full implementation of this framework. Other than the data quality measures and calibration methods, mechanisms to detect misplacement of sensors and filter out the sensor readings which are not the true representative of the outdoor air temperature is of crucial importance. In other words, the sensors which are not exposed to the outdoor environment in the crowdsensing procedure needs to be detected and filtered out. Community-centric clustering of heat stresses is another challenge where organizations can devise insightful strategies to mitigate heat hazard effects on their respective communities. Considering that the data from this framework correlates with health-related issues, a new level of privacy consideration, beyond anonymity, is required so that businesses such as insurance companies will not be able to take advantage of the heat exposure profile of communities to impose higher health insurance rates. Incentivization mechanism is the other challenge to motivate volunteers to participate, especially in the areas with more potential extreme heat events.

4 PRELIMINARY RESULTS

To have a comprehensive understanding of the heat hazards and the effectiveness of such a crowdsensing framework, we had couple of rounds of data collection.

Figure 3. Temperature Map of 28 Sept 2017

The most cloud-free date we could find was 28 Sept 2017, when four individuals were walking around the UGA campus with sensors attached to their backpacks around noon. The heat exposure map in Fig. 3 shows different walking routes along with the range of experienced air temperature during the 45-minute course of data collection. The range of temperature experienced by different individuals shows the high spatio-temporal heterogeneity of air temperature.

The only weather station in the area is located on the map, as well as the exact location of each person at 12:05 PM (the time when Landsat 8 satellite image was taken). While the individuals experienced up to about 14 °C variation in the highlighted routes, the stationary weather station recorded only around 1 °C variation during the same period. The experiment underlines the unreliability of weather stations for measuring the precise individually experienced temperature which is a crucial factor for heat-related health issues.

Now we compare the crowd-sensed data with the satellite-based heat map data. Fig. 3 shows the zoomed location of person B in the heat map generated using Landsat 8 image. While each 30-meter resampled pixel represents a single temperature value, the actual recorded temperature values are denoted on the yellow line. Although this cloud-free experiment shows around 3 °C difference between the two approaches, there is no consistency in this difference among different locations and dates. For instance, we recorded up to 21 °C difference between the generated heat maps' pixel values as opposed to the crowd-sensed temperature values.

5 SUMMARY

Extreme heat events are increasingly becoming a threat to human health and wellness in many countries around the world. It is of crucial importance to analyze and mitigate them in a practical way using the available technologies. In this study, we first demonstrate the limitations of current approaches to quantify the heat hazards. Then, we envisage the SCOUTS

framework, to address the limitations and to create heat exposure maps with high spatio-temporal resolution. SCOUTS helps city officials to understand the heat variation in urban areas better and devise mechanisms to make the cities more resilient. Finally, we present preliminary results to show the effectiveness of such a framework to analyze and mitigate urban heat hazards.

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