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Long-term impact of rapid urbanization on urban climate and human thermal comfort in hot-arid environment

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ABSTRACT

The long-term impact of rapid urbanization on air temperature (T_a), relative humidity (RH), vapor pressure (VP) and human thermal comfort in the Cairo governorate of Egypt was analyzed. Land use change (LUC) between 1973 and 2017 were derived from Landsat satellite data. Next, non-parametric change point and trend detection algorithms were applied to T_a, RH and VP over 1950–2017 to estimate the impacts of urbanization on urban climate. Three historical thermal comfort indices: temperature humidity index (THI), effective temperature index (ETI) and relative strain index (RSI) were estimated from climate data collected between 1950 and 2017 to assess the impact of urbanization on human thermal comfort. The results reveal substantial LUC, rapid increasing impervious surface areas in low-lying areas of Cairo at 75.2 km^2/decade since the 1990s. Rapid urbanization had resulted in a statistically significant change point in T_a after 1995 with a warming trend of 0.19 °C/decade, a negative trend in RH of 0.55%/decade and a rising trend in VP of 0.24 hPa/decade. Severe heat stress levels emerged and persisted every July–September since 1994. THI, ETI, and RSI show statistically significant change points at 1994 and a rising trend of 0.33 °C/decade, 0.29 °C/decade, and 0.06/decade, respectively. The highest thermal discomfort risk was found in urban areas of the old Cairo, but the risk is marginally smaller at new cities where there are vegetation covers. This study clearly demonstrates the impacts of rapid urbanization on the urban climate of hot-arid environment.

1. Introduction

Since the 1970s, population growth in Egypt has increased dramatically from 35 million (1970) to about 100 million (2017) and therefore urbanization has become a major issue socially and politically. The Cairo governate, the capital of Egypt, is likely one of the most densely populated regions in the world with a population of over 10 million concentrated in an area of 2886 km^2 [1]. Rapid urbanization has led to an imbalance between demand and supply, the available infrastructure is under stress, and the urban climate in Egypt is altered. A rapid expansion of urban areas within Cairo governates has resulted in serious environmental and social problems, such as the rise of urban slum communities. Many studies have showed the usefulness of remotely sensed (RS) data in monitoring landuse information and the earth surface obtained from an integration of RS data and geographic information systems (GIS) [2–5]. Various change detections techniques were used in past studies such as band differencing, principal component analysis and band ratioing, to detect the change and to monitor historical land use changes [4,6,7]. In addition, neural network models such as the support vector machine (SVM) have been successfully applied in land use classifications of small cities, and small-scale studies [8,9]. There are studies that used ensemble learning techniques to detect long-term land use and land cover changes [10–12].

In the last few decades, several studies have investigated the impact of rapid urbanization on urban climate [13–17]. According to these studies, urban growth has caused increased air temperature [14,18–20], but decreased relative humidity [14,21]. Relative humidity, a ratio of actual to saturation water vapor of air, and is closely dependent on the air temperature, has a significant impact on the local climate [22]. In addition, relative humidity and air temperature are important climate variables because of their impact on human physiological comfort [22,23]. Wolkoff and Kjaergaard [21] stated that variability in temperature and relative humidity have a great impact on human health and energy requirements. Adebayo [23] found that urbanization has a significant effect on relative humidity and vapor pressure. Similar observations were found in other countries e.g. Lee [18] found a strong relationship between the urban heat island and urban vapor pressure in London, UK. In a different study, Liu et al. [14] analyzed urban-rural humidity and temperature differences in the Beijing area, China. Their study showed that urbanization has led to a

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significant increase in air temperature and a decrease in relative humidity. Most of earlier studies that investigated the impact of urbanization on urban heat island have assessed the relation between urbanization and human thermal comfort in cities e.g. Refs. [24–30]. These studies have shown that increased air temperature in cities will increase heat stress, energy consumption that causes an increase in the emissions of greenhouse gases. Furthermore, several studies reported that urbanization has a significant impact on human thermal comfort. For instance, Shaharuddin et al. [24] reported that land use change caused an increase in air surface temperature and led to the Urban Heat Island effect (UHI). In a different study, Mahmoud [29] who investigated users' thermal comfort in an urban park in Cairo, Egypt found the human comfort to depend on landscape zones because human thermal comfort varies widely in a hot and arid environment. Li et al. [30] shows that under both reanalysis data and simulations of CMIP5 global climate models, apparent temperature, the human-perceived equivalent temperature, has increased faster than air temperature over land.

Various studies reported positive improvement in urban climate by increasing areas occupied by vegetation cover, which help to decrease air temperature and increase the air humidity or water vapor [29,31]. Emmanuel [32] analyzed the implications of land cover change on human thermal comfort based on two indices; the temperature humidity index (THI) and relative strain index (RSI]) in the Colombo Metropolitan Region, Sri Lanka. He found a strong correlation between thermal discomfort and land cover change, with an increasing trend in thermal discomfort in urban areas compared to rural areas. Similarly, in Malaysia, Morris et al. [27] found that the level of urbanization had a significant effect on urban climatology and human thermal comfort, resulting in a significant increase in THI, RSI and the effective temperature index (ETI). In eastern China, Cao et al. [33] found that future urban expansion will lead to an increase in air temperatures and sensible heat flux, and urban expansion (increase in impervious surfaces) will greatly reduce relative humidity, which will increase the thermal discomfort of urban residents.

This study will provide important information to the influence of rapid urbanization on long-term air temperature, relative humidity, vapor pressure and human thermal comfort in Egypt. Similar impacts are found in many if not all Middle Eastern countries of arid climate. The main objectives of our study are (1) to detect land use change at different spatial and temporal scales in Cairo, Egypt; (2) to estimate the effects of historical land use change on the urban climate of Egypt; and (3) to assess impacts of land use change on human thermal comfort. To achieve these objectives, earth observation data was employed to measure land use change in Cairo governorate between 1973 and 2017. Buishand's non-parametric change point detection and Mann-Kendall tests were applied on monthly air temperature, relative humidity, and vapor pressure data over 1950–2017, to estimate the impacts of urbanization on urban climate in the region. Then, the non-parametric Mann–Kendall was used to detect trends in annual air temperature, relative humidity, vapor pressure, and their anomalies between 1950 and 2017. To detect the impact of urbanization on human thermal comfort, three historical thermal comfort indices series were developed between 1950 and 2017: Temperature Humidity Index-THI, Relative Strain Index-RSI, and Effective Temperature Index (ETI). Change point detections and trend analysis techniques were applied to monthly, annual THI, RSI, and ETI and their anomalies to assess the influence of urbanization on human thermal comfort. The results will be useful to urban planners for regions of other arid environments.

2. Data and research methods

2.1. Study area and data sets

Cairo governate of Egypt (Fig. 1), located at 30°02′N and 31°21′E, in the middle of the Delta Region in Egypt. Cairo, is one of the densest urban areas on Earth, where there has been extensive land use changes but no official studies have been conducted on how urban expansion has affected the urban climate. The rapid urban expansion that is not well planned has resulted in an imbalance between demand and supply, and has resulted in the stress of available infrastructure. Any data on when and how urban changes have affected the climate and human thermal comfort could be of great help in city planning and management. Two new cities within Cairo; Shrouk city (67 Km^2) and New Cairo (275 Km^2) are considered in this study to track their urban growth in the last 45 years over the desert of old Cairo. Landsat images were obtained from the U.S. Department of the Interior U.S. Geological Survey (Table 1). Digital elevation model, population, road network, land price, in addition to ground control points obtained from Visual interpretations of Google Earth images and field survey were used to support the land use classification process. Monthly air temperature, relative humidity data between 1950 and 2017 were derived from the 20th Century Reanalysis V2 Dataset, and monthly vapor pressure data from the CRU TS4.01 vapor pressure dataset. Natural disaster events for Egypt between 1954 and 2016 were obtained from the Emergency Events Database of Universite Catholique de Louvain [34] which consists of meteorological, hydrological, and climatological disasters data such as flooding, extreme temperature, dry mass movement and convective storm and their impacts on human health issues in Egypt. The number of heat-related deaths and people affected by extreme temperature in Cairo and Egypt between 1954 and 2016 were extracted from this database and checked against historical thermal comfort indices.

2.2. Historical land use dynamics

Cloud-free Landsat images of 30 m spatial resolution were resampled using the nearest neighbour algorithm, keeping the original brightness and pixel values. The resultant root mean squared error of each image was less than 0.64 pixel. Furthermore, the images have been radiometrically corrected to a base image (SPOT-5 “2.5 m”) using manually identified pseudo-invariant features (PIFs). After identifying 14 PIFs, a linear regression was used to transform the data of each band onto the same radiometric reference. Finally, prior to land use classifications, these images were preprocessed and corrected for atmospheric absorption using the cost function of IDRISI Selva. Two field surveys were conducted to collect data to support land use classification, which include ground control points, visual interpretations of Google Earth images together with satellite night images that highlight locations of urban areas. More than 700 ground control points were collected. A database for each land use class was developed using ArcGIS. The Maximum Likelihood Supervised Classification (MLC) and the ISO Cluster Unsupervised Classification methods were performed on Landsat images to produce land use maps. The Iso Cluster Unsupervised Classification was used to collect more training data and to check the results obtained from the two supervised classification methods.

Based on the collected ground control points, a supervised signature extraction using the MLC to classify the Landsat images into different land use maps. These two methods are widely used in land use classification [6,35,36]. 70% of data collected in the two field surveys was used for landuse classification and 30% of the data for validating the classified land use maps. Four main land use categories have been identified in Cairo: Water bodies, Urban and built-up areas, Cropland or Vegetation, and Bare soil. Finally, each land use map developed was checked against the validation dataset with respect to some simple random patterns. Then, a change detection technique was applied between two land use maps to evaluate the dynamics and patterns of land use change in Cairo. The area percentages of each land use category over time were calculated to detect the trends in land use change. To estimate land use dynamics, a net change between earlier and newer land use maps was derived for each land use category. Historical change or urban expansion in new cities in Cairo was also derived to provide essential information about the state of land uses or urbanization in