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Urban Heat Island: Dynamic Simulation, Assessment and Measuring Mitigation in Cities of Extreme Dry Weather

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Abstract: Increasing urbanization in the cities of northern Mexico reflects a general trend to increased temperatures, so it is likely that heat waves amplify the frequency and intensity in urban centers, mainly located in arid and semiarid as Mexicali city with extremely arid climate, very hot in summer and cold and rainy in winter. Mexicali, Baja California, Mexico is located at N32º38' and W115º20'. The urban area is expanded over 14,890 hectares, with a population rise the 689,775. In the last four decades has experienced an accelerated industrial growth and mismatched land uses, for example: most of the industrial parks were established before the 1980 in what was the outskirts of the city, but nowadays practically are inside of the urban area contributing to the increase the urban temperature. The heat islands profile shows that are intensified in industrial areas as well as trade and services. The preliminary scenarios of climate change for Mexicali indicate that for the decade of 2080 the temperature will increase between 4.2°C and 4.4°C. This paper addresses in a simulation context, an industrial and commercial city sector and their ability to implement urban heat island mitigation strategies. The simulation of this process requires several spatial analysis tools and specific knowledge about the processes that increase urban temperatures. In this work, only land use, land cover and buildings are considered. The proposed method takes into account the actual spatial organization to analyze trends for the proposed growth areas.

Key words: Urban heat island; dynamic modeling, mitigation strategies, urban planning.

1. Introduction

The urban growth that most cities have experienced, has caused great impact on the environment, vegetation has been replaced by construction elements that show a high absorption of solar radiation, high thermal capacity which modify the energy balance, such as paved avenues, buildings, enormous surfaces used as parking lots. As a consequence, consumption of energy and atmospheric pollution has increased. Therefore, identified as health problems, these have become research topics in urban weather modification [1–3].

The interest over of study the increase of temperature in cities, started almost two centuries ago, when Luke Howard documented temperature increment in urban areas compared to temperatures shown in peri-urban areas in 1833 [1].

It has been demonstrated that the production and storage of heat in cities are above the rural areas in a range from 18°C to 31°C where there has not been a dramatic change of the vegetation [3]. This heat storage is called UHI (urban heat islands) [4].

The UHI is built by a first hot layer that expresses the thermal variation of all the elements of the city, and another layer that includes the first one and that makes the transition to regional weather. The use of satellite figures do not allow discrimination of these two layers vertically, for this purpose, other devices and methodology that analyze the characteristics of each one are used. Nevertheless, the use of satellite figures makes possible to evaluate the behavior and intensity of each thermal extent and the decrease in the transition from the city to rural areas [5].

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Arnfield [6] examines the state of the art over the last two decades about the UHI phenomenon; Unger et al. [7] refer to the studies on thermal pollution when they were carried out using meteorological stations placed on vehicles or through a network of meteorological stations distributed in the cities. Other authors, as Voogt and Oke [8], present an overview of the evolution in the use of remote sensing in studies on urban heat islands.

Nowadays, most studies on UHI have taken place on densely populated cities, most of them located in mild and subtropical weathers [6]. Opposite to this, cities located in desert ecosystems have been studied very little [9]. This type of studies are even more scarce for North American deserts, which have an extreme dry weather, and except for cities like Phoenix and Tucson, Arizona [10–12] in the United States of America and more recently in the city of Mexicali in Baja California, México [13].

The aim of this research was to determine the ability to implement urban heat island mitigation strategies in an industrial and commercial city sector by a LCLUC (land use land cover change) simulation context. The proposed method takes into account the actual spatial organization to analyze feasibility and trends for the proposed growth areas.

This paper addresses in a simulation context, an industrial and commercial city sector and their ability to implement UHI mitigation strategies. The simulation of this process requires spatial analysis tools and specific knowledge about the processes that increase urban temperatures. In this work, only land use, land cover and buildings are considered.

2. Climatic and Urban Characteristics

The Mexicali Valley is located at 32º38' North and 115º20' West, a border city adjoins with Calexico, California in the United States of America (Fig. 1). The entire region belongs to the physiographic sub province of the Colorado River Delta, in the Sonoran Desert [14]. As a consequence, the city has a very arid, hot and dry climate, with rainfall during winter and an extreme thermal oscillation throughout year. In summer, higher temperatures have exceeded 50ºC; while in winter the temperatures may drop under 0ºC [15].

The 2010 census states that the city had a population of 689,775 people, covering a surface of 14,890 ha with a density of 46 Pop/ha., showing a city with horizontal expansion, that in the last three decades has suffered a demographic and economic explosion due to the growth of the manufacturing industry. Currently, there are 11 industrial parks with a total of 1,164 companies from the manufacturing industry, covering a surface of 825 ha.

The city was founded 108 years ago on a floodplain area, its physiographic is almost flat, for this reason, it shows very uniform heat transmission. It is a city with poorly planned development, uneven growth, incompatibility land use, which has provoked that the manufacturing industry has spread in almost the whole urban area. Most of these industrial parks were constructed in the 80s in the peripheral area of that time on what used to be agricultural land use; with population growth at the present time a great part of the manufacturing industry is practically inside the city.

This situation has caused that buildings made for the manufacturing industry consume a lot of energy and contribute to the increase of urban temperature, causing thermal pollution and atmospheric problems (Fig. 1). In contrast, the city has about 140 ha of urban green spaces; such surface represents about 2.1 m^2 per inhabitant, which shows a deficit of 131.35 ha according to the Mexican Norm of 4 m^2 per inhabitant [16].

According to this, we can see that the effects of the high heat emitting urban spaces are spread throughout the urban area. In contrast low heat emitting spaces or urban thermal sumps such as: green areas, sporting facilities, bodies of water, urban periphery with agriculture, represent a minimal surface compared with the industrial land use.

An overlay of the urban fabric map with an

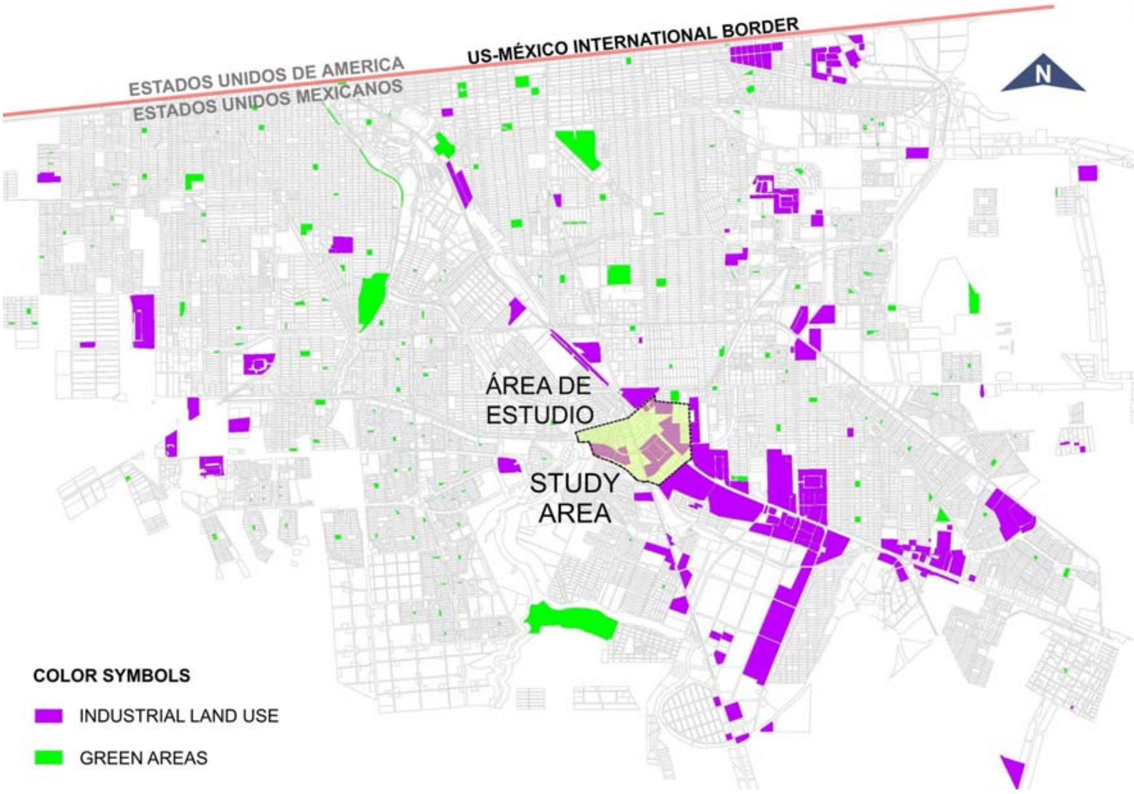

Fig. 1 Study area location and city land use.

AVHRR-NOAA satellite figure shows the different temperatures within the study area in the form of spots [13]. One of these spots is the study area presented here. It is located in an industrial and services zone adjacent to a main corridor of the city (Fig. 2) which has 232.5232 ha, the percentage for the each one of the land use is as follows: 12.4% residential, 0.5% institutions, 51.2% industrial, 18% commerce, 5% mixed use and 12.9% for infrastructure.

Regarding the construction materials used in the area of study, we found that asphalt was used for roads, sheet metal in dark red and some red brick details were used for the walls, gray sheet metal for roofing and concrete block walls and sheet metal are used in commercial and services buildings. With regards to the residential area, different construction systems were found, materials such as concrete block, clay bricks, wood, as well as light materials such as sheetrock, together with roof sealing materials such as asphaltic cement and membranes.

3. Model Methods and Materials

Modeling has been an endeavor that has caught the attention of regional and urban planners like other specialties. A common definition of model is "a simplification of reality" [17]. The modeling objective is to take a given complex system and identify the elements that define the system and how these relate to each other. In this case, our intention is to contribute to the understanding of the benefit of applying UHI mitigation strategies in cities like Mexicali with an extreme dry weather.

A study by Lawrence Berkeley National Laboratory estimated the average surface temperature under different land cover conditions [18] — this is relevant when you look the temperatures profiles of a place. The study states the surface temperature as:

$$T_{vegetation} \times A_{vegetation} + T_{paving} \times A_{paving} + T_{roof} \times A_{roof} + T_{misc} \times A_{misc}$$

where, T is the temperature and A is the fraction of the

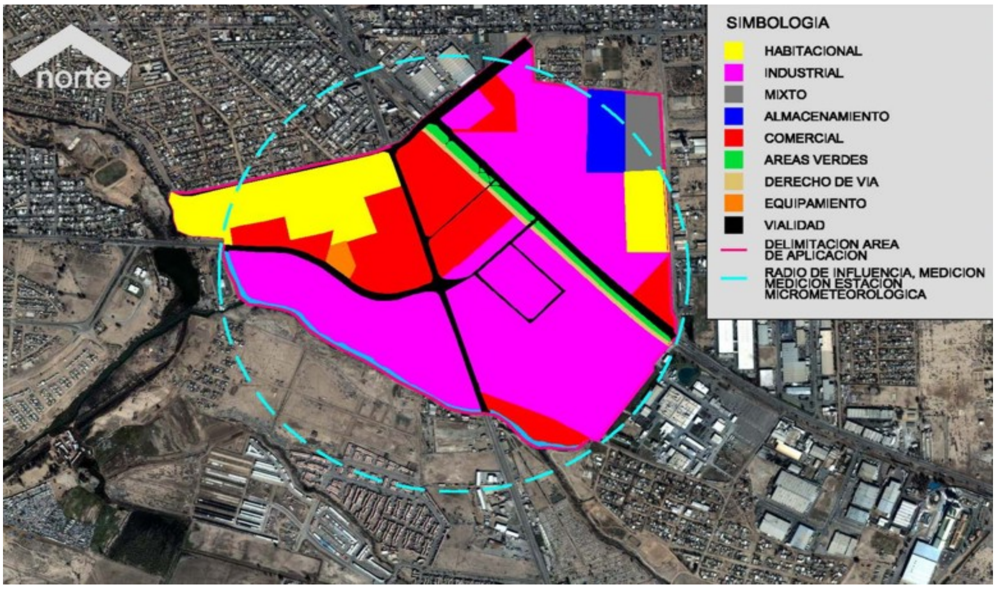

Fig. 2 Study area land use.

total area. The profile of the UHI depends on how the air is heated by hot surfaces, so cooling the average surface temperatures can have a significant effect.

Meanwhile Jusuf and Hien [19] suggest a model to predict air temperature in Singapore through relating the temperature (minimum, average and maximum) of a place with a radius of fifty meters and its relation to radiation solar day, the percentage of paved surfaces, average height of construction, total area of walls, green area ratio, the factor of open sky and the average surface albedo.

Both studies work with the physical composition and surface temperature of space, which is no different in this work, the model uses the land cover and land use characteristics and its relationship with the mitigation strategies implementation and their temperatures. The presented model was developed in *Stella*® in order to simulate the effect of applying the mitigation strategies based on a land use fabric, which seeks to establish the potential for mitigation (Table 1). The model was conceptualized in a modular fashion, so the integration of several modules constructs the land use fabric of the study area; the model main elements are:

- Land use and land cover characterization;
- UHI mitigation strategies;
- Mexicali's climate change scenarios [20];
- UHI increased temperature [21];
- City sector temperature balance in relation to land use and land cover (focus on strategies implementation).

4. Simulation Run

The model show a reasonable fit between the predicted and the real surface temperature, the simulation show that the temperature differential can be up 8°C between the trend and the potential for mitigation. In this case green and cool roofs offers more performance by lowering temperature in 5.8°C; without neglecting the contribution of green spaces which also provides other benefits to the urban environment (Fig. 3). Mitigation of UHI in arid areas like Mexicali is a reality that must be taken into account in urban development policies and construction codes, as well as in the implementation of actions against climate change.

The "as is" scenario shows the trend average maximum temperature of 52.8°C to 2080 — this increase can be mitigated by building green roofs (houses and shops) and cool roofs (industrial buildings and warehouses). Forestation also can be effective, so it is only necessary to consider the growing time of trees (Table 2).

Table 1 Land use and its UHI mitigation strategy potential.

Land use	Area (ha)	%	Mitigation strategy	Potential aplication per use (%)	Mitigation cover (ha)
Pesidential	28.8418	12.4%	Green roof	26%	7.4989
			Cool roof		
Institutions (education)	1.2326	0.5%	Green roof	19%	0.2342
			Cool roof		
			Forestation	60%	0.7395
Industrial	119.0415	51.2%	Cool roof	31%	36.9029
			Forestation	3%	3.5712
Commercial	41.8188	18.0%	Cool roof	30%	12.5456
Mixed (Storage, commercial)	11.5532	5.0%	Cool roof	40%	4.6213
			Forestation	3%	0.3466
Infraestructure (roads, water channel, right-of-way)	30.0353	12.9%	Forestation	80%	24.0282
Study Area (ha) = 232.5232		100.00%	Area of application of strategies (ha) = 90.4885		

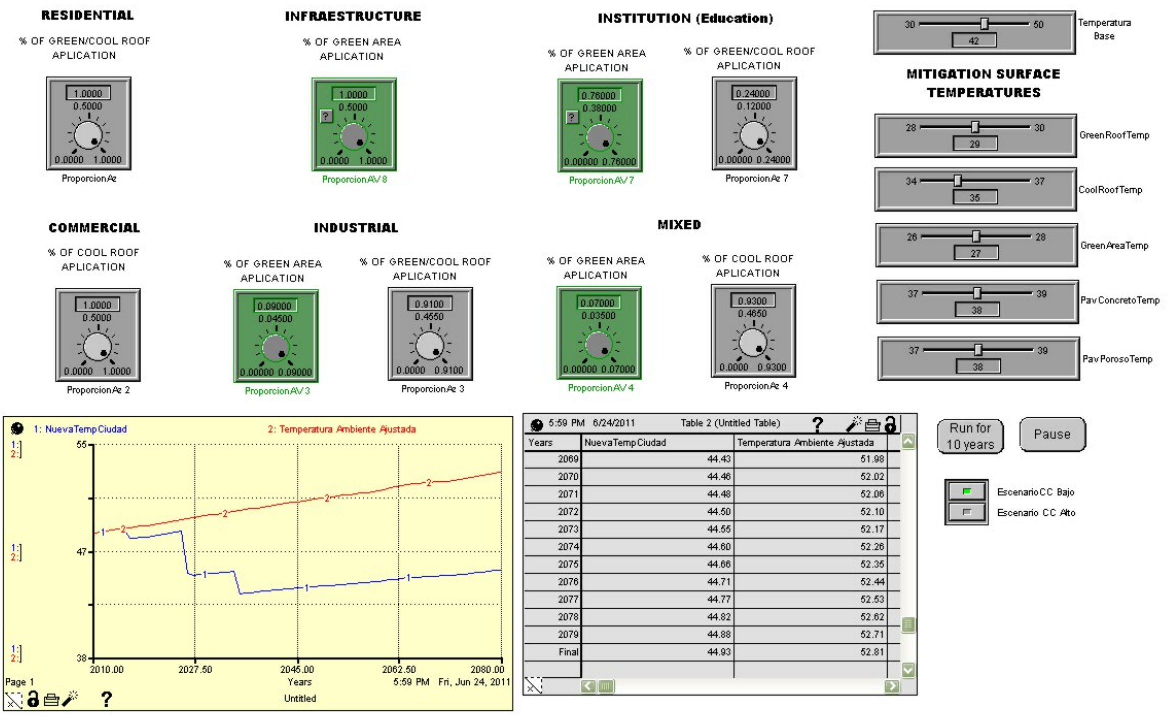

Fig. 3 Simulation interface.

Table 2 Simulation results.

Mitigation strategy	Scenario to 2080	
	As is	Cool scenario
Without strategy	52.8°C	52.8°C
Just green roofs	52.8°C	50.8°C
Cool & green roofs	52.8°C	47.0°C
Cool & green roofs & forestation	52.8°C	44.8°C

5. Discussions

One way in which cities could improve their environmental quality is by designing the urban space to mitigate the effects produced by the UHI. That is to reduce waterproof surfaces, especially those with a low albedo, and increase green coverage. This will help reduce the air temperature.

Solar reflectance and thermal emittance have important effects in the increase or decrease of temperature. The surfaces of conventional rooftops have a low reflectance and a high thermal emittance, reaching temperatures between 66°C and 88°C. Sheet metal roofs or metallic surfaces have a high reflectance and a low thermal emittance, reaching temperatures between 60°C and 77°C, as opposed to high reflectance and emittance roofs which can reach temperatures between 37°C and 49°C in the summer [22].

Baker et al. [10] suggested for Phoenix Arizona a redesign of the city to reduce urban heating through narrower streets, high albedo materials for roads and roofs, more green areas between buildings. These are strategies suggested by other authors that are applicable to the existing meteorological conditions in Mexicali.

Increasing albedo in rooftops and pavements, as well as urban forestation are the three main strategies suggested by Akbari et al. [23, 24]. According to the data obtained in this research, surfaces covered by plants keep temperatures below 27ºC. Increasing the albedo in rooftops as a measuring mitigation is important since the surface covered by rooftops within the urban area is very big. Therefore it makes sense to consider these options that will help reduce the thermal load in them.

Meredith [22] says, an increase the albedo in 0.07 on building and road surfaces can help reduce ambient temperature up to 30ºC. It is estimated that if the solar radiation absorbed by roads and parking lots is reduced from a 90% to a 65%, the peak temperature of the air can be reduced by 18°C [25].

Another mitigation measure involves increasing the urban green spaces like break winds curtains and floor coverings [26]. The first one, besides functioning as a filter for wind currents, will intercept solar radiation before it is absorbed by waterproof materials and also help decrease air temperature through evapotranspiration [22]. At the same time, those areas covered by vegetation will not allow an increase in surface temperature.

6. Conclusions

As a tool, dynamic modeling allows to apply urban concepts through the development of simple models, with which trends can be inferred. Despite not being a tool with a space interface, models can build to be given a spatial reference.

The development of a model and the simulation of different scenarios can be an important tool for urban planning. An advantage of systems dynamics, such as the one presented here, is that it allows us to develop other types of scenarios related with urban development and its interaction with their environment. This paper has contributed to developing a model that forecasts key variables in a long-term scenario into 2080 (climate change scenario). Incorporating dynamic modeling is important to guide urban planners making; the model would allow the planners to explore different case scenarios and to observe the result of their actions. Furthermore, the urban planners can experiment with different policy options and simulate results by changing the parameters in the model, for instance, the effect of urban expansion and their relation with UHI.

In the particular case, the results enable the trends to increase in temperature resulting from the UHI. The model structure showed their feasibility to be adapted modularly, so it is possible to adapt the overall structure of city land uses established in the urban development city plan “PDUCPM 2025” in order to evaluate the city development strategy.

In sum, this particular case enables the trends to increase in temperature resulting from the UHI. The model structure showed their feasibility to be adapted modularly, so it is possible to adapt to the overall land use fabric established in the urban development city plan “PDUCPM 2025” in order to evaluate the city development strategy. Besides helping planners and policy makers to forecast the UHI mitigation for the next decades. As previously stated, the model could help to determine how city can adapt to the UHI across the different land uses.

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