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Remotely sensing the cooling effects of city scale efforts to reduce urban heat island

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ABSTRACT

While recent years have seen many analyses of techniques to reduce urban heat island, nearly all of these studies have either been evaluations of real small scale applications or attempts to model the effects of large scale applications. This study is an attempt to analyze a real large scale application by observing recent vegetated and reflective surfaces in LANDSAT images of Chicago, a city which has deployed a variety of heat island combative methods over the last 15 years. Results show that Chicago's new reflective surfaces since 1995 produced a noticeable impact on the citywide albedo, raising it by about 0.016, while citywide NDVI increase is around 0.007. This finding along with counts of pixels with increased albedo and NDVI suggest that the reflective strategies influenced a larger area of the city than the vegetative methods. Additionally, plots between albedo increase and corresponding LANDSAT temperature change over the test period have linear regressions with steeper slopes (−15.7) and stronger linear correlations (−0.33) than plots between NDVI increase and temperature change (−8.9 slope, −0.17 correlation). This indicates that the albedo increases produced greater LANDSAT cooling than the NDVI increases. Observation of aerial images confirmed that typical instances of efforts to increase albedo, such as reflective roofs, produced stronger LANDSAT cooling than common instances of NDVI efforts, such as green roofs, street trees and green spaces. Accordingly, the reflective strategies were likely much more effective at cooling Chicago's LANDSAT heat island and may signify a generally more effective strategy for similar cities.

1. Introduction

Since the first observations of the urban heat island (UHI) effect, in which urban areas can be a few degrees warmer than surrounding rural areas, there has been a growing agreement that strategies to cool cities must be developed and tested. The present urbanization projections that estimate 6.3 billion people living in cities by 2050 have intensified the need to make urban environments more comfortable and livable [27]. At the same time, recent concerns about energy consumption have placed emphasis on minimizing the energy used to achieve thermal comfort, urging people to rely on passive ventilation from their UHI-altered surroundings [22]. Moreover, with global warming projections threatening to further increase urban temperatures world-wide, urban cooling techniques may prove even more important in the coming decades [22].

Faced with these issues, many scientists are developing a number of possible urban cooling strategies [14,28] and two have gained acceptance to the point that they are being implemented in a number of cities. These implemented strategies include one that seeks to increase urban reflectivity [6] and another that seeks to increase urban vegetation [10]. Both of these accepted methods focus on mitigating one of the primary causes of UHI outlined by [18] – the fact that urban materials, when compared to rural materials, tend to have properties conducive to higher temperatures. These properties include lower moisture contents, lower thermal roughness lengths, and lower surface albedos. By increasing the reflectiveness of urban surfaces, the former strategy helps remove solar radiation that would otherwise be converted into heat. In the latter strategy, increased vegetation provides enhanced evapotranspiration, which converts absorbed solar radiation into latent heat instead of sensible heat [12]. Additionally, increasing vegetation increases land surface roughness, which

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promotes the transfer of heat to the air and the convection of heat away from the ground [4]. Typical urban strategies belonging to the former category include the installation of reflective roofs or pavement [23] while strategies belonging to the latter category include the introduction of vegetation by means of green roofs, street/yard trees, and green spaces [10].

Numerous studies have revealed that both the reflective and vegetative strategies have the potential to significantly cool urban environments. However, these studies have either been on a small scale, observing individual instances of cooling method application [7,8,23,25]; or they have been attempts to model what would happen if such methods were adopted on a city scale or larger [1,2,6,24]. This study is one of the first to present data regarding the actual implementation of urban cooling strategies on a city scale. Up until this point, the cooling efforts of most cities appear to be too small to have noticeable impacts on this scale and their effects are likely indistinguishable amid other alterations such as land use change with development. However, after almost two decades of minimal development while implementing UHI-combative strategies in both the vegetated and reflective categories (outlined in Appendix A), the city of Chicago has established itself as an optimal testing ground for the comparison of such efforts.

This study's analysis of Chicago's cooling efforts is particularly helpful for informing the debate over the comparative effectiveness of the reflective and vegetated methods. To date, this debate has been informed only by the aforementioned means of analysis and this has had limitations in terms of the complex issues cities face as they seek to reduce their temperature. For example, while the replacement of vegetation with impermeable surfaces is a major cause of UHI and one should probably favor vegetated surfaces over impermeable ones when drafting cooling strategies [16]; some studies have revealed that this may not always be the best route to follow. One multi-year study in Hyōgo, Japan found that highly reflective impermeable white roofs were slightly cooler than grassy green ones, suggesting that these roofs could compete with vegetative methods [25]. Supporting these findings are a number of studies verifying that vegetation must be dense and include shrubs/trees in order to produce the large cooling effects needed to affect changes on a city scale [5,8,19]. When viewed in relation to vegetation-based strategies, this may arouse economic concerns since dense vegetation often has high planting and maintenance costs in urban areas. Some have suggested that the additional ecosystem services offered by a vegetative strategy, such minimized storm water runoff and air purification, might be enough to make it a worthwhile investment [17,20]. However, it is difficult to quantify the value of such benefits and understand how they will impact the effectiveness of strategies as they are implemented over an entire city.

It is because of complications such as these that information on the actual implementation of cooling strategies over cities is particularly helpful. Issues such as maintenance costs and ecological services are difficult to factor into computer models and observations of small-scale applications often have unique situations that are different than that of an entire city. Accordingly, this study will observe a real-world example in an attempt to address some of the limitations in these previous studies. Specifically, this study will observe the citywide increases in Chicago's vegetation and albedo over the last 15 years and compare each of their effects on remotely-sensed surface temperature.

2. Material and methods

Data collection began with the selection of LANDSAT 5 images to represent Chicago at present and prior to the implementation of cooling strategies (around 1995). Only the area within the political borders of the city was considered for analysis since it was within these limits that the most intense and organized efforts took place. An attempt was made to find images without cloud cover, with comparable anniversary dates, and with similar atmospheric conditions in order to minimize error in the comparison of the images' vegetation, albedo and surface temperatures. Ultimately, 8 individual images were selected and these were arranged to produce 5 pairs of past/present images. Table 1 displays data regarding the atmospheric conditions of the images and illustrates that the disparities between each of the pairs are not great enough to compromise the integrity of the analysis. In the course of the study, the only disparity that seems to have produced an anomalous result was the difference in previous day's and month's precipitation in Image pair 5. However, the pair represents an interesting finding that may have relevance for long-term cooling strategies factoring in precipitation increases from global warming and, thus, it was kept in the study. It is important to note that,

Table 1
The atmospheric conditions over Chicago when each of this study's LANDSAT images was taken. "Ground" refers to values that are an average between those recorded at O'Hare International Airport and Midway Airport in the hour the satellite passed overhead. "Balloon" refers to an average of values recorded at a pressure/height of 925 hpa by weather balloon soundings in nearby Lincoln, IL and Davenport, IL. Since soundings occur every 12 h, the values were interpolated to the time that the satellite passed over.

Date	Average LANDSAT surface temp. (°C)	Ground air temp (°C)	Ground Dewpt. (°C)	Balloon air temp (°C)	Balloon Dewpt. (°C)	Ground wind speed (km h-1)	Prev. day's rain (cm)	Prev. month's rain (cm)	Percent of city in cloud/shadow
Image Pair 1									
May 30 1995	29.8	22.9	13.1	15.1	4.5	6	0.0	8.9	0.0
June 5 2009	30.9	20.6	6.4	14.7	3.0	14	0.0	14.2	0.0
Difference	**+1.1**	**−2.3**	**−6.7**	**−0.4**	**−1.5**	**+8**	**0.0**	**+5.3**	**0.0**
Image Pair 2									
July 3 1996	31.3	22.9	14.0	16.5	10.5	21	0.0	11.4	1.5
July 2 2007	30.2	21.5	8.8	17.9	6.8	15	0.4	6.4	0.0
Difference	**−1.1**	**−1.4**	**−5.2**	**+1.4**	**−3.7**	**−7**	**+0.4**	**−5.0**	**−1.5**
Image Pair 3									
June 15 1995	32.4	27.5	13.8	18.1	9.9	10	0.3	8.1	0.0
June 16 2007	35.0	30.5	15.3	24.0	11.1	14	0.0	5.5	0.0
Difference	**+2.6**	**+3.0**	**+1.5**	**+5.9**	**+1.2**	**+4**	**−0.3**	**−2.6**	**0.0**
Image Pair 4									
July 1 1995	29.8	20.3	8.2	12.3	5.5	17	0.0	6.6	2.4
July 2 2007	30.2	21.5	8.8	17.9	6.8	15	0.4	6.4	0.0
Difference	**+0.4**	**+1.2**	**+0.6**	**+5.6**	**+1.3**	**−3**	**+0.4**	**−0.2**	**−2.4**
Image Pair 5									
June 15 1995	32.4	27.5	13.8	18.1	9.9	10	0.3	8.1	0.0
June 24 2010	32.0	23.7	15.9	18.4	12.2	16	3.1	18.6	4.0
Difference	**−0.4**	**−3.8**	**+2.1**	**+0.3**	**+2.3**	**+6**	**+2.8**	**+10.5**	**+4.0**