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OEFS Final Paper

Title: Evaluating Chicago's Urban Heat Island Policy with Remote Sensing

Abstract:

Since the great Chicago heat wave of 1995, the city government has enacted a large number of policies under the pretense that it is combating its urban heat island. While much investigation on the subject thus far has focused on either the local benefits of policies or broad descriptions of the entire region, few studies have evaluated whether the small-scale benefits of policies have begun to collectively impact the larger heat island. This study addresses this issue by using LANDSAT imagery to observe changes in Chicago's vegetated and reflective surfaces in relation to changes in surface temperature since 1995. This is accomplished using two images from early June of 1995 and 2009 with similar air temperature and atmospheric conditions. Results indicate that reflective policies (especially reflective roofs) were very successful and increased the overall albedo of the city from 0.150 to 0.173 in addition to cooling certain neighborhoods by 2°C – 3°C. Vegetation policies produced noticeable results but their overall impact was slightly less impressive, generating a weaker correlation to temperature decrease and often affecting small areas instead of the larger region. Also, the fact that the number of vegetated pixels in Chicago decreased by 9,727 since 1995 indicates that an optimal current urban heat strategy would probably involve a restraint of development over vegetated areas in conjunction with good reflective policies.

Introduction:

Since the issue of heat island effect first entered Chicago's public discussion after the 1995 heat wave, the city has arguably done the most out of any in the US to combat its urban heat island. (Changnon *et al*.) (Whitman *et al*.) While the city does not possess the largest heat island in the nation (a title presently held by Los Angeles), it does have a lot to be concerned with as a large metropolis in the middle of a continent, where temperature extremes are more common. Figure 1 gives a sense of the present city's heat island with a satellite image derived from the Landsat Thermal Infrared (TIR) band in early June 2009. It is important to note that this image displays the surface heat island of the city, which often has a greater variance in temperature than the canopy heat island. The canopy heat island of Chicago, which has been more heavily investigated to date, is only about 2.8°C warmer than that of the surrounding landscape and is noticeably different than the temperature spread we see in Figure 1 (EPA Urban Heat Island Pilot Project).

At present, scientists have identified two main strategies for combating the heat island effect: 1) increasing vegetation within the city and 2) increasing reflectivity of city roofs and pavement. Vegetation cools the city primarily through evapotranspiration and the Chicago region has traditionally relied on this process to regulate its temperature in the summer. Increasing the reflectivity of urban surfaces cools the city by reflecting more solar radiation into the atmosphere and space, thereby preventing it from being dissipated on the ground as heat. Traditionally, citizens concerned with heat island effect have tended to emphasize the vegetation method for its historical precedent and because it includes many other benefits such as increased urban biodiversity and fresher air. However, the effectiveness of these two strategies in terms of policy has been widely debated since there are clear cost benefits to the reflective method even if it does not have the environmentalist selling-power of the vegetation approach. (Hutchinson)

Accordingly, the city of Chicago has adopted a dual strategy for the past 15 years, implementing a large number of policies. Some of the vegetation policies include providing incentives for over 500 new greenroofs, replacing more than 300 acres of asphalt at 80 public schools with grass fields, zoning more than 57 new community parks, and planting at least 5,000 new street trees each year. (EPA Urban Heat Island Pilot Project) (City of Chicago Department of Environment) Some of the reflective policies that the city has implemented include new energy efficiency zoning codes that require buildings to have "cool roofs" or meet a minimum roof shingle reflectivity, a gradual re-paving of major roadways with reflective materials, and a replacement of 68 city alleyways with bright gravel. (City of Chicago Department of Environment) (Hutchinson) All of these policies have undeniably produced tangible local benefits whether they have been in the form of lessened building cooling loads or general citizen accessibility to green space.

However, the changes over the entire surface heat island have not been studied in depth since the EPA terminated its Urban Heat Island Pilot Project in 2002. The likely reason why there have been few, if any, such studies is that most of the policy initiatives since then have been small and fairly recent. Accordingly, it would have been inconceivable for any one project to have a noticeable impact on Chicago's entire heat island unless there were many of such projects over a course of several years. Just now, we finally seem to be getting to a time when the combined heat island impacts might conceivably be analyzed on a large scale.

This study will assess these possible large-scale impacts by observing changes in the groundcover of Chicago over the past 15 years and comparing these to changes in the city's surface temperatures. Ultimately, the goal is to determine whether the policies have produced noticeable impacts on temperature and, if so, which policies have been particularly effective. At the very least, an attempt will be made to understand whether vegetation policies or reflective policies have had more of a cooling impact.

Methods:

Before defining a specific procedure for the study, it is first necessary to set the spatial and temporal boundaries of the investigation. Since the study is concerned with the policies of the city government, the political borders of Chicago will define the spatial area to be analyzed. Figure 2 depicts the boundaries of this area in relation to the entire heat island and Figure 3 shows a true color image of the region itself in June 2009.

As one could probably guess from the previous discussion, the temporal boundaries will be set roughly from 1995 to the present. The heat wave of 1995 predates the aforementioned policies and the 514 citizen deaths that the wave caused have been noted as a primary motivating factor behind many of the initiatives. (Changnon *et al*.) (Whitman *et al*.) In this study, LANDSAT images from May 30, 1995, and June 5, 2009, were selected to represent the start of Chicago heat island policy and the present, respectively. The specific dates were chosen largely because they enabled observation of the city's vegetated surfaces, provided cloud-free views of the city, and had comparable atmospheric temperature conditions (Figure 4). Also, the 1995 image was taken before the heat wave, which struck in mid July, so one can be certain that it represents the state of the city before policy changes.

Data collection began by calculating the Normalized Difference Vegetation Index (NDVI) for both the 1995 and 2009 image using LANDSAT bands 3 and 4. Next, a threshold NDVI of .3 was applied to both images in order to single out vegetated pixels. The 1995 NDVI was then subtracted from the 2009 NDVI to produce Figure 5, a grayscale image depicting NDVI change of the city's vegetated areas from 1995 to 2009. While this image may be ideal for quantitative analysis, it does not grant the best qualitative understanding of the changes. Accordingly, the 1995 and 2009 NDVI images were loaded respectively into the red and green channels of the screen to produce Figure 6, which depicts areas of vegetation gain in green, vegetation loss in red and constant vegetation in yellow.

Albedo was calculated by first using the information in the LANDSAT Metadata file to generate reflectances for each reflective band in the LANDSAT file. Next, these multi-band reflectances were entered into Liang's formula for a weighted-average albedo to give overall albedo values for both scenes. (Liang) The 1995 albedo was then subtracted from the 2009 albedo to produce Figure 7, a grayscale image depicting the albedo change within the city between the two dates. Again we find that this is not the optimal format for qualitatively viewing the changes so the 1995 albedo and 2009 albedo were loaded into the red and green channels respectively to produce Figure 8. Here, the areas of albedo gain are shown in green, areas of albedo loss are shown in red, and areas of constant albedo are shown in yellow or brown.

In order to understand the effects of NDVI and albedo change on the heat island, a change in surface temperature image was created. This was accomplished by using the LANDSAT Metadata file to change the digital numbers of each image's TIR bands to radiance. Next, these radiance values were converted to temperature by using the inverse of the Planck function. The 1995 temperature was then subtracted from the 2009 temperature and color-coded to produce Figure 9, which roughly records the changes in surface temperature between the two dates. Here, the parts of the city that experienced a warming are shown in yellow, orange and red, while the parts of the city that experienced cooling are shown in teal, blue and dark blue. Green areas represent places where surface temperature was relatively stable between the two dates. Caution should be exercised when drawing conclusions with this image since it is clearly impossible to obtain identical weather conditions for any two LANDSAT images taken on different dates. However, it is likely that Figure 9 does truly reflect the variations in surface temperature resulting from NDVI and albedo changes since the atmospheric conditions on both days that are very similar (Figure 4).

A number of statistics were generated from the images including the number of vegetated pixels in each scene from NDVI images and the average city albedo for each scene from the albedo images. Also, the correlation and covariance between NDVI change and temperature change were calculated using Figures 5 and 9. Similarly, the correlation and covariance between albedo change and temperature change were calculated using Figures 7 and 9. 2D scatter plots depicting the nature of these correlations were also generated and can both be seen in Figure 10.

Lastly, an attempt was made at understanding the impacts of individual policies by identifying instances of specific initiatives using Google Earth imagery. Figure 11 displays one such instance by comparing a neighborhood where reflective roofs were implemented with one where they were not. These instances were traced back to the corresponding LANDSAT pixels, where the effect of the policy was verified using either the albedo change or the NDVI change image. Figure 11 uses the red-green channel albedo change image to verify that this reflective roof instance is, in fact, a place where the albedo increased (that is, there are many green pixels in the scene). Next, the temperature change of the area was observed in order to gauge the policy's overall effectiveness at decreasing the urban heat island. The temperature cooling effects produced by the reflective roof instance of Figure 11 can be seen in Figure 12.

This method was repeated several times with the different policies to produce Figure 13, a chart roughly displaying the qualitative effectiveness of each heat island policy. Clearly, the specifics of this chart should be observed with caution since the process described above is highly subjective and has likely been influenced by the biases of the individual making the qualitative judgments. Also, the Google Earth imagery that was used in this study was taken in 2010 while the recent LANDSAT image is from 2009, which could create some potential discrepancies. Nevertheless, such a method is not completely devoid of truth and the results may be useful in supporting certain conclusions drawn from other data in the study.

Results:

General Vegetation Policies

From Figure 6, it is clear that Chicago's policies aimed at increasing the city's vegetation have produced noticeable results as evidenced by the image's green pixels, indicating areas of vegetation gain. A few of the city's new parks stand out along with some neighborhoods boasting new street trees, which follow the city grid. Despite the fact that many of these initiatives are noticeable, it seems that the total amount of vegetation within Chicago actually declined in the 15-year test period. Statistical analysis reveals that the number of vegetated pixels fell from 185,016 to 175,289, producing a net loss of 9,727 pixels between 2009 and 1995. Of course, this loss probably has much to do with the construction of new terminals at O'Hare Airport in the northwest of the image and the construction of a few new developments in the southeast corner of the image, both of which are not a part of Chicago's heat island policy. However, this fact does suggest that a more effective vegetation-based policy could have been achieved by limiting development rather than implementing the present policies. Such a notion is reinforced by the fact that the city's population was relatively stable and possibly declined during the test period, indicating that the observed development was probably not entirely necessary. (U.S. Census Bureau)

Figure 10 illustrates that areas of increased vegetation produced a decrease in surface temperatures, as indicated by the negative correlation of -0.273539. However, the scatter plot in the figure shows that much of this negative correlation actually had to do with increasing temperatures from removed vegetation rather than the opposite, since most pixels lie left of the zero NDVI-change line. Finally, Figure 10 shows that the NDVI changes did not have as strong of a correlation to temperature decreases as the albedo changes did.

General Reflective Policies

Figure 8 illustrates that Chicago's reflective policies have produced noticeable results with a large number of green pixels indicating areas of albedo increase. While these green pixels can be found throughout the city, they seem to be very concentrated in the residential and industrial urban fabric, suggesting that they resulted primarily from the city's new roof zoning laws. Altogether, the reflective polices increased the average albedo of the entire city from 0.150 to 0.173, which is a total albedo increase of 0.023 and indicates a fairly high success level. This trend is only augmented if one excludes pixels associated with vegetation changes, which increased the area's average albedo from 0.148 to 0.175 for a total gain of 0.027.

Additionally, as Figure 10 illustrates, the albedo increases had a fairly strong correlation to temperature decreases as indicated by the negative correlation value of -0.369368. Furthermore, the fact that many of the pixels lie to the right of the zero albedo change line indicates that this correlation was, in fact, the result of a correlation between albedo increase and temperature decrease instead of the opposite. This fact also shows that the policies had a widespread impact on the city's many non-vegetated pixels by confirming that most of them saw an overall albedo increase. Lastly, it is important to note that the albedo change, with a correlation of -0.369 to temperature decrease, had a stronger correlation than that of the NDVI change, which was -0.274.

Specific Policies

As mentioned earlier, the results displayed in Figure 13 should be observed with caution. Nevertheless, the table's assertion that the reflective roof policies were the most effective is probably accurate considering the previous results indicating a higher success rate with reflective policies. This notion is further justified by Figure 8, which illustrates that much of the city's observed albedo increase in the past 15 years has been in residential or industrial fabric (areas where roofs predominate the scene). At the very least, Figures 10, 11, 12 and 13 all support the claim that the reflective roof policies produced identifiable results and contributed to a cooling of certain areas in the city.

Figure 13's assertion that the green roof and reflective alleyway policies were the least successful is also a fairly convincing argument. The inability to observe these policies with 30m LANDSAT resolution is a clear indication that they do not operate on the scale of the other initiatives and, thus, they probably had an insignificant impact on the greater urban heat island.

Finally, the policies in between the most effective and least effective seem to be the most contentious in terms of their impact. However, perhaps the new parks, new street trees, and road pavement changes can all be placed in one category of mildly successful initiatives that could be better ranked with further investigation.

Conclusion:

First and foremost, it is important to note that Chicago's policies have produced noticeable impacts on the large-scale urban heat island. Of course, there is clearly still room for improvement, but large, policy-induced increases in vegetation and reflectivity have been identified in parts of the city and have corresponded to decreasing surface temperatures.

From observation of Figures 10 and 13, it seems that the reflective policies were more effective than the vegetation policies in both the size of the area impacted and the strength of the correlation to temperature decrease.

The study might even go as far as to claim that reflective policies generally tend to affect larger areas than those of vegetation. This is primarily because there is such a noticeable difference between the number of increased albedo pixels and the number of increased vegetation pixels between the two dates (Figure 10). This general claim is further supported by the fact that there are much bigger swaths of green pixels in Figure 8 than in Figure 6, which suggests that the albedo polices operate on a larger scale. Finally, such a claim is explainable by the fact that reflective policies almost always cost less to implement and maintain. Consequently, it is clear that more people are able to contribute to reflective strategies and this allows for more widespread adoption throughout the city.

The overarching claim that reflective policies generally have a stronger correlation to temperature decrease is much harder to support with the findings of the study. This is primarily because the correlations of vegetation to temperature and albedo to temperature are actually fairly close (vegetation is -0.274 and albedo is -0.369). Also, there is a very important limitation of this study in relation to this claim, which is that only early June LANDSAT images were analyzed. Oftentimes, vegetation will reach its maximal evapotranspiration and cooling capabilities when the temperature is warmest and the leaf size is the largest. Both of these conditions tend to exist from mid July to mid August, which is also Chicago's usual season for heat waves. Accordingly, the correlation of vegetation change to temperature change may be much larger for LANDSAT images taken later in the summer and might actually be comparable to the correlation of albedo change to temperature change. Thus, it will be necessary to analyze surface temperature changes in July and August before such a general claim can be applied to policy decisions regarding heat waves.

In any case, this study does seem to provide a rough framework for addressing the heat island effect in relation to the reflective vs. vegetated debate. This framework is based on the fact that a vegetation strategy which impacts the heat island as much as a reflective strategy would probably have to limit new development over large vegetated areas. At the very least, the fact that Chicago lost 9,727 vegetated pixels during the test period indicates that the government could have done more to prevent the heat island effect by controlling its rate of development than by using the many vegetated policies that it did. Accordingly, an effective heat island strategy for the moment would likely involve managing heat island gain from new development and overcompensating for such with new reflective cooling policies. The current vegetation policies of green roofs, street trees and converting lots to parks are helpful, but it would clearly take many tax dollars to make them as effective as the combination of methods stated above. Perhaps, at a point when enough control has been gained with reflective policies, the city can step in with major promotion of these other green policies, since these strategies produce some benefits that the reflective strategies lack. However, one can understand from a rough cost-benefit analysis that reflective strategies produce more urban heat benefits for their cost and, thus, they should probably be employed first in order to gain some control over the heat island.

A final important conclusion of this study revolves around a specific policy that has clearly demonstrated immense potential: reflective roof zoning codes. In fact, such a discovery seems to be an ironic conclusion to draw considering the initial reasons behind the codes' passage. The reduction of heat island effect has of course been used to help justify their implementation but these laws are actually listed in the Chicago government's archives as a group of energy efficiency codes.

In spite of this, many recent studies have shown that the reduction in cooling loads offered by the roofs has actually been counteracted by their increase in heating loads within the city of Chicago. (Hutchinson) Figure 14 shows an image from one such study indicating that Chicago lies right on a line where the sum of heating and cooling costs is the same with or without the roofs. (Hoff) North of this line, reflective roof strategies tend to increase overall costs and, consequently, such methods may not be worth pursuing in Chicago. With the understanding that these policies are not necessarily increasing energy efficiency, the city has since revised some of its roofing codes to incorporate more diverse types of materials. However, it seems that priority has been given mostly to how energy-efficient these materials are, since large-scale effects on the heat island have been largely unknown. Accordingly, perhaps the best advice that this study can offer is that some of these older codes be re-introduced in the form of urban heat policy. Most of the future investigation following this project will likely take place in this area of study and, hopefully, progress can be made towards a more effective urban heat strategy for the city of Chicago.

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Figure 1

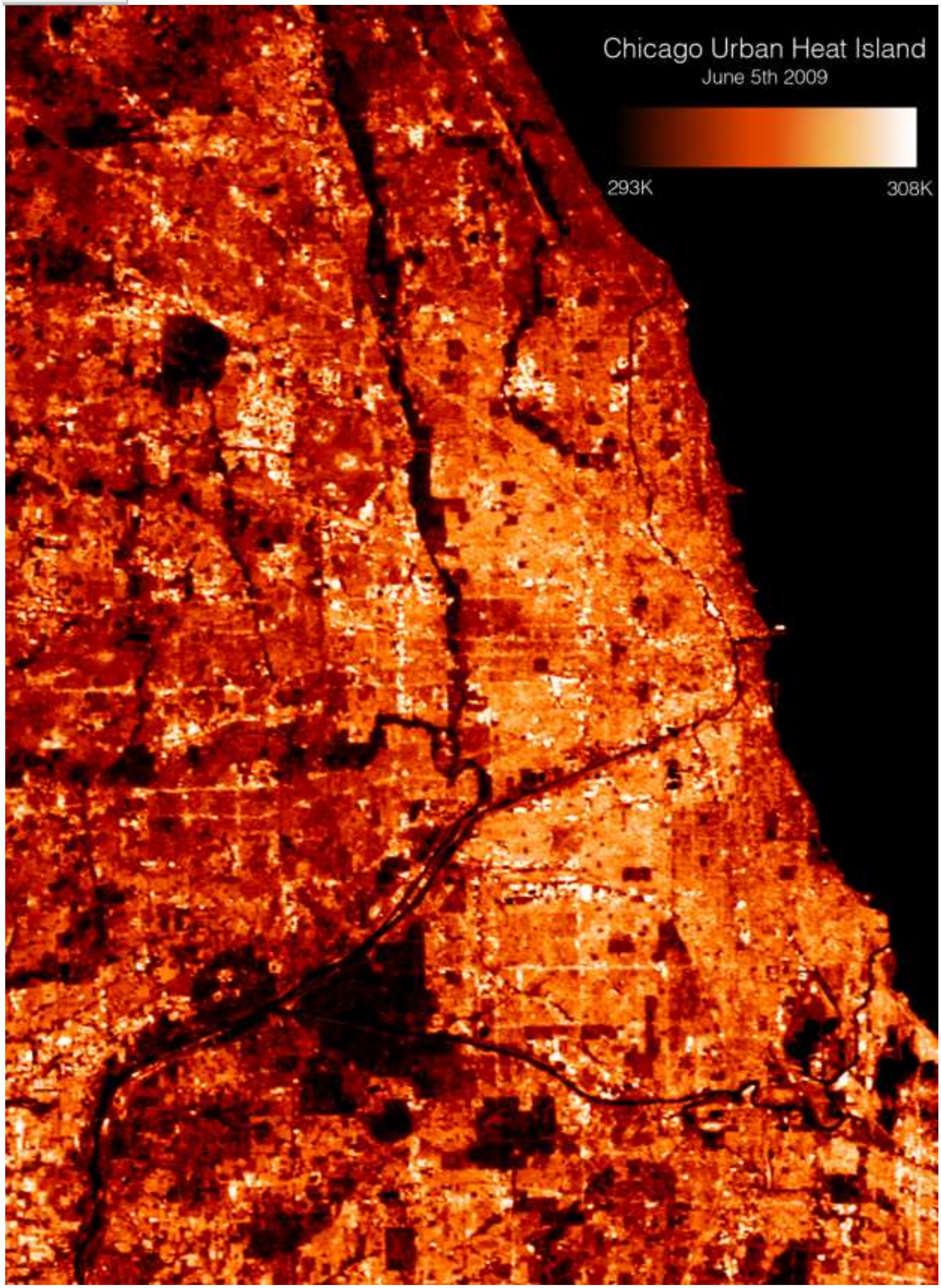


Figure 2

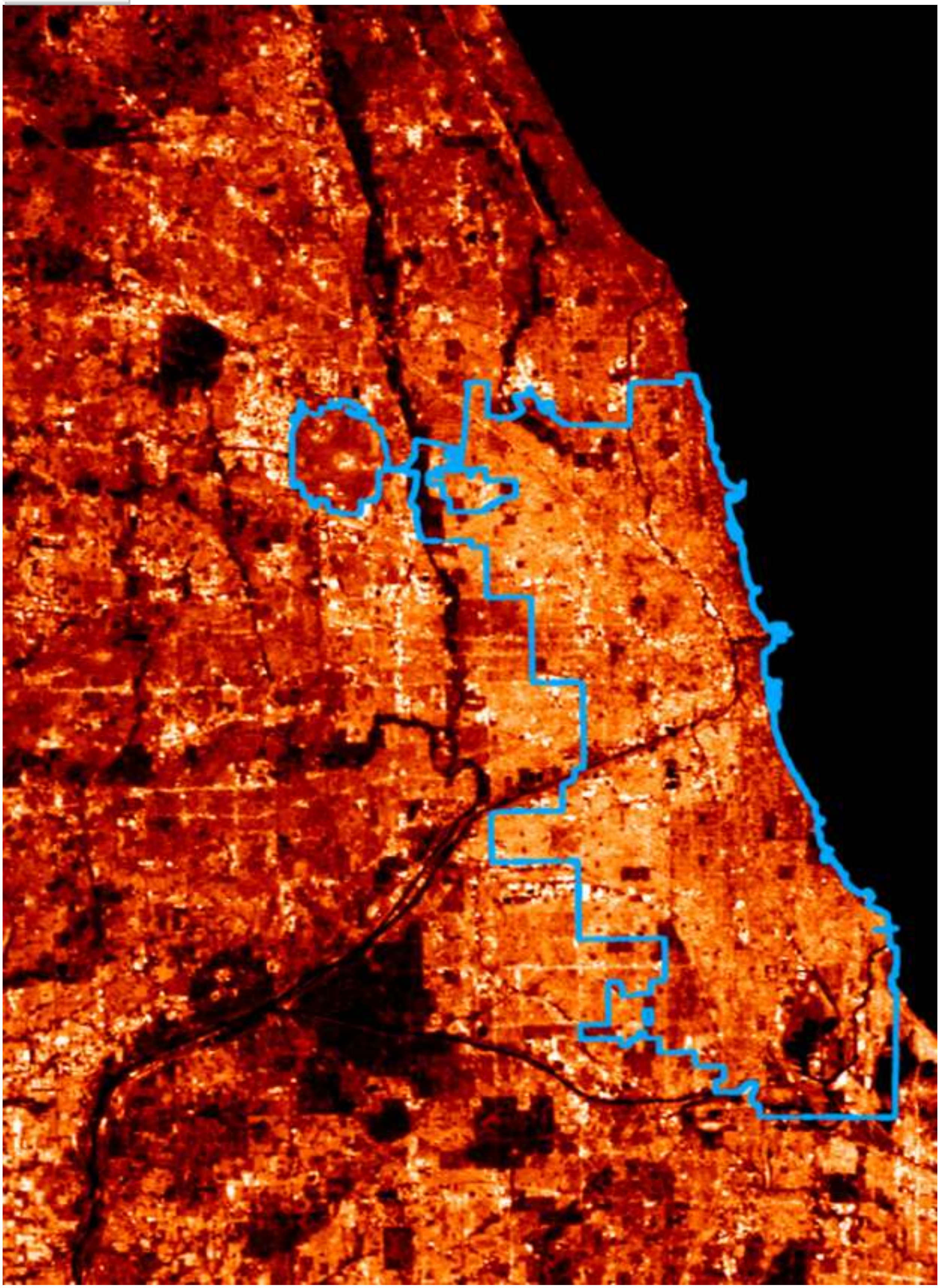


Figure 3

Figure 4

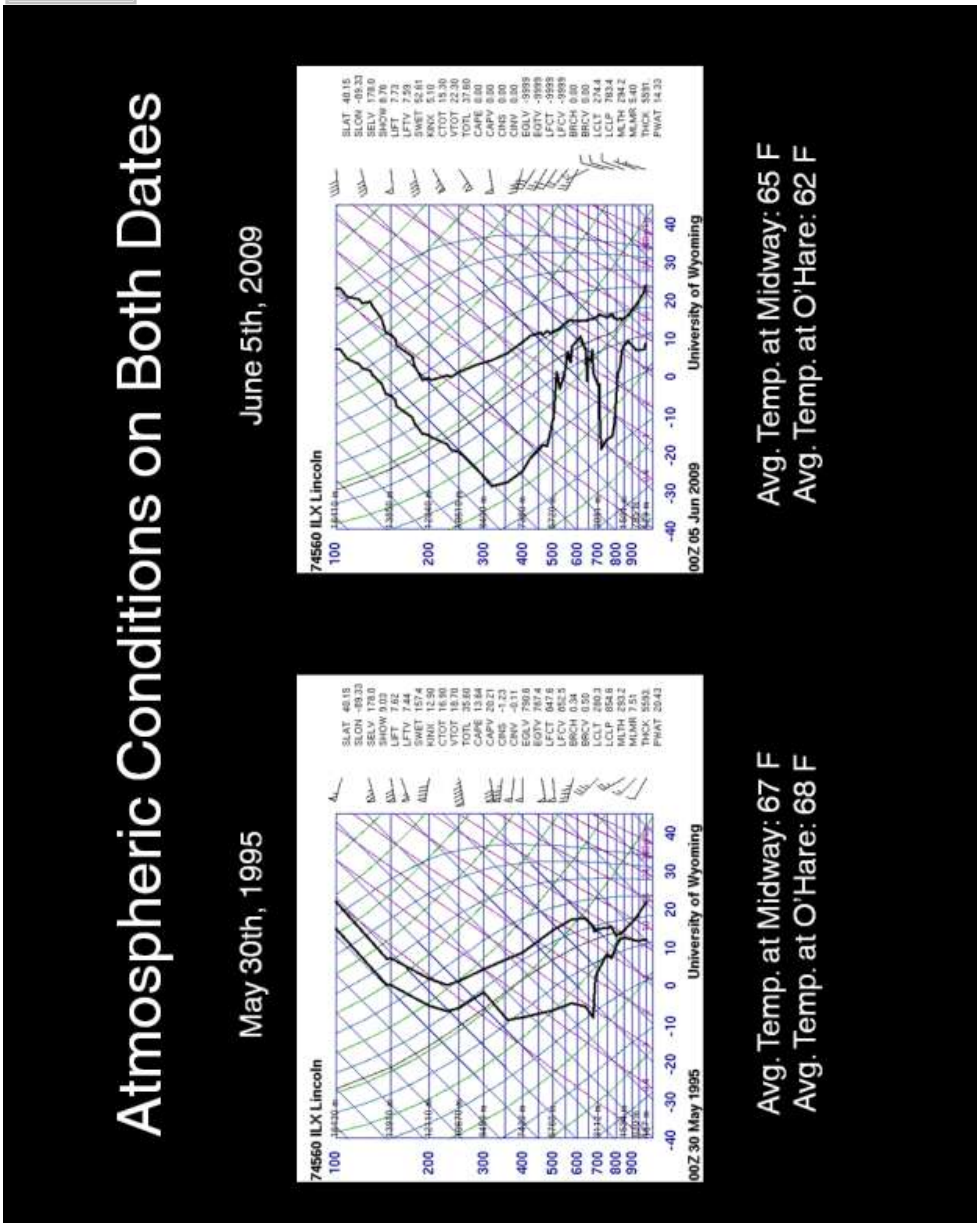

Atmospheric Conditions on Both Dates
May 30th, 1995
74560 ILX Lincoln
00Z 30 May 1995
University of Wyoming
Avg. Temp. at Midway: 67 F
Avg. Temp. at O'Hare: 68 F
June 5th, 2009
74560 ILX Lincoln
00Z 05 Jun 2009
University of Wyoming
Avg. Temp. at Midway: 65 F
Avg. Temp. at O'Hare: 62 F

Figure 5

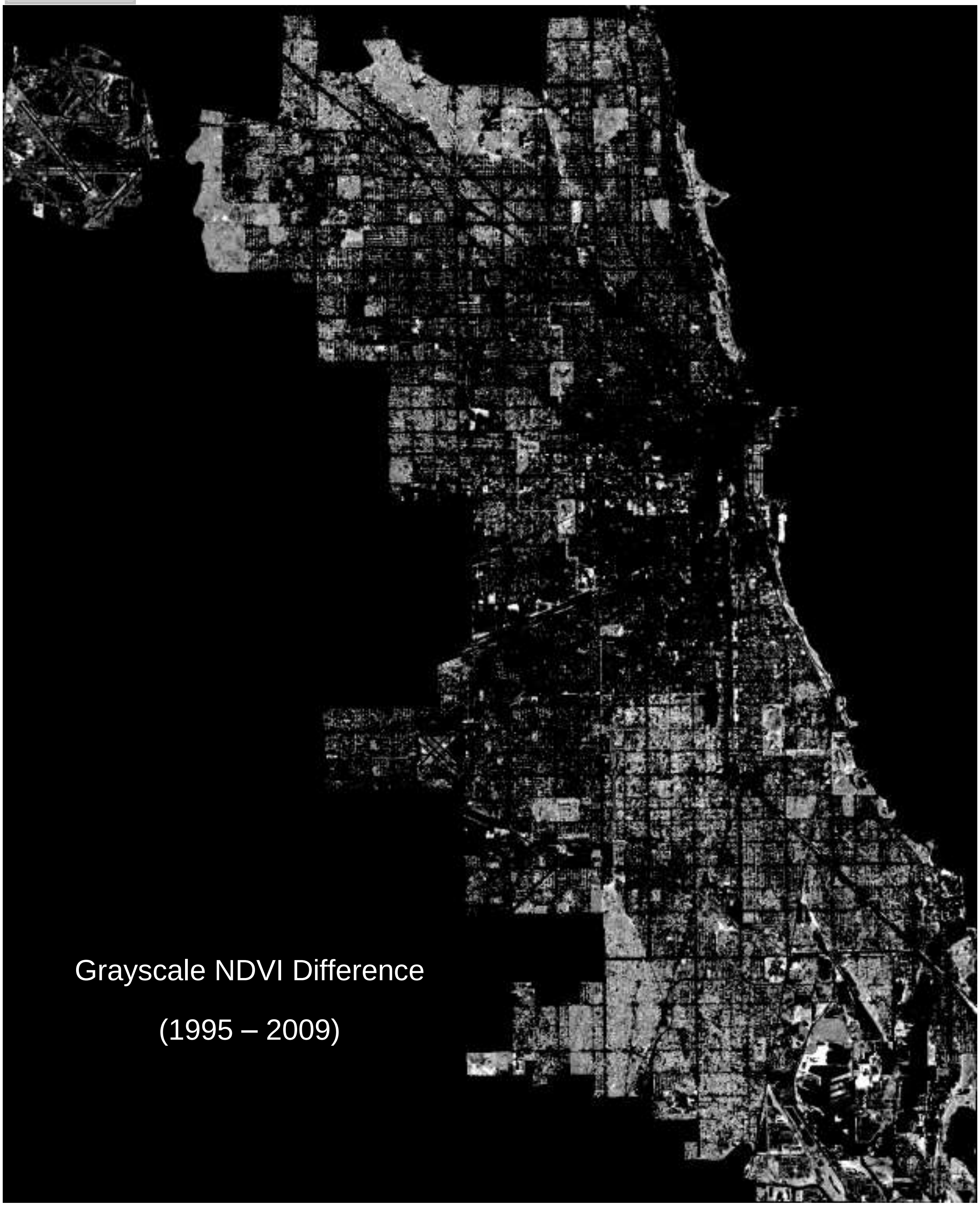


Figure 6

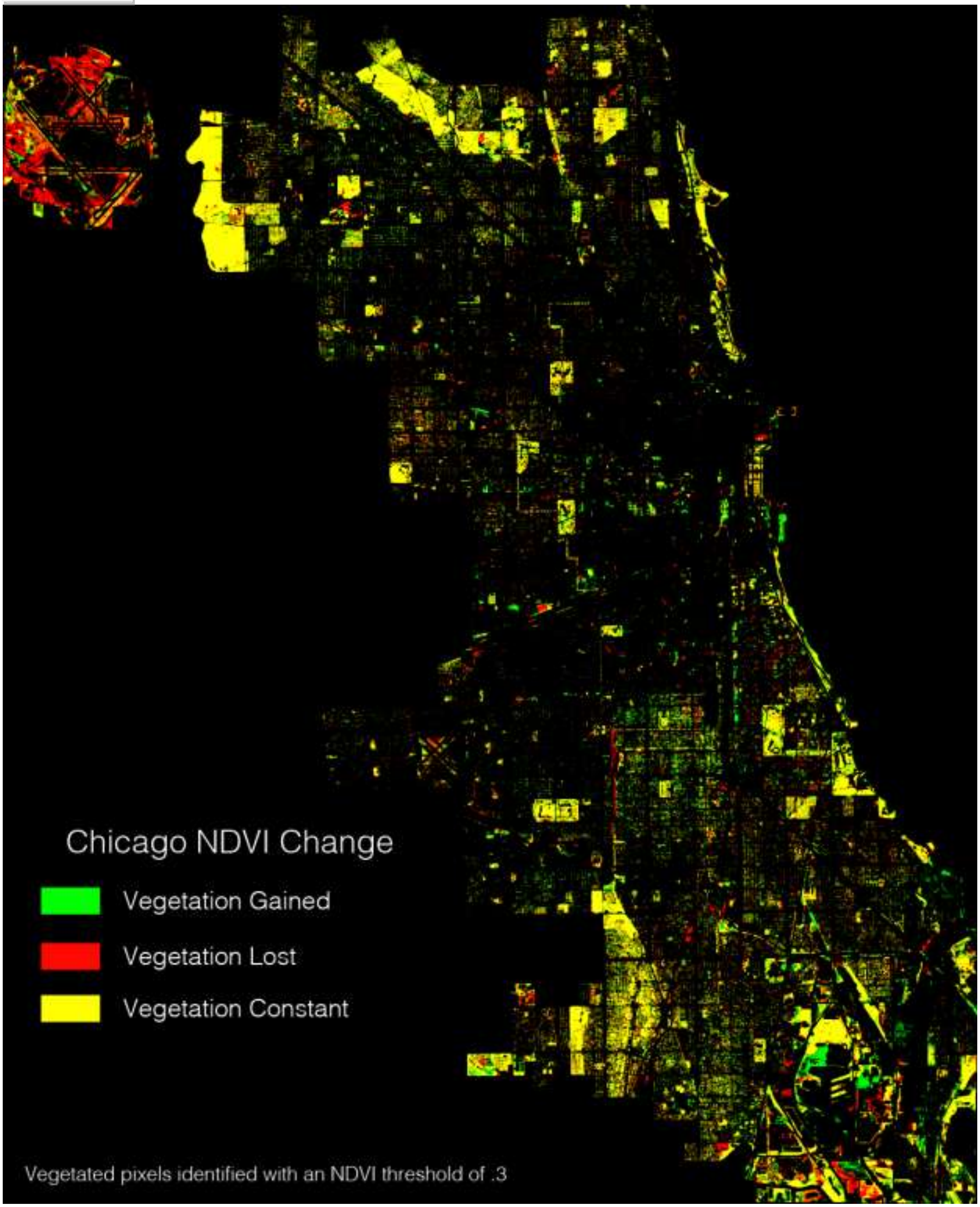

Chicago NDVI Change
Vegetation Gained
Vegetation Lost
Vegetation Constant
Vegetated pixels identified with an NDVI threshold of .3

Figure 7

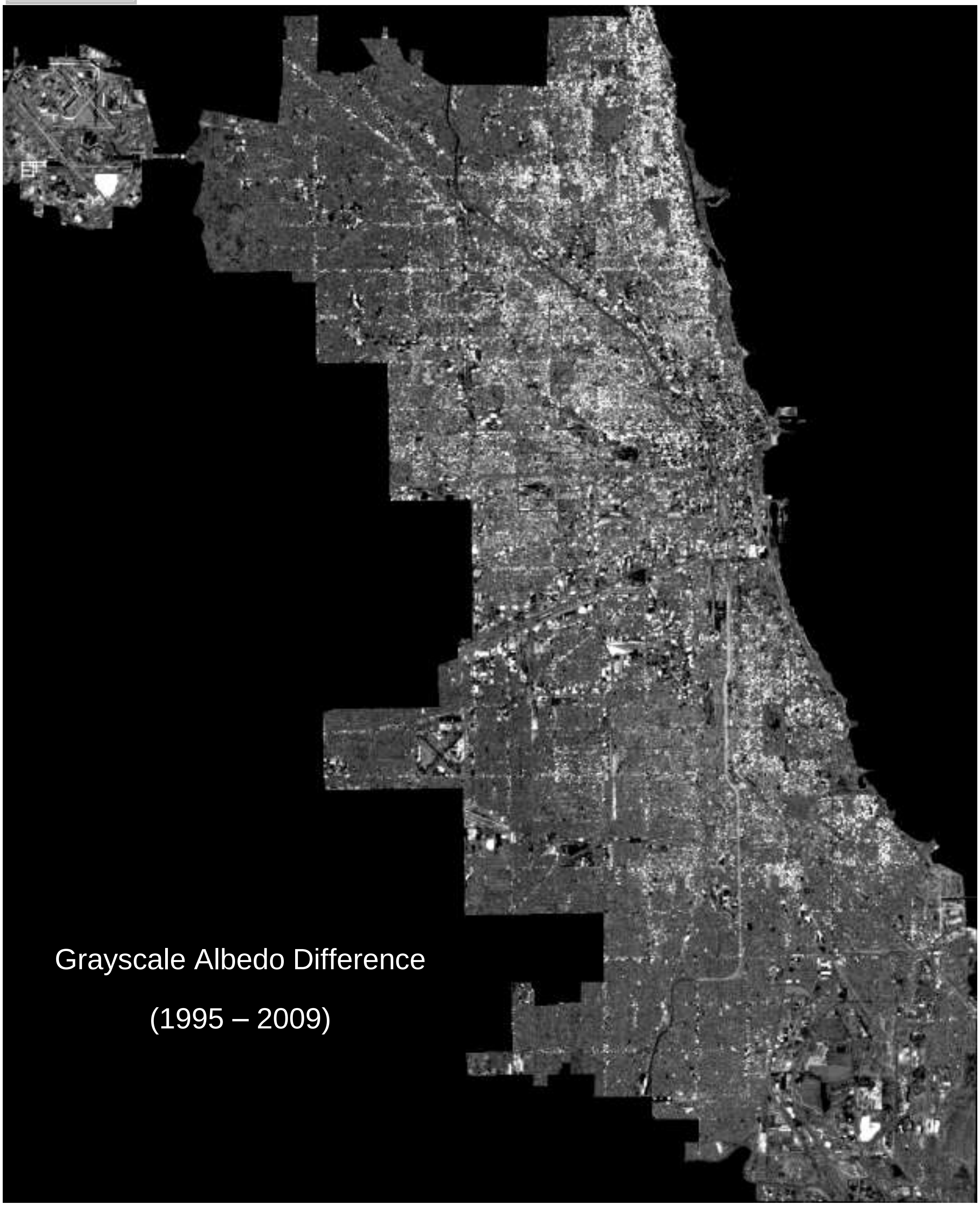
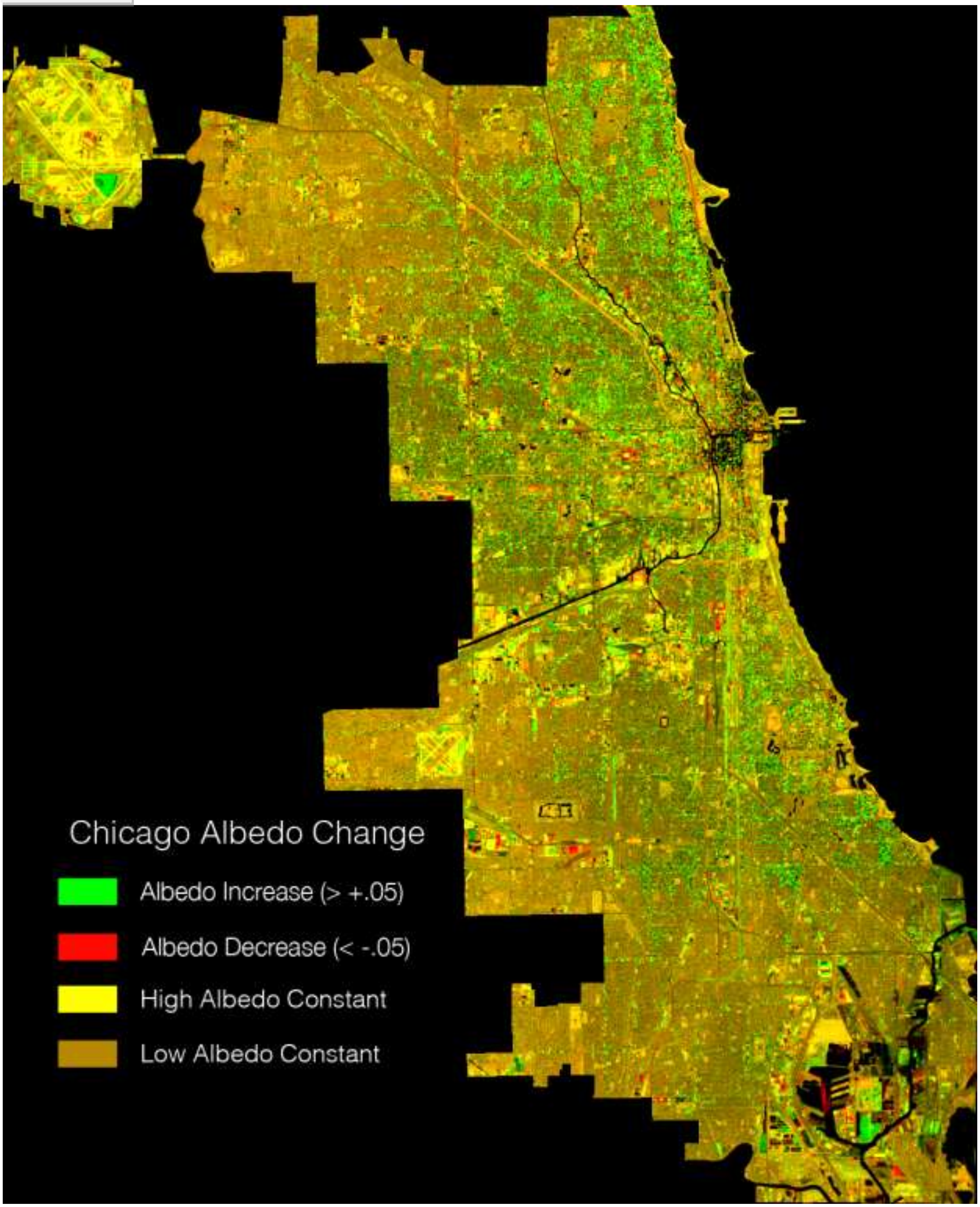


Figure 8



Chicago Albedo Change
Albedo Increase (> +.05)
Albedo Decrease (< -.05)
High Albedo Constant
Low Albedo Constant

Figure 9

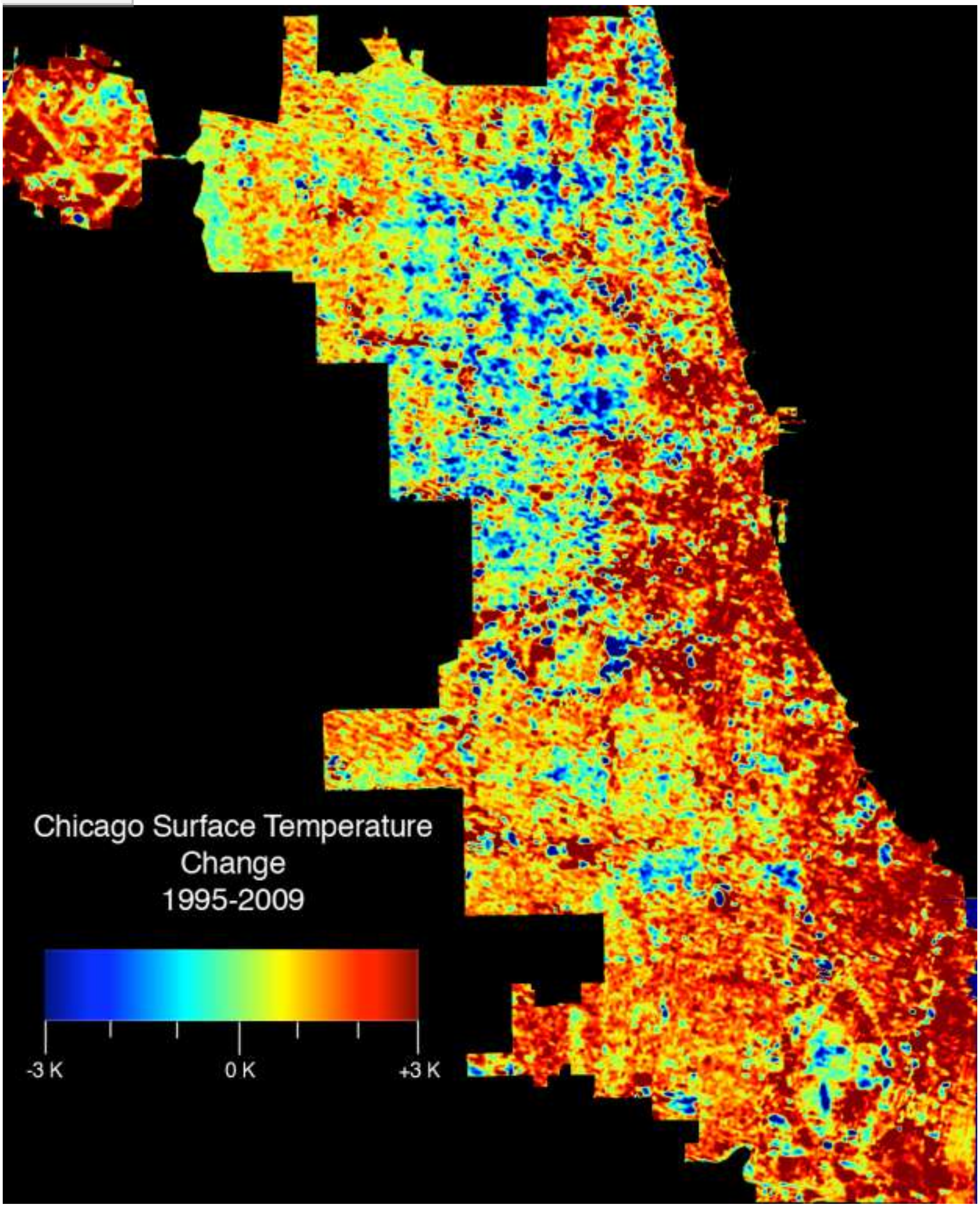


Figure 10

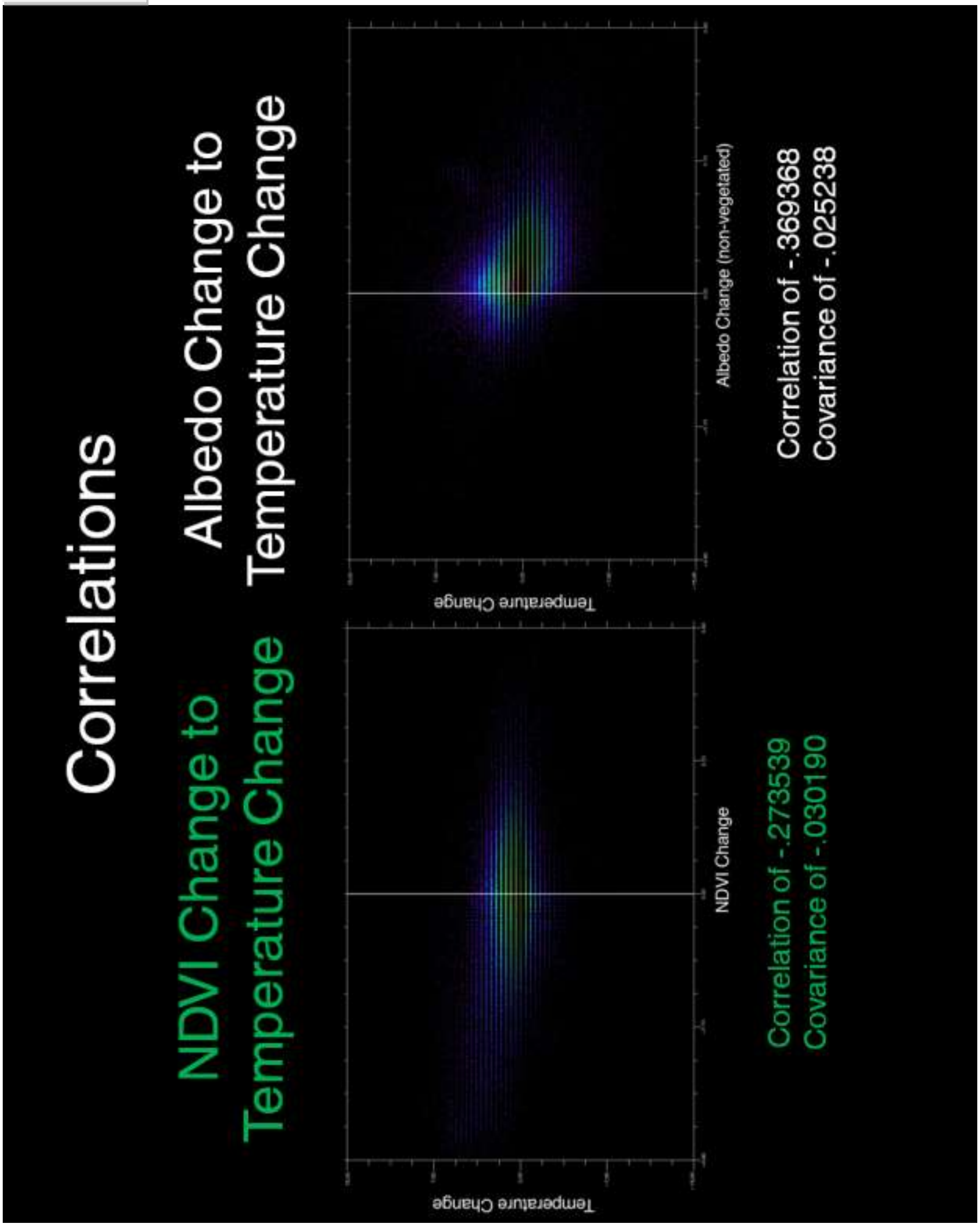

Correlations
NDVI Change to Temperature Change
Albedo Change to Temperature Change
Temperature Change
NDVI Change
Correlation of -.273539
Covariance of -.030190
Temperature Change
Albedo Change (non-vegetated)
Correlation of -.369368
Covariance of -.025238

Figure 11

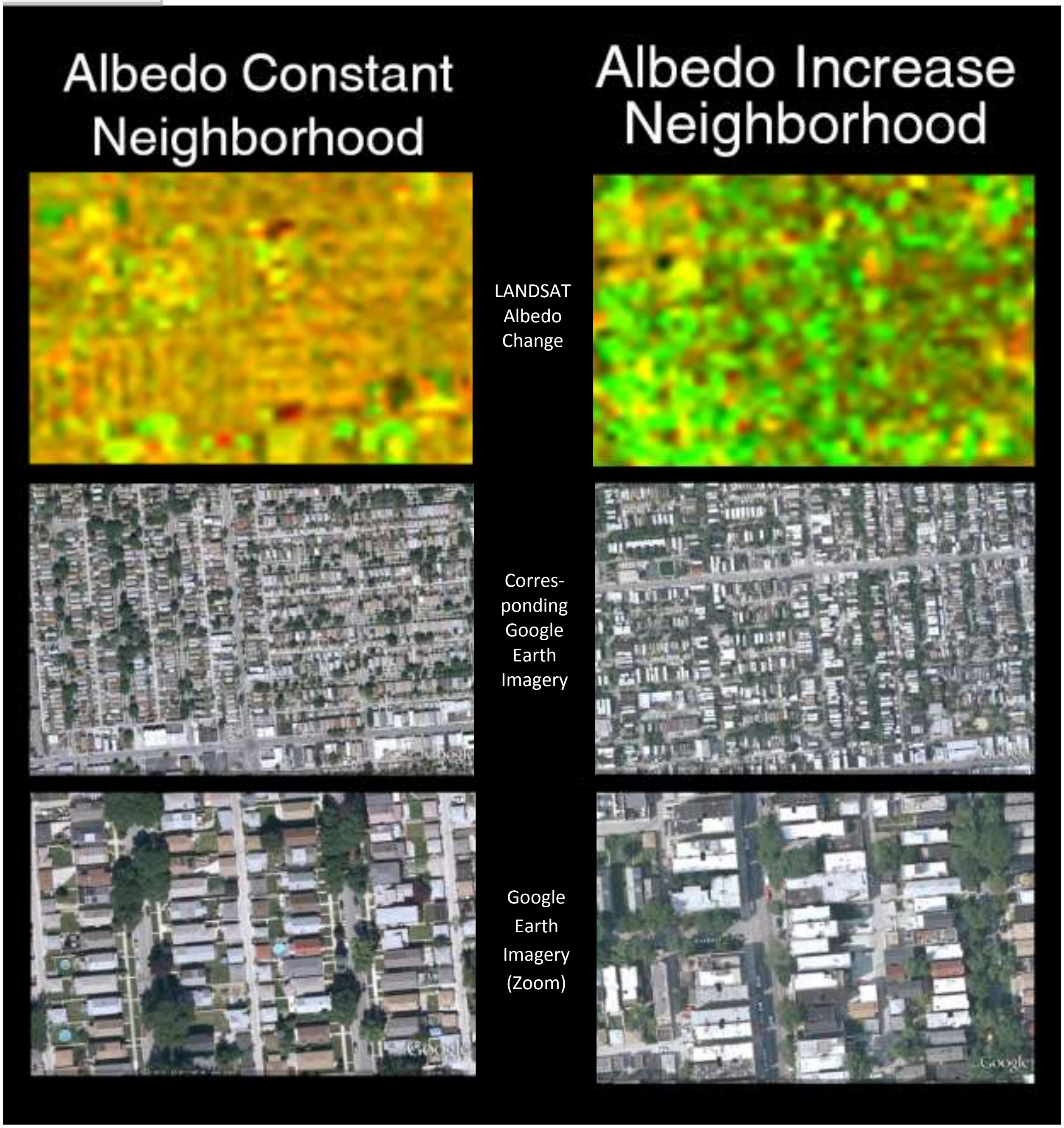

Albedo Constant Neighborhood
Albedo Increase Neighborhood
LANDSAT Albedo Change
Corres-ponding Google Earth Imagery
Google Earth Imagery (Zoom)

Figure 12

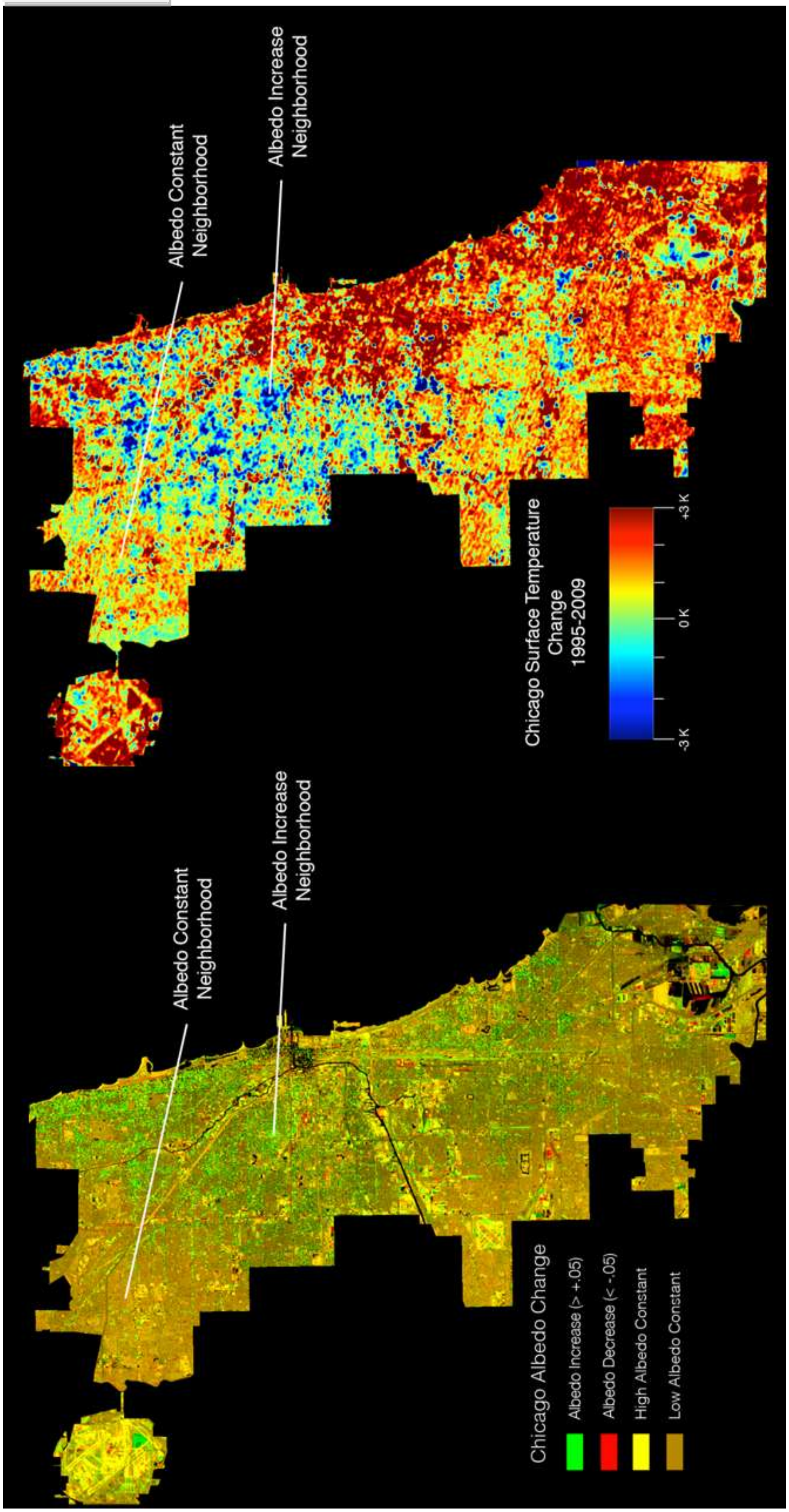

Albedo Constant Neighborhood
Albedo Increase Neighborhood
Chicago Surface Temperature Change 1995-2009
-3 K
0 K
+3 K
Albedo Constant Neighborhood
Albedo Increase Neighborhood
Chicago Albedo Change
Albedo Increase (> +.05)
Albedo Decrease (< -.05)
High Albedo Constant
Low Albedo Constant

Figure 13

Rough Qualitative Analysis of Policies

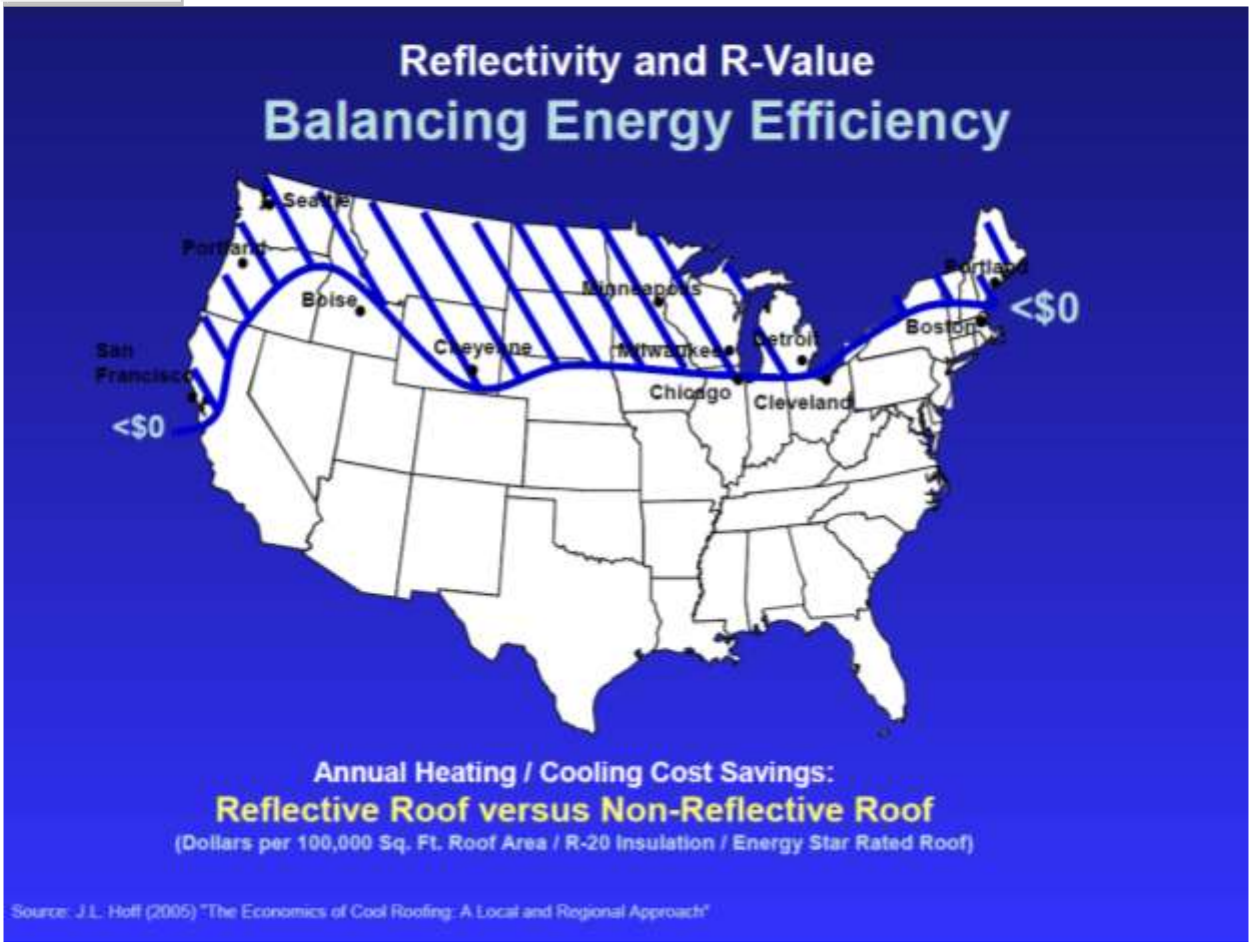
Green Policies

Policy	Visually Noticeable (w/ 30m res.)	Effect on Temperature	Area Affected
Green Roofs	No	None	Single Building
Small Parks	Yes	Stabilize	Few Blocks
Large Parks	Yes	Cool	Neighborhood
Street Trees	Yes	Stabilize	Regional

White Policies

Policy	Visually Noticeable (w/ 30m res.)	Effect on Temperature	Area Affected
Road Pavement	Yes	None	Regional
Alleyways	No	None	Few Blocks
Residential Reflective Roofs	Yes	Cool	Regional
Industrial Reflective Roofs	Yes	Cool	Regional

Figure 14



(image taken from a study by Hoff, James)