

INVESTIGATION OF HUMAN MODIFICATIONS OF LANDSCAPE AND CLIMATE IN THE PHOENIX ARIZONA METROPOLITAN AREA USING MASTER DATA

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ABSTRACT:

Humans directly alter surficial processes and climate at the local or “neighborhood” scale (typically on the order of hundreds of hectares) where process - response is not well understood. Investigation of surficial processes at this scale requires very high resolution (both spatial and spectral) data over a wide wavelength range. Commercial data from satellite-based sensors such as IKONOS and Quickbird now provide excellent spatial resolution in the visible through near-infrared wavelengths; however data with high spectral and spatial resolution at longer wavelengths, particularly the mid-infrared, are still the province of multispectral to hyperspectral airborne sensors. Superspectral data acquired by the NASA MASTER airborne sensor is being used to investigate social-biogeophysical microclimate interactions in Phoenix, Arizona neighborhoods. This sensor acquires data in 50 bands in the visible through mid-infrared wavelengths, placed to match the bandpasses of the satellite-based MODIS and ASTER instruments. Ground resolution of data acquired over the Phoenix metropolitan region varies from 5 – 12 m/pixel depending on aircraft height. Surface temperature and vegetation density spatial variations between neighborhoods spaced along an income gradient in Phoenix have been mapped using 12 m/pixel data. These data correlate with ethnicity and income level, and demonstrate inequity in the microclimates experienced by Phoenix residents.

1. INTRODUCTION

1.1 Modification of Surface Processes in Urban Systems

Urbanization is a significant, and perhaps the most visible, anthropogenic force on earth—affecting its surface, atmosphere, and seas; its biodiversity and its people. Reliable baseline data on the state of many urban area’s ecosystems and biodiversity is lacking, and our progress in obtaining these data is moving slower than our ability to alter the environment. Characterization and monitoring of urban center land cover/land use change is only of limited use in understanding the development pathways of cities and their resilience to outside stressors (Longley, 2002). Geological, ecological, climatic and social/political data are also necessary to describe the developmental history of a given urban center and to understand its ecological functioning (Grimm et al., 2000).

The modification of surface processes have direct impacts on humans and other species living in urban systems from the standpoint of increased vulnerability to geological and environmental hazards (Haff, 2002; Valentine, 2003), and regional to local climate change (Brazel et al., 2000; Voogt and Oke, 2003). Likewise, human inhabitants of cities develop several different types of “capital” (economic, political, natural, etc.) to either guard against or favor such changes that can provide further feedbacks to physical systems (Constanza and Daly, 1992; Prugh, 1999). Remotely sensed data and analytical techniques provide useful tools for assessing and monitoring these changes (Jensen, 2000; Donnay et al., 2001; Mesev, 2003), and perhaps provide increased understanding of the social/physical processes that operate along this interface.

While physical scientists have been the typical users of remotely sensed data social scientists, social geographers, urban planners, and local to regional governments have begun to recognize the potential uses of remotely sensed data for the study of socio-political dynamics and urbanization (Donnay and Unwin, 2001; Harris, 2003).

We must set some working definitions of spatial and spectral resolution for the purposes of discussion within this paper. Sensors with spatial resolutions of 5 m/pixel or less are considered to be “very high resolution”. Spatial resolutions greater than 5 m/pixel and up to 30 m/pixel will be considered “moderately high resolution”. Sensors with greater than 30 m/pixel ground resolution will be considered “coarse resolution”. Systems with more than one wavelength band are similarly defined as “multispectral” (less than 20 bands); “superspectral” (less than 100 bands); and “hyperspectral” (over 100 bands). The following sections provide an overview of high resolution satellite-based (1.2) and airborne (1.3) sensor systems of interest to the study of urban/peri-urban surface processes. Section 2 provides a case study of the use of one such high resolution system, the MODIS/ASTER simulator or MASTER, to understand climatic patterns in the city of Phoenix, Arizona, USA. Abbreviations not defined in the text are listed in Appendix A.

1.2 Satellite-Based High Resolution Systems

There is a long legacy of urban and peri-urban analysis using automated high resolution satellite-based sensors. Much of this work, however, has focused on delineation of urban vs. nonurban land cover at coarse to moderate spatial resolutions (Donnay, et al., 2001; Longley, 2002; Mesev, 2003). Extensive use has been made of the Landsat TM/ETM+ and ASTER sensors to characterize urban extent and materials (Haack, 1983, Haack et al., 1987; Gong and Howarth, 1990; Vogelmann et al., 1998; Donnay et al., 2001; Stefanov et al., 2001, 2003; Zhu and Blumberg, 2002; Mesev, 2003; Stefanov and

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Netzband, in review) and to conduct basic comparisons between urban centers (Ridd, 1995; Ridd and Liu, 1998; Netzband and Stefanov, 2003; Ramsey, 2003). The major characteristics of several past and currently-operating active and passive sensors are presented in Table 1. These sensors provide excellent temporal resolution (typically 14-16 day repeat cycle from 1972 to present) over the majority of the globe. Other satellite-based sensors with moderately high to very high spatial resolution (15 m/pixel to less than 1 m/pixel) have been developed primarily by the commercial sector and include the SPOT (Martin et al., 1988); IKONOS (Dial et al., 2003; figure 1), and Quickbird (Sawaya et al., 2003). The increasing availability of SAR data from satellites has also spurred urban research in the areas of urban feature mapping and land cover classification (Dell'Acqua et al., 2003), and monitoring of urban ground subsidence (Raucoles et al., 2003).

Sensor	Resolution (m)	Wavelength (Bands)	Temporal Coverage
TM	30/120	VSWIR (6)	1984-
ETM+	15/30/60	TIR (1) Pan VNIR (1) VSWIR (6)	1999-
ASTER	15/30/90	TIR (1) VNIR (4) SWIR (6) TIR (5)	1999-
SPOT HRV, HRVIR	10/20	Pan VNIR (1) VNIR (3) or VSWIR (4)	1986-2000 2000-
IKONOS	1/4	Pan VNIR (1) VNIR (4)	1999-
Quickbird	0.6/.70 2.4/2.8	Pan VNIR (1) VNIR (4)	2001-
RADARSAT	10 - 100	5.7 cm (C-band)	1995-
CORONA, ARGON, LANYARD	< 2 - 140	Pan visible	1960-1972
Hyperion	30	VSWIR (220)	2000-
Astronaut	Variable;	Pan visible	1961-
Photography	< 6 (digital cameras)	VNIR	

Table 1. Characteristics of selected high spatial- and spectral-resolution orbital sensor systems. Definitions of abbreviations are in Appendix A.

These very high resolution systems enable highly detailed land cover/land use and ecological characterization of urban and suburban regions (Weber, 1994; Greenhill et al., 2003; Sawaya, et al., 2003; Small, 2003; Weber and Puissant, 2003). Data from these commercial systems are typically limited in both spatial and temporal coverage however, and spectral coverage is limited to the visible and near-infrared wavelengths (Jensen, 2000). These data also tend to be expensive relative to governmentally built and operated programs. An additional data source for moderately high to potentially very high resolution visible to near-infrared digital data is astronaut photography. Photographs are acquired by astronauts from both the Space Shuttle and International Space Station and represent a rich database for urban/peri-urban studies (Robinson et al., 2000, 2002; Stefanov et al., 2003).

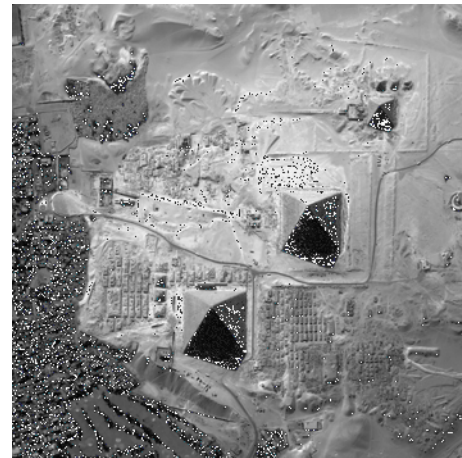


Figure 1. Panchromatic IKONOS image of the Great Pyramids at Giza, Egypt (1 m/pixel spatial resolution, acquired 17-November-1999). Image courtesy of Space Imaging, <http://www.spaceimaging.com>.

1.3 Airborne High Resolution Systems

Throughout much of the history of urban remote sensing, aerial photographs have been the primary data source. Film cameras have been used since the mid-1800s with a variety of platforms including balloons, kites, gliders, fixed-wing and unmanned aircraft (Jensen, 2000). These cameras have typically recorded information in the visible to near-infrared wavelengths as either panchromatic or RGB images at spatial resolutions now less than or equal to 1 m/pixel. Such data for urban areas have generally been gathered by commercial providers, and have proven very useful for extraction of geospatial relationships, digital terrain and surface models, and monitoring of vegetation health using both manual interpretation and sophisticated photogrammetric techniques. Airborne LIDAR systems have also come into common use for mapping of urban topography and surface features (Fujii and Arikawa, 2002).

Recent improvements to aerial photographic systems include the incorporation of GPS/INS (Global Positioning Systems/Inertial Navigation Systems) and the construction of new, fully digital sensor systems such as the ADS40. This sensor incorporates a line-array of charge-coupled devices (CCDs), and is capable of acquiring visible to near-infrared stereo data at ground resolutions of 0.21 m/pixel (Sandau et al., 2000). The major limitation to most commercial airborne digital aerial photograph data at the present time is wavelength coverage restricted to the visible and near-infrared wavelengths (Baltasavias and Gruen, 2003).

Multispectral, superspectral, and hyperspectral remote sensing in the visible through mid-infrared wavelengths at moderately high to high spatial resolution is still the province of airborne sensor systems. A complete discussion of all past and present airborne scanner systems is beyond the scope of this contribution, but the interested reader is directed to Jensen (2000) for a general review. Table 2 presents the characteristics of several active and passive airborne sensor systems currently in operation. There have been relatively few studies of urban /peri-urban systems performed using airborne multispectral to hyperspectral sensors acquiring data in the visible through shortwave infrared wavelengths (Wharton, 1987; Meinel et al., 1996; Roessner et al., 2001; Herold et al., 2003). Study of urban systems with hyperspectral sensors (AVIRIS, HyMap) is

particularly useful for the construction of urban spectral endmember libraries that could be used with current and planned multispectral to hyperspectral satellite data (Roessner et al., 2001; Herold et al., 2003).

Sensor	Resolution (m)	Wavelength (Bands)	Temporal Coverage
MASTER	5 - 50	VNIR (11) SWIR (14) TIR (25)	1998-
AVIRIS	4 - 20	VSWIR (224)	1994-
HyMap	3 - 10	VSWIR (126) and/or TIR (32)	1996-
AirSAR	3 - 10 (horiz./vert.)	5.6 cm (C) 23.5 cm (L) 68 cm (P)	1988-
LIDAR	< 1 cm	NIR to SWIR	1987-
Aerial Photography	~1	Pan visible, color visible, VNIR	mid-1800s to present

Table 2. Characteristics of selected high spatial- and spectral-resolution airborne sensor systems. Definitions of abbreviations are in Appendix A.

Studies of urban/peri-urban areas with mid- (or thermal) infrared airborne multispectral sensors such as the TIMS, ATLAS, and MASTER have been primarily driven by climate research (Voogt and Oke, 2003). These studies have used the multispectral thermal data available from these sensors to produce accurate models of urban climatic effects such as heat islands (Quattrochi et al., 2000), correlate specific heat inputs with land cover types and vegetation (Quattrochi and Ridd, 1994), and monitor environmental effects of regional climate change and increasing urbanization (Hook et al., 2001). Airborne sensors such as HyMap and MASTER also offer the potential to build mid-infrared urban spectral libraries similar to those discussed above for the visible through shortwave wavelength regions. Such libraries will help to extend the usefulness of ASTER and MODIS data for urban studies.

2. PHOENIX, AZ CLIMATE STUDY USING MASTER

2.1 Research Question

Modification of regional to local climate associated with urban centers is a well-known phenomenon, particularly as expressed by urban heat islands and oases (Brazel et al., 2000; Voogt and Oke, 2003). Urban heat islands are formed primarily due to atmospheric inversions caused by topographic effects, but a significant component of urban heating is caused by solar heating and re-emission from built materials such as asphalt, concrete, and buildings (Brazel et al., 2000). The Phoenix, AZ, USA metropolitan area is considered to be a “classic” example of the urban heat island effect as it is surrounded by mountain ranges that trap warm air, and has experienced high degrees of conversion of natural to built materials due to rapid expansion of the urban area over the past 60 years (Gammage, 1999). This conversion of surface materials is thought to be a major contributor to the significant rise of mean annual air temperatures observed in the Phoenix region over the same 60 years (figure 2; Brazel et al., 2000).

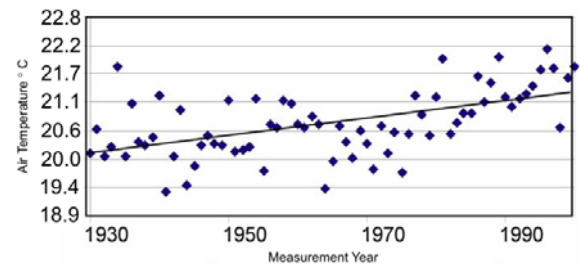


Figure 2. Mean annual air temperatures for Maricopa and Pinal Counties, Arizona.

Moderately high spatial resolution satellite and airborne remotely sensed data (TM, ETM+, ASTER, MASTER) are a major component of ongoing urban climate research in the Phoenix region. The majority of these studies focus on measurement and modeling of physical and climatic variables. These data are used to characterize land cover, vegetation density, and surface temperature in order to improve the determination of urban/rural gradients for heat island calculation (Hawkins et al., 2004); improve the NCAR/UCAR MM5 mesoscale climate model (Zehnder, 2002; Grossmann-Clarke et al., in review); and explore the relationships between social and physical variables important to urban climate (Jenerette, 2004).

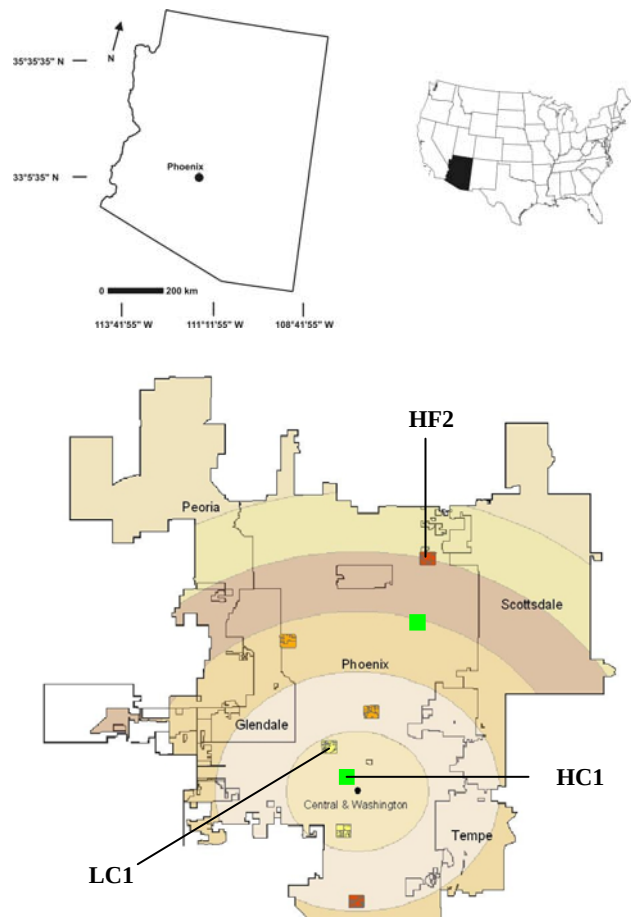


Figure 3. Upper left – location of the Phoenix metropolitan region within AZ (black polygon in USA map). Lower map of City of Phoenix extent shows locations of neighborhoods used in climate study (colored squares). Sites discussed in text are labeled.

The physical processes that modulate urban climatic response take place within a human-dominated ecosystem, and therefore the role of social forcings and feedbacks to urban climate must also be considered. The authors are engaged in an ongoing study of the relationships between social variables (income level, population per mile, percent Hispanic) and physical variables of importance to urban climate (land cover, vegetation density, surface and air temperatures) at the scale of individual neighborhoods located within the City of Phoenix proper (figure 3). The major research questions for this project are:

- What impact does the development, and observed intensification, of the urban heat island have on different groups of people?
- Are different population groups within the city more vulnerable to the effects of extreme temperature?
- Are specific modes of vulnerability identifiable, and can exposure to undesirable effects of heat be mitigated?



Figure 4. Representative photographs of study neighborhoods. A – xeric residential site HF2; B – mesic residential site HC1; C – urban residential site LC1.

There are several discrete physical data sources used in this interdisciplinary study including: historical climate records; weather station network data; air temperature data from automated loggers; and remotely sensed data from the ETM+, ASTER, and MASTER sensors (described below). Social data includes: 2000 United States Census block group information; a 2003 Omnibus Social Survey conducted on a random sample of Phoenix-Mesa MSA households, which included questions about respondents' perceptions of climate; and the Phoenix Area Social Survey, or PASS, an intensive study of eight neighborhoods (Harlan et al., 2003; Larsen et al., in press).

A total of eight 1 km² area neighborhoods were selected for the current study. Most of the discussion in this paper is focused on three "endmembers" (presented as being representative of the variation within the eight neighborhoods studied; figures 3 and 4). Neighborhood HF2 is a high-income xeric (low vegetation or natural desert) residential development (figure 4A). The HC1 neighborhood is an example of mesic (or heavily vegetated) high-income residential development (figure 4B). Neighborhood LC1 exemplifies low-income residential areas with little to no vegetation (figure 4C). Figure 3 illustrates the relative locations of these neighborhoods within the City of Phoenix.

2.2 Data Acquisition and Processing

Three remotely sensed datasets were used in the neighborhood climate study:

- Landsat ETM+ data acquired at approximately 10:00 local time on May 21, 2000 and June 9, 2001. These data provide daytime surface temperature from a 60 m/pixel broad band at 10.4 – 12.5 μm , and vegetation index information using the 30 m/pixel visible red (0.63 – 0.69 μm) and near-infrared (0.75 – 0.90 μm) bands (Jensen, 2000).
- ASTER nighttime data acquired on September 22, 2001; December 14, 2001; and March 20, 2003. All scenes were acquired at approximately 23:00 local time. These data provide surface temperature derived from five 90 m/pixel bands spanning wavelengths of 8.12 – 11.65 μm (Abrams, 2000).
- MASTER data acquired at approximately 12:00 local time on June 3, 2000. While MASTER acquires 50 bands of data in the visible through mid-infrared wavelengths (Hook et al., 2001), only the 10 mid-infrared bands (7.8 – 12.8 μm) were used to determine surface temperature.

Details of atmospheric correction and image registration for Landsat and ASTER data of the Phoenix region are presented elsewhere (Stefanov et al., 2001; Stefanov and Netzbach, in review). The MASTER data have the highest spatial and spectral resolution information of the above sensor systems and are the most useful for investigation of fine-scale surface temperature variations recorded for the three endmember neighborhoods. We will therefore limit the subsequent discussion of data processing to this dataset.

A radiative transfer code (MODTRAN 3.5) was used to remove atmospheric effects from the MASTER data. This code is implemented in the software package VICAR (and the Windows-based version WINVICAR) available from NASA's Jet Propulsion Laboratory (Hook et al., 2002). A standard midlatitude-summer, urban aerosol climate model was used as input to MODTRAN as contemporaneous atmospheric profile

data were not collected during the MASTER overflight. The atmospheric profile derived from MODTRAN was then convolved with the MASTER radiance-at-sensor values to obtain land-leaving radiance values (Eisinger, 2002).

Surface temperature was obtained from the land-leaving radiance values using the TEMIS algorithm in VICAR. This algorithm uses an estimated maximum surface emissivity value (0.985 was used in the present work) to calculate a Planck curve at a wavelength for which most surface materials will have the assumed emissivity. This curve is used for derivation of the surface temperature at this wavelength. The Planck equation can then be inverted using this temperature to calculate emissivity for all other bands (Kahle et al., 1993). It was observed during validation that MASTER bands 41 and 42 (located at 7.8 and 8.2 μm , respectively) had anomalously high emissivity values due to incomplete removal of atmospheric water by the MODTRAN code. The resulting surface temperature values obtained using the method described above were then compared to a calibration target in the MASTER scene (Tempe Town Lake) with known temperature values to validate the results. The validation target was used to select Band 44 (9.1 μm) as having the most accurate surface temperature retrieval. Surface temperatures obtained from this band were used in all subsequent analyses.

2.3 Data Analysis and Results

The surface temperatures calculated from MASTER, ETM+, and ASTER for the eight study neighborhoods were correlated using linear-least squares regression with Soil-Adjusted Vegetation Index (SAVI) values obtained from the ETM+ data (data not shown). The SAVI was selected for use as it incorporates a correction factor for soil reflectance, which is a significant factor in vegetation reflectance in arid environments due to the open canopy structure of most desert plants (Huete, 1988). All data were georeferenced to UTM Zone 12 using the NAD83 datum. A strong negative correlation between surface temperature and vegetation density ($r^2 = -0.673$) was obtained between 2000 MASTER surface temperature and 2000 ETM+ SAVI data at the neighborhood scale. Lower correlations of SAVI and ASTER surface temperature data were noted (r^2 ranging from -0.45 to -0.54). This is most probably due to the large seasonal differences between the ASTER, ETM+, and MASTER data.

Mean SAVI from ETM+	% Hispanic	Population per Mile	Mean Household Income
<i>Pearson</i>	0.120	-0.076	0.071
<i>Correlation</i>			
<i>Significance (two-tailed)</i>	0.778	0.858	0.867
Mean Surface Temperature from MASTER			
<i>Pearson</i>	0.390	0.492	-0.689
<i>Correlation</i>			
<i>Significance (two-tailed)</i>	0.340	0.216	0.059

Table 3. Social and physical variable correlation results for study neighborhoods.

Census block group data were then used to define polygons corresponding to the study neighborhoods for comparison of social variables obtained from the 2000 US Census data

(income, percent Hispanic, and population per mile) using a GIS. These variables were then regressed against the mean surface temperature and SAVI values obtained from the remotely-sensed data (MASTER and ETM+). Table 3 presents the correlation results for the eight study neighborhoods ($n = 8$).

2.4 Discussion

Qualitative analysis of the MASTER surface temperature data for the three endmember neighborhoods suggests temperatures are highly variable within each neighborhood (figures 5, 6, and 7). Higher temperatures generally correlate to areas with relatively little vegetation cover as depicted in 3 m/pixel digital aerial orthophotographs included in each figure. For example, surface temperatures are generally high over the spatial extent of neighborhoods LC1 (figure 5) and HF2 (figure 7) due the relative lack of dense vegetation cover in these two neighborhoods.

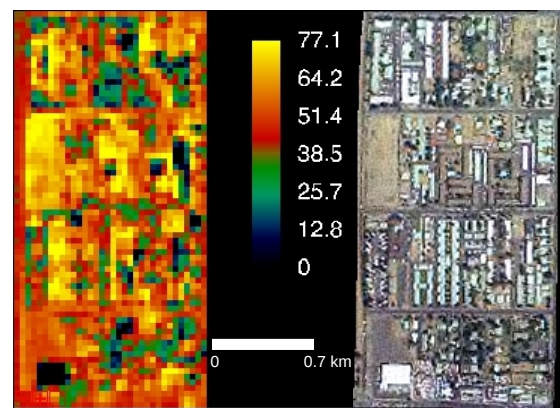


Figure 5. MASTER surface temperature map of site LC1 (left). RGB aerial orthophotograph acquired 1999 of site LC1 (right). Surface temperatures are in Celsius.

In terms of social variables, neighborhood HF2 is a high-income area with low percent Hispanic (the major non-Caucasian ethnic group in the Phoenix area) while neighborhood LC1 is a low-income, high percent Hispanic area. The HF2 neighborhood is located along the current northern urban fringe of Phoenix and has a low proportion of vegetation due to the dominant presence of natural desert and xeric landscaping. The LC1 neighborhood is located within the built-up urban region of Phoenix and the lack of vegetation here is due mainly to vacant lots and poorly maintained landscaping (Harlan et al., 2003).

In contrast to these two endmembers, the HC1 neighborhood has fairly evenly distributed green space and overall cooler surface temperatures (figure 6). This neighborhood is comprised primarily of high-income mesic residential properties with grassy lawns and significant canopied vegetation (figure 4B). The percent Hispanic in this neighborhood is also relatively low. Like neighborhood LC1, the HC1 neighborhood is located within the built-up portion of Phoenix rather than on the urban fringe. This neighborhood also has a very active voluntary neighborhood association, and access to flood irrigation, which maintains the observed level of lawn maintenance (Harlan et al., 2003).

The results presented in Table 3 for all eight neighborhoods indicates a strong negative correlation between mean household income and surface temperature, suggesting that poorer households (the highest percentage of which are Hispanic) generally experience higher environmental temperatures. Weaker positive correlations are observed between percent Hispanic, increased population per mile and higher surface temperatures. No clear correlations are noted between the selected social variables and SAVI data, suggesting that the observed correlations with surface temperature cannot be explained solely by vegetation abundance.

The results derived from analysis of the MASTER and ETM+ SAVI and surface temperature data closely agree with other data obtained from independent sources. The Omnibus Survey results for the Phoenix region indicate that people's perceptions of urban climate change are closely related to their economic status and physical environment. For example, only 22.9% of low-income respondents indicated that they perceived their neighborhood as cooler than other neighborhoods. In contrast, 32.7% of high-income respondents perceive their neighborhoods to be cooler than others. Hope et al. (2003) report a "luxury effect" expressed by higher diversity of plant species associated with high-income residential areas in comparison to low-income residential areas. Their results were derived in part from field data collection from 206 sites located throughout the Phoenix metropolitan area.

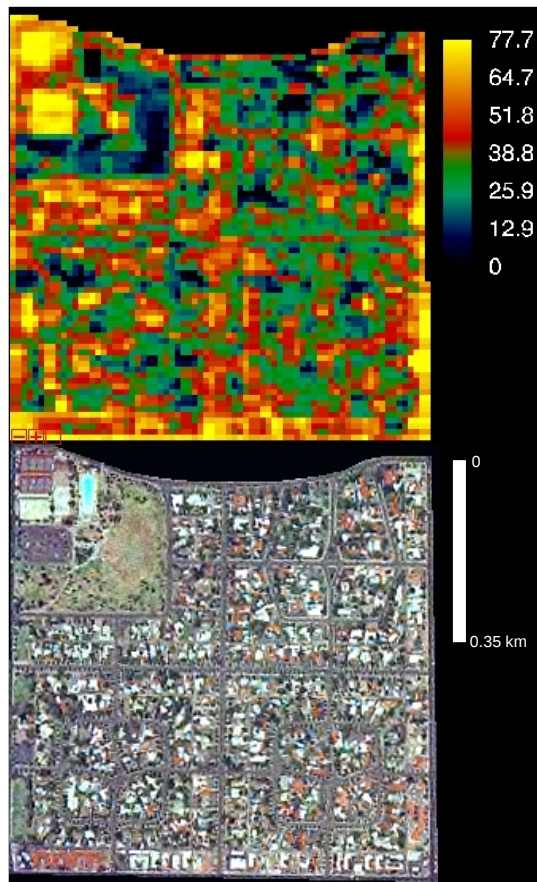


Figure 6. MASTER surface temperature map of site HC1 (top). RGB aerial orthophotography acquired 1999 of site HC1 (bottom). Surface temperatures are in Celsius.

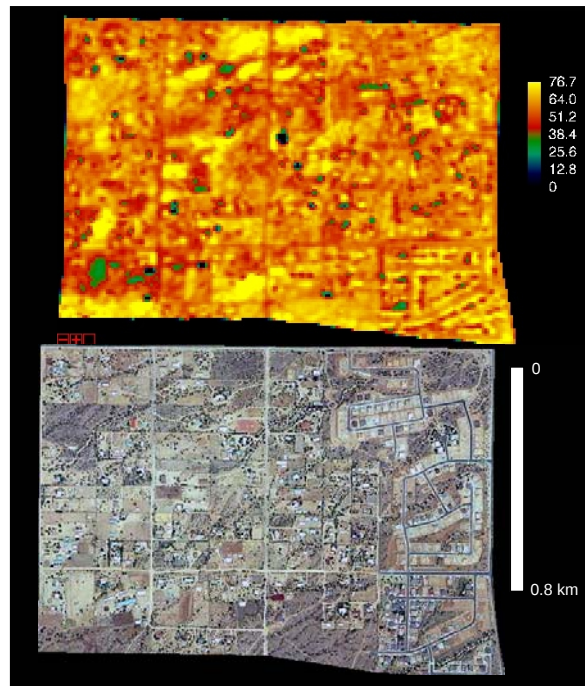


Figure 7. MASTER surface temperature map for site HF2 (top). Aerial orthophotograph acquired 1999 for site HF2 (bottom). Surface temperatures are in Celsius.

3. CONCLUSIONS

Data from moderately to very high spatial resolution satellite and airborne sensors are now available from a variety of commercial and governmental sources. Multispectral visible to near-infrared data with spatial resolutions of less than or equal to 1 m/pixel of the Earth's surface are now routinely acquired by satellite sensors such as IKONOS and Quickbird. Multispectral, superspectral, and hyperspectral airborne and satellite data (e.g. HyMap, MASTER, AVIRIS, ASTER, Hyperion) for the visible through mid-infrared wavelengths are also available albeit with restricted spatial and temporal coverage. Airborne LIDAR and spaceborne SAR sensor data are also available for many of the Earth's regions. The remote sensing community now has data available to characterize and monitor urban/peri-urban surfaces and processes in three dimensions (x, y, z) from the scales of sidewalks to entire watersheds.

This increased ability to resolve important surficial processes resulting from social/physical interactions in urban areas is demonstrated by "neighborhood-scale" microclimate studies using the airborne superspectral MASTER sensor. We present the spatial distribution of surface temperatures derived from the mid-infrared MASTER bands for three neighborhoods in Phoenix, AZ that represent endmembers of income, ethnicity, vegetation density, and geographic location. Correlations of surface temperature data derived from MASTER, vegetation density information obtained from Landsat ETM+, and a number of social variables collected by the US Census and other surveys indicate that lower-income neighborhoods experience urban heat island effects to a significantly greater degree than high-income neighborhoods.

Studies of this type that incorporate high resolution data improve our understanding of urban climate processes and help to improve models of regional to neighborhood-scale climate and personal "comfort levels". This information is of great

interest to urban planners, air quality officials, climate and ecological researchers, utility service providers, and those exploring means to mitigate the effects of urban heat islands. The availability of high spatial- and spectral-resolution data for urban centers located around the globe will also encourage the development of spectral endmember libraries for urban materials. Such libraries (some of which already exist for some cities) will facilitate the use of spectral unmixing and feature-matching approaches for urban studies with moderately high resolution multispectral and hyperspectral data available from Hyperion and ASTER. This would enhance the capability for global urban environmental characterization and observation of urban ecological processes.

4. REFERENCES

- Abrams, M., 2000. The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER): Data products for the high spatial resolution imager on NASA's Terra platform. *International Journal of Remote Sensing*, 21, pp. 847-859.
- Baltsavias, E.P., and A. Gruen, 2003. Resolution convergence: A comparison of aerial photos, LIDAR, and IKONOS for monitoring cities. In V. Mesev (Ed.), *Remotely Sensed Cities* (pp. 47-82). London, UK: Taylor & Francis.
- Brazel, A.J., N. Selover, R. Vose, and G. Heisler, 2000. The tale of two climates: Baltimore and Phoenix LTER sites. *Climate Research*, 15, pp. 123-135.
- Constanza, R., and H. E. Daly. 1992. Natural capital and sustainable development. *Conservation Biology*, 6 (1), pp. 37-46.
- Dell'Acqua, F., P. Gamba, and G. Lisini, 2003. Improvements to urban area characterization using multitemporal and multiangle SAR images. *IEEE Transactions on Geoscience and Remote Sensing*, 41, 1996-2004.
- Dial, G., H. Bowen, F. Gerlach, J. Grodecki, and R. Oleszczuk, 2003. IKONOS satellite, imagery, and products. *Remote Sensing of Environment*, 88, pp. 23-36.
- Donnay, J.-P., M.J. Barnsley, and P.A. Longley, 2001. Remote sensing and urban analysis. In P.A. Longley, J.-P. Donnay, & M.J. Barnsley (Eds.), *Remote Sensing and Urban Analysis* (pp. 3-18). London, UK: Taylor and Francis.
- Donnay, J.-P., and D. Unwin, 2001. Modelling geographical distributions in urban areas. In P.A. Longley, J.-P. Donnay, & M.J. Barnsley (Eds.), *Remote Sensing and Urban Analysis* (pp. 205-224). London, UK: Taylor and Francis.
- Eisinger, C., 2002. *Characterizing the composition of silicic lavas using infrared remote sensing*. MS Thesis. Tempe: Arizona State University.
- Fujii, K., and T. Arikawa, 2002. Urban object reconstruction using airborne laser elevation image and aerial image. *IEEE Transactions on Geoscience and Remote Sensing*, 40, 2234-2240.
- Gammage, G., Jr., 1999. *Phoenix in Perspective: Reflection on Developing the Desert*. Tempe: Arizona State University.
- Gong, P. and P.J. Howarth, 1990. The use of structural information for improving land – cover classification accuracies at the rural – urban fringe. *Photogrammetric Engineering and Remote Sensing*, 56, pp. 67-73.
- Greenhill, D.R., L.T. Ripke, A.P. Hitchman, G.A. Jones, and G.G. Wilkinson, 2003. Characterization of suburban areas for land use planning using landscape ecological indicators derived from Ikonos-2 multispectral imagery. *IEEE Transactions on Geoscience and Remote Sensing*, 41, 2015-2021.
- Grimm, N. B., J.M. Grove, C.L. Redman, and S.T.A. Pickett, 2000. Integrated approaches to long-term studies of urban ecological systems. *BioScience*, 70, pp. 571-584.
- Grossman-Clarke, S., J.A. Zehnder, and W.L. Stefanov, Urban modifications in a mesoscale meteorological model and the effects on surface energetics in a semi-arid metropolitan region. *Journal of Applied Meteorology* (in review).
- Haack, B., 1983. An analysis of Thematic Mapper Simulator data for urban environments. *Remote Sensing of Environment*, 13, pp. 265-275.
- Haack, B., N. Bryant, and S. Adams, 1987. An assessment of Landsat MSS and TM data for urban and near-urban land-cover digital classification. *Remote Sensing of Environment*, 21, pp. 201-213.
- Haff, P.K., 2002. Neogeomorphology. *American Geophysical Union EOS Transactions*, 83 (29), pp. 310, 317.
- Harlan, S., T. Rex, L. Larsen, E. Hackett, A. Kirby, S. Wolf, R. Bolin, A. Nelson, and D. Hope, 2003. *The Phoenix Area Social Survey: Community and Environment in a Desert Metropolis, Central Arizona - Phoenix Long-Term Ecological Research Project Contribution No. 2*. Tempe: Arizona State University.
- Harris, R., 2003. Population mapping by geodemographics and digital imagery. In V. Mesev (Ed.), *Remotely Sensed Cities* (pp. 223-241). London, UK: Taylor & Francis.
- Hawkins, T.W., A.J. Brazel, W.L. Stefanov, W. Bigler, and E.M. Safell, The role of rural variability in urban heat island determination for Phoenix, Arizona. *Journal of Applied Meteorology*, 43 (3), pp. 476-486.
- Herold, M., M.E. Gardner, and D.A. Roberts, 2003. Spectral resolution requirements for mapping urban areas. *IEEE Transactions on Geoscience and Remote Sensing*, 41, 1907-1919.
- Hook, S.J., R.E. Alley, and M.N. Orton, 2002. WINVICAR – A Windows based image analysis software package suitable for manipulating EOS data. *American Geophysical Union EOS Transactions*, 83 (47).
- Hook, S.J., J.J. Myers, K.J. Thome, M. Fitzgerald, and A.B. Kahle, 2001. The MODIS/ASTER airborne simulator (MASTER) – a new instrument for earth science studies. *Remote Sensing of Environment*, 76, pp. 93-102.
- Hope, D., C. Gries, W. Zhu, W.F. Fagan, C.L. Redman, N.B. Grimm, A.L. Nelson, C. Martin, and A. Kinzig, 2003. Socioeconomics drive urban plant diversity. *Proceedings of the National Academy of Science*, 1000 (15), pp. 8788-8792.

- Huete, A.R., 1988. A soil-adjusted vegetation index (SAVI). *Remote Sensing of Environment*, 25, pp. 295-309.
- Jenerette, G.D., 2004. *Landscape complexity and ecosystem processes of the Phoenix, AZ metropolitan region*. PhD Dissertation. Tempe: Arizona State University.
- Jensen, J.R., 2000. *Remote Sensing of the Environment: An Earth Resource Perspective*. Upper Saddle River, NJ: Prentice Hall.
- Kahle, A.B., F.D. Palluconi and P.R. Christensen. 1993. Thermal emission spectroscopy: Application to the Earth and Mars. In C.M. Pieters and P.A.J. Englert (Eds.), *Remote Geochemical Analysis: Elemental and Mineralogical Composition* (pp. 99-120). Cambridge, MA: Cambridge University Press.
- Larsen, L., S. Harlan, R. Bolin, E. Hackett, D. Hope, A. Kirby, A. Nelson, T. Rex, and S. Wolf, Bonding and bridging: Understanding the relationship between social capital and civic action. *Journal of Planning Education and Research* (in press).
- Longley, P.A., 2002. Geographic information systems: will developments in urban remote sensing and GIS lead to 'better' urban geography? *Progress in Human Geography*, 26 (2), pp. 213-239.
- Martin, L.R.G., P.J. Howarth, and G. Holder, 1988. Multispectral classification of land use at the rural-urban fringe using SPOT data. *Canadian Journal of Remote Sensing*, 14 (2), pp. 72-79.
- Meinel, G., M. Netzband, V. Amann, R. Stätter, and G. Kritikos, 1996. Analysing an ATM-Scanner flight over the city of Dresden to identify urban sealing. *International Archives of Photogrammetry and Remote Sensing*, 31 (B7), pp. 486-492.
- Mesev, V., 2003. Remotely sensed cities: An introduction. In V. Mesev (Ed.), *Remotely Sensed Cities* (pp. 1-19). London, UK: Taylor & Francis.
- Netzband, M., and W.L. Stefanov, 2003. Assessment of urban spatial variation using ASTER data. *The International Archives of the Photogrammetry, Remote Sensing, and Spatial Information Sciences*, 34 (7/W9), pp. 138-143.
- Prugh, T., 1999. *Natural Capital and Human Economic Survival* (2nd ed.). Boca Raton, FL: Lewis Publishers.
- Quattrochi, D.A., J.C. Luvall, D.L. Rickman, M.G. Estes, Jr., C.A. Laymon, and B.F. Howell, 2000. A decision support information system for urban landscape management using thermal infrared data. *Photogrammetric Engineering and Remote Sensing*, 66, pp. 1195-1207.
- Quattrochi, D.A. and M.K. Ridd, 1994. Measurement and analysis of thermal energy responses from discrete urban surfaces using remote sensing data. *International Journal of Remote Sensing*, 15, 1991-2022.
- Raucoules D., S. Le Mouélic, C. Carnec, C. Maisons, and C. King, 2003. Urban subsidence in the city of Prato (Italy) monitored by satellite radar interferometry. *International Journal of Remote Sensing*, 4, pp. 891-897.
- Ramsey, M. S., 2003. Mapping the city landscape from space: The Advanced Spaceborne Thermal Emission and Reflectance Radiometer (ASTER) Urban Environmental Monitoring Program. In G. Heiken, R. Fakundiny, & J. Sutter (Eds.), *Earth Science in the City: A Reader* (pp. 337-361). Washington, D.C.: American Geophysical Union.
- Ridd, M.K., 1995. Exploring a V-I-S (vegetation-impervious surface-soil) model for urban ecosystem analysis through remote sensing: Comparative anatomy for cities. *International Journal of Remote Sensing*, 16, pp. 2165-2185.
- Ridd, M.K., and J. Liu, 1998. A comparison of four algorithms for change detection in an urban environment. *Remote Sensing of Environment*, 63, pp. 95-100.
- Roessner, S., K. Segl, U. Heiden, and H. Kaufmann, 2001. Automated differentiation of urban surfaces based on airborne hyperspectral imagery. *IEEE Transactions on Geoscience and Remote Sensing*, 39, 1525-1532.
- Robinson, J. A., D.L. Amsbury, D.A. Liddle, and C.A. Evans, 2002. Astronaut-acquired orbital photographs as digital data for remote sensing: Spatial resolution. *International Journal of Remote Sensing*, 23, pp. 4403-4438.
- Robinson, J. A., B. McRay, and K.P. Lulla, 2000. Twenty-eight years of urban growth in North America quantified by analysis of photographs from Apollo, Skylab and Shuttle-Mir. In K.P. Lulla and L.V. Dessinov (Eds.), *Dynamic Earth Environments: Remote Sensing Observations from Shuttle-Mir Missions* (pp. 25-42). New York, NY: John Wiley & Sons.
- Sawaya, K.E., L.G. Olmanson, N.J. Heinert, P.L. Brezonik, and M.E. Bauer, 2003. Extending satellite remote sensing to local scales: land and water resource monitoring using high-resolution imagery. *Remote Sensing of Environment*, 88, pp. 144-156.
- Small, C., 2003. High spatial resolution spectral mixture analysis of urban reflectance. *Remote Sensing of Environment*, 88, pp. 170-186.
- Stefanov, W.L., and M. Netzband, Characterization and monitoring of urban/peri-urban ecological function and landscape structure using satellite data. In C. Jürgens and T. Rashed (Eds.), *Remote Sensing of Urban and Suburban Areas*, Kluwer Academic Publishers, Dordrecht, Netherlands (in review).
- Stefanov, W.L., M.S. Ramsey, and P.R. Christensen, 2001. Monitoring urban land cover change: An expert system approach to land cover classification of semiarid to arid urban centers. *Remote Sensing of Environment*, 77 (2), pp. 173-185.
- Stefanov, W.L., M.S. Ramsey, and P.R. Christensen. 2003. Identification of fugitive dust generation, deposition, and transport areas using remote sensing. *Environmental and Engineering Geoscience*, 9 (2), pp. 151-165.
- Stefanov, W.L., J.A. Robinson, and S.A. Spraggins, 2003. Vegetation measurements from digital astronaut photography. *The International Archives of the Photogrammetry, Remote Sensing, and Spatial Information Sciences*, 34 (7/W9), pp. 185-189.

Valentine, G.A. 2003. Towards integrated natural hazard reduction in urban areas. In G. Heiken, R. Fakundiny, & J. Sutter (Eds.), *Earth Science in the City: A Reader* (pp. 63-73). Washington, D.C.: American Geophysical Union.

Vogelmann, J.E., T. Sohl, and S.M. Howard, 1998. Regional characterization of land cover using multiple sources of data. *Photogrammetric Engineering and Remote Sensing*, 64, pp. 45-57.

Voogt, J.A., and T.R. Oke, 2003. Thermal remote sensing of urban climates. *Remote Sensing of Environment*, 86, pp. 370-384.

Weber, C., 1994. Per-zone classification of urban land cover for urban population estimation. In G.M. Foody and P.J. Curran (Eds.), *Environmental Remote Sensing from Regional to Global Scales* (pp. 142-148). Chichester, UK: John Wiley & Sons.

Weber, C., and A. Puissant, 2003. Urbanization pressure and modeling of urban growth: example of the Tunis metropolitan area. *Remote Sensing of Environment*, 86, pp. 341-352.

Wharton, S., 1987. A spectral-knowledge-based approach for urban land-cover discrimination. *IEEE Transactions on Geoscience and Remote Sensing*, GE-25, pp. 272-282.

Zhu, G., and D.G. Blumberg, 2002. Classification using ASTER data and SVM algorithms: The case study of Beer Sheva, Israel. *Remote Sensing of Environment*, 80, pp. 233-240.

TIR – Thermal Infrared

TM – Thematic Mapper

UTM – Universal Transverse Mercator

VNIR – Visible to Near-Infrared

VSWIR – Visible to Shortwave Infrared

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APPENDIX A. ABBREVIATIONS IN TEXT

ASTER – Advanced Spaceborne Thermal Emission and Reflection Radiometer

ATLAS – Airborne Terrestrial Applications Sensor

AVIRIS – Airborne Visible/Infrared Imaging Spectrometer

ETM+ - Enhanced Thematic Mapper Plus

GIS – Geographic Information System

LIDAR – Light Detection and Ranging

MASTER – MODIS/ASTER Simulator

MM5 – Mesoscale Model 5

MODTRAN – Moderate Resolution Transmittance

MSA – Metropolitan Statistical Area

NCAR/UCAR – National Center for Atmospheric Research/University Corporation for Atmospheric Research

RGB – Red, Green, Blue

SAR – Synthetic Aperture Radar

SPOT - Système Probatoire d' Observation de la Terre: HRV (High Resolution Visible); HRVIR (High Resolution Visible and Infrared)

SWIR – Shortwave Infrared

TIMS – Thermal Infrared Multispectral Scanner