CHALLENGES FOR APPLIED REMOTE SENSING SCIENCE IN THE URBAN ENVIRONMENT

M. Netzband [a] , C. L. Redman[a] , W. L. Stefanov [b]

[a] Institute for International Sustainibility, Arizona State University, Tempe, AZ 85287-3211 USA; maik.netzband@asu.edu,
charles.redman@asu.edu
[b] Image Science & Analysis Laboratory, Lyndon B. Johnson Space Center, 2101 NASA Road 1, Houston, TX 77058 USA;
william.l.stefanov1@jsc.nasa.gov

Commission VIII, WG

KEY WORDS: Urban analysis, Urban Planning Applications

ABSTRACT:

Land cover and land use changes associated with urbanization are important drivers of local geological, hydrological, ecological, and climatic change. Quantification and monitoring of these changes in 100 global urban centres are part of the mission of the ASTER instrument on board the NASA Terra satellite, and comprise the fundamental research objective of the Urban Environmental Monitoring (UEM) Program at Arizona State University. Data have been acquired for the majority of the target urban centres and are used to compare landscape fragmentation patterns on the basis of land cover classifications at both local and global scales. Despite the promising and exciting possibilities presented by new and fast-developing sensors and technologies we still perceive a gap between the generally academic and research-focused spectrum of results offered by the "urban remote sensing' community and the application of these data and products by the local governmental bodies of urban cities and regions. In a recently organized workshop with partners from six urban regions all over the world we tried to determine what the important questions are, and how we can use our data and scientific skills to help answer them.

1. CURRENT RESEARCH OBJECTIVES

Arizona State University (ASU, the host of the Urban Remote Sensing conferences 2005) through its Urban Environmental Monitoring project (UEM, http://elwood.la.asu.edu/grsl/UEM/) is particularly qualified to provide remote sensing technology and expertise in promoting urban sustainability around the world. The Department of Geological Sciences' Geological Remote Sensing Laboratory, in conjunction with the Center for Environmental Studies, has initiated research on 100 cities around the world using data from NASA's Earth Observing System (EOS) as well as other satellite- and airborne-based datasets (Stefanov and Netzband, in press). These high spatial and spectral resolution image data can provide key information that allows decision makers to monitor: urban densities; urban geo-hazards; new developments on the urban fringe; the spread of impermeable surfaces, soil erosion and dust formation; the transformation of agricultural lands; changes in local microclimates, surface water flow and reservoir capacity; primary productivity of local vegetation; condition of transportation arteries; and key aspects of air pollution.

Over the past two years, ASU scientists from a variety of disciplines including geology, engineering, geography, ecology, and sociology have been developing a comprehensive series of metrics to characterize the spatial and socio-ecological structure of cities together with methods to validate the inferred patterns. Much of this current work focuses upon Phoenix, taking advantage of the extensive on-the-ground resources of the Central Arizona–Phoenix Long Term Ecological Research (CAP LTER) project. To further test these methods, we are now forming an expanding network of partner cities in the developed world where scientific resources are readily available, and in developing countries where there is great enthusiasm for applying this approach to pressing environmental problems. In parallel with the growth of this network, we are collaborating with government agencies (such as NASA) and the scientific community to establish an enhanced satellite system that directly serves the needs of urban areas.

While characterization and monitoring of ongoing urbanization processes is important, equally important is the ability to predict the local and regional environmental effects and feedbacks associated with expanding urban centres (Grimm et al., 2000). We define six major research objectives to achieve this goal:

Objective 1: Tracking urban area growth and change: speed, density, direction, structures, impervious surfaces, land use consumed.

Objective 2: Spatial arrangement of green/open space within cities and at periphery: amount distribution, links.

Objective 3: Track changes in peri-urban regions: farmland conversions, wetland infringement, biodiversity threats.

Objective 4: Monitor land cover/land use changes that influence urban climatology and atmospheric deposition.

Objective 5: Monitor urban growth as it intersects areas of potential environmental hazards: earthquake, subsidence, mudslides, floods, etc.

Objective 6: Map environmental parameters such as micro-climate, heat island, access to open space, percent impervious surface, percent green space and assess the geographic differences within regions and whether they correlate with social, economic, or ethnic divisions.

The UEM project is using a variety of remotely sensed and GIS datasets (ASTER, Landsat, MODIS, astronaut photography, socioeconomic data, historical maps) to establish development trajectories within a pilot study for 8 urban centers located around the globe.

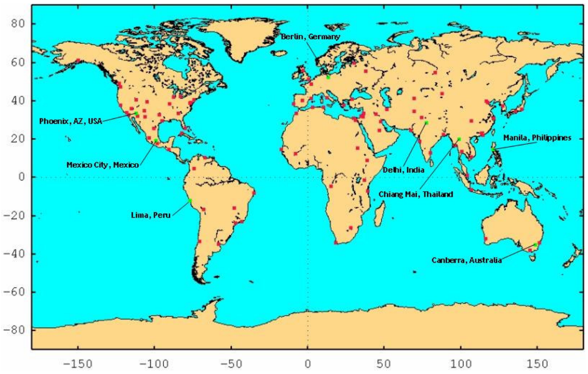

Figure 1. Location map of eight "intensive study" cities. Red squares indicate other UEM cities.

These urban centers (Berlin, Germany; Cairo, Egypt; Chiang Mai, Thailand; Delhi, India; Mexico City, Mexico; Lima, Peru; and Phoenix, Arizona, USA) are selected on the basis of urban growth projections, geologic/geographic setting, and climatic patterns. Our initial goal is to determine classes or groupings of urban development trajectories defined by several variables (land use/land cover, landscape metrics, climatic patterns, geologic hazard assessment, and development history). The understanding of how these urban centers have developed and responded to various environmental, climatic, and sociopolitical stressors will inform models of how sustainable they are given similar future stressors (Alberti and Waddell, 2000). Improvement in understanding of urban resilience and sustainability is of great importance to scientists, policy-makers, and citizens alike. The models we develop will allow policy-makers to incorporate remotely sensed data into their local and regional planning efforts.

Within the UEM project we will continue to produce standardized land cover classifications for 100 urban centers located around the globe using ASTER data throughout the duration of the Terra mission. In addition, we will monitor the geological and ecological status of these cities using ASTER and MODIS. Classification of urban development trajectories and spatial structure will be determined for a representative subset of 8 urban centers (see figure 1) using a coherent methodological approach to ensure comparability of the results. Ongoing research in this area includes development of detailed land cover classification models for the eight study cities (figure 2).

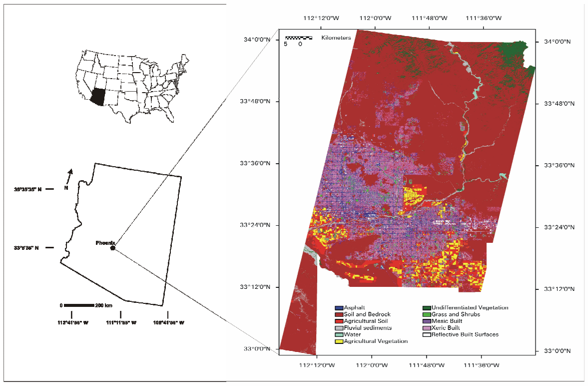

Figure 2. Land cover classification for the eastern Phoenix area.

2. KEY PROBLEMS THAT NEED TO BE ADDRESSED BY URBAN REMOTE SENSING

At Arizona State University (ASU) a brainstorming meeting took place on February 18, 2004 in order to assess and evaluate the potentials and demands on Remote Sensing in Urban Areas. The following topical questions were considered as a framework:

1. What are the key social and physical questions that should be addressed using urban remote sensing technology and data?
    a. In general, what challenges to sustainability are faced by urban regions?
    b. b. Which of these challenges do you see in the urban regions with which you are familiar?
    c. What (if any) solutions are applied to these challenges?
    d. How can the outcome of these solutions be enhanced with the application of remote sensing?
2. What are the regional and global impacts of the social problems associated with urban regions?

2.1 Social problems

Human settlements are a product of social evolution over long periods of time. Today we are facing collective action problems such as increasing diversity, expanding populations and global inequalities and these are especially concentrated in the urbanized landscapes. The western urban development model is consumption and growth-oriented. Technology may allow some increase in resource use, but this will not offset the increasing demands in the developing world.

Resource use in the developed world may have to go down and could lead to political and social upheavals. Some big cities are powers in the world; other big cities are just trying to survive. In order to study the global urban system one could imagine a generation of a global urban GIS dataset that is based on historic land-use and constantly updated with recent data. Suburbanization is a commonly observed development and it would be most interesting to know about its global rates and how it differs across regions.

What are the present main challenges (threats) to the urban population?

- Suburbanization and urban growth make them vulnerable to crises (e.g., pipeline breaking, outbreaks of disease).
- Urban growth ‘consumes’ the surrounding land resources that are generally nonrenewable in terms of surface water, groundwater and food resources. In arid climatic zones the threat of dwindling water resources is especially serious.
- Dense cities may be more vulnerable to terrorist attack due to the interdependence of services and concentrations of population, educational centers, industry, etc.

Rindfuss and Stern (1996, http://books.nap.edu/books/0309064082/html/index.html) discuss the gap between social science and Remote Sensing but suggest to overcome the separating differences, yet they see the benefits for both sides in bridging the two fields. Remote Sensing scientists state the social utility as the expensive government financed data and techniques become more valuable for the society. Vice versa some social scientists see the role of Remote Sensing in helping gather information on the context that influences social phenomena or the environmental consequences of various social, economic, and demographic processes. Social science itself can contribute to the accuracy of Remote Sensing research by validating and interpreting the data as well as supporting data confidentiality and public use.

There is a need to create typologies of urban structure such as building density, spread of impervious services, commute times and other infrastructure issues. Such a typology of cities could also take into consideration open space structures, parks, dedicated park areas in the hinterland, and green corridors to determine dedicated recreational space per person. Parks are becoming intertwined with power and wealth (private parks and open spaces). Remote sensing and GIS can provide precise and geo-referenced information on accessibility, size, shape, ownership, context and distribution of open and green areas. In the following we discuss selected applications.

2.2 Inner Urban Differentiation (Urban Structure)

Different technical approaches to the "urban environment" require a common spatial working basis, which can integrate essentially heterogeneous investigation features by using an adequate surface classification. The "urban structure type" concept was developed and used as a practicable and appropriate method to organize the urban spatial order, and to provide a uniform methodological framework for the different tasks within an interdisciplinary network of projects.

Environmentally-based urban administration decisions require characterization and rational analysis of urban landscapes according to ecologically relevant features. Data integration of different sources (remotely sensed, field-based, and map-based) with various spatial/temporal resolutions and thematic contents is now operational in GIS environments, and promises to deliver integrated data packages to urban and regional planners. Biotope and urban mapping using color infrared aerial photographs has been commonly used in the past in order to acquire basic structural information about urban areas on the basis of a visual land use classification. New high resolution remote sensing data (IKONOS, Quick Bird) combined with advanced object-oriented analysis methods can also achieve this goal for cities located throughout the globe.

Maps of growth and resulting classified urban structure derived from remotely sensed data can improve visualization of urban trajectories in order to understand the underlying systems of the city, how it functions, and its structures. This information has to come to policy makers in a form that makes sense to them. To meet this goal we need to improve our capabilities in forward (future) modeling and the combination of remotely sensed, DEM, and GIS data to produce 3D visualizations and flythroughs.

2.3 Climatic, Atmospheric and Geologic Applications for Urban Remote Sensing

2.3.1 Urban Climate

One of the most evident problems facing urban agglomerations around the world is the formation and intensification of urban heat islands (UHI; Voogt and Oke, 2003). Phoenix, AZ is a "classic" example, but heat islands are present in most every city and contribute to increased energy cost, water use, potential biodiversity change, and decrease in human comfort (Brazel et al., 2000). The increased cost of dealing with rising urban temperatures may also increase social and environmental injustices commonly present in cities (Jenerette, 2004; Stefanov et al., 2004). Finally, the aggregate effects of UHI on regional and global climate are poorly understood. Day and night thermal infrared data acquired by ASTER, MODIS, and Landsat can be used to model the UHI affect and quantify the contributions of different materials to the thermal budget.

2.3.2 Urban Air Quality

Urban/peri-urban regions in both the developed and developing world are frequently associated with reduced air quality due to industrial processes, automobile use, residential wood and coal burning, agricultural activities, and disruption of soil surfaces due to construction or informal settlement (Krzyzanowsk and Schwela, 1999; Williams, 1999). While many developed world cities have in-place ground level sensor networks to measure air quality on a real-time basis (such as Phoenix), this capability does not exist in much of the developing world. The availability of surficial and atmospheric remotely sensed data at a variety of scales (ranging from less than 1 meter/pixel to 40 km/pixel) for urban centers around the world presents an opportunity to improve climatic models and potentially monitor urban air quality in these regions (Zehnder, 2002; Stefanov et al., 2003; Grossman-Clarke et al., in press). Some of the important parameters that can be measured with remotely sensed data include high-resolution land cover (IKONOS, Quickbird), biogeophysical variables such as albedo, vegetation cover, and aerosols (ASTER, MODIS, Landsat), and important constituents of air pollution such as ozone (TOMS). Incorporation of these sources of data would greatly improve the effectiveness of climatic models such as MM5 for use in developing cities.

It is well known that the urban climate is a function of urban structure and urban activity (e.g., microclimates), and in each specific case one is dealing with very different physical and cultural conditions. How do we perform comparative studies in different cities when each will have different priorities? In general one must maintain the scientific interest yet be practical and therefore structure some basic work that provides a unit of analysis that is attractive to each city or at least subsets of cities. But at first one should take advantage of what has already been studied and then ask "what else can we add by using remote sensing?" It is important that the UEM project continues to perform worldwide data collection but also create clusters of cities with similar histories, socio-demographic components, and structure to reveal commonalities and discover differences in urban development.

How can we incorporate urban remote sensing results embedded in complex relationships among local/regional/global networks with the more theoretical/conceptual framework of sustainable development and resilience of urban landscapes? As an example, global scenarios need to be linked with research down-scaled to a local level, with local impacts sorted out from global impacts and vice versa. This can be achieved to first order by using historical weather records when available, but the representativeness of these records is questionable as input for global models due to potential site-specific bias in the results (i.e. location of weather stations at airports). We perceive a clear need for calibration of comparative studies and input of data from urban centers to global climatology models.

Satellite-based remote sensing currently cannot provide atmospheric information at a small (i.e. < 1 km) scale but is very useful in describing the aspects of the climate pattern of urban areas by recording surface temperatures, soil moisture, land cover, and vegetation density. Nevertheless there is a need of other data sources for climatological modeling. Remote sensing products that can provide 3-D urban topography information on cities is very important in this regard, and is now available for many urban centers from commercial vendors. Furthermore remote sensing can provide multiple cities with periodically updated land use/land cover data useful for revision and refinement of meteorological models for local climate prediction and air pollution models such as the NCAR MM5 code (Grossman-Clarke et al., in press).

Concerning the air pollution problem, remotely sensed data are useful for improvement of land use/land cover information to models, rather than actual monitoring of air quality. Atmospheric sounders can also record data useful for analysis of atmospheric composition and opacity, but the spatial scale of these data is typically too coarse for urban pollution monitoring. In the case of large dust storms and pollution plumes, current sensors are quite useful in tracking the movement and extent of these atmospheric materials. Urban structure characterization achieved using remote sensing can demonstrate how the urban structure correlates with differing air quality acquired by ground measurements. Another interesting and promising topic is: what are the contributions of cities and urbanized regions to regional, sometimes national and international (across borders) pollution patterns? The pattern and spatial distribution of the plume, how far and where does it go? How does it mix with neighboring cities? These are all components of the problem of modeling air flow and pollution production, and are closely connected to open space preservation, urban form, urban topography, etc.

2.3.3 Urban Geohazards and Environmental Monitoring

The surrounding (and underlying) geology of an urban center plays a direct role in determining the types of structures that can be built, and the susceptibility of the city to various geologic hazards (Valentine, 2003). Some of these hazards are obvious – expansion into areas with close proximity to active volcanoes, or building on sediments that can fluidize during earthquakes. Mexico City is exposed to both of these geologic hazards for example. Other less obvious hazards include subsidence beneath cities due to groundwater withdrawal, potential slope failures related to building on unstable hillslopes, and mobilization of contaminant-laden dust due to agricultural, industrial, and construction activities. A variety of remotely sensed data can be useful in assessing these potential hazards. The subtle decreases in elevation due to subsidence can be measured by use of radar remote sensing (InSAR) and LIDAR (Mapping of surficial deposits and landforms resulting from prior earthquakes and volcanic activity can be significantly augmented by using multispectral, superspectral, and hyperspectral sensors (Landsat, ALI, ASTER, Hyperion). Increased temperatures that can herald volcanic eruptions can be measured using AVHRR, ASTER, and MODIS (Ramsey and Flynn, 2004). Spectral analysis techniques can also be used to map areas of potential soil contamination – for example the presence of certain clay species that can absorb heavy metals (Ben-dor et al., 1999)

Urban geohazards and environmental geology are a growing subfield within the larger discipline of geology. A key synergy of this field is the combination of social data with geohazards knowledge and predictive potentials. The direct benefit to cities is greater knowledge of where geologic hazards might occur (areas of earthquake rupture, past extent of debris flows). This can help guide future expansion, create hazard response plans, and encourage appropriate engineering guidelines for buildings and infrastructure. What are the implications for a given urban center when a natural catastrophe happens? Can slower-timescale “catastrophes” such as pollution of groundwater or structural failure due to subsidence be averted by cities with adequate information? Why does urban growth move towards high-risk areas? Remote sensing combined with GIS (e.g. DEMs) could help provide the knowledge necessary to assess the implications for growth and develop plans to mitigate some of the geohazard risks.

2.3 Urban Landscape Applications

2.3.1 Urban Form and Periphery

The present development stage of urban landscapes is strongly shaped by the given penetration of settlement and open space structures (Kuehn, 2003). This challenges urban planning authorities to develop new planning strategies instead of only judging the existing urban landscapes in a negative manner. Mixed neighborhood structures of settlements and open spaces in the suburban areas can be very easily detected and evaluated by the currently available remote sensing data. The current reality of widespread urbanization suggests that we need to understand the urbanized landscape as a new independent type of cultural landscape. Therefore, remote sensing could provide a very helpful tool on the regional scale to evaluate the role that landscape plays, on the one hand, to *connect* different settlements within city regions to a so-called ‘Regional City Network’ and, on the other hand, to *separate* city and countryside.

Seventy percent of people in the US urban regions are living in suburban areas (Leichenko, 2001), the intermediate zones between the city centers and the rural hinterland. This trend might be spearheaded in the US but is also recognized as a worldwide development. What are the global implications of living in suburban structures? Who are these “suburbanites”, and how do they differ from dwellers in the urban core? The main question for planners today seems to be: How should urban areas grow? Can we influence the growth in a sustainable way, and what does that mean? Is urban sustainability a global concern, or is it only of regional importance? In a worldwide urban remote sensing network we could develop sustainability parameters on 100 or more urban regions and develop tools to address these questions.

In general remote sensing provides the most recent, spatially accurate, and spatially continuous data sources for reasonable prices. Frequently it is the only available data source in inaccessible, provisional and insecure areas (e.g. informal settlements, shanty towns, rescue camps) to monitor and evaluate infrastructure needs and urban growth, and short-term changes such as wars, natural disasters, etc. There still is a research and applications need for the dynamic calibration of the data and tools in order to ensure accuracy. Another relevant question is how urban form has modified landscape in both the urban and surrounding areas. For example, detection and evaluation of the spatial distribution of impervious, sealed surfaces is a key parameter for urban ecology (surface and groundwater availability and runoff, vegetation dynamics) and planning (stormwater runoff, flooding hazards, heat islands) that remotely sensed data can provide.

2.3.2 Open Space Preservation

Another important feature for a sustainable development in urban regions is the preservation of open spaces, mostly green areas (Ward Thomson, 2002). Particularly in former heavy industrial regions a sharp contrast exists between large industrial abandoned 'brownfield' sites with high remediation costs and insufficient traffic links to the core area, and a development boom in the suburbs with more favorable location features. In the city centers several problems regarding landscape consumption are recognized such as the sealing of surfaces, contamination of soils and water bodies, and increased air pollution. Thus a fundamental goal for the sustainable development of urban regions is the improvement, protection, and development of urban and suburban green spaces or landscapes; understanding of their ecological functionality and economic load carrying capacity; and increasing the quality of life of the inhabitants in the urban areas (Breuste, 2003). A regional open space protection agenda covers both the suburban space and the open spaces in the city.

Urban/peri-urban features of importance that are measurable by remote sensing and GIS techniques include:

- semi-natural areas (protected areas) within and at the fringe of urban areas,
- unused open spaces (fallow land),
- park systems and private green spaces,
- open spaces in the suburban cultural landscape (protected areas, arable and forest land).

Numerous cities are developing or have developed an open space model/concept/strategy to prioritize areas for preservation (Cook, 2003). Remotely sensed data can provide additional information such as vegetation indices, land cover, and enhance monitoring capabilities. There is special importance attached to small urban gardens and urban agricultural areas for subsistence as well as for recreational purposes in both rich and poor countries. Such areas also feed back to the urban ecological system (i.e., improvement of green structure, urban climate, etc.). Urban garden areas may also strengthen the resilience of urban areas by decreasing vulnerability to food crises.

2.3.3 Urban Landscape Evaluation

The evaluation of urban landscapes is often based upon different sub-functions which refer to landscape features such as soil, groundwater and biotope types. The sub-functions can be characterized as indicators of performance for interconnected landscape factors. If one overlays these sub-functions spatially in a GIS it will be clear that in some regions individual landscape components do not only overlay, but enhance their mutual function. The sub-functions can therefore act as monitors and warning systems for ecological functions in urban environments.

For example, soil and groundwater monitoring is frequently used as an indicator of habitat "health" for various species, and can initiate action when quality levels become low. Areas with a particularly high suitability for natural restoration and preservation are of special interest for biotope preservation and protection of species. An effective integrative strategy of landscape evaluation is necessary to clarify which management options provide the most ecological, biodiversity, and health benefits while minimizing potentially negative outcomes (pollution, reduced biodiversity, etc.). Remote sensing techniques can contribute to this goal by offering spatial information that shows how different aspects of landscape are connected – which can help guide development along ecologically sound and sustainable paths.

The main question remains: How do we value different aspects of cities? There is a need to introduce intangible elements such "comfort", and psychological well-being, into the cost-benefit analysis that so often governs political and planning decisions. Use of remotely sensed and GIS data to better define the physical context of urban centers and how various systems function may provide useful information towards crafting better socioeconomic models.

3. CONCLUSION AND OUTLOOK

Despite the promising and exciting possibilities presented by new and fast-developing sensors and technologies we still perceive a gap between the generally academic and research-focused spectrum of results offered by the urban remote sensing community and the application of these data and products by the local governmental bodies of urban cities and regions.

A study on 'Transforming Remote Sensing Data into Information and Applications' (National Research Council, 2000, http://books.nap.edu/catalog/10257.html) examined the remote sensing technology transfer process and identified a number of problems that must be overcome in order to develop effective civilian applications:

1. Information needed about the realistic potentials and also the limitations of remote sensing data, and transformation of data into information a critical step.
2. Producers and technical processors of remote sensing data must be able to understand the needs, cultural context, and organizational environments of end users. Education and training can also help to ensure that new end users have a better understanding of the potential utility of the technology.
3. Purchase of data is only the step affecting the cost of a successful application, long-term financial investment in staff, ongoing training (both technical and user training), hardware, and software or, alternatively, purchase of services from a value-adding provider is recommended.

There is no end of interesting science questions that we can ask about cities, but sometimes these questions don't match well with what the operational problems and concerns of a given city are. Our hope is that through the UEM project and collaborations with partners from other urban regions we can determine what the important questions are, and how we can use our data and scientific skills to help answer them.

4. REFERENCES

Alberti, M., and P. Waddell, 2000. An integrated urban development and ecological simulation model. *Integrated Assessment*, 1, pp. 215-227.

Ben-Dor, E., J.R. Irons, and G.F. Epema, 1999. Soil reflectance. In A.N. Rencz (Ed.), Remote Sensing for the Earth Sciences: Manual of Remote Sensing (3rd Ed.), Vol. 3 (pp. 111-188). New York, NY: John Wiley & Sons.

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.

Breuste, J., 2004. Decision making, planning and design for the conservation of indigenous vegetation within urban development. Landscape and Urban Planning, Vol. 68, Issue 4, pp. 439-452.

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).

Krzyzanowsk, M., and D. Schwela, 1999. Patterns of air pollution in developing countries. In S.T. Holgate, J. M. Samet, H.S. Koren and R.L. Maynard (Eds.), *Air Pollution and Health* (pp. 105-113). San Diego, CA: Academic Press.

Kuehn, M., Greenbelt and Green Heart: separating and integrating landscapes in European city regions. *Landscape and Urban Planning*, 64 (2003) 19–27.

Jenerette, G.D., 2004. Landscape complexity and ecosystem processes of the Phoenix, AZ metropolitan region. PhD Dissertation. Tempe: Arizona State University.

Leichenko, R., 2001. Growth and Change in US Cities and Suburbs. *Growth and Change*, Vol. 32 (2001), pp. 326-354.

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.

Ramsey, M.S. and L.P. Flynn, 2004. Strategies, insights, and the recent advances in volcanic monitoring and mapping with data from the Earth Observing System. Journal of Volcanology and Geotherm. Research, 135 (1-2), pp. 1-11.

Rindfuss, R.R. and P.C. Stern, 1998. Linking Remote Sensing and Social Science: The need and the challenges. In: People and Pixels. National Academy Press.

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*. Dordrecht, Netherlands: Kluwer Academic Publishers (in press).

Stefanov, W.L., Prashad, L., Eisinger, C., Brazel, A., and Harlan, S. (2004) Investigations of human modification of landscape and climate in the Phoenix Arizona metropolitan area using MASTER data. The International Archives of the Photogrammetry, Remote Sensing, and Spatial Information Sciences 35, B7, pp. 1339-1347.

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.

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

Ward Thomson, C., 2002. Urban open space in the 21st century. *Landscape and Urban Planning*, 60 (2002) 59–72.

Williams, M.L., 1999. Patterns of air pollution in developed countries. In S.T. Holgate, J. M. Samet, H.S. Koren and R.L. Maynard (Eds.), *Air Pollution and Health* (pp. 83-104). San Diego, CA: Academic Press.

Zehnder, J.A., 2002. Simple modifications to improve fifth-generation Pennsylvania State University-National Center for Atmospheric Research mesoscale model performance for the Phoenix, Arizona metropolitan area. *Journal of Applied Meteorology,* 41, pp. 971-979.