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The Built Environment Induced Urban Heat Island Effect in Rapidly Urbanizing Arid Regions – A Sustainable Urban Engineering Complexity

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ABSTRACT

As recently as 1950, 30% of the world's population lived in urban areas. By the year 2030, 60% of the world's population will live in cities, according to the United Nations (2001) World Population Prospects Revision Report. Urbanization is quickly transitioning communities from the natural rural vegetation to man-made urban engineered infrastructure. The anthropogenic-induced change has manifested itself in microscale and mesoscale increases in temperatures in comparison to adjacent rural regions which is known as the *urban heat island* (UHI) effect and results in potentially adverse consequences for local and global communities. One of the great challenges facing our current generation of scientists and engineers is how to support the growth of the new and existing arid urban centers in a sustainable manner. This is even more pronounced in arid regions, which will sustain the greatest rate of urbanization. This paper is focused on understanding the interdependency of the infrastructure used to support the growth of urban regions and their environmental, social and economic consequences with an emphasis on the rapidly urbanizing arid region of Phoenix, Arizona.

Keywords: urban heat island; urbanization; arid regions; climate change; sustainable development; Phoenix; Arizona; engineering; energy

1. INTRODUCTION

I believe that the existence of the classical "path" can be pregnantly formulated as follows: The "path" comes into existence only when we observe it.

Werner Heisenberg

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The importance of the statement by Heisenberg (1927) is his argument that every concept has a meaning only in terms of the experiments used to measure it. Sustainable development is an often-used term but one that requires the user to associate it with a defined problem. This article intends to advance the concept that the Phoenix, Arizona region, which is one of the world's most rapidly urbanizing arid regions, risks measurably high social, economic and environmental consequences associated with a growth-induced *urban heat island* (UHI) effect. The region provides researchers a platform to explore scientifically mitigation strategies for global cities in terms of sustainable development.

The beginnings of the modern-day sustainable development movement can be traced back to the 1960s and Rachel Carson's book *The Silent Spring* (Carson, 1962). In the following years a number of publications, including Paul Erlich's *Population Bomb* (Erlich, 1968) and the Club of Rome's *Limits to Growth* (1972) drew attention to global development issues. In 1986, the UN held meetings of the World Commission on Environment and Development to study the dynamics of global environmental degradation and make recommendations to ensure the long-term viability of human society. The Commission was chaired by Gro Harlem Brundtland, who at the time was the Prime Minister of Norway. The product of this meeting was their report, *Our Common Future* (1987). The Brundtland Report, as it came to be known, was the benchmark for thinking about the global environment and the first to popularize the term ''sustainable development.'' It was defined as ''development that meets the needs of the present without compromising the ability of future generations to meet their own needs (UN 1986).''

The 1992 Conference on Environment and Development held in Rio de Janeiro (also called the Earth Summit, 1992, or the Rio Summit) focused on environment and development issues. More than 35,000 people attended, including 106 heads of state or governments and 9,000 journalists (United Nations, 2003). The Conference led to a number of important conventions including those on biodiversity and climate change, as well as to Agenda 21, a sustainable development action plan for various levels of government. The most recent international sustainable development conference was held in 2002 in Johannesburg, South Africa. The World Summit on Sustainable Development (WSSD) focused on the issues of poverty reduction.

2. URBAN POPULATION DYNAMICS

International attention paid to sustainable development has occurred at a time when urban areas are gaining an estimated 67 million people per year – about 1.3 million every week. By 2030, approximately 5 billion people are expected to live in urban areas – 60% of the projected global population of 8.3 billion (United Nations, 2002a). Most of the world's future population growth will occur in arid regions of the world (Baker, Brazel, & Westerfhoff, 2004). The urban population of developing countries is projected to grow at an average annual rate of 2.4%, twice the rate of 1.2% in the developed world.

The urban population of developed countries will grow faster than their total population and these countries will remain far more urbanized than the developing world. Urban growth in developing countries is more rapid and, in absolute numbers, much greater. Research of rapid urbanization is important due to the far-reaching impacts urban centers create on the environment not only within the urban core but extending to regions that supply the consumed materials such as energy and water (McMichael, Butler, & Ahern, 2002). In many cases, these natural resources are consumed by the urban core to offset the urban heat impacts.

Urban areas take up just 2% of the Earth's surface but account for an unbalanced amount of resource usage. For example, urban areas account for about 75% of industrial wood use, and 60% of the water withdrawn is for human use (O'Meara, 1999). The extent of urban impacts upon the environment increases not only as population grows but also as per capita

Table 1. Urban Population Dynamics. Source: United Nations (2002b).

| Region | Population (in millions) | | | | | | % Urban | | |
| | 1975 | | 2000 | | 2030 | | | | |
	Urban	Rural	Urban	Rural	Urban	Rural	1975	2000	2030
Africa	102	304	295	498	787	702	25	37	53
Asia	592	1805	1376	2297	2679	2271	25	37	54
Latin America and Caribbean	198	124	391	498	127	608	61	75	85
Europe	455	221	534	193	540	131	67	73	80
North America	180	64	243	71	335	61	74	77	84
Oceania[*]	15	6	23	8	32	10	72	74	77

Note. [*]Oceania = Australia, New Zealand, Melanesia, Micronesia, and Polynesia.

demand for resources rises, both from industries and consumers. Additionally, the number of households has grown even faster than the population itself, reflecting a trend to smaller families and thus a decline in the average number of people per household. Analyzing data from 141 countries, a recent study calculated that the annual growth in the number of households (at 3.1%) was much more rapid than population growth itself (at 1.8%) between 1985 and 2000 (Hinrichsen, Blackburn, & Robey, 2002). As regions transform from rural agricultural to urban built environments, various climate changes become manifest. First, native vegetation that provide shade and evapotranspiration are removed. Secondly, engineered materials used to transform the land to accommodate shelter, mobility, sanitation, and culture transform the surfaces that comprise the urban setting. These lower albedo (darker) and impervious surface properties can include streets, roofs, walls, lawns, landscape and parking lots. Additionally, urban geometry begins to manifest itself, impacting air flows and radiative characteristics.

Groups of urban buildings, which are generally made of engineered materials (glass, metal) with sharp edges, generally contain larger buildings with mixed height and dimensions. Commercial buildings and high rise multi-family units typically are taller and display high thermal mass and unique canyons which increase the impact of the built environment on urban climate (Arnfield, Herbert, & Johnson, 1999; Samuels, 2003). It is the combinations of these designs that impact air flow above and within urban environments. These impacts, which have both beneficial and negative impacts based on the local scale setting, include atmospheric turbulence, shading and various radiation parameters such as albedo and emissivity (Grimmond & Oke, 1999). An additional consideration is that global rapid urbanization is taking place at a time that one of the most contentious international issues facing sustainable development has emerged – global climate change. Global warming gases, which contribute to the trend of climate change, transmit incoming radiation from the sun but absorb and trap the infrared radiation subsequently emitted from the Earth's surface.

As a result, the presence of these gases in the atmosphere raises temperatures near the Earth's surface. Naturally occurring substances such as carbon dioxide (CO_2) and water vapor are global warmers but the phenomenon of global warming has been intensified by the release of additional CO_2 and other gases to the atmosphere as a result of industrial activity, such as energy production. In 1988, the International Panel on Climate Change (IPCC) was founded under the auspices of the UN, with

strong support from the international community including the Mulroney, Reagan, and elder Bush administrations. It is part of the UN Environment Programme (UNEP) and the World Meteorological Organization (WMO). The IPCC has issued three *Assessment Reports* to date (IPCC 1990, 1996, 2001).

According to the IPCC (2001), since the start of the satellite record in 1979, both satellite and weather balloon measurements show that the global average temperature of the lowest 8 km of the atmosphere has changed by $+0.05 \pm 0.10°C$ per decade, but the global average surface temperature has increased significantly by $+0.15 \pm 0.05°C$ per decade. The difference in the warming rates occurs primarily over the tropical and subtropical regions. Currently, 14 of the top 20 mega-cities are characterized as tropical or subtropical. The solar forcing can be extreme in these regions, especially at subtropical (higher latitude) regions where cloud cover is generally less.

Table 2. Top 20 Mega-Cities and Latitude. Expected Growth in Cities with Populations of 8 Million or More, 1995 and 2015. Source: UN Population Division (200X).

City	Population (millions)		Latitude
	1995	2015	
Tokyo, Japan	26.96	28.89	35°41′N
Mexico City, Mexico	16.56	19.18	19°24′N
São Paulo, Brazil	16.53	20.32	23°33′S
New York, USA	16.33	17.6	40°44′N
Bombay, India*	15.14	26.22	18°54′N
Shanghai, China	13.58	17.97	31°12′N
Los Angeles, USA	12.41	14.22	33°93′N
Calcutta, India	11.92	17.31	22°32′N
Buenos Aires, Argentina	11.8	13.86	34°35′N
Seoul, Korea, Rep.	11.61	12.98	37°34′N
Beijing, China	11.3	15.57	39°55′N
Osaka, Japan	10.61	10.61	34°54′N
Lagos, Nigeria*	10.29	24.61	6°27′S
Rio de Janeiro, Brazil	10.18	11.86	22°55′S
Delhi, India*	9.95	16.86	28°35′N
Karachi, Pakistan*	9.73	19.38	24°48′N
Cairo, Egypt	9.69	14.42	29°52′N
Paris, France	9.52	9.69	48°49′N
Tianjin, China	9.42	13.53	38°42′N
Metro Manila, Philippines*	9.29	14.66	14°35′N

Note. *Cities expected to grow by >50% by 2015.

Heat trapping and modifying the surface energy budget is likely to have an amplified effect upon these areas.

3. ENGINEERED ENVIRONMENTS AND THE UHI

The urban built environment – the nexus of architecture, engineering, and commerce – is one of the main attractors of population shifts from rural to urban areas. As the dynamics of this population shift occur, the 21st century phenomenon of rapid urbanization is creating extreme changes in land use that result in unintended environmental, economic, and social consequences. In urban areas, buildings and paved surfaces have gradually replaced preexisting natural landscapes. As a result, roads and rooftops absorb solar energy, causing the surface temperature of urban structures to become 50–70°F higher than the ambient air temperatures (Taha, Sailor, & Akbari, 1992). As surfaces throughout a community or city become hotter, overall ambient air temperatures increase in the urban region greater than that in the rural region ΔT_{u-r}. This phenomenon, known as an ''urban heat island'' (UHI), can raise temperatures in a city from 2 to 8°F (Bornstein, 1987; Chandler, 1965; Landsberg, 1981; Oke, 1987). This localized regional effect is in addition to IPCC estimates that put the potential of global warming to be $+1.4$°C to $+5.0$°C ($+2.5$°F to $+10.4$°F) over the next 100 years, in addition to the 0.6°C temperature increase already observed during the 20th century. As presented
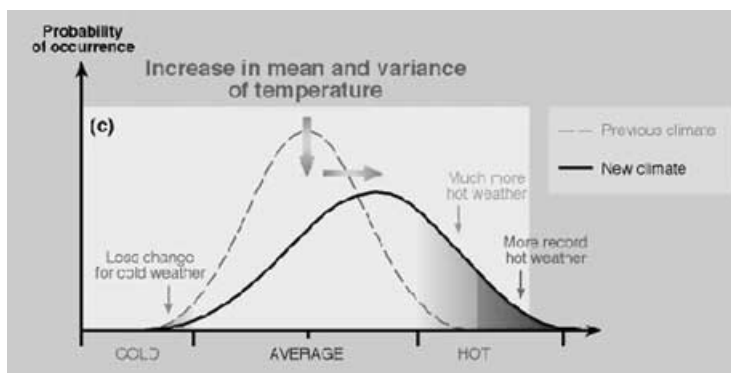

Fig. 1. Potential for increased hot weather due to global climate. Source: IPCC, 2001, *Climate Change*, *Third Assessment Report.*

in Figure 1, climate change in the form of global warming may increase frequency of temperature extremes and the UHI effect may prolong the duration of these events.

The first known documentation of the UHI is attributed to Luke Howard in *The Climate of London, Deduced from Meteorological Observations, Made in the Metropolis and at Various Places around It* in three volumes (Howard, 1833). As rural areas become urban, the region replaces existing vegetation with paved surfaces, which results in the Sun's energy heating the man-made surfaces rather than being used for evapotranspiration (Taha, 1997). Urban–rural temperature differences are usually greatest after sunset or overnight, and smallest, sometimes even negative, after sunrise or during the morning or early afternoon. The hottest temperatures are generally found in areas with the least vegetation and the greatest urban development (heat island reduction initiative, US Environmental Protection Agency, 2004). The urban environment, with its impervious paved surfaces and reduced vegetation, causes less of the incoming radiant energy from the sun to be reflected from urban areas and, likewise, less of this energy is converted to latent energy associated with evaporation or transpiration of moisture. Compounding this effect is that the larger volume of asphalt, brick, concrete, and other materials gives urban areas a much higher thermal storage capacity than natural surfaces. One result is that large amounts of energy are stored in the urban canopy during the day and released after sunset – the hysteresis lag effect. Anthropogenic sources in the urban environment generate additional heat by way of air conditioning, automobiles, and machinery. Hence, urban temperatures tend to remain relatively high into the evening hours (Oke, 1987; Sailor & Pavlova, 2003).

Hansen, Hodges, and Jones (1998) estimate that albedo changes have resulted in a forcing of $-0.4\,\mathrm{W\,m^{-2}}$, about half of which is estimated to have occurred in the industrial era. They performed a simulation with pre-industrial vegetation replaced by current land-use patterns and found the global mean forcing to be $-0.21\,\mathrm{W\,m^{-2}}$, with the largest contributions coming from deforested areas in Eurasia and North America. Assuming that half of the land clearance occurred after the Industrial Revolution this equates to a forcing of $-0.10\,\mathrm{W\,m^{-2}}$ by land use over this period. These changes are mainly attributed to modifications from existing landscape to man-made infrastructure which results in decreasing surface albedo, as a result of roads and buildings. Increases in cloud cover cause further localized reductions in the net surface short-wave radiation in some regions. However, some areas exhibit higher temperatures in their dry season, consistent with a decrease in

evapotranspiration due to reduced access of soil moisture. This would be consistent with an arid desert climate.

In addition to anthropogenic heat, urban geometry has changed net radiation and altered convection due to slowing winds near buildings (Voogt & Oke, 1997). Changes in land use can also exert other kinds of climatic impacts, for example, changes in roughness length, turbulent fluxes, soil moisture, and heat budgets (IPCC, 2001).

Two types of UHI can be distinguished: (1) the canopy-layer heat island and (2) the boundary-layer heat island (Oke, 1979). The canopy layer consists of air between the roughness elements (e.g., streets) with an upper boundary just below roof level. The boundary layer is situated above the canopy layer, with the lower boundary subject to the influence of the urban surface (Weng & Taylor, 2003). The focus of this paper is geared towards the complexities within the urban canyon layer, which is roughly from ground to roof level (Oke, 1987). This is the layer in which the engineered environment has the most pronounced effect, as the airflow and energy exchanges are controlled by microscale, site-specific characteristics (Arnfield, 2002). By contrast, the urban boundary layer above the roof level is affected by the land-use zones and mesoscale phenomenon and controlled by processes operating at larger spatial and temporal scales (Oke, 1987). From an engineering perspective, more refined mesoscale modeling can be achieved by quantifying the volumetric and climatic state of the man-made materials comprising the urban region. Additionally, continued engineering schemes used in the ongoing urbanization of the region can be modified to meet the sustainable development trilogy. That is, by addressing the UHI, policy makers at all levels will be able to craft policies, incentives and regulations that meet economic, social and environmental imperatives.

4. PHOENIX, ARIZONA AS A PLATFORM OF STUDY

The State of Arizona, located in the southwest corner of the United States, is famous for one of the Seven Wonders of the World, the Grand Canyon. It is the sixth largest state in land area (113,635 square miles) in the United States. Arizona is an arid land with average annual rainfall varying from three inches in Yuma in the southwest corner to seven inches in Phoenix in the center of the state. At statehood in 1912, Arizona was populated by approximately 200,000 people and had a population density of two people per square mile. Over the
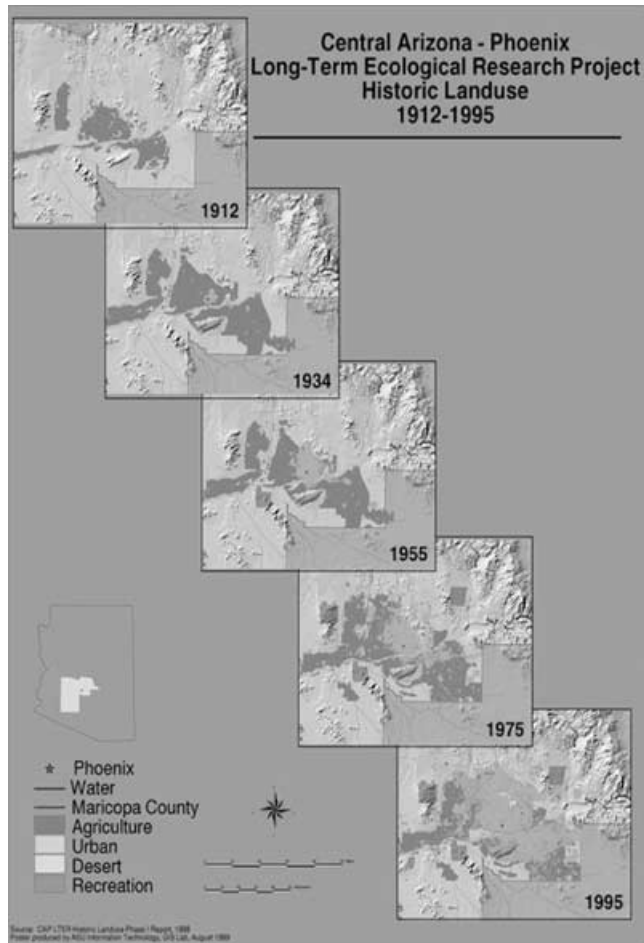
Fig. 2. The rapid urbanization of the greater Phoenix region from 1912 to 1995. Source: CAP LTER, 1998.

last 100 years, the ratio between Arizona's rural and urban populations has essentially reversed. In 1900, less than 20% of the state's population lived in an urban setting; in 2000, more than 88% live in an urban setting.

Since 1990, the fastest growing region in the United States has been the West, increasing by 19.7% or 10.4 million people, to total 63.2 million (US Census, 2000). Of the top 10 US cities by per cent of population growth from 1990 to 2000, six are Western cities, with Arizona at a 40% growth rate. Phoenix,
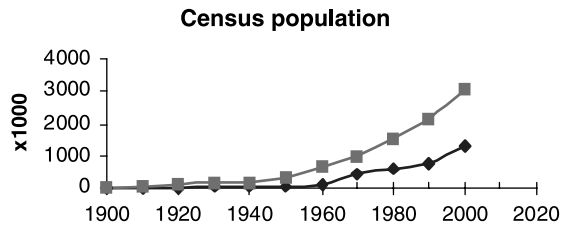
Census population

Fig. 3. US Census population data for Phoenix, Arizona (bottom line) and Maricopa County (top line). Source: US Census (2000).
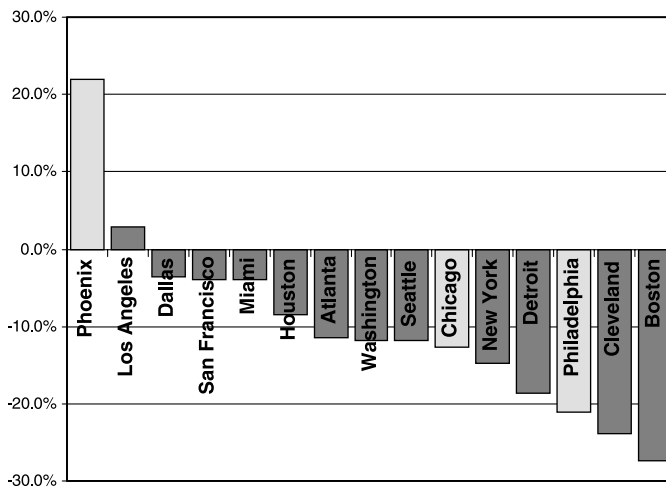

Fig. 4. Density changes in the 15 largest US metropolitan areas 1982–1997. Source: Brooking Institution (2001) and Solimar Research Group (2001).

Arizona which dates back to 700 AD when the region was home to the Pueblo Indians, is now the nation's fifth-largest city, recently overtaking Philadelphia in population. The regional population increased from 1,600,000 in 1980 to 2,238,000 in 1990; the population reached 3,379,000 as of July 2001, an annual gain of 101,400 people since 1990 (Housing and Urban Development, 2002).

The city of Phoenix is now larger than Los Angeles, California in geographic extent, surpassing 484 square miles. The region lacks a well developed and mature urban downtown core. Rather the region is defined by multiple cities and towns which connect to the city of Phoenix via a distribution network of roads and highways. Researchers have examined
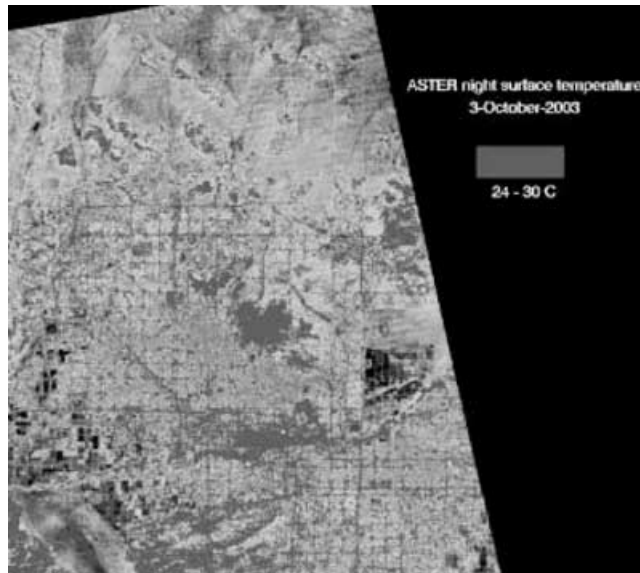
Fig. 5. ASTER thermal imagery isolating the top 20% temperature range for the surface of the
        Phoenix region. Sky Harbor International Airport as well as the network of roads,
        highways and corner shopping centers present the highest volume of the man-made
        urban fabric with elevated surface temperatures (source: Stefanov & Golden, 2003).

multiple ASTER satellite thermal imagery and identified that roads, highways
and parking lot pavements form the largest percentage of the man-made urban
fabric with the highest nocturnal surface temperatures in the region as a
function of the hysteresis lag effect.

The study area of the greater Phoenix region comprises the two county
region of Maricopa and Pinal of central Arizona (146,000 square miles,
$37,813 \, km^2$). The rapid urbanization of the region also brings a multiple set of
population research parameters including increased density of housing.
Phoenix led the major 15 metro areas in the United States in the percentage
change of urbanized density from 1982 to 1997 (Fulton, Pendall, Nguyen, &
Harrison, 2001). In part this can be explained as a function of the expanding
geographic region dominated by closely built single-family housing units.

The semi-tropical region of Phoenix, Arizona is characterized by a daytime
"oasis" effect and a very strong hysteresis lag effect at night. Daytime
temperatures in comparison to the desert rural setting in Phoenix are
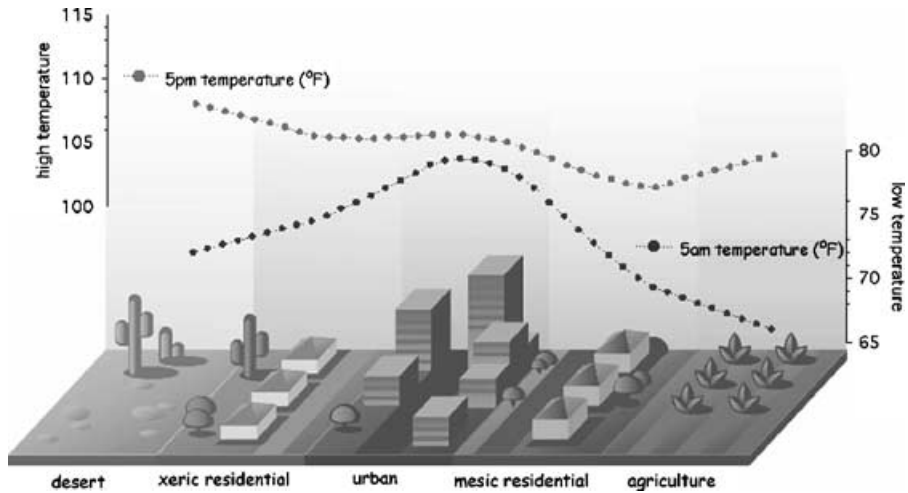influenced by urbanization as well as by the addition of residential and

Fig. 6. The Phoenix region UHI effect presenting a daytime oasis effect and a night-time hysteresis lag effect (source: Zehnder & Golden, 2004).

agricultural irrigation (Balling & Brazel, 1989). The urban portions have a pronounced higher maximum minimum mean than the rural area $\Delta T_{\text{u} - \text{r}}$ which is the UHI effect (Bornstein, 1987; Chandler, 1965; Landsberg, 1981; Oke, 1987, 1995). Over the 20th century, average annual temperatures in the arid subtropical Phoenix region (33°26′N, 112°W) have increased 3.1°F (Brazel, Selover, Vose, & Heiser, 2000). However the urban portions of the region have realized mean annual temperature increases of 7.6°F, a rate of three times the total region mean increase.

A comparison of the Phoenix region annual minimum high temperatures to a representative rural setting presents a very pronounced UHI effect that corresponds to the rapid urbanization of the urban region. Official daily temperatures from the National Weather Service Station at Phoenix Sky Harbor International Airport were compared with those from the National Park Service Casa Grande Ruins, the first national archaeological preserve in the United States. This rural site is located approximately 60 miles southeast of Phoenix and has remained rural in characteristic with a native desert setting and vegetation (creosote bush, white buresage and salt bush). The temperature readings at the airport (urban setting) reflects the change in location of the weather station within the boundaries of the airport in 1978 (central), 1994 (northeast of runways) and 1997 (south of the runways).

Rapid Urbanization & the Urban Heat Island Effect
Annual Minimum Temperatures
Phoenix, Arizona v. Rural Setting
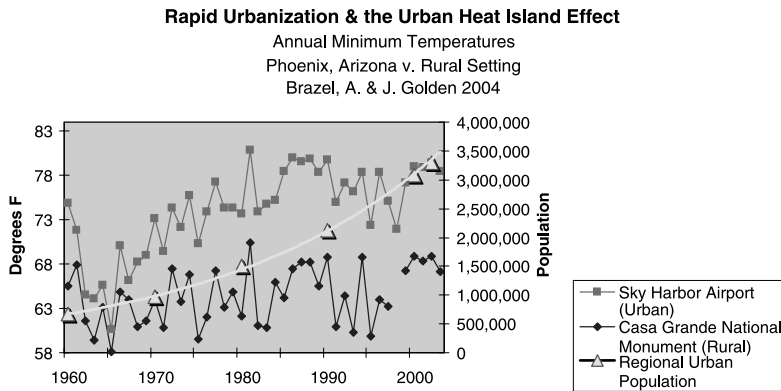Brazel, A. & J. Golden 2004

Fig. 7. Rapid urbanization and the Phoenix, Arizona regional UHI (source: Brazel & Golden, 2004).

The 0.86°F per decade warming rate for Phoenix is one of the highest in the world for a population of its size and can be compared with other cities to highlight the effects of rapid urbanization in the region. For example, Los Angeles's rate was 0.8°F per decade; San Francisco, 0.2°F per decade; Tucson, 0.6°F per decade; Baltimore, 0.2°F per decade; Washington, 0.5°F per decade; Shanghai, 0.2°F per decade; and Tokyo, 0.6°F per decade (Hansen, Hodges, & Jones, 1999).

Phoenix has an average of 89 days per year of greater than 100°F (37.7°C) and has experienced 143 days of greater than 100°F (37.7°C) as recently as 1989. The region reaches extremely hazardous temperatures as evidenced with an official daytime high of 122°F (50.4°C) in 1990 and 121°F (49.4°C) in 1995. These late day/early evening spikes, in conjunction with the hysteresis diurnal, weekly and monthly heat storage lags, amplify the UHI effect. Additionally, the influences of the engineered urban fabric, including the projection of anthropogenic heat sources can further exacerbate the complete diurnal cycle.

5. SUSTAINABLE IMPERATIVES AND THE UHI

Roseland (1997) argued that sustainable cities represent an ethical goal and direction for a community but that planners who use the sustainable development trilogy (environmental, economic and social imperatives) have found much inspiration but little guidance. Policy makers need a hierarchical

mitigation scheme or set of indicators to address the UHI effect within a sustainable development context. Researchers from Arizona State University and the Cambridge-MIT Institute (CMI) sponsored Engineering for Sustainable Development Programme at the University of Cambridge have undertaken a joint multi-disciplinary effort to further understand the dynamics of urban climate and the UHI effect as well as to examine mitigation strategy alternatives that can be deployed by policy makers in rapidly urbanizing regions globally.

A first step in this process is to understand the initial impacts, both positive and negative, in regards to the pronounced UHI effect in the Phoenix region. Secondly, researchers will volumetrically and spatially identify the various man-made and natural geologic/vegetative materials that comprise the urban fabric of the Phoenix region via remote sensing and on-site documentation. Thirdly, the research will identify which existing surface materials independently and by their 3-D arrangement induce the most retained heat and therefore experience the most hysteresis lag effect of heat storage over a 24 h period – hence explaining the UHI. Fourth, researchers will undertake an extensive evaluation of existing and emerging materials and technologies that can potentially mitigate the hysteresis lag effect. Those results will be modeled in step 6 from the micro-scale to the local scale and eventually on a mesoscale interaction model.

Finally, working with community stake-holders on an international basis, a hierarchical mitigation structure will be developed based on environmental, economic and social considerations. This will take the form similar to a Life Cycle Management guidebook. During initial evaluations of Phoenix, researchers have identified multiple impediments to achieving a sustainable balance between rapid urbanization and quality of life. Phoenix is:

- moving into the seventh consecutive year of drought in an already arid region of less than 7 inches of rain per year;
- a federal non-attainment area for ground-level ozone;
- seeing increased costs of electricity and fuel; and
- experiencing increasing levels of childhood and adult obesity – potentially worsened by the influence of high temperatures throughout the diurnal cycle which limit the ability to be outdoors.

Understanding these regional imperatives allow researchers to undertake the development of strategies to mitigate the UHI in respect to the sustainable imperatives of environment, economics and social well being.
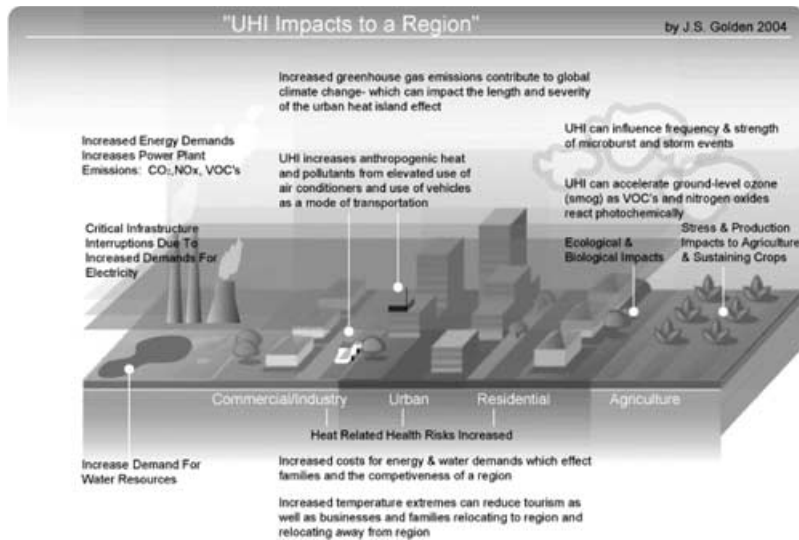
Fig. 8. The potential impacts associated with UHI (source: Golden, 2004).

5.1. Water Resources

The US Southwest provides a compelling example of the importance of understanding the linkages between climate, water resources and society (Morehouse, 2000). This paper expands that concept to include that society's selection and use of engineered materials and the resultant UHI effect also provides an understanding of the integrated sciences of climate and water resources, utilizing the arid Phoenix region as an example for global arid regions.

The Phoenix region, which lies in the Sonoran Desert, receives an average of 18 cm per year of rainfall. However, as a result of 6 years of below-average precipitation including 2002, which was the driest water year for many parts of the state, Arizona Governor Napolitano signed Executive Order 2003–12, establishing the Arizona Drought Task Force, on 20 March 2003 (McPhee, Comrie, & Garfin, 2004). The Executive Order requires that a short-term drought plan be prepared to respond to potable water needs, as well as non-potable needs for agricultural operations, wildlife and wildfire mitigation. The Order also requires that the State develop a long-term, comprehensive plan to provide for drought planning efforts throughout the state and a coordinated response framework. This longer-term effort is

U. S. Seasonal Drought Outlook
Through April 2004
Released January 15, 2004

Improvement
Expected

Some Improvement

PERSIST

PERSIST

K E Y :

Drought to persist or intensify

Drought ongoing, some improvement

Drought likely to improve, impacts ease

Drought development likely

Depicts general, large-scale trends based on subjectively derived probabilities guided by numerous indicators, including short and long-range statistical and dynamical forecasts. Short-term events -- such as individual storms -- cannot be accurately forecast more than a few days in advance, so use caution if using this outlook for applications -- such as crops -- that can be affected by such events. "Ongoing" drought areas are schematically approximated from the Drought Monitor (D1 to D4). For weekly drought updates, see the latest Drought Monitor map and text.
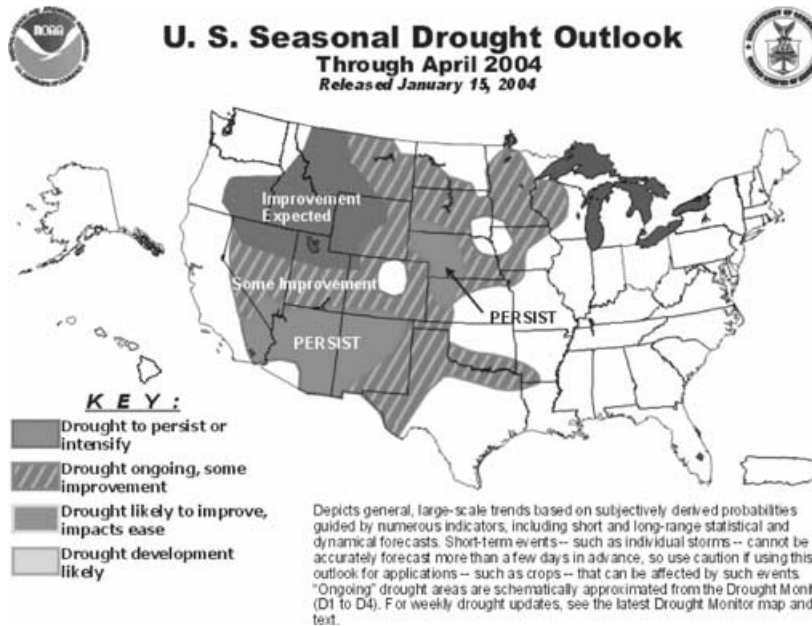
Fig. 9. US seasonal drought outlook 2004 (source: National Oceanic and Atmospheric Administration).

intended to recognize and build upon existing drought efforts, and reduce the impact of drought on economic activities, communities and habitat throughout the state. The final major assignment is the development of a conservation strategy that focuses on education, technology transfer and assistance.

Approximately 70% of Phoenix's municipal water (from surface and groundwater supplies) is used for landscape irrigation at a per capita water consumption of 880l per day, among the highest in the world (Baker et al., 2004). Preliminary research of residential water usage has indicated that the hysteresis lag effect does influence the amount of water consumed. This takes into consideration the evaporation rate of water from residential pools and irrigation as well as potable water usage in households. The city of Tempe was selected as a study area since it is a mature and landlocked community with minimal household census growth. Further research is seeking to quantify the water use impacts of the UHI hysteresis lag effect as a function of urbanization.

Tempe, Arizona Residential Water Usage in Relation to Temperatures
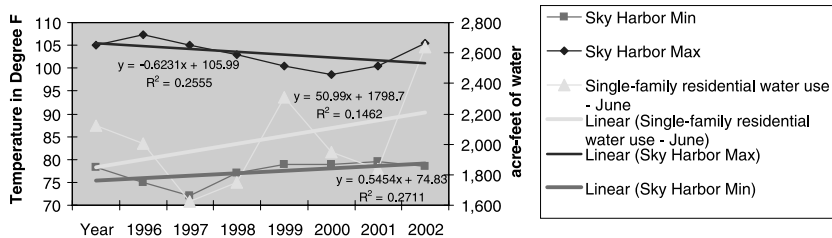**1996-2003**
J.Golden 2004

Fig. 10. A linear trend analysis of residential water usage and minimum temperature (source: Golden, 2004).

5.2. Energy

The hysteresis lag effect as a function of the UHI promotes the use of additional power consumption for mechanical cooling in buildings. Where historically, Phoenix residents were able to reduce the demand for night-time mechanical cooling as temperature decreased, they now must rely on mechanical cooling through a greater portion of the diurnal cycle as a result of the hysteresis lag. The first consequence is that the residential and commercial sector accounts for about one-third of carbon emissions from fossil-fuel combustion. Its share of the total emissions has increased at 1.8% since 1971, which is faster than in other sectors (Price, Michaelis, Worrell, & Khrushch, 1998). Despite improved technology and the adoption of improved technology in many countries, energy use in buildings has grown more rapidly than total energy demand from 1971 to 1995, with commercial building energy registering the greatest annual percentage growth (3.0% vs 2.2% in residential buildings, IPCC, 2001).

Additionally, increased power consumption due to the UHI results in the additional usage of water. The arid Phoenix region is primarily served by thermoelectric power generation. The major energy sources in Arizona for 2002 were coal (40.3%) and nuclear (32.8%). Coal-derived electricity is primarily generated by the SRP Navajo plant (2,250 MW), APS Cholla plant (995 MW), SRP Coronado (785 MW) and the SRP Agua Fria plant (626 MW). The nation's largest nuclear power plant, APS Palo Verde (three pressurized light water reactors) is located just west of the Phoenix metropolitan region with a generation capacity of 3,733 MW, which can serve 4 million customers. Conventional power plants use large amounts of water for the condensing

portion of the thermodynamic cycle. For coal plants, water is also used to clean and process fuel. The total consumptive use of water for thermoelectric power plants in the western US has a range of 1.4 l per kWh to 2.3 l per kWh (Gipe, 1995; Torcellini, Long, & Judkoff, 2004). This takes into consideration that thermoelectric power plants use approximately 5% of their gross generation to power equipment as well as additional distribution and line losses (Energy Information Administration, 1996).

In Arizona, thermoelectric power water withdrawals in 2000 equaled 74 million gallons per day (MG per day) of groundwater and 26 MG per day of surface water – the equivalent of 113,000 acre-fee per year (US Geological Survey, 2004). One effort towards sustainability has been implemented by the operators of Palo Verde Nuclear Generating Station (PVNGS) who utilize tertiary treated water from the main wastewater treatment plant for the Phoenix region. In 1999, the water reclamation facility at PVNGS received a total of 22,558,664,730 gallons of treated effluent. UHI researcher goals are to identify designs, materials and technologies which minimize electricity demands for cooling via UHI mitigation – a more proactive sustainable engineered approach.

Beyond water usage, increased electricity generation by power plants as a result of the UHI leads to higher emissions of sulfur dioxide, carbon monoxide, nitrous oxides, and suspended particulates, as well as CO_2, a greenhouse gas known to contribute to global warming and climate change. The increased use of fossil fuels to support mechanical cooling will no doubt play a key role in the development of urbanizing regions in developing countries that encounter the UHI effects. China witnessed its initial production

Peak Electricity Demand in Comparison to Climate - Desert Southwest Power Area and National Weather Service Phoenix, Arizona
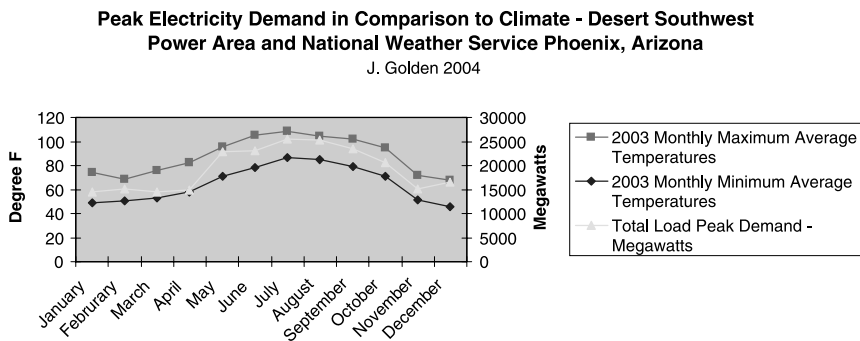
J. Golden 2004

Fig. 11. Peak electricity demand and the impact of temperatures to cooling degree days (source: Golden, 2004).

of those household air conditioners in the year 1978 when no more than 223 air conditioners of this type were manufactured. However, restricted by the capacity of production and development as well as the industrial policies of China, the total production in 1980 remained less than 20 thousand. In the 1990s, especially during the recent years, the industry of household air conditioners has undergone such a dramatic expansion that the total production soared to 0.22 million in 1990, to 18.2667 million in 2000 and to 23.1288 million in 2001, during which the annual increase has remained above 20%. Today, the production of air conditioners (for both domestic use and export) in China has approximated one-third of the global total (Air Conditioning Industry Report, 2002).

5.3. Health

Because extremes of summertime heat are thought to have a greater impact on human health than any other form of severe weather in the US (Changnon, Kunkel, & Reinke, 1996), more frequent occurrences of extreme heat as a function of the UHI will have important global public health implications. This consequence was evident by the estimated 35,000 people who died during the European heatwave of August 2003 (see Table 3) and the Chicago

Table 3. The Human Toll of Heat Waves: Selected Examples from Europe in August 2003. Source: Earth Policy Institute (2003).

Country	Fatalities	Other details
France	14,802	Temperatures soared to 104°F in parts of the country; temperatures in Paris were the highest since record-keeping began in 1873
Germany	7,000	High temperatures of up to 105.4°F, the hottest since records began in 1901, raised mortality some 10% above average
Spain	4,230	High temperatures coupled with elevated ground-level ozone concentrations exceeding the European Union's health-risk threshold
Italy	4,175	Temperatures in parts of the country averaged 16°F higher than previous year
UK	2,045	The first triple-digit (Fahrenheit) temperatures were recorded in London
Netherlands	1,400	Temperatures ranged some 14°F warmer than normal
Portugal	1,316	Temperatures were above 104°F throughout much of the country
Belgium	150	Temperatures exceeded any in the Royal Meteorological Society's records dating back to 1833
Total	35,118	

heatwave in July 1995, which is thought to have caused 465 deaths (WHO, 1996). Heatwaves claim more lives each year than floods, tornadoes and hurricanes combined (Earth Policy Institute, 2003).

The Chicago heatwave of 13–16 July 1995 (3-day average mean temperature of 91.16°F or 32.86°C) death toll was in part contributed by elevated temperatures and a loss of electricity to over 49,000 households. A similar risk for the Phoenix region can best be presented by evaluating the region's diurnal temperatures from 14–16 July 2003. The Phoenix region experienced sustained diurnal temperatures (with humidity variance) for the 3-day period with an average mean temperature of 104.67°F (40.37°C). During one diurnal cycle, the minimum temperature was 96°F (35.5°C) and the following day (16 July 2004) had a maximum of 117°F (47.2°C). The region was fortunate to have a robust electricity system that could serve this peak demand. Without the impact of lost residential electricity, the number of heat-related deaths in Arizona for the period of 1992–2002 reached 570. The distribution of those deaths trends with the summer months of increased temperatures. Although a portion of the deaths are as a result of illegal

DEATHS FROM EXPOSURE TO EXCESSIVE NATURAL HEAT*
OCCURRING IN ARIZONA BY MONTH IN THE
ELEVEN-YEAR PERIOD, 1992-2002

*The underlying cause of death was classified as E900.0 by ICD-9 (1992-1999) or as X30 by ICD-10 (beginning in 2000). Included are deaths occurring in Arizona from excessive heat due to weather conditions as the cause of heatstroke or sunstroke among both residents of Arizona and non-residents. Excluded are deaths due to excessive heat of man-made origin.
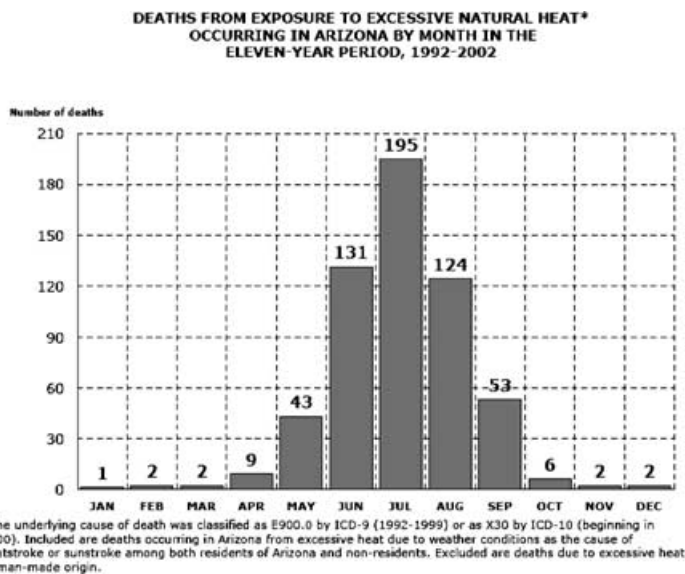
Fig. 12. Deaths from excessive natural heat in Arizona (source: Arizona Department of Health Services – Bureau of Public Statistics).

migration through the desert outside of Phoenix, the largest percentage of deaths during this period are from Arizona residents. It was found that 60.3% of the resident deaths occurred in the Central counties of the state (Phoenix region) during the study period. In addition to heat deaths, the City of Phoenix Fire Department reported over 500 heat-related incidents in 2001 alone (ADHS, 2002).

The temperal impacts associated with the UHI are increased by the selection of engineered materials deployed in the urban regions. Anthropogenic resiliency in our modern world is heavily dependent on mechanical cooling systems. Interruptions of these systems as a result of peak demand, storm events or malicious activity can result in catastrophic impacts. As regional population and the UHI increase, the risk of a power outage is real. It is unknown how many heat-related deaths the region might experience if there were to be a loss of household electricity. Similar for developing countries that will rapidly urbanize yet do not have the same robust electrical infrastructure.

Finally, regional health in global settings that experience summer daytime heat islands can be impacted as the daytime UHI often accelerates the formation of harmful smog, as ozone precursors such as nitrous oxides (NO_x) and volatile organic compounds (VOCs) combine photochemically to produce ground-level ozone (SOS, 1995).

5.4. Societal Factors

Both anthropogenic influences and mitigative strategies in regards to the UHI must account for societal influences. Arizona as a border state to Mexico and the developing countries of Latin and South America showed a net positive migration of 113,527 Hispanic immigrants for the period of 1995–2000. This number is the largest for any mountain or pacific state excluding California (US Census, 2003, Special Report). The number also does not reflect undocumented migrants. For the greater Phoenix region, Hispanics/Latinos represent 24.8% of the regional population and that percentage is expected to grow. The region is also home to 21 Native American tribes, whose sovereign Nations comprise over a quarter of the state land including areas within the Phoenix region. The opportunities to develop mitigation strategies for the region must reflect these yet to be defined varied and changing demographic realities. Similarly, as regions around the globe face variations of the UHI effect (daytime, nighttime or a combination), the parameters that reflect the societal influences must be accounted for in the mitigation process.

Governmental and communal institution plans for managing urban growth impact society in many ways, with the burden of urban environmental problems invariably falling disproportionately on the poor or disadvantaged (Hardoy, Mitlin, & Satterthwaite, 1999). This inequity can be manifested in the inability to have safe water or secure solid-waste disposal. In regards to the Phoenix regional UHI effect, social economics come into play when those who cannot afford the capital costs or operating costs of air conditioning or climate-controlled shelter can face increased risks of extreme heat. Additionally, the influence of affluence on the inability to mitigate the UHI as a result of construction methods, spatial design, technologies, and purchasing power for shelter and urban landscape/forestry need to be examined. Research in the Phoenix region indicates that socioeconomic status is a useful predictor of perennial landscape vegetation in residential neighborhoods and that the lower economic neighborhoods will have lower amounts of residential landscape – a potential low-cost micro-scale UHI mitigation strategy (Hope et al., 2003; Martin, Warren, & Kinzig, 2004).

5.5. Economics

Recent research has indicated that if current UHI mitigation strategies could realize a 1.8–3.6°F decrease in average temperature, the annual energy savings could reach $26 million for three demonstration US cities (Konopacki & Akbari, 2000). In areas of high solar capacity, such as the desert southwest, modeling the adaptation of renewables such as photovoltaics within mitigation strategies merits due to the enhanced benefits to the environment. According to an EPA report (US Environmental Protection Agency, 2001), the heat island in Los Angeles, California raises ozone concentrations by 10–15% and contributes to millions of dollars in medical expenses due to respiratory and other problems. The same report indicates that heat-island reduction measures could alleviate $360 million per year of the city's smog-related expenses. In the arid southwest, extreme temperatures present other sets of economic impacts. As one example, the US Federal Aviation Administration requirements restrict planes from taking off when temperatures reach 120°F (48.9°C) due to a lack of appropriate procedures. The economic impacts are significant for the region since Phoenix Sky Harbor International Airport is the fifth busiest airport in the world for takeoffs and landings and contributes over $20B (US) annually to the region. The first such restriction occurred when temperatures reached 122°F (50°C) on 26 June 1990 and halted airport operations.

6. MITIGATION

The changing dynamics of increased urbanization has resulted in the transition toward a more man-made and engineered infrastructure. The resulting change in energy balance and increase of anthropogenic heat has led to the creation of UHIs. Various studies have advanced three primary mitigation strategies: (1) urban forestry, (2) cool roofs and (3) cool pavements.

Urban forestry is touted as a means to increase evapotranspiration while providing daytime shading (Pielke & Avissar, 1990; US Environmental Protection Agency, 2003; urban forests – McPherson et al., 1999). Examples of its application include direct shading of housing (south and west) to provide shade. Additionally, many jurisdictions are incorporating urban tree planting in parking lots to reach a 50% canopy coverage in the lots. The Lawrence Berkeley National Laboratory has estimated that within 10–15 years – the time it takes a tree to grow to a useful size – trees placed in strategic locations will reduce heating and cooling costs by an average of 10–20%. Yet, in an arid region, the issues of water balance are essential in evaluating regional policies and ordinances as are the issues of night-time radiation trapping due to the canopy effect.

Reflective paving (Ting & Koomey, 2001) has also recently been introduced into the mitigation hierarchy. Two mechanisms for creating a cool pavement are increased surface reflectance, which reduces the solar radiation absorbed by the pavement, and increased permeability, which cools the pavement either through increased convection, lower thermal storage or evaporation of water.

Cool roofing (Akbari & Sezgen, 1993; Bretz & Akbari, 1997; Parker, Barkaszi, & Sonne, 1994) is another form of UHI mitigation. This approach has modeled the impacts of increasing albedo on rooftops. Akbari's research found that black roofs typically have a 6% rate of reflectivity and low emissivity values while highly reflective white roof membranes can have reflectivity and emissivity values greater than 80%.

As strong as each of the above listed and other mitigation techniques might be at a given demonstration location, for any of these strategies to be effective in national or international context, they must be vetted in association with the given localized economic, environmental and social structure of a community. Global arid regions such as Phoenix, Arizona face water balance questions that could preclude the utilization of a given mitigation strategy such as increased urban forestry. Urban forestry mitigation would require extensive

planting of new and potentially non-native vegetation throughout the region. However, this mitigation strategy should be balanced by the potential benefit via increased carbon sequestration gained from an increase in regional vegetation. This benefit is important as the Phoenix region has a well documented CO_2 dome (Idso & Balling, 1998). Additionally, for any mitigation policy or regulation to be effective, there must be a mechanism for its implementation with funding a major obstacle.

7. DISCUSSION

Policy makers in urbanized and urbanizing regions can create opportunities to reduce the coupled impacts associated with rapid urbanization and changing urban climates as exemplified by the UHI effect. These opportunities can be based upon sound science and engineering and with a strong economic foundation. However, for policy makes on an international basis to garner
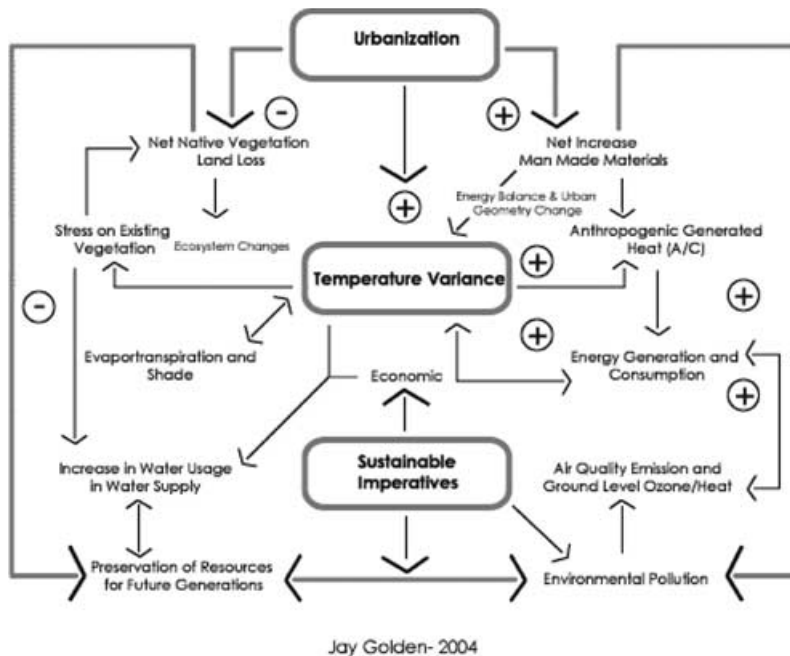

Fig. 13. The influence of the engineered environment and urbanization (source: Golden, 2004).

multi-party consensus within the construct of their geo-political boundaries, understanding UHI causation and mitigation strategies should be presented in an integrative and interdependent manner. Potential UHI impacts based on the geographic and economic complexities are presented in Figure 13.

Research to date has been structured to gain a greater understanding of the complexities of the UHI effect with respect to mesoscale interactions primarily at the urban boundary layer (Brazel, 2003; Oke, 1987). The interdependencies and interactions of the built environment with climatic and atmospheric sciences is a driving basis for the variations in the severity of the UHI effect. However, for policies to be developed and implemented at the local level, there must be an understanding of materials, technologies and practices which are under the control of the policy-making branch. There currently exists an opportunity within the engineering and scientific communities to develop a robust understanding of the coupled volumetric and material make-up of surface materials within an urban region and their impacts on the UHI effect. This multi-disciplinary research effort aims to develop engineering-based policies constructed in a holistic framework based on environmental, social and economic sustainable imperatives for use by communities around the globe.

ACKNOWLEDGEMENTS

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