

Observing Human-induced Linkages between Urbanization and Earth's Climate System

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Abstract:

Urbanization is one of the extreme cases of land use change. Most of world's population has moved to urban areas. Although currently only 1.2% of the land is considered urban, the spatial coverage and density of cities are expected to rapidly increase in the near future. It is estimated that by the year 2025, 60% of the world's population will live in cities. Human activity in urban environments also alters atmospheric composition; impacts components of the water cycle; and modifies the carbon cycle and ecosystems. However, our understanding of urbanization on the total Earth-climate system is incomplete. Better understanding of how the Earth's atmosphere-ocean-land-biosphere components interact as a coupled system and the influence of the urban environment on this climate system is critical.

The goal of the 2003 AGU Union session "Human-induced climate variations on urban areas: From observations to modeling" was to bring together scientists from interdisciplinary backgrounds to discuss the data, scientific approaches and recent results on observing and modeling components of the urban environment with the intent of sampling our current stand and discussing future direction on this topic. Herein, a summary and discussion of the observations component of the session are presented.

Popular Summary

The Earth's landscape is constantly changing, and the development of cities is an extreme example of such change. Most of world's population has moved to cities. Although currently only 1.2% of the Earth's surface is covered with urban landscape, this is expected to grow rapidly in the near future. It is estimated that by the year 2025, 60% of the world's population will live in cities. Human activity in urban environments also alters pollutants in the atmosphere precipitation and flood run-off, plant ecosystems, and climate (e.g. temperature, etc.). Yet, scientists are only now beginning to understand how cities and their environments can impact the Earth system. Current and future advances in observation systems and models are enabling better understanding and prediction capabilities so that influence of cities on the environment can be understood.

The goal of the 2003 AGU Union session "Human-induced climate variations on urban areas: From observations to modeling" was to bring together scientists from different backgrounds to discuss the data, scientific approaches and recent results on observing and modeling city environments with the intent of identify our current stand and discussing future direction on this topic. This paper summarizes the observation section of the session.

Introduction and Overview

Urbanization is one of the extreme cases of land use change. Most of world's population has moved to urban areas. Although currently only 1.2% of the land is considered urban, the spatial coverage and density of cities are expected to rapidly increase in the near future. It is estimated that by the year 2025, 60% of the world's population will live in cities (UNFP, 1999). In the United States, the current urban growth rate is approximately 12.5%, with 80% currently living in urban areas. The U.S. population is not only growing but is tending to concentrate more in urban areas in coastal zones (Culliton et al. 1990). Urban construction changes surface roughness, albedo, heat capacity and vegetation coverage. Human activity in urban environments also alters atmospheric composition; impacts components of the water cycle; and modifies the carbon cycle and ecosystems. However, our understanding of urbanization on the total Earth-climate system is incomplete. Better understanding of how the Earth's atmosphere-ocean-land-biosphere components interact as a coupled system and the influence of the urban environment on this climate system is critical.

The goal of the AGU Union session "Human-induced climate variations on urban areas: From observations to modeling" was to bring together scientists from interdisciplinary backgrounds to discuss the data, scientific approaches and recent results on observing and modeling components of the urban environment with the intent of sampling our current stand and discussing future direction on this topic. An interdisciplinary effort combining remote sensing, boundary layer microphysics, GCM to mesoscale modeling, and human dimension study is desired to address questions such as:

How does urbanization modify the climate system and how will nature respond?

How should urban environments be characterized in models (cloud to climate scale)?

What would be the ranges and extremes of urban effects on the climate system?

How could we quantitatively generalize these modifications in GCMs?

How does the urban area affect the global water cycle processes such as precipitation?

What are the impacts and feedbacks of the urban environment on atmospheric composition?

What current and future observation capabilities can be utilized to advance the ability to understand, characterize, and predict the impact of the urban environment on the climate system?

Session U51 and U52 at the 2003 Fall American Geophysical Union meeting gathered an array of scientists with expertise in observing and modeling components of the urban environment. The authors report on the modeling-focused papers in a separate paper (Jin and Shepherd 2004). In this paper, we summarize the session papers addressing observations of the urban environment by organizing them into the following components: (1) Observing the Urban Environment from Space, (2) Observing Thermodynamic and Dynamic Changes due to the Urban Environment, (3) Observing Precipitation Variability Linked to the Urban Environment, (4) Observing Atmospheric Composition Variability Linked to the Urban Environment, and (5) Observing Land Cover, Carbon, and Ecosystems Change Linked to the Urban Environment

Observing the Urban Environment from Space

As a percentage of overall land cover on the Earth's surface, urban land use is relatively small (< 2%). However, urbanization is prevalent on each of the planet's populated continents and is increasingly being recognized as playing a role in altering components of the Earth system, including weather, climate, atmospheric composition, the water cycle, the carbon cycle, and ecosystems. New remote sensing capabilities from space have enabled new perspectives on the characteristics of the urban environment and broadened the scope of urban study beyond individual or a few cities. Dr. Michael King (NASA Earth Observing System (EOS) project scientist) presented an invited talk on the promise and capability of NASA's Earth Observing System to monitor human-induced climate variations. The Earth Observing System is a space-based observing system comprised of a series of satellite sensors to monitor and measure major components of the dynamic Earth system. Two major EOS platforms have been launched. Terra was launched in December of 1999, and Aqua was launched in May 2002. The Moderate Resolution Imaging Spectroradiometer (MODIS) flies on both spacecraft and is designed to meet the scientific requirements to measure clouds, aerosols, water vapor, land characteristics, and ocean properties. Terra and Aqua also carry other relevant instruments for assessing the urban environments land and atmospheric state. Aura, the third major EOS platform, will be launched in the first half of 2004 and will provide critical measurements of the atmospheric composition in the Earth system. Other key NASA satellites providing relevant information on the urban environment are LANDSAT 7 launched April 1999 and the Tropical Rainfall Measuring Mission (TRMM) launched November 1997.

Dr. King discussed the MODIS Aerosol Product (King et al. 2003a, Kaufman et al. 2002). The product is derived from seven MODIS bands (0.47, 0.55, 0.65, 0.86, 1.24, 1.65, and 2.12 micron). Over land, aerosol optical depth and fraction of optical thickness (in fine particle mode) can be retrieved. These products are of particular importance since urban environments have been shown to be a source for anthropogenic aerosols. Figure 1 shows aerosol optical thickness for May 2001 in the eastern United States. Figure 1 also indicates that heavily urbanized regions like New York, Philadelphia, and Washington, D.C. are directly correlated with larger aerosol optical thickness.

Dr. King also discussed several other satellite-based observations and products relevant to characterizing the urban environment. The MODIS land classification product (Friedl et al. 2002) provides a global assessment of land class, including urban and built-up (figure 2a). The MODIS surface reflectance product (Vermote and Vermeulen, 1999) is useful for determining the relative surface albedo of urban and other surfaces (figure 2b). The MODIS cloud product (King et al. 2003a, Platnick et al. 2003) is increasingly vital for assessing what role the urban environment (dynamic forcing, aerosols) is having on cloud radiative and microphysical processes (figure 2c). Dr. King's presentation concluded with a combined IKONOS and LANDSAT 7 image of the Baltimore-Washington urban region. He stated that such images are being used to monitor and assess impervious surfaces.

Dr. Menglin Jin (University of Maryland) and colleagues also addressed issues related to observing the urban environment from the vantage point of space. Dr. Jin discussed how urban surfaces are currently poorly represented in regional and global climate models. Yet, it is

increasingly apparent that urban forcing must be considered to properly understand and predict the subtleties and general impacts of possible human-induced climate change. The basic motivation for her work is to optimally combine satellite data into climate models to properly resolve urban features. Dr. Jin's work will be summarized in other sections of this paper, and the urbanization and modeling issues are addressed in Jin and Shepherd (2004).

Observing Thermodynamic and Dynamic Changes due to the Urban Environment

Urban areas modify boundary layer processes through the creation of an urban heat island (UHI). In cities, natural land surfaces are replaced by artificial surfaces that have different thermal properties (e.g., heat capacity and thermal inertia). Such surfaces are typically more capable of storing solar energy and converting it to sensible heat. Other contributing factors to the onset of the UHI may be attributed to differences in surface albedo and anthropogenic heat release in the urban area. As sensible heat is transferred to the air, the temperature of the air in urban areas tends to be 2-10 °C higher than surrounding non-urban areas. As early as the late nineteenth century, European scientists detected the presence of an UHI in Paris, Berlin, Vienna, and London (Landsberg 1956). Figure 3 illustrates an archipelago of urban heat islands (e.g. Dallas, Austin, San Antonio and Houston) along the I-35 corridor in Texas as viewed from the GOES satellite's 3.9-micron channel.

To further understand the origins of the UHI, it is instructive to examine a surface heat budget equation,

$$Q_{SW} + Q_{LW} + Q_{SH} + Q_{LE} + Q_G + Q_A = 0. \quad (1)$$

In equation (1), the terms are: Q_{SW} (net short-wave irradiance), Q_{LW} (net long-wave irradiance), Q_{SH} (surface sensible heat flux), Q_{LE} (latent turbulent heat flux), Q_A (anthropogenic heat input), and Q_G (ground heat conduction).

An equilibrium surface temperature is required for (1) to balance. At the surface, if no heat storage is permitted, differential heating results from horizontal gradients in one or more of the terms in (1). Spatial gradients in this equilibrium temperature in conjunction with the overlying thermodynamic and moisture stratification will dominate the upward or downward flux of heat for thermally-forced systems, which results in horizontal temperature gradients required to drive a mesoscale circulation. In the case of the UHI, the difference in surface properties of urban and rural areas leads to the differences in the thermal fluxes in (1). Vukovich and Dunn (1978) used a three-dimensional primitive equation model to show that heat island intensity and boundary layer stability have dominant roles in the development of heat island circulations. Additionally, Huff and Vogel (1978) found that the urban circulation is primarily enhanced by the increased sensible heat fluxes and surface roughness of the urban area.

Dr. Menglin Jin and colleagues presented results using 5 km EOS MODIS-observed skin temperature, land cover, albedo, emissivity, leaf area index, aerosol optical depth, and cloud properties to examine the surface-atmosphere interactions and urban heat island effects from selected urban areas like New York City, Beijing, Phoenix, and Houston as well as globally. Dr.

Jin and colleagues used MODIS-derived skin temperature to examine zonally averaged nighttime temperatures (figure 4). Her findings indicate that the largest urban impacts in terms of temperature are observed over the latitudinal band of 30-60 N, where most cities are located. In addition, her results showed that urban regions decrease surface albedo by 3-5% and decrease surface emissivity by 1-2%.

Several presenters focused on specific urban heat islands or specific aspects of the thermal environment of the urban environment. Winston Chow and Matthias Roth (National University of Singapore) examined an urban heat island in a tropical city. They emphasized that much of the literature on urban heat islands has been primarily focused on cities in temperate climates. Chow and Roth's work represents one of the first comprehensive studies of temperature and humidity distributions of a tropical city, Singapore, Malaysia. They measured various climate parameters in different land-use types (e.g., commercial, central business district, industrial, high-rise and low-rise residential). Their preliminary findings suggest that there are significant differences in the magnitude and timing of the peak UHI in Singapore compared to mid-latitude cities. They also presented evidence linking the role of moisture and UHI intensity. Drier periods were generally associated with larger UHI intensity differences. They concluded with some preliminary data addressing the role of different urban canyon geometries on temperature cooling rates.

Lela Preshad and colleagues (Arizona State University) described urban heat island connections to neighborhood microclimates in Phoenix, Arizona. They pointed out that Phoenix is known to have an urban heat island that significantly increases minimum and maximum temperatures. The objective of their study was to: (1) identify social factors and behaviors that influence temperature scale (1 square kilometer) and relate fluctuations to the overall UHI; (2) determine the effect of land use on temperature at the neighborhood and regional scales; (3) evaluate a range of thermal infrared (TIR) remotely sensed data and compare the remotely sensed surface temperatures to air temperature. They used daytime TIR data from LANDSAT sensors (TM, ETM+) (Goward et al. 1999) and the airborne MASTER (Capolsini et al. 2003) to obtain surface temperatures at neighborhood scale. Nighttime temperatures were obtained from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) sensor aboard the Terra satellite (Stefanov et al. 2001). Vegetation indices were created from the LANDSAT and MASTER imagery. Climate monitors installed in each neighborhood recorded air temperature and dewpoint readings every 5 minutes. Preshad et al. found that surface temperatures correlate strongly with air temperature. The 12.5 m MASTER and 30m LANDSAT thermal data can highlight surface temperature gradients within the neighborhood while nighttime ASTER data provides better mean surface temperature discrimination of local diurnal temperature variations. Interestingly, neighborhoods with low mean income, high Hispanic populations, and low educational attainment were hotter than high-income, non-Hispanic areas. Urban core areas with high income also correlate strongly with high amounts of vegetation ($R=-.637$) and have significantly lower surface and air temperatures than model projected UHIs. The suggestion, according to Preshad et al., is that neighborhoods with the means to alter their environments can produce amenable microclimates.

Effects of surface warming due to urbanization on subsurface thermal structure have been found in many cities of the world, but a thorough evaluation has been lacking. Makoto Taniguchi (Nara

University of Education) and colleagues discussed work seeking to identify and quantify the effects of urbanization and global warming on subsurface temperature in three megacities in Japan-Tokyo, Osaka, and Nagoya. They also hope to evaluate a relationship between groundwater flow and the subsurface temperature regime under conditions of warming caused by urbanization or global warming. Taniguchi and colleagues presented comparisons between observed and calculated subsurface temperatures. Their early results indicated that urbanization has increased subsurface temperatures in the three cities. They also showed that the inversion depth increases with the magnitude of urbanization (surface warming) and downward groundwater flux (e.g. Tokyo > Osaka > Nagoya).

Prof. Sue Grimmond (Indiana University) and Prof. Tim Oke (University of British Columbia) presented recent observations and modeling results of surface-atmosphere exchanges in urban areas. They noted that increasing attention is being directed to the climates of urban areas because urbanization may have profound impacts on the natural environment. Their paper summarized the most significant findings from measurements of fundamental energy, mass, and momentum exchanges taken during field campaigns across North America (Vancouver, Mexico City, Los Angeles, Chicago, Sacramento, Tucson, Oklahoma City, Baltimore), Europe (Lodz, Marseille), and Africa (Ouagadougou). Observations from these urban sites are being used to evaluate numerical simulations of the Town Energy Balance (TEB) model. TEB couples the micro- and meso- scales and accurately represents the urban energy budget in mesoscale atmospheric models. TEB uses local canyon geometry with surface and substrate radiative, thermal, moisture and roughness properties to simulate the effects produced by urban buildings. Calculating energy balances for the surfaces of building, roads, and other relevant surfaces simulates the urban system. These processes are subsequently integrated to resolve the local scale surface energy balance. Sarah Roberts (University of British Columbia) and colleagues presented research from central Mexico City, a light industrial site in Vancouver and the city center of Marseille, France. They showed that at these sites, TEB simulated net radiation to within less than 10 W m^{-2} and its partitioning into turbulent and storage heat fluxes to within a few tens of W^{-2} . Results from the observation site in Marseille revealed that the wind regime plays the dominant role in energy partitioning in that environment.

Andres Soux (University of British Columbia) and colleagues stressed that there have been very little measurement of longwave radiation divergence since studies in the 1960's and 1970's. Though mainly ignored, Soux et al. suggests that longwave radiation divergence may play an important role in balancing nocturnal energy budgets in a range of environments. For example, they pointed out that in the urban environments surface temperature relates well to the energy balance whereas air temperature does not. They hypothesized that this is due to the effects of longwave divergence. Soux et al. discussed the application of a new dual-channel infrared radiometer (DCIR) that measures the directional infrared radiation in two wavelength bands and produces a direct measurement of longwave radiative flux divergence after some differencing and signal processing. They also discussed the first deployment of the DCIR as part of Basel Urban Boundary Layer Experiment (BUBBLE), a larger study of the urban boundary layer of Basel, Switzerland (Middleton 2002). During BUBBLE, an urban canyon was heavily instrumented to measure turbulent and conductive fluxes, radiation, and standard meteorological parameters. They noted that preliminary results showed that the onset of canyon air-volume cooling, measured cooling rates are slightly lower than ($< 0.5 \text{ deg C}$) radiative cooling rates.

This contrasts sharply with previously measured above roof level and rural differences of greater than 5 deg C. They hypothesize that the differences are related to differences in the radiative, temperature, and wind environment.

Observing Precipitation Variability Linked to the Urban Environment

Several observational and climatological studies have theorized that the urban environment can have a significant influence on mesoscale circulations and resulting precipitation processes. Recent papers (Shepherd and Burian 2003, Shepherd et al. 2002, Dixon and Mote 2003) provide thorough literature reviews on the subject. Changnon (2003) even recently found evidence that the urban heat island can impact the frequency of freezing rain events during the winter months. However, a recent U.S. Weather Research Panel report (Dabberdt et al. 2000) indicated that more observational and modeling work is required because previous results were heavily based on a few specific cities and statistical inferences.

Shepherd and Burian (2003) and Shepherd et al. (2002) recently established that space-based precipitation observing systems might be able to detect UHI-induced rainfall variability (figure 5). This is particularly intriguing because understanding of urban effects on rainfall is far from complete. First, previous research used ground observations to study one or few selected cities. However, urban effects vary with the micro- to mesoscale features of individual cities. Globally assessment of urban climate is necessary to generalize the most important characteristics of urban effects. Second, previous studies, via different approaches, reached conflicting understanding on urban-rainfall relations. It is reported that urban reduces rainfall due to cloud microphysics (Ramanathan et al. 2001), although historical and more recent studies showed that urban enhances rainfall over and downwind of cities (see references in section 1). The mechanisms of urban effects on rainfall are complex. On one hand, cloud microphysics, in response to increased urban aerosols may reduce rainfall, as suggested by Rosenfeld (1999). On the other hand, local dynamics and thermodynamics associated with an UHI-induced convergence zone and a destabilized boundary layer may enhance urban rainfall (Shepherd and Burian 2003; Shepherd et al. 2002; Changnon and Westcott 2002; Ohashi and Kida 2002a).

There is renewed debate on how the urban environment might affect precipitation variability. Possible mechanisms for the urban-induced rainfall include one or a combination of the following: (1) enhanced convergence due to increased surface roughness in the urban environment; (2) destabilization due to UHI-thermal perturbation of the boundary layer and resulting downstream translation of the UHI circulation or UHI-generated convective clouds; (3) enhanced aerosols in the urban environment for cloud condensation nuclei sources; or (4) splitting or diverting of precipitating systems by the urban canopy or related processes. Others have also hypothesized that urban areas serve as moisture sources needed for convective develop. Recently investigators have suggested that urban areas near coastal zones like Houston can experience enhanced convergence zone created by urban heat island-sea breeze convergence zone interactions in subtropical environments. To date, there is no conclusive answer to what processes lead to observed anomalies in precipitation around cities. The AGU Session provided an open forum to continue and advance the discussion.

Invited speaker, Professor Daniel Rosenfeld (Hebrew University) presented a synopsis of how the urban aerosol environment might impact precipitation processes. Professor Rosenfeld referred to past and current literature indicating enhanced precipitation over and downwind of major urban areas. He noted that dynamic processes associated with the urban heat island and urban topography are generally considered of first order significance in altering or creating rainfall processes. Prof. Rosenfeld has recently observed that urban and industrial aerosols may actually suppress rain and snow by providing large concentrations of small cloud condensation nuclei (CCN), which lead to large quantities of small cloud droplets (Rosenfeld, 2000). He further explained that the clouds must grow to greater depth and colder cloud top temperatures for the onset of precipitation. This requirement means that precipitation would be suppressed when aerosols are ingested into relatively shallow and short-lived clouds. Professor Rosenfeld showed that such clouds occur in the winter over orographic barriers downwind of coastal cities. He discussed the ratio of rainfall over the hills versus the upwind lowland rainfall (RO) of sites in California and Israel. He also included some fascinating images from his flight into San Francisco that seemed to validate aerosol suppressed clouds downwind of San Francisco that were observed in MODIS satellite imagery. Professors Rosenfeld's preliminary results indicated that downwind of San Francisco, San Diego, and Jerusalem RO has decreased by 15 to 25 percent during the last century whereas no change occurred in regions not downwind of urban areas. Rosenfeld also argued that aerosols suppress the onset of precipitation in warm base convective clouds that develop in moist tropical air masses (e.g. St. Louis or Houston). In numerical simulations with explicit microphysical processes, Rosenfeld and colleagues found that delay of warm rain onset results in delayed downdraft formation. This process allows for a more invigorated updraft that produces deeper and stronger convection. Professor Rosenfeld proposed that this initial suppressive process is actually an additional enhancement mechanism in addition to UHI-related dynamics. Furthermore, he argued that the transition from warm to ice phase precipitation processes advects more cloud water to the supercooled levels higher in the cloud. The additional cloud water and strong updraft prime the cloud for enhanced electrical activity as observed recently in Houston by Orville et al. (2001). The general conclusion is that aerosols can have large impacts on the precipitation processes in clouds and can enhance or suppress precipitation depending on cloud type, seasonality, climate regime, or orographic profile of the urban area.

An important result of Prof. Rosenfeld's presentation is that it provides evidence of convergence in both the UHI-dynamics arguments and aerosol-microphysics arguments for precipitation variability in urban environments. Marshall Shepherd (NASA Goddard Space Flight Center) and colleagues offered new model results that begin to explain how the Houston UHI circulation and convergence zone interacts with the coastal sea-bay breeze to produce enhanced low-level convergence in a destabilized boundary layer over the Houston urban area. These conditions are necessary for convection. Shepherd and Burian (2003) identified precipitation anomalies, primarily during the warm season, over and downwind of Houston using TRMM-derived rainfall rates and a network of rain gauges. Using the MM5 mesoscale model coupled to a series of land surface models, Shepherd and colleagues illustrated that when urban surface parameters were excluded from model simulations, precipitation evolution around the Houston urban area was dramatically different than when the urban surface is included. These differences are attributed to changes in the low-level convergence field and the boundary layer thermodynamic stability.

Professor Steve Burian (University of Utah) presented results on behalf of his graduate student Parastou Hooshalsadat (University of Utah) along with collaborations with Marshall Shepherd. Professor Burian showed results from an analysis of 50 rain gauges within and nearby Houston. The intent of the study was to identify annual and warm season (June, July, August) rainfall trends from 1950 to 2000. Professor Burian showed that the immediate urban area of Houston has experienced higher average annual and warm season rainfall amounts during the 50-year time period than the upwind region (defined by the mean 700 hPa steering flow as in see Shepherd et al. (2002)). The downwind or "urban impacted region" also experienced higher rainfall amounts. However, in their statistical analysis, neither the urban or downwind region amounts met required thresholds for statistical significance.

Professor Burian also discussed trend analyses performed on the 50-yr time series of annual and warm season rainfall amounts by calculating a statistic representing the differences in annual and warm season rainfall amount for each year between the urban area and upwind region, and the urban area and downwind region. The trend of the difference statistic versus time and population was assessed using line plots and regression analyses. The regression results suggested that there is an increasing trend for the urban area-upwind region difference with both time and population growth, but no significant trend for the downwind-upwind region and urban area-downwind region difference statistics.

Professor Robert Bornstein (San Jose State University) closed the discussion on precipitation variability by presenting results from his observation and modeling research for the cities of New York and Atlanta. Professor Bornstein presented evidence that precipitating storms or frontal systems can be split or deformed by the urban topography or other urban-related factors. He showed several examples of this phenomenon around New York City. He suggested that the downwind region of cities might be preferred regions for merging of the "split" storms thereby explaining apparent downwind anomalies. Professor Bornstein also showed examples of model simulations of precipitating storms observed around Atlanta during the 1996 Olympics. His model analyses showed evidence that urban-induced convergence and boundary layer destabilization explained the presence of precipitation on these fairly weakly forced synoptic days.

Observing Atmospheric Composition Variability Linked to Urban Environment

As with many components of the earth system, the atmospheric composition is a dynamic component of the Earth system and is constantly being changed by natural and human-related processes. The urban environment is one of many possible human-related source regions for altering the composition of the atmosphere. As illustrated in figure 1, higher concentrations of aerosols are strongly correlated with proximity to major urban areas. The source of these "urban" aerosols is likely human-related activities related to transportation, energy production, and industrial processes.

Dr. Menglin Jin (University of Maryland) presented results using data from the NASA AERONET network site at the Goddard Institute for Space Studies in New York City. Using a temporal data set from June-September 2001, Dr. Jin showed that aerosol optical thickness peaks during the middle of the week (e.g. Wednesday). The weekly cycle clearly depicted a decrease

during the weekend days (e.g. Friday and Saturday) and an increase at the beginning of the "work" week. Dr Jin correlates this cycle to the increased transportation activity at the beginning of the business week.

D, Allen Chu (NASA Goddard Space Flight Center) and colleagues demonstrated that MODIS-derived columnar aerosol loading has shown good correlation ($R=0.8-0.9$) with Environmental Protection Agency (EPA) PM_{2.5} (particulate matter with particle size less than 2.5 μm) at the surface in urban areas like Houston, New York and Chicago. They noted that the EPA and regional planning organization decision support systems rely heavily on urban scale models and ground networks. Chu and colleagues further indicated that MODIS aerosol data can play a significant role in tracking the movement of pollutants, a proxy for PM_{2.5}. NASA collaborated with EPA and NOAA in providing MODIS aerosol data to benchmark PM_{2.5} forecasts in the Eastern United States during the summer of 2003. They emphasized that the MODIS-based approach offered the possibility to monitor global pollutants, improve assessments of spatial variability, and distinguish contributions of urban sources, biomass burning, etc.

Observing Land Cover, Carbon, and Ecosystems Change Linked to the Urban Environment

The cycling of carbon and water is essential to Earth's unique status as the only known life-bearing planet in our solar system. The biogeochemical system is constantly changing and it is becoming increasingly apparent that urban environments can contribute to this change. The carbon cycle, vegetation fraction, and land use are revealing the signature of increasing urbanization on the planet.

Marc Imhoff (NASA Goddard Space Flight Center) and colleagues posed the question, "how has urbanization altered the carbon cycle in the United States?" Using satellite data and a terrestrial carbon model, they quantified the impact of urbanization on net primary productivity (NPP) and its consequences on carbon balance and food production. They demonstrated that different classes of urbanization have a recognizable satellite-based Normalized Difference Vegetation Index (NDVI) signal at spatial resolution of 1 km. A significant result presented by Marc Imhoff et al. is that urbanization is taking place on the most fertile lands and has a disproportionately large overall negative impact on regional and even continental scale NPP. They showed that urban land transformation in the U.S. has reduced the amount of carbon fixed through photosynthesis by 1.6 percent of pre-urban values. This reduction nearly offsets the 1.8 percent gain made by the conversion of land to agricultural use. Dr. Imhoff noted that this is a striking fact given that urbanization covers less than 3% of the land in the U.S., while agricultural lands approach 29%. He also showed that, at local and regional scales, urbanization increases NPP in resource-limited regions, and through localized UHI warming contributes to the extension of the growing season in cold regimes. He noted that in terms of biologically available energy, the loss of NPP due to urbanization alone is equivalent to the caloric requirement of about 6 percent of the U.S. population annually.

Crisinal Milesi (University of Montana) and colleagues discussed the use of the Fractional Impervious Surface Area (ISA), a measure of urban density estimated from the Defense Meteorological Satellite Program/Operational Linear Scanner (DMSP/OLS), NDVI, and

MODIS-derived land surface temperature (LST) to understand how urbanization impacts local climate. They conducted analyses for Chicago, Atlanta, and Phoenix to characterize different climate regimes and urban densities. They found that NDVI does not necessarily decrease linearly as the fractional ISA increases, and may eventually increase with the density of development due to vegetation management practices. They illustrated that nighttime LST consistently increased with the fractional ISA. The urban-rural differences in the nighttime LST are similar in each city for equal values of imperviousness, indicating that ISA and MODIS products have value for providing a continental physically based characterization of the surface.

Annemarie Schneider (Boston University) and colleagues presented their efforts (1) to map and monitor urban areas globally, and (2) to understand urban growth and its drivers during the last decade at regional and local scales, in a cross section of cities. Schneider et al. emphasized that global climate and weather models are increasingly including urban information in the land parameterizations. Yet, the most common surrogate data source for global cities, the Digital Chart of the World urban data is outdated, while the DMSP nighttime lights data overestimates urban extent due to the "blooming" effects. Schneider et al. discussed a technique called boosting which integrates MODIS data with prior ancillary data sources to improve supervised classification accuracy. Their results showed that fusion of data types improves urban classification by resolving confusion between urban and other classes. In synthesizing the second objective, they discussed the need for global comparisons of cities as opposed to local scale, "case by case" approaches of the past. They used change detection in a sample of cities using Landsat imagery and statistical analysis combining land cover data with socioeconomic data. Early results indicate the emergence of several city "types" based on commonalities in spatial patterns, rates, and mechanisms of growth.

Conclusions

The session, "Human-Induced Climate Variations Linked to Urbanization: From Observations to Modeling" brought some of the world's leading scientists to the 2003 Fall AGU meeting to discuss urban-induced climate impacts. Two invited speakers, Dr. Michael King and Prof. Daniel Rosenfeld, provided discussions of observational capabilities and findings related to urbanization and climate variability. Prof. Robert Dickinson, the third invited speaker, provided a framework for how improved observations and knowledge will enable needed representation of urban surfaces in emerging climate models.

Scientists with expertise in observations, theory, and modeling presented compelling results illustrating that urbanization is impacting essentially every component of the earth-climate system: weather, climate, water cycle, carbon cycle, ecosystems, and atmospheric composition. Interest in the urban-climate relationship is currently very high because urbanization will increase globally to reflect population migration to cities. The complexities of the Earth system are well known, but the relative influences of human-induced and natural forcings are not. Therefore, the renewed focus on the urban environment is timely and critical.

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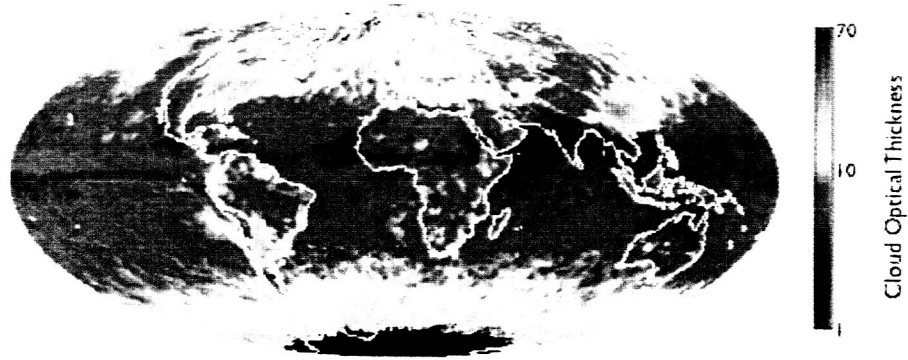
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Cloud Optical Thickness (Water)



Cloud Optical Thickness (Ice)



Figure 2-MODIS cloud optical thickness product (courtesy of M. King, NASA/GSFC)

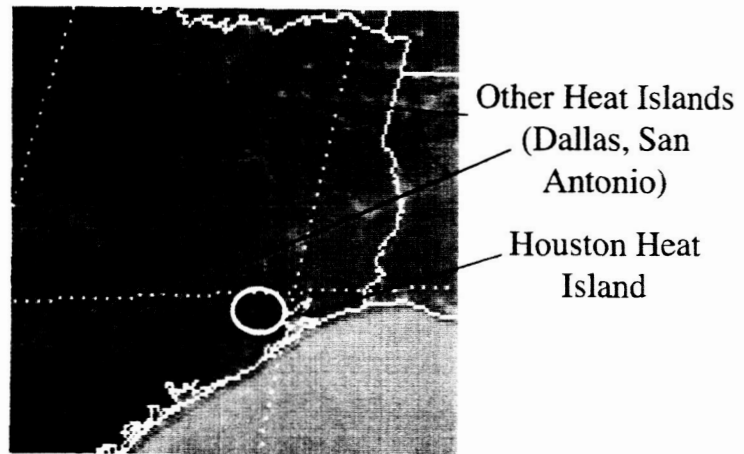


Figure 3-3.9 micron infrared channel from GOES indicating "urban heat islands" in Texas.

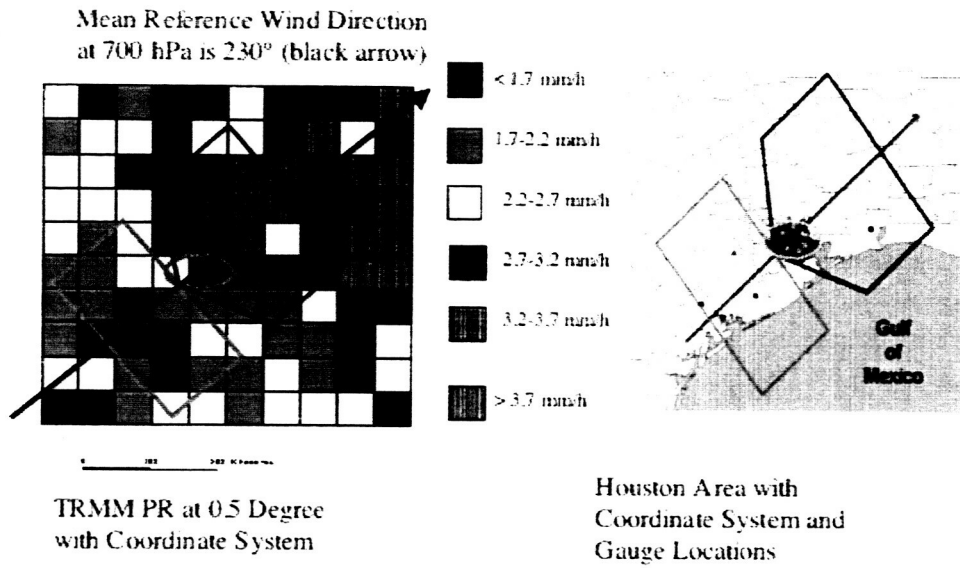


Figure 5-TRMM Precipitation Radar-derived mean rainfall rates over a 5-year period (1998-2002) indicating elevated rainfall rates over the Houston metropolitan area (orange oval) and just downwind of the city (black trapezoid).