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The footprint of urban climates on vegetation phenology

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[1] Human activity, through changing land use and other activities, is the most fundamental source of environmental change on the Earth. Urbanization and the resultant "urban heat islands" provide a means for evaluating the effect of climate warming on vegetation phenology. Using data from the Moderate Resolution Imaging Spectroradiometer, we analyzed urban-rural differences in vegetation phenological transition dates and land surface temperatures for urban areas larger than 10 km^2 in eastern North America. The results show that the effect of urban climates on vegetation phenology decays exponentially with distance from urban areas with substantial influence up to 10 km beyond the edge of urban land cover, and that the ecological "footprint" of urban climates is about 2.4 times that of urban land use in eastern North America. The net effect is an increase in the growing season by about 15 days in urban areas relative to adjacent unaffected rural areas. *INDEX TERMS:* 0315 Atmospheric Composition and Structure: Biosphere/atmosphere interactions; 0330 Atmospheric Composition and Structure: Geochemical cycles; 1615 Global Change: Biogeochemical processes (4805); 1620 Global Change: Climate dynamics (3309); 1640 Global Change: Remote sensing. **Citation:** Zhang, X., M. A. Friedl, C. B. Schaaf, A. H. Strahler, and A. Schneider (2004), The footprint of urban climates on vegetation phenology, *Geophys. Res. Lett.*, *31*, L12209, doi:10.1029/2004GL020137.

1. Introduction

[2] More than one third of the land surface on the Earth has been transformed by human activities [*Vitousek et al.*, 1997]. Among these activities, urbanization is an increasingly important anthropogenic influence on climate, and has significantly affected terrestrial ecosystems. One of most evident effects associated with urbanization is the so-called urban heat island effect, in which urban areas tend to be warmer than surrounding rural areas. Moreover, urbanization has important consequences with respect to primary productivity [*Imhoff et al.*, 2000], biodiversity, and biogeochemical cycles [*Bonan*, 2002].

[3] A number of recent studies have shown that global warming has a measurable influence on the growing season of terrestrial vegetation at mid- and high latitudes [e.g., *Myneni et al.*, 1997]. However, more studies are required to fully understand how climate change affects vegetation phenology. In this context, urban heat islands provide a useful means to assess the effect of warming on vegetation phenology. For example, by examining vegetation phenology using satellite data, several studies have shown that vegetation greenup occurs earlier in urban areas than that in rural areas [*White et al.*, 2002; *Zhang et al.*, 2004]. Further, field observations have demonstrated that the onset of flowering dates in urban areas in Europe occurs about 4–17 days earlier than in rural areas [*Franken*, 1955; *Roetzer et al.*, 2000].

[4] In this study, we examine the effect of urban heat islands on vegetation phenology in eastern North America. However, unlike previous studies, we specifically investigate the magnitude and form of urban heat island effects on vegetation phenology in rural areas surrounding urban land cover. To do this, we used satellite data obtained from the Moderate Resolution Imaging Spectroradiometer (MODIS) to evaluate the differences in both phenological transition dates and land surface temperatures (LST) between urban vegetation and surrounding natural vegetation for about seventy urban areas in eastern North America. Measurements of phenological differences were related to MODIS LST values to assess phenological responses to spatial variability in LST.

2. Data and Methods

2.1. Remotely Sensed Data

[5] We used MODIS Nadir Bidirectional Reflectance Distribution Function (BRDF) Adjusted Reflectances (NBAR) acquired between 1 January and 31 December, 2001. MODIS NBAR data are produced every 16 days with a spatial resolution of 1 km [*Schaaf et al.*, 2002]. To detect seasonal variation in vegetation phenology, annual time series of the enhanced vegetation index (EVI) [*Huete et al.*, 2002] was calculated from NBAR data, which consists of 23 values for each pixel. Because EVI values for snow-covered surfaces differ significantly from those of soil and vegetation, snow-contaminated EVI values were substituted with the most recent snow-free values when snow was present in any pixel. Note that because the EVI is specifically designed to be resistant to variation in background reflectance, it is well suited for monitoring seasonal vegetation dynamics in urban areas, where vegetation can be relatively sparse [*Huete et al.*, 2002].

[6] Phenological transition dates were identified using the rate of change in curvature of logistic models fitted to time series of EVI values at each pixel [*Zhang et al.*, 2003]. Periods of sustained EVI increase and decrease were detected using a moving window technique, and piecewise logistic functions were used to depict vegetation growth curves as a function of day of year (DOY). The resultant phenological cycles are characterized by four transition points consisting of the onsets of vegetation growth, maturity (when plant green leaf area reaches maximum), senescence, and full dormancy [*Zhang et al.*, 2003]. In this context, it is important to note that the 16-day temporal

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resolution of the MOMDIS NBAR data is a key factor constraining the precision of retrieved transition dates. However, initial assessment of this issue suggests that the method of phenology detection is quite robust. Specifically, we performed a set of sensitivity analyses in which simulated daily NBAR data were composited to 16-day time periods. The results from this analysis revealed that the mean deviation between actual versus retrieved transition dates was 1.7 days, with a standard deviation of 0.8 days. In the future, we hope to resolve this issue by using higher frequency NBAR data, as available.

[7] The land surface temperature data used here were provided by the MODIS LST product obtained in 2001. MODIS LST measures the surface skin temperature, and is calculated using satellite thermal-infrared measurements for clear-sky pixels with a spatial resolution of 1 km. The MODIS LST product provides LST for 8-day time periods [*Wan et al.*, 2002]. To match the temporal scale of the NBAR data and to further reduce the number of missing values (because of cloud cover), the 8-day daytime LST data were aggregated to 16 days using quality assurance information from the LST product. Thus, the LST data calculated from MODIS observations are temporally and spatially comparable with MODIS NBAR data. Note, however, that MODIS LST is not equivalent to the near surface air temperature. At the same time, a variety of studies have shown that the presence of vegetation tends to increase the correlation and decrease the difference between LST and near surface air temperatures [*Friedl and Davis*, 1994].

[8] Urban areas were determined by classifying multiple sources of data including MODIS NBAR spectral data from October 2000 to October 2001, so-called nighttime lights data derived from the Defense Meteorological Satellite Program Operational Linescan System [*Elvidge et al.*, 1996], and gridded population density data [*Schneider et al.*, 2003]. This urban map identifies all 1 km^2 cells for which urban land use is dominant.

2.2. Identifying Differences Between Urban Areas and Surrounding Rural Areas

[9] We hypothesized that the effect of urban heat islands on vegetation phenology is stronger close to urban areas and decreases gradually towards rural areas. To demonstrate this effect, a series of buffers extending 0–3, 3–5, 5–8, 8–10, 10–15, and 15–20 km from the edges of urban land cover in eastern North America were created. Only cities with urban areas larger than 10 km^2 were included in the analysis.

[10] To calculate the difference in phenology and LST between urban areas and surrounding rural landscapes in each buffer, the following formula was used:

$$\Delta P = \frac{\sum_{k=1}^{M} P_{uk}}{M} - \frac{\sum_{k=1}^{N} P_{ik}}{N} \qquad (1)$$

where ΔP represents the difference in a given parameter (LST or phenology), P_{ik} is the value for a pixel in buffer i, N is the number of pixels in this buffer, P_{uk} is the value in an urban pixel, and M represents the total number of urban pixels in the city of interest. In other words, ΔP is equal to the difference in the mean values for either phenology or LST between urban and rural areas.

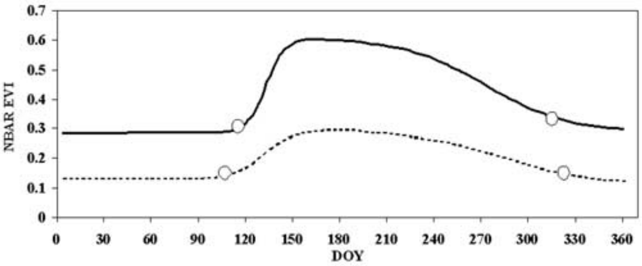

Figure 1. Sample fitted temporal trajectories of NBAR EVI data using logistic functions for urban areas (dash line) and deciduous forests in adjacent rural areas (solid line). The circles represent the detected dates of greenup onset and dormancy onset.

[11] Using this method, differences in the dates for both greenup onset (ΔG) and dormancy onset (ΔD) for each city were estimated. By convention, we define ΔG to be positive ($-\Delta P$) since greenup onset always occurs earlier in urban areas relative to rural areas in the data set we considered. Note that croplands were excluded since planting and harvesting of crops are primarily controlled by human activities.

[12] Since spring greenup onset is mainly controlled by spring temperatures while dormancy onset is associated with temperatures during autumn and early winter [*Kramer*, 1994; *Hänninen et al.*, 1990], we also calculated differences in LST between urban areas and adjacent rural areas using equation (1). These LST differences include the mean spring LST (January to May, ΔLST_{1-5}) and mean autumn-winter LST (middle September to December, ΔLST_{9-12}). These quantities are referred to as the urban heat island intensity [*Oke*, 1993].

3. Results and Discussion

3.1. Effect of the Urban Heat Island on Vegetation Phenology in Rural Buffers

[13] Vegetation in urban areas exhibits longer growing seasons and lower canopy density relative to rural areas (Figure 1). Greenup onset occurred earliest in urban areas, with progressively later onset further away from the urban core. Figure 2 illustrates differences in phenology and temperature between urban areas and surrounding buffers in the northeastern United States. ΔG is especially pronounced in the Washington-Philadelphia-New York Corridor, where greenup occurs about 5.5 days and 8.7 days earlier than in the 0–3 km and 8–10 km buffers, respectively. As expected, ΔG increases with distance from urban areas.

[14] Variation in spring LST is strongly correlated with observed trends in ΔG. In particular, ΔLST_{1-5} is very large for the buffer zone extending 0–3 km and decreases gradually to roughly 10 km beyond the actual edge of urban land cover (Figure 2). In the Washington-Philadelphia-New York corridor, for example, LST in urban areas is 1.8°C, 2.2°C, and 2.5°C higher than those in the 0–3 km, 3–5 km, and 8–10 km buffers, respectively. The rural/urban boundary exhibits a steep temperature gradient, which has been previously referred to as a “cliff” [*Oke*, 1993].

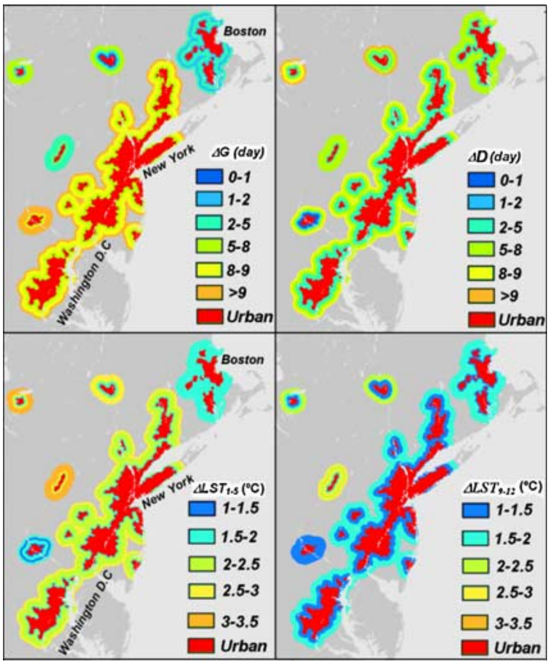

Figure 2. Spatial patterns in differences in greenup onset (ΔG), dormancy onset (ΔD), spring time temperature (ΔLST_{1-5}), and autumn-winter temperature (ΔLST_{9-12}) for the Washington-Philadelphia-New York urban corridor.

[15] In contrast to greenup onset, dormancy onset occurs later in urban areas than in surrounding rural areas, because LST from late September to December is generally higher in urban areas. Both ΔD and ΔLST_{9-12} increase with distance from the urban perimeter but the rate of increase decreases gradually with distance from urban center. This trend is particularly evident in the northeastern United States (Figure 2). For example, dormancy onset in the Washington to New York Corridor is delayed by about 2.5 days and 6 days relative to the onset of dormancy in 0–3 km and 8–15 km buffers outside of this area, respectively. Such differences are mainly the result of the urban heat island effect, where ΔLST_{9-12} is about 1.2°C for the 0–3 km buffer, and 1.5 °C for the 8–15 km buffer.

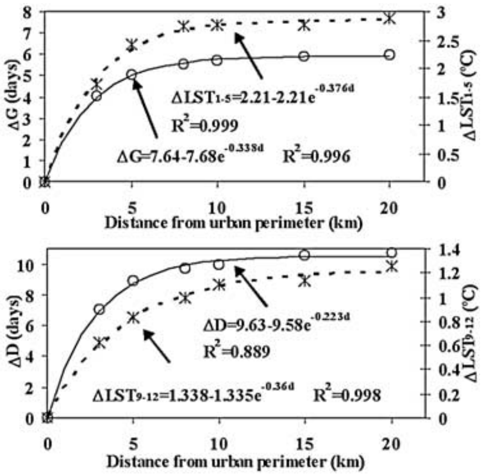

Figure 3. Advance in greenup onset (ΔG), delay in dormancy onset (ΔD), and increase in both ΔLST_{1-5} and ΔLST_{9-12} in urban and surrounding areas as a function of distance (d) from urban perimeter.

[16] Differences in phenological transition dates and LST are exponential functions of distance from the urban perimeter. Figure 3 plots average ΔG, ΔLST_{1-5}, ΔD and ΔLST_{9-12} against distance from all urban areas in eastern North America. If we assume that the footprint of urban effects can be determined based on the distance at which each of the exponential models reaches 95 percent of their asymptotic values, then urban influences extend about 8 km, 9 km, 9 km, 14 km beyond the edge of urban land cover for ΔLST_{1-5}, ΔLST_{9-12}, ΔG, and ΔD respectively. Evidently, urbanization strongly affects vegetated ecosystems, with significant and detectable effects extending to about 10 km beyond the perimeter of urban land cover. This represents an increase of 138% in the ecological footprint of urban climates relative to the area of land actually occupied by urban land cover. In other words, the footprint is 2.4 times that of the actual urban area.

3.2. Geographic Pattern in the Urban Heat Island Effect

[17] Figure 4 shows the spatial distribution of ΔLST_{1-5} and ΔG between urban areas and the 10–20 km buffer where the effect of urban heat islands is negligible. Thus, these results represent the maximum magnitude of the urban heat island effect in each city in eastern North America. Spring temperatures in urban areas are larger than in rural landscapes by 2.28 ± 0.80°C (Figure 4a). ΔLST_{9-12}

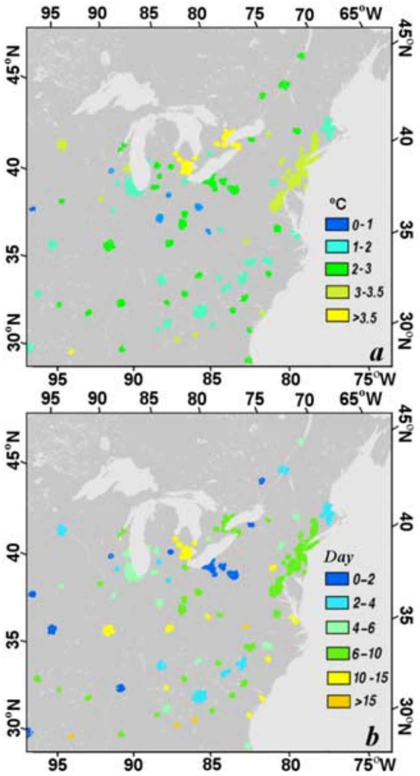

Figure 4. Increase in spring LST (a) and advance in vegetation greenup onset (b) in urban areas. Urban areas are slightly enlarged for display purposes.

exhibits a spatial pattern comparable with ΔLST_{1-5}, but the magnitudes of ΔLST_{9-12} values are consistently smaller (1.48 ± 0.79°C).

[18] Similarly, greenup onset in urban areas occurs earlier than in rural areas (Figure 4b). Vegetation greenup onset occurs 6.92 ± 4.85 days earlier in urban areas relative to adjacent rural areas. The onset of dormancy in urban areas is delayed by 7.91 ± 7.12 days.

[19] Spatial patterns in ΔG indicate that phenological differences between urban and rural areas are a function of ΔLST. There is a significant linear trend between ΔG and ΔLST_{1-5} ($\Delta G = 0.66 + 3.15\ \Delta LST_{1-5}$, $n = 67$, $p < 0.0001$). This trend generally indicates that vegetation greenup advances 3 days for each 1°C increase in temperature. This result is closely comparable with the values (3–4 days per °C) observed from field measurements [e.g., *Fitter et al.*, 1995; *Rötzer and Chmielewski*, 2000]. However, variance in this relationship shows that greenup onset is also influenced by winter chilling duration [*Zhang et al.*, 2004]. The relationship between ΔD and ΔLST_{9-12} is not statistically significant, suggesting that delay in the onset of dormancy is a complex function of ΔLST_{9-12} and other factors such as photoperiod and water availability. Moreover, statistical analysis indicates that ΔG and ΔLST_{1-5} are not significantly related to urban size. It is likely that population density plays an important rule in heat island intensity [*Landsberg*, 1981]. However, the larger the city, the larger area of the surrounding landscapes that is influenced with respect to vegetation phenology.

4. Conclusions

[20] The results from this work show that vegetation phenology in both urban core areas and surrounding regions is significantly influenced by urban heat island regimes, although the strength of urban influence decays exponentially with distance from the perimeter of urban land cover. For both temperature and vegetation phenology, the ecological footprint of urban land cover extends about 10 km beyond the perimeter of urban areas, and the footprint of urban climates on vegetation phenology is 2.4 times the size of the actual urban land cover. On average, spring greenup in urban areas occurs about 7 days earlier than surrounding rural areas and dormancy is delayed by 8 days. At larger spatial scales the geographic pattern of both urban heat islands and vegetation phenology show that climatic regimes substantially complicate urban effects on the biosphere.

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