J3.3 LAND-COVER INFLUENCES ON BELOW-CANOPY TEMPERATURES IN AND NEAR BALTIMORE, MD

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1. INTRODUCTION

As a contribution to the Baltimore Ecosystem Study (BES), a U.S. National Science Foundation Long Term Ecological Research (LTER) site, weather variables are being measured continuously at five locations near Baltimore, MD. Data also are available from two National Weather Service Automated Surface Observing System (ASOS) stations (Fig. 1). Measurements include temperature at a height of 1.5 m at all stations.

One object of the analysis of these measurements is to develop an empirical model of below-canopy air temperature differences. Such a model is important for evaluating urban structural and vegetation influences on air temperature for studies related to human thermal comfort, carbon cycling, soil and stream temperatures, ozone formation, and interaction with effects of UV radiation. An anticipated application of the temperature-differences model is for mapping predicted temperatures across Baltimore based on 30- by 30-m imagery from the National Land Cover Database (NLCD). The mapping will be for times of special interest, such as early evening, when temperature differences usually are greatest, and midafternoon, when temperatures usually reach a maximum.

At the five non-ASOS sites, measurements have been continuous since June 2003. These sites include a lawn area with nearby trees near a large apartment complex (Apartments, 1 in Fig. 1); a residential area with heavy tree cover but few buildings (Residential under trees, 2); a residential area with some trees and large lawn areas (Residential open, 3); a woodlot next to a large cultivated field (Woods, 4); and a large open pasture, (Rural open, 5). The ASOS sites are in downtown Baltimore (Downtown, 6), and at the Baltimore/Washington International (BWI) Airport (Airport, 7)

Temperature differences on an hourly basis between each site and the Downtown ASOS site are related empirically by regression analysis to upwind tree, impervious, and water land cover from the NLCD 2001 (Homer et al. 2004). Additional predictor variables for temperature difference are atmospheric stability, vapor pressure deficit, antecedent precipitation, sky view and transmitted direct-beam solar radiation estimated from hemispherical photographs at each site, and topography. The initial analysis is for May through September 2004. In this paper we report preliminary results in the development of predictor variables.

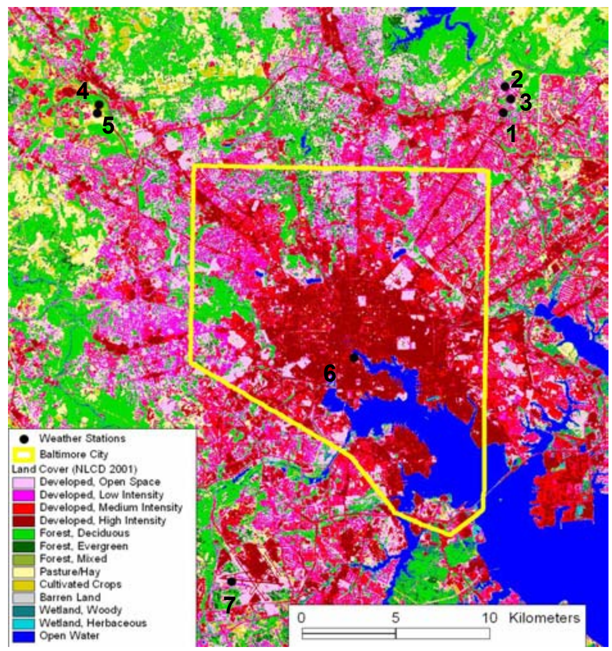

Figure 1. Land use in Baltimore and vicinity and location of seven weather stations; from NLCD 2001 (http://www.mrlc.gov).

2. METHODS

The planned analysis is similar to that carried out in Heisler and Wang (1998). The temperature differences (ΔT) for each hour between the generally warmest site--the Downtown site--and each of the other sites form the dependent variable. A major challenge is created by the range of the scales of influences on temperature and the correlation between potential predictor variables.

2.1 *Sites*

The sites are separated by as much as 19 km (Fig. 1). Land uses around the sites according to the NLCD

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classification included low-, medium-, and high-intensity developed; open-space developed, deciduous forest; and pasture. The sites generally were not in large continuous blocks of a particular land use. For example, the Apartment Site 1 was in a strip of lawn with scattered trees between two large "garden" apartment complexes with large parking lots. Residential with trees Site 2 was under large deciduous trees, but within 20 m of two small buildings and about 50 m from a wooded area about a 2 ha in size. The Downtown reference Site 6 is in a heavily developed part of central Baltimore City yet within 50 m of water in Baltimore's Inner Harbor.

2.2 *Meteorological data*

At the non-ASOS sites, Instrument packages with data loggers recorded wind speed, wind direction, and air temperature, but the sensors differed somewhat. At all sites including the ASOS sites, air temperature, T, was measured at 1.5 m above ground. At sites 1, 3, and 4, T was measured with thermistors in naturally ventilated Gill-type radiation shields. With these systems, maximum errors with high radiation loads probably exceed 1ºC. Station 2 measured T with a thermistor in a double-tube, power-aspirated radiation shield for which maximum combined electronic and radiation errors probably are 0.25 ºC. The Rural Open Site 5 is the primary weather station for the BES LTER site. A PRT device in a double-tube, fan-aspirated radiation shield measures air temperature with maximum errors of about 0.1ºC.

The non-ASOS sites sampled T at 5-s intervals and averaged over 15-min. For the analysis described here, the 15-min averages from 15 min before the hour to the top of each hour were compared to data from the ASOS sites, which average and make available temperature and relative humidity over a 2-min period at 6 to 8 min before each hour.

The data used in this analysis were collected from May 5 through September 30 in 2004. Times when any station had missing data were excluded from the analysis, resulting in a data set with 3091 h (86% of possible), or 18,546 values of ΔT. Most of the missing observations were at the Downtown ASOS site.

2.3 *Atmospheric stability*

To characterize atmospheric stability, which has a strong influence on urban heat islands, we used wind speed and cloud cover from the BWI Airport to derive the Turner Class (Panofsky and Dutton 1984) for each hour. Turner ranges from 1 for very unstable conditions when wind is light and insolation is high, to 4 for neutral stability, to 7 for very stable conditions when wind is light and the sky is clear at night. Actual stability across the area will vary with surface conditions.

2.4 *Land cover*

Land cover was derived from tree, impervious, and water land-cover classifications in the NLCD (Fig. 2). This classification is based on Landsat images with a resolution of 30 by 30 m. To derive upwind land-cover differences between sites, we assumed that wind direction over the entire domain of the urban area was uniform during each hour and represented by airport wind reports. We used GIS analysis to average tree-, impervious-, and water-cover density over segments created by circles with 0.5, 1, 2, 3, and 5 km radii centered on each of the sites and by lines radiating from the sites to create pie-shaped wedges extending in the 8 compass directions (N, NE, E, etc.) as illustrated in Fig. 3.

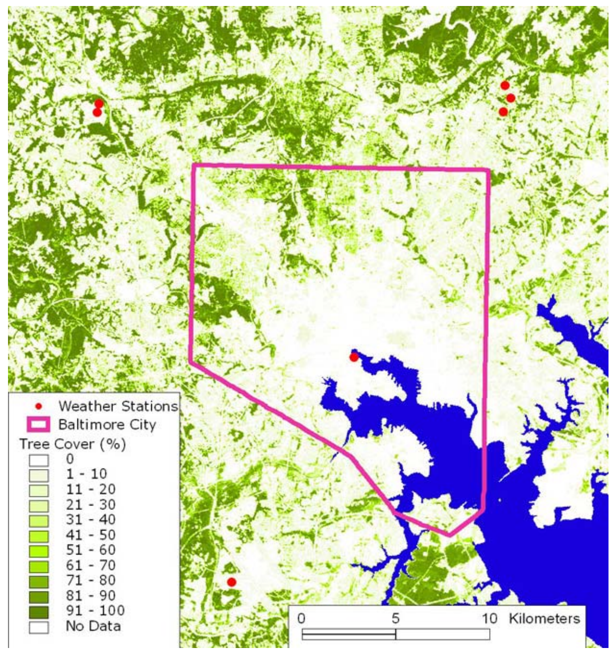

Figure 2. Tree cover from NLCD 2001.

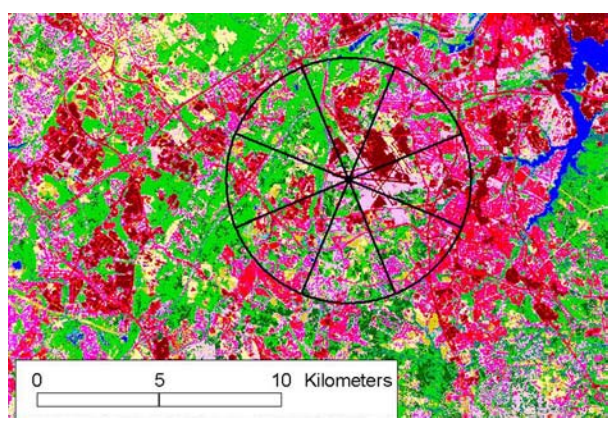

Figure 3. Area analyzed for upwind land cover around the Airport (site 7) illustrated by the circle with a 5-km radius and lines radiating to separate the different compass directions.

2.5 *Adjacent tree and building structure*

The influence of trees and buildings on solar irradiance and thermal radiation exchange with the sky was evaluated from 180-degree hemispherical photos taken looking directly upward from the 1-m height at each site. Sky view and the fraction of transmitted direct solar radiation were derived by analysis with the Gap Light Analyzer (GLA) program (www.ecostudies.org/gla/). Differences in the sky view percentages between Downtown (sky view of 78%) and Sites 1 through 5 and 7, respectively, were 47, 53, 41, 72, -18, and -22.

2.6 *Topography*

The City of Baltimore and the suburban areas included in our study span the transition from the Coastal Plain in the southeast of the area and the Piedmont Plateau to the northwest. The lower elevation Coastal Plain is clearly differentiated by the lighter areas in Fig. 4. Elevations of the sites range from 3 m at the Downtown Site 6 to 156 m at the Rural Open Site 5 (Table 1). Topography has several influences on air temperature, which include the average atmospheric lapse rate and cold air drainage.

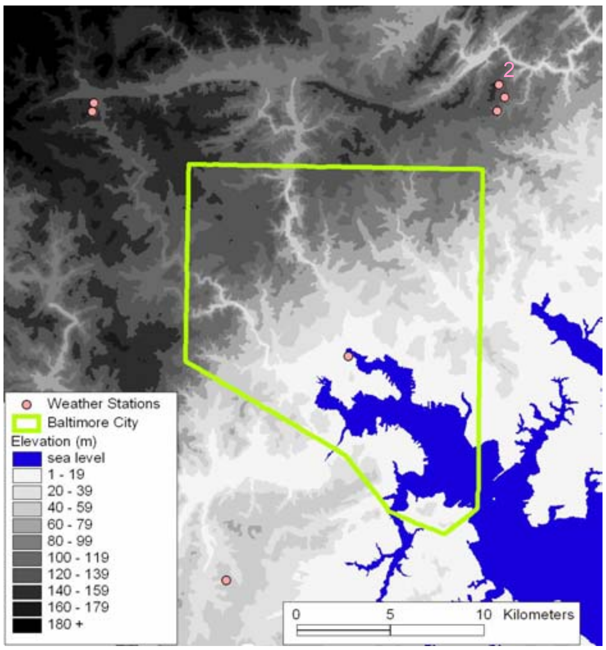

Figure 4. Topographic relief in the study area.

3. RESULS AND DISCUSSION

The Downtown site generally was warmer than the other sites, with temperature differences between downtown and more rural sites being as large as 10ºC. Though many independent variables were correlated with ΔT, the most important generally was Turner Class (Fig. 5). Even with temperatures adjusted for a standard atmospheric lapse rate (-0.0065ºC m^{-1}), ΔT averaged 3.7ºC with Turner Class 7. With neutral stability, Class 4, which would be with windy, cloudy weather, average ΔT was only 1.4ºC.

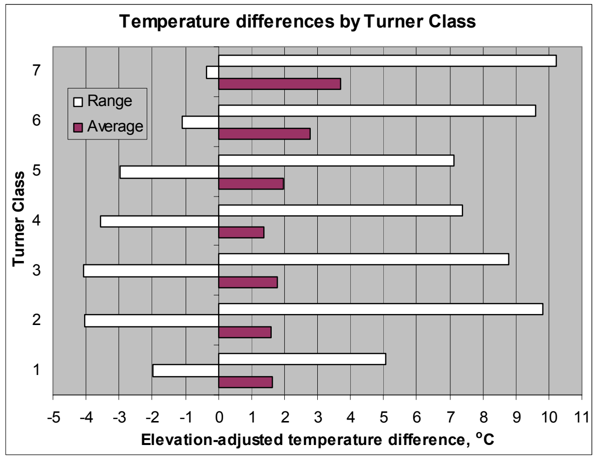

Figure 5. The range and average ΔT stratified by Turner stability Class (at BWI) for all sites and all observations over the summer. Temperatures are adjusted by the standard atmosphere lapse rate.

The effect of stability is evident in Fig. 6, which shows elevation-adjusted ΔT averages by site and hour of the day. Temperature differences for most sites are largest at night. This anticipated urban heat island pattern is seen frequently in the literature.

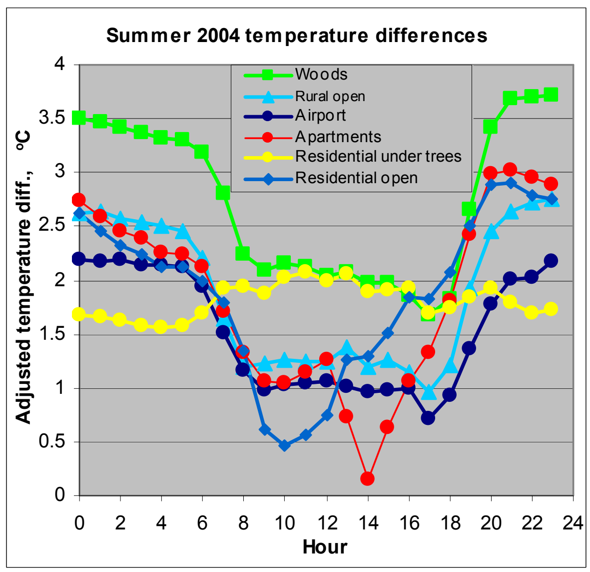

Figure 6. Average temperature differences by hour of the day over the entire summer.

The pattern of larger temperature differences at night is clear for all sites except for the Residential area (2) which had smaller temperature differences at night

(Fig. 6). Although there are buildings not far from Site 2, the different pattern there probably is due to topography.

Table 1. DEM-based ground elevations and relative elevations for all sites. Relative elevation is the ratio of site elevation to total relief over all points within 2 km of the site. Relative total elevation is the ratio of site elevation to the total range of elevation at all sites. Above lowest is the absolute elevation above the lowest elevation within 2 km.

	Site	Elev.	Relative elev., 2 km	Relative total elev.	Above lowest , 2 km
1	Apartments	102	0.45	0.51	39
2	Resident. trees	145	0.95	0.74	106
3	Resident. open	103	0.56	0.52	61
4	Woods	138	0.19	0.70	14
5	Rural open	156	0.52	0.80	33
6	Downtown	3	0.08	0	3
7	Airport	46	0.75	0.22	30

This topographic effect is not a simple function of elevation; Site 5 is higher. Site 2 is at the top of a hill, but Site 5 is similarly located on a low ridge, though there are higher elevations nearby. We might expect the large trees overhead at site 2 to reduce nighttime outgoing radiation to clear night skies; however, the other wooded site, 4, has lower sky view.

The important difference at Site 2 probably is the greater relief to the north and northeast at this site than at others (Fig. 4, Table 1). The Woods, Site 4, may cool considerably under Turner 7 conditions because it is at a low elevation compared to other locations within 2 km (Table 1) and, therefore, is subject to cold air drainage toward the site. The high relative elevation at Site 2 may lead to warmer temperatures (smaller ΔT) owing to cold air drainage away from the site and temperature inversions in the valleys below.

In developing diagnostic equations for ΔT, the Turner Class may be used as a predictive variable, or the data can be separated by Turner Class and separate equations developed for each class. We first used the separated data method. If the data are not separated by Turner, many of the predictor variables have varying influence depending on Turner Class, that is, interaction terms must be included. Even if data are separated by Turner class, Turner still must be included as an independent predictor variable because it is not only Turner class at the hour of observed ΔT that affects the ΔT but also Turner over the previous 1 or 2 hr. Therefore, we derived a variable (Turner3), the average of the current and previous two hourly observations of Turner Class. The effect of Turner on ΔT is not linear (see Fig. 5); the effect was best represented by a cubic power of Turner3.

In preliminary regression analyses, many independent variables entered into regression equations as statistically significant in predicting ΔT. For example, using only data for Turner Class 7, a regression equation with 16 predictor variables was derived easily by entering terms that were most closely correlated with ΔT. There is obvious correlation between many of these independent variables, which means that interpretation of the regression coefficient R^2, 0.43 in this case, is questionable. This analysis left much of the variance in ΔT unexplained, but it did not include the important interaction between Turner Class and elevation.

Land-cover variables correlated with ΔT included water cover, impervious cover, and tree cover over various distances upwind. Other significant variables were sky view, antecedent precipitation, harbor water temperature, vapor pressure deficit, and Turner over 3 hr. The next step is regression modeling with noncorrelated independent variables and including interactions of relative elevation with Turner Class over the previous 3 hr.

4. CONCLUSION

Summertime temperature differences between inner city Baltimore and a rural wooded area, which represents the intensity of the urban heat island, were commonly 7°C or more under stable atmospheric conditions at night. Land cover in urban areas has a decided influence on air temperature but there are strong interactions between land cover and other factors that influence air temperature, particularly atmospheric stability and topography. The relatively simple Turner Class is a useful indicator of the magnitude of urban heat island effects. Land-cover differences out to at least 5 km in the upwind direction were significantly related to temperature differences under stable atmospheric conditions.

5. ACKNOWLEDGMENT

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6. References

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