**J2.7   EMPIRICAL MODELING AND MAPPING OF BELOW-CANOPY AIR TEMPERATURES
IN BALTIMORE, MD AND VICINITY**

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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. At the five non-ASOS sites, measurements have been continuous since June 2003.
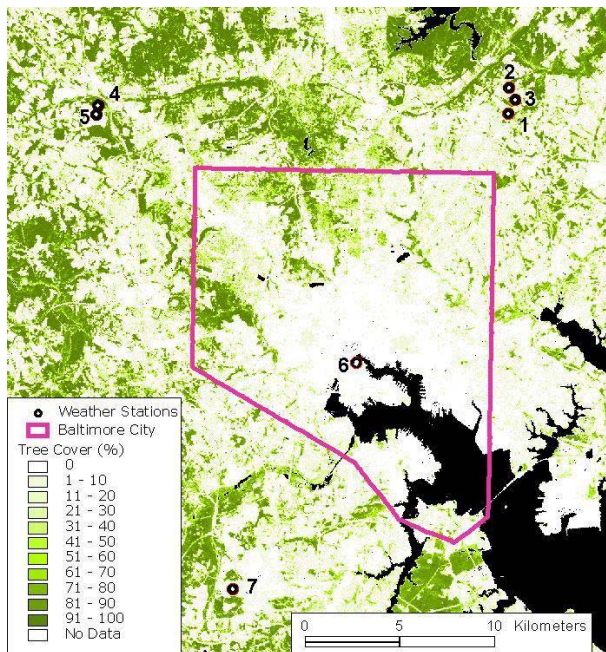

Fig. 1. Tree cover from NLCD 2001. The location of stations is shown by numbered circles. Six are outside of city boundaries.

Analysis of these measurements has been used to develop empirical models of below-canopy air temperature differences. Such models are important for evaluating urban structural and vegetation influences on

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air temperature for studies related to human thermal comfort, carbon cycling, soil and stream temperatures, ozone formation, and interaction with effects of ultraviolet radiation.

The modeling uses multiple regression to relate hourly temperature differences (ΔT) between the Downtown ASOS site and each of the other sites to upwind tree canopy, impervious surface, and water land cover from the 30-m resolution imagery from the National Land Cover Database (NLCD 2001) (Homer et al. 2004). Additional predictor variables for ΔT are atmospheric stability, vapor pressure deficit, antecedent precipitation, and topography.

An initial application of the ΔT model is for mapping predicted temperatures throughout Baltimore and nearby areas. The mapping assists in model validation and a series of maps on hourly intervals will serve to illustrate the progression of temperature patterns across the city. Maps showing ΔT juxtaposed with tree cover and topography will indicate the relative importance of these factors. Times of special interest for mapping are days with clear skies and light winds, especially in the early evening, when temperature differences usually are greatest.

In this paper, we report initial results of regressions and mapping of ΔT for summer conditions. Exploratory correlation analysis with potential independent variables was reported earlier (Heisler et al. 2006a; 2006b). The focus is on effects of urban forest cover on air temperatures. Sorting out the effects of one variable is difficult because of the multitude of interacting determinants of urban air temperature (Whitford et al. 2001).

2. METHODS

The regression analysis is similar to that reported by Heisler and Wang (1998), who related temperature differences between points in an urban area to upwind land cover, modeled solar input, vapor pressure deficit, and antecedent precipitation by a linear multiple regression model. In the current study, additional predictor variables are considered along with alternatives to common linear models because of the correlation between many of the potential independent variables. A major challenge is created by the range of the spatial scales of influences on temperature.

2.1. *Sites*

The non-ASOS sites include a lawn area with nearby trees near a large apartment complex (termed

Apartments, coded 1 in Fig. 1 and Table 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).

Table 1. Ground elevations and relative elevations for all sites based on a 30-m-resolution Digital Elevation Model (DEM) analysis. Relative elevation is the ratio of site elevation to total relief within 2 km of the site. Total relative elevation is the ratio of site elevation to the total elevation range (196 m) within 2 km of all sites. Above lowest is the elevation in m above the lowest elevation within 2 km. CDI=Cold drainage index=Relative elevation over 2 km X absolute elevation above 2 km.

	Site	Elev.	Relative elev., 2 km	Total Relative elev.	Above lowest, 2 km	CDI
1	Apartments	102 m	0.45	0.51	39 m	18
2	Resident. trees	145	0.95	0.74	106	101
3	Resident. open	103	0.56	0.52	61	34
4	Woods	138	0.19	0.70	14	3
5	Rural open	156	0.52	0.80	33	17
6	Downtown	3	0.08	0.02	3	0
7	Airport	46	0.75	0.22	30	23

The sites generally are not in large continuous blocks of a particular land use. According to the NLCD classification, dominant land uses around the sites can be characterized as low-, medium-, and high-intensity developed; open-space developed, deciduous forest; and pasture. For example, Apartment Site 1 is in a strip of lawn with scattered trees between two large "garden" apartment complexes with large parking lots. Residential with trees Site 2 is under large deciduous trees, but within 20 m of two small buildings and about 50 m from a wooded area about 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. The other sites are separated by as much as 19 km from the Downtown site (Fig. 1).

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) is measured at 1.5 m above ground. At sites 1, 3, and 4, T is measured with thermistors in naturally ventilated Gill-type radiation shields. With these systems, maximum errors with high radiation loads probably exceed 1 ºC. 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 (Heisler et al. 2000). Here a platinum resistance thermometer (PRT) device in a double-tube, fan-

aspirated radiation shield measures air temperature with maximum errors of about ±0.1 ºC.

The non-ASOS sites sample T at 5-s intervals and average over 15 min. For this analysis, 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 record average temperature and relative humidity over a 2-min period at 6 to 8 min before each hour.

The data 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 ∆T. 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 BWI 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 during the day, to 4 for neutral stability when wind is strong and clouds prevail, to 7 for very stable conditions when wind is light and the sky is clear at night. Actual stability across the area varies with microscale and local-scale conditions.
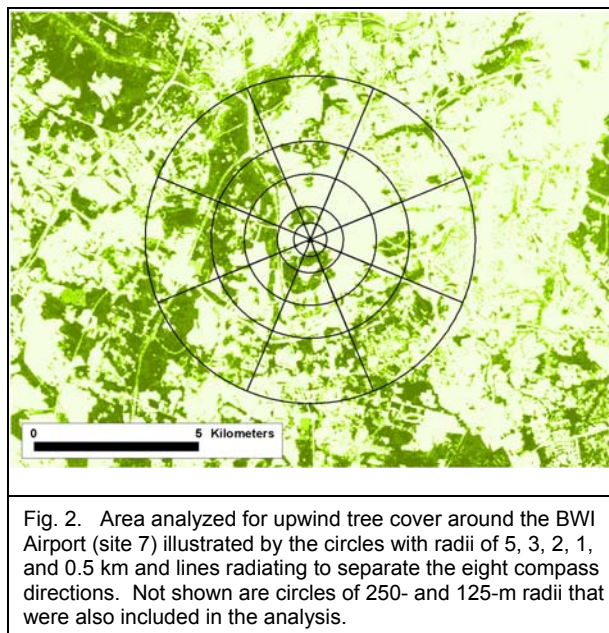

Fig. 2. Area analyzed for upwind tree cover around the BWI Airport (site 7) illustrated by the circles with radii of 5, 3, 2, 1, and 0.5 km and lines radiating to separate the eight compass directions. Not shown are circles of 250- and 125-m radii that were also included in the analysis.

2.4. Land Cover

Land cover variables (Figs. 1 and 2) were derived from the 2001 NLCD in which percent tree canopy, impervious surface, and water cover were classified from 30-m resolution LANDSAT imagery. 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 Geographical Information System (GIS) analysis to average tree-, impervious-, and water-cover density over segments created by circles with 0.125-, 0.250-, 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 centered on the eight compass directions (N, NE, E, etc.), as illustrated in Fig. 2.

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 180º 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 (http://www.ecostudies.org/gla/). Differences in the sky view percentages between Downtown (Site 6) with sky view of 78%, and Sites 1 through 5 and 7, respectively, were 47, 53, 41, 72, -18, and -22.

2.6. *Topography*

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. 3. 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, including the atmospheric lapse rate and cold air drainage.
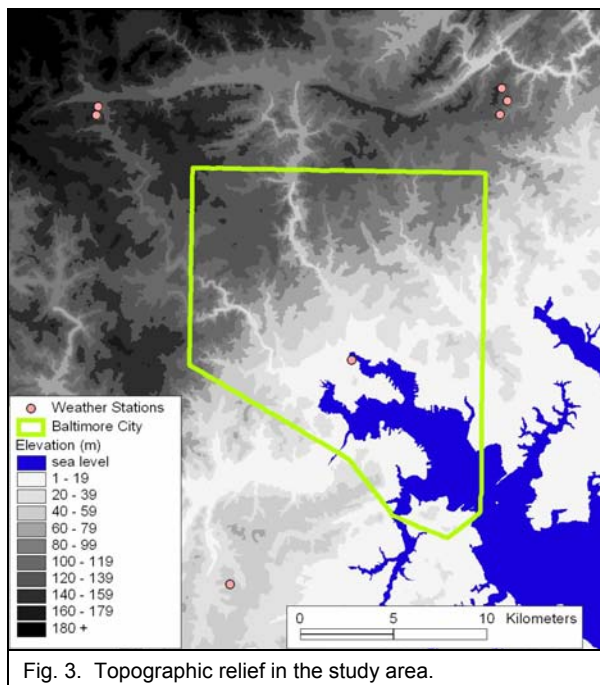

Fig. 3. Topographic relief in the study area.

2.7. *Statistical Analysis*

In preliminary analysis to develop independent variables for predicting ΔT, we looked at time series of ΔT with possible predictor variables and examined their Pearson correlations. As expected, the urban structure effect on ΔT varied so that the correlations between structural variables and ΔT differed by Turner Class. In developing diagnostic equations for ΔT, the Turner Class might be used as a predictive variable or tested as an interaction term with structural attributes. Alternatively, the data may be stratified by Turner Class and separate regressions developed for each class. That was the primary approach used here.

In developing equations for GIS mapping of ΔT, we used only independent variables or interactions of variables that related to land cover. Thus, antecedent precipitation, vapor pressure deficit, and bay water temperature were entered only as interaction terms with a land cover variable. The reasoning was that although a variable such as antecedent precipitation might influence ΔT, there would be no ΔT without differences in cover or topography.

For mapping, it was desirable to find relatively efficient models with a small number of predictors. Because this was an exploratory study, we used multiple linear regression with Proc Reg and stepwise independent variable selection (SAS Institute Inc. 2003). For input to the stepwise, we selected 23 (the maximum number allowed in SAS) from more than 130 possible predictor variables, following as much as possible the advice of Burnham and Anderson (1998) to choose variables on the basis of likely physical relationship with the dependent variable. We also considered the results of the preliminary correlation analysis, choosing candidates more highly correlated with ΔT and less highly correlated with other predictors.

Because many of the potential independent variables were unavoidably correlated, when running the regressions we used the tolerance option (TOL) and repeatedly ran the analysis removing the candidate predictor with the lowest tolerance until tolerance for all variables was at least 0.40. Though there is no strict rule for minimum acceptable tolerance, Allison (1999) suggests that tolerance should be at least 0.40 to avoid excessive multicollinearity.

2.8. *GIS Mapping*

Hourly maps of predicted ΔT were produced with ArcGIS 9.1. Tree canopy, impervious surface, and classified land cover were obtained from the 30-m-resolution 2001 NLCD to calculate for each cell in the map domain the upwind average of percent canopy, impervious surface, and water cover for each of the pie-shaped wedges over the 7 distances and 8 directions described in Fig. 2. According to the regression model applied, the appropriate raster layer derived from the step above was subtracted from the corresponding value at the downtown weather station location to produce a difference raster layer. The difference layer was then entered as one of the several variables of the

regression equation to produce the layer of predicted temperature difference.

3. RESULTS AND DISCUSSION

3.1. *Measured Temperatures*

For 3091 hours over the summer, all of the seven stations had complete temperature data. With six observations of ΔT each hour, the number of observations ranged from 546 (91 hours) in Turner Class 1 to 5586 (931 hours) for Turner Class 4.

The Downtown site generally was warmer than the other sites. Though many independent variables were correlated with ΔT, the most important generally was Turner Class (Fig. 4) with Pearson correlation r=0.40 for the composite of all data hours. Even with temperatures adjusted for a standard atmospheric lapse rate (-0.0065 °C m^{-1}), ΔT varied up to 10 °C (11 °C unadjusted) and averaged 3.7 °C with Turner Class 7. With neutral stability, Class 4, which would be with windy, cloudy weather, average elevation-adjusted ΔT was only 1.4 °C.
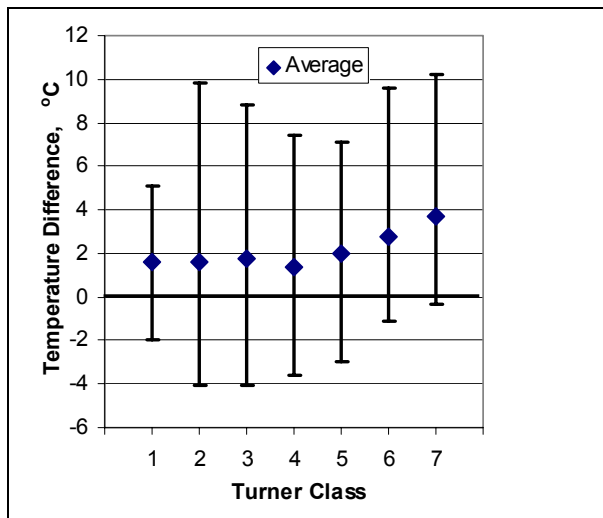

Fig. 4. Range and average ΔT stratified by Turner stability Class (at BWI) for all sites and all observations over the summer. Temperatures are adjusted by the standard atmosphere lapse rate.

The effect of stability is evident in Fig. 5, which shows elevation-adjusted ΔT averages by site and hour of the day. Temperature differences for most sites are largest at night, peaking between 2100 and midnight. This anticipated urban heat island pattern is seen frequently in the literature.

The pattern of larger temperature differences at night is clear for all sites except for the Residential area (2), which had smaller average temperature differences at night (Fig. 5). Although there are buildings near Site 2, the different pattern there probably is due to topography. 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 located similarly on a broad ridge.
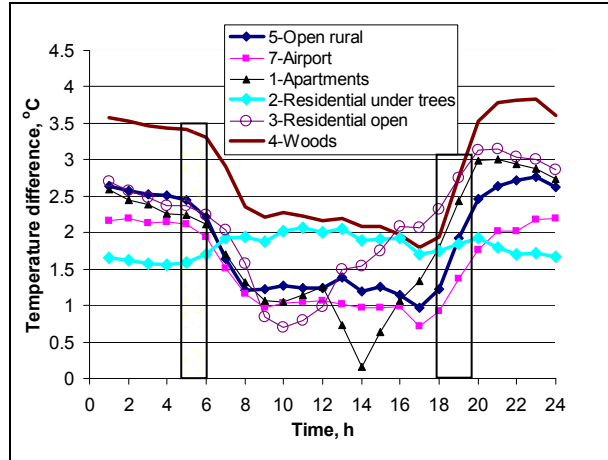

Fig. 5. Average elevation-adjusted temperature differences (Downtown minus site) by hour of the day over the summer for the six sites. Sunrise (yellow shade) ranged from 0440 to 0602 and sunset (blue shade) from 1750 to 1937.

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. 3, 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.

3.2. ΔT Prediction Equations

Prediction equations for ΔT were derived for each Turner Class. However, another independent variable (Turner3) was also calculated as the average Turner Class for the observation hour and the previous two hours, because it is not only Turner class at the hour of observed ΔT that affects the ΔT, but also Turner over previous hours. The effect of Turner on ΔT is not linear (see Fig. 4); the effect was best represented by a cubic power of Turner3. For all data combined, Pearson correlation coefficient r for ΔT with (Turner3)^3 was 0.49.

An assumption in regression is that the observations are independent, an assumption not fully met in our data, because each hourly observation of ΔT is related to the previous one. However, some separation is achieved by the fact that we used only 15-min sampling periods out of each hour, and by the analysis of the data separately for each of the seven Turner Classes.

The final regression equations had 4 to 7 predictor variables in addition to intercepts, which ranged from -0.12 to 1.04. Because of the considerable sources of variability in ΔT, R^2 values were fairly low, ranging from 0.27 for Turner Class 2 to 0.49 for Turner Class 7. Many factors lead to variability in measured ΔT. Among

them are the large distances between sites, instrumental errors in temperature measurements, the short sample time of the ASOS temperature averages, the limited precision of ASOS temperature reporting to the nearest 1 ºF, inaccuracies in cover analysis in the NLCD, projection errors in the GIS images, the limited (30-m) resolution of the GIS images, and lack of consideration of vertical dimensions in the predictor variables.

For producing ∆T maps, we assumed that the intercept term in the prediction equations should be 0, and reran the final equations using the no intercept option. This distributed the intercept term among the independent variables. The effect on predicted ∆T was small, as seen in residual analysis plots.

Total elevation difference from the reference site was a significant predictor variable for all Turner classes. The elevation difference parameter ranged from -0.00667 to -0.01109 in no systematic order by Turner Class. The units for the parameter would be ºC m^{-1}, thus the predicted lapse rates were slightly greater than the standard atmospheric lapse rate of -0.0065 ºC m^{-1}.

To account for anomalous temperature difference at Site 2, a simple cold air drainage index (CDI) was defined intuitively as the product of relative elevation over 2 km around the point and absolute elevation above the lowest elevation within 2 km. CDI was a significant predictor variable in some form for Turner Classes 5, 6, and 7, with negative regression coefficients, i.e. smaller ∆T for higher CDI.

Recent antecedent precipitation had the effect of reducing predicted ∆T. In the regressions for mapping equations, we treated the inverse of an antecedent precipitation index as an interaction with cover terms. For example, for antecedent precipitation (in inches=2.54 cm) over the past 24 h, the precipitation term was 1/(precipitation*100 +1), with the +1 added to avoid division by 0. The interaction terms were consistently more highly correlated with ∆T than the cover terms alone.

Vapor pressure deficit, VPD (saturation – actual vapor pressure), from BWI was included as an interaction term with tree and impervious cover differences, and at least one term including VPD was significant for all Turner Classes.

In the regressions for Turner Classes 2 and 6, harbor water temperature had a significant effect on temperature differences as (Downtown air temperature – water temperature) * (difference in water cover up to 3 km). Water temperature data were acquired from the Maryland Department of Natural Resources continuous monitoring site at Fort McHenry in the Baltimore Harbor (http://www.dnr.state.md.us/bay/monitoring/index.html). We assumed that temperatures there were representative of all water areas within 3 km of any of the sites.

The sky view and estimated direct solar radiation transmitted were significantly correlated with ∆T, but were not included in the regression analysis for temperature mapping because of the difficulty of estimating sky view from the NLCD.

Tree cover and impervious cover in some form were significant predictors of ∆T for all Turner Classes with usually negative coefficients (more tree canopy = cooler temperatures) for tree canopy and positive coefficients for impervious cover. In the regression results, the largest tree-cover effects were with Turner Class 7, where the potential tree influences were up to about 10.5 ºC. Class 7 occurs only at night with low wind speed and clear sky.

3.3. ∆T Maps

As anticipated, the range of predicted temperature differences across the mapped areas is largest at night with Turner Class 7 (Fig. 6). With daytime Turner Classes, much of the predicted ∆T is related to elevation differences (Fig. 7). The influence of parkland in urban areas becomes evident with Turner Class 7 (Fig. 8). The reasonable pattern of ∆T across the mapped areas is one check on the validity of the regression equations. Future checks will use measured temperatures at weather stations other than those used in the regressions.
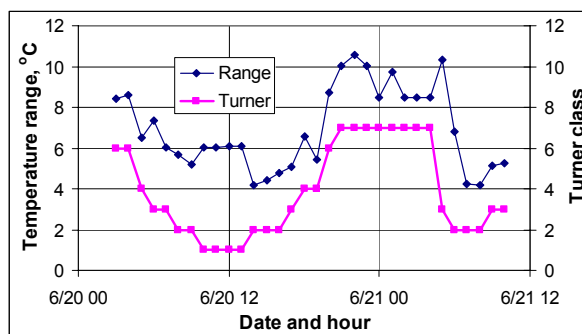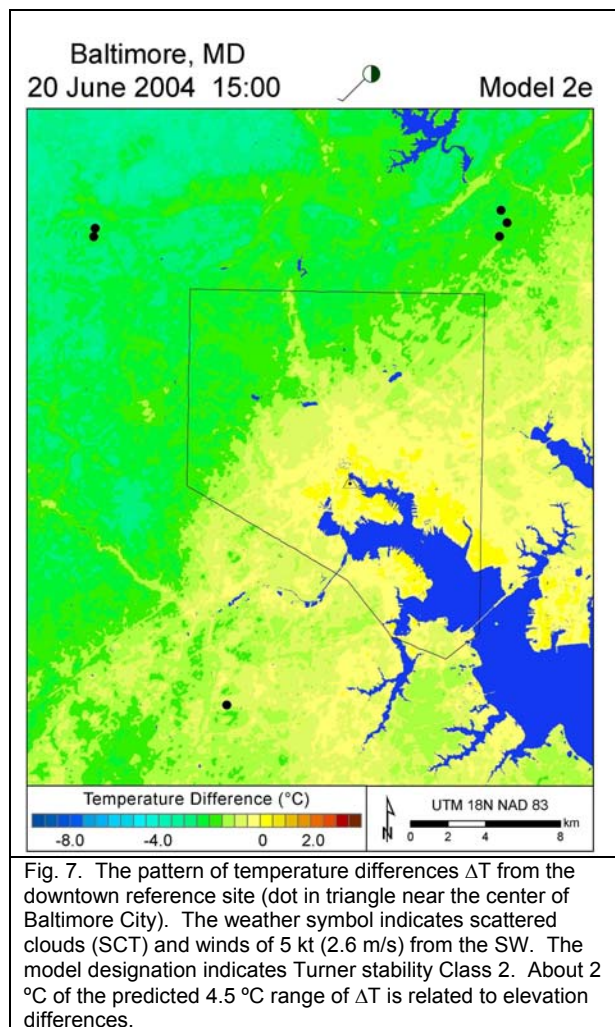

Fig. 6. The range of predicted temperature differences, ∆T, and Turner Class across the map domain during a 32-h period on June 20 and 21, 2004 that were selected as representative of generally clear conditions near the solstice.

Maps of ∆T for a 30-h sequence with relatively clear sky conditions in mid June are available at http://www.fs.fed.us/ne/syracuse/Pubs/pubs_prod.htm#powerpoint. After three introductory slides in the PowerPoint presentation, the slide show continues as an animation with each map indicating wind speed and direction, cloud cover, day or night, and Turner class. In Figs. 6 and 7, the temperature differences are relative to the Downtown reference site. In the on-line animation, the differences are relative to the warmest pixel in the mapped area.

4.0 CONCLUSION

Differences in summer temperatures between inner city Baltimore and a rural wooded area, which represent the intensity of the urban heat island, were commonly 7 ºC or more under stable atmospheric conditions at night. Land cover in urban areas has a decided influence on
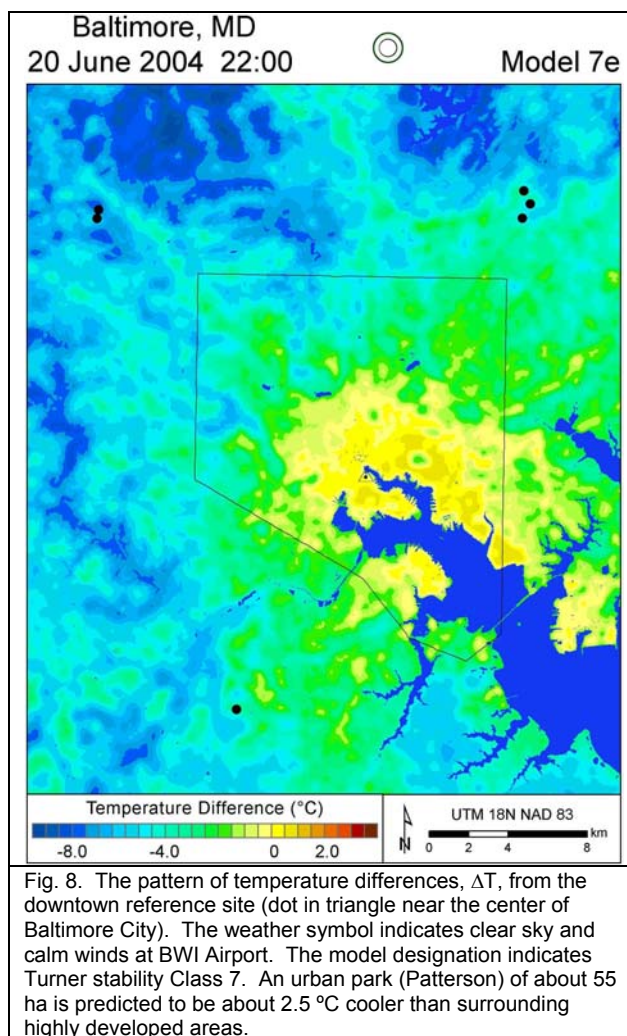
Fig. 7. The pattern of temperature differences ΔT from the downtown reference site (dot in triangle near the center of Baltimore City). The weather symbol indicates scattered clouds (SCT) and winds of 5 kt (2.6 m/s) from the SW. The model designation indicates Turner stability Class 2. About 2 ºC of the predicted 4.5 ºC range of ΔT is related to elevation differences.

influences on temperature. It might be used to model the influence of added tree cover where information is available by land use on the potential space for planting trees. A source of information on planting space includes field tree surveys, such as by the UFORE method (Nowak et al. 2004). The empirical models could be improved with data from a greater number of weather stations, higher resolution land cover data, and incorporation of vertical-dimension analysis.

Fig. 8. The pattern of temperature differences, ΔT, from the downtown reference site (dot in triangle near the center of Baltimore City). The weather symbol indicates clear sky and calm winds at BWI Airport. The model designation indicates Turner stability Class 7. An urban park (Patterson) of about 55 ha is predicted to be about 2.5 ºC cooler than surrounding highly developed areas.

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 5 km in the upwind direction were significantly related to temperature differences under stable atmospheric conditions.

Antecedent precipitation reduced temperature difference. This is contrary to the expectation that promotion of evapotranspiration by adequate moisture availability should result in increased cooling for more vegetated areas, and a larger differential in temperature between areas with greater impervious cover and those with greater vegetation.

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. 5). Although there are buildings near Site 2, the different pattern there probably is due to topography which causes cold air drainage.

There is much potential for increasing the application of this approach to modeling urban

5. ACKNOWLEDGMENT

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