In this final year of the project we have partially funded two PIs, one undergraduate student employee, and one research scientist. Most of the effort in the last two years of the project has focused on reporting of research (writing manuscripts), maintaining the Twin Cities dense urban monitoring network, and conducting additional research on the contribution of grey and green infrastructure features of the Twin Cities to the observed urban warming. Here we focus on two aspects of the project that have led to substantial research contributions.

**Objective #1 – Evaluation of the Heat Island Behavior of the Planet’s Largest Cities**

Through the work of our former graduate student (Will Hertel; M.S. 2014), we have documented the environmental and human factors contributing to urban warming in 77 cities around the planet. This includes cities in a variety of climate zones, biomes, elevation, and proximity to water. We have written this up in a Journal of Applied Meteorology and Climatology paper that we expect will be accepted soon.

**Overall**

The annual average UHI magnitude for all cities analyzed ranges from 2.14 °C for Phoenix, AZ, USA to -0.39 °C for Sao Paulo, Brazil, with an average of 1.00 °C (1.23 °C for medium and high quality cities only). On average, the nighttime UHI is 1.62 °C while the daytime is only 0.23 °C (1.89 °C and 0.40 °C for medium and high quality nighttime and daytime, respectively). All of the medium to high quality cities have a greater UHI during night. Seasonally, there is little difference between summer and winter when all cities are averaged, with a UHI of 1.04 °C in winter and 0.97 °C in summer (1.20 °C in winter and 1.22 °C in summer for medium and high quality only), but this average masks strong variability between summer and winter on an individual basis. Just over half of the cities (35) show a stronger summer UHI while 28 show a stronger winter UHI; the average difference between the seasons is 0.51 °C. Nighttime UHI has a strong seasonal variability. For example, the nighttime UHI of Mexico City varies from 1.98 °C in summer (JJA) to 4.89 °C in winter (DJF).

**Latitude**

When one considers environmental factors, temperate cities have a stronger correlation between nighttime UHI magnitude and total summertime daily insolation ($R^2 = 0.66$) than all extratropical cities together ($R^2 = 0.44$; $p < 0.001$), but there is no significant correlation at the monthly scale. Only temperate cities alone showed a significant correlation between UHI and latitude ($R = 0.23$) and insolation ($R = -0.23$) in winter. All medium and high quality cities located at latitudes greater than 38 degrees show a stronger UHI in summer, while cities at lower latitudes display no consistent seasonal pattern (Figure 1).
Temperature
There is a significant correlation between air temperature and UHI indicating that high heat events lead to stronger UHIs. Four times as many cities show stronger UHI on summer nights when the overnight temperature is high (> 1 SD above normal) than when the temperature is low (< 1 SD below normal); however, the relationship between air temperature and UHI is stronger during daytime than nighttime—a feature unique to other variables analyzed here. Of the cities that show a significant response (n = 34), nine times as many cities show stronger UHI during warm events than during cool periods. For example, UHI magnitude increases as afternoon temperature increases in New York City, NY (Figure 2). The New York UHI is nearly 1.5 °C. Greater during high heat events than during cool periods. During summer heat waves, the UHI increases by over 1.0 °C in 13 cities during the day and 21 at night, with 8 cities having an increase in the nighttime UHI of over 2.0 °C. In winter the influence of temperature on the UHI is less clear as the cities are split between showing increased UHIs with high temperatures or low temperatures. The high quality cities alone show a nighttime UHI that is stronger during cold periods, particularly as the winter average temperature decreases; however, each of the seven Chinese cities with a significant relationship show an increased UHI during warmer periods.

Figure 1. Difference between each city’s winter nighttime UHI and summer nighttime UHIs plotted by latitude.
Figure 2. New York City, NY summer daytime UHI and temperature scatterplot of all summer afternoon (1400-1600 local time) UHI and temperature measurements for New York City.

Humidity
In most of the cities analyzed, stronger UHI is correlated with lower dew point temperature (i.e., lower humidity) in both summer and winter. This relationship is strongest in summer at night with 37 cities having a 1.0 °C increase in UHI during humid conditions compared with dry conditions, and 10 cities showing an increase of 2.0 °C. Figure 3 shows this inverse relationship between summer nighttime UHI magnitude and dew point temperature for Atlanta, GA, although there is substantial variability around the regression. The correlation between UHI magnitude and dew point depression is positive (R = 0.63) and shows less noise than dew point temperature (Figure 3b).
Figure 3. Atlanta, GA UHI and dewpoint temperature scatterplot of a) summer nighttime UHI and dewpoint temperature measurements and b) summer nighttime dewpoint depression and UHI for Atlanta under clear or scattered conditions with the linear regression line plotted.

Objective #3 – Twin Cities Dense Urban Meteorological Network

Our dense monitoring network has been in place since 2011 and we are now entering our fifth year of data collection. We have made many scientific and methodological advances to implementation of a dense network and we have begun making recommendations to other researchers considering implementing their own networks.

As of August 2015 we have 180 sensors deployed in the field (Figure 4). We collect data every three months, quality control/assurance it, and co-kreig the data to a gridded format. Data is then analyzed and made available to those interested in working with it. We are continuing to evaluate the causes of urban warming throughout the Twin Cities with the goal of determining how best mitigation practices can be adopted. This is especially relevant in areas of the Twin Cities where low income and at-risk communities reside. As a separate thread of research, we are analyzing patterns of urban warming along with census data, air conditioner and some power consumption data, and other environmental factors. We hope to document this in a new manuscript early next year.

The following is a selected summary of some findings from the Twin Cities monitoring network.
Figure 4. (a) The seven-county Twin Cities Metropolitan Area (TCMA) in East Central Minnesota; (b) the distribution of temperature sensors that comprise the urban meteorological network (UMN) described in this study, rural airport observations used to define the rural background reference temperature, and urban airport observations used to validate the spatial interpolation schemes. Major interstate highways are indicated with dark grey lines. Major lakes and rivers are indicated with light blue shading. The largest lake in the TCMA, Lake Minnetonka, is located west of the urban area, and highlighted with dark blue outline. Percent impervious surface area is indicated with grey shading, based on NLCD2011 data (30-m resolution, see text for details). Spatial interpolation is performed over the entire study area, whereas data are analyzed only within the TCMA domain, bounded by a dashed box; (c) the urban, suburban, and rural areas within the TCMA. The locations of the Minneapolis and St. Paul central business districts (CBDs) are indicated with black stars.

Overall
The annual average Twin Cities daily-mean urban heat island (UHI) is shown in Figure 5 and is expressed as anomalies (°C) relative to the background rural reference surface air temperature. The annual average UHI exceeds 1 °C over most all the metro area and nears 2 °C in the core downtown regions as well as the 35W corridor south of downtown Minneapolis down to Bloomington.
Diurnal Variability

The TCMA UHI has a strong diurnal signal with warming dominating during the nighttime hours (Figure 6). This result is consistent with other observational studies of UHIs. This signal also extends to the suburban areas, which are traditionally considered immune to warming. The suburban warming is especially apparent in the suburbs of Woodbury, Bloomington, and Eden Prairie. This signal is consistent both in the summer and winter months.

Figure 6. Diurnal variations in the TCMA UHI (°C) averaged across the three-year study period, August 2011 to August 2014, over (a,c,d) urban and (b,d,f) suburban areas, indicated in Fig. 1c, for all calendar months (a,b), summertime, (c,d; June through September), and wintertime (e,f; December through March). The area-average is indicated with a solid line, and the spatial 5th to 95th percentile range (nearest-rank method) is indicated with shading. Times correspond to Central Standard Time (CST).
Spatially, the diurnal variability is consistent with where the built environment is most extensive (i.e., the downtowns of Minneapolis and Saint Paul). Again, on an annual average, the nighttime-mean UHI dominates the daytime signal, as the warmth absorbed by the built environment during the daytime is re-reradiated to the atmosphere after sunset (Figure 7).

Figure 7. The spatial distribution of the TCMA UHI (°C) averaged over two seasonally varying diurnal periods: (a) nighttime, defined as sunset to sunrise; and (b) daytime, defined as sunrise to sunset.

Seasonality of the TCMA UHI
The seasonality of the TCMA UHI is consistent with that of the pattern displayed on an annual average, however, a different pattern emerges in terms of the seasonality between the daytime and nighttime (Figure 8). In particular, our findings suggest that the nighttime-mean in the summer (June-July-August-September) dominates the Twin Cities UHI, but the wintertime (December-January-February-March) UHI is in fact stronger during the daytime. We have found that presence or absence of snow cover is the controlling factor in producing these two seemingly inconsistent patterns. With snow present during the daytime in winter, the brightness of the rural areas relative to the snow free (or cleared of snow) areas in the urban regions produces a large gradient in temperature (because of a reduced or enhanced reflectivity of solar radiation). At night the presence or absence of snow affects the temperature little because the reflectivity is not a factor (only the snow’s insulating effect). In summertime, when snow is not present, the traditional UHI signal of nighttime warming dominates because during the daytime the reflectivity of the rural and urban areas are not markedly different.
Figure 8. The spatial distribution of the TCMA UHI (°C) averaged over nighttime and daytime, disaggregated by season: (a,b) summertime (June through September); and (d,e) wintertime (December through March).

Urban Warming and the Heat Index
The deleterious effect of urban warming during heat wave events is illustrated in Figure 9. During heat wave events the addition of several degrees of warming to already high temperatures can put a certain population of at risk individuals over the threshold to the point that their human wellbeing is jeopardized. Given that heat wave events in this climate zone typically occur in conjunction with high humidity, heat index values in urban areas can exceed values in the rural areas by as much as 15-20 °F.
Figure 9. The spatial distribution of the TCMA heat index anomaly (°C) resulting from a strong UHI during a heat wave event (high of 39°C) in July 2012. Heat index anomalies based on average July daytime heat index values from 2011-2014. The UHI exceeded 5°C during the daytime and occurred in conjunction with high relative humidity (52%). Excess anthropogenic waste heat contributed to the strong daytime UHI signal and the high heat and relative humidity conditions resulted in numerous health-related emergencies.

Outreach

Results from the TCMA urban monitoring network and the Islands project are featured in an upcoming documentary produced by TPT. Minnesota Stories in a Changing Climate is funded by the Will Steger Foundation (now Climate Generation) and will be premiered on Oct. 6, 2015 at the St. Anthony Main theater in Minneapolis.

Results from these findings were presented at the 2014 Fall Meeting of the American Geophysical Union in a poster and two other oral presentations over the year.