The Urban Heat Island in the St. Louis Region - Preliminary Analysis

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by:

East-West Gateway Council of Governments

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Preface

East-West Gateway Council of Governments (EWG) research staff were approached by transportation staff regarding measuring urban heat in the region and did some preliminary research on data sources and developed a workflow to derive land surface temperature from satellite imagery in 2019. In addition to the impact of urban heat island (UHI) on infrastructure, EWG staff is also concerned with the transportation network's contribution to the UHI, the connections between UHI and air quality, and the relationship between transportation planning and land use planning in alleviating the UHI. In the spring of 2022, EWG Community Planning staff was approached by the Missouri Public Service Commission regarding measuring urban heat in the region. Around the same time, Ameren engaged EWG staff along with members of the OneSTL Energy and Emissions Working Group to discuss tracking urban heat in the Ameren service area. In the summer of 2022, EWG staff refined the land surface temperature workflow and conducted an urban heat island preliminary analysis.

I. Introduction

The *Urban Heat Island Effect* is the condition in which human activities cause differences in outdoor surface and air temperatures within a city or metropolitan area. An *Urban Heat Island* is the identified physical location of higher temperatures caused by the urban heat island effect.

It is important to study the St. Louis region's urban heat island because high temperatures have adverse impacts on people, the environment, and the economy. Various studies have found that excessive exposure to high temperatures can:

- Cause heat stroke, heat exhaustion, heat cramps
- Trigger health issues such as asthma and depression
- Limit time spent safely recreating and working outdoors
- Increase crime
- Cause rail buckling, increasing frequency of pavement maintenance, and stress on bridge expansion joints
- Increase energy costs
- Increase energy use and associated pollution levels
- Decrease water quality from algae blooms, fish die-offs
- Raise hazards of using alternative transportation modes including bicycle, pedestrian, and transit
- Exacerbate the impact of air pollution, such ground level ozone and PM2.5, on air quality conformity determinations.

Identifying the location and extremity of the urban heat island (UHI) in St. Louis can help local governments and other parties take steps to adapt to and mitigate the impacts of the heat. For this preliminary analysis, we will explore sources of data that can be used to map the UHI and analyze energy use data for a select number of census tracts to determine if there is a correlation between the UHI and energy demand.

II. Analysis

A. Mapping the Urban Heat Island

Three sources of data for analyzing the UHI were considered for use in for this analysis. Those include ground-level surveying, local weather stations, and satellite imagery.

Ground-level surveying involves taking atmospheric readings from mobile instruments several times during a single day in a small area, usually the size of a city or sub-county. There are no existing data from this source in the region and it was not feasible to initiate a data-gathering event for use in this analysis.

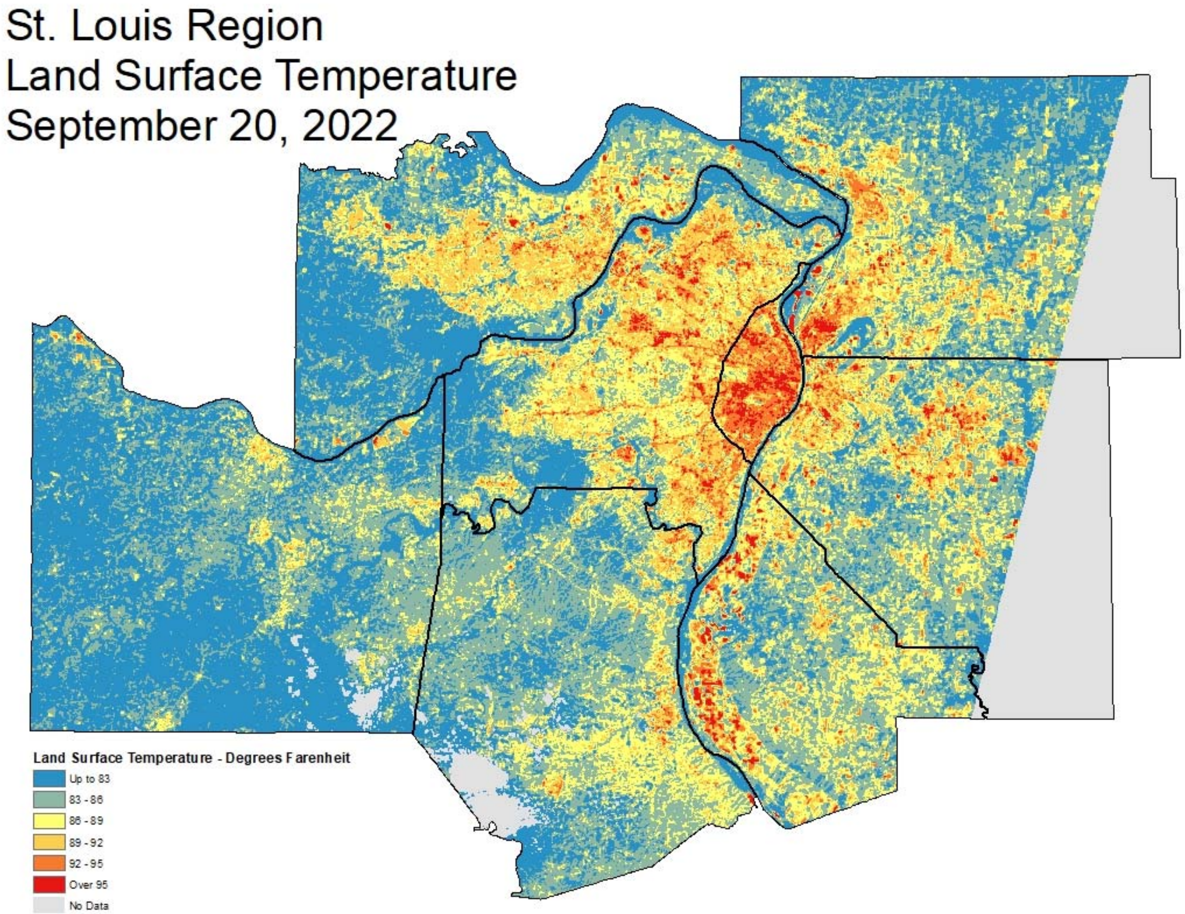
However, Landsat satellite imagery from U.S Geological Survey (USGS) and local weather readings from National Oceanic and Atmospheric Administration (NOAA) are readily available. Satellite imagery is a common source of data used for mapping UHIs because the data is accessible, covers large areas and is standardized across the United States. Satellite data from the red and infrared bands are used to determine emissivity from which the temperature is derived. However, satellite data is used to calculate land surface temperatures (LST) as opposed to air temperature. LST can be used as a proxy for air temperature when looking at large (multi-county) geographies. NOAA collects data from a nation-wide network of weather stations. This data includes actual air temperatures and is collected on a continuous basis.

1. Land Surface Temperature Map

LST is derived from Landsat 8 Operational Land Imager and the Thermal Infrared Sensor (see Appendix for process). Landsat 8 passes over the St. Louis region twice every 16 days alternating between daytime and nighttime. The daytime image is captured at approximately 11:50 am. The nighttime images are difficult to use for mapping UHI because the red and near-infrared bands register mostly as noise. There are techniques that pair data from daytime visible light bands with nighttime thermal bands, but they have not been explored in this analysis.

The data for the image below was recorded by Landsat 8 on September 20, 2022. The mean land surface temperature recorded by the satellite at its pass was 83 degrees and ranged from 72 degrees to 98 degrees. Approximately 33% of the land area covered by the satellite data displayed a surface temperature 3 degrees or greater than the mean of 83. That area includes almost the entire City of St. Louis, large areas of suburban development and areas of cropland adjacent to the Mississippi River.

The map below illustrates the surface temperature for the St. Louis region. The grey areas to the east are outside of the satellite image. The grey areas to the south are cloud cover and obscure the surface temperature. The darker red areas correspond primarily with commercial and industrial areas. Another trend to note are dark red areas in rural locations. The rural “hot” areas correspond with cropland and we suspect that those fields have been harvested and the heat is the result of bare soil exposed to direct sunlight.



2. Air Temperature

NOAA collects atmospheric information from 93 weather station locations positioned across the region. Locations of the stations are displayed on the map below.

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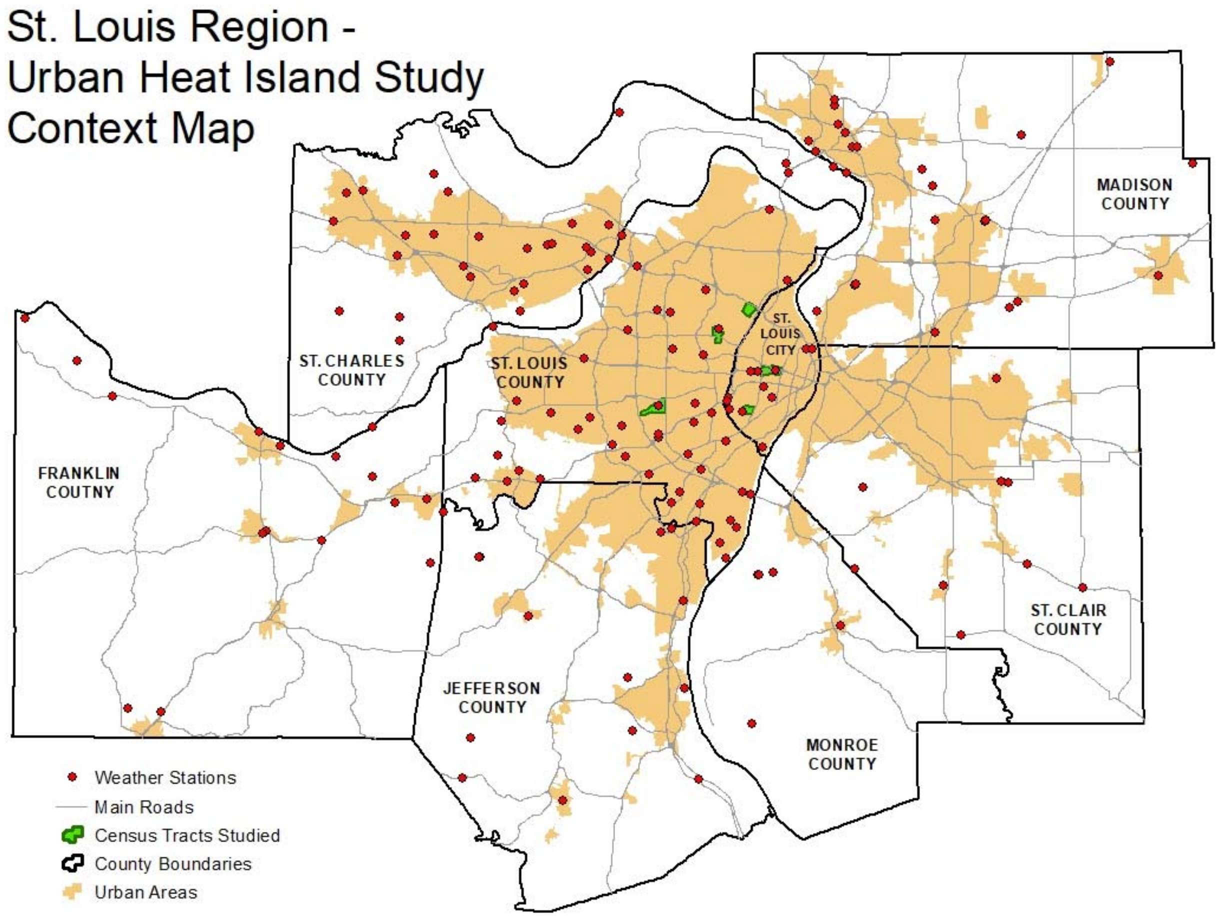
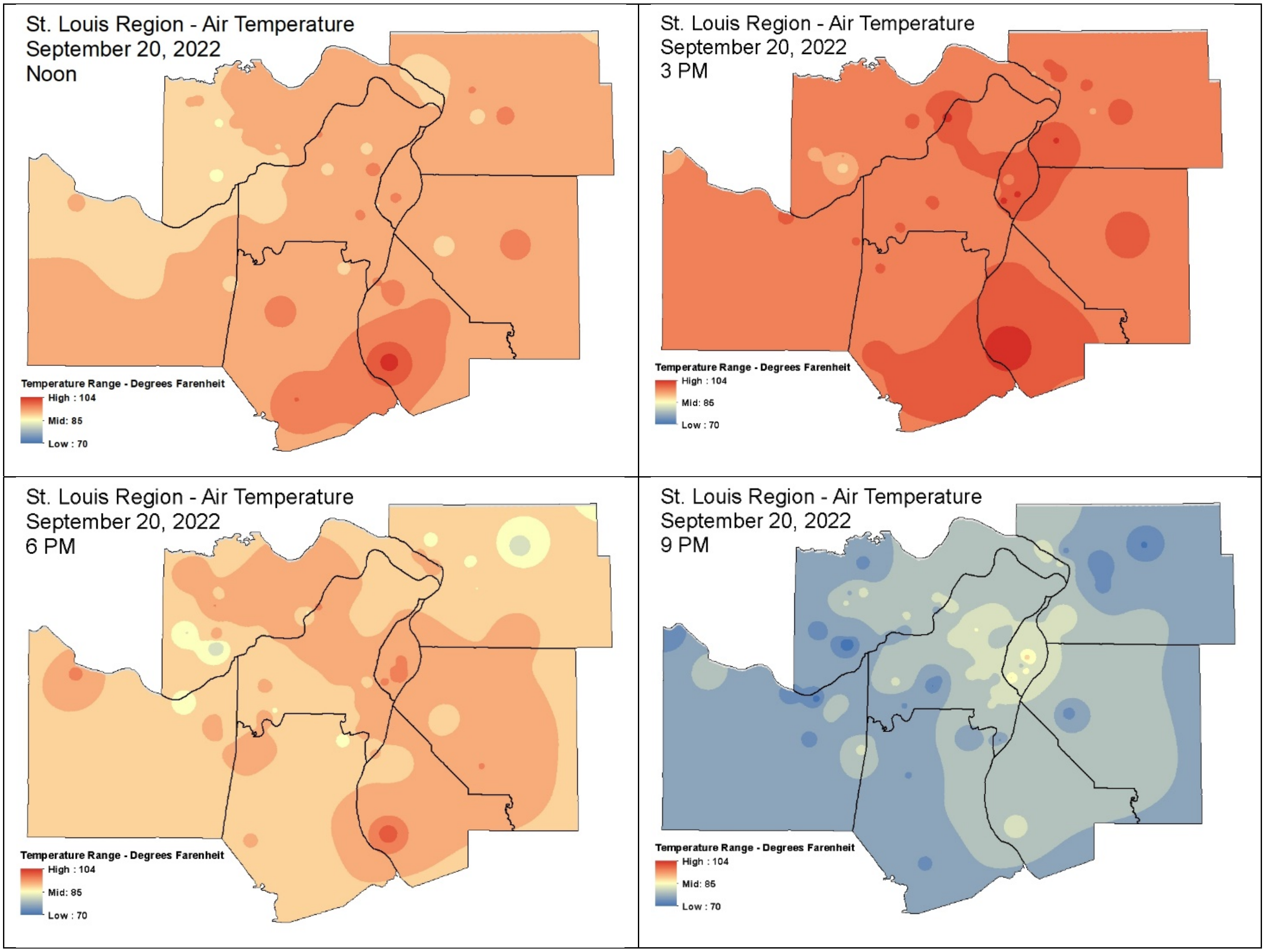


To supplement information from satellites, we downloaded 24 hours of air temperature data from weather stations for September 20, 2022 and averaged temperature readings to the hour. The panel of four images below shows temperatures at noon, 3pm, 6pm, and 9pm. Peak heat of the day occurs around 3pm. A number of hot spots are visible that show locations where temperatures rise earlier, get hotter, and stay hotter longer. The color gradients on the map are an interpolation function of PostGIS. Actual temperatures are only known at the weather stations. The software estimates the temperature between the points. In cases where weather stations are far apart, the confidence level of temperature decreases the farther the distance from the station. One example of this is the station in southern Monroe County, IL. That one station shows a relatively large hot spot based on the radius calculation used by the software. We believe actual temperatures in that area would more likely follow the contours of land use, topography, and crop cover as opposed to simple proximity to the station.

A few other hot spots identifiable on the panels are commercial and industrial areas in Granite City and Earth City, and South St. Louis City. Section B.1. of this report outlines a more detailed description of the temperatures at the weather stations categorized by their surrounding land use.

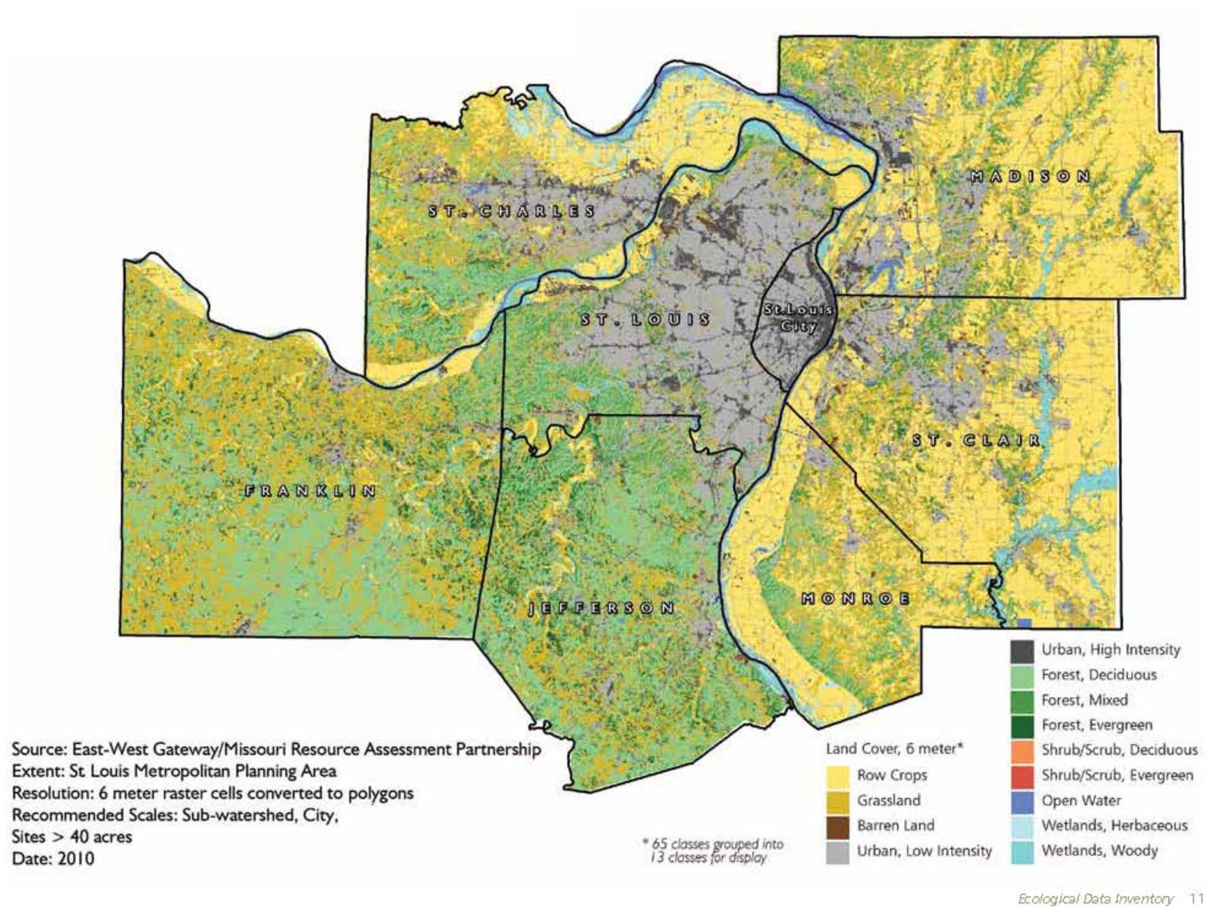


B. Impacts

1. Air Temperature and Land Cover

Urban heat researchers often combine several types of data to study the characteristics and impacts of UHI on a city. Those types of data include urban form, vegetation, land cover, and water. For this preliminary analysis, we compared temperature readings taken at the NOAA weather stations to land cover. The source of land cover is a dataset developed by Missouri Resource Assessment Partnership for East-West Gateway Council of Governments' regional environmental framework. Development of the dataset involved use of remote sensing, aerial photography and digital soil maps. The result is a regional land cover dataset with 25 times the resolution of the standard National Land Cover Database provided by the Multi-Resolution Land Characteristics consortium of Federal Agencies.

LAND COVER & NATURAL COMMUNITIES



NOAA air temperature readings from September 20, 2022 were compared to the land cover data. The land cover was selected to a radius of 50 meters from the location of the weather stations and an average temperature was calculated by hour for each land use based on the temperature readings. See the table below. Urban areas experienced less than 2 degrees higher of a temperature, but warmed up 2 hours earlier and cooled down 4 hours later than forested areas. The Woody-dominated wetland areas recorded the highest temperatures. It will require further study of land cover and aerial photography to determine potential conditions that lead to the higher temperatures.

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	Average Temperature by Land Cover - September 20, 2022								
Hour	Barren / Sparsely Vegetated	Cold Deciduous Forest and Woodland	Grassland	High Intensity Urban	Low Intensity Urban	Mixed Cold Deciduous / Evergreen Forest and Woodland	Open Water	Row Crops	Woody-dominated Wetland
0	78.06008	75.09408	75.2356	79.18781	76.76605	73.37686	77.93626	75.02535	82.23484
1	76.68466	74.66401	74.16266	77.6334	75.50488	72.4391	77.50386	73.93266	82.32994
2	75.92814	73.64187	73.00378	76.60701	74.21997	71.54249	76.57616	73.27928	80.79665
3	74.63108	72.78401	72.27732	75.61667	73.33935	70.76788	75.82937	72.24558	79.50137
4	74.41972	71.8882	71.31615	74.56615	72.51986	70.396	75.44031	71.55273	78.53055
5	73.45437	71.03842	70.43425	73.48384	71.8179	69.96364	74.84874	70.98722	77.45806
6	72.28401	70.28177	69.79063	73.3835	71.18902	69.03961	74.74203	70.48518	76.62742
7	73.26999	70.57669	70.25184	74.08899	71.64425	69.80989	74.28406	70.62508	77.58092
8	76.62044	74.13766	74.81082	77.41117	75.84587	73.1401	76.73952	76.39	80.62451
9	81.55343	80.25927	80.08908	82.09763	81.65637	80.0817	80.631	82.52407	84.58231
10	85.80531	85.18981	85.12368	87.00244	86.38207	85.60404	85.2922	87.34568	88.69118
11	88.27	88.53167	88.93178	90.1282	89.7859	89.07958	87.44282	91.10251	91.97384
12	90.65883	91.29818	91.96367	93.21694	92.60914	91.97479	89.51438	93.87308	95.02289
13	92.76999	93.80524	94.14586	95.23245	94.60424	94.35585	91.13731	96.06984	97.51776
14	95.32093	95.46642	95.70283	96.63179	96.06417	96.12751	94.38572	96.8512	98.90748
15	96.12031	96.18182	96.51141	97.37049	96.74358	96.80727	96.08819	97.62686	99.42392
16	96.68559	95.95381	96.53198	97.35286	96.41123	96.01869	95.11545	97.22861	99.27466
17	96.43377	94.01013	95.10548	96.42669	95.12569	93.31123	94.39892	95.89117	98.30404
18	94.30532	89.34972	90.55575	93.31316	91.33791	87.80697	92.25678	91.58432	95.60477
19	87.2708	83.227	83.26033	89.35719	85.87768	81.62074	86.85007	83.96795	90.96353
20	85.16502	79.62829	79.55801	86.96307	82.67836	78.27465	83.48073	80.67718	87.181
21	82.9866	77.66361	77.52013	84.43884	80.70487	76.7498	81.72851	78.53057	85.40417
22	81.62047	76.3455	75.91851	82.42499	79.22826	76.08572	80.56466	77.7052	81.78766
23	79.68471	75.43215	75.14051	80.95276	78.2222	75.5998	80.22876	76.19955	81.52993

2. Energy Use

We compared hourly energy usage of 5 census tracts on September 20, 2022. The census tracts represent a variety of urban and suburban locations and show results that contradict expectations. We predicted that energy use in the denser urban areas of the City of St. Louis would have higher average energy use than suburban areas that are less dense and have more vegetation. However the chart shows that the highest per customer energy use occurred in Kirkwood, which is the least dense of the locations, and energy use was the lowest in Midtown St. Louis which is the most dense and has the least vegetation. The other three locations show relatively consistent use of energy between them at different times of the day.

	Energy Usage By Tract					
	Hour	29189212201 - Northwoods	29189215901 - U City	29189218402 - Kirkwood	29510114300 - St. Louis Hills	29510118600 - Midtown
(Electricity kWh/Household)	0	1.70073043	1.62500936	2.31180000	1.82676919	1.19542708
	1	1.56441471	1.50611901	1.75672500	1.67765931	1.07987433
	2	1.44923571	1.36476033	1.50832500	1.56063460	0.96955922
	3	1.35367114	1.25882260	1.57365000	1.45210478	0.92272507
	4	1.26464571	1.17907298	1.41112500	1.38036993	0.87389340
	5	1.22016900	1.10733039	1.48230000	1.31042372	0.86373657
	6	1.18432886	1.08338091	1.45522500	1.30117389	0.88242103
	7	1.21840286	1.14649109	1.25025000	1.27895239	0.97276799
	8	1.28873143	1.17374004	1.04025000	1.26901532	1.04271554
	9	1.42766229	1.32418540	0.98550000	1.41367216	1.10089068
	10	1.61889129	1.56583630	0.84442500	1.65042010	1.20078101
	11	1.85371971	1.78173413	1.16917500	1.87108048	1.30234457
	12	2.08172829	2.01424820	1.35885000	2.09194063	1.40768293
	13	2.25512271	2.24283877	2.71402500	2.30182034	1.48865875
	14	2.40798771	2.45075711	3.55267500	2.46200552	1.57528906
	15	2.49844200	2.49773488	3.63345000	2.50169469	1.58151307
	16	2.60882400	2.61538870	4.30612500	2.63430235	1.68174023
	17	2.65824429	2.69011362	3.65482500	2.78128678	1.76950490
	18	2.58962743	2.61299603	3.12600000	2.74611182	1.78251579
	19	2.48727471	2.49074723	3.10815000	2.67437563	1.73850285
	20	2.43065143	2.41569903	3.31365000	2.62485031	1.70823644
	21	2.31001757	2.30820127	3.12855000	2.49568456	1.71023423
	22	2.17230386	2.10280082	3.08002500	2.31496896	1.58535930
	23	2.01487843	1.93176332	2.66520000	2.10217695	1.43482486

III. Conclusions/Recommendations

Both the Land Surface Temperature and air temperature maps show that heat is not distributed evenly across the region. The maps show that generally urban and suburban areas experience the urban heat island effect, but that there are also pockets of higher heat in rural areas. Areas that experience higher temperatures also heat up earlier in the day and stay hotter longer into the evening. When comparing air temperatures to land cover, trends were visible that showed warmer temperatures in urban areas and cooler temperatures in more rural/vegetated areas.

By looking at residential energy usage in various census tracks, we were anticipating that the tracks that are more urban and have less vegetation would show higher energy use. Those expected results did not show true in the examined tracts. However, we only examined a small sample of tracts in the region. We need to examine are larger sample of census tracts to draw a more statistically confident conclusion on whether the UHI effect increases energy use.

As this was a preliminary analysis that only looked at a limited set of data, more data collection and analysis is necessary. The recommendations below outline several focus areas where more research can be conducted. They are grouped into categories of further defining the urban heat island, studying the effects of the urban heat island, and researching practices that alleviate the impacts of the urban heat island. Staff at East-West Gateway will continue to pursue research related to agency projects and programs. Research on other topics related to UHI can be conducted by organizations and collaborations such as the OneSTL Biodiversity Working Group, the Midwest Climate Collaborative, and SIUE GeoMARC.

Proposed further analysis:

1. Through satellite data and weather information we've identified that there is an urban heat island effect in the St. Louis region. However, data from only one date was used. We recommend further analysis to define the spatial and temporal characteristics of urban heat in the St. Louis region.
    a. Apply research conducted in other regions on the correlation between surface temperature and air temperature to St. Louis. Research an algorithm to interpolate the station reading data that accounts for other factors such as land cover and topography.
    b. Compare satellite data from multiple days to reveal temperature variation due to persistent causes such as human activity versus seasonal or localized causes such as plant phenology.
    c. Begin collecting additional data sets that can be used in producing Local Climate Zones such, detailed land cover, LiDAR, and tree canopy.
    d. Engage with researchers collecting site-specific data such as Southern Illinois University in Edwardsville and Metropolitan Congregations United that are collecting data on impacts of greenways on UHI and local air quality monitors respectively.
2. For this report we conducted a small preliminary analysis with energy use data. However energy use is only one aspect of the impacts of UHI on a region. We recommend continuing to explore and define the impacts of UHI on people and infrastructure.
    a. Compile existing studies on the impacts of UHI.
    b. Analyze additional census tracts for energy use using various days and geographies.
    c. Include more variables into energy use analysis such as building square footage and number of units.
    d. Look for data sources that overlap LST with pavement, bridge, and conditions.

3. There are multiple ways to deal with impacts of the UHI. Some practices can help communities adapt to UHI effects while other help mitigate UHI by lowering temperature variations. Practitioners need to be aware of the complex nature of implementing adaptation and mitigation practices since they can have different effects on LST and air temperature.

    a. Compile studies on UHI adaptation and mitigation.
    b. Continue to engage with organizations working on adaptation and mitigation. Share data and research with those organizations.
    c. Determine if there are collaborative targets that can be set.

Appendix – Land Surface Temperature Mapping Workflow

Land Surface Temperature

Notes

Regarding Radiometric and Geometric Calibration, "data from the two sensors, the Operational Land Imager (OLI) and the Thermal Infrared Sensor (TIRS), are calibrated to better than 5 percent uncertainty in terms of Top of Atmosphere (TOA) reflectance or absolute spectral radiance and have an absolute geodetic accuracy better than 65 meters circular error at 90 percent confidence (CE 90)" (Landsat 8 Data Users Handbook https://www.usgs.gov/media/files/landsat-8-data-users-handbook).

Process

Download Bands 4, 5, and 10 from Landsat 8

Included with the download is a text file containing metadata for the scenes downloaded. This metadata includes correction factors and constants used in the subsequent calculations.

Calculations

Top of Atmosphere Spectral Radiance (TOA)

"Conversion to TOA reflectance is a linear transformation that accounts for solar elevation and seasonally variable Earth-Sun distance" (Using the USGS Landsat Level-1 Data Product https://www.usgs.gov/landsat-missions/using-usgs-landsat-level-1-data-product).

The constants used in the formula are from the metadata included with the raster download. The constant RADIANCE_MULT_BAND_10 is the rescaling factor and RADIANCE_ADD_BAND_10 is the correction.

```
toa <- calc(band_10, fun = function(x) { RADIANCE_MULT_BAND_10 * x + RADIANCE_ADD_BAND_10 })
```

At-Sensor Temperature (Brightness Temperature or BT)

Apply the thermal constants (supplied in metadata) to convert radiance to temperature.

```
bt <- calc(toa, fun = function(x) { (K2_CONSTANT_BAND_10 / log((K1_CONSTANT_BAND_10 / x) + 1)) - 273.15 })
```

Emissivity (E)

The land surface emissivity is a function of the land cover and thus will change over the extent of the raster image. The Normalized Difference Vegetation Index and Percent Vegetation derived from the satellite image data will be used to conditionally correct the brightness temperature with an appropriate emissivity factor.

Normalized Difference Vegetation Index (NDVI)

Plants absorb light at specific wavelengths. Thus the red and near-infrared bands can be used to calculate NDVI.

```
ndvi <- overlay(band_04, band_05, fun = function(r, nir) { ((nir - r) / (nir + r)) })
```

Percent Vegetation (Pv)

NDVI less than 0.2 is considered bare soil. NDVI greater than 0.5 is fully vegetated. For values between 0.2 and 0.5, mix of vegetation and soil, we calculate the percent of vegetation to be used in the emissivity correction.

```
pv <- ((ndvi - ndvi@data@min) / (ndvi@data@max - ndvi@data@min)) ^ 2
```

Land Surface Emissivity

For NDVI values less than 0.2, we use 0.97 as the emissivity factor. For NDVI values over 0.5, we use 0.99. For values in the range greater than or equal to 0.2 to less than 0.5 we apply the formula 0.004 * x + 0.986 where x is the percent of vegetation (Sobrina et al). This formula needs further review, see Stathopouloua, Cartalisa, and Petrakis for alternate values in an urban environment.

```
calc_e = function(x) {
  return(
            ifelse(
                      is.na(x[1] || is.na(x[2]),
                      NA,
                      ifelse(
                                x[1] < 0.2,
                                0.97,
                                ifelse(
                                            x[1] <= 0.5,
                                            0.004 * x[2] + 0.986,
                                            0.99
                                )
                      )
            )
  )
}

e <- calc(stack(ndvi, pv), fun = calc_e)
```

Output

Land Surface Temperature (LST)

Apply the emissivity factor to the brightness temperature to get the land surface temperature. This step is also open to review.

```
lst <- overlay(bt, e, fun = function(bt, e) { (bt / (1 + (0.00115 * bt / 1.4388) * log(e))) })
```

Alternate formula:

Rho = Boltzmann Constant * (velocity of light / Planck's Constant). Then convert meters to µm.

The average wavelength of Band 10 = 10.895 = (10.60 + 11.19) / 2.

```
r <- (6.626 * 10 ^ -34) * ((2.998 * 10 ^ 8) / (1.38 * 10 ^ -23)) * 10 ^ -6
r <- r * 10 ^ 6
lst <- overlay(bt, e, fun = function(bt, e) { bt / ( 1 + ((10.895 * bt / r) * log(e))) })
```

References:

"Algorithm for Automated Mapping of Land Surface Temperature Using LANDSAT 8 Satellite Data" Ugur Avdan and Gordana Jovanovska - Journal of Sensors - Volume 2016, Article ID 1480307

"Land Surface Temperature Retrieval from LANDSAT TM 5" by José A. Sobrino, Juan C. Jiménez-Muñoz, and Leonardo Paolini - Remote Sensing of Environment - Volume 90 (2004), pages 434 - 440

"Integrating Corine Land Cover data and Landsat TM for surface emissivity definition: application to the urban area of Athens, Greece" M. Stathopoulou , C. Cartalis and M. Petrakis - International Journal of Remote Sensing - Volume 28 (2007) Issue 15, pages 3291 - 3304.

https://www.usgs.gov/media/files/landsat-8-data-users-handbook

https://www.usgs.gov/landsat-missions/using-usgs-landsat-level-1-data-product

Air Temperature

Notes

The temperature observations are made by a network of entities across the country and are run through a rigid quality control process. The observation data is downloaded in NetCDF files which contain the specific quality control measures taken and the results of the measures. Not all data is submitted to every quality control test, but all observations are flagged with the tests appropriate to that instance. Data for this analysis is filtered to observations passing observations by checking the summary flag for C (level 1), S (levels 1 and 2), or V (levels 1, 2 and 3). Level 1 tests for valid data. Level 2 tests for internally consistent data. Level 3 tests for spatially consistent data. Observations that have been flagged with X or Q, rejected or questioned respectively, are not included.

Process

Download Mesonet Observations from NOAA

Load

The download file is a single NetCDF database file which contains a variety of weather observations beyond temperature including wind speed, precipitation, etc. Only temperature is recorded to conserve storage space. Also part of the database are the locations for each of the observations.

Stations / Providers

The station observations are collectively organized by providers. The stations themselves can submit multiple observations. Subsequent submissions of a chronologically duplicate observation are recorded as a modification.

Locations

The observations are tagged with a longitude, latitude, and elevation. The longitude and latitude are converted to spatial data in a subsequent step to perform spatial analyses on the data.

Chronology

The granularity of the chronology varies by station, but is recorded at the level reported. Analyses generally aggregate to the hour.

Temperature Observations

Both air temperature and soil temperature are recorded.

Analysis

Average Temperature by Land Cover per Hour (September 20th, 2022)

This spreadsheet is a crosstab illustrating the change of air temperature through the course of the day for each land cover type. The temperature is the average for the region. The date matches the flyover of the Landsat scene for comparison with surface temperature.

Electrical Usage

Notes

The electrical usage data is customer level data in 15 minute increments. The customers are anonymous and are not tied to a location other than being identified as residing within a Census tract.

Process

Acquire

All of the electrical usage data is pulled by Ameren personnel and shared as CSV files.

Load

The CSV files are loaded as raw and then linked to their respective tract. The level of temporal granularity is retained.

Analysis

Average Electricity Usage by Tract per Hour

This spreadsheet is a crosstab illustrating the changing electricity consumption throughout the day. There is no aggregation to land cover type since the spatial granularity is too great. However, the ratio of land cover types for the reported tract are included on the spreadsheet.