Eric Anderson
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Pinpointing land and surface air temperature variability across topographically diverse locales in Washington State via spatial joining of spaceborne and terrestrial data

Abstract:

Digital weather applications that provide near-real time surface air temperature data often receive data from scattered weather stations across Washington State. In topographically diverse locales, temperature may vary greatly, rendering these applications inaccurate depending on the geographic coordinates queried. This research project strives to correct this by incorporating four predictor variables of surface air temperature (land surface temperature, land cover type, month, and solar azimuth) into live ground-based weather reports. To determine this correction, this project links terrestrial weather data from 5,323 Weather Underground personal weather stations (PWS) between April 2020 and April 2021 with cloudless remotely sensed land surface temperature data from the ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS) sensor at a 70-meter spatial resolution. Cross-referencing this with Washington land cover GIS data and hillshade models, an algorithm is created to assign temperature “penalties” for each month at each of the fifteen land cover types with or without sunlight (totaling 360 possible penalties). These penalties are affixed to each 70-meter raster grid, assessed for accuracy, and visualized over time using fine-scale isopleth maps. With these corrections integrated into digital weather applications, a mobile user would have more confidence receiving a temperature that matches a co-located thermometer. These corrections will also help scientists identify unusually warm or cold locations that may have been overlooked in broader climate studies. Preliminary results demonstrate that flat industrial surfaces swing hot to cold greater than any other surface in both urban and rural spaces, supporting related research of the urban heat island (UHI) effect. Future research may produce more precise results by accounting for other atmospheric effects such as humidity and wind.

Keywords:

- Land Surface Temperature (LST)
- Surface Air Temperature (SAT)
- Land Use Land Cover (LULC)
- Spatio-temporality
- Remote Sensing
- ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS)

Introduction:

This project falls within the field of remote sensing, or the acquisition of electromagnetic radiation from distant sensors such as those mounted on Earth observing satellites. A commonly observed band of the electromagnetic spectrum is the thermal infrared (TIR) band. This band is useful for its ability to measure an object's reflected and/or emitted energy on the Earth's surface that is otherwise undetectable by visual light optics like the human retina. Deriving atmospherically corrected land surface temperature (LST) from solar radiant emittance is one application of TIR-band data acquisition, and is necessary for this project.

Some remote sensing endeavors require simultaneous collection of ground-truth data, or "on-the-ground" measurements, to ensure proper instrument calibration and robustness of data analysis for policymaking (Eliezer et al., 2019). For this project, the inclusion of terrestrial weather station data at 5-minute intervals from Weather Underground is essential for modeling surface air temperature from the ECOSTRESS land surface temperature. Since ground-truth data is only collected at discrete coordinate points, unlike continuous remotely sensed data, ground data points are distributed as evenly as possible across diverse land cover types, to capture maximum variation in the data. Crowdsourced data not only accomplishes this the best by accounting for human activity across all terrains, but also by confirming the legitimacy of official meteorological reporting stations, such as those at airports (Vetner et al., 2020).

Weather satellites equipped with microwave spectrometers have consistently measured and calculated Earth sea surface temperatures since 1969. Within a decade, land surface measurement also became routine, though more difficult because land emits noisier radiation than water (Yates, 1970). Within another decade, atmospheric temperature measurement became commonplace. Today, a great deal of Earth surface temperature measurements are global in scale, contrasting this project's use of high spatial resolution data. Even the finer temperature sensors, such as the Visible Infrared Imaging Radiometer Suite (VIIRS) and the Moderate Resolution Imaging Spectroradiometer (MODIS), scarcely produce data as sharp as 250 x 250 meters. Micro-scale surface temperature research primarily concentrates on annual heat patterns in well-populated industrialized areas and seasonal heat patterns across disturbed and undisturbed ecosystems.

The chosen predictor variables for surface air temperature were inspired by a 2008 study that gave geographical variables (altitude, continentality, etc.) and remote sensing variables (albedo, LST, etc.) to ground-based meteorological stations. The study concluded that both in tandem could significantly predict air temperature 87% of the time, with LST being the most important variable (Cristóbal, Ninyerola, & Pons, 2008). More advanced spatial data has become available since this study was published, which is why this project adds land cover and hillshade as geographic variables, retains LST as the remote sensing variable, and summarizes by month. Nonetheless, the methods of interpolating temperature in the 2008 study will be followed closely to account for the 36-hour gap between ECOSTRESS flyovers, when remotely sensed data is inaccessible.

Where this project deviates from more conventional surface temperature research is that it will analyze unusually high spatial resolution data across all known temperature zones in Washington, instead of restricting itself to one zone such as an urban center. The idea is to compare these known temperature zones with the variations between the zones, in pursuit of unearthing tiny, yet ubiquitous regions that exhibit surprising thermal characteristics. This project aims to find the most skewed surface air temperatures from those reported by nearby weather stations; when they are most skewed; and, synthesize the two to assess their impacts on regional climate change and public well-being. Recognizing such spatio-temporalities will provide climate change researchers another lens to look through.

Methods:

In order to accomplish these goals, careful consideration of spaceborne and terrestrial data was made. A balance of strong spatial resolution, temporal resolution, and programmatic runtime must be established before beginning. What follows are the three main phases for this project. A timeline is also presented at the conclusion of this section.

Phase 1: Data Gathering in *R* and Preliminary Processing

To identify topographically diverse regions on the finest scale, the remotely sensed land surface temperatures will be obtained from the ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS) sensor, which provides 70-meter spatial resolution over Washington roughly every 36 hours (derived from Cawse-Nicholson & Anderson, 2018). The ECOSTRESS mission began in 2018 and will continue through 2021, covering this project's one-year study period from April 2020 to April 2021. The data will be batch downloaded from the NASA Earthdata LPDAAC website under the product designations ECO2LSTE, ECO2CLD, and ECO1BGEO. Each are packaged as Hierarchical Data Format (HDF5) files, with the first containing land surface temperature fields (in Kelvin), the second containing probable cloud mask, and the latter containing solar azimuth, zenith, latitude, and longitude fields. A publicly available[1] Python script will be run to georeference ECO2LSTE and ECO2CLD using ECO1BGEO. This converts them into Tagged Image File Format (.tiff) files, with pixels denoting land surface temperature and cloud mask, respectively.

Before geoprocessing the .tiff files, the Weather Underground (WU) personal weather stations in Washington will be collected from the WU website[2]. This task will be automated using a custom web harvesting script in *R*, utilizing the *RSelenium* utility package. Latitude and longitude (to the thousands place) and station ID for all online stations during the time period will be converted into a comma-separated values (.csv) file. Stations deemed offline at the beginning, middle, and end of the study period will be discarded. Stations deemed online will be spatially joined with each .tiff file; those within the extent of a .tiff file will have their historical surface air temperature data at the time of ECOSTRESS flyover harvested via *R*.

Additional data for this project include: a 2016 Washington State land cover raster from the National Land Cover Database; a 2013 one arc-second digital elevation model (DEM) from the Terra ASTER satellite; and Washington municipal and state boundary shapefiles from the WA Department of Transportation website.

Phase 2: Automated Geospatial Analysis in Python

As with the georeferencing and web harvesting processes, it will be crucial to automate the geospatial and statistical analyses to ensure the success of this project, as copious data will be managed. Python scripts utilizing the *arcpy* library and its dependencies will be used to accomplish this for their versatility in geospatial analysis. To begin, the ECO2CLD .tiff probable

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[1] https://git.earthdata.nasa.gov/projects/LPDUR/repos/ecostress_swath2grid/browse

[2] https://www.wunderground.com/pws/overview

cloud mask will remove cloudy pixels from the ECO2LSTE .tiff file via pixel reclassification. This reformatted file will have its units converted from Kelvin to Fahrenheit, its null values omitted, and its boundary clipped to Washington state to create a compact feature layer. The next step will be to spatially join this feature layer with the online terrestrial weather stations, to populate the *R* harvesting script with station IDs (however many are joined with the feature layer; 5,323 maximum). Subsequently, raster calculation will need to be performed to get the temperature differences between ECO2LSTE land surface temperature and WU surface air temperature (henceforth called 'temperature penalties'). The month, land cover type, and shade status will be aggregated in a "master" .csv file for each temperature penalty during the automation process. The solar azimuth and zenith angles of the centroid of the corresponding ECO1BGEO file will be used to calculate an approximate a hillshade effect at ECOSTRESS flyover time, to establish the shade status of each pixel. The analysis in this paragraph will be repeated for as many valid HDF5 files there are available.

With enough pixel representation from cloudless ECOSTRESS swaths for all land cover types, shade statuses, and months, the next step will be to create a multiple linear regression model to predict ECO2LSTE and WU temperature penalties. The data source of this model will be the aforementioned "master" .csv file containing every temperature penalty recorded, categorized by the three aforementioned predictor variables. In tandem, the predictor variables will create 15 x 2 x 12 = 360 categories from which to predict temperature penalties for any 70 x 70-meter region detected by ECOSTRESS. Equally large training and validation data sets, where an ECOSTRESS flyover is considered an "observation" and placed in either set, will be defined to test and boost the accuracy of the model. Further validation will come from comparing the observed terrestrial station temperatures to the fitted surface air temperatures after applying the penalties. This will be dissected variable by variable to see which pairs produce the highest and lowest correlation coefficients.

Phase 3: Data Visualization for Climate Discussion

Ultimately, by applying the temperature penalties to the remotely sensed land surface temperatures, this project seeks to predict surface air temperature within any pixel, regardless of a weather station existing there or not (e.g., within all CLEARCUT pixels in NO SHADE during APRIL). And, by holding predictor variables constant in this model, it will be possible to identify the land cover type, shade status, and month that most significantly skews the surface air temperature. Upon visualizing these predicted temperatures, one can begin to identify local regions that have consistently hotter or colder air temperatures (not just land surface temperatures) than surrounding regions. Such regions would be better delineated by performing geographic weighted regression (GWR) and spatial autocorrelation (SA) via the *arcpy* library in Python. Raster interpolation techniques, such as kriging and inverse distance weighting, will create isographs symbolized by familiar temperature color palettes that weather maps frequently use. To help draw the climate impact conclusions, these isographs will be lined up in a temporal series to illustrate temperature fluctuation per month.

Two approaches for making use of these analyses will be realized. The first will be creating a rudimentary web tool that estimates near real-time surface air temperature using the results of this project. Or, at the very least, the tool would show where unusually hot or cold air temperature patterns exist based on user input. This can be achieved by simply amalgamating the data from this project and binding it to HTML format using Python. The second approach is how these analyses might contribute to broader climate and public health discussions, and to related research described in this project concerning urban heat islands (UHI) and policymaking surrounding land use land cover (LULC) classification.

Timeline:

Autumn 2020

- Research remote sensing satellites that convert ground radiation to temperature. Settle on ECOSTRESS. Procure data download links.
- Research existing work about urban heat islands, LULC, and temperature phenomena.
- Establish workflow for georeferencing .h5 ECOSTRESS files by modifying pre-existing public Python files.

Jan 2021

- Procure WA state shapefiles, Land Cover raster data, and 30-meter DEM from public sources.
- Develop web harvesting scripts in *R* to obtain WA state online weather stations and their temperature data from Weather Underground.

Feb-Apr 2021

- Obtain and filter coordinates of weather stations via web harvester. Begin batch download of .h5 files from April 2020 to April 2021. Harvest historical temperature data at appropriate ECOSTRESS flyover times; save as .csv file.
- Build models using the *arcpy* Python library to calculate time-appropriate hillshade and cloudless regions using azimuths, zeniths, and cloud flags from ECOSTRESS.

May-Jun 2021

- Via Python scripts, for each ECOSTRESS file, calculate temperature difference between each in-situ weather station and remotely sensed ground temperature, and save as feature class. Categorize by land cover type, shade status, hour of day, and season.
- Employ spatial autocorrelation, GWR, and other statistical techniques to predict magnitude of temperature variation by category.

July 2021

- Creating training and validation data sets to test model accuracy. Establish temperature 'penalties' for each category to predict actual surface air temperature across all space via multiple linear regression.
- Use raster interpolation such as kriging to visualize these temperatures on isographs over hour of day and/or season.

Aug 2021

- Analyze results and identify areas that are consistently hotter or colder for climate discussion. Gather feedback before finalizing write-up and exporting model.
- Time-permitting and if relevant, develop a tool that calculates estimated real-time temperature based on my work and assess potential public impact.

Literature Review:

This project expands upon two well-documented remote sensing subjects: the urban heat island (UHI) effect, and land use land cover (LULC) classification. Despite being used often in micro-scale studies (e.g., studying a single city), the marriage of the two with this project contribute greatly to climate change discussions at large.

The Urban Heat Island Effect

An urban heat island is a high concentration of thermal radiation in cities and industrial regions compared to outlying cooler rural regions. A critical component of climate change analysis, the UHI effect is by far the most obvious example of localized temperature variation independent of meteorological patterns. Highly urbanized lands contain dark, artificial, carbon-based materials (such as asphalt and other metals) that absorb an astonishing amount of solar radiation, rather than reflecting it back towards the sky as terrestrial radiation (Elmes et al., 2020). Thus, these surfaces become energized and ultimately emit the absorbed solar radiation back into the air as heat, raising air temperature. This consequence is augmented further by urban air pollution from machine energy consumption, creating a greenhouse effect that traps the already warm air.

Most research about the urban heat island effect is currently aimed at minimizing city absorption of solar radiation by identifying surfaces with low albedo, or low ratio of reflected solar radiation to incoming solar radiation (Aleksandrowicz et al., 2017). Albedo is measured on a scale from zero to one: asphalts and dirt are nearly zero, while forest canopies and snow are near one. Replacing low albedo surfaces with high albedo surfaces is considered a crucial public health measure. Novel solutions are implemented every year, such as: planting gardens of vegetation atop city roofs; planting bushy deciduous trees in dry residential (especially low-income) areas; painting black surfaces white after construction is finished; and strategically unsealing surfaces that generate excess stormwater runoff (Johnson et al., 2020). Other researchers focus on improving air quality by designing “zero-heat” or “microclimate neutral” buildings that cut back electricity use and excessive indoor heat emission (He, 2019).

Conceptually, this project does not seek to differentiate urban heat islands from rural temperature variation; however, the skewed distribution of terrestrial weather stations favors highly populated areas. Therefore, urban regions will have more data samples to draw from and will yield more statistically robust tests, such as spatial autocorrelation of temperature penalties (surface temperature minus air temperature) for pinpointing homogeneous low albedo (hot) surfaces. Ideally, rural heat variation will still be dramatic enough to warrant discussion about warm overlooked surfaces – natural or synthetic. Regardless, the use of temperature (not albedo) data in this project to describe terrestrial environmental conditions is meant to produce more visceral results for the average person, who is more familiar with associating heat with degrees Fahrenheit or Celsius.

Land Use Land Cover Classification

Second, this project incorporates literature about land use and land cover (LULC) classification, particularly rural ecological land. LULC classification is the assignment of pixels in an image file that exhibit similar spectral characteristics to spectral classes via a supervised or unsupervised clustering algorithm. These pixel classes represent various visible features on the Earth’s surface (e.g., water, snow, croplands), which, when cross-referenced with how those features are modified by humans, reveal subtle phenomena such as localized temperature variation. For example, land cover and ground moisture is highly correlated in rural areas due to agriculture (this is especially true in Washington), suggesting that minimum and maximum air temperatures per season fluctuate more in rural areas (Lawston et al., 2020).

LULC depends significantly on ground-truthing, or the collection of observations about the size, type, condition, and any other important physical or chemical properties concerning the materials on the Earth's surface (Hoffer, 1972). Quite often, whether a result of mechanical error or radiometric interference, remotely sensed pixels are misclassified; ignoring this may lead to disastrously incorrect conclusions. A common misclassification (one addressed in the land cover data obtained for this project) is the assignment of water pixels as tree-cast shadows, or vice versa. Verifying a sample of ground features within various pixels of a study area can reveal misclassification patterns across the entire study area and beyond. It also reduces the chance of a classification algorithm assigning improper classes to regions undergoing unprecedented, rapid ecological change (Nagai et al., 2020). The validity of classification algorithms is measured by both producer's accuracy (percentage of an LULC type on the ground correctly classified from the map) and user's accuracy (percentage of a class on the map that matches the corresponding class on the ground) (Tran et al., 2017). Urban and environmental policymaking rely substantially on this. By judging historical aerial imagery against modern imagery, policymakers can predict what the future environment footprint may look like, and apply models such as the one this project seeks to create to estimate climate impact.

The marriage between the urban heat island effect and LULC classification is inexorable. For example, the normalized difference vegetation index (NDVI), which uses spectral band math to delineate probable areas of vegetation, measures the growing amount of green space in urban areas – this has a negative correlation with surface temperature (Bokaie et al., 2016). Appropriately sized, dense, amorphous, and cohesive green patches distributed in clusters around a city (meant to imitate undisturbed nature) most radically disperses urban heat (Kowe et al., 2021). Similar normalized indices for other land cover types, combined with cloud cover raster data, has yielded sophisticated statistical techniques that estimate seasonal variability of urban land surface temperature, with greater success across homogenous land cover types (Guha, Govil, & Diwan, 2019).

New technologies like the ECOSTRESS experiment, docked with the International Space Station (ISS), make projects studying this crossover increasingly more powerful than previous research. The ECOSTRESS experiment was selected because of its sensor's desirable temporal resolution (90% of CONUS every 4 days), radiometric resolution (8 - 12.5 μm), and excellent spatial resolution (~70-meter) (Cawse-Nicholson & Anderson, 2018). Launched into space in June 2018, the experiment seeks to learn more about how plants use water to regulate temperature, which impacts regional evapotranspiration and indicates whether or not a region may be entering a period of drought (Hulley et al., 2015). Despite its emphasis on vegetation, its land surface temperature and emissivity product (ECO2LSTE) is sufficient for measuring temperature across any surface type.

Climate Change Relevance

This project acknowledges the depth to which the UHI and LULC crossover has been examined, and incorporates the scientific findings of this crossover. Since 62% of the Weather Underground stations exist on well-developed land, this project will supplement existing efforts to mitigate UHI and to establish ecologically friendly land cover types. However, it will differentiate itself by hypothesizing that pockets of air temperature variation exist everywhere (rural and urban). This is a less common research angle, as urban areas experience anywhere from 1.4 to 15 times more heat stress than rural areas – justifying the vast body of UHI research (Wouters et al., 2017). Yet, as Wouters et al. point out, rural heat stress varies by topography, implying that the UHI effect is not solely responsible for localized air temperature variation. Though minor, non-UHI phenomena may also influence climate patterns; this project strives to pinpoint and quantify the nature of these phenomena in Washington state.

Conclusion:

By blending the advantages of spaceborne and terrestrial temperature data, this project will create a robust algorithm for estimating highly localized temperature variation across Washington state. Such an algorithm could be coded into digital weather applications for public use, and also coded into rigorous climate analyses that aim to pinpoint phenomena that contribute to global warming.

While performing the innumerable spatial processes to map temperature difference between ground and air, this project will reaffirm existing research and discover some surprising anomalies. First, temperature penalties will likely be increasingly negative during colder, darker times, and increasingly positive during warmer, brighter times. This will be exacerbated by the amount of sunlight a pixel receives each month and its land cover type, and will not be evenly distributed by population. Second, surface air temperature in heavily developed flat land will swing hottest to coldest the most significantly, implying that man-made surfaces warm up air faster than natural surfaces at several meters above ground.

Future research can expand upon this project in multiple ways. First, remedies exist for the fact that the ECOSTRESS experiment requires nearly 100 hours to probe the contiguous United States, while terrestrial weather stations provide 5-minute updates. It would certainly be plausible to extract the temperature penalties from this project and apply them to data from a higher temporal resolution satellite like MODIS, resampling to match the 70-meter ECOSTRESS grid. In this scenario, land surface temperature would be coarser with most of the 70 x 70-meter cells matching one another, but the penalties would still be applied at their proper coordinates and offer unique temperature values. Second, historical LULC data sets could be juxtaposed with the 2016 data set used in this project to ascertain how disparate air temperature may have been if land were being used differently today. For instance, research documents how clearcut areas created by deforestation upset soil runoff and species habitation over time – the same could be true for air temperature.

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