Automated generation of Land Surface Temperature estimates

Overview

Regional land surface temperature estimates are a key dataset for urban heat island studies, climate change resilience research, and several other components of urban planning. Among other topics, CMAP's Climate Resilience strategy paper is exploring climate change impacts resulting from increased surface temperatures and extreme heat events. This exploration necessitates the development of land surface temperature (LST) estimates for the CMAP region. Fortunately, the USGS Earth Resources Observation and Science (EROS) Center provides easy access to free Landsat 8 reflectance and temperature data, which can be converted to LST estimates through a series of automated image processing techniques.

Data Inputs

The data inputs used to generate LST estimates for the CMAP region were collected by the Landsat 8 satellite, which was selected after investigating a variety of potential sources for remotely-sensed thermal infrared data. Landsat 8 was identified as the best source since it provides free, medium-resolution data at a frequent re-visit period (every 16 days). Specific inputs are detailed below.

Band 10 Brightness Temperature

Band 10, also known as the Thermal Infrared Sensor (TIRS) 1 band, collects 100m resolution thermal infrared imagery. It is re-sampled to 30m to match the resolution of the majority of Landsat 8 bands. There are actually two TIRS bands on Landsat 8, collecting across slightly different wavelengths. However, calibration issues have led to notable stray light contamination of the TIRS 2 data collected by Band 11 (Barsi, 2014), hence the selection of Band 10 as the primary TIRS dataset.

The Brightness Temperature is a provisional USGS data product, which converts the spectral radiance values stored in TIRS band 10 to brightness temperature in Kelvin using the formula shown below (U.S. Geological Survey, 2015).

$$T = \frac{K_2}{ln(\frac{K_1}{L_\lambda} + 1)}$$

T = At-satellite brightness temperature (K)
L_λ = Top of Atmosphere spectral radiance (Watts/(m2 * srad * µm))
K_1 = Band-specific thermal conversion constant from the metadata
K_2 = Band-specific thermal conversion constant from the metadata

CFmask

The CFmask product identifies cloud, cloud shadow, snow, and water at 30m resolution, using reflectance values and brightness temperatures from multiple Landsat 8 bands. As with the TOA Brightness Temperature, it is a provisional USGS data product. The CFmask algorithm is a C programming language implementation of the Function of Mask (FMask) algorithm developed for MATLAB by Boston University researchers.

The algorithm characterizes the occurrence probabilities of clouds and similar features using object-based image processing techniques. Probabilities above specified thresholds are then classified as cloud, water, etc. FMask is described in greater detail in Zhu and Woodcock, 2012.

Normalized Difference Vegetation Index (NDVI)
NDVI is a commonly-used surrogate for biomass, vegetative health, and other plant and soil properties. NDVI can also be used for generalized land cover classifications. It is a ratio ranging from -1 to 1 which is created using Landsat 8's Visible Red band (No. 4) and Near Infrared band (No. 5) in the following formula: (Near Infrared – Visible Red) / (Near Infrared + Visible Red). NDVI is available as a provisional USGS data product at a 30m resolution.

Data Acquisition
All three inputs are available through the EROS Center's Science Processing Architecture (ESPA) interface. ESPA automatically generates provisional data products on-demand, so, in order to obtain data from the website, exact Landsat scenes and desired secondary products must be specified. An easy way to identify scenes that are of interest is through USGS EarthExplorer.

Enter in a location and date range, select "L8 OLI/TIRS" as the data set, and select a cloud cover threshold under Additional Criteria -- "Less than 80%" is a recommended starting point. Click "Results" to generate a list of available scenes and note the Landsat Scene Identifiers of interest, and create a text file with each Scene Identifier on a single line. Navigate to the ESPA bulk ordering website, and upload the newly-created text file as the Scene List. Select "Brightness Temperature", "CFMask", and "Surface Reflectance NDVI" and submit the order. You will receive a notification e-mail when the files are available for download; this could take a few hours or a few days, pending ESPA's request load.

Theoretical Approach
The surface temperature estimation is based on three key components – Land Surface Emissivity (LSE), brightness temperature conversion, and the NDVI Thresholds Method ($NDVI^{THM}$).

Emissivity is a measure of a surface's efficiency at radiating heat. Different materials have different emissivity values (ranging from 0 to 1), which can be measured using specialized equipment. Similarly, different land surface types have different ranges of emissivity. LSE coefficients reflect the average emissivity for specific or grouped land surface types, as calculated using field measurements of radiance and surface temperature (Njoku, 2013).

As mentioned previously, the thermal input used in this analysis is Landsat 8's Band 10 brightness temperature. Brightness temperature differs from surface temperature, in that it assumes an idealized emissivity value of 1. Fortunately, brightness temperatures can be converted to land surface temperature using LSE coefficients corresponding to the land surface types which are present.

There are a variety of techniques to accomplish this conversion, including many that require some form of land cover classification as an integral step. A simpler approach is the $NDVI^{THM}$, which applies LSE coefficients based on NDVI values. The method assumes that NDVI values < 0.2 are un-vegetated (referred to as bare soil) and NDVI values > 0.5 are vegetated, then applies the corresponding LSE coefficients to each presumed land surface type. The coefficients used for bare soil (0.9668) and vegetation (0.9863) are specific to Landsat 8 TIRS Band 10 and were obtained from Yu et al., 2014.

For NDVI values between 0.2 and 0.5, the vegetation proportion (P_V) is calculated using the method established by Carlson and Ripley, 1997 as detailed by Sobrino et al., 2004. Note that the formula, shown on the following page, uses an $NDVI_{min}$ value of 0.2 and an $NDVI_{max}$ value of 0.5.

$$P_v = \left[\frac{\mathrm{NDVI} - \mathrm{NDVI}_{\min}}{\mathrm{NDVI}_{\max} - \mathrm{NDVI}_{\min}}\right]^2$$

The emissivity (E_V) can then be calculated using a formula that incorporates P_V, the LSE coefficients for bare soil and vegetation, and a surface roughness adjustment. Sobrino et al., 2004 describes the components of this formula, as applied to Landsat 5 data, in greater detail. An updated version of the formula, which takes into account LSE coefficients specific to Landsat 8, is shown below.

$$E_V = 0.00149\ PV + 0.98481$$

The NDVI-derived LSE coefficients are then used to convert the Band 10 Brightness Temperature to surface temperature (S_t) estimates, using the emissivity correction formula (Artis & Carnahan, 1982) as described by Weng et al., 2004. This is followed by a final conversion from Kelvin to Fahrenheit.

$$S_t = \frac{T_B}{1 + (\lambda \times T_B/\rho)\ln\varepsilon}$$

T_B = Brightness Temperature
$\mathcal{E}$ = LSE coefficients
λ = center wavelength of emitted radiance (10.9 µm)
$p = h * c/k_B$ ($1.438 * 10^{-2}$ m K)
h = Planck's constant ($6.626 * 10^{-34}$ Js)
c = velocity of light ($2.998 * 10^{8}$ m/s)
k_B = Boltzmann constant ($1.38 * 10^{-23}$ J/K)

Caveat

Land surface temperature estimates that are generated using this method are suitable for relative temperature comparisons. Precise measurement of surface temperatures using Landsat data would require in situ emissivity and temperature measurements to calibrate emissivity coefficients, as well as a detailed land cover classification.

Technical Implementation

The image processing approach was automated using a custom Python script tool within ArcGIS 10.3.1, which is shown in the Appendix. The script uses a series of raster calculator expressions to implement the formulas described in the Theoretical Approach section. A general outline of processing steps is shown below.

1) Convert Julian date from Landsat file name to Gregorian.
2) Use CFMask to remove cloud and cloud shadow from TIRS 1 and NDVI.
3) Calculate LSE coefficients from NDVI using the NDVI^{THM}.
4) Convert Brightness Temperature to LST using the LSE coefficients.
5) Convert Kelvin to Fahrenheit.
6) (Optional) Clip raster to study area.

References

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Appendix: l8_lst_processing.py

```
### Purpose: Converts LANDSAT scenes and derived products into Land Surface Temperature grid (in °F)
### Author: Zach Vernon
### Updated: 03/03/2016

import datetime

# Define parameters
thermal_band = arcpy.GetParameterAsText(0) # Band 10 brightness temperature
cloud_band = arcpy.GetParameterAsText(1) # CFMask
ndvi_band = arcpy.GetParameterAsText(2) # NDVI
clip_feature = arcpy.GetParameterAsText(3)
out_gdb = arcpy.GetParameterAsText(4)
arcpy.env.workspace = out_gdb
arcpy.env.overwriteOutput = 'TRUE'

# Parses date from Landsat string
image_year = int(thermal_band[9:13])
image_julian_day = int(thermal_band[13:16])
date_conversion = datetime.datetime(image_year, 1, 1) + datetime.timedelta(image_julian_day-1)
output_date = date_conversion.strftime('%Y%m%d')

# Removes clouds and shadow from thermal and NDVI bands
thermal_removal_expression = 'Con(("'+cloud_band+'" == 0) | ("'+cloud_band+'" == 1) | ("'+cloud_band+'" ==
3),0.1) * "'+thermal_band+'"'
arcpy.gp.RasterCalculator_sa(thermal_removal_expression,'toa_clouds_removed_'+str(output_date))
ndvi_removal_expression = 'Float(Con(("'+cloud_band+'" == 0) | ("'+cloud_band+'" == 1) | ("'+cloud_band+'" ==
3),.0001) * "'+ndvi_band+'")'
arcpy.gp.RasterCalculator_sa(ndvi_removal_expression,'ndvi_clouds_removed_scaled_'+str(output_date))

# Converts NDVI values into emissivity values
ndvi_emissivity_conversion_expression='(Float(Con("ndvi_clouds_removed_scaled_'+str(output_date)+'" < 0.20,
0.9668, Con( ("ndvi_clouds_removed_scaled_'+str(output_date)+'" >=  0.2) &
("ndvi_clouds_removed_scaled_'+str(output_date)+'" <= 0.50),
0.00149*((("ndvi_clouds_removed_scaled_'+str(output_date)+'" -
0.20)/(0.30))*("ndvi_clouds_removed_scaled_'+str(output_date)+'" - 0.20)/(0.30)) + 0.98481, 0.9863))))'
arcpy.gp.RasterCalculator_sa(ndvi_emissivity_conversion_expression,'ndvi_emissivity_'+str(output_date))

# Applies emissivity correction
lst_emissivity_conversion_expression = '"toa_clouds_removed_'+str(output_date)+'" / (1+
(((10.9*"toa_clouds_removed_'+str(output_date)+'")/14380)*Ln("ndvi_emissivity_'+str(output_date)+'")))'
arcpy.gp.RasterCalculator_sa(lst_emissivity_conversion_expression,'lst_kelvin_'+str(output_date))

# Converts K to °F
conversion_expression = '1.8 * ("lst_kelvin_'+str(output_date)+'"-273.15) + 32'
arcpy.gp.RasterCalculator_sa(conversion_expression,'land_surface_temp_'+str(output_date))

# Clips raster
if clip_feature != '':
        arcpy.Clip_management('land_surface_temp_'+str(output_date),'#',out_gdb+'/LST_clipped_'+str(output_
        date),clip_feature,'#','ClippingGeometry','NO_MAINTAIN_EXTENT')
```