Calculating surface temperature with thermal imagery

Twitchell Island is located in the Sacramento-San Joaquin River Delta, which is an important agroecosystem of the Central Valley of California. Twitchell Island is two meters below sea level and exists due to an intricate network of levees. The State of California manages the island for agricultural research. Irrigated rice (blue), corn (yellow) and alfalfa (pink) are the primary crops grown on the island as seen in the CropScape screen capture below.

One of the irrigated rice fields contains an eddy covariance flux tower. Eddy covariance flux towers collect a number of micrometeorological data every 30 minutes, including CO_2 and moisture flux. Scientists use these fluxes to estimate carbon assimilation (biomass accumulation) and evapotranspiration, respectively. The two can be combined (biomass/evapotranspiration) to estimate crop water productivity ("more crop per drop"). Further information on the flux tower, including its coordinates can be found at https://ameriflux.lbl.gov/sites/siteinfo/US-Twt.

This exercise consists of three phases: (i) download Landsat-7 ETM+ imagery over Twitchell Island during the 2011 growing season; (ii) calculate at-sensor (TOA: top-of-atmosphere) brightness temperature (˚C) from TOA radiance and Digital Numbers (DNs); and (iii) track changes in TOA brightness temperature and evapotranspiration during the 2011 growing season.

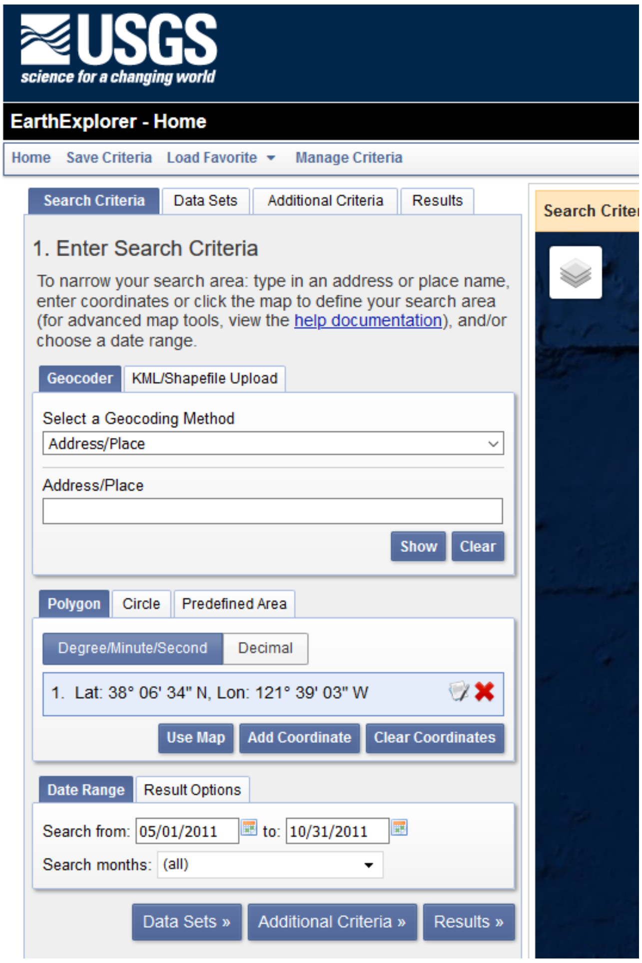
Learning outcomes:
At the end of the exercises, you will have

- calculated at-sensor (top-of-atmosphere) brightness temperature from Landsat-7 ETM+ Digital Numbers (DNs)
- examined the relationship between TOA brightness temperature and evapotranspiration

Download Landsat-7 ETM+ imagery over Twitchell Island

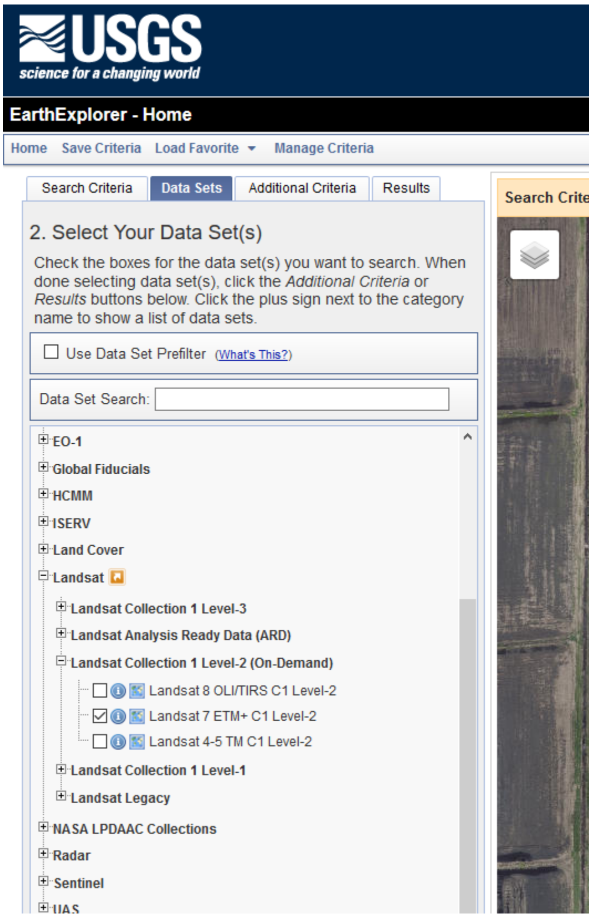
Go to https://earthexplorer.usgs.gov/. Use the search criteria tab to identify the Landsat scene. You can do this by entering the latitude and longitude provided in the site info link above or by entering the path-row (44-33).

Identify the Twitchell growing season using the accompanying excel spreadsheet (**twitchell_ET_2011.xls**). The spreadsheet contains daily data on minimum temperature in ºC (Tmn), maximum temperature in ºC (Tmx), vapour pressure deficit in kPa (VPD) and evapotranspiration in mm (ET). The farm manager provided planting and harvesting dates, which was used to define the crop.type column. When "RI" is in the column, it means rice was in the field. Eight-day NDVI and EVI derived from MODIS has also been included for comparison purposes. Use the growing season to constrain the search criteria.



Click on the next tab (Data Sets) to select the Landsat imagery (Landsat Collection 1 Level-1). Level-2 is atmospherically corrected surface reflectance (0-1) and should be downloaded for analyses in most cases. Unfortunately, the Level-2 product does not include the thermal band (Landsat band 6). Check the box for Landsat-7 ETM+.

More information about Landsat-7 ETM+ can be found at https://eos.com/landsat-7/.



You can enter additional criteria to constrain the results. I usually use for example, a cloud cover threshold of 10-20%. Lastly, click on the results tab and interactively select Landsat images and download them one-by-one or add them to your basket for bulk download. <u>Choose images with path-row 44-33 **NOT** 44-34</u>. More images are available for 44-33. You should download ~9 images depending on your cloud criteria threshold.

If you selected the bulk download option, you will receive an email when the images are available. You can download them from the link provided or using the Bulk Download Application (BDA: https://earthexplorer.usgs.gov/bulk/). BDA is particularly powerful when you need to download several images.

<u>I would suggest downloading the zipped GEOTIFF files, because they increase functionality with some GIS software.</u>

<u>Please keep in mind if you chose the bulk download option, it can take some time for your order to be processed.</u>

Calculate at-sensor TOA brightness temperature (°C)

Depending on the GIS software you are using, you can open the Landsat images all together or by individual bands. You may notice there are two thermal bands (band 6-1 and band 6-2). The bands consist of "low" and "high" gain filtering to accommodate the low radiometric resolution of the instrument. The low gain band is appropriate for very bright surfaces (e.g., deserts) while the high gain band is appropriate for darker surfaces (e.g., vegetated areas). For this exercise, you will use band 6-2 (VCID 2).

To convert TOA brightness, you must first convert thermal DNs (0-255) to TOA radiance. This can be done with calibration coefficients provided in the metadata. Open the metadata file (_MTL extension) in WordPad (DO NOT USE NOTEPAD) to view the calibration coefficients. DNs can be converted to TOA radiance with the following formula:

$$L_\lambda = \frac{L_{max,\lambda} - L_{min,\lambda}}{Q_{cal,max} - Q_{cal,min}} \times \left(DN - Q_{cal,min}\right) + L_{min,\lambda}$$

```
GROUP = MIN_MAX_RADIANCE
  RADIANCE_MAXIMUM_BAND_1 = 293.700
  RADIANCE_MINIMUM_BAND_1 = -6.200
  RADIANCE_MAXIMUM_BAND_2 = 300.900
  RADIANCE_MINIMUM_BAND_2 = -6.400
  RADIANCE_MAXIMUM_BAND_3 = 234.400
  RADIANCE_MINIMUM_BAND_3 = -5.000
  RADIANCE_MAXIMUM_BAND_4 = 241.100
  RADIANCE_MINIMUM_BAND_4 = -5.100
  RADIANCE_MAXIMUM_BAND_5 = 31.060
  RADIANCE_MINIMUM_BAND_5 = -1.000
  RADIANCE_MAXIMUM_BAND_6_VCID_1 = 17.040
  RADIANCE_MINIMUM_BAND_6_VCID_1 = 0.000
  RADIANCE_MAXIMUM_BAND_6_VCID_2 = 12.650
  RADIANCE_MINIMUM_BAND_6_VCID_2 = 3.200
  RADIANCE_MAXIMUM_BAND_7 = 10.800
  RADIANCE_MINIMUM_BAND_7 = -0.350
  RADIANCE_MAXIMUM_BAND_8 = 243.100
  RADIANCE_MINIMUM_BAND_8 = -4.700
END_GROUP = MIN_MAX_RADIANCE
```

Lmax, Lmin

```
GROUP = MIN_MAX_PIXEL_VALUE
    QUANTIZE_CAL_MAX_BAND_1 = 255
    QUANTIZE_CAL_MIN_BAND_1 = 1
    QUANTIZE_CAL_MAX_BAND_2 = 255
    QUANTIZE_CAL_MIN_BAND_2 = 1
    QUANTIZE_CAL_MAX_BAND_3 = 255
    QUANTIZE_CAL_MIN_BAND_3 = 1
    QUANTIZE_CAL_MAX_BAND_4 = 255
    QUANTIZE_CAL_MIN_BAND_4 = 1
    QUANTIZE_CAL_MAX_BAND_5 = 255
    QUANTIZE_CAL_MIN_BAND_5 = 1
    QUANTIZE_CAL_MAX_BAND_6_VCID_1 = 255
    QUANTIZE_CAL_MIN_BAND_6_VCID_1 = 1
    QUANTIZE_CAL_MAX_BAND_6_VCID_2 = 255
    QUANTIZE_CAL_MIN_BAND_6_VCID_2 = 1
    QUANTIZE_CAL_MAX_BAND_7 = 255
    QUANTIZE_CAL_MIN_BAND_7 = 1
    QUANTIZE_CAL_MAX_BAND_8 = 255
    QUANTIZE_CAL_MIN_BAND_8 = 1
  END_GROUP = MIN_MAX_PIXEL_VALUE
```

Qcalmax, Qcalmin

1) Compare the radiance values to the DNs in the image. Ignore the stripping in the images. This is due to a known sensor problem in Landsat-7 ETM+ (SLC-off).

We will need another equation (reformulated Plank's radiance function) to convert TOA radiance to TOA brightness:

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

Where L_λ is the TOA radiance as above, T is the TOA brightness temperature in Kelvin and K_1 and K_2 calibration coefficients. For Landsat-7 ETM+, K_1=666.09 (W m^{-2} sr^{-1} μm^{-1}) and K_2=1282.71 (Kelvin). After you have calculated TOA brightness temperature, you can convert it to Celsius to improve interpretation.

TOA brightness temperature is particularly sensitive to the moisture content of the atmosphere, so it is not ideal for analyses. We did not convert TOA brightness temperature to land surface temperature, because this requires a radiative transfer model.

2) Compare your TOA radiance and brightness temperatures to those provided in the sub-folders: LS TOA and LS Brightness T. These images were produced automatically with a calibration tool in ENVI®.
3) Visualize TOA brightness temperature side by side with a true colour or visible-NIR image composite. A colour infrared (CIR) or agriculture composite is quite useful here. CIR displays near infrared (5), red (4) and green (3) as Red-Green-Blue. Similarly, an agriculture composite uses SWIR-1, NIR and blue. I have also provided a clip of Cropscape (https://nassgeodata.gmu.edu/CropScape/) around the study area in a zipped file. Cropscape is a classified map of crop types for the entire United States.
4) Look at different targets (water bodies, agricultural fields, urban areas, etc.). Differentiate differences by land cover type.

Track changes in TOA brightness temperature and evapotranspiration

Extract the TOA brightness temperature for one pixel or average many pixels for the irrigated rice field immediately west of the eddy covariance flux tower. This is the field the flux tower takes measurements from. The tower is visible on Google Earth.

5) Plot the TOA brightness temperatures against the NDVI (or EVI) and ET provided. In conditions where soil moisture is a constraint on plant health, we would expect a proportional response of NDVI (vegetation) to latent heat (energy equivalent of ET). Due to the conservation of energy, we would expect an increase in latent heat to lead to a decrease in sensible heat and land surface temperature. Do you see an inverse relationship between TOA brightness temperature and ET? Explain your answer.

Challenge: Convert TOA brightness temperature to Land Surface Temperature

The challenge requires a radiative transfer model. You have two options. The first is the Atmospheric Correction Parameter Calculator (ACPC: http://atmcorr.gsfc.nasa.gov) which is very course (~100 km spatial resolution) and therefore makes the correction for the entire scene. It should be sufficient for Twitchell Island given the time of year (i.e., cloud cover is near 0%). The second is ATCOR® in Erdas Imagine, which performs atmospheric correction on a pixel-by-pixel basis.

6) Use either option to convert TOA radiance from the Landsat imagery to LST. Compare the results of your TOA brightness temperature evaluation with that of LST.

If you select ACPC, use Equation 2 to convert radiance to LST. This time however you need to calculate radiance with the following equation:

$$L_\lambda = \left(\frac{L_{TOA} - LW^\uparrow}{\tau} - (1 - \varepsilon) \cdot LW^\downarrow\right) \cdot \left(\frac{1}{\varepsilon}\right) \quad (3)$$

Where L_λ is essentially the atmospherically corrected radiance, L_{TOA} is the TOA radiance as calculated in Equation 1, τ is the atmospheric transmission, $LW^\uparrow$ is the longwave radiation coming from the ground, $LW^\downarrow$ is the longwave radiation coming from the atmosphere and ε is emissivity. For NDVI ranging from 0.157 to 0.727, we can approximate ε with the following equation[1]:

$$\varepsilon = 1.0094 + 0.047 \cdot \ln(\mathrm{NDVI}) \quad (4)$$

[1] Van de Griend, A.A. and Owe, M. 1993. On the relationship between thermal emissivity and the normalized difference vegetation index for natural surfaces. *International Journal of Remote Sensing*, 14: 1119-1131.