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science for a changing world

Retrieval and Application of On Demand Global Field-scale Actual Evapotranspiration Data Since 1982

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Workshop 105 – Ballroom E

U.S. Department of the Interior
U.S. Geological Survey

WaterSciCon24
Catalyzing Collaborations • St. Paul, MN • 24–27 June 2024

Presenters

- Dr. Gabriel B. Senay

  Research Physical Scientist

- Stefanie Kagone

  Research Scientist

- Gabe E.L. Parrish

  Remote Sensing Scientist

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Workshop Topics

- Overview of remote sensing evapotranspiration modeling and mapping (SSEBop focus)
- Acquiring overpass Evapotranspiration (ET) from ESPA (EROS Science Processing Architecture) On Demand Interface

Coffee Break (10.00 – 10.30am)

- Creating seasonal aggregations from overpass ET
- Applications of ET data

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Overview of remote sensing evapotranspiration

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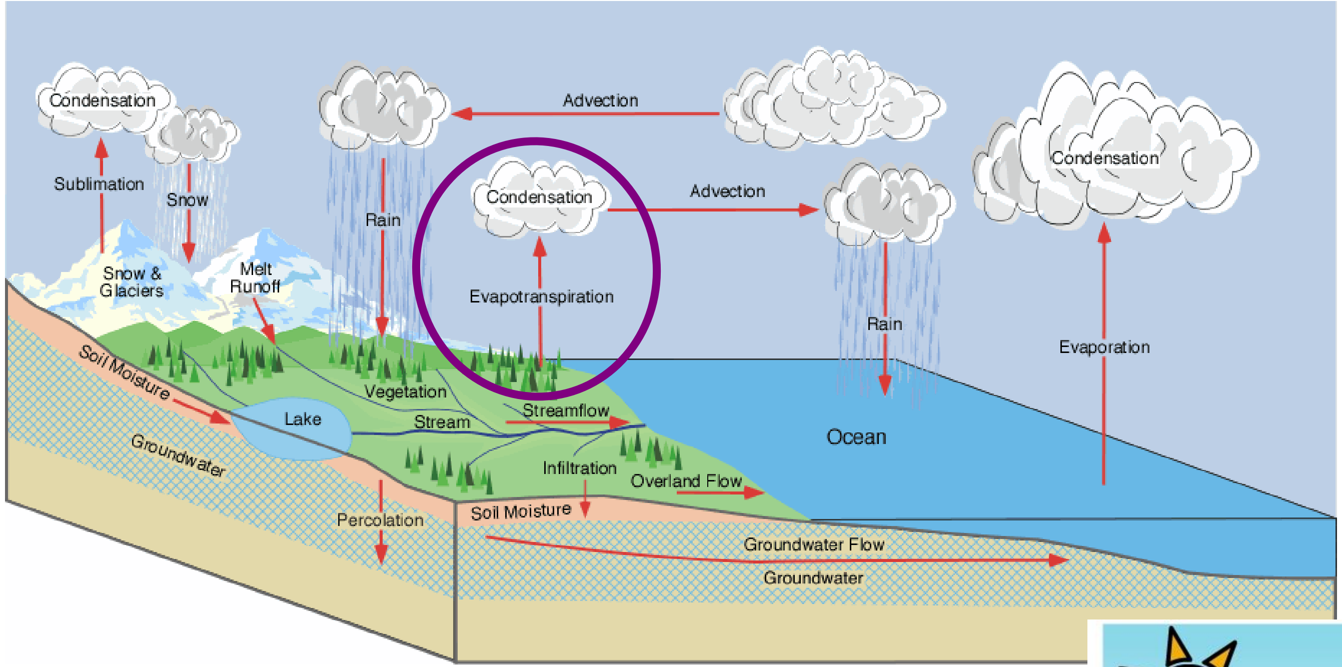
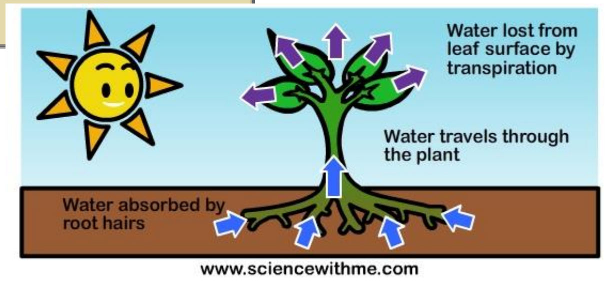
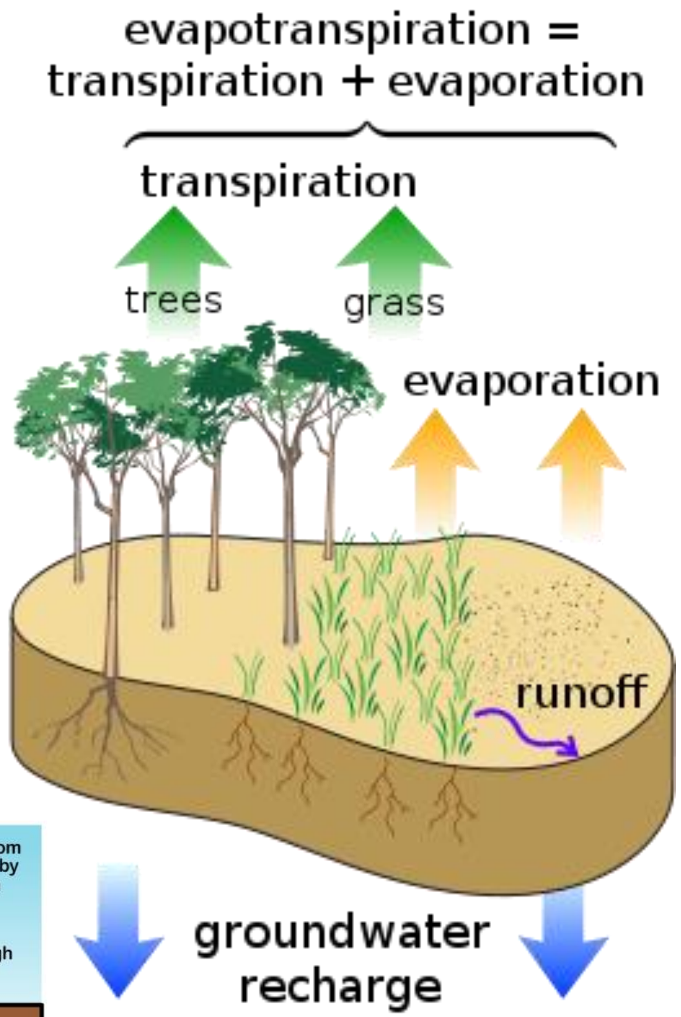
Hydrologic cycle







Challenge with ET:

1) Gaseous state
2) Invisible
3) Only indirect measurement

ET = 60-70% Precipitation

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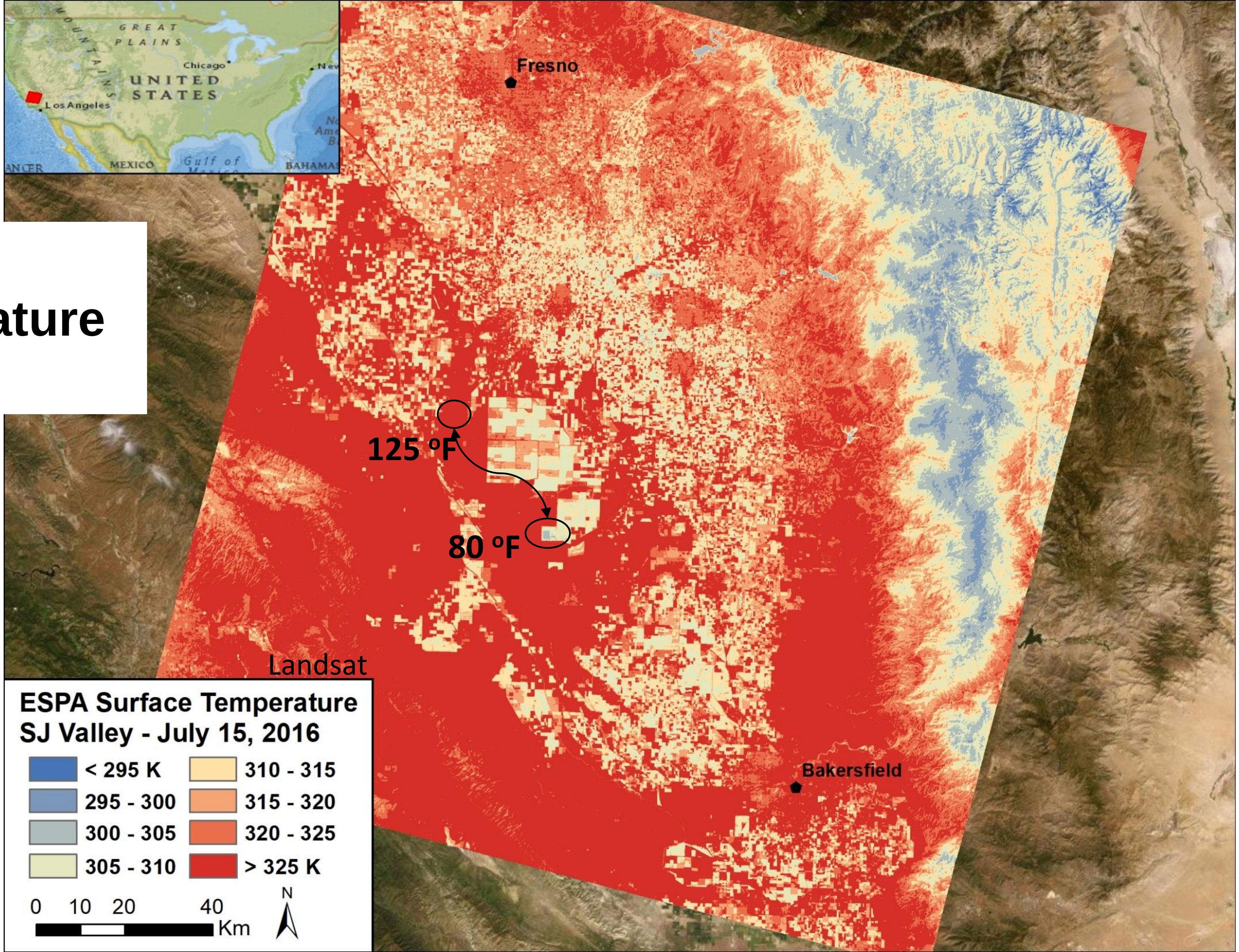
Surface Temperature to ET



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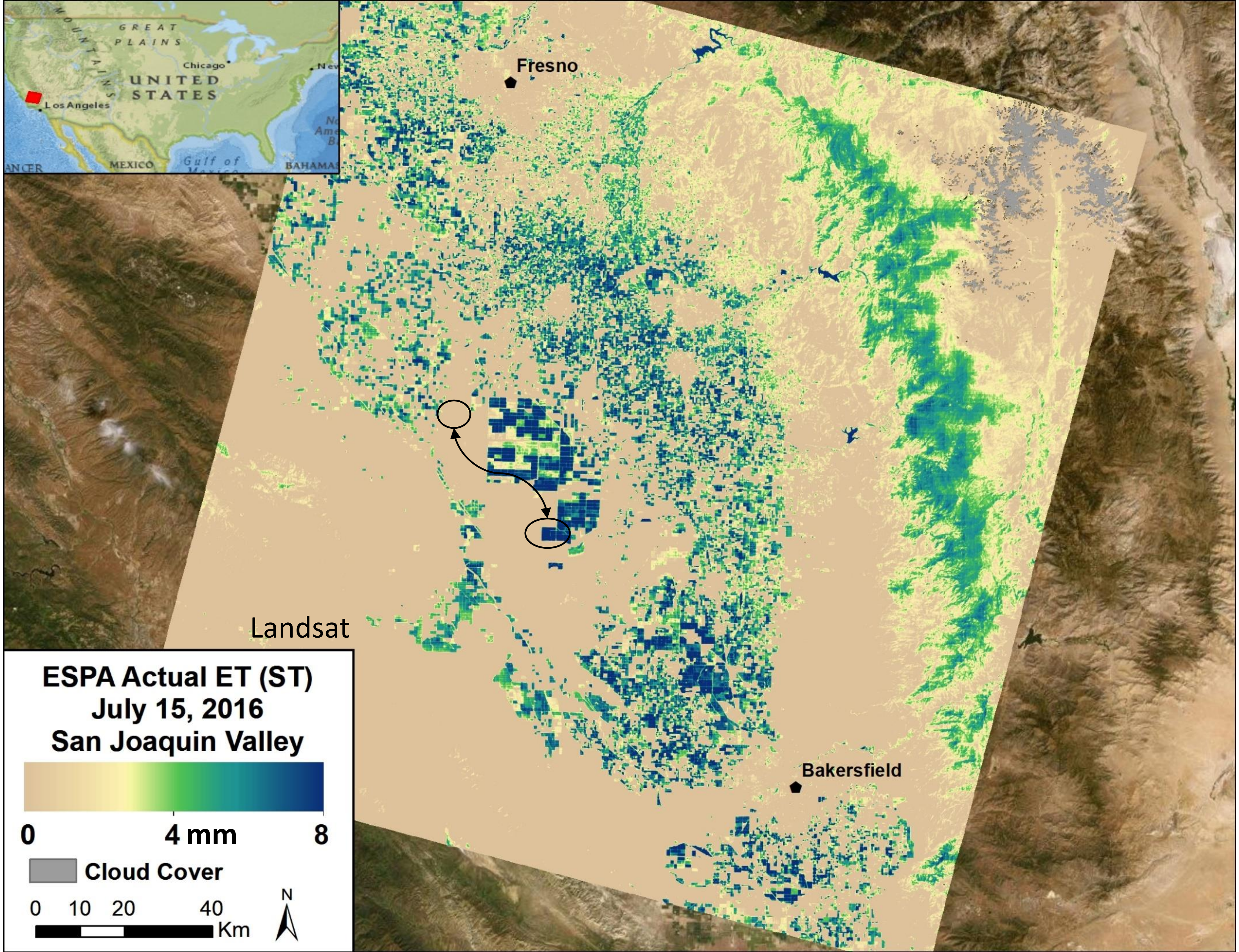
GREAT PLAINS
Chicago
UNITED STATES
Los Angeles
MEXICO
Gulf of
BAHAMAS
Fresno
Bakersfield
Landsat
ESPA Actual ET (ST)
July 15, 2016
San Joaquin Valley
0
4 mm
8
Cloud Cover
0 10 20 40
Km
N

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ET Estimation in Agriculture…

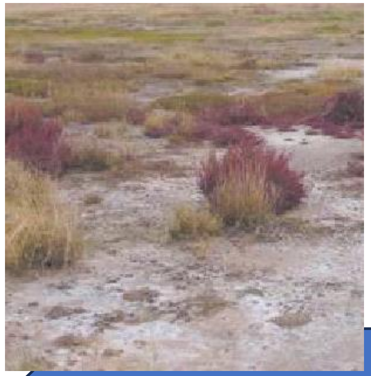
- It is a RESPONSE variable as opposed to precipitation (driver)
- It reflects the integrated effects of energy/aerodynamics, soil moisture, vegetation, and environmental stress

Potential

Energy | Wind/RH

Limitations

Moisture | Vegetation | Env. Stress



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Challenge: ET under potential vs water limiting conditions

- Landscape is at different levels of stress; thus,
  actual ET is <= potential

- Allen et al. (1998)
  - **ET = Ks * Kc * ETo**
    - Kc = type and stage of crop (~0.15 – 1.2)
    - Ks = soil moisture stress factor (0 to 1.0)

(This requires knowledge of crop types, stage and moisture distribution.)

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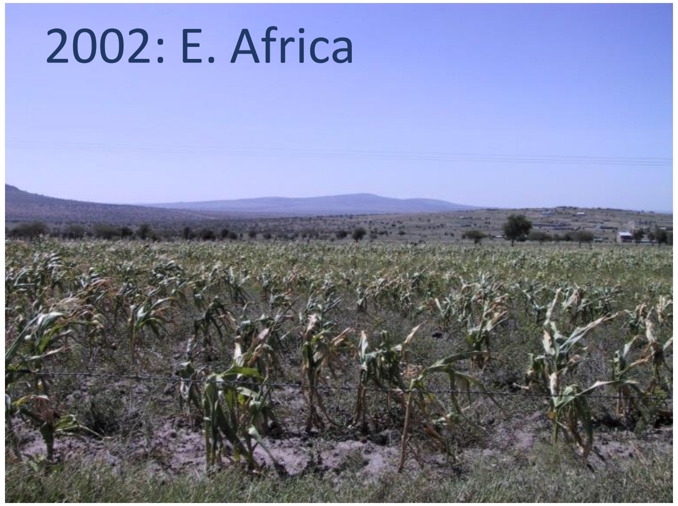
More direct estimation of stress using remote sensing approaches…

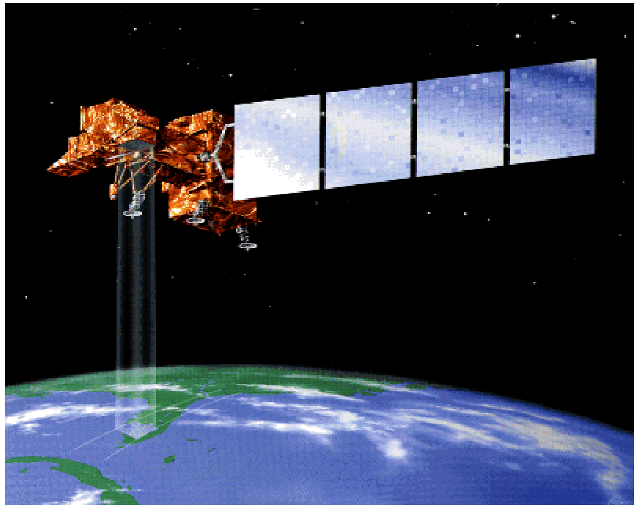
Land surface temperature (LST) derived from remotely sensed imagery can be used to estimate the combined effects of soil moisture and environmental stress factors on vegetation.

$$ET = ETf * ETo$$

$$ETf = Ks * Kc$$

Satellite data: The Great Equalizer!





Global Monitoring using Satellite Data and Evapotranspiration Modeling

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Role of Remote Sensing: Input Data

- Land Surface Temperature (Energy Balance Method)
  - Landsat (~100m)
  - MODIS/VIIRS (1km)
  - AVHRR (1km)
  - GOES (10km)

- Precipitation Estimate (Water Balance Method)
  - NOAA NEXRAD (5km): US
  - METEOSAT RFE/CHIRPS (10km): Global
  - NASA TRMM, IMERG (25km), etc.: Global

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Several Approaches…

- Soil Moisture Modeling
  - Land Surface Models such as Noah, SWAT, VIC…
- Vegetation Index based
  - NDVI/LAI-based: MOD16, P-M, P-T
- Mixed Approach
  - NDVI-LST (Trapezoid, Triangle…)
- Surface Energy Balance
  - SEBAL/METRIC, SEBS, Two-Source, ALEXI, S-SEBI, SSEBop…

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SSEBop Evapotranspiration

Background and Principles: "Satellite Psychrometry"

Psychrometry: the science of measuring the water-vapor content of the air.

Rn = H + ETa + G
ETa = Rn – H – G
ETa = Rn – H; G ~ 0 at daily time step

ETa = **ETf** * ETo/ETr

$$ETa = ETo - \gamma^{s}(Ts - Tc)ETo$$

Rn = net radiation
H = sensible heat
G = ground heat flux
ETa = actual ET
ETo (ETr) = reference ET (maximum)
ETf = ET Fraction (0-1.0)
Ts = Land Surface Temperature (LST)
Tc = wet reference boundary; f(Ts,γ^{s},NDVI)
γ^{s} = surface psychrometric constant; f(Rn, air density)

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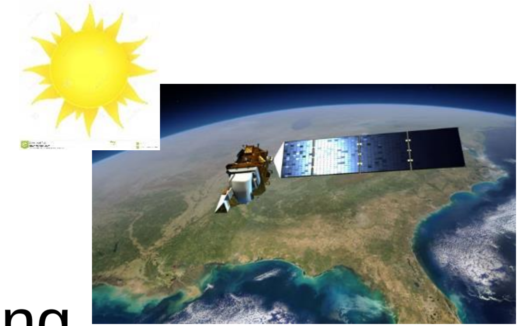
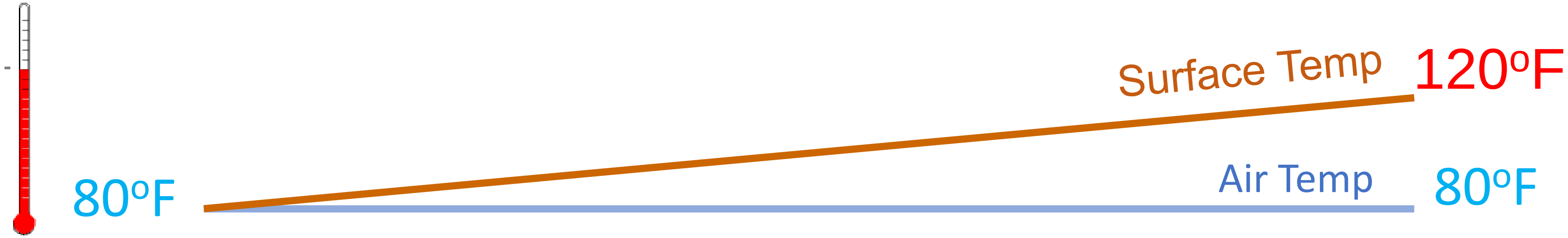
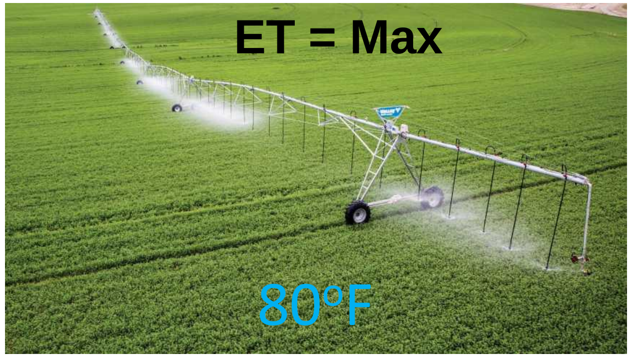
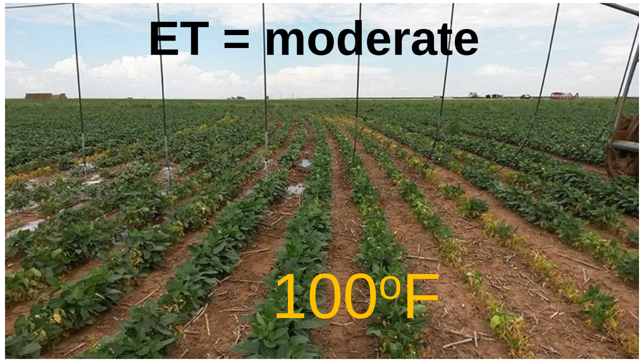
SSEBop: ET Fraction



- Land surface temperature differences are used to measure landscape water use rates through the effect of evaporative cooling







http://www.croplife.com/equipment/

https://www.irrigationaustralia.com.au/

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$$ETf = 1 - \gamma^{s}(Ts - Tc)$$

Air vs. Satellite Psychrometry

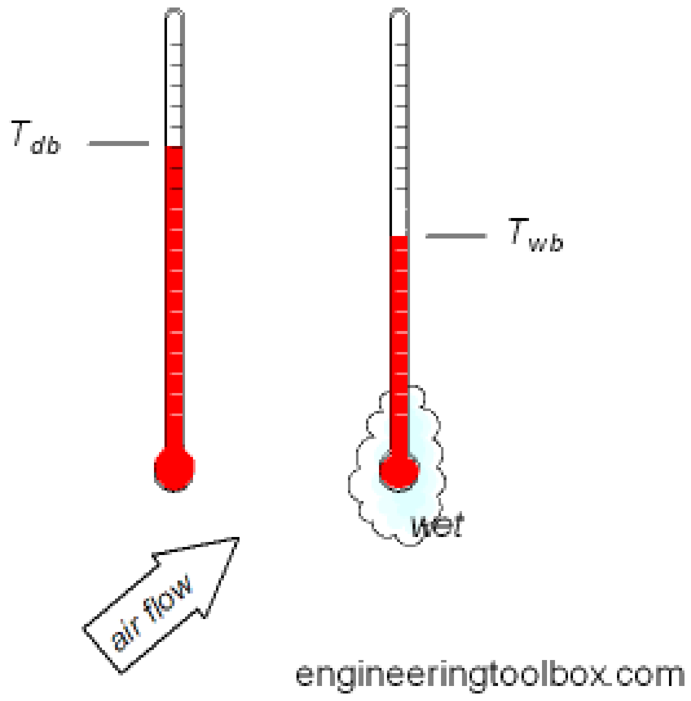
$$ETa = ETo - \gamma^{s}(Ts - Tc)ETo$$

Satellite Psychrometry

$$ea = es - \gamma\ (Td - Tw)$$

Air Psychrometry

$$\gamma = \frac{CpP}{\varepsilon\lambda} = 0.665 * 10^{-3} P$$



ea = actual vapor pressure (kPa)
es = saturated vapor pressure (kPa) at Tw
Td: dry bulb (ambient) air temp, $°C^{-1}$
Tw: wet bulb air temp, $°C^{-1}$
γ = psychrometric constant [kPa $°C^{-1}$]
P = atmospheric pressure [kPa]
λ = latent heat of vaporization, 2.45 [MJ kg^{-1}]
c_p = specific heat of air at constant pressure, 1.013 10^{-3} [MJ kg^{-1} $°C^{-1}$]
ε ratio = molecular weight of water vapor/dry air = 0.622

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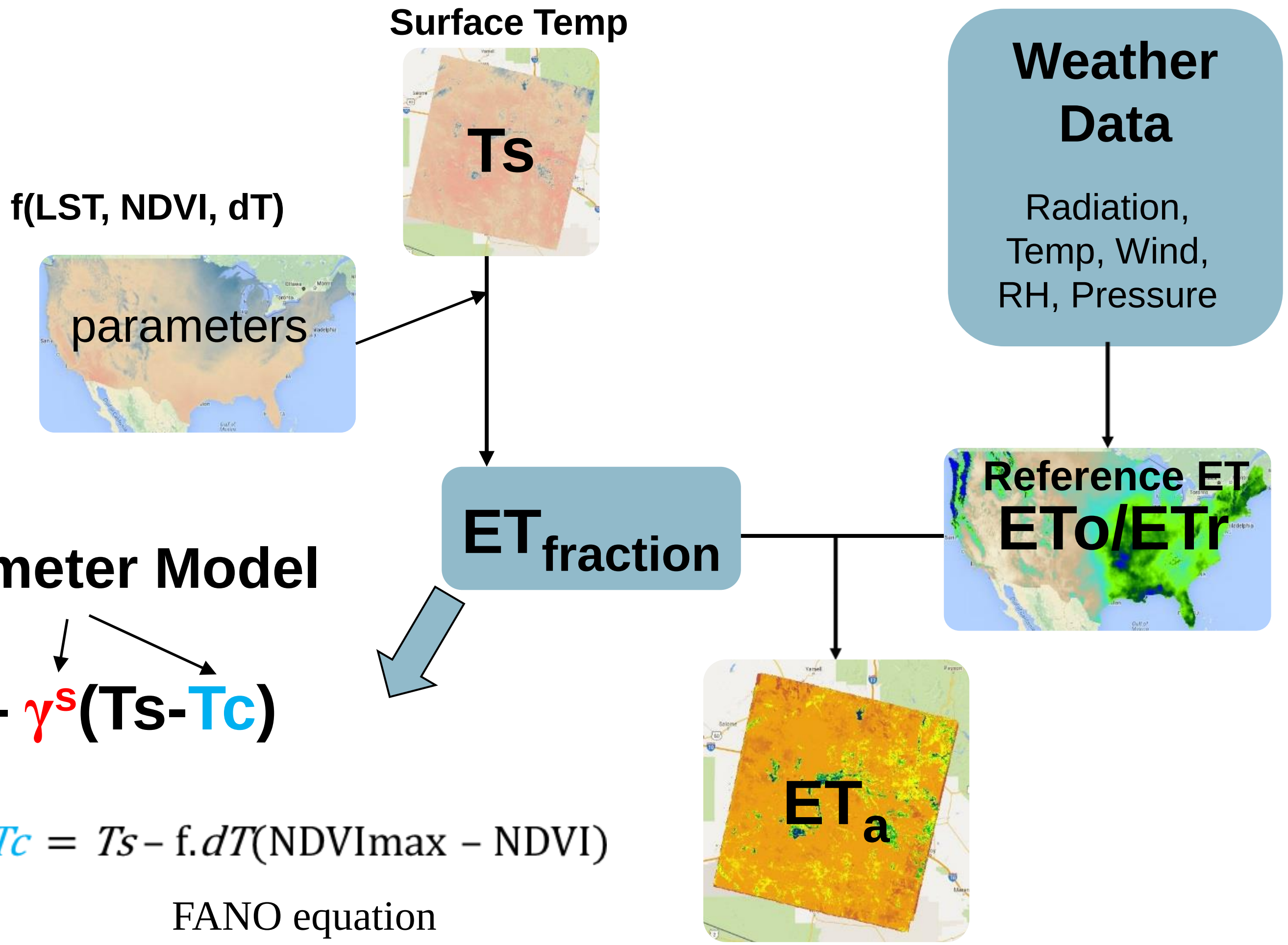
Ferrel, W.M. (1886); Allen et al. (1998)

Operational Simplified Surface Energy Balance (SSEBop) Modeling Approach



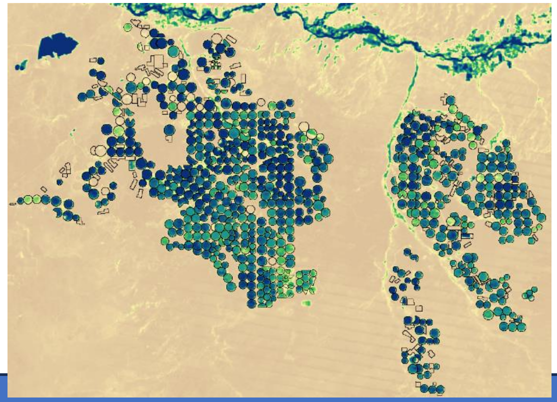
Two–Parameter Model

$$ETf = 1 - \gamma^{s}(Ts - Tc)$$

$$\gamma^{s} = \frac{\rho . C_p}{R_n . r_{ah}} \qquad Tc = Ts - f.dT(\text{NDVImax} - \text{NDVI})$$

FANO equation

ETa = ETf * ETr



SSEBop: Senay et al., 2013 JAWRA; 2018 App. Eng. in Ag; 2023 RS

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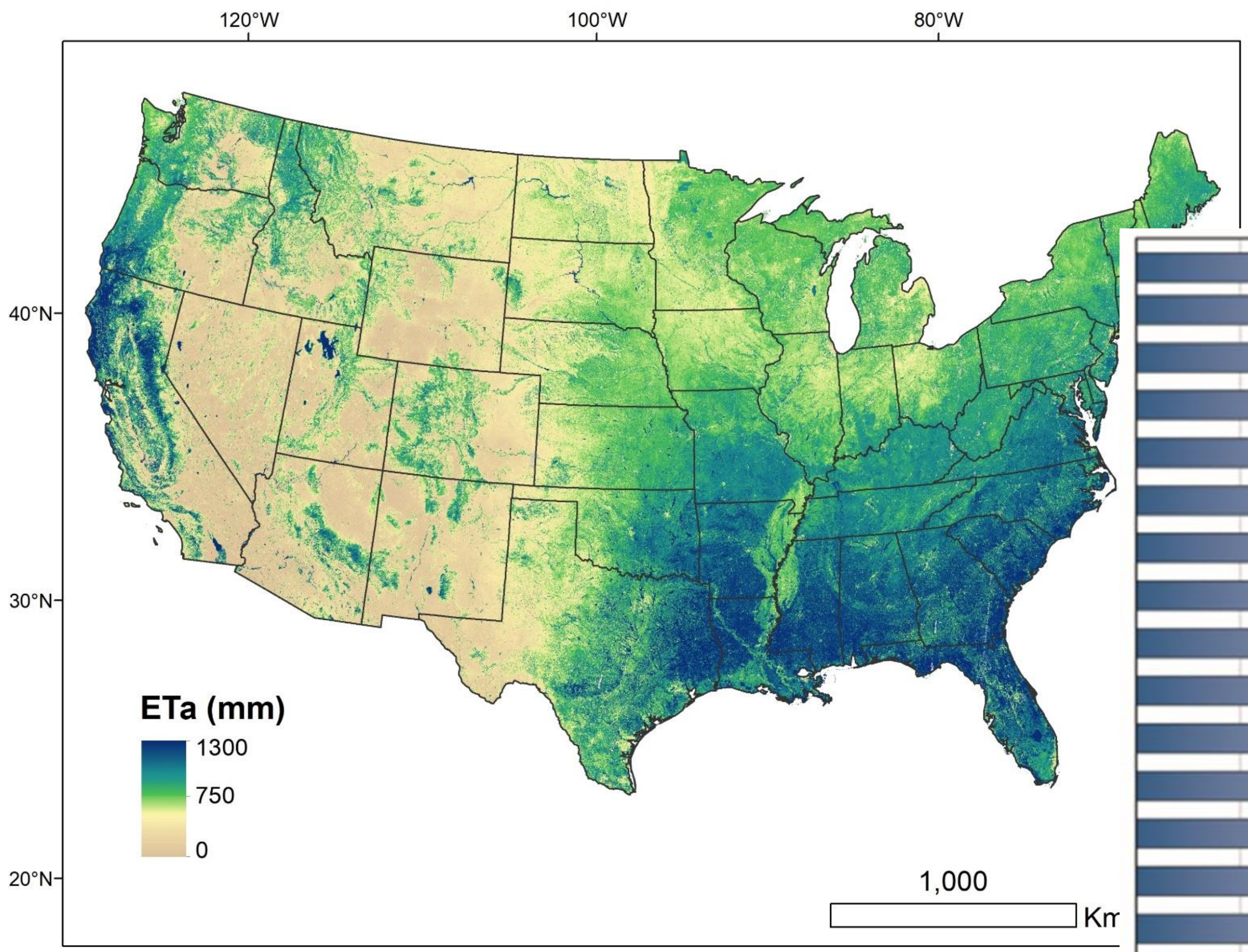
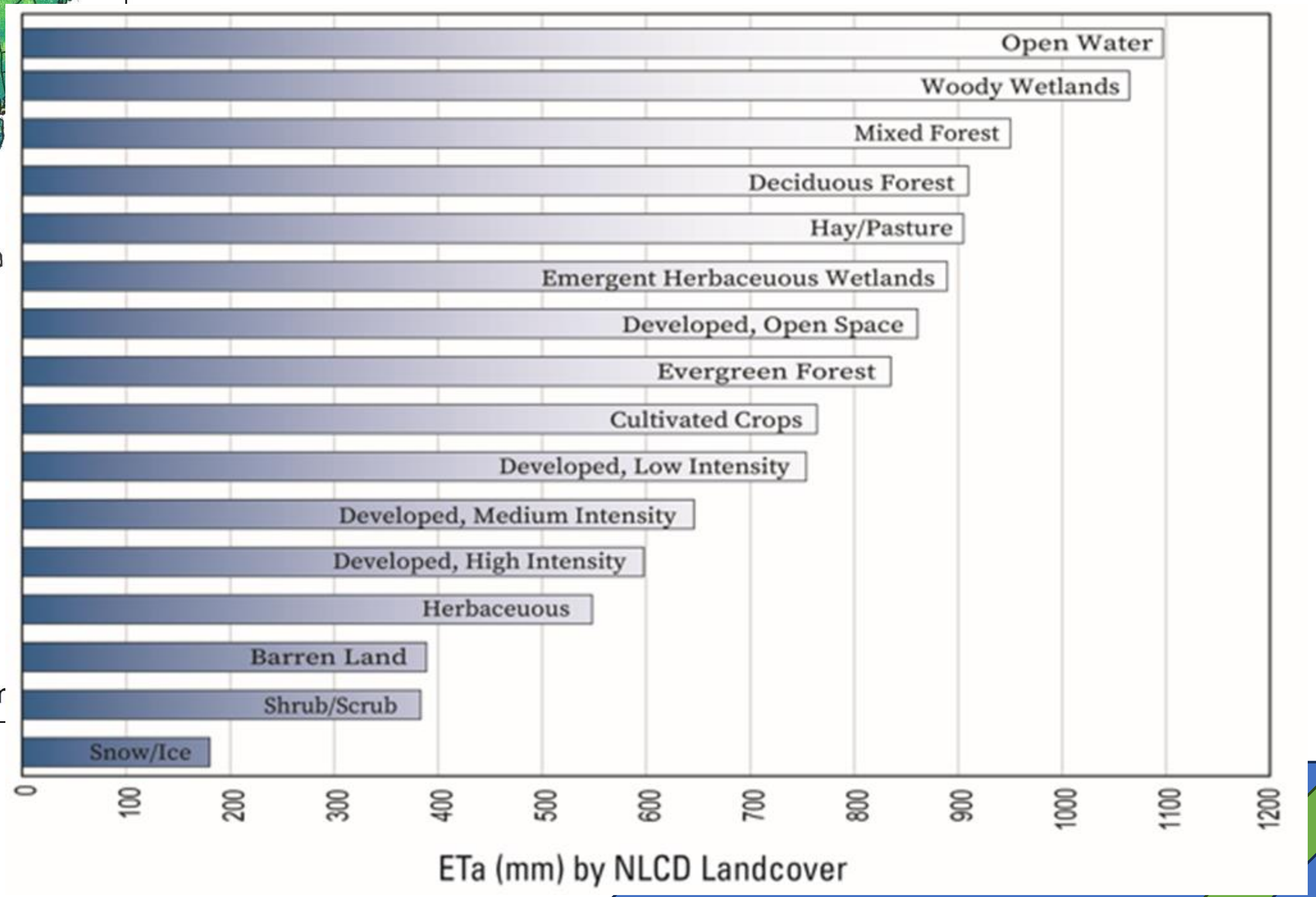
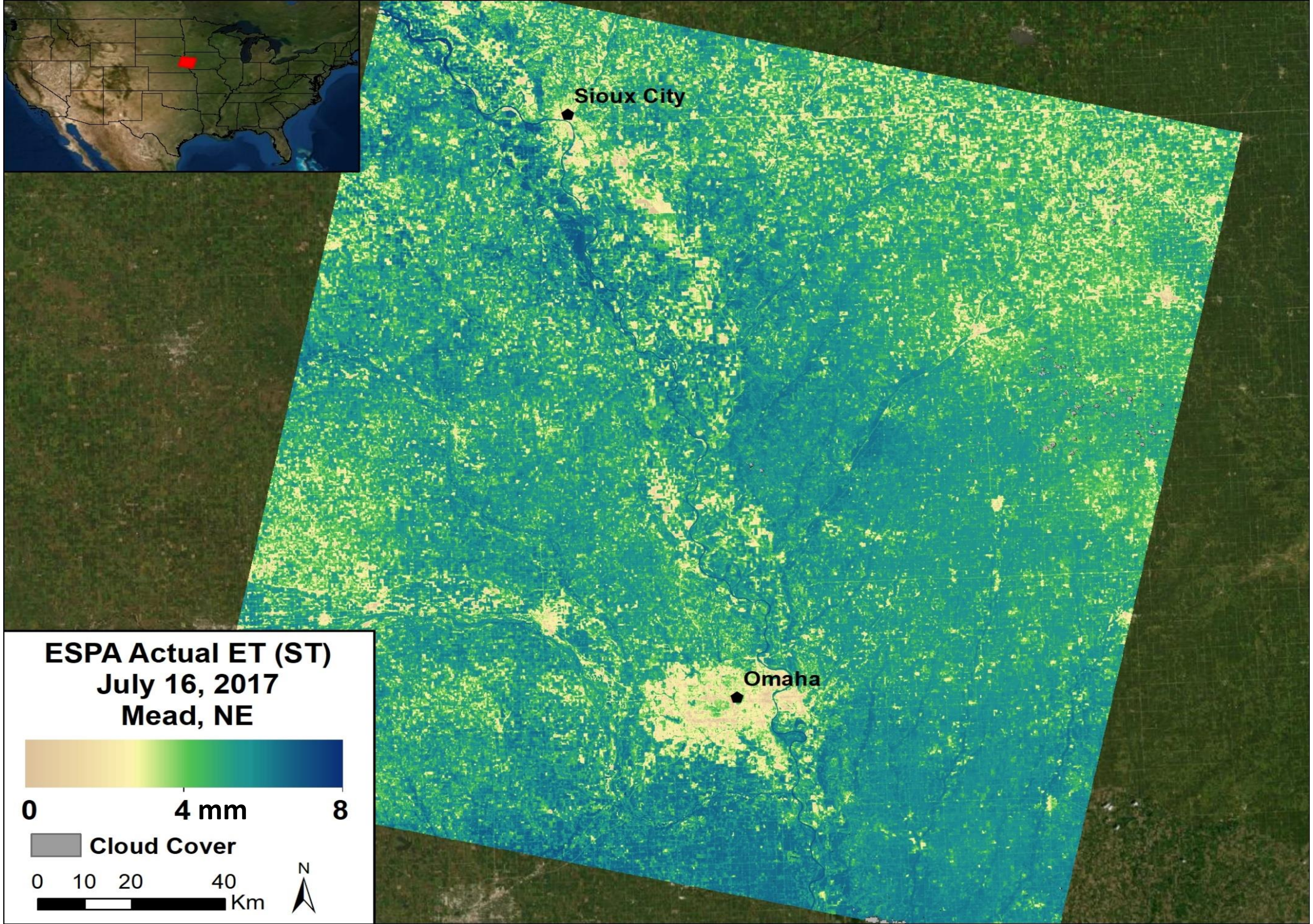
Landsat Scale CONUS ETa (SSEBop, 30 m)



Annual Total in mm



ESPA-based SSEBop ETa July 16, 2017



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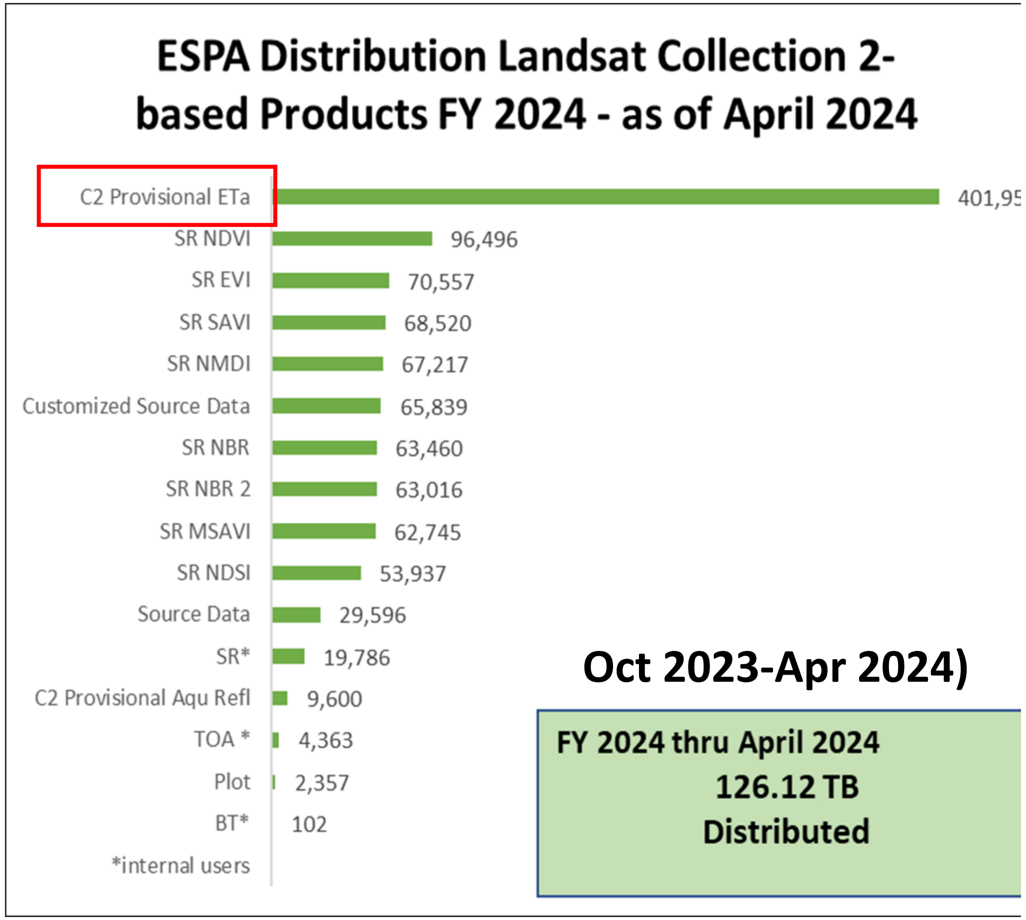
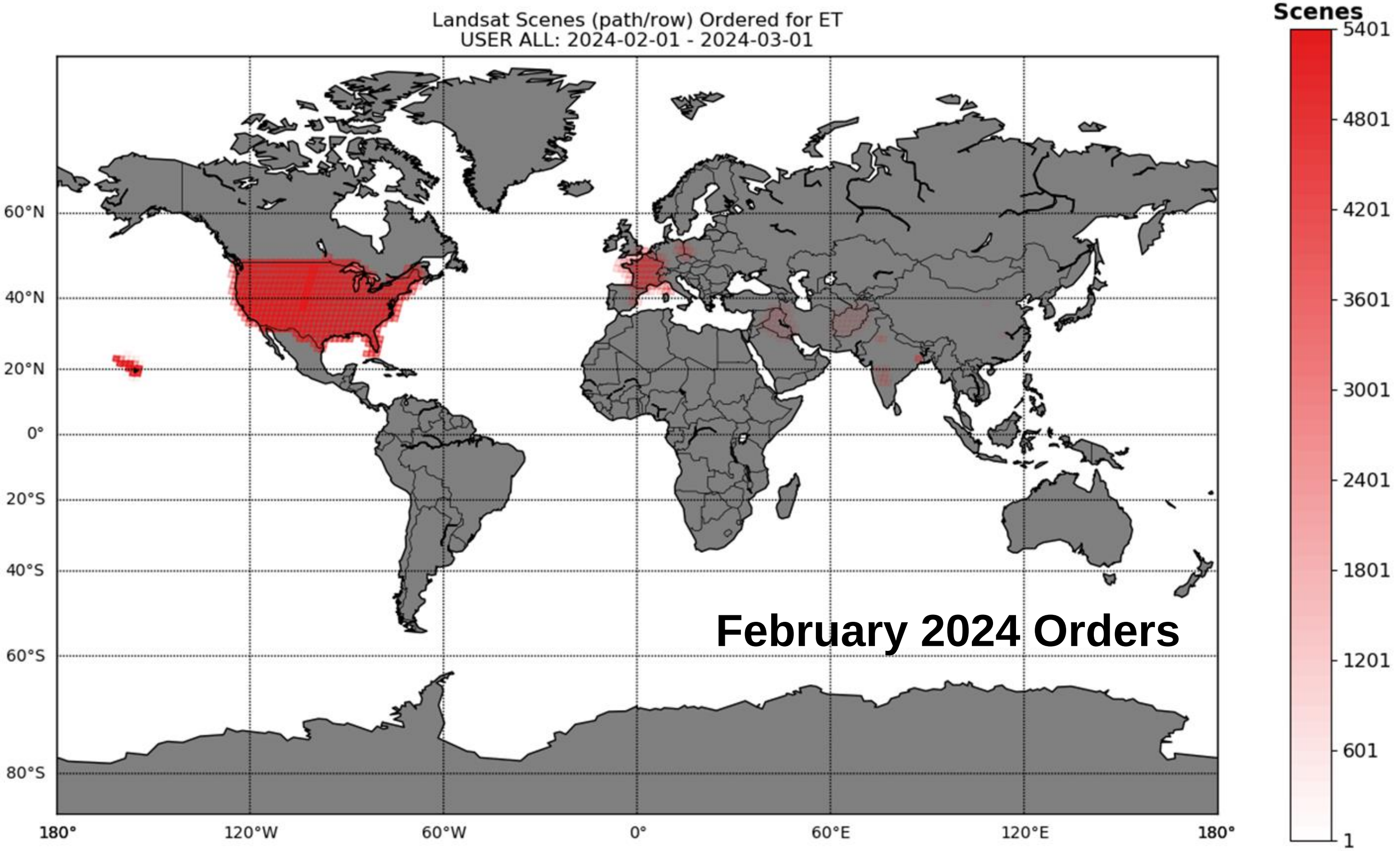
ESPA ET download stats vary by month…





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Model Performance Evaluation…

- Visual, qualitative spatial patterns
- EC (Eddy covariance) Flux Tower
- Basin Water Budget

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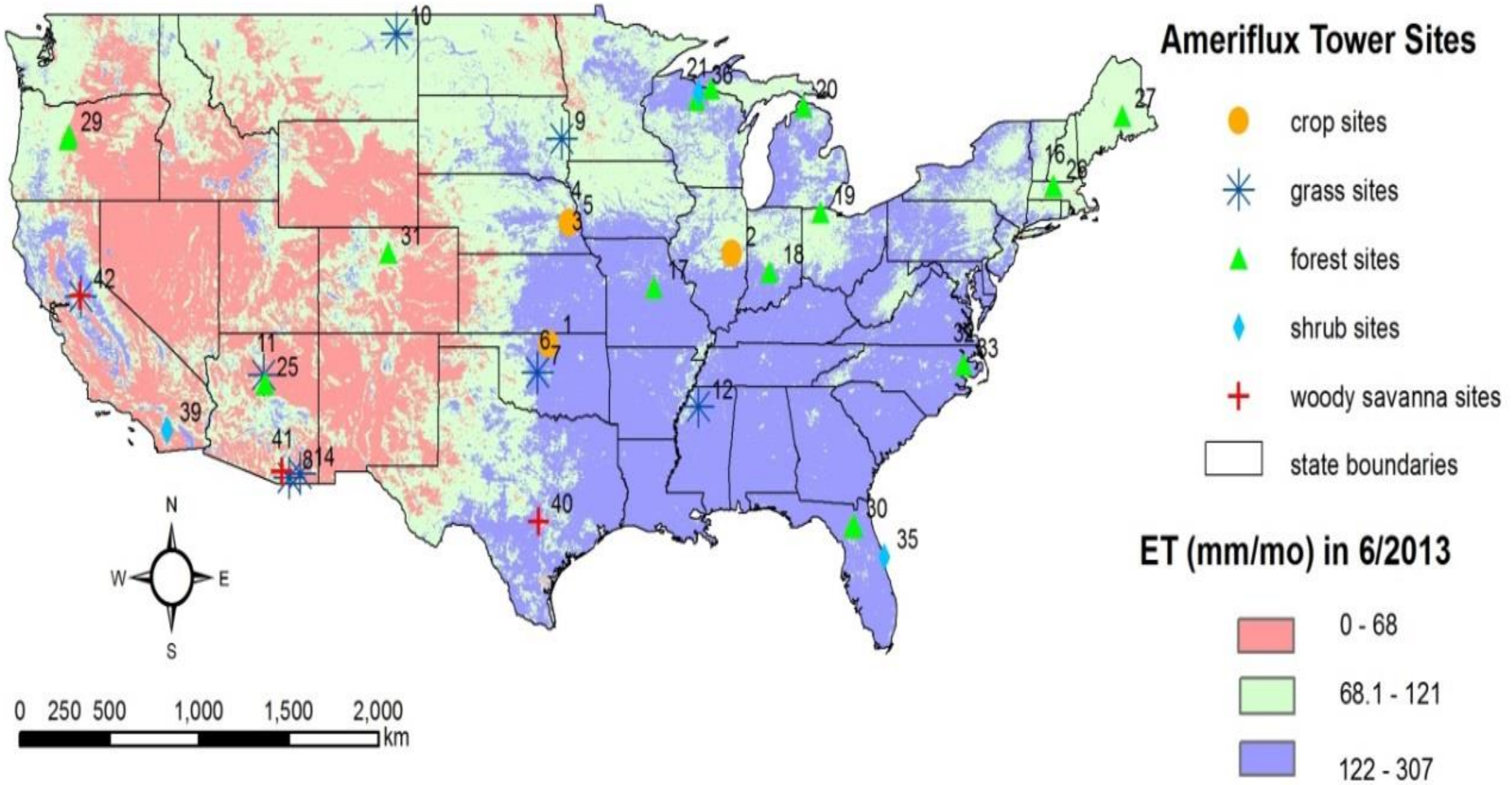
Validation with EC Flux Towers



42 Ameriflux tower stations (2001-2007) with five land cover types—crop, grass, forest, shrub and woody savanna. The background color represents the ET range for June 2013.

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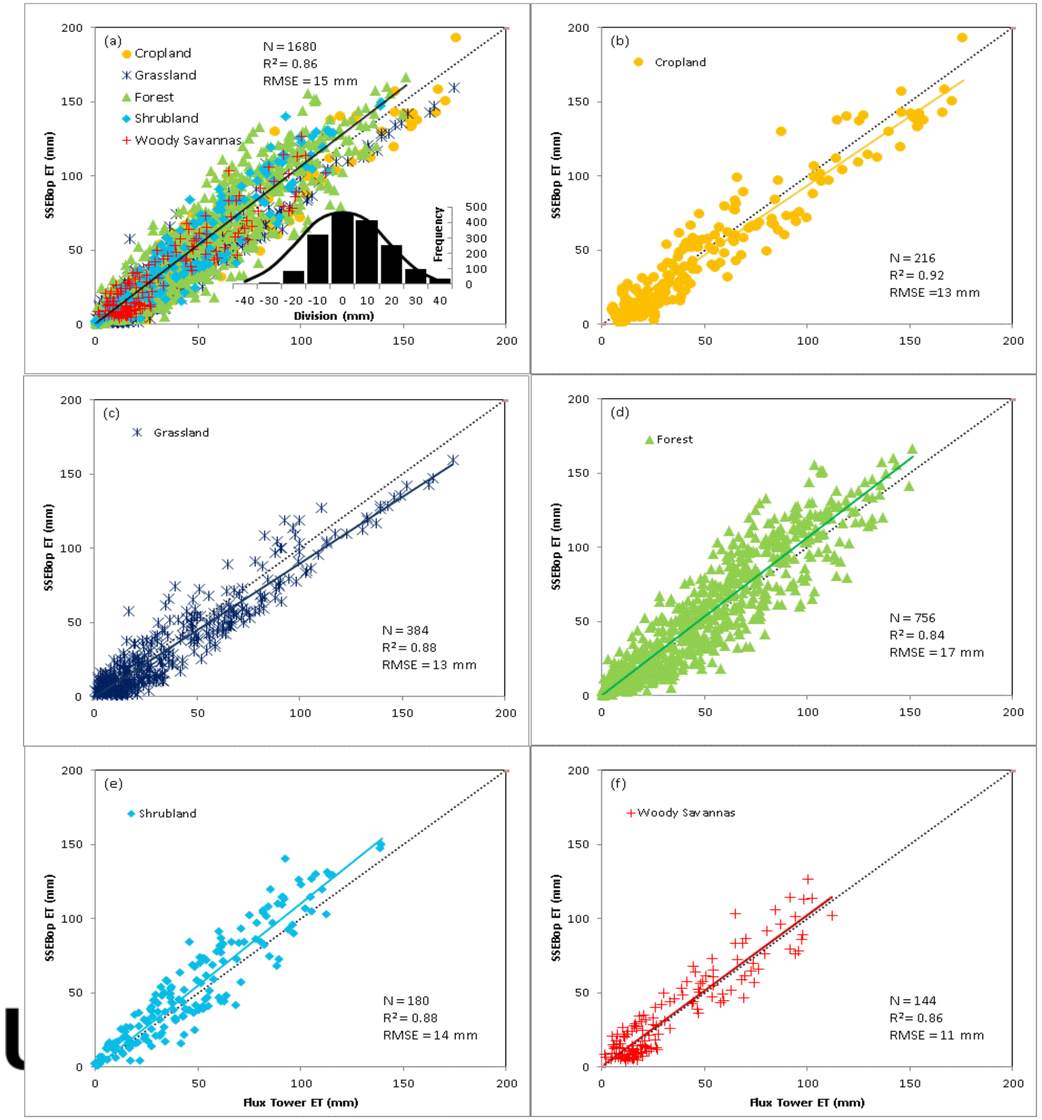
Model validation with EC Flux Towers by cover type



MODIS-based

Comparison scatterplot between monthly ET (mm month^{-1}) from the SSEBop and the ET measurements by eddy covariance method across 42 Ameriflux tower sites during 2001 - 2007.

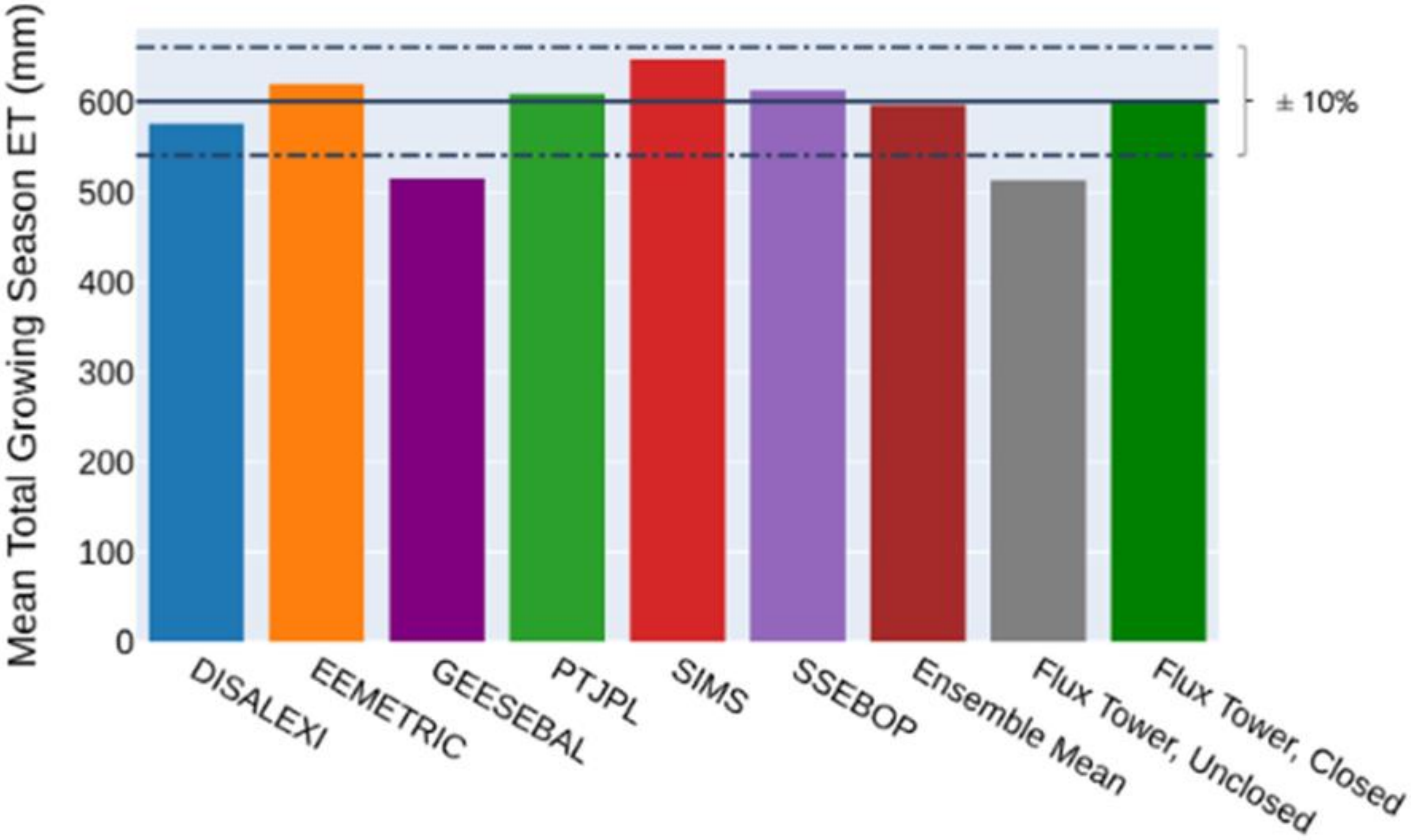
Overall model uncertainty is around 20% for monthly.

Chen et al., 2016 Journal of Hydrology

OpenET Phase I : Model Intercomparison

15 EC Flux Towers over Croplands

Total growing season weighted mean ET (n = 15 sites with 40 total growing seasons) for 6 satellite-driven ET models, the ensemble mean ET, and ET calculated from the closed and unclosed energy balances at each flux tower site.



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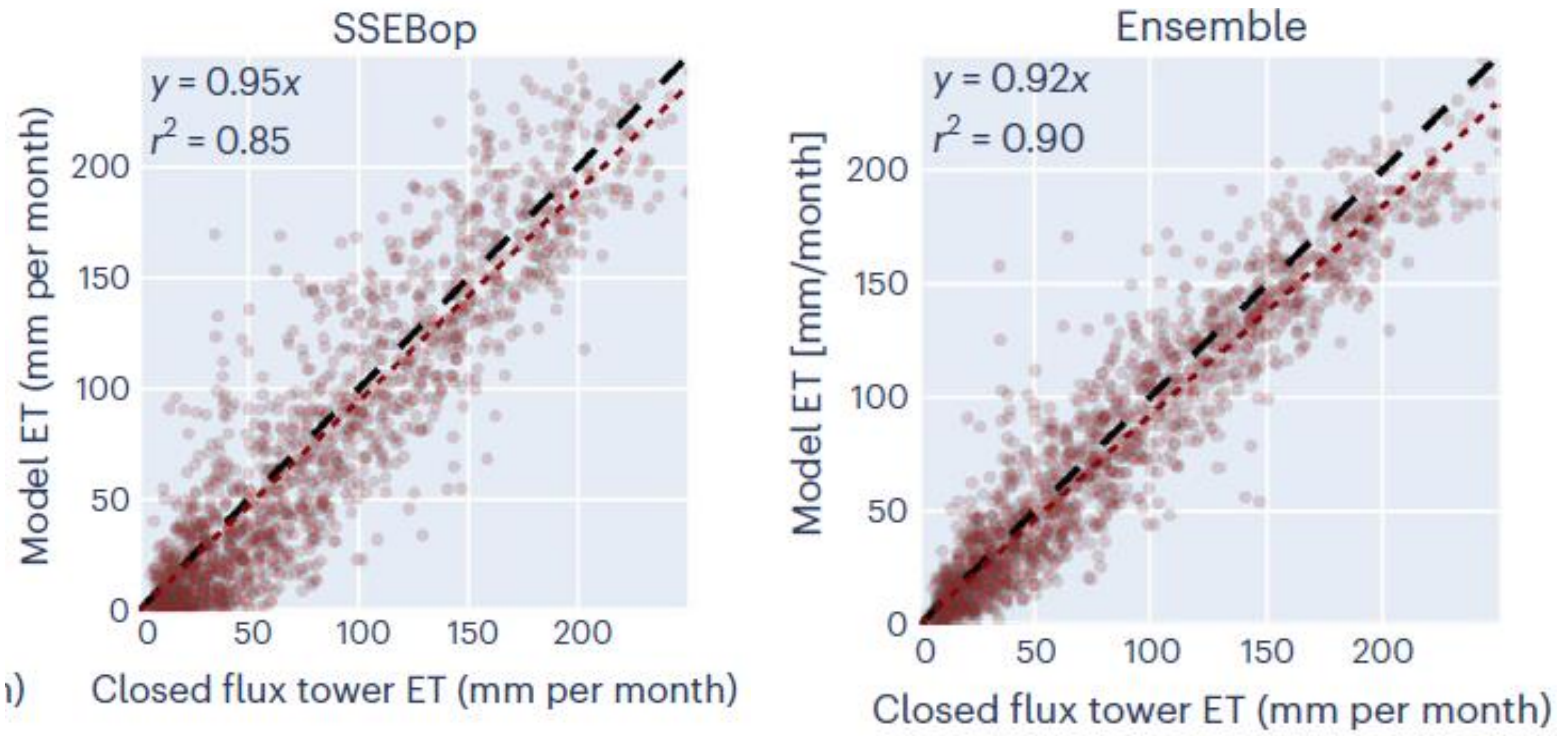
OpenET Phase II : SSEBop Evaluation with 53 Cropland EC Sites in CONUS



Volk et al., 2024.
Nature Water.

nature water

Analysis https://doi.org/10.1038/s44221-023-00181-7

Assessing the accuracy of OpenET satellite-based evapotranspiration data to support water resource and land management applications

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Check for updates

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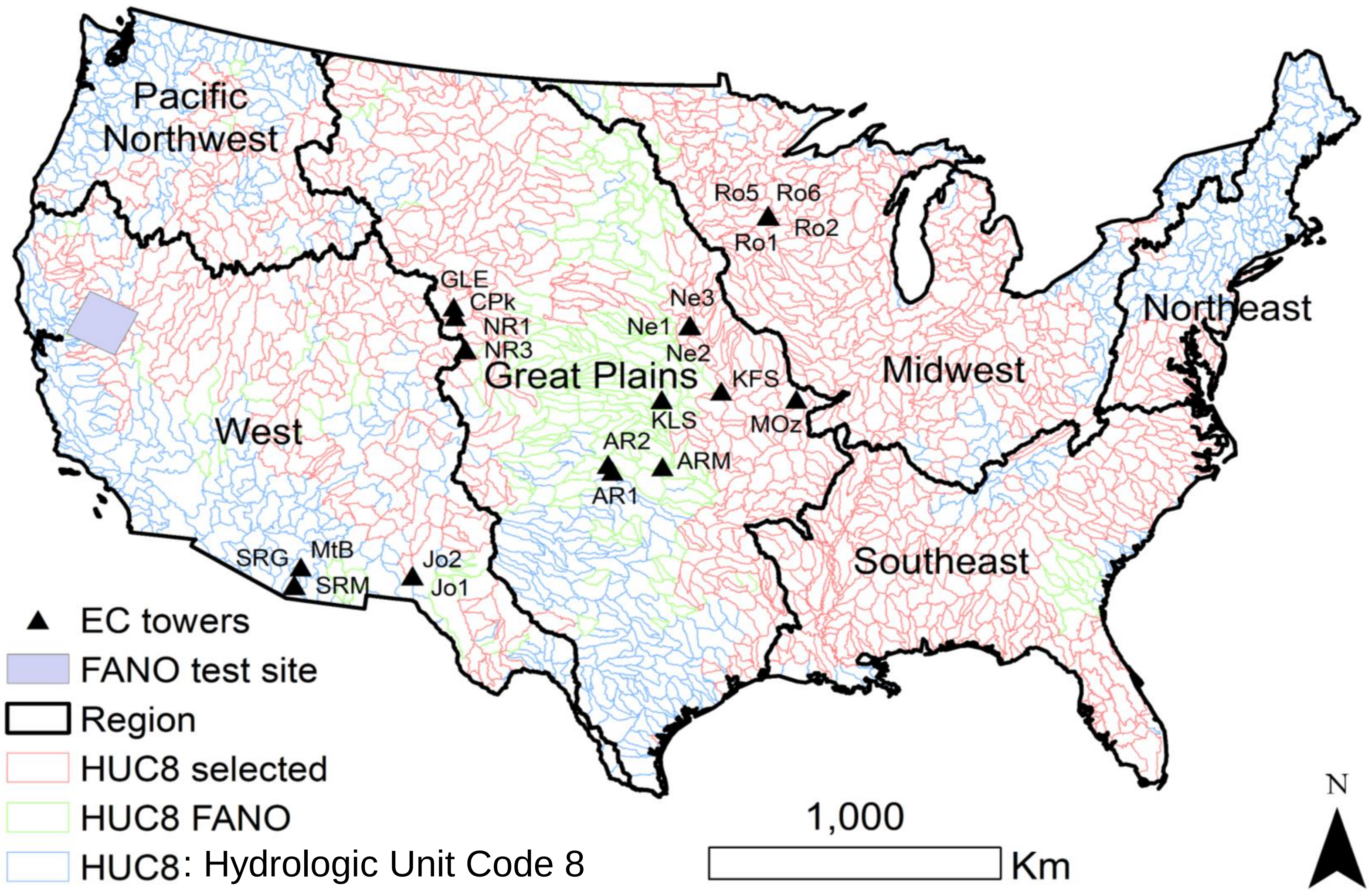
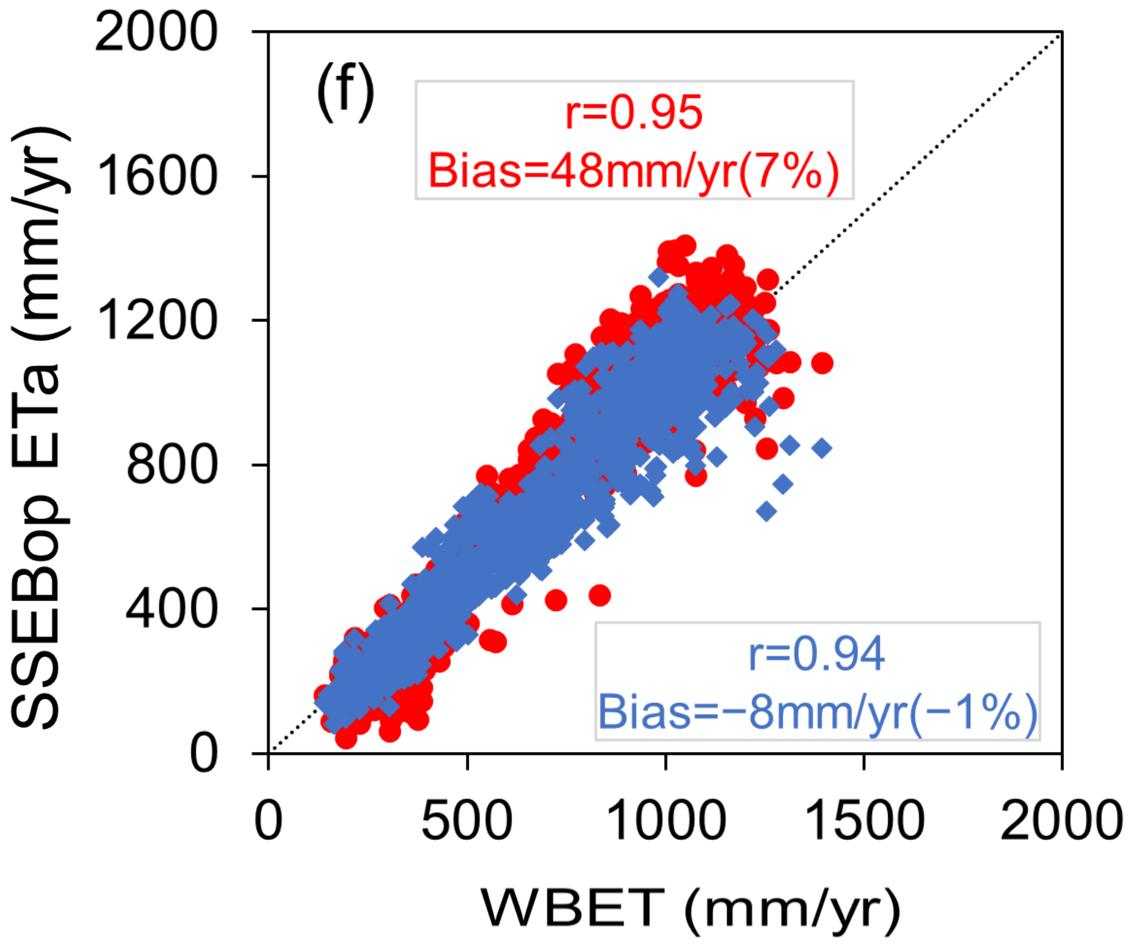
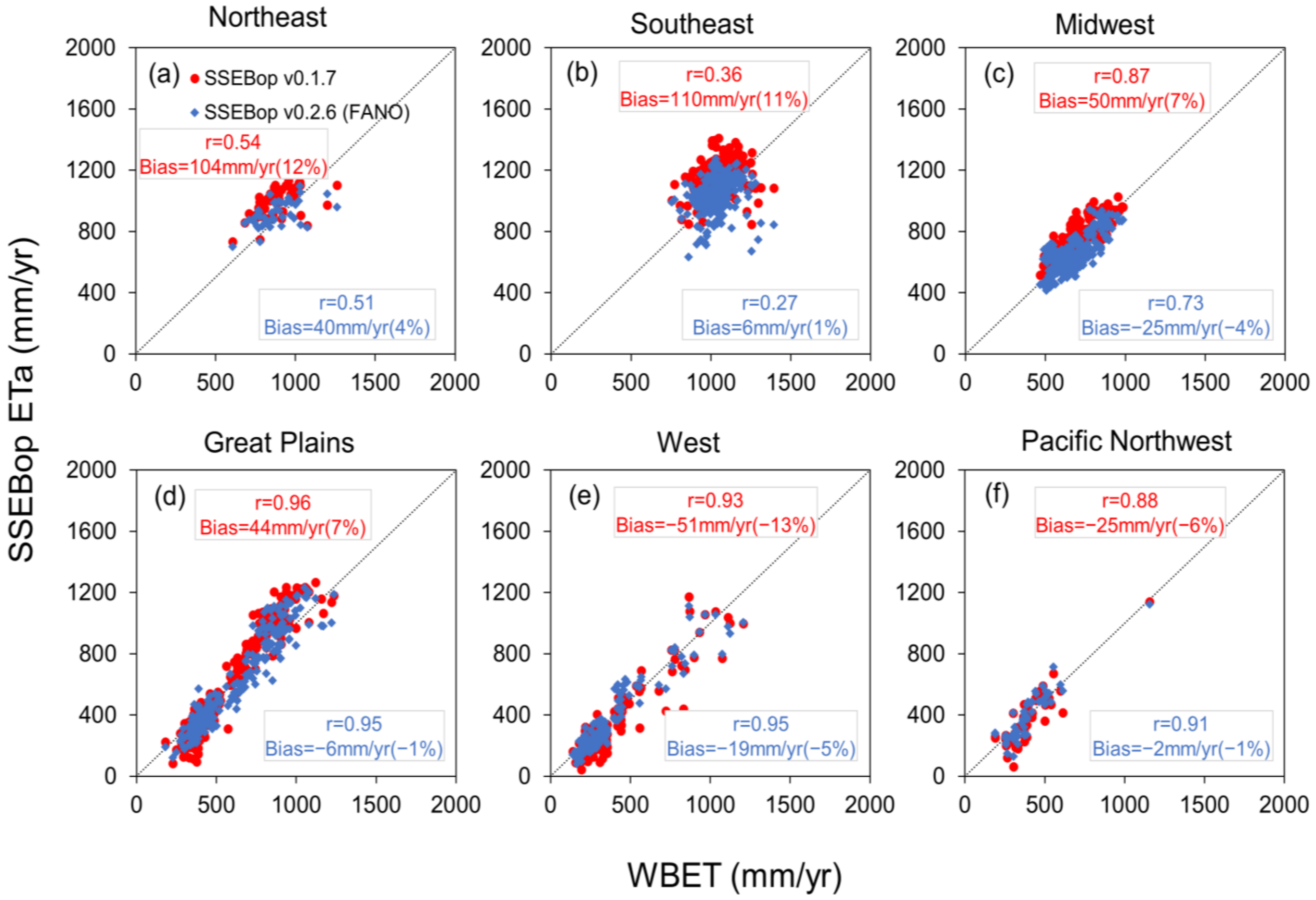
Water Balance ET Evaluation (HUC-8 Basins) grouped by 6 Regions



Water Balance ET Evaluation (continued)





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Summary

- (Provisional) Landsat ETa is useful for field-scale water use mapping and historical (1982-present) analysis.
- Bias Correction: one-time bias correction using locally available observed data (water balance, EC flux tower) will improve the absolute accuracy.
- Operational global SSEBop ET is being generated using thermal imagery (MODIS/VIIRS/Landsat) and gridded weather datasets.

Acquiring actual ET data from ESPA

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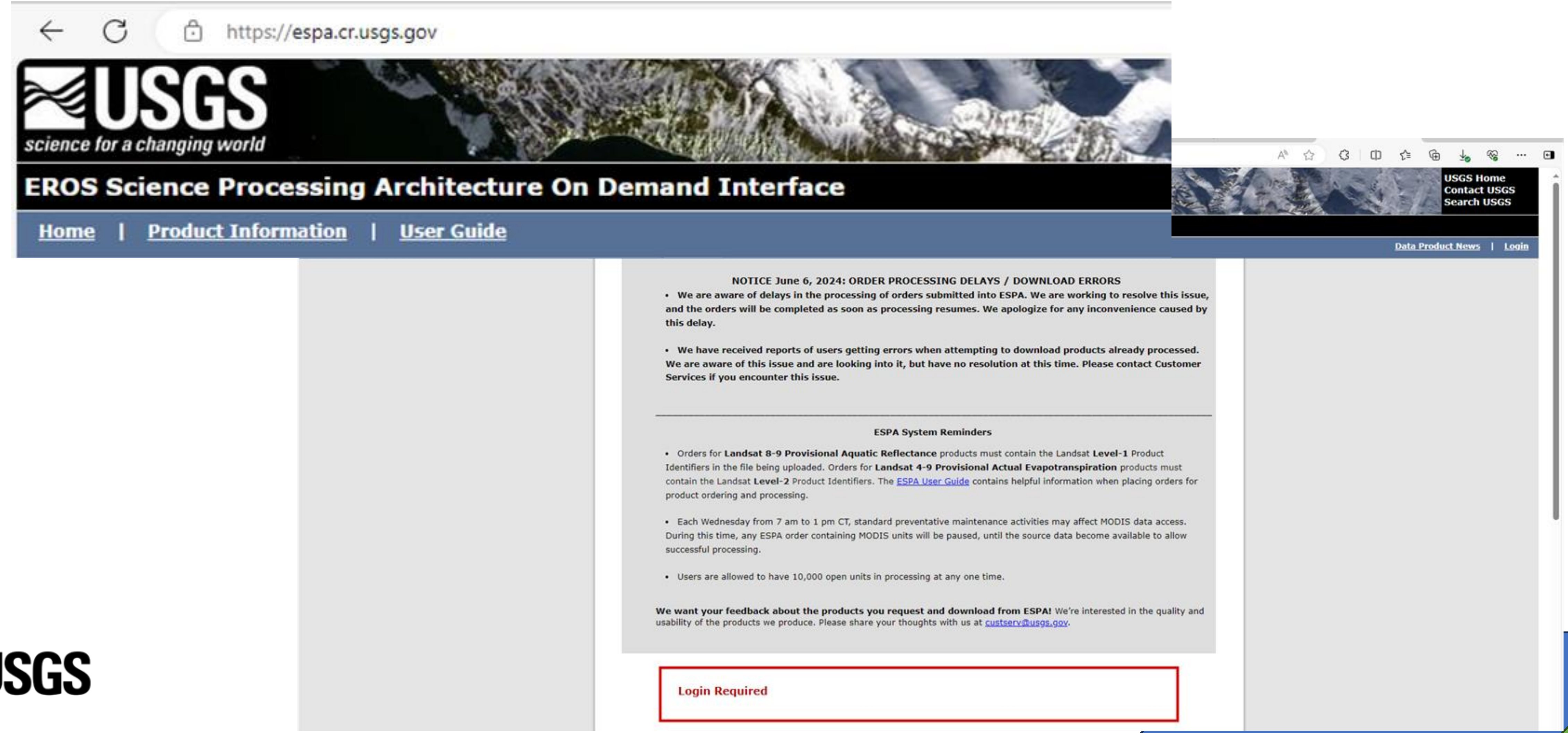
ESPA - EROS Science Processing Architecture On Demand



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Landsat

Since 1972, Landsat satellites have continuously acquired images of the Earth's land surface, providing uninterrupted data to help land managers and policymakers make informed decisions about natural resources and the environment. Data acquired by Landsat satellites are distributed from the USGS Earth Resources Observation and Science (EROS) Center in Sioux Falls, South Dakota.

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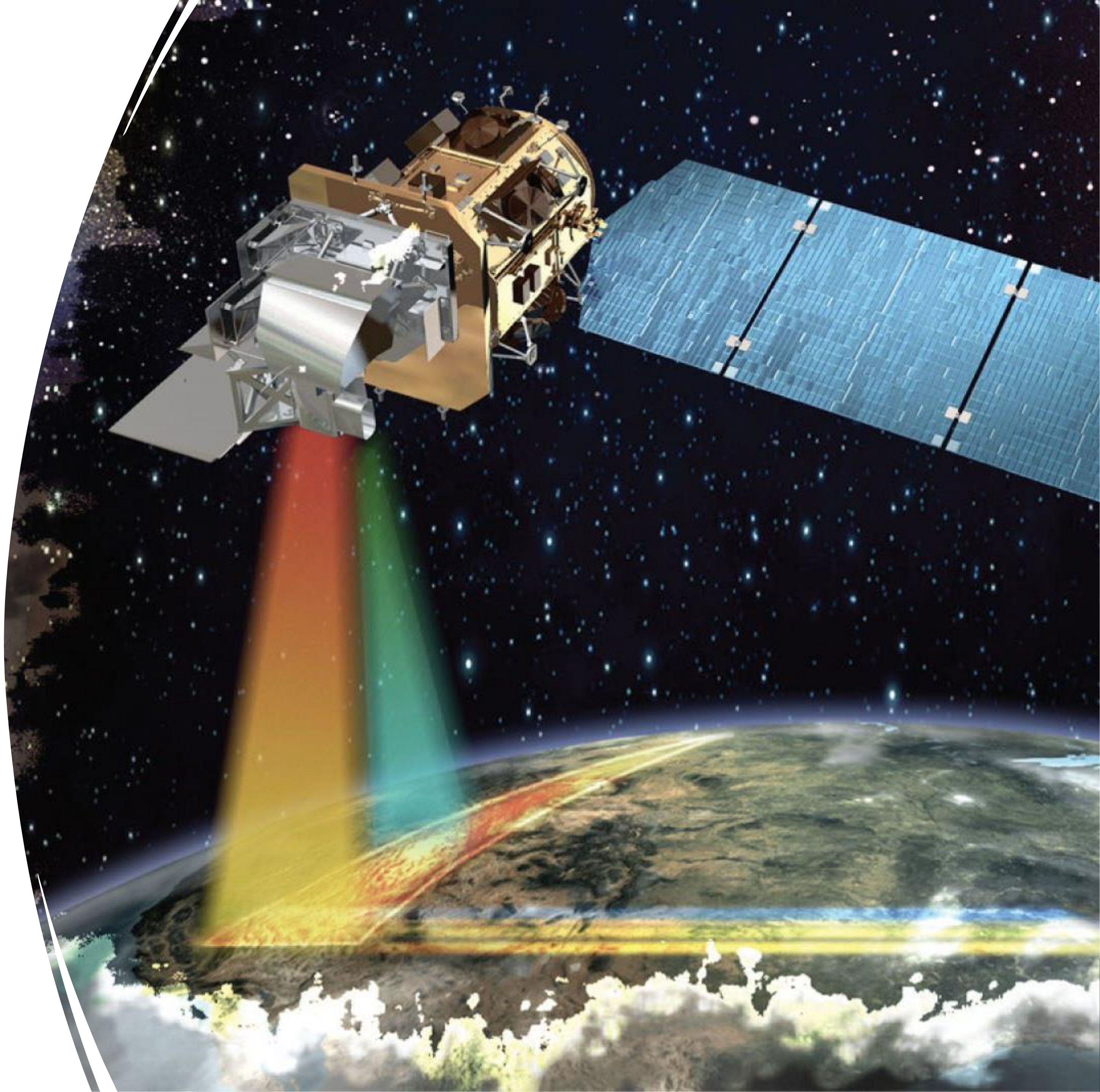
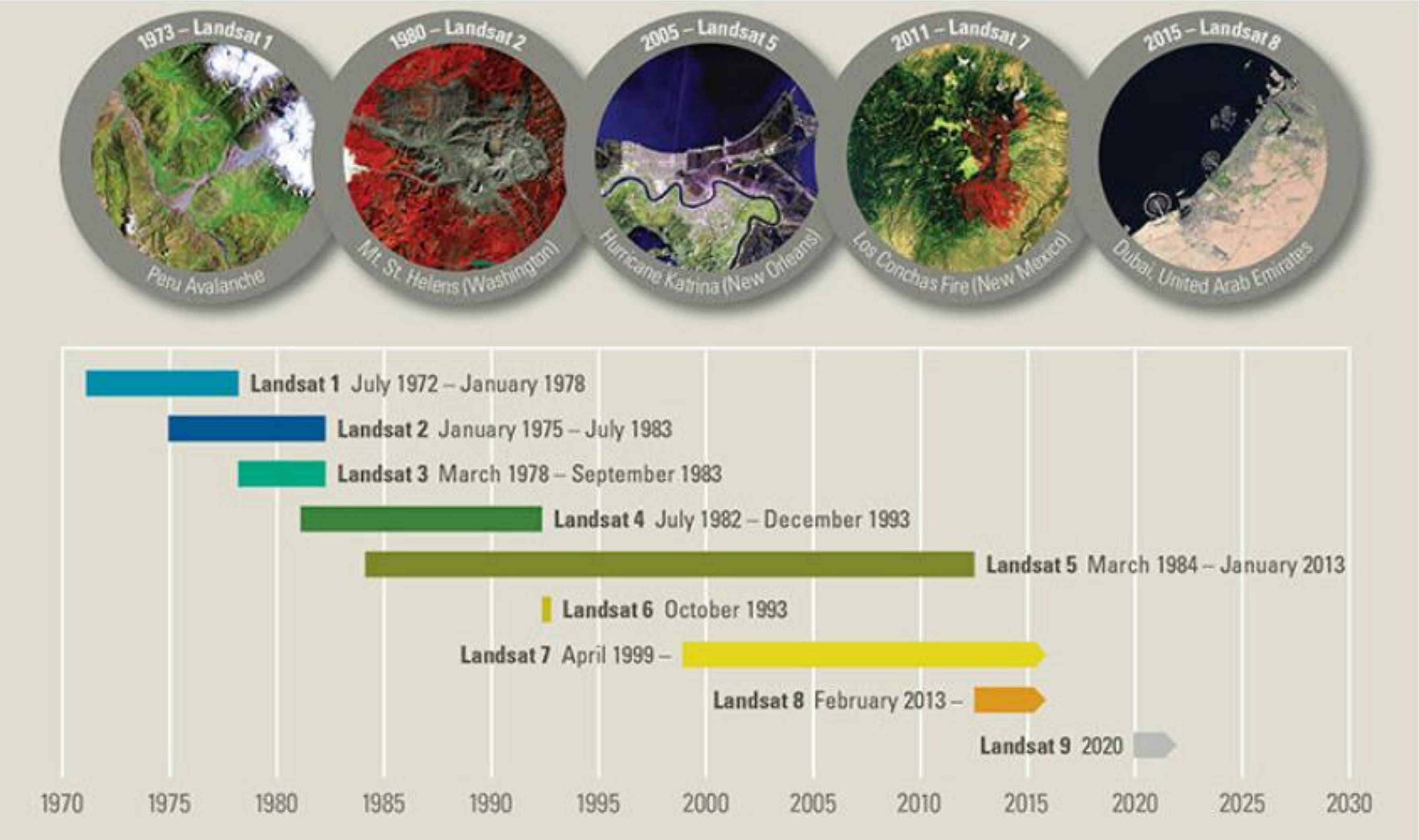


Landsat data history



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Data is organized in collections:

- Collection 1

Original collection of all Landsat data (Landsat 1-7)

- Collection 2

Second major reprocessing effort on the Landsat archive; resulted in several data product improvements that applied advancements in data processing, algorithm development, and data access and distribution capabilities

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- Level-1 → data from Landsat 1-9, radiometrically calibrated and geometrically corrected using ground control points (GCPs) and digital elevation model (DEM) data to correct for relief displacement
  - Real-Time (RT) tier - available for download 4-6 hours after Level-1 product generation
  - Tier 1 (T1) - highest available data quality
  - Tier 2 (T2) - scenes not meeting Tier 1 criteria during processing are assigned to Tier 2 including less accurate orbital information (specific to older Landsat sensors), significant cloud cover, insufficient ground control, etc.

- Level-2 and Level 3 Science Products

- U.S. Analysis Ready Data
  - Level-1 data that are processed into Albers-projected Level-2 Surface Reflectance and Surface Temperature serve as inputs for generating U.S. ARD using an ARD tiling system.

Level-2 Science Products

Level-2 Science Products are time-series observational data of sufficient length, consistency, and continuity to record effects of climate change, and serve as input into Landsat Level-3 Science Products.

Product	Collection
Landsat Surface Reflectance (Landsat 4-9, worldwide) *Measures the fraction of incoming solar radiation that is reflected from Earth's surface to the Landsat sensor*	2
Landsat Surface Temperature (Landsat 4-9, worldwide) *Represents the temperature of the Earth's surface in Kelvin (K)*	2
Landsat Surface Reflectance-Derived Spectral Indices (Landsat 4-9, worldwide) *Vegetation, moisture, burn ratio, and snow measurements data*	2
Provisional Aquatic Reflectance (Landsat 8-9, worldwide) *Measures the spectral distribution of visible solar-reflected radiation upwelling from the upper water column*	2

Level-3 Science Products: Analysis Ready Data (ARD) Inputs

The following Level-3 science products represent biophysical properties of the Earth's surface and are generated from Landsat U.S. Analysis Ready Data (ARD) inputs.

Product	Collection
Dynamic Surface Water Extent (Landsat 4-9, Conterminous U.S., Alaska, Hawaii) *Describes the existence and condition of surface water*	2
Fractional Snow Covered Area (Landsat 4-9, northern and western Conterminous U.S., Alaska) *Indicates the percentage of a pixel covered by snow*	2
Burned Area (Landsat 4-8, Conterminous U.S.) *Represents per pixel burn classification and burn probability*	2

Level-3 Science Products: Scene-based Inputs

The following Level-3 science products are generated from Landsat Level-2 scene-based inputs.

Product	Collection
Provisional Actual Evapotranspiration (Landsat 4-9, Worldwide) *The quantity of water that is removed from a surface due to the processes of evaporation and transpiration*	2

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Standard Processing Parameters

All Landsat Collection 2 Level-2 products are produced by the Landsat Product Generation System (LPGS) using the following parameters:

- Georeferenced Tagged Image File Format (GeoTIFF)
- Cubic convolution (CC)
- Universal Transverse Mercator (UTM) map projection (Stereographic is used for scenes with a center latitude greater than or equal to -63.0 degrees)
- World Geodetic System (WGS) 84 datum
- MAP (North-up) image orientation

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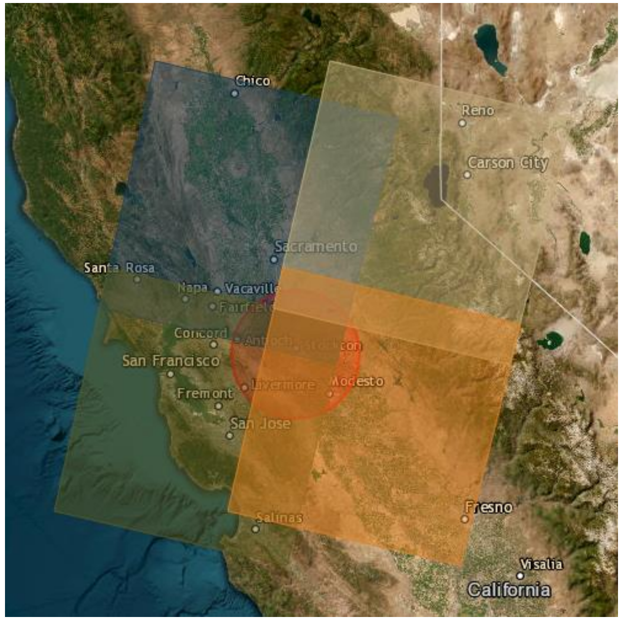
Landsat Scene Properties

Landsat Product Identifier L2: LC09_L2SP_168037_20230714_20230716_02_T1
Landsat Product Identifier L1: LC09_L1TP_168037_20230714_20230714_02_T1
Landsat Scene Identifier: LC91680372023195LGN00
Date Acquired: 2023/07/14
Collection Category: T1
Collection Number: 2
WRS Path: 168
WRS Row: 037
Target WRS Path: 168
Target WRS Row: 037
Nadir/Off Nadir: NADIR
Roll Angle: 0.001



Date Product Generated L2: 2023/07/16
Date Product Generated L1: 2023/07/14
Start Time: 2023-07-14 07:32:57
Stop Time: 2023-07-14 07:33:29
Station Identifier: LGN
Day/Night Indicator: DAY
Land Cloud Cover: 0.00
Scene Cloud Cover L1: 0.00

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Ground Control Points Model: 333
Ground Control Points Version: 5
Geometric RMSE Model: 6.453
Geometric RMSE Model X: 4.728
Geometric RMSE Model Y: 4.391
Processing Software Version: LPGS_16.3.0
Sun Elevation L0RA: 66.57548678
Sun Azimuth L0RA: 113.44698551
TIRS SSM Model: N/A
Data Type L2: OLI_TIRS_L2SP
Sensor Identifier: OLI_TIRS
Satellite: 9
Product Map Projection L1: UTM
UTM Zone: 38
Datum: WGS84
Ellipsoid: WGS84

Scene Center Lat DMS: 33°10'37.31"N
Scene Center Long DMS: 45°02'51.97"E
Corner Upper Left Lat DMS: 34°13'21.58"N
Corner Upper Left Long DMS: 43°47'45.56"E
Corner Upper Right Lat DMS: 34°13'18.16"N
Corner Upper Right Long DMS: 46°17'50.50"E
Corner Lower Left Lat DMS: 32°06'34.92"N
Corner Lower Left Long DMS: 43°49'28.31"E
Corner Lower Right Lat DMS: 32°06'31.75"N
Corner Lower Right Long DMS: 46°15'59.76"E
Scene Center Latitude: 33.17703
Scene Center Longitude: 45.04777
Corner Upper Left Latitude: 34.22266
Corner Upper Left Longitude: 43.79599
Corner Upper Right Latitude: 34.22171
Corner Upper Right Longitude: 46.29736
Corner Lower Left Latitude: 32.10970
Corner Lower Left Longitude: 43.82453
Corner Lower Right Latitude: 32.10882
Corner Lower Right Longitude: 46.26660

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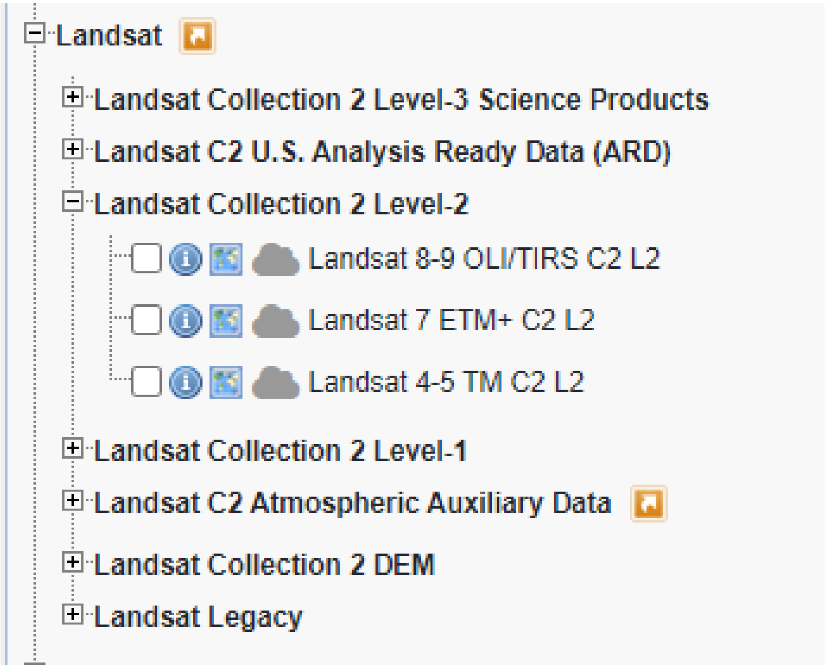
Data Access

- Landsat Collection 2 Level-1 and Level-2 data are available for download from

- EarthExplorer
- GloVis
- LandsatLook Viewer



The data are located under the Landsat category, Landsat Collection 2 Level-1/Level-2 subcategory, and listed as -Landsat 9, Landsat 8, Landsat 7, Landsat 4-5 TM, and Landsat 1-5 MSS datasets.

The EarthExplorer "Additional Criteria" tab for each Collection 2 dataset allows users to select parameters for each Landsat sensor (i.e., Landsat 7 SLC-on/SLC-off, T1/T2/RT, or RMSE range)

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Hands-On Demo

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Hands-On demo

- Establish NASA Earth account
- Scene selection (sensor, time period, cloud cover, etc.)
- Download scene IDs
- Prepare text file with scene ID listings
- Order ET data from ESPA website
- Receive status email with download link
- Unzip data files and content
- Display and inspect in GIS

Coffee Break
10.00 – 10.30am

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Creating Summaries and Aggregations of ET

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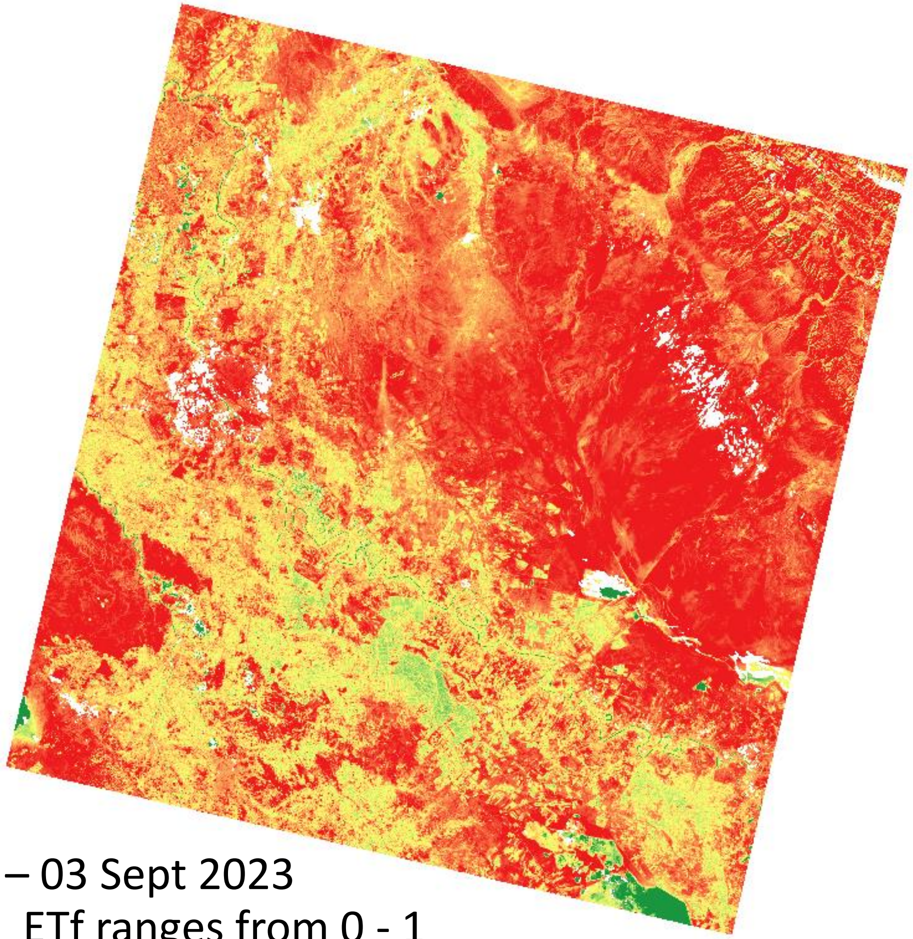
What is an Overpass ET image?

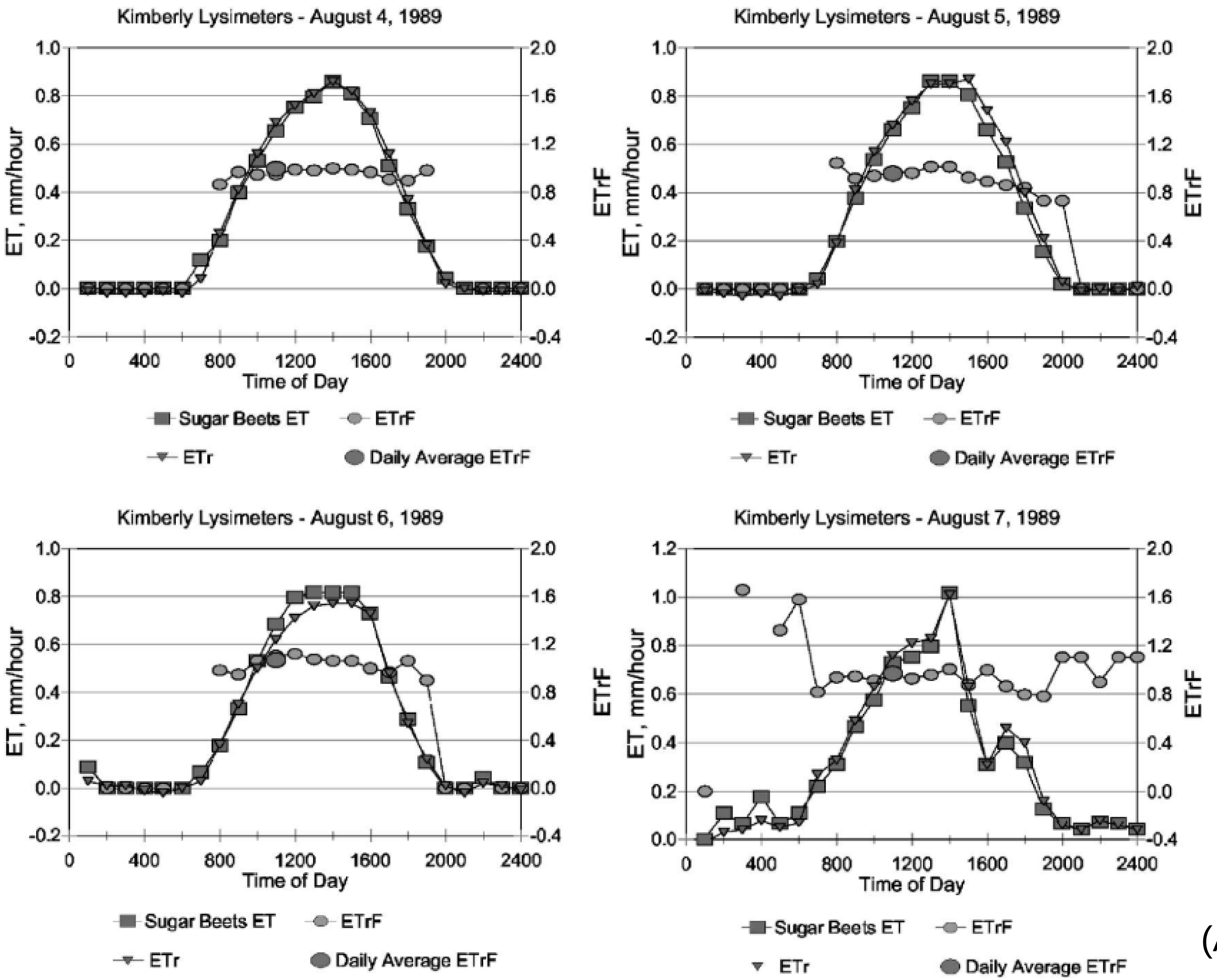


ETf – 03 Sept 2023

ETf ranges from 0 - 1

- Snapshot in time of ET
- ETf instant ~ ETf all day long
- ETf instant * ETo daily = ETa Daily

- Overpass ETf → Daily ETf? That's the beauty of ETf



(Allen et al., 2007)

Fig. 2. Hourly ET and ET_rF for sugar beet crop versus time [based on lysimeter observations by Wright (1982), USDA-ARS, Kimberly, Idaho] for a series of four days in August (ET_rF for the 24 h period is the larger circle plotted at 11:00, which is satellite overpass time)

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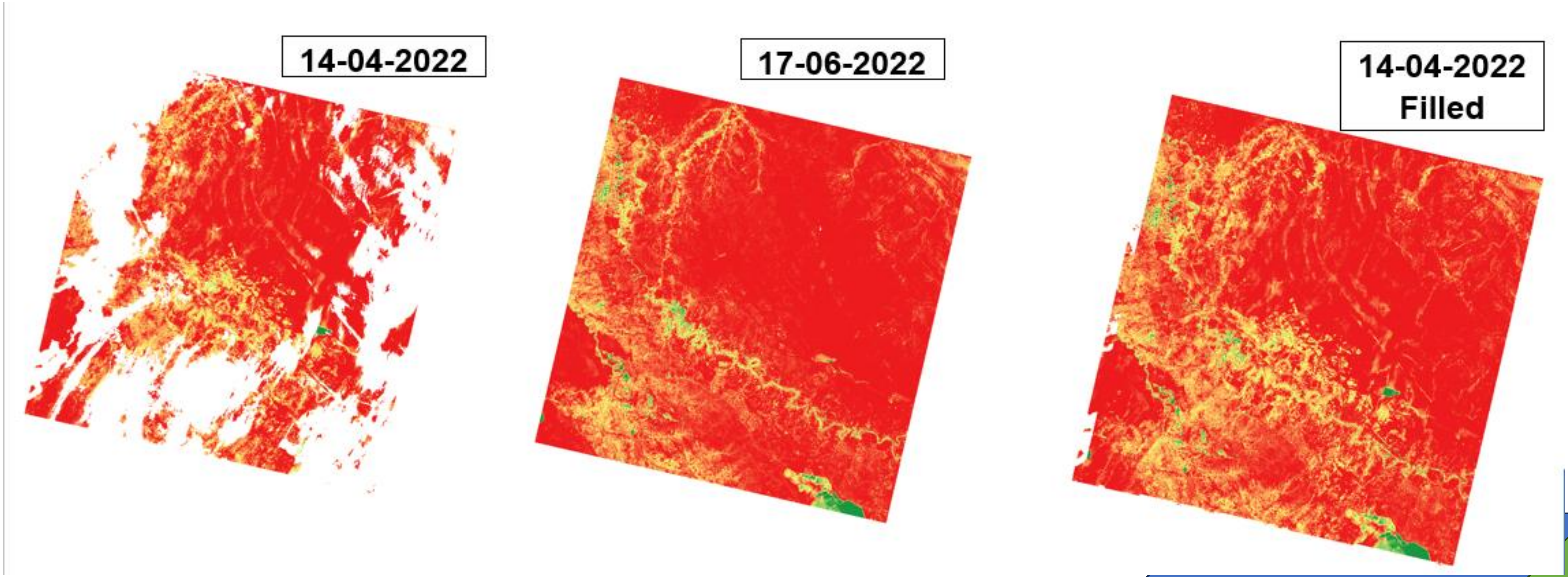
Gapfilling the ETf rasters

- Holes in rasters from clouds, other issues…We fill them with images from before/after



(Allen et al., 2007)

From overpass to daily ETf

- We interpolate ETf from overpasses…
- But how to Interpolate? linear, spline, other?
- ETf is analogous to a crop coefficient

ETo/ETr * Kc = ETc

ETo/ETr * ETf = ETa

Very Similar!

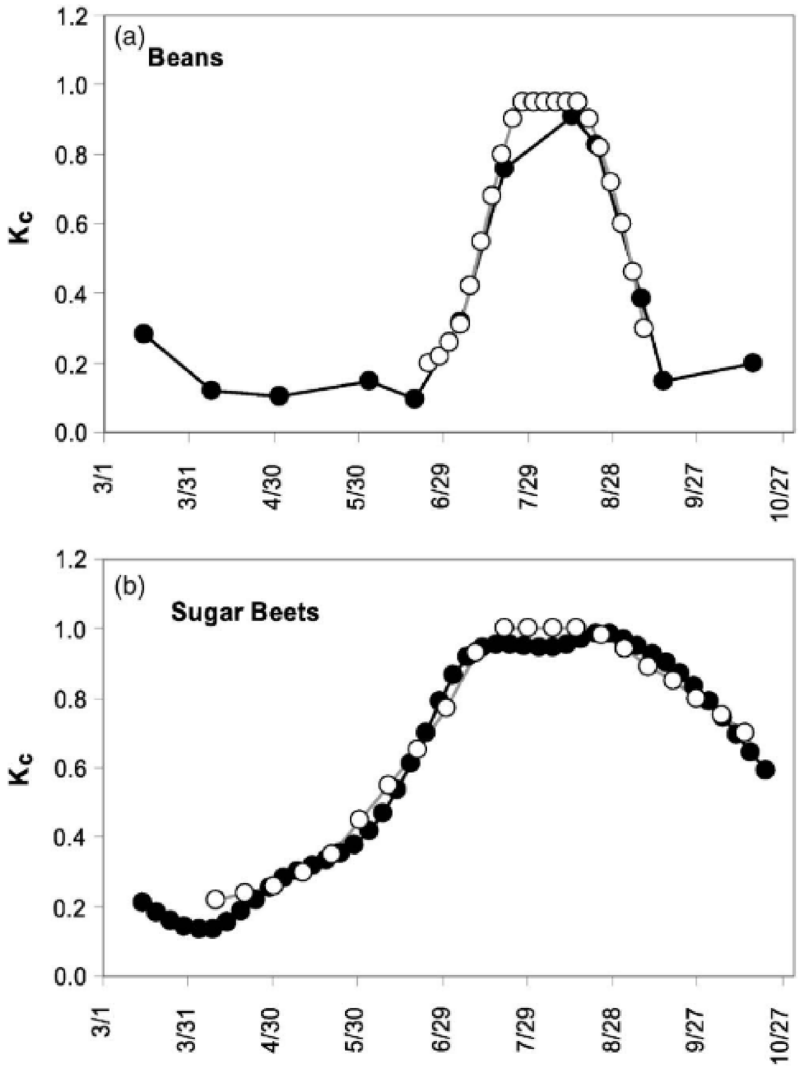
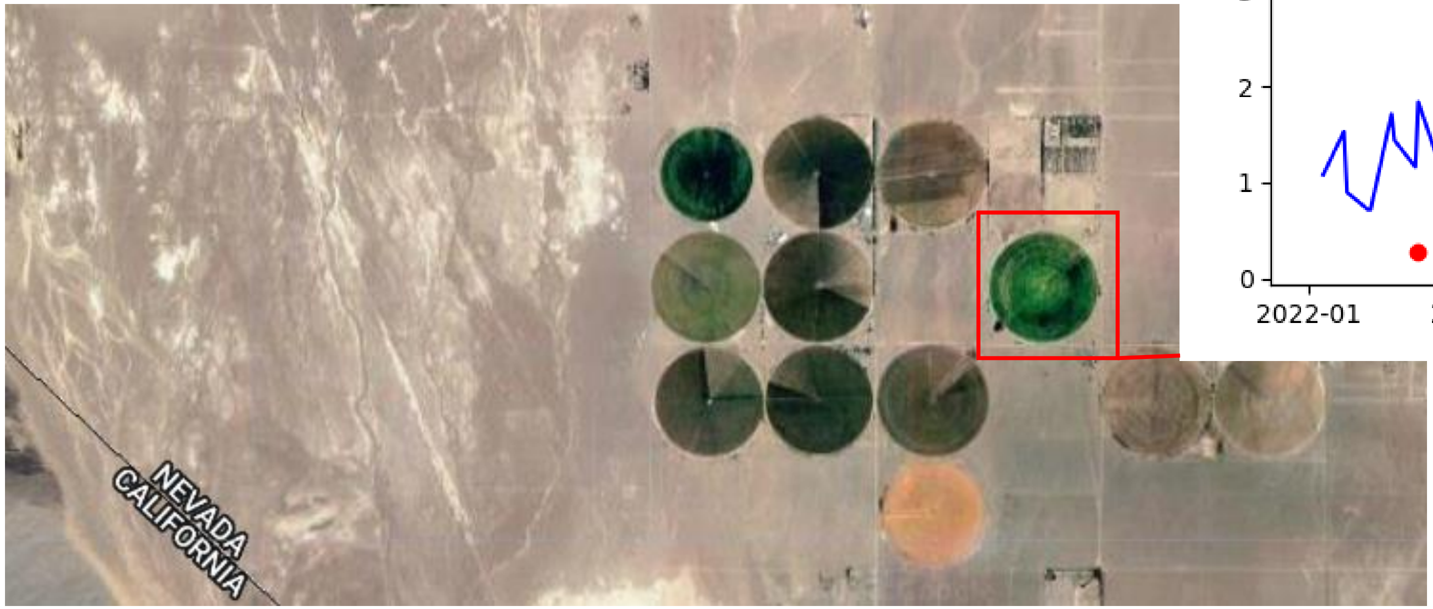
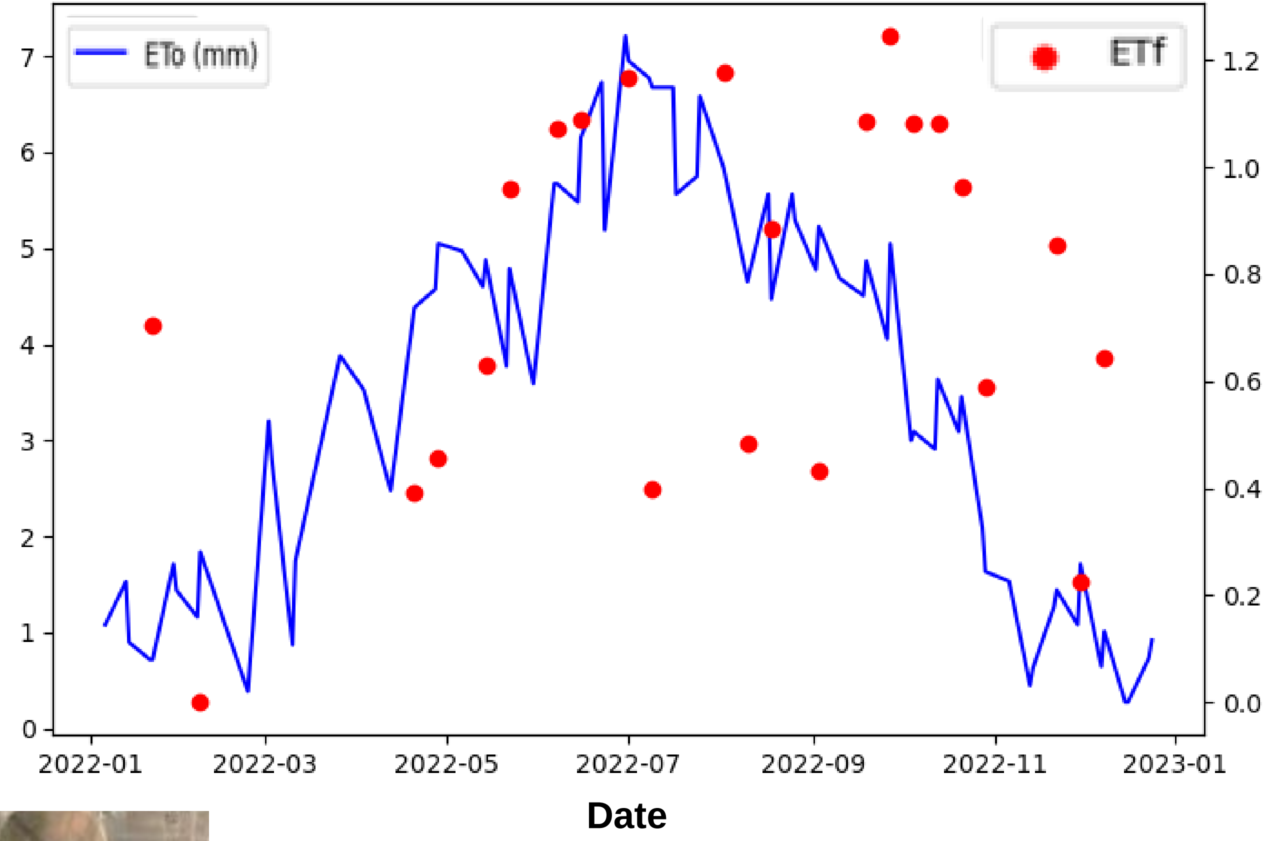


Fig. 4. ET_rF from METRIC for: (a) dry bean crop in southern Idaho in 2000 (solid symbols) compared to a K_c curve [published by the USBR AgriMet (2000) (open circles) (adapted from Tasumi et al. 2005a,b]; (b) sugar beet crop where a cubic spline has been used to interpolate between satellite image dates

Illustration of Interpolation





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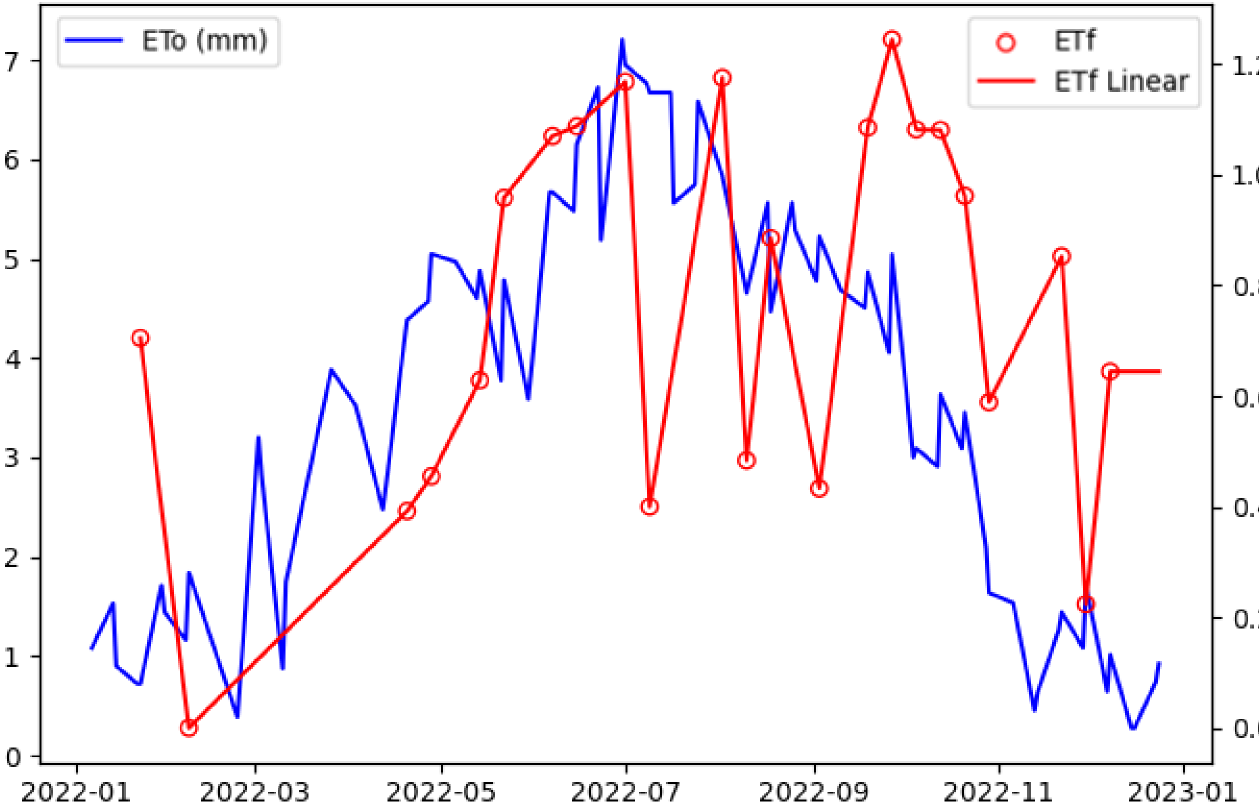
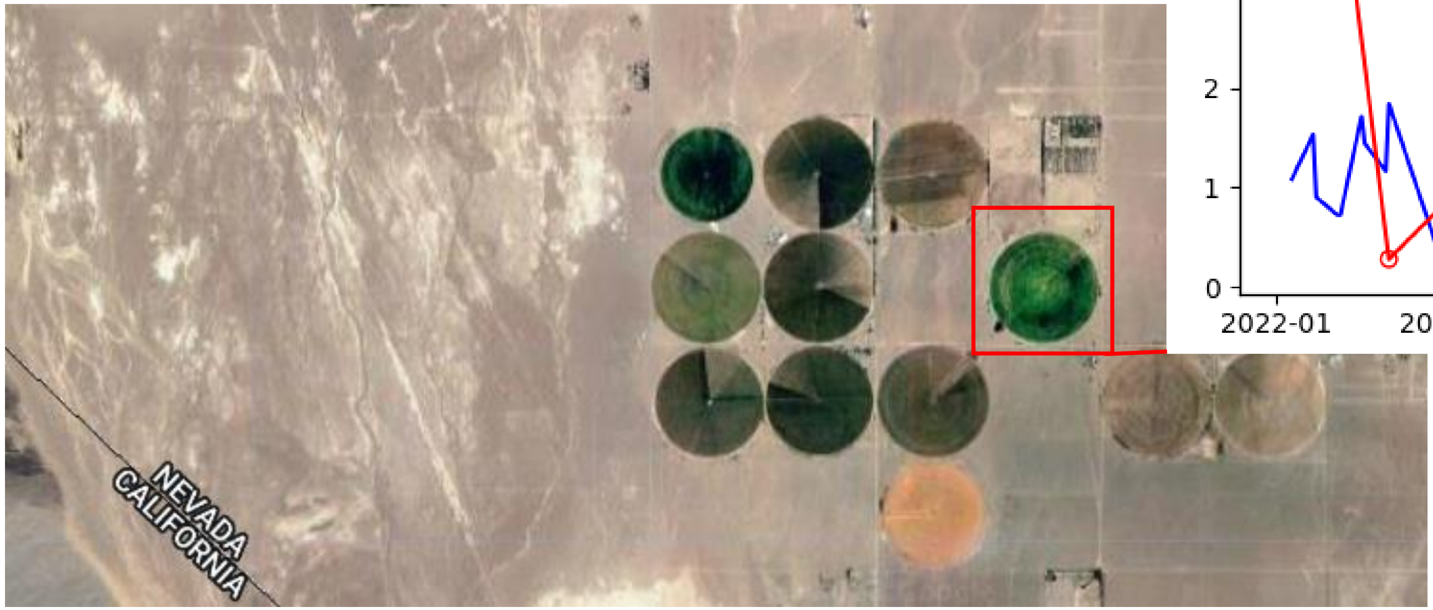
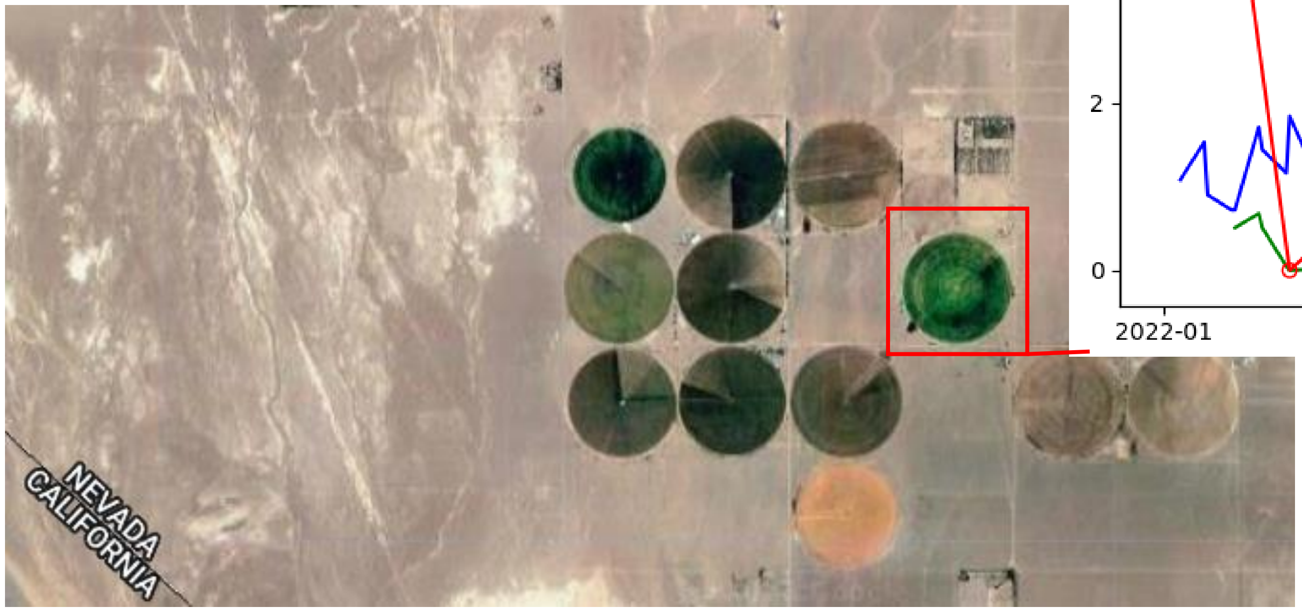
Interpolation continued

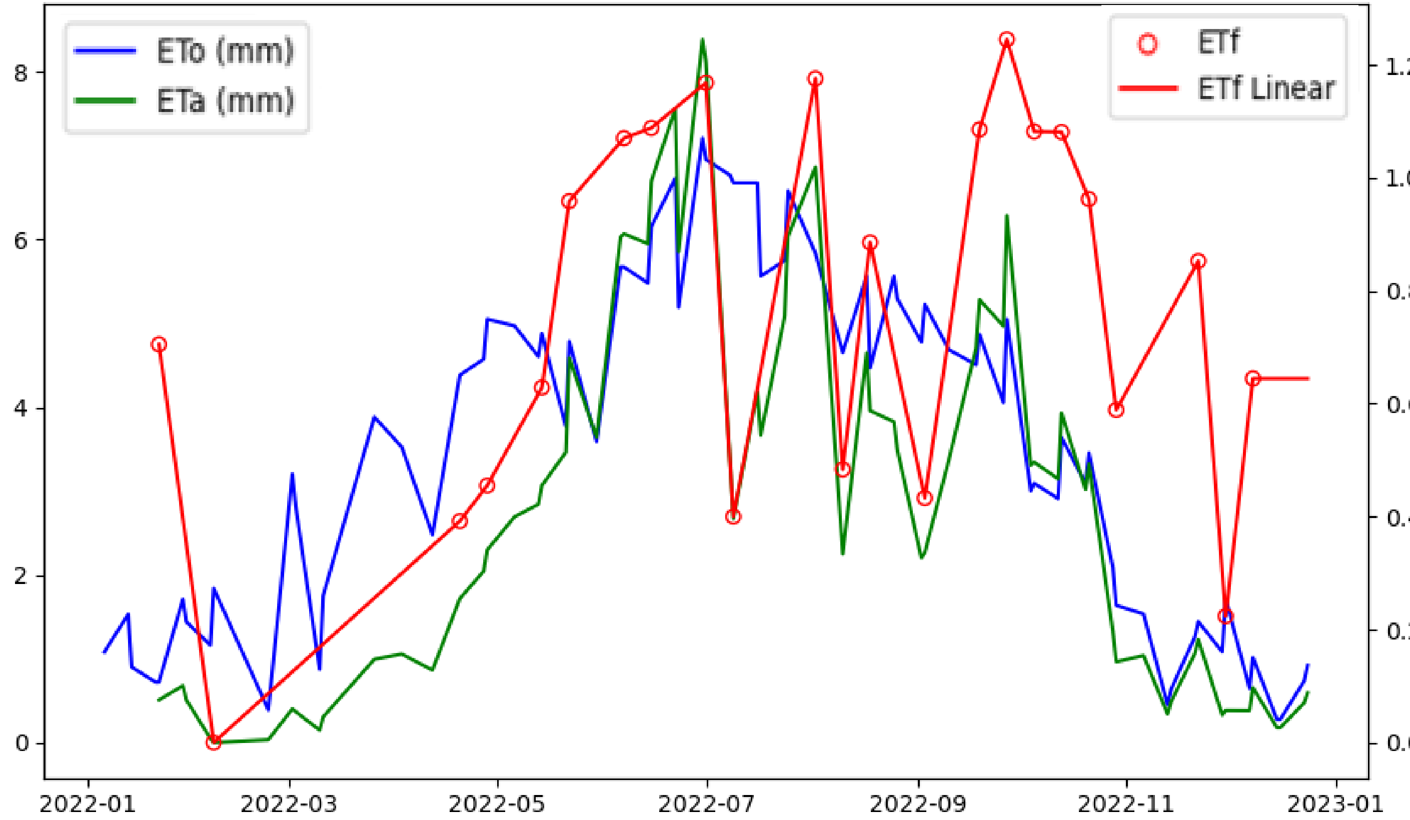




USGS

Interpolation continued





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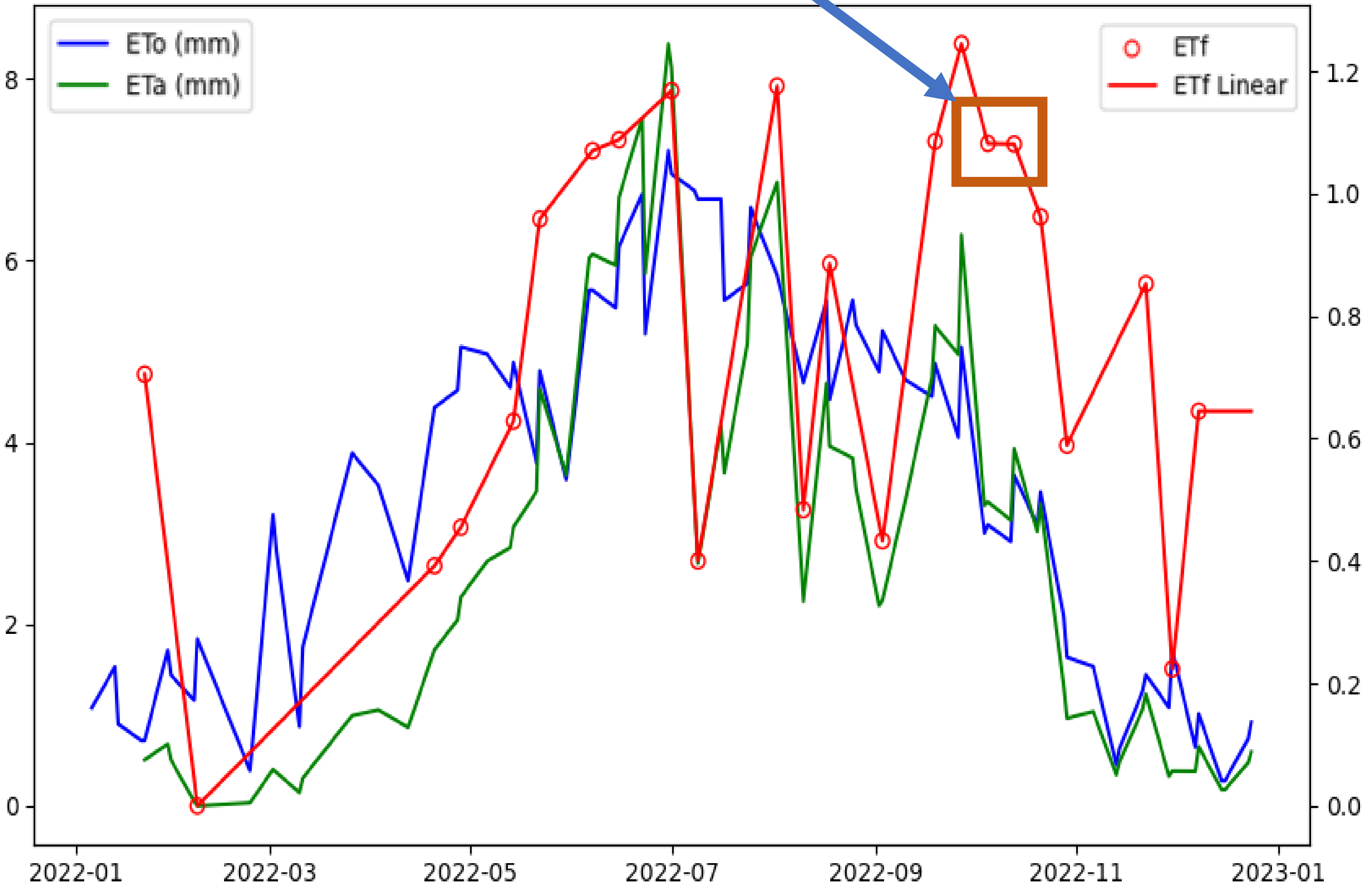
Two identical ETfs in a row… A telltale sign of gap-filling



Now we have daily ETa, which can be aggregated into:

- Monthly ETa
- Yearly ETa
- Seasonal ETa
- Anything you want (except for hourly!)

Hands-On Demo

Creating Aggregations of ET

- Activate conda environment (ArcPy, open source)
- Navigate to GIT repository “eros-hydro”
- Install appropriate version
- Run script
  - Script 1: postprocessing of ESPA files (unzipping, scaling, etc.)
  - Script 2: gap filling of overpass ET fraction (ETf)
  - Script 3: interpolating gap filled overpass ETf to daily ETf and ETa
  - Script 4: Aggregating daily ETa (monthly, seasonal, annual)

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Applications of ET

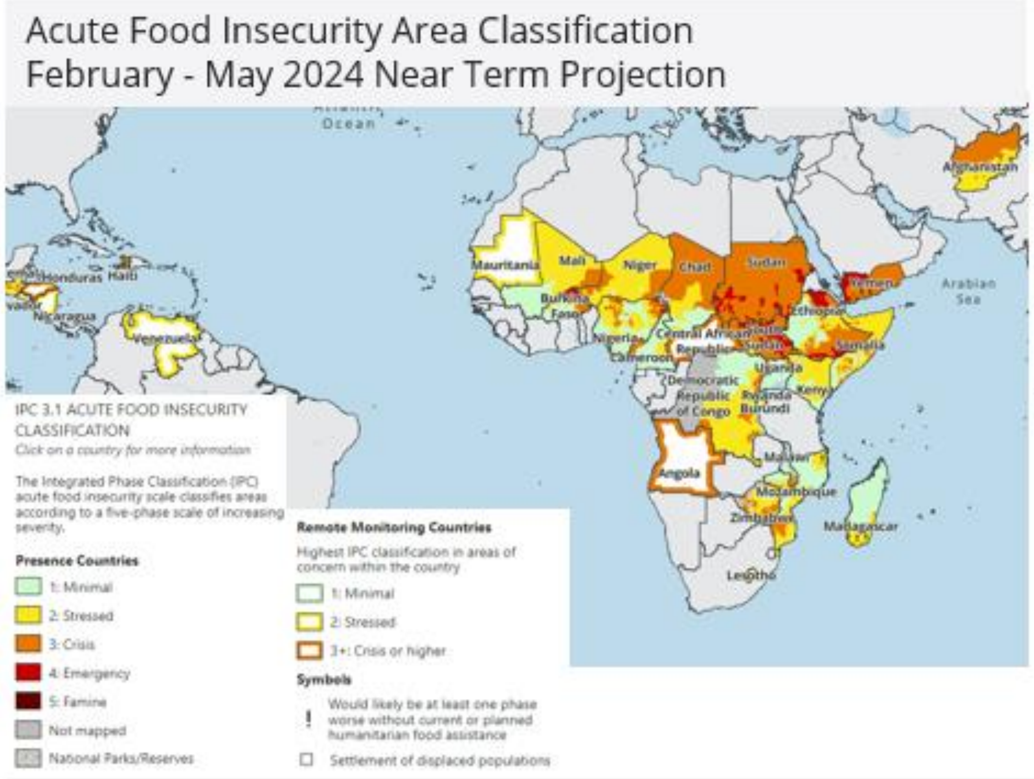
- Drought Monitoring (FEWS NET)
- Crop Water Use Mapping (Open ET)
- Water Budget: Blue Water - Green water

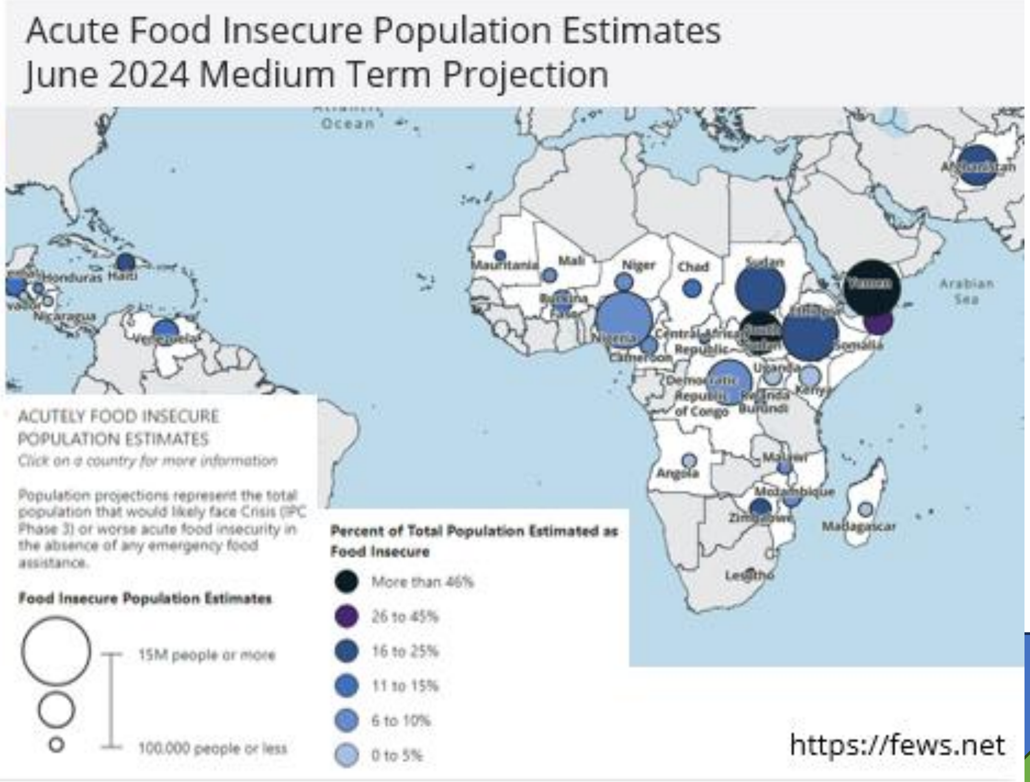
USGS

Drought Monitoring

Famine Early Warning Systems Network (FEWS NET)

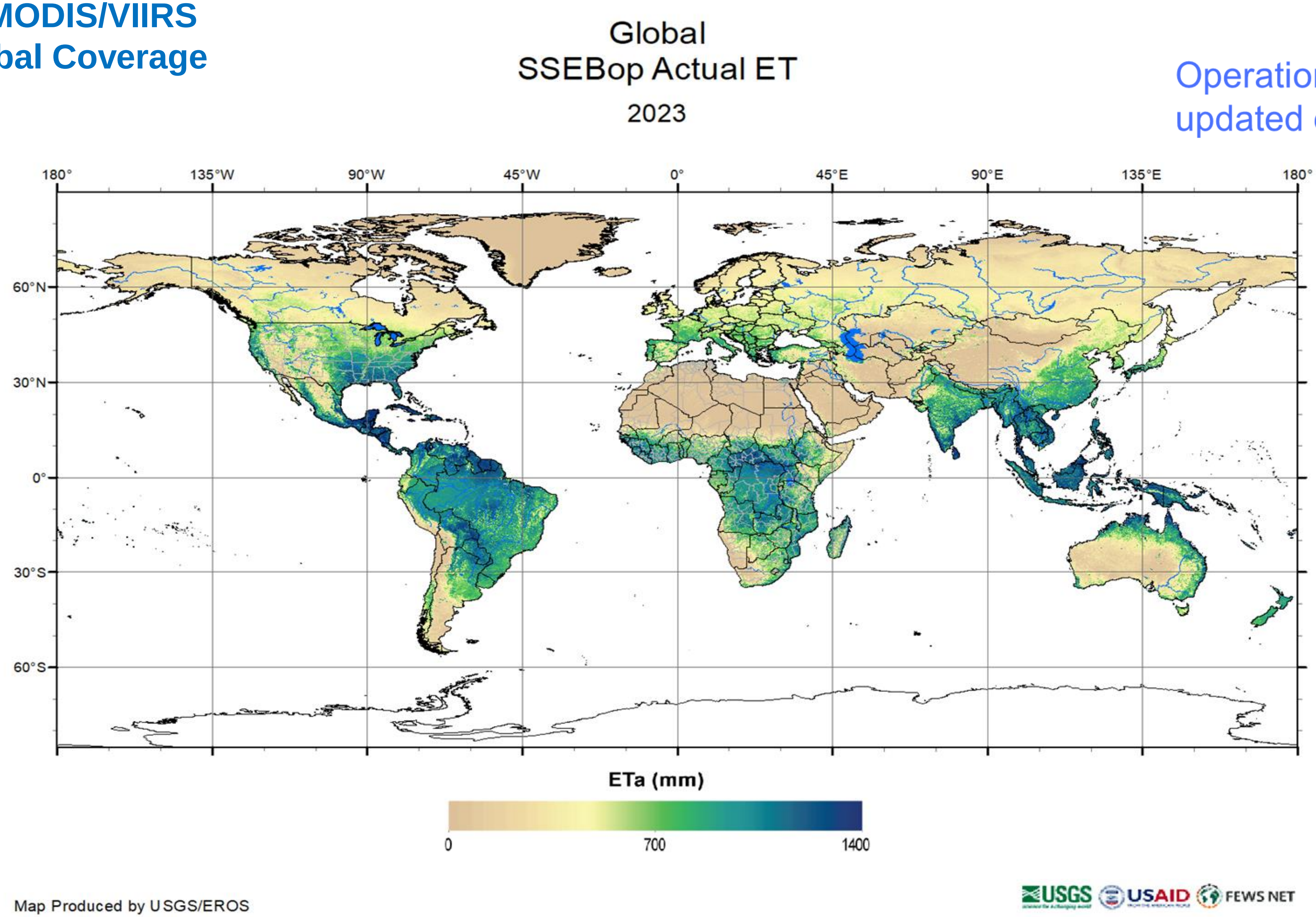
- FEWS NET monitors and provides early warning analysis of ongoing, imminent, or emerging threats to food security around the world.
- FEWS NET analyses advises USAID on the need for humanitarian assistance for those populations most vulnerable to food crises.





Using MODIS/VIIRS for Global Coverage

Operational: 1 km, updated every 10 days



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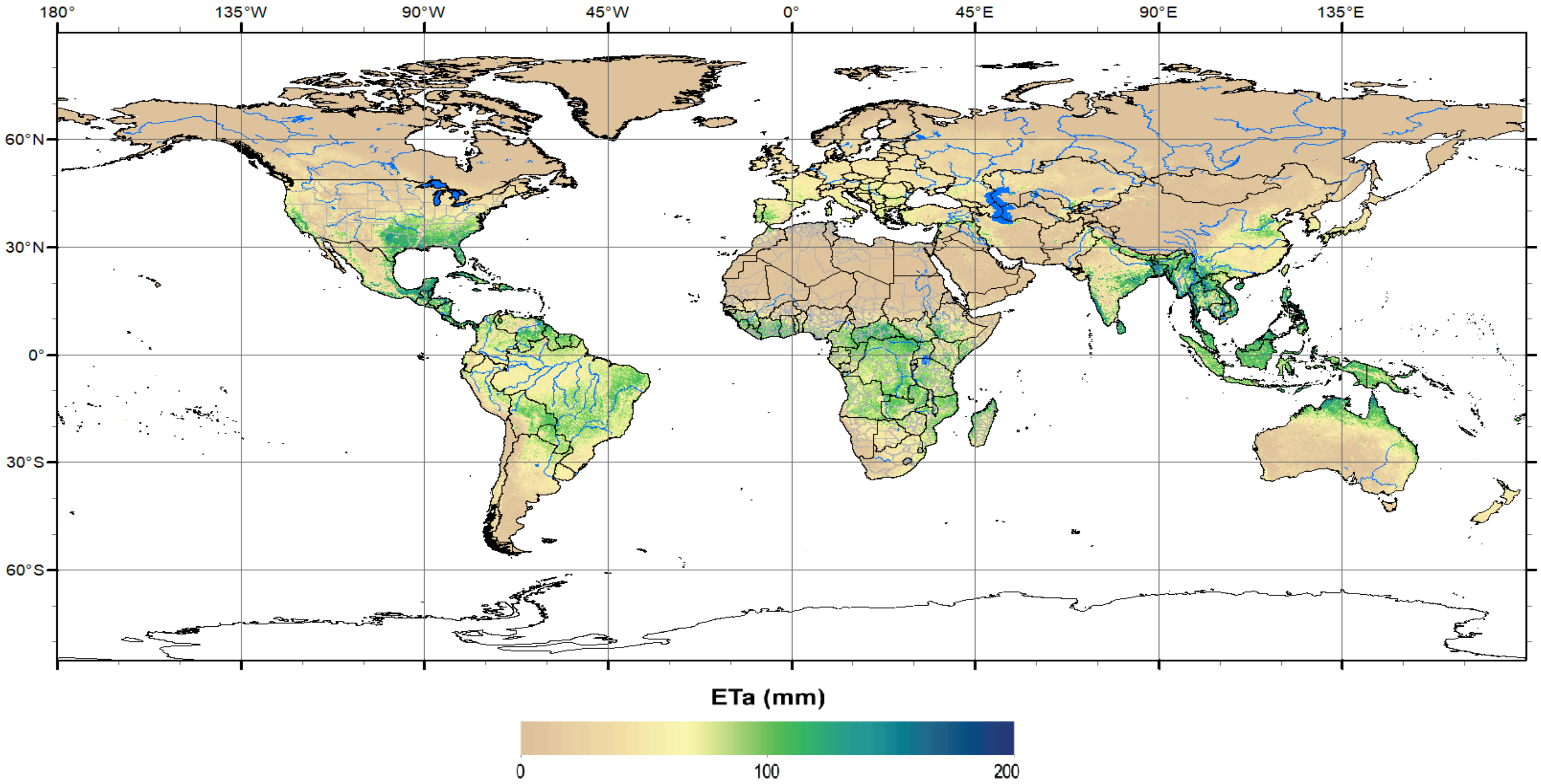
[Products | Early Warning and Environmental Monitoring Program (usgs.gov)]

Global
SSEBop Actual ET

April 2024

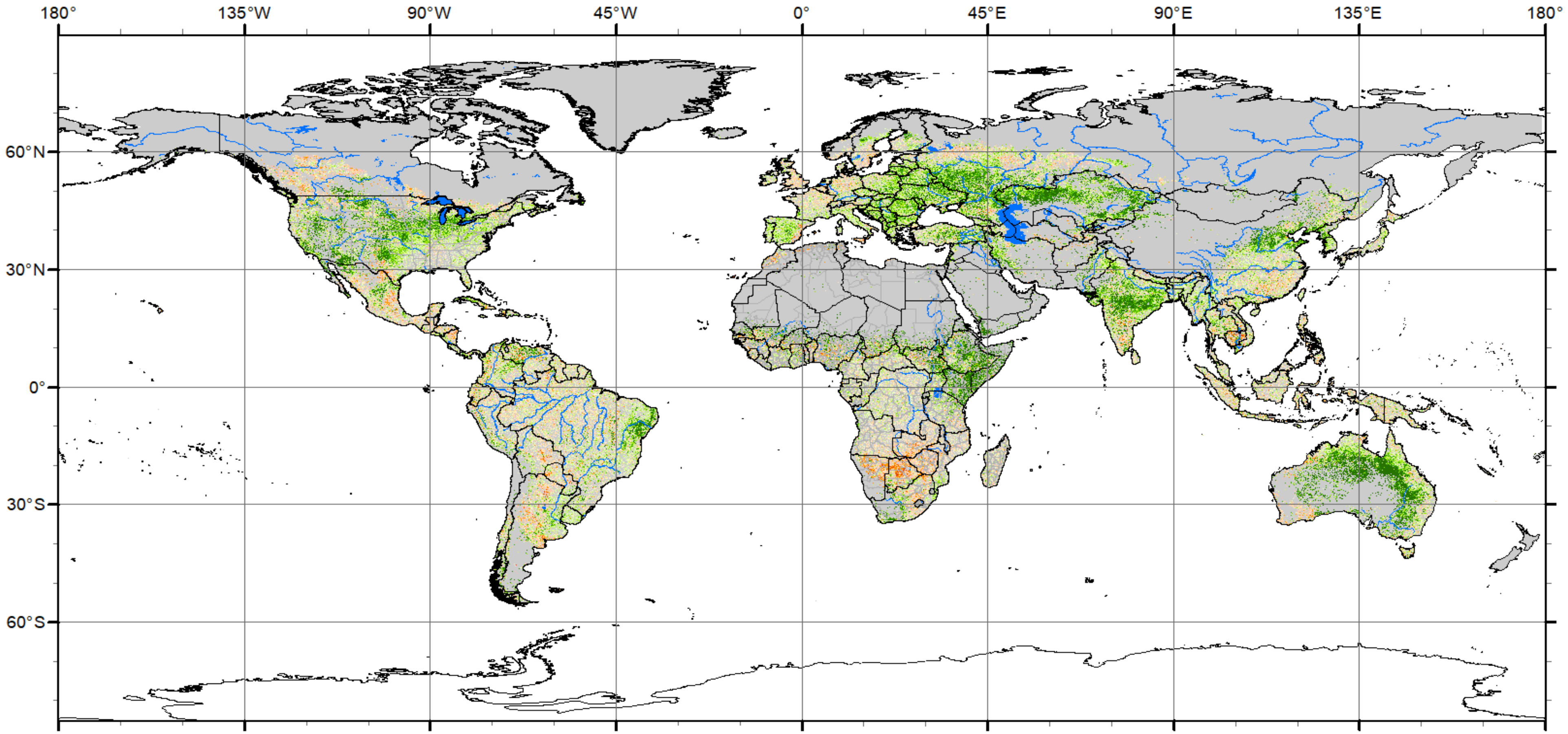


Map Produced by USGS/EROS

[Products | Early Warning and Environmental Monitoring Program (usgs.gov)](https://www.usgs.gov)

Global
SSEBop ET Anomaly

Percent of Median (2013-2022)
April 2024

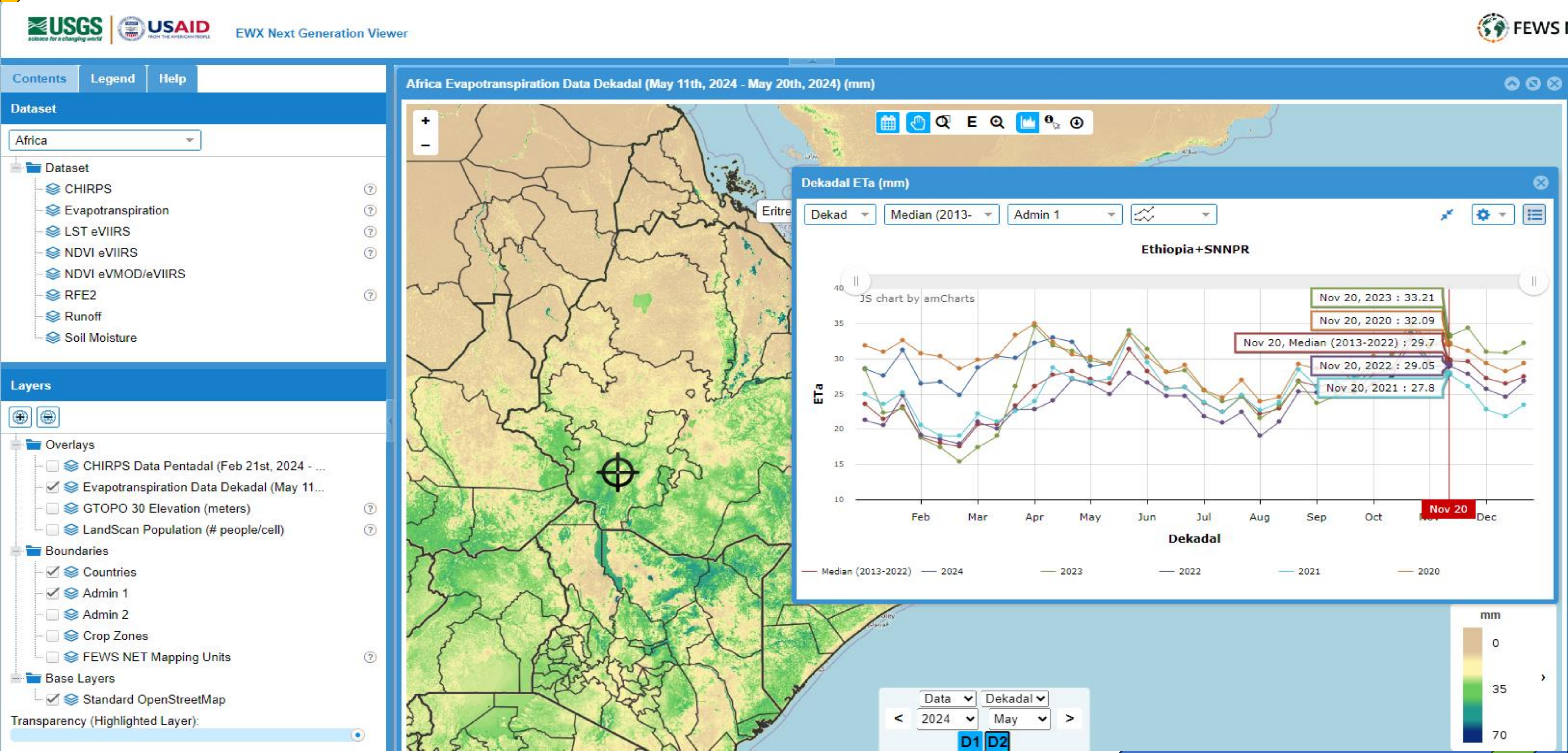


ET Anomaly (%)

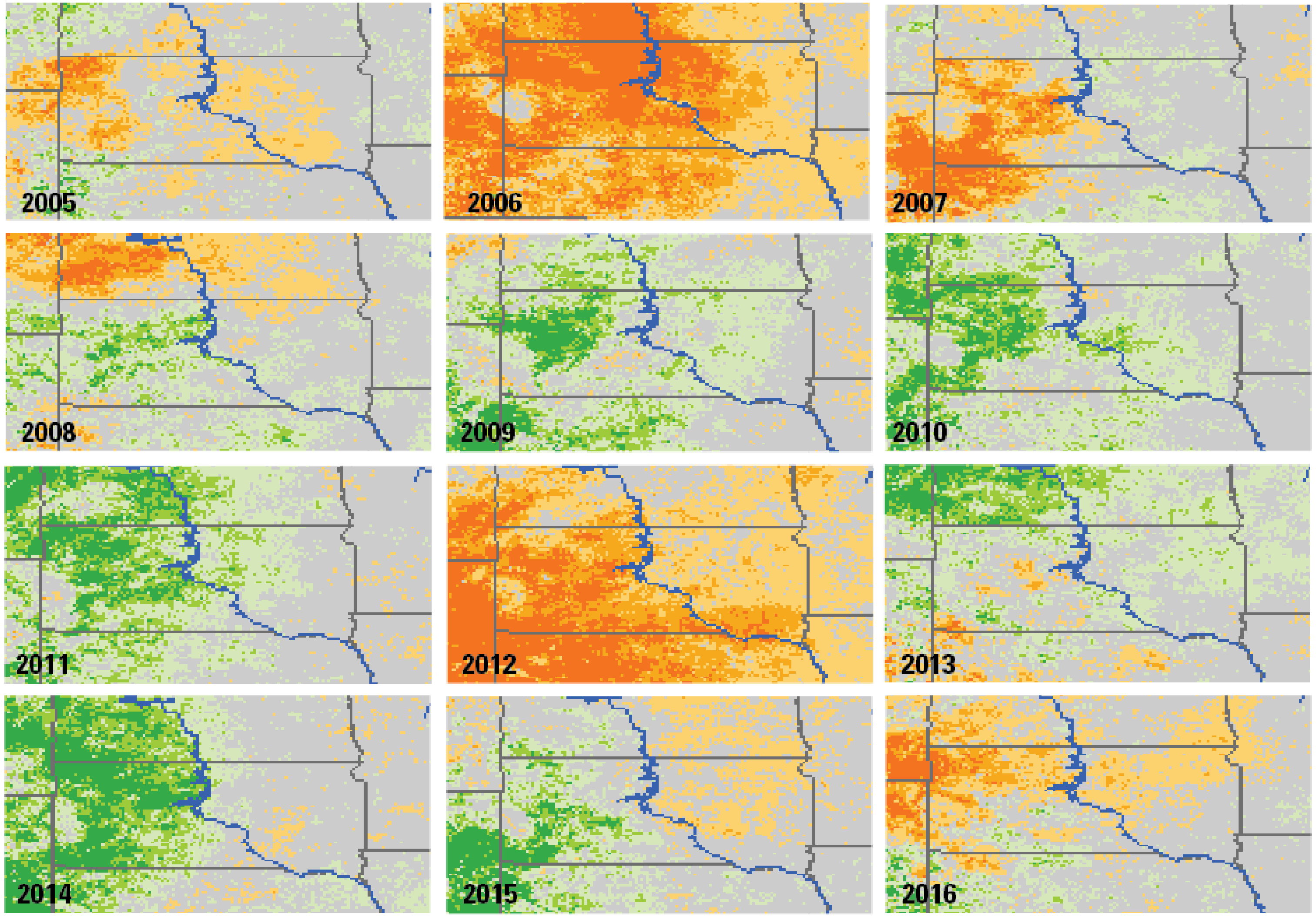
< 50	50 - 70	70 - 80	80 - 90	90 - 95	95 - 105	105 - 110	110 - 120	120 - 130	130 - 150	> 150

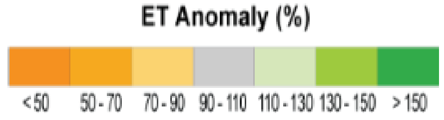
Map Produced by USGS/EROS

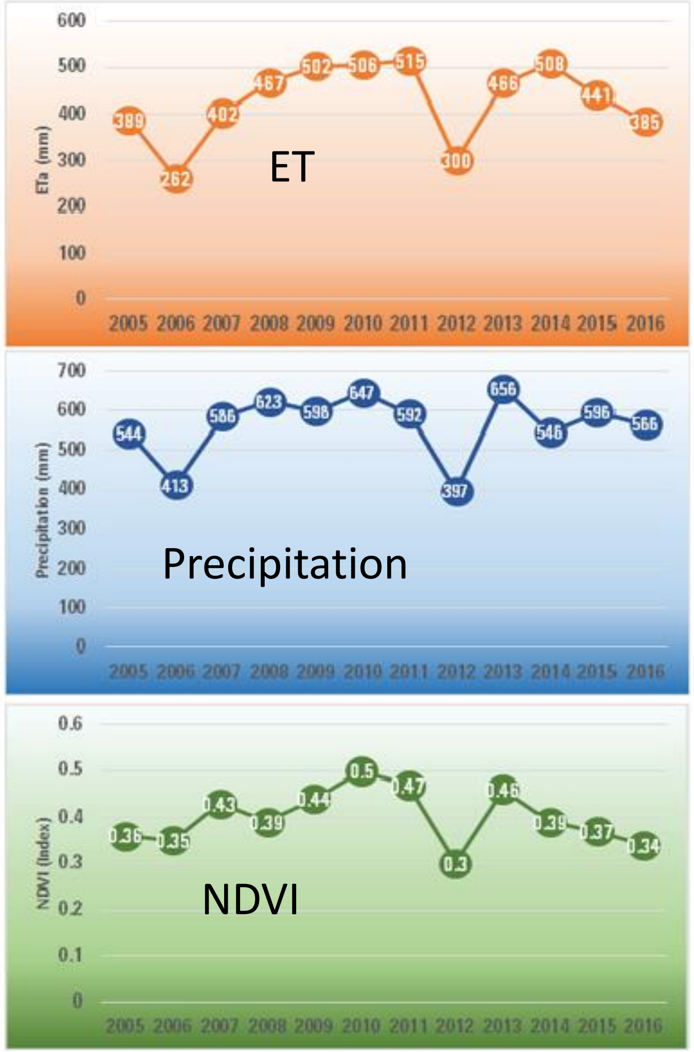
EWX (Early Warning eXplorer) Viewer



Annual ET Anomaly for South Dakota







Convergence of Evidence

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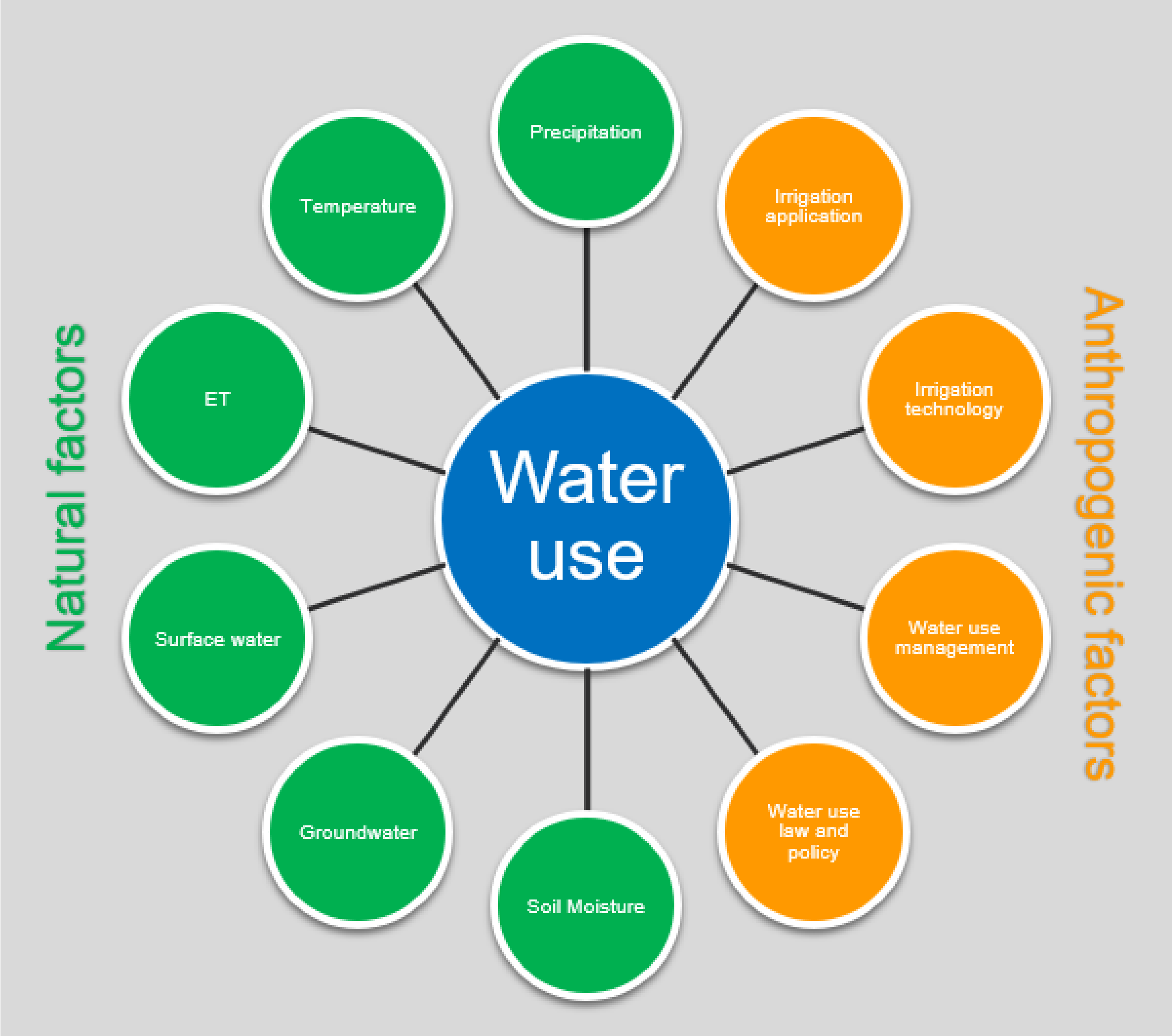
Crop Water Use and Irrigation Management

ET is used to plan, manage, and regulate agricultural water resources. Water use is controlled by hydroclimatic conditions, and by the management of water sources, such as:

- agriculture technology
- irrigation innovation
- water law and policy
- water use governance



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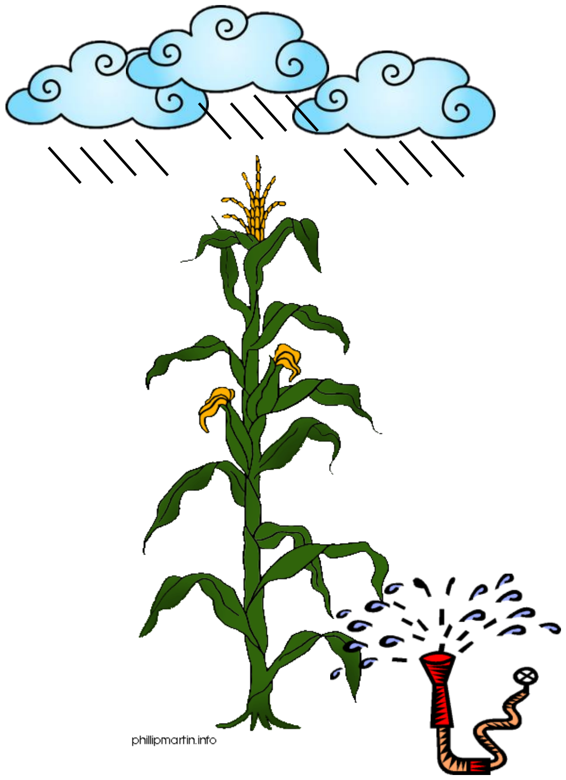
Blue and Green Water (FAO, 1995)

Green Water



Blue Water

Green Water

(moisture in unsaturated soil layer)

Blue Water

(water in the rivers, streams, surface water bodies and groundwater)

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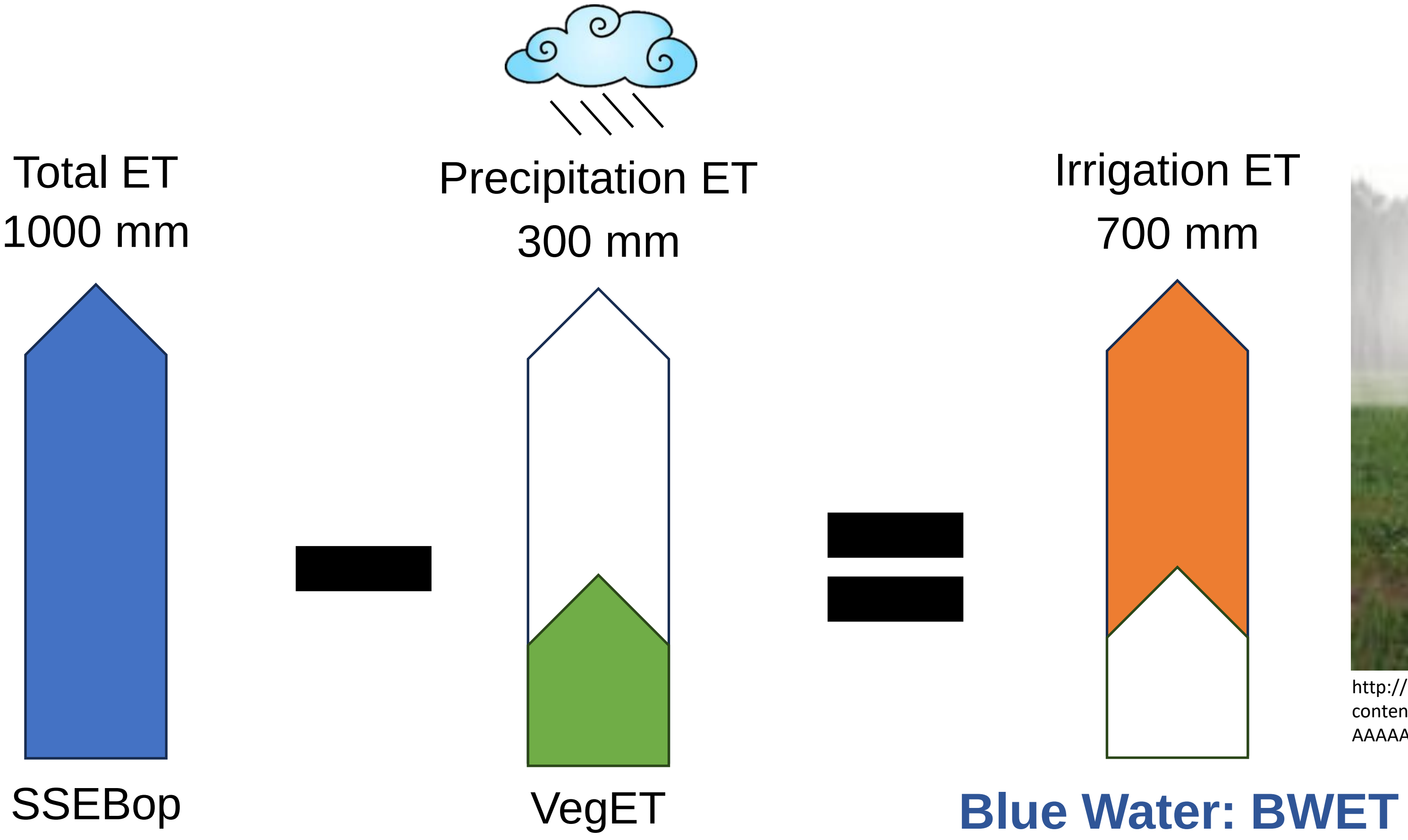
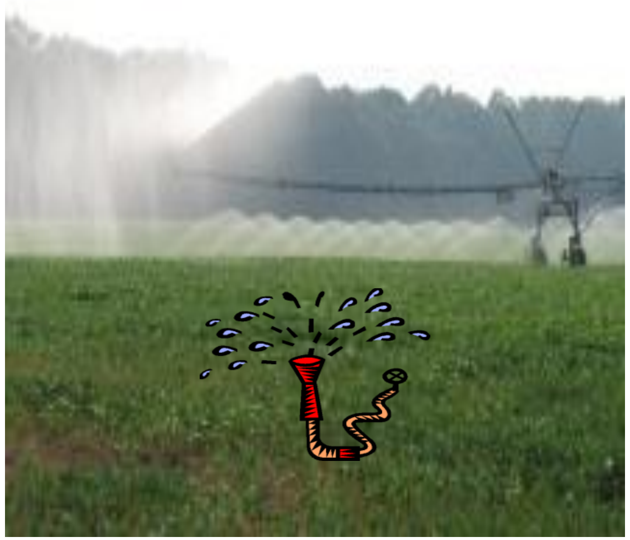
Net ET: ET from Irrigation Sources





http://extension.udel.edu/kentagextension/wp-content/blogs.dir/11/files/blogger/_8xC9bwq6AVU/RsR81Dw3CfI/AAAAAAAAAfI/gNmSobCFpAE/s1600/soyirrigate.JPG

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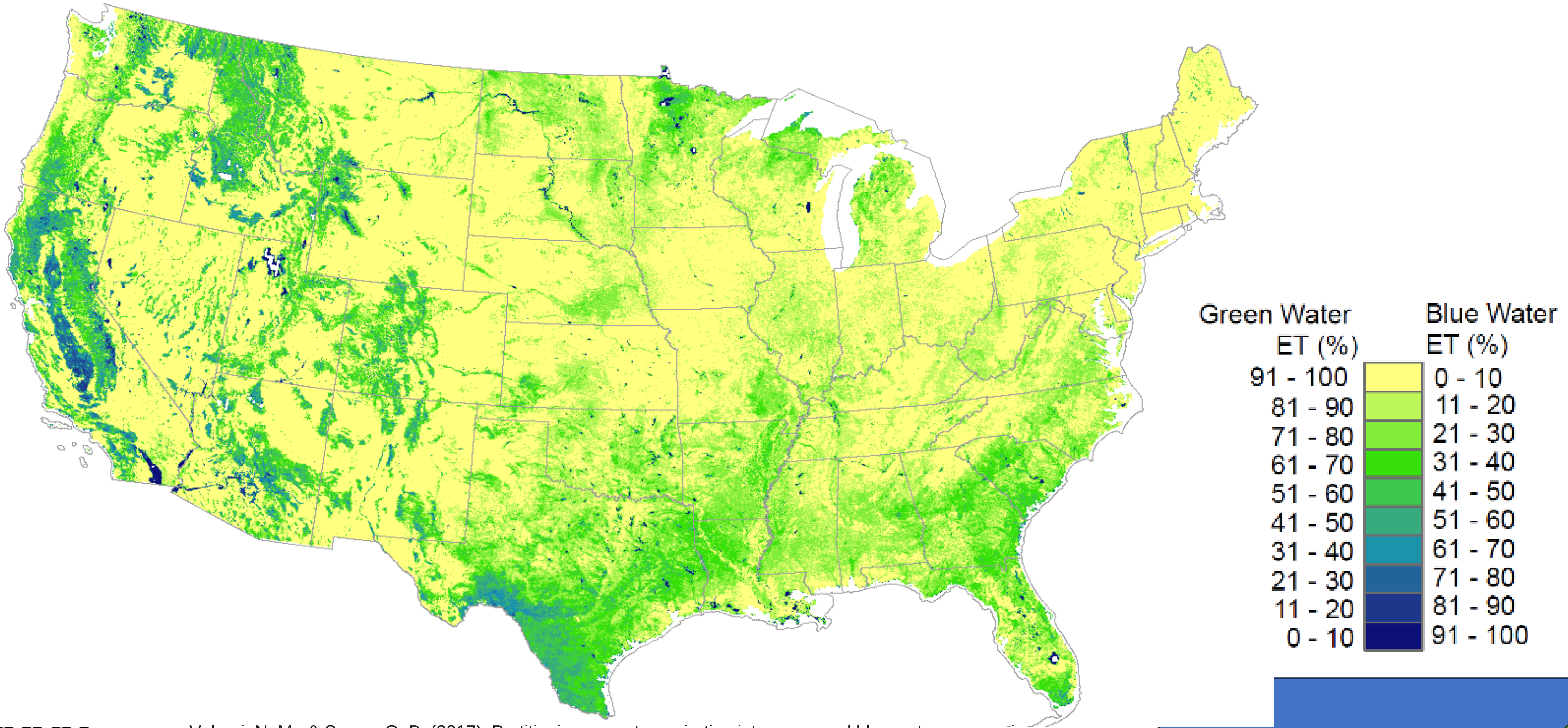
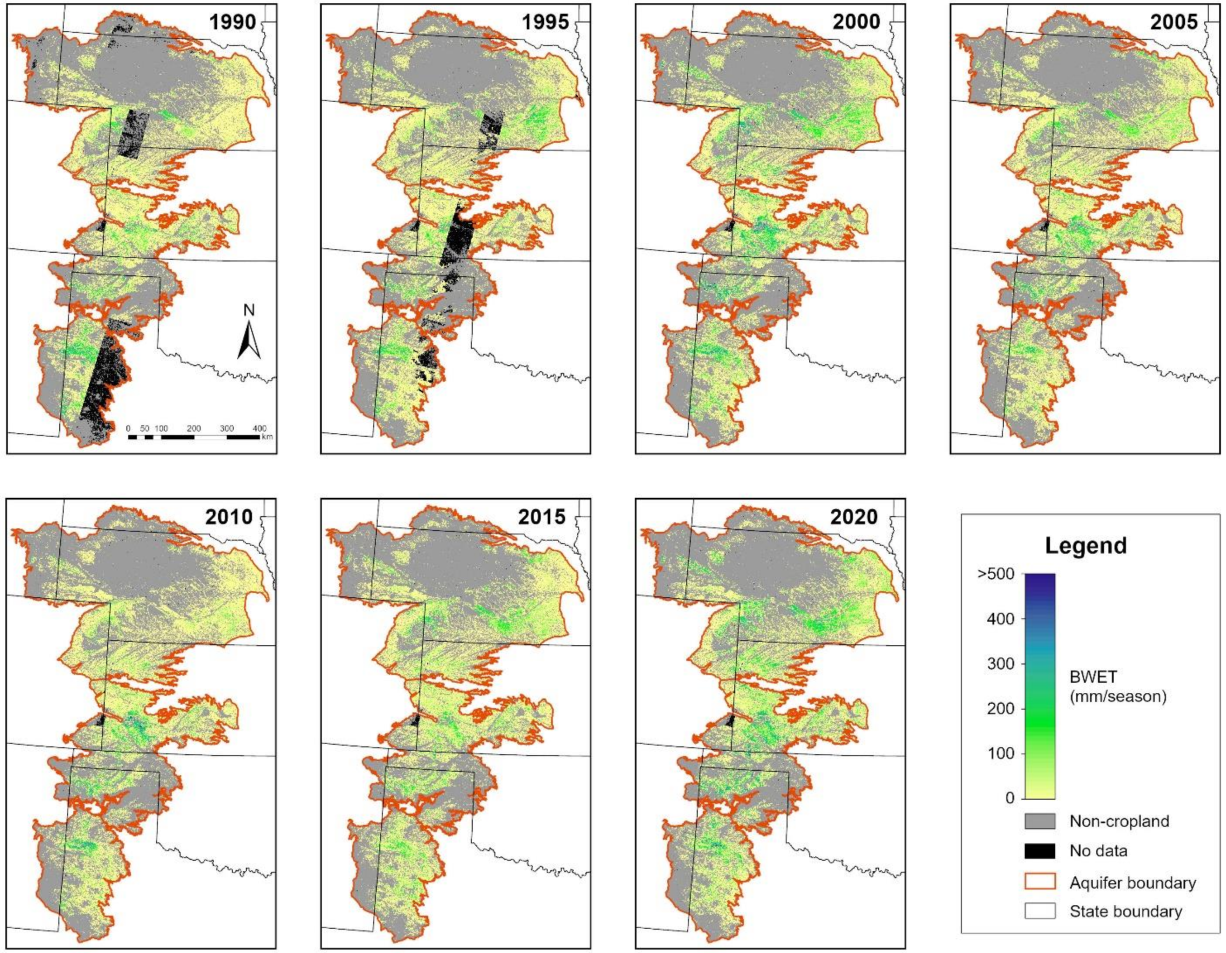
Velpuri and Senay, 2017. Scientific Reports.

GW (precipitation) and BW (surface- and ground-water) ET in the CONUS



Velpuri, N. M., & Senay, G. B. (2017). Partitioning evapotranspiration into green and blue water sources in the conterminous United States. *Scientific reports*, *7*(1), 6191.

Seasonal (1 May to 30 September) BWET timeseries for croplands in the High Plains aquifer region



Remote Sensing Benefits:

- High Spatial Detail
- Yearly
- Affordable

Missing = < 5 images per season with single satellite (L5)

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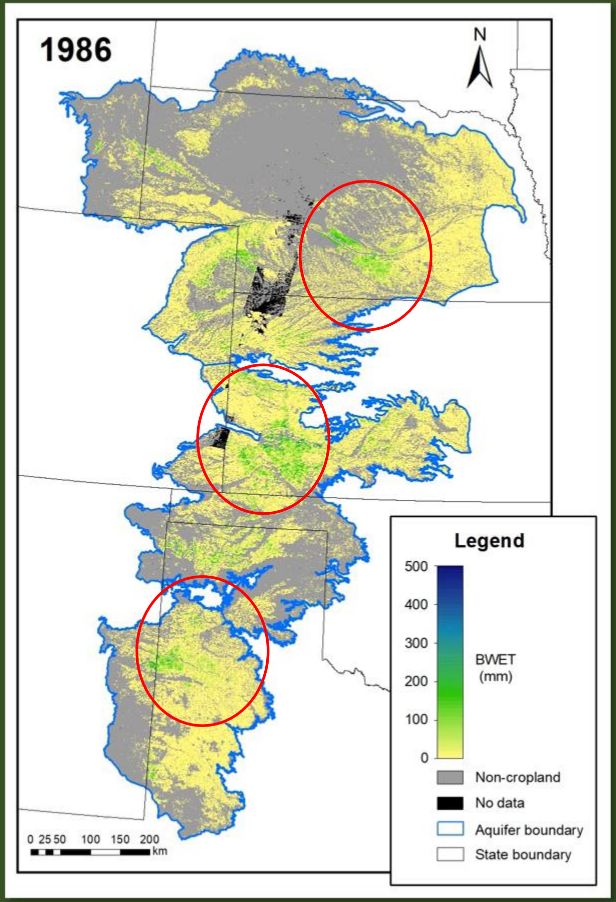
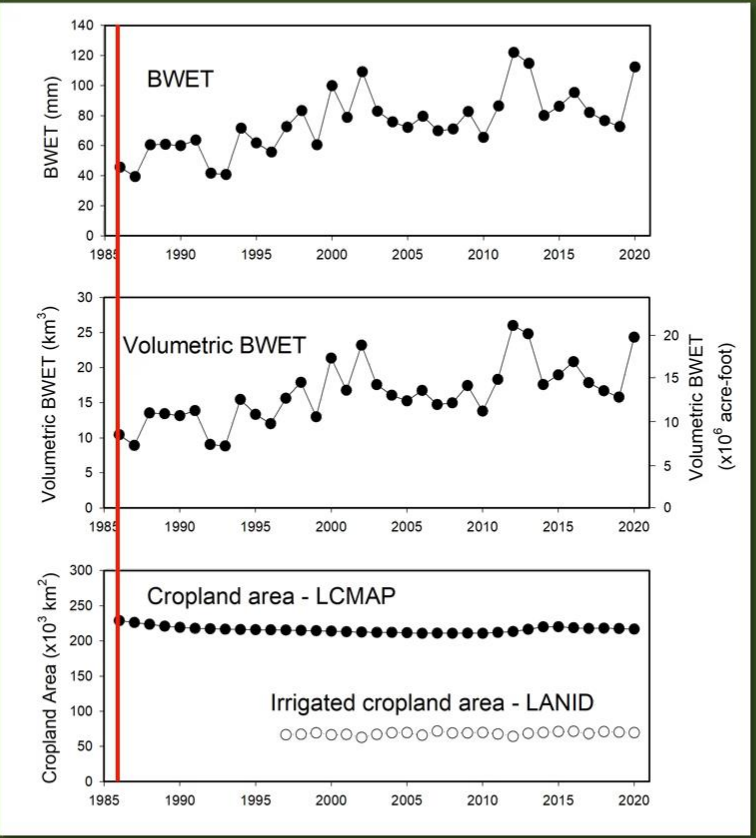
Yearly Blue Water ET over High Plains Croplands (No Yearly Withdrawal Data for High Plains)

BWET Maps for High Plains (1986 – 2020)



Increasing until 2000
Stable after 2000

BWET Timeseries Chart



Dry years tend to show an increase in BWET

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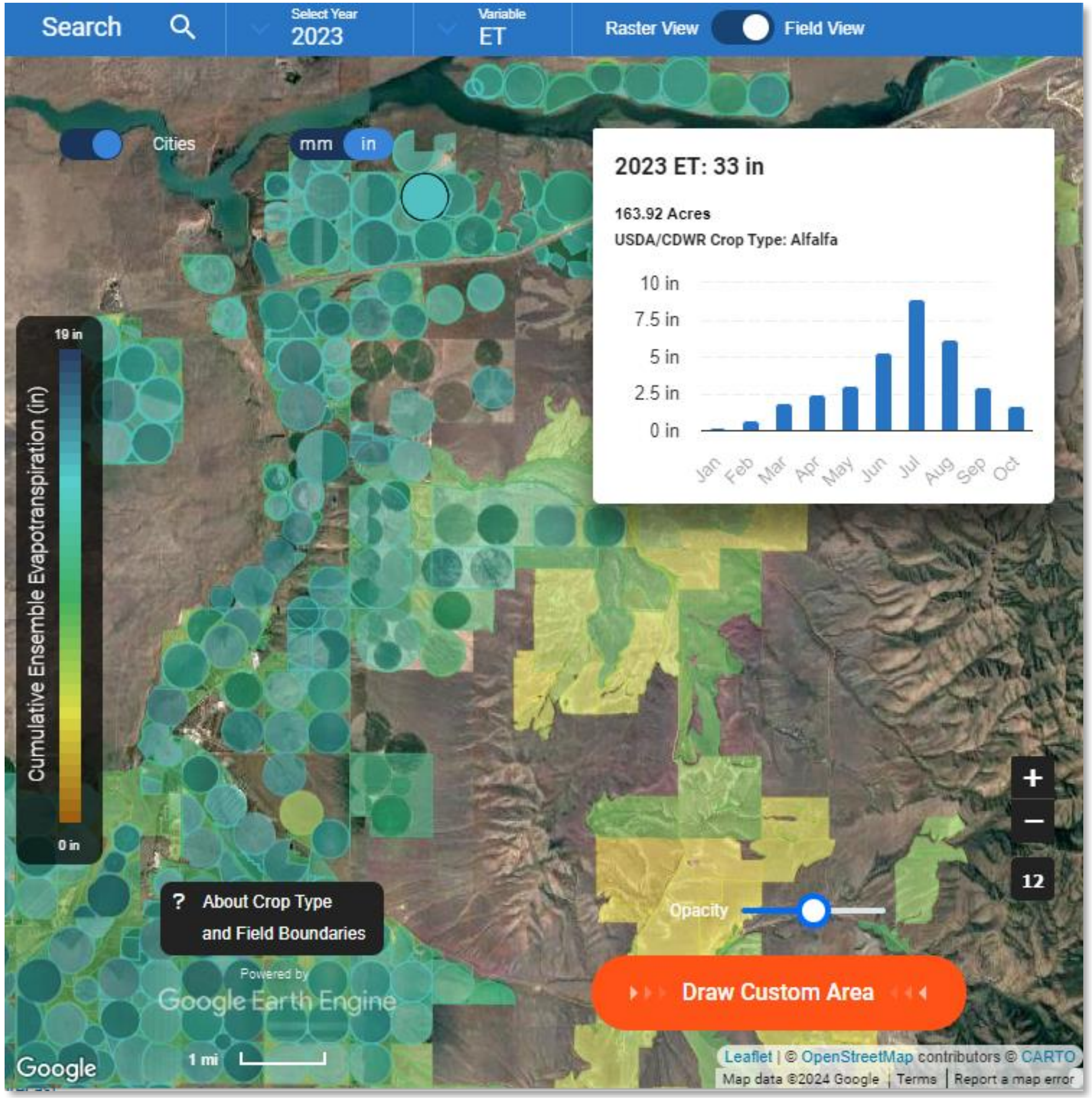
OpenET (OPENET)

Multi-agency collaboration among government, research institutions, universities, Google, and use case partners

- OpenET uses best available science to provide easily accessible satellite-based evapotranspiration (ET) data for improved water management across the western United States.

- Field-scale data at daily, monthly, and annual time steps.

- Multiple satellite-driven models that are used to map ET and provide a single “ensemble ET” value that is calculated from those models for each location and timestep.



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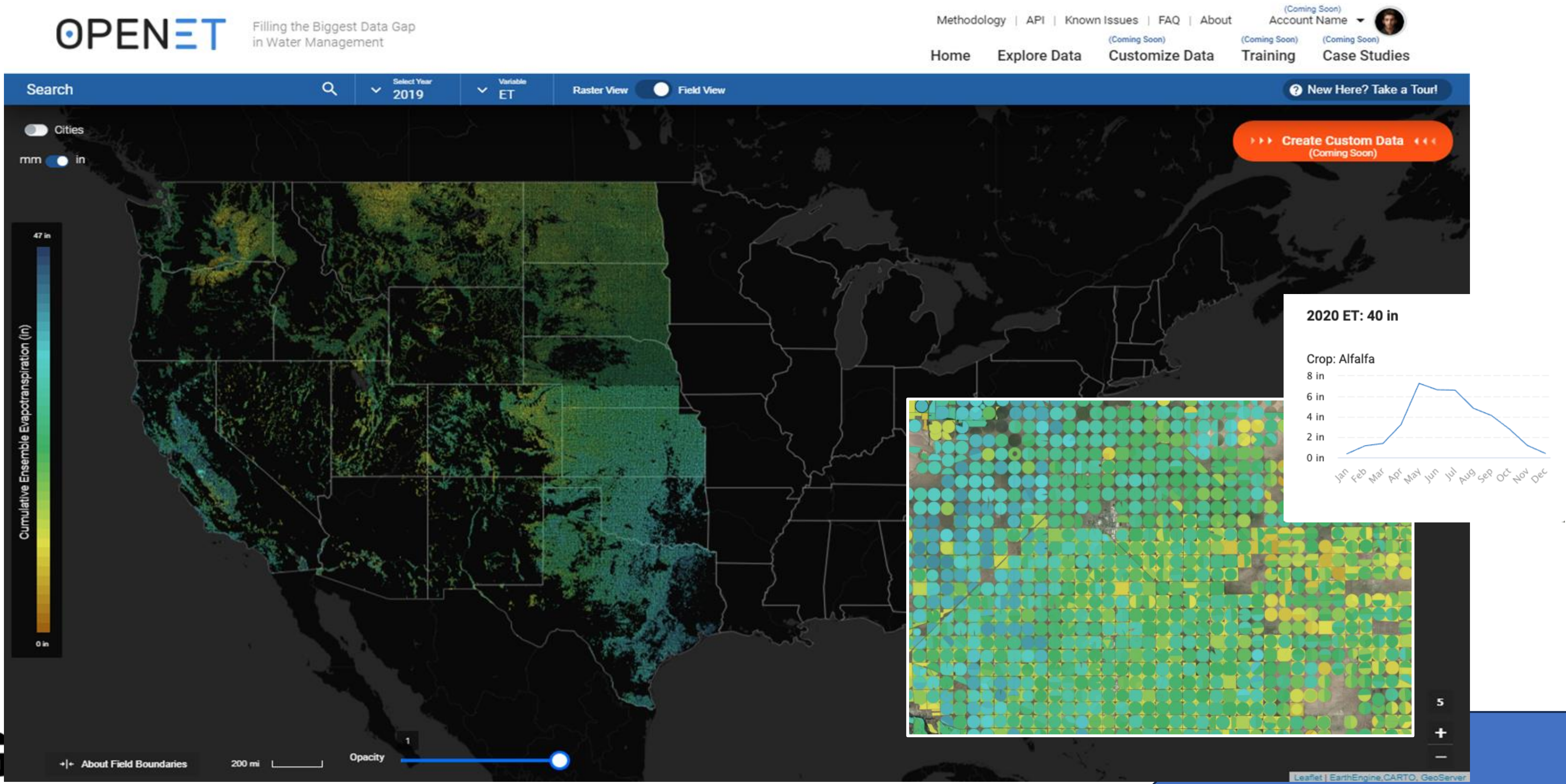
[OpenET – Filling the Biggest Gap in Water Data (etdata.org)](https://etdata.org)

OpenET: Reliable water use data



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Related sessions:

202 - OpenET: Satellite-Based Evapotranspiration Data to Support Advances in Hydrology and Water Resources Management
Tuesday, June 25th, 2024
8.30 – 10.00 am
Ballroom D

111 - Ensuring Water Secure Future Using Next Generation Innovative Data Solutions
Monday, June 24th, 2024
13.00 – 14.30 pm
Ballroom C

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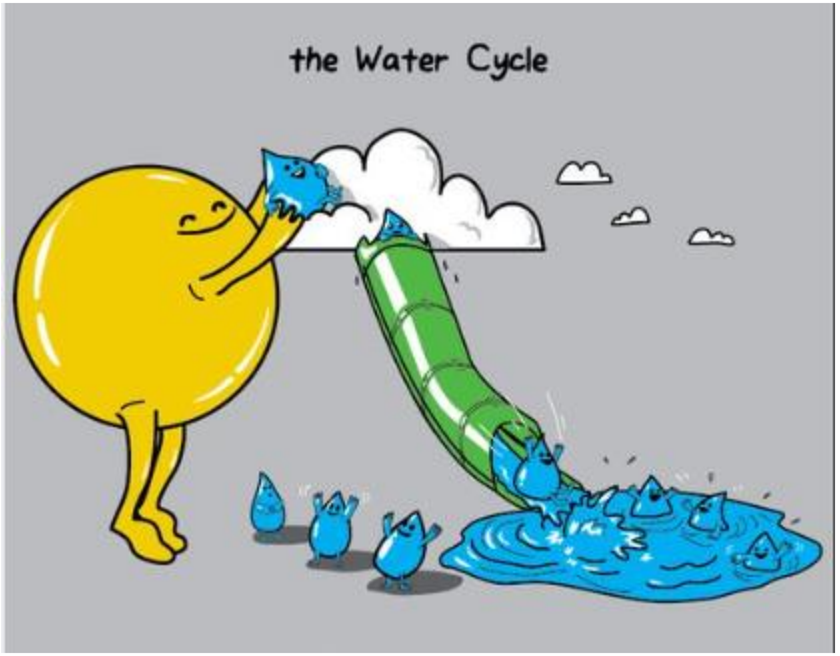
Questions ???



How do you use/plan to use ET data in your work?

USGS

Thank You

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- EROS website: https://www.usgs.gov/centers/eros
- Instagram: usgs_eros
- X(Twitter): @USGS_EROS
- Eyes on Earth podcast: https://www.usgs.gov/centers/eros/eyes-earth

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