Field-scale actual ET estimates using the Operational Simplified Surface Energy Balance (SSEBop) approach with Landsat imagery

Gabriel Senay, Ph.D., P.E.
USGS EROS/NCCSC
October 13, 2016

Colorado ET Workshop
Latest Methods in Evapotranspiration and Supporting Technologies
Fort Collins, Colorado

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

Team and Contributors

- **USGS EROS:**
  - Jim Verdin, USGS EROS
  - Stafanie Bohms, EROS SGT
  - MacKenize Friedrichs, EROS SGT
  - Matt Schauer, EROS Innovate! Inc.
  - Ramesh Singh, EROS InuTeq
  - Manohar Velpuri , EROS InuTeq
  - Mingshi Chen, EROS InuTeq

Outline

- Summary
- Background, Justification, SSEBop Approach
- Landsat Based ET maps
- Accuracy Assessment and Evaluation
- Concluding Remarks

Summary

- **Satellite-based ET is estimated operationally using Land Surface Temperature (LST) as the main driver.**
- **Applications for drought monitoring (relative change detection) is reliable as is.**
- **Applications for water balance studies require calibration with local observations for bias removal.**

Background

Water Census: Crop Water Use

- USGS has been compiling the nation's water use information since 1950, every 5 years

FEWS NET: Global Monitoring and Early Warning

- Convergence of Evidence
  - Rainfall, Vegetation Index, ET

1950

1955

1960

1965

1970

1975

1980

1985

1990

1995

2000

2005

2010

“These reports, ‘Estimated Water Use in the United States,’ have been published every five years since 1950 and are one of the most widely cited publications of the USGS.”
National Research Council, 2002

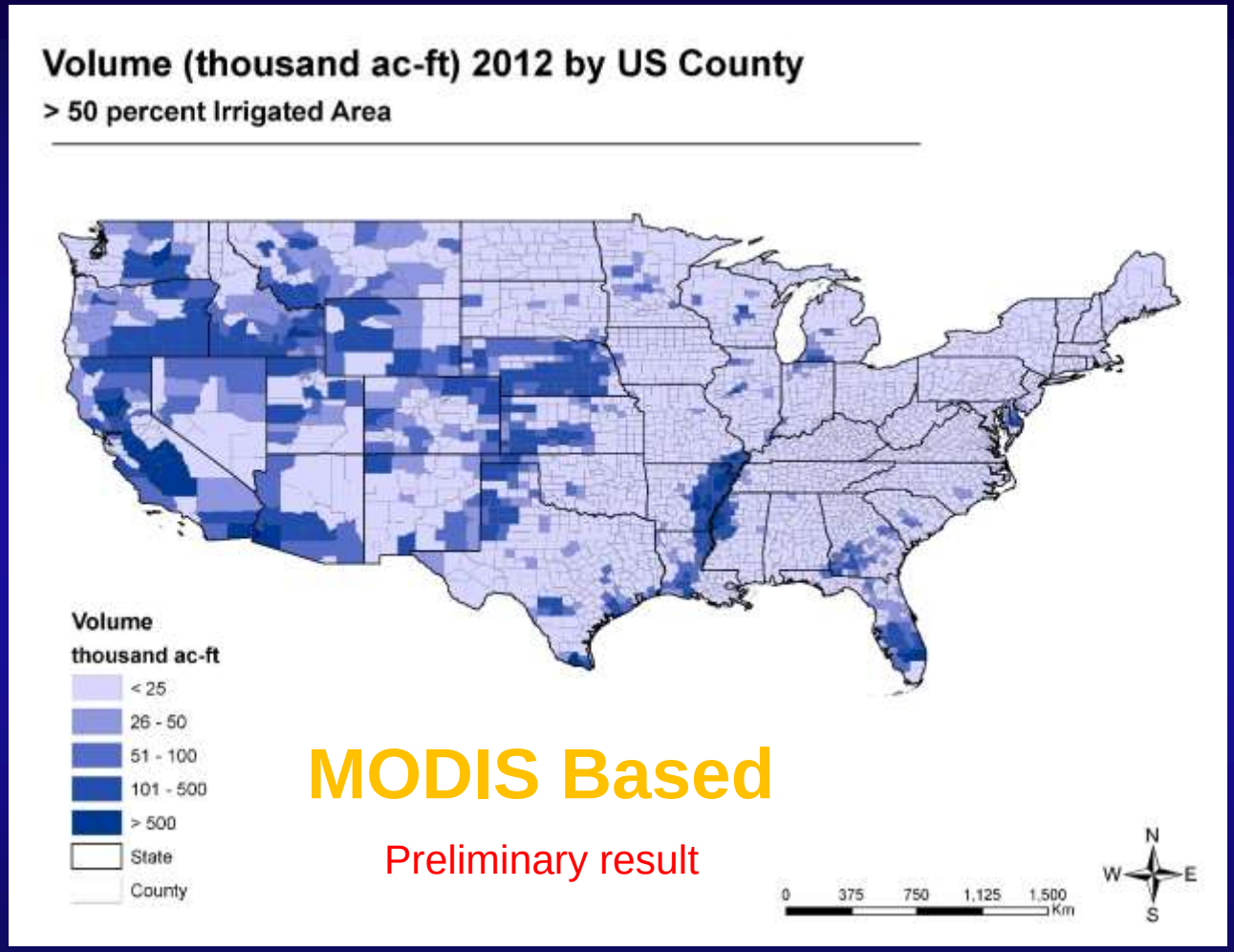
USGS

Why the Need for Remote Sensing ET

- Since 2000, only water withdrawal was reported and not consumptive use:
  - Because of differing methods and data unavailability across the nation

- USGS Water Census/WaterSMART (2011): improving the methods, remote sensing ET research was funded as a topical area

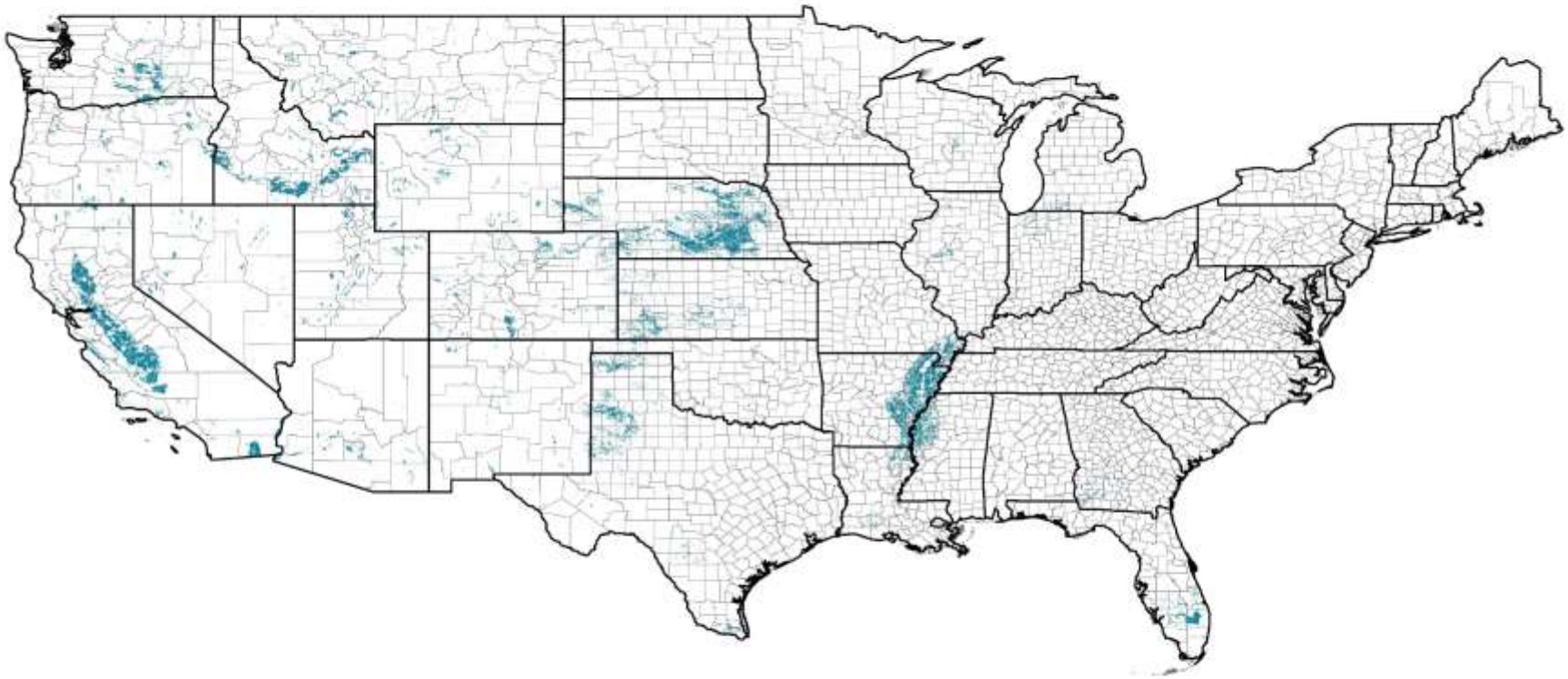
2012 Remote Sensing Based County-Scale Consumptive Use Volume (ac-ft)



USGS

Irrigated Area

> 50 percent Irrigated Area



MIrAD-US: J. Brown

State

County

0 375 750 1,125 1,500 Km

N

W E

S

SSEBop Approach…

Why ET?

- 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

USGS

Challenge: ET under potential vs water limiting conditions

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

- Allen et al (1998)*
  - ETa = Ks * Kc * ETo
    - Kc = type and stage of crop (~0.15 – 1.2)
    - Ks = soil moisture stress factor (0 to 1)

*:well established, but requires knowledge of crop types, stage and moisture distribution

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.

ETa = ETf * ETo

Ks Kc

Energy Balance Approach for ET:

Accounts for water, agronomic and environmental stresses

USGS WaterSMART and FEWS NET use the SSEBop (Operational Simplified Surface Energy Balance) approach for:

1) Water Use and Availability Assessment

2) Drought Monitoring & Early Warning

USGS

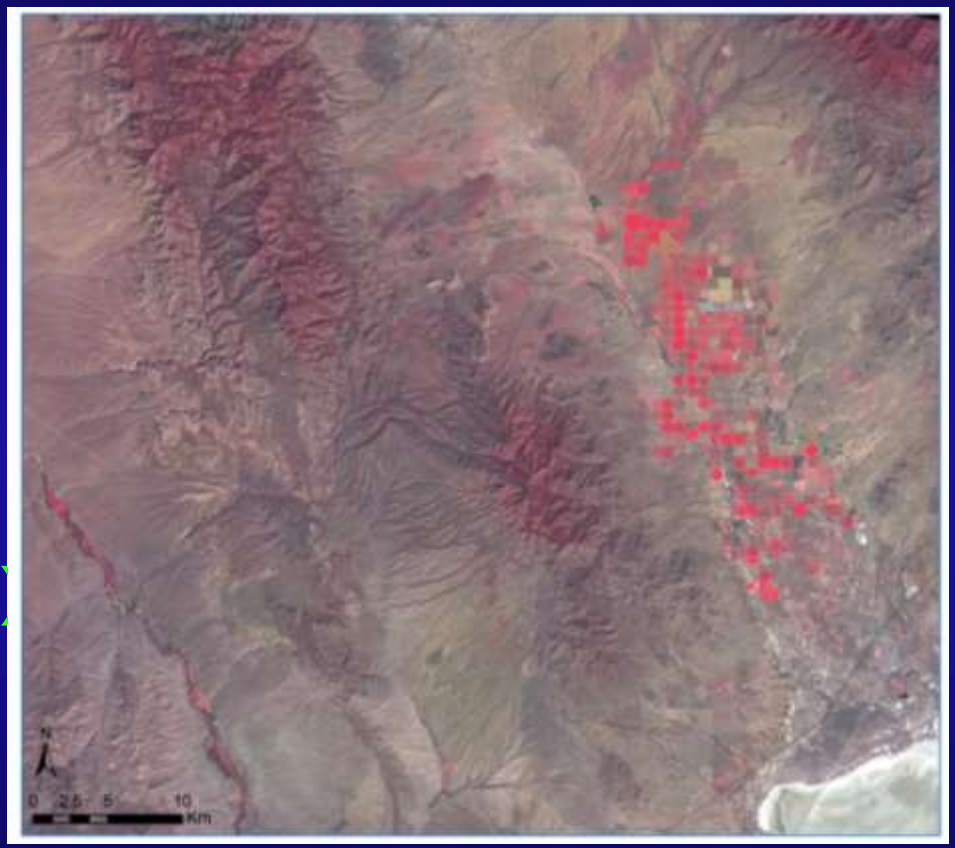
LST and Evaporative Cooling

(1) Emitted radiation from earth is a function of its surface temperature and emissivity

(2) Evaporative cooling lowers the surface temperature

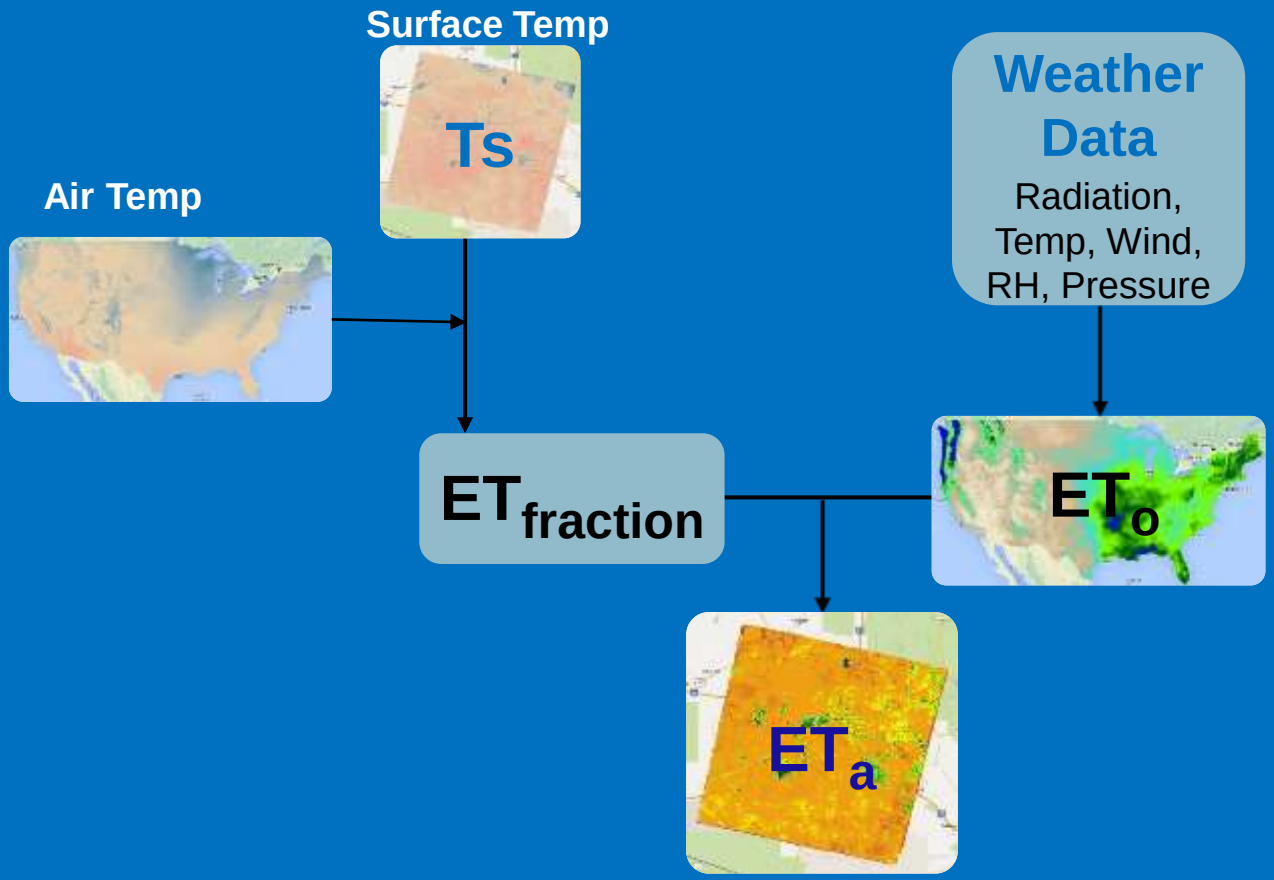
(3) Cold surface ET (irrigated crop) is close to potential (maximum)

(4) dry-bare surface can be +20°C higher than wet-vegetated surface



USGS

Operational Simplified Surface Energy Balance (SSEBop) Modeling Approach



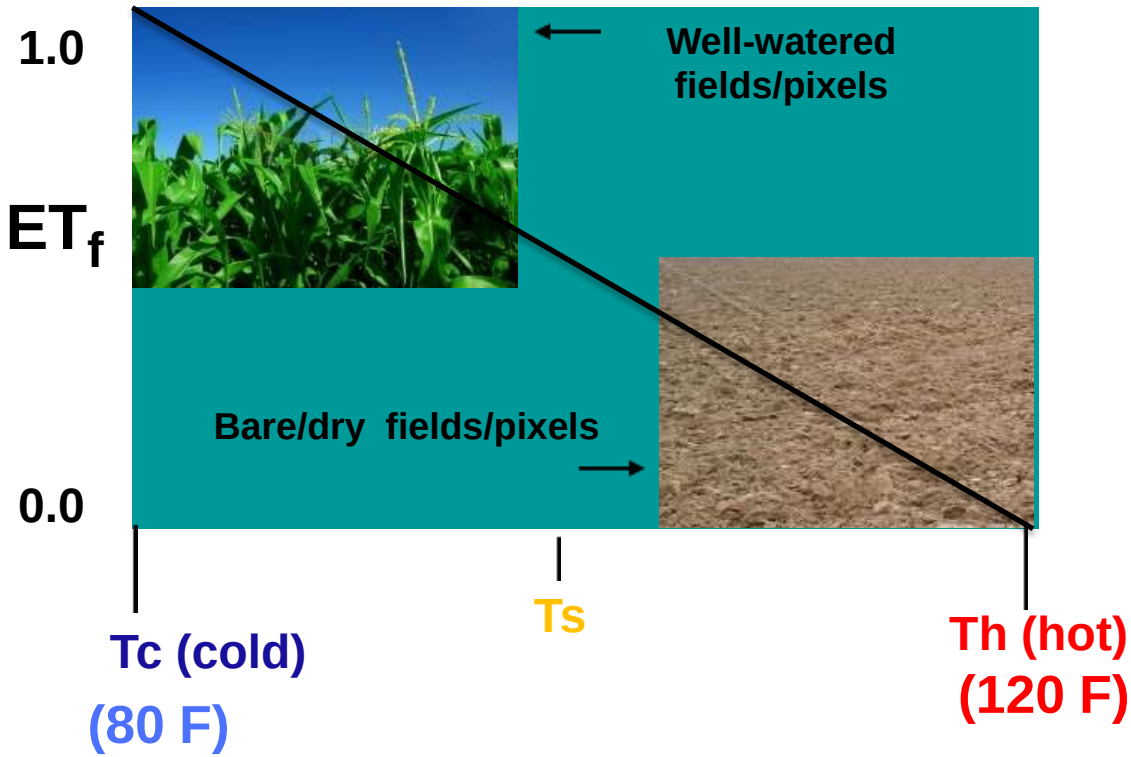
Adapted the "hot" and "cold" pixel concept from SEBAL (Bastiaanssen et al., 1998) and METRIC (Allen et al., 2007) to calculate ET fraction…

SSEB: Senay, et al., 2007 Sensors; 2011 AWM; SSEBop: 2013 JAWRA, 2016 RSE

USGS

Operational Simplified Surface Energy Balance (SSEBop) Modeling Approach

$$ET_f = 1 - \frac{(Ts - Tc)}{dT}$$



Simple, but not easy: Establishing Tc and Th is the challenge!

SSEBop: No need to identify the Th reference from image

- The hot reference limit (Th) is calculated as part of a constant

- ET fraction is essentially calculated from the difference between satellite LST and air-temperature-based cold reference value

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

$$\gamma^{s} = \frac{\rho Cp}{Rn\, r_a}$$

USGS

Using surface energy balance principles

ET as a Residual:

Rn = H + LE; G = ~0

heating evaporation

$$H = \frac{\rho C_p (Ts - Ta)}{r_a}$$

LE = Rn – H

G =~ 0 for daily estimate

SSEBop: Pre-defined dT

Varies in space and season but constant from year-to-year under clear-sky conditions

RS-ET possible under “clear sky” conditions only.

ET Direct, SSEBop:

$$\lambda ET = ET = ETf * ETo$$

$$ETa = (1 - \frac{Ts - Tc}{dT}) * ETo$$

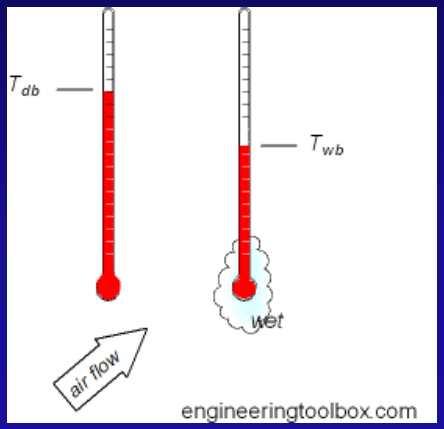
$$dT = \frac{R_n r_a}{\rho C_p}$$

$$ETa = (1 - \frac{\rho C_p (Ts - Tc)}{R_n r_a}) * ETo$$

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

USGS

SSEBop Explained with the "Psychrometry" Principle



Sling Psychorometer

Definition of PSYCHROMETER

A hygrometer consisting essentially of two similar thermometers with the bulb of one being kept wet so that the cooling that results from evaporation makes it register a lower temperature than the dry one and with the difference between the readings constituting a measure of the dryness of the atmosphere.

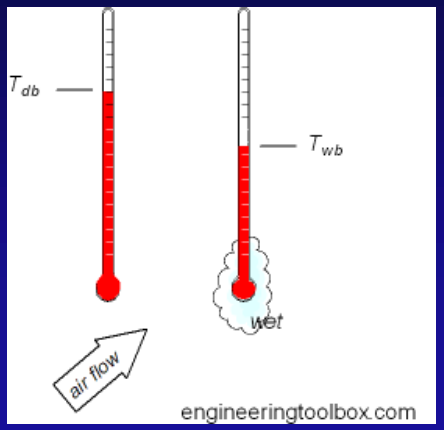
http://www.merriam webster.com/dictionary/psychrometer

USGS

SSEBop Explained with the "Psychrometry" Principle, Cont'd

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

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



ea = actual vapor pressure (kPa)
es = saturated V.P. (kPa) at Tw

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.

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

USGS

Air vs surface psychrometry
(Thermometer vs Satellite Psychrometry)

Vapor pressure/relative humidity (standard psychrometry)

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

Large temp difference is a result of dry air (low RH) and hence low vapor pressure

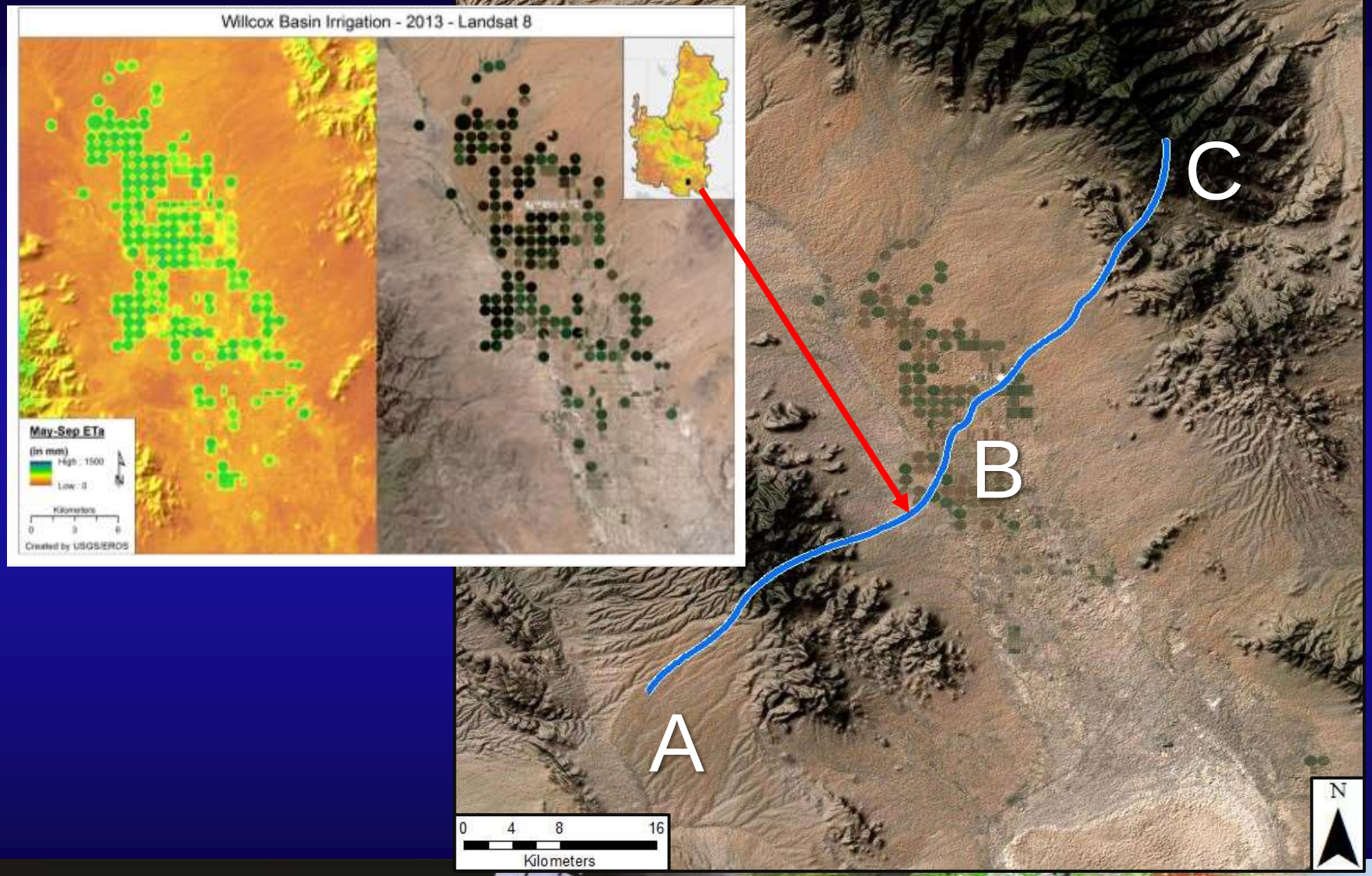
Actual ET (Satellite Psychrometry Approach: SPA)

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

Large temp difference is a result of dry soil (low soil moisture) and hence low actual ET

USGS

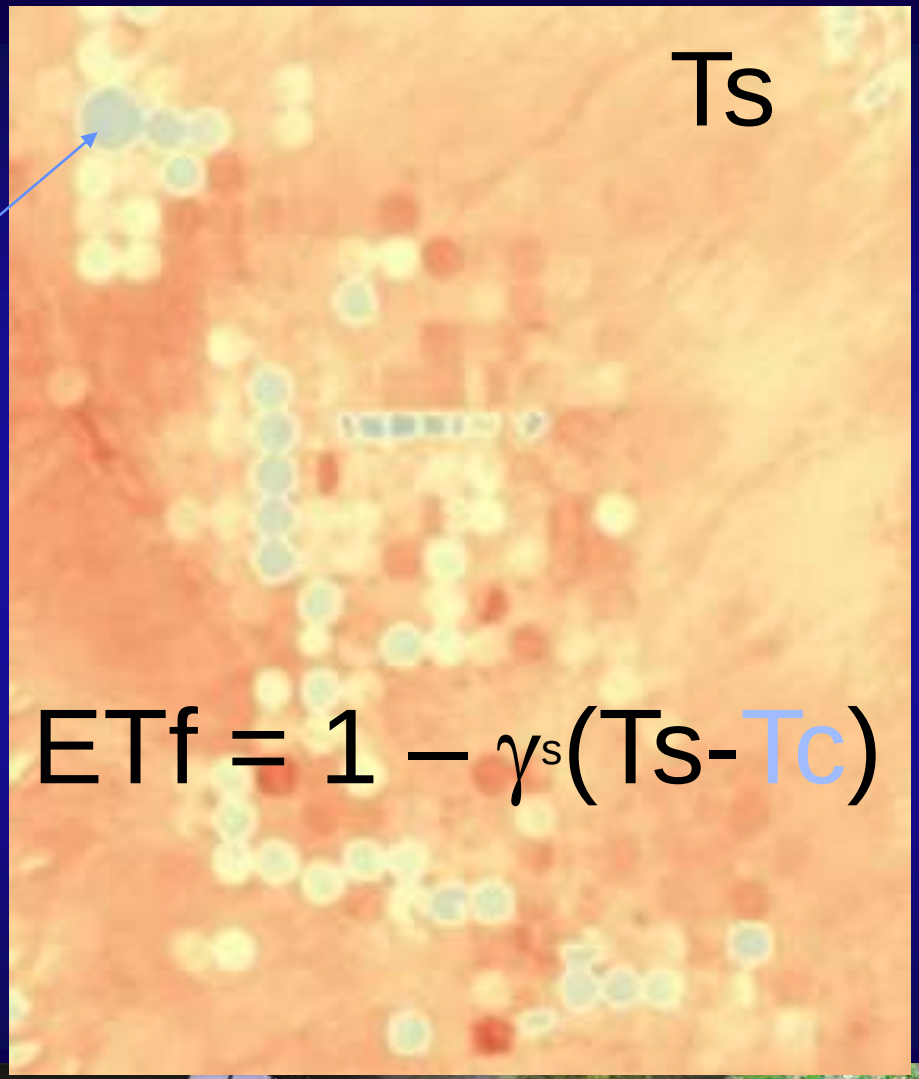
Transect in Willcox Irrigation Basin



USGS

LST (Ts) distribution in an irrigated valley Willcox, AZ,: March 21 2015)

Ts=Tc



Tc=
f(air temp)

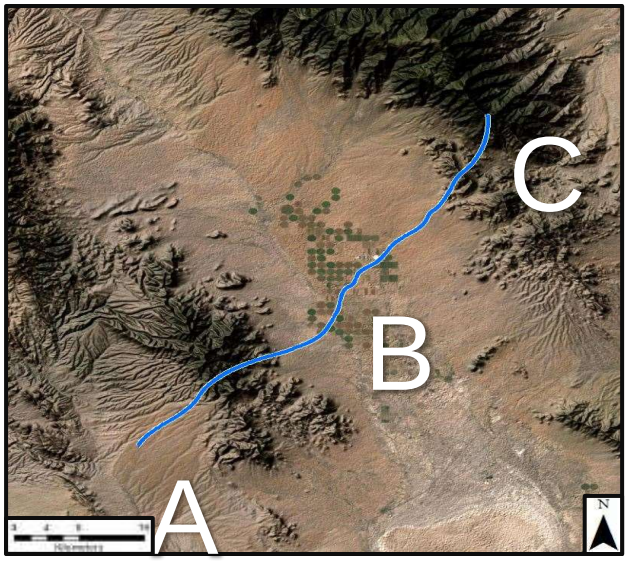
USGS

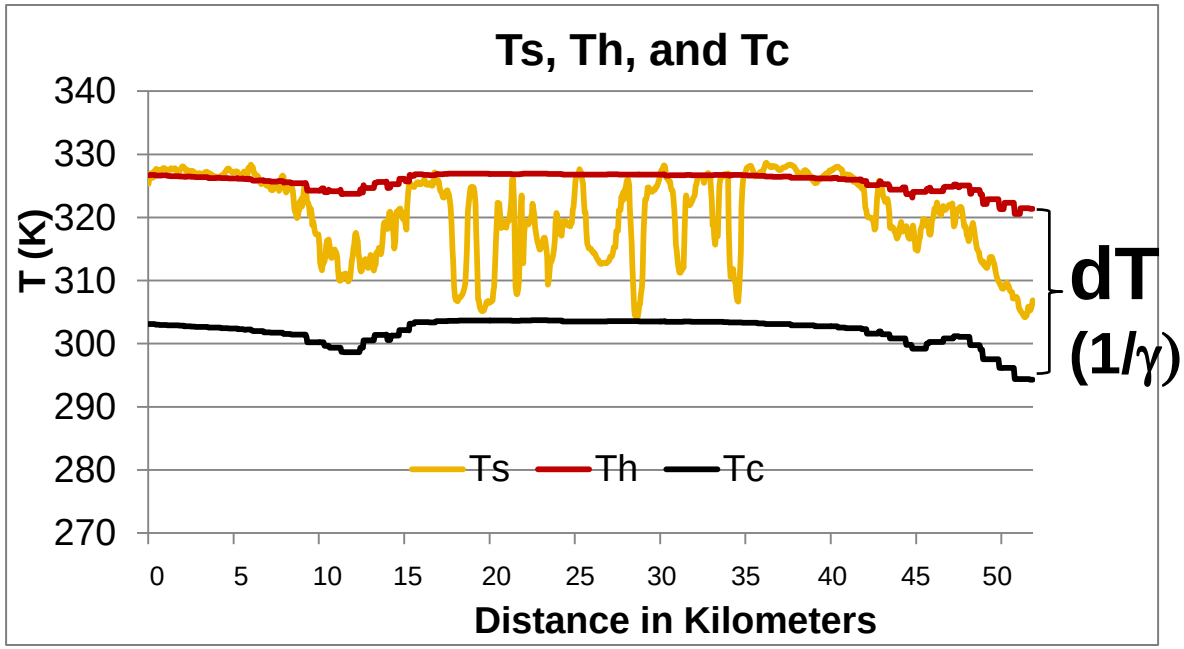
LST(Ts), Hot (Th)/Cold (Tc) Limits for Jun 23, 2014

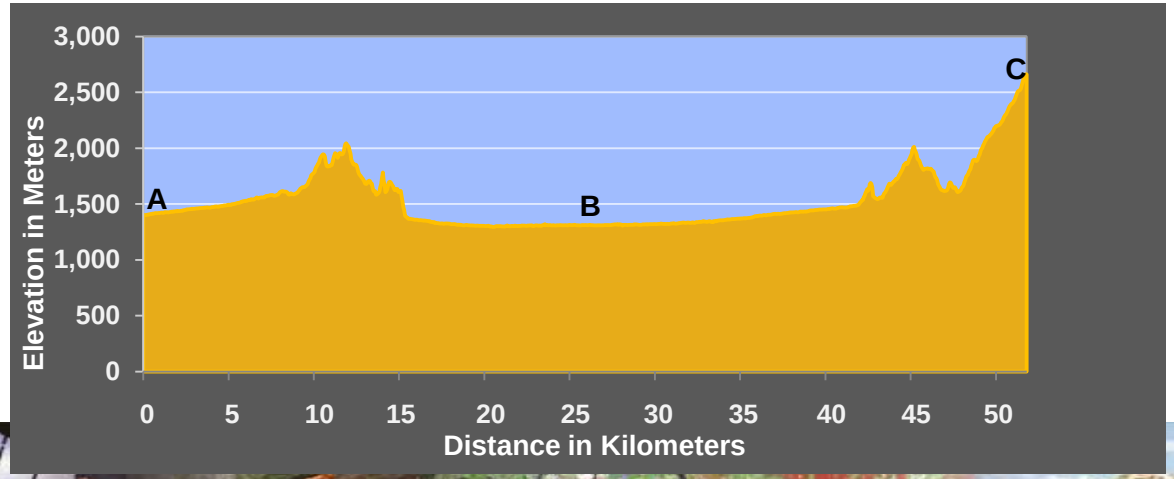
$$ETf = 1 - \gamma^{s}(Ts - Tc) \quad (0 - 1)$$

$$\gamma^{s} = \frac{\rho Cp}{Rn\, r_a}$$

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



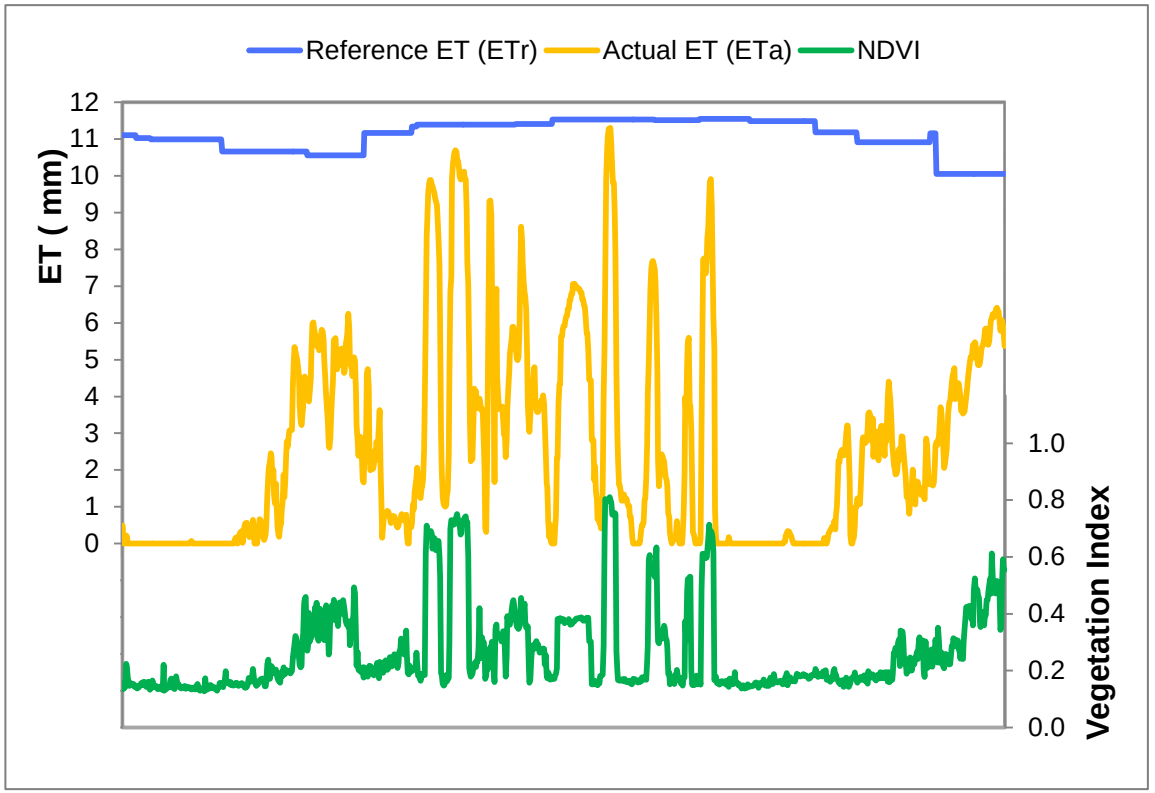


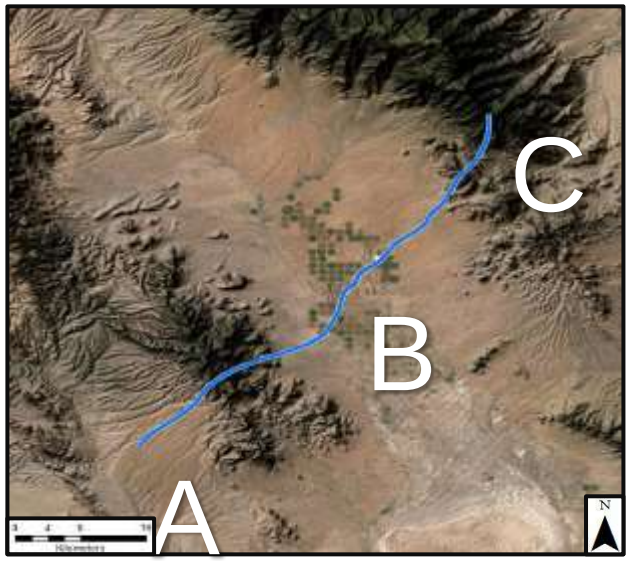


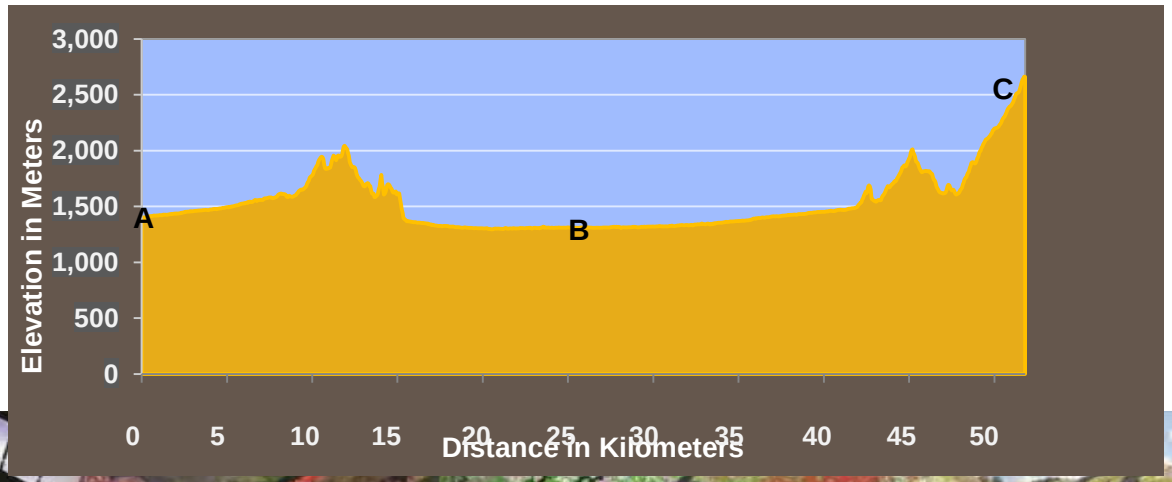
USGS

ETa, PET (ETr), NDVI

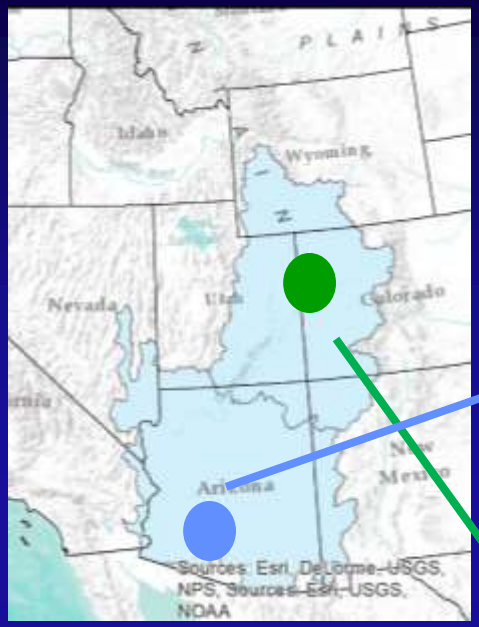
$$ETa = ETo - \gamma^{s}(Ts - Tc)ETo$$





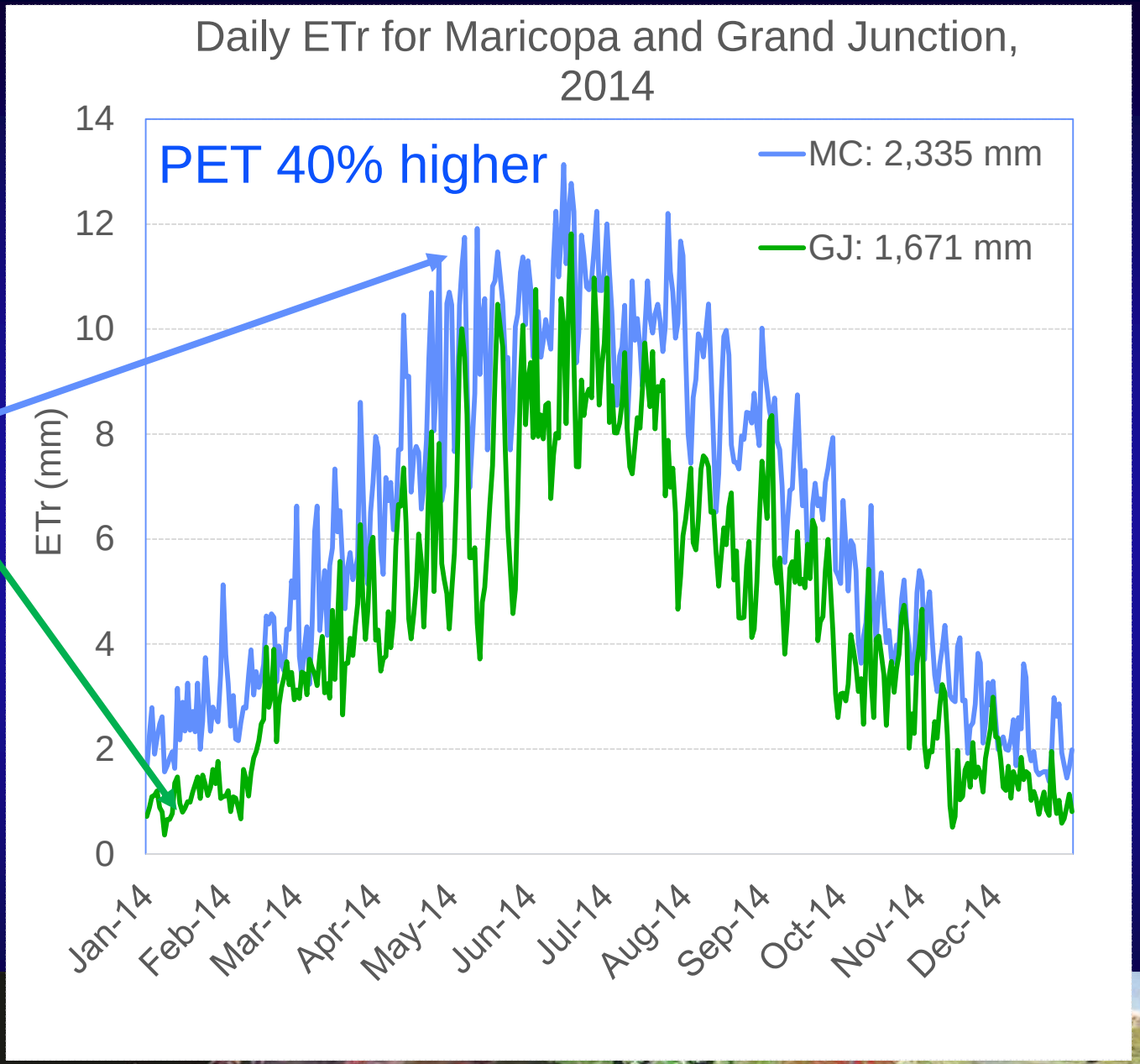


USGS



Elevation:
MC: 358 m
GJ: 1,397 m

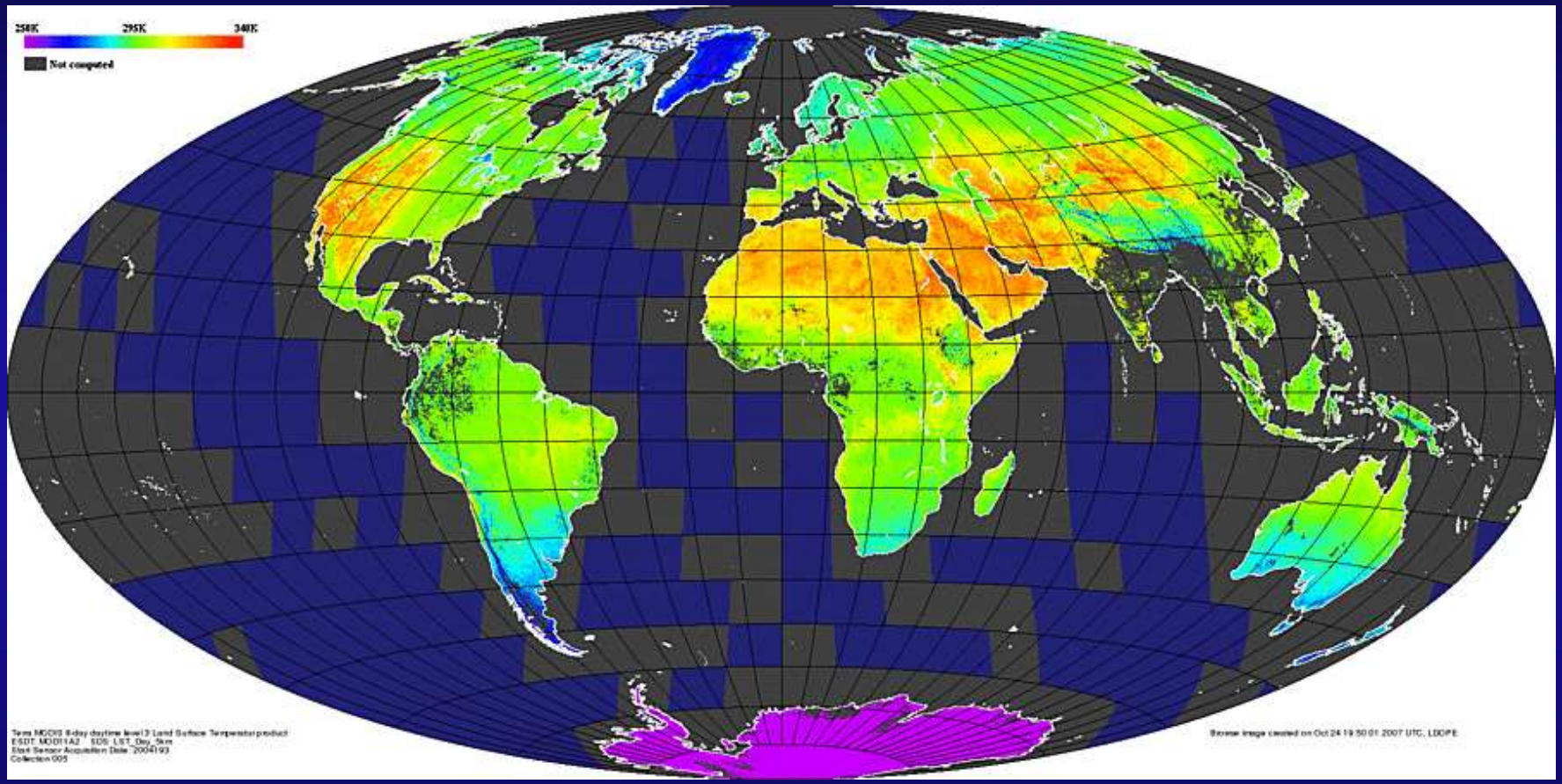
ETr processed from GRIDMET (Abatzoglou, 2012)



Source of input data: LST, T air, ETo

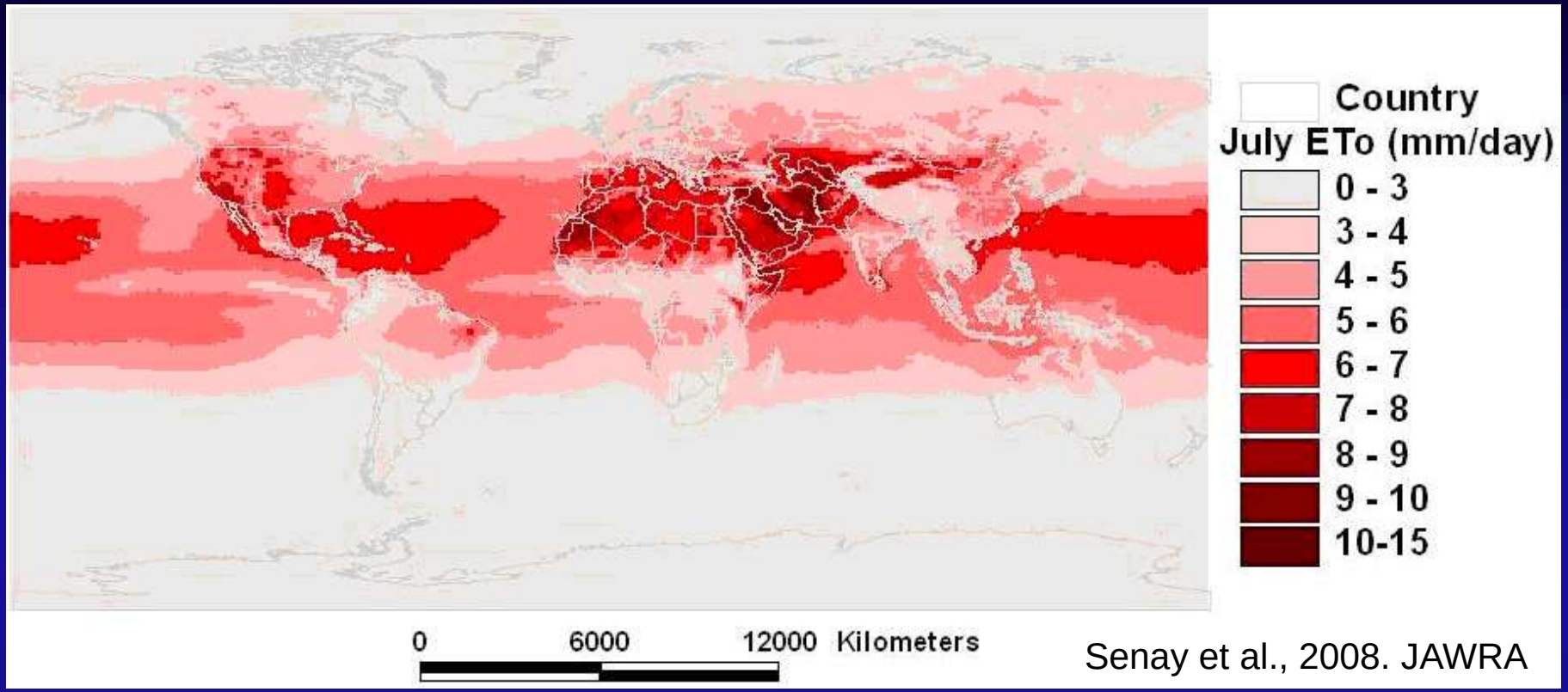
- Land Surface Temperature (LST) from thermal imagery
  - Current implementation with SSEBop
    - Landsat (~100m)
    - MODIS (1km)
- Air Temp: PRISM, Daymet, TopoWx, GLDAS, Worldclim
- ETo: model assimilated global weather datasets such as GDAS, NLDAS, GRIDMET or station-based P-M ETo fields.

MODIS 8-day Land Surface Temperature (1-km spatial resolution)



USGS

Daily Global GDAS ETo for July 2004



Senay et al., 2008. JAWRA

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)}$$

6-hr weather forecast data from NOAA: Radiation, temp, wind, RH and pressure to solve the standardized P-M Equation

http://earlywarning.usgs.gov/Global/dwnglobalpet.php

USGS

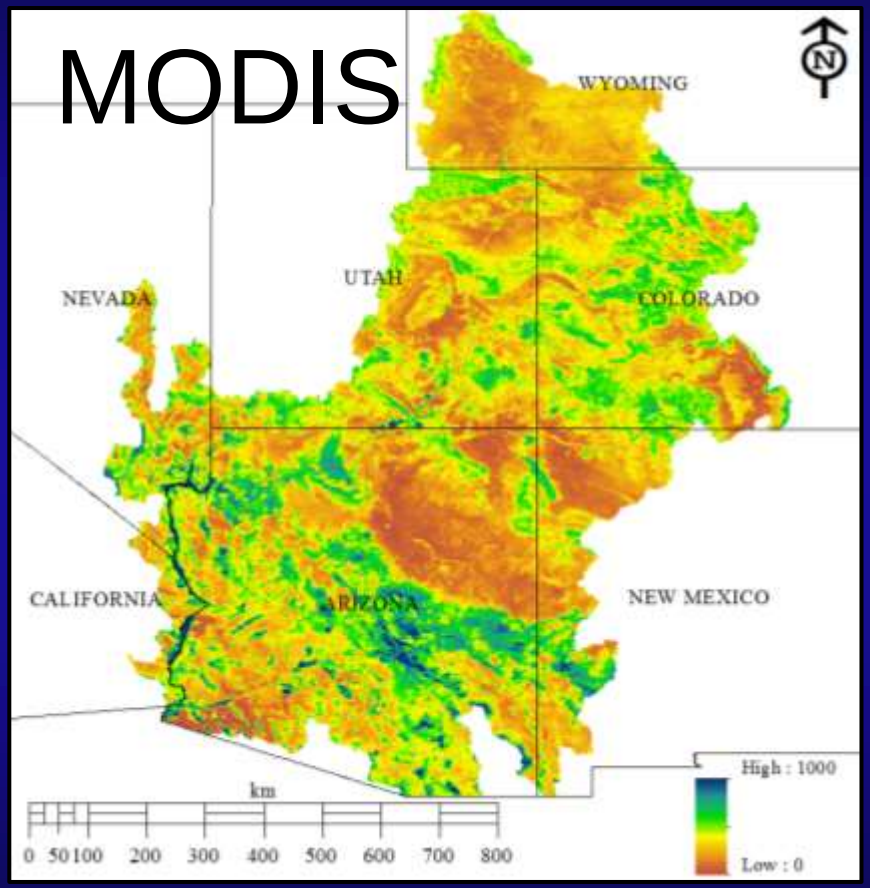
Landsat Scale ET:
Water use at a field scale…

44 Landsat path/row
Scenes to cover
The Colorado River Basin

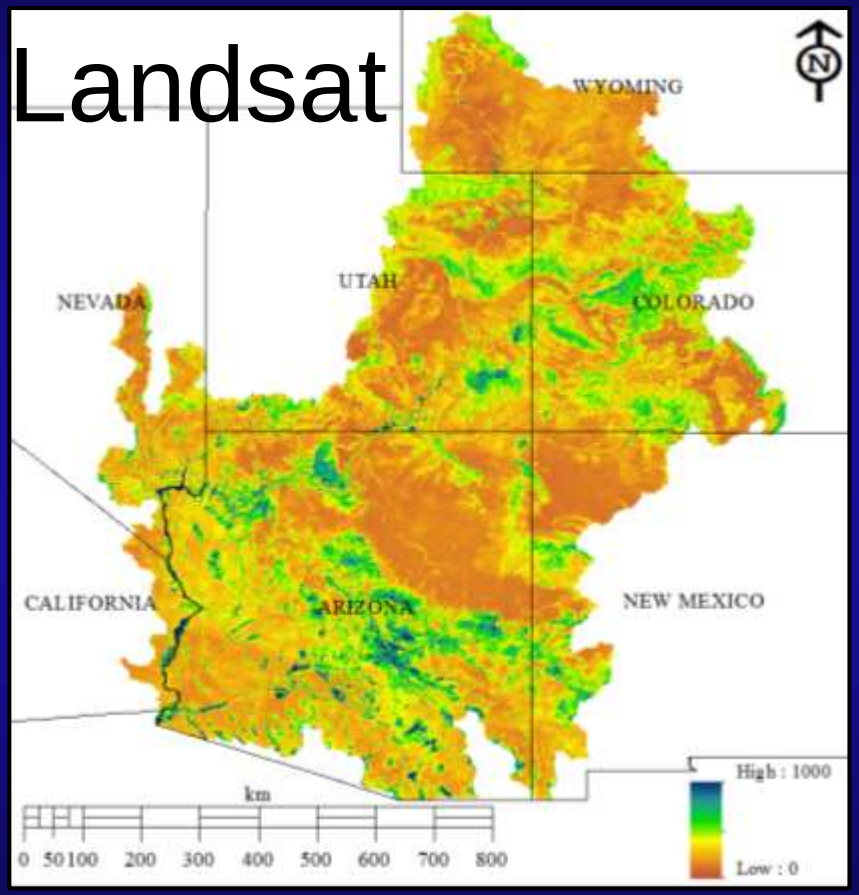
Clouds Issues:
9 to 15 images
for each p/r

Total = 400 – 500 images

Colorado River Basin Annual ET 2010 (mm): 1st ever for CRB, seamless Landsat ET!



Senay et al, 2013



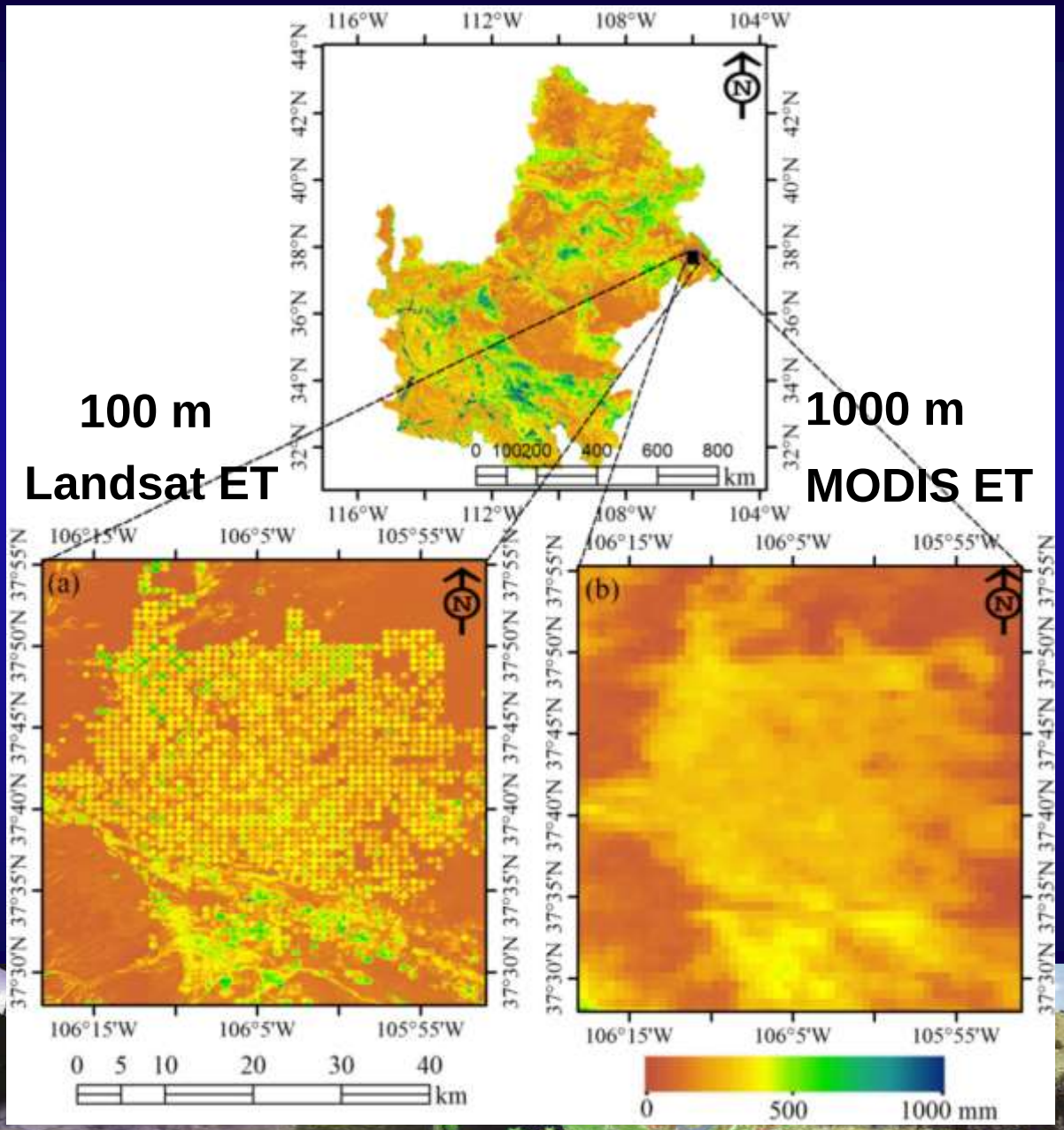
Singh et al, 2014

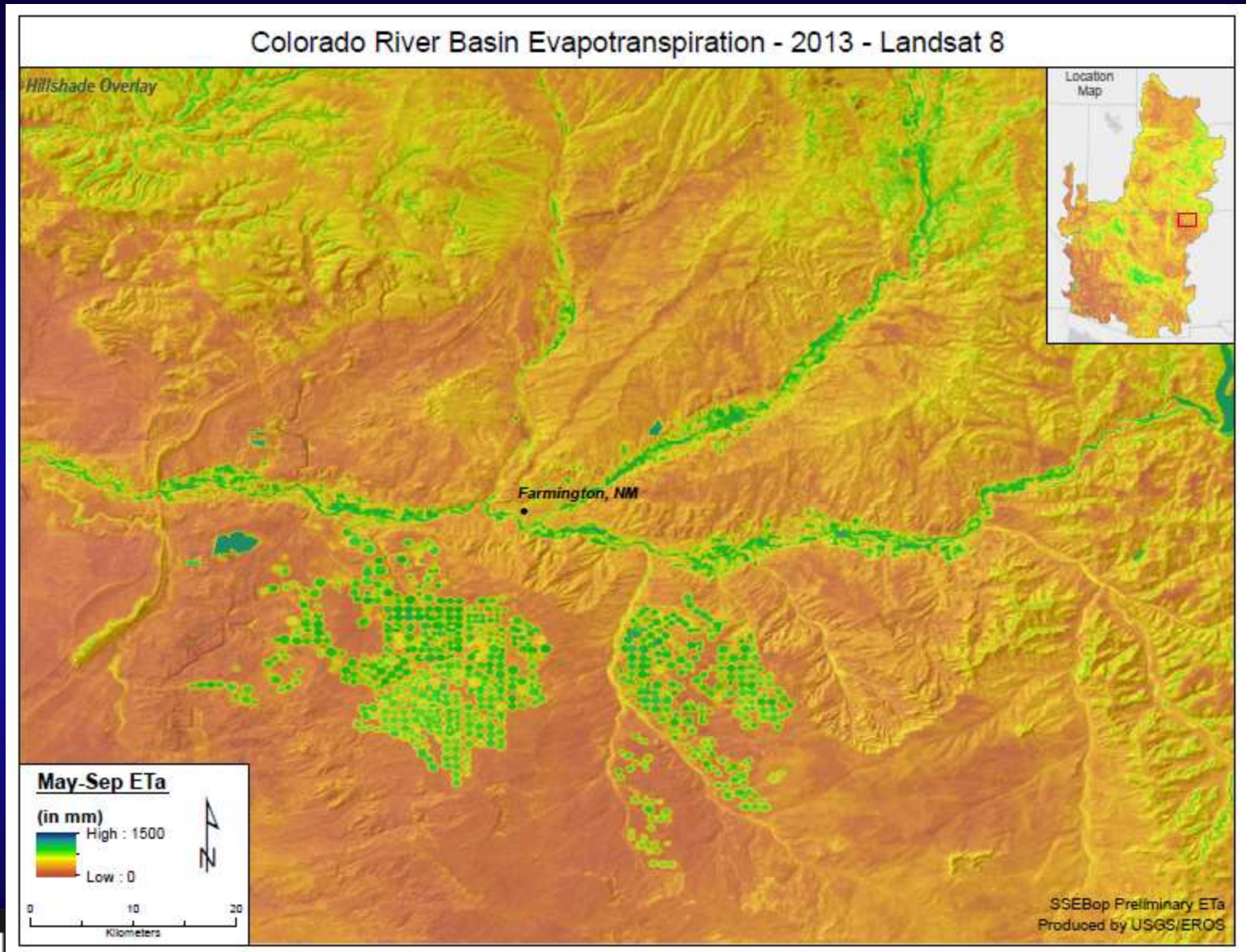
USGS

MODIS vs Landsat ET and Spatial Resolution

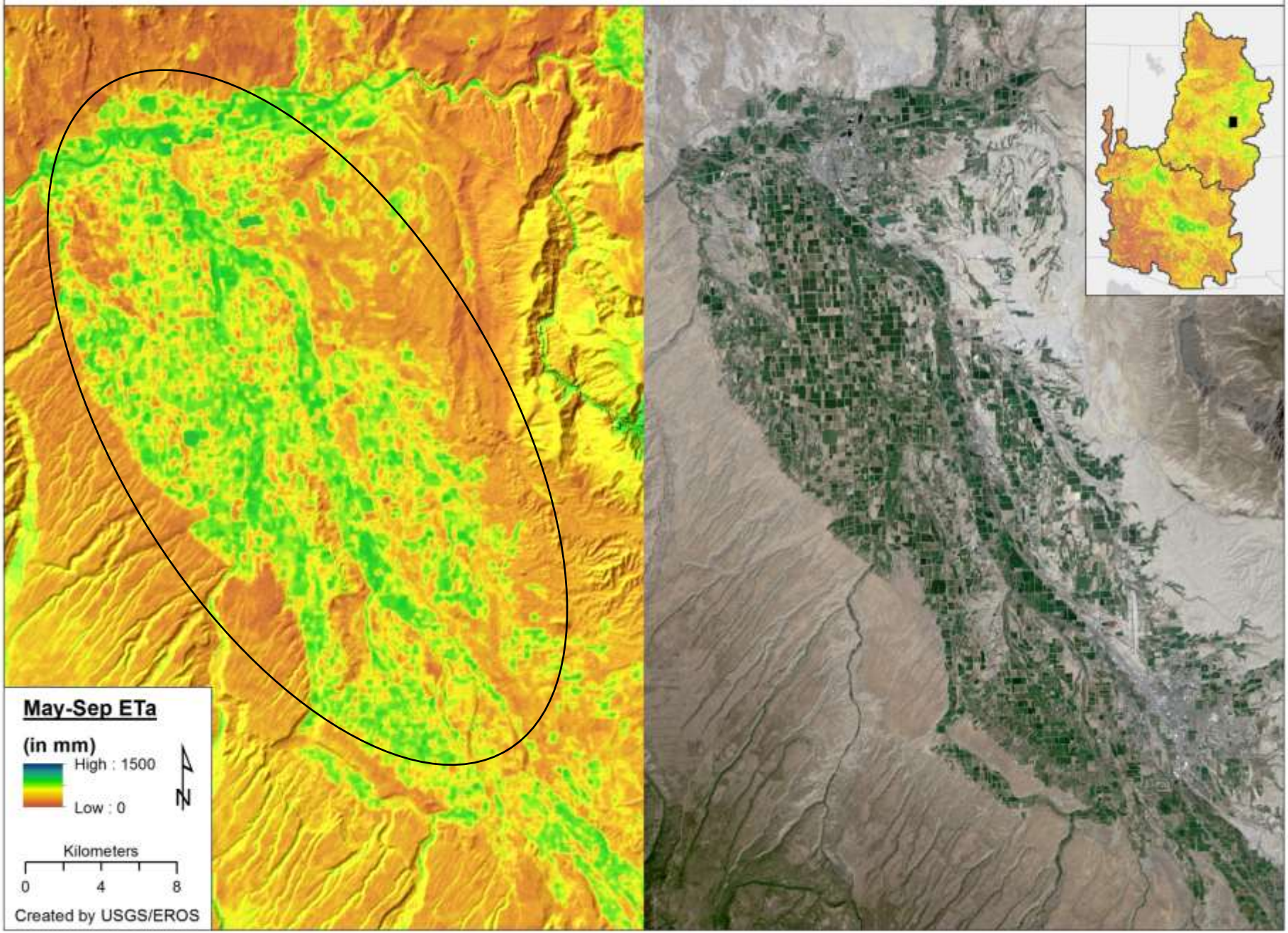
Singh et al, 2014

Base Map

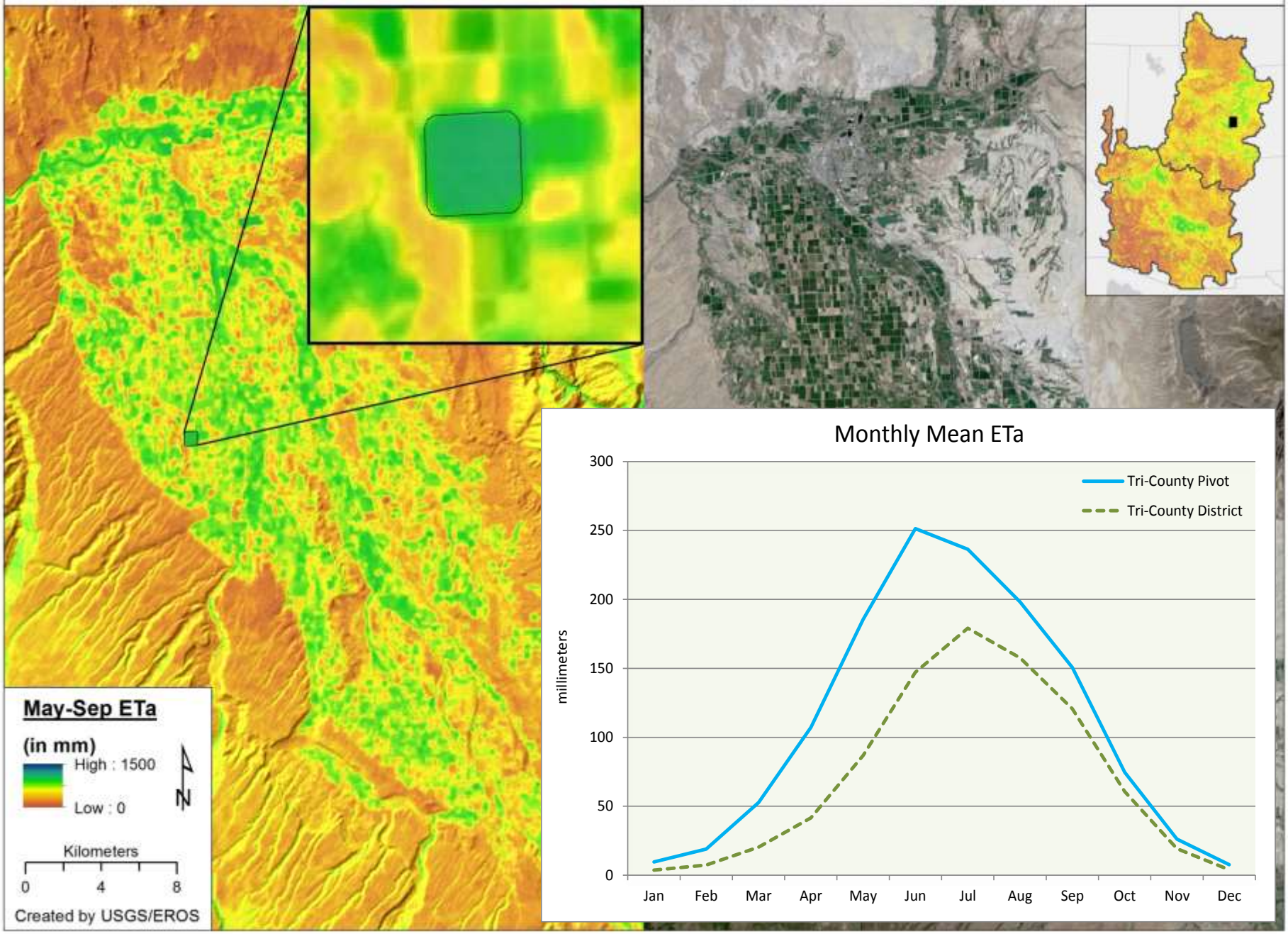



Colorado River Basin Evapotranspiration - 2013 - Landsat 8
Hillshade Overlay
Location Map
Farmington, NM
May-Sep ETa
(in mm)
High : 1500
Low : 0
N
0
10
20
Kilometers
SSEBop Preliminary ETa
Produced by USGS/EROS

Tri-County Water Conservancy District - 2013 - Landsat 8

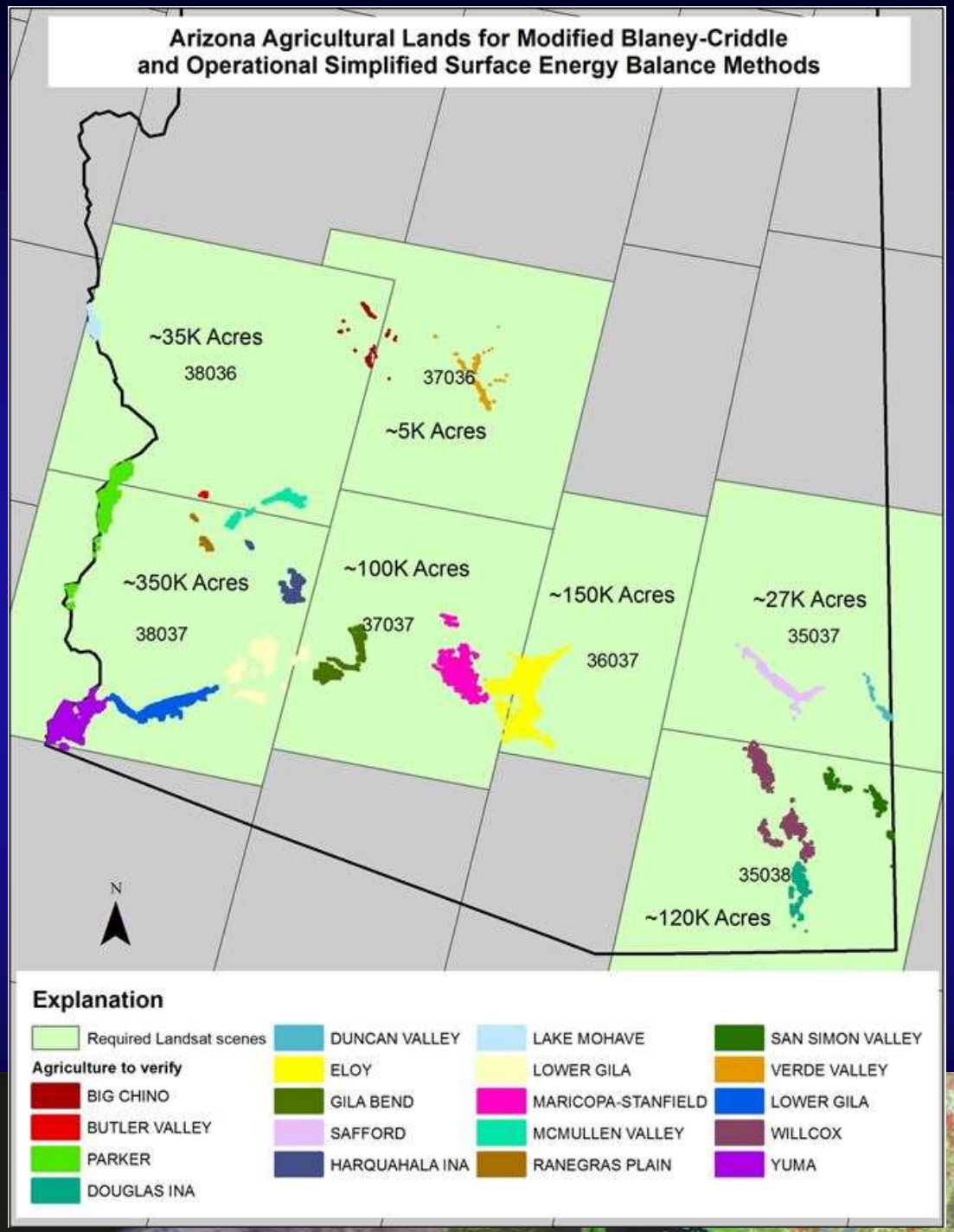


Tri-County Water Conservancy District - 2013 - Landsat 8



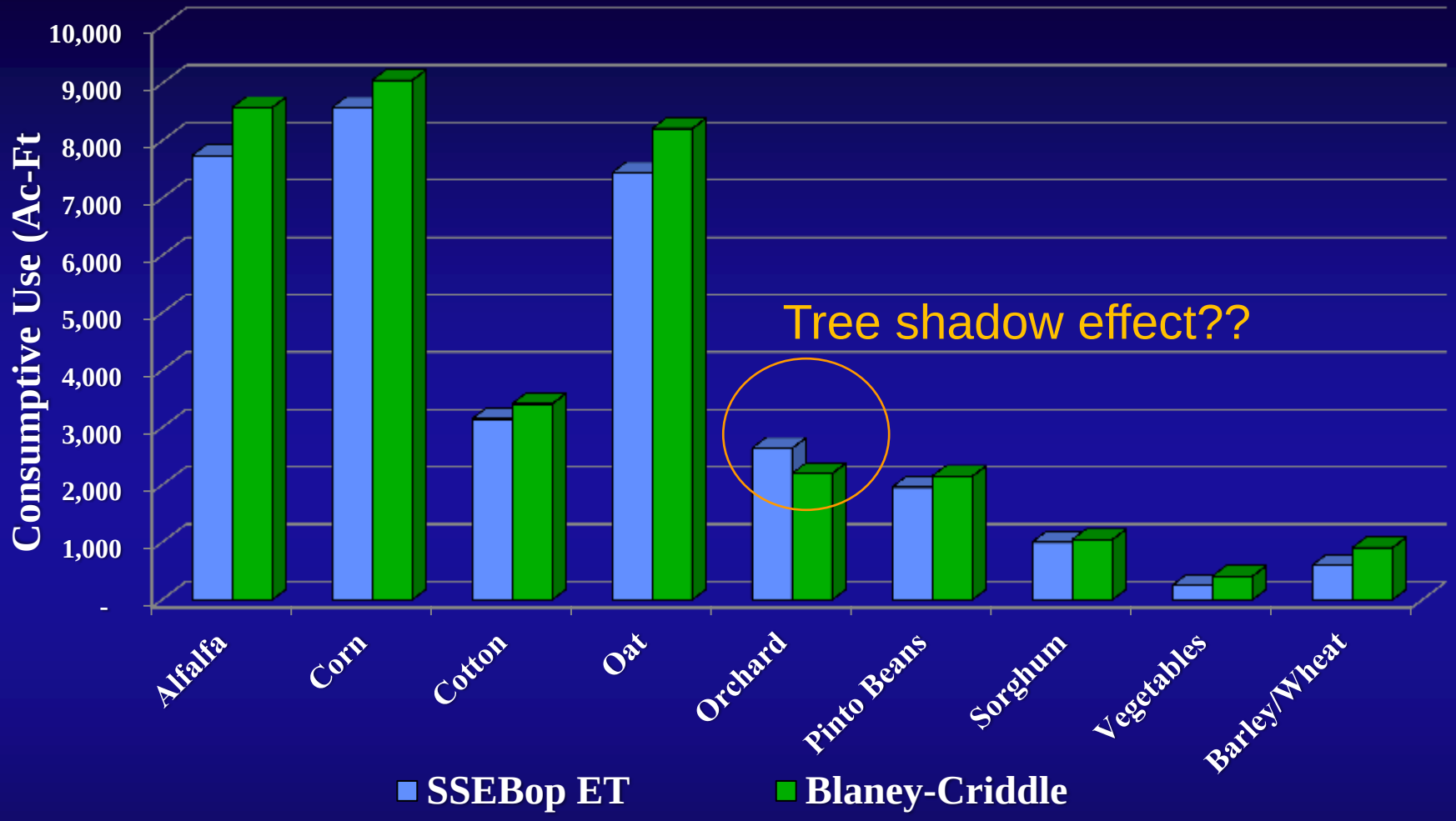
Model Performance Evaluation…

- Visual, qualitative spatial patterns
- EC Flux Tower
- Water Balance


Arizona Agricultural Lands for Modified Blaney-Criddle
and Operational Simplified Surface Energy Balance Methods
~35K Acres
38036
37036
~5K Acres
~350K Acres
38037
~100K Acres
37037
~150K Acres
36037
~27K Acres
35037
35038
~120K Acres
N
Explanation
Required Landsat scenes
Agriculture to verify
BIG CHINO
BUTLER VALLEY
PARKER
DOUGLAS INA
DUNCAN VALLEY
ELOY
GILA BEND
SAFFORD
HARQUAHALA INA
LAKE MOHAVE
LOWER GILA
MARICOPA-STANFIELD
MCMULLEN VALLEY
RANEGRAS PLAIN
SAN SIMON VALLEY
VERDE VALLEY
LOWER GILA
WILLCOX
YUMA

USGS

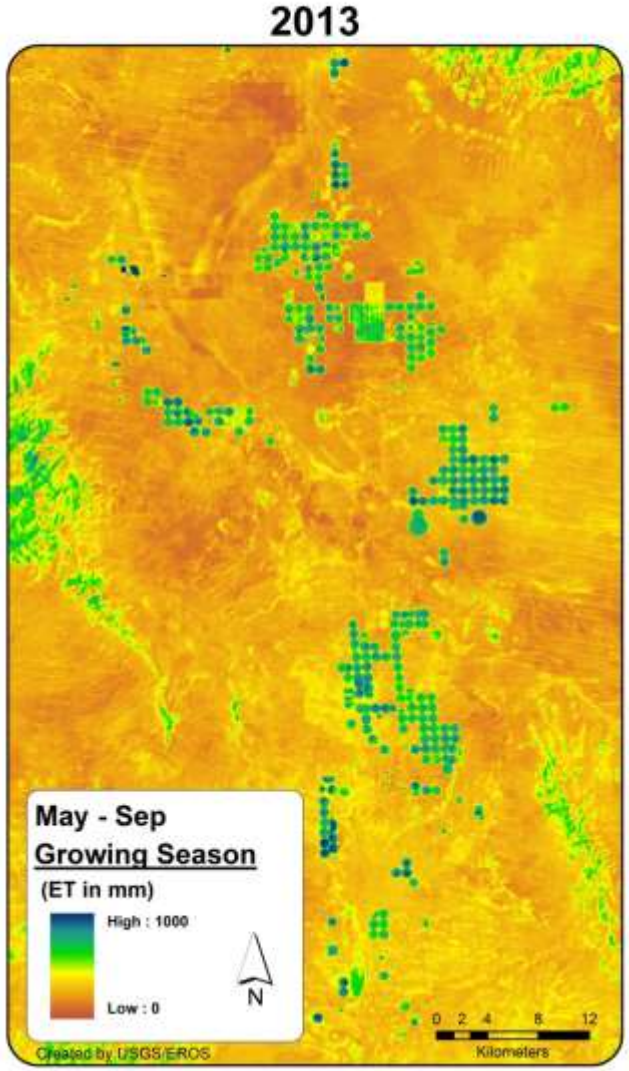
SSEBop vs Blaney-Criddle Consumptive Use, 2010 Douglas Basin

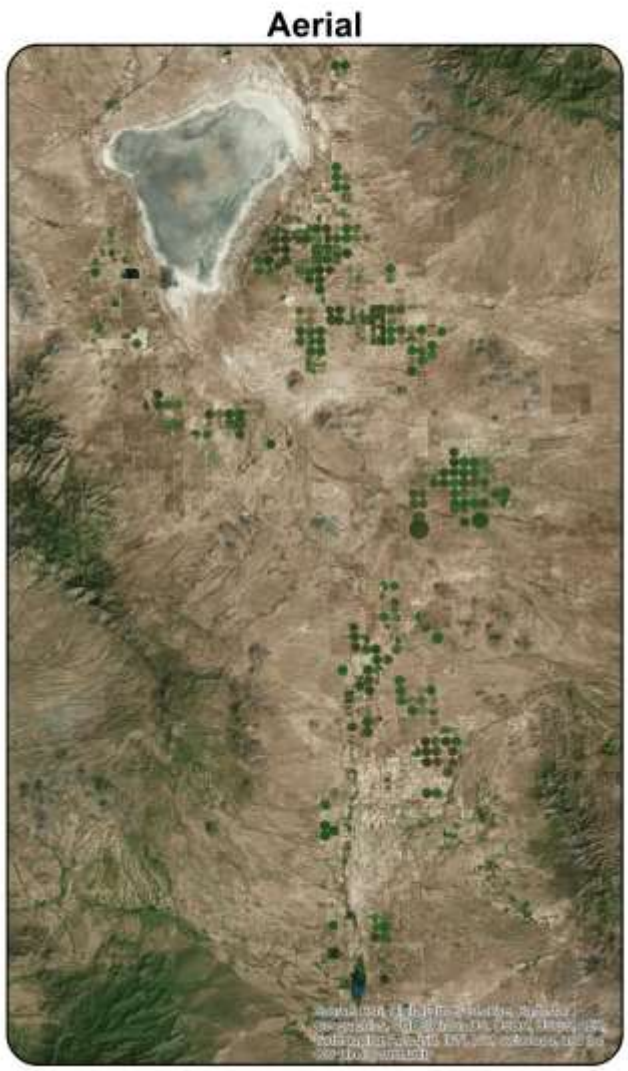


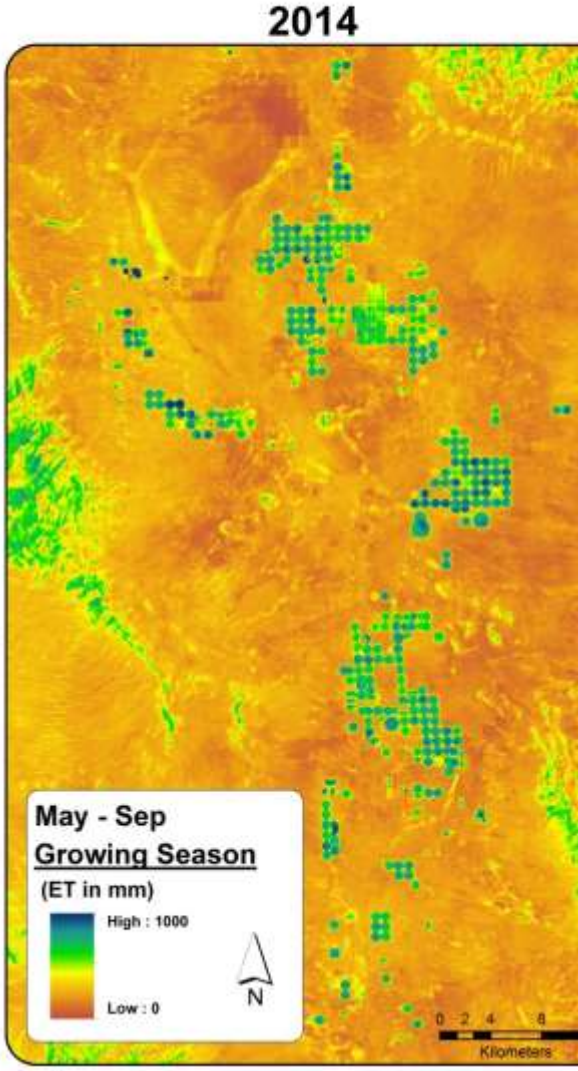
From AZ Water Science Center: Amy Read and Saeid Tadayon, 2015

USGS

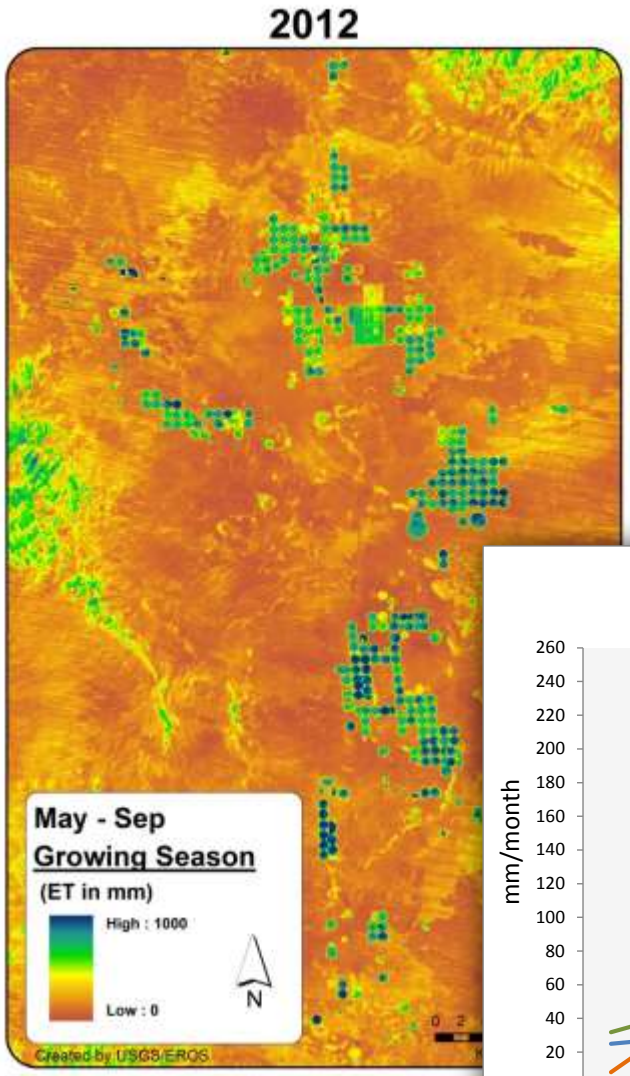
Douglas and Willcox Irrigation Basin Evapotranspiration

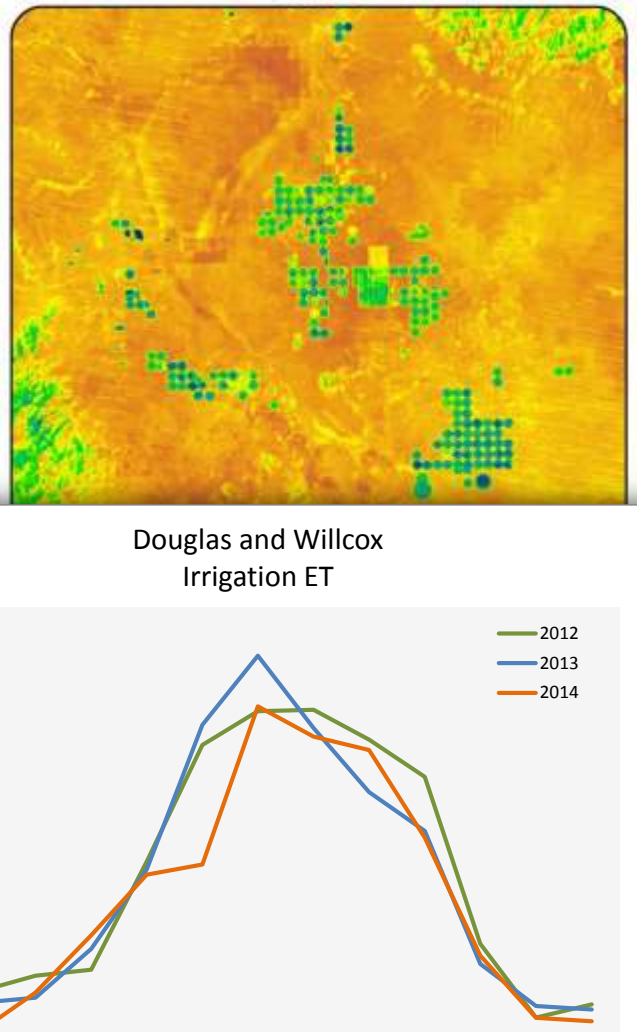


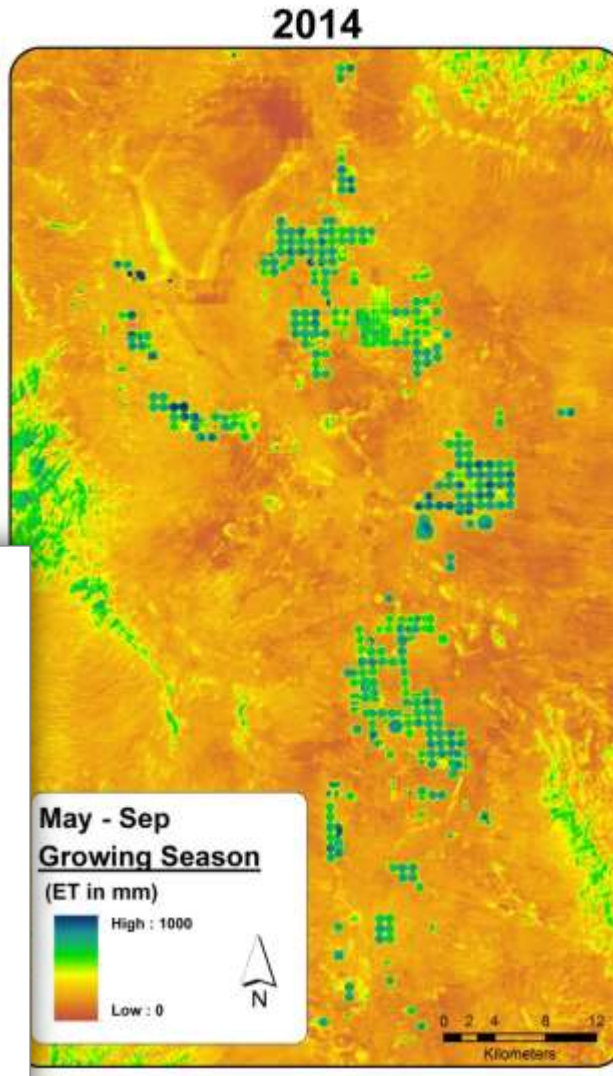


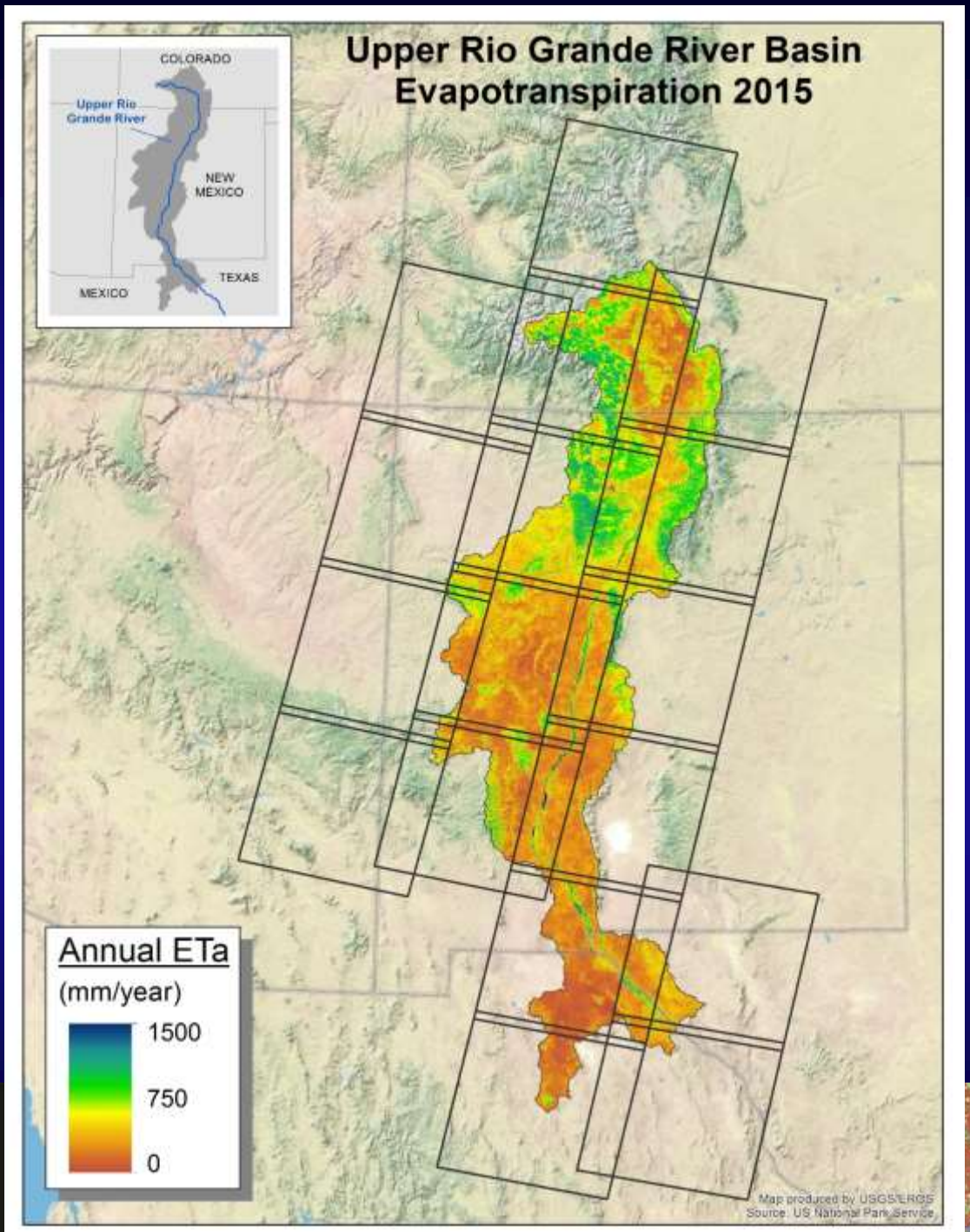


Douglas and Willcox Irrigation Basin Evapotranspiration

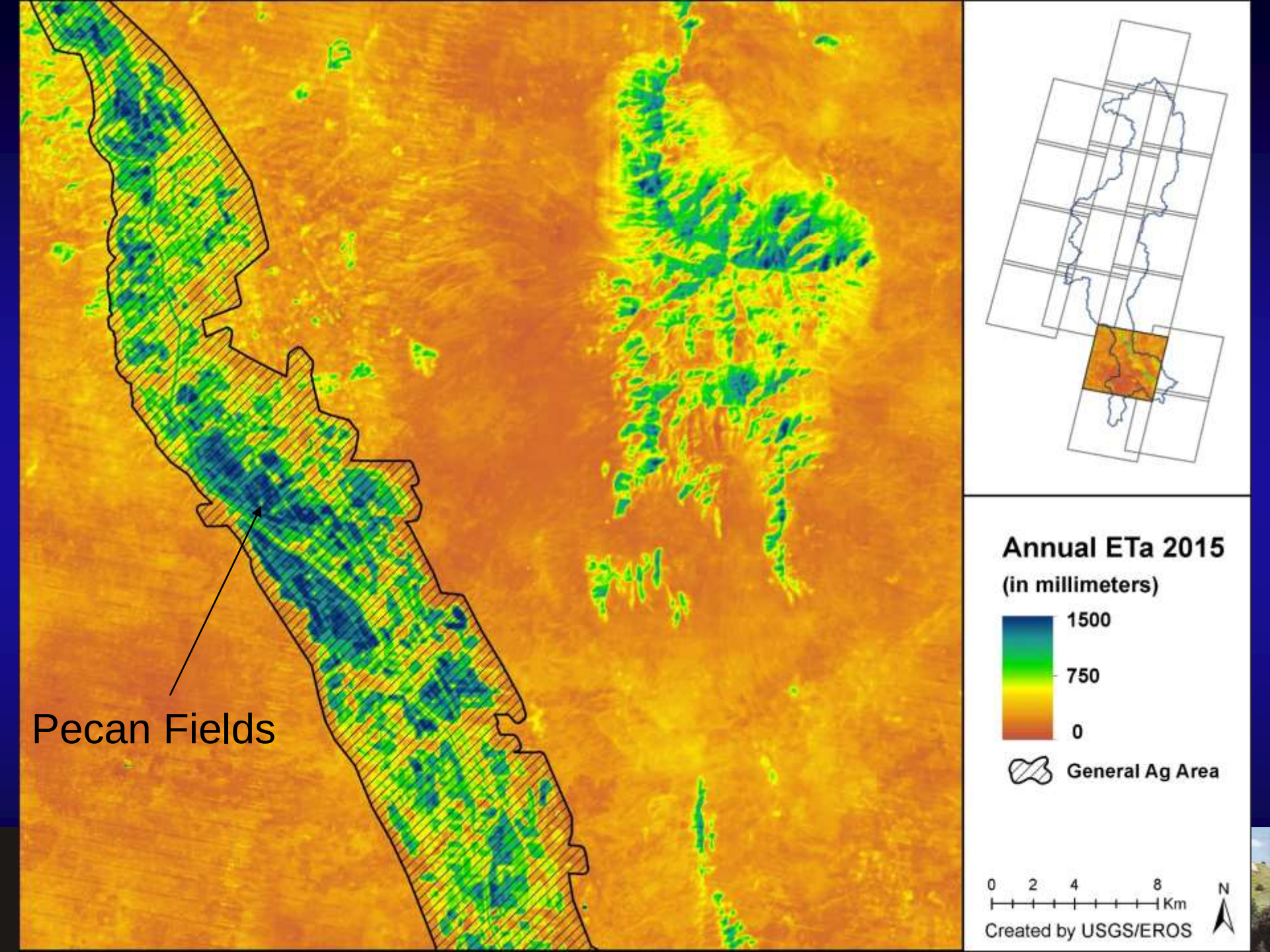




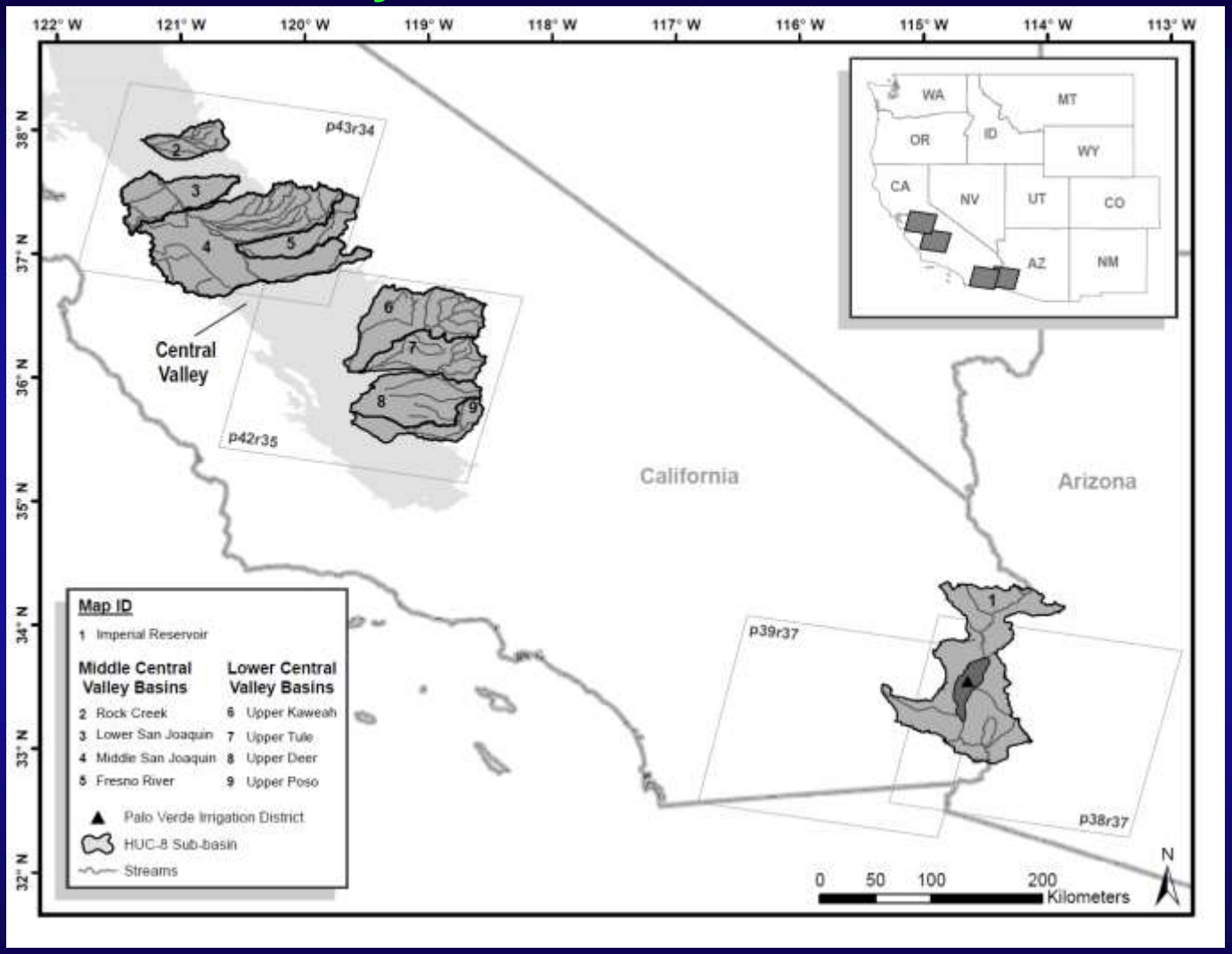



Upper Rio Grande River Basin
Evapotranspiration 2015
COLORADO
Upper Rio Grande River
NEW MEXICO
TEXAS
MEXICO
Annual ETa
(mm/year)
1500
750
0
Map produced by USGS/EROS
Source: US National Park Service

USGS


Pecan Fields
Annual ETa 2015
(in millimeters)
1500
750
0
General Ag Area
0 2 4 8
Km
N
Created by USGS/EROS

Historical ET with Landsat:
Central Valley and Palo Verde, California

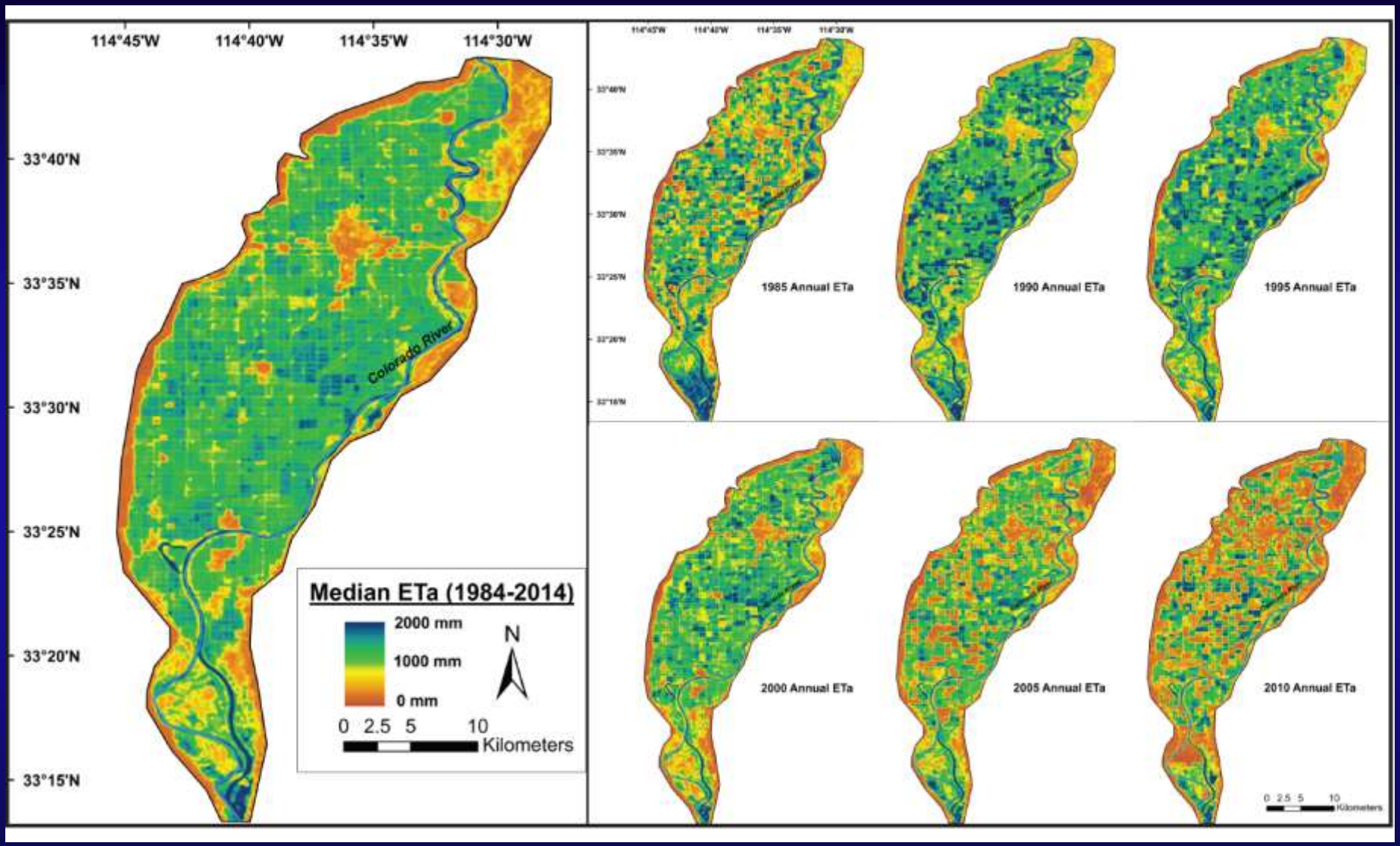


Under Review with RSE

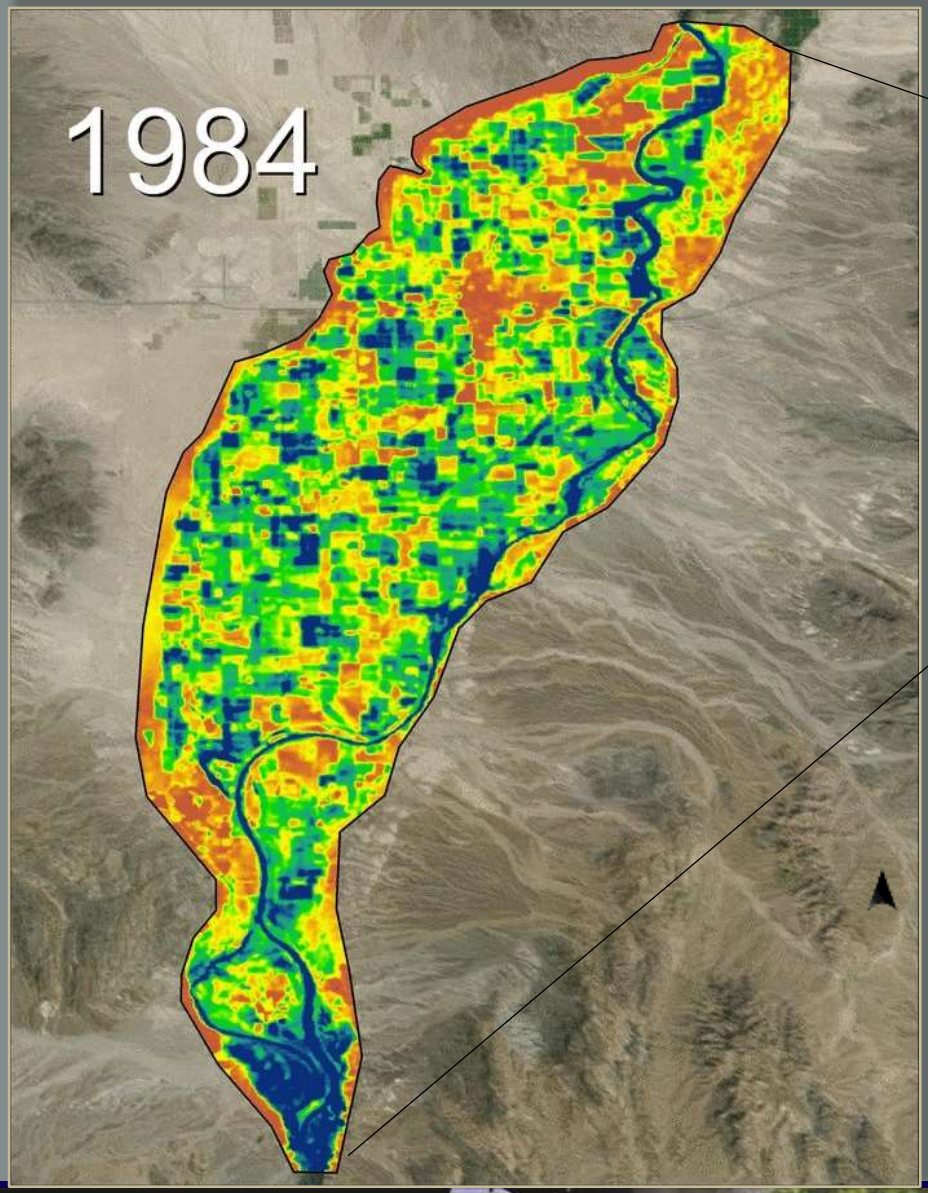
USGS

Under Review with RSE

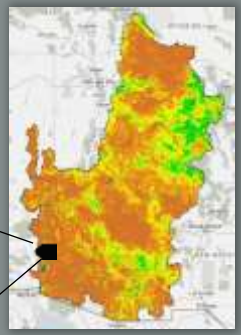
Palo Verde Irrigation District



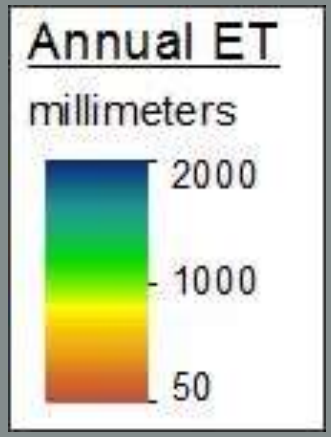
USGS



Historical ET
from Landsat
1984-2014



Palo Verde
Irrigation District

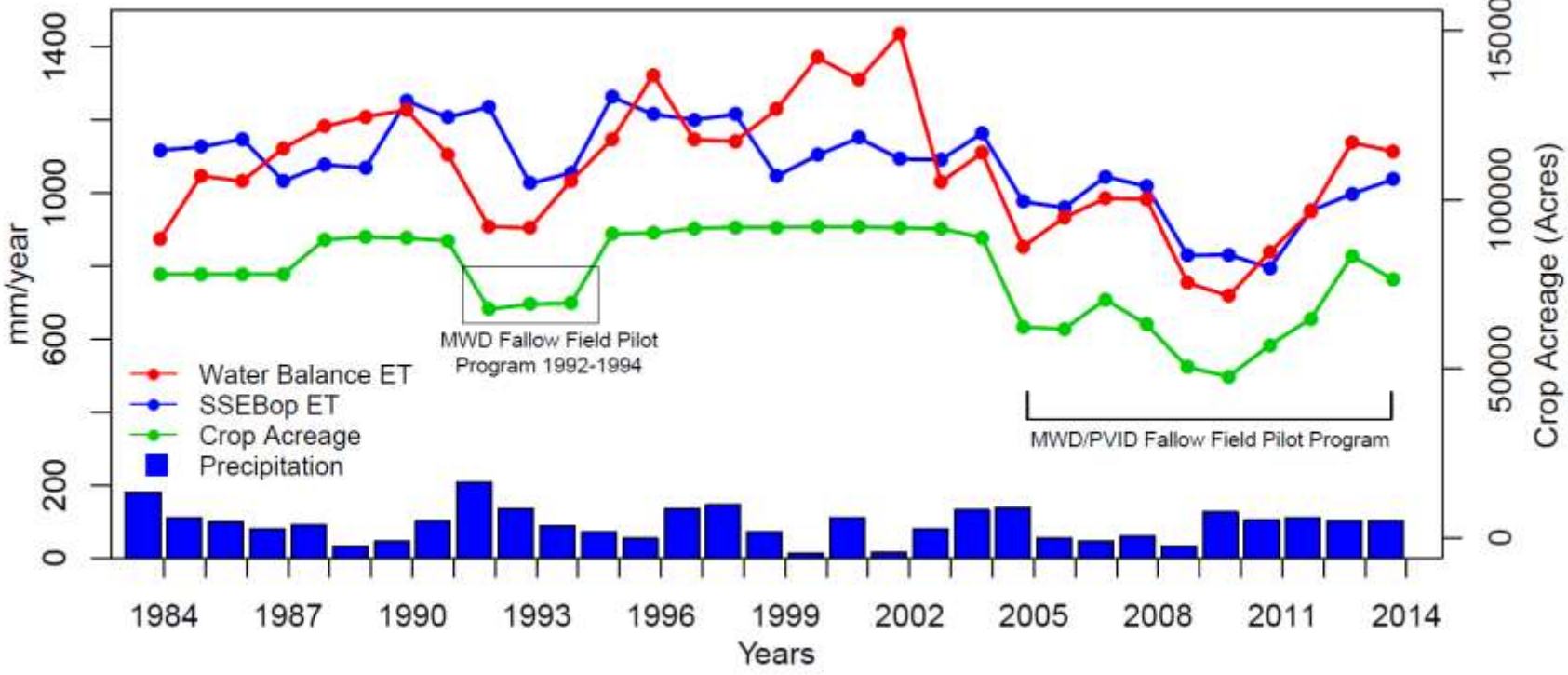


Path 37 Row 37 (1984-2015)

30+ years of Landsat

USGS

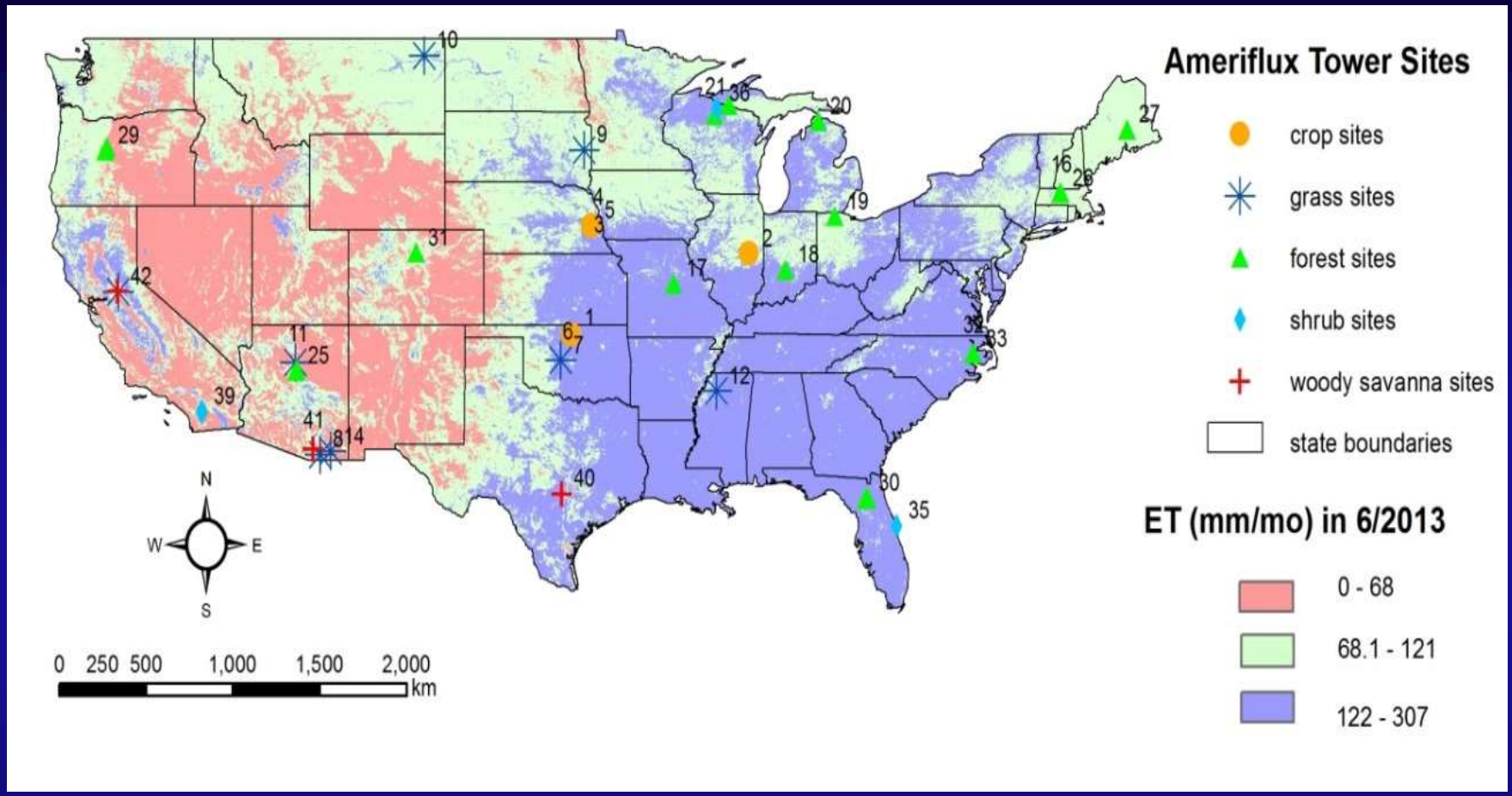
Annual ET (mm): RS vs USBR Consumptive Use Report
Palo Verde Irrigation District



Under Review with RSE

EC Flux Towers and Water Balance

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.

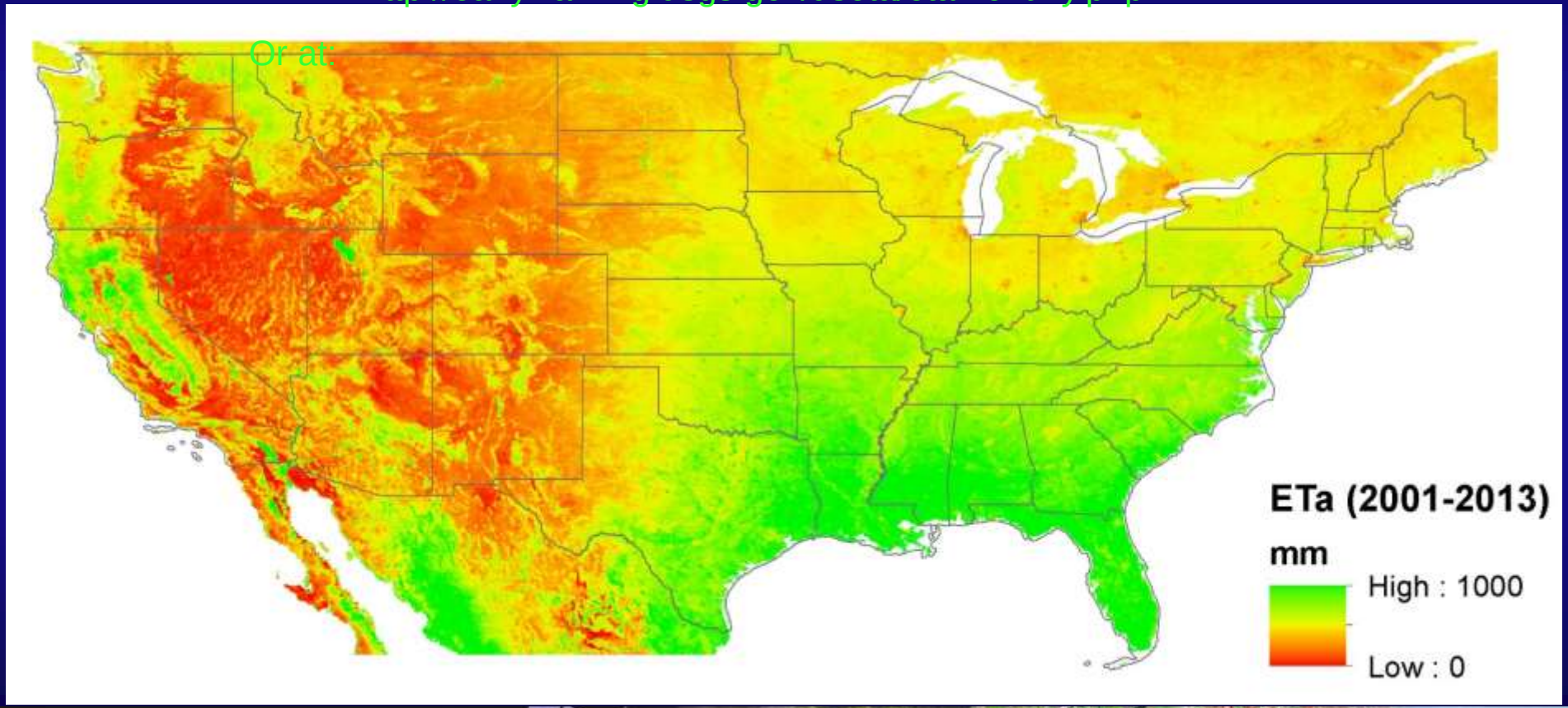
Regional Products: CONUS (MODIS)

Annual ETa Distribution (mm)
(median of 2001-2013, SSEBop)

http://cida.usgs.gov/thredds/catalog/ssebopeta/files/07-2016/catalog.html

http://earlywarning.usgs.gov/useta/etamonthly.php

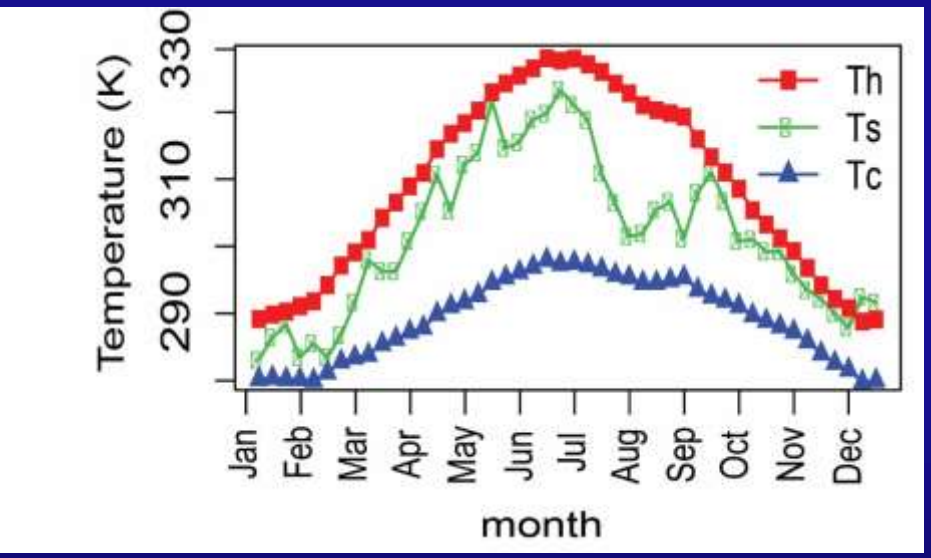
Or at:

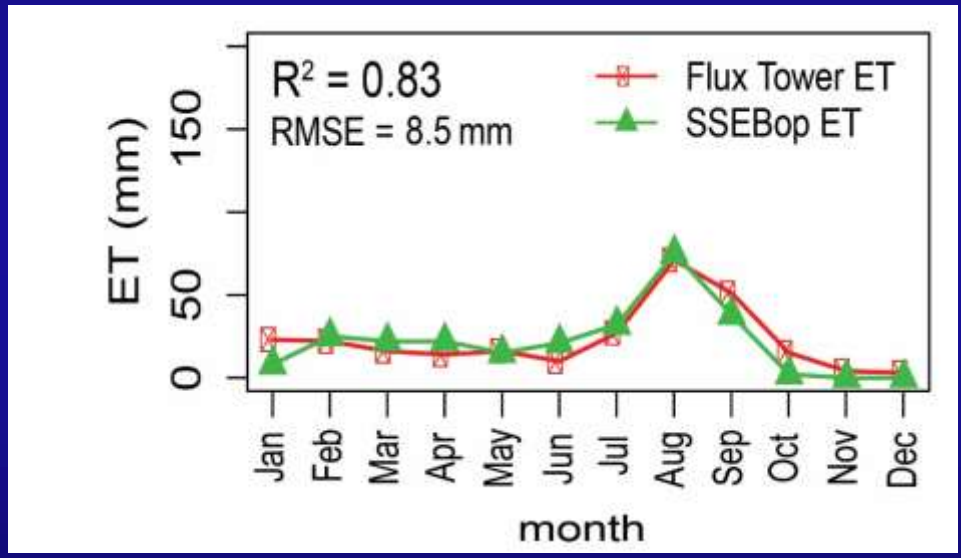


USGS

SSEBop Illustrative Validation with EC Flux Towers

EC Flux Tower: Audubon, AZ, 2005



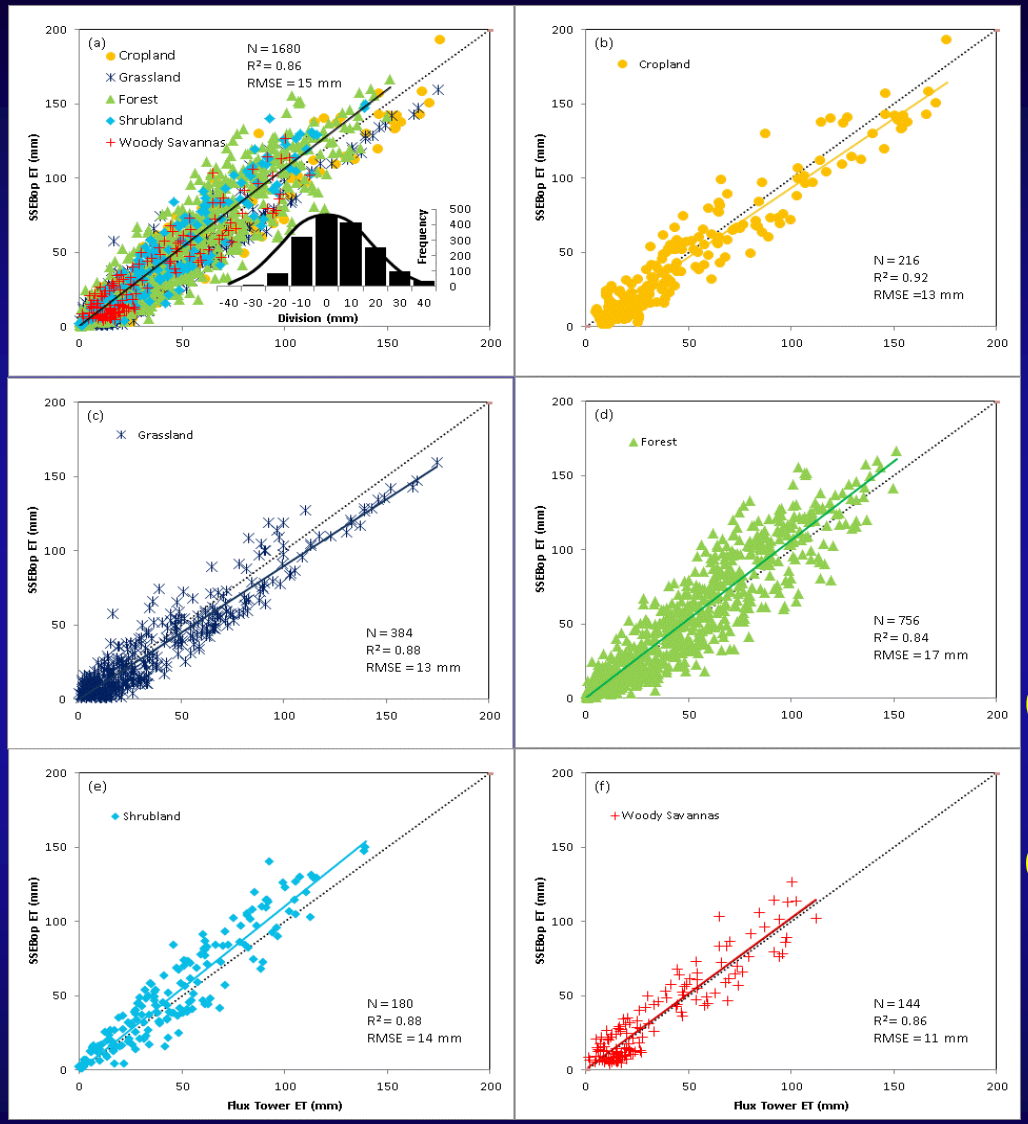


Senay et al., 2013

MODIS-based

USGS

Model validation with EC Towers by cover type



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

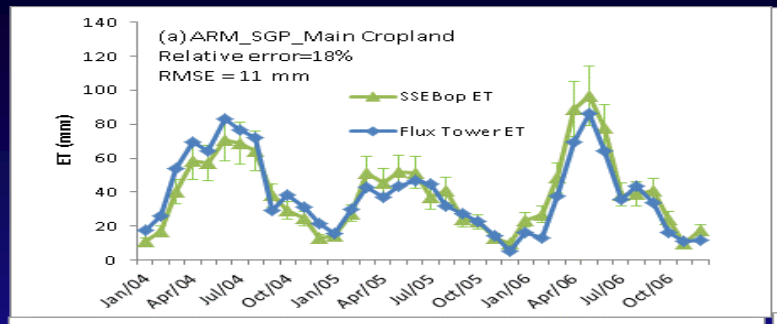
Overall model uncertainty is around 20% for monthly, comparable to most EB models

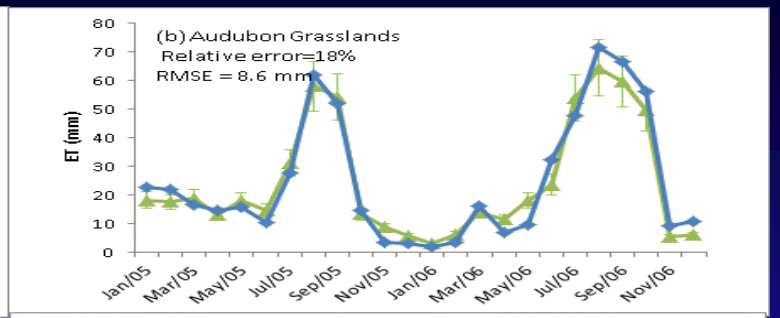
Chen et al, 2016, Journal of Hydrology

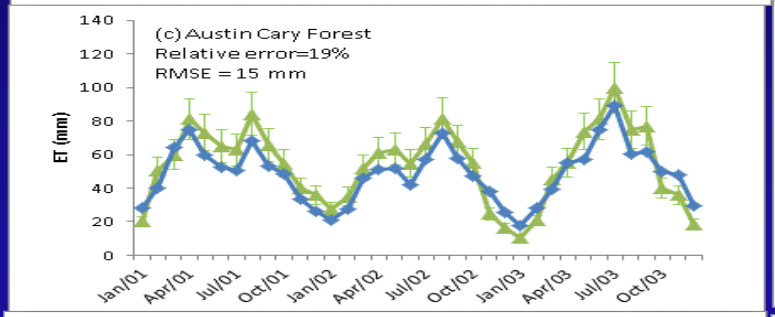
MODIS-based

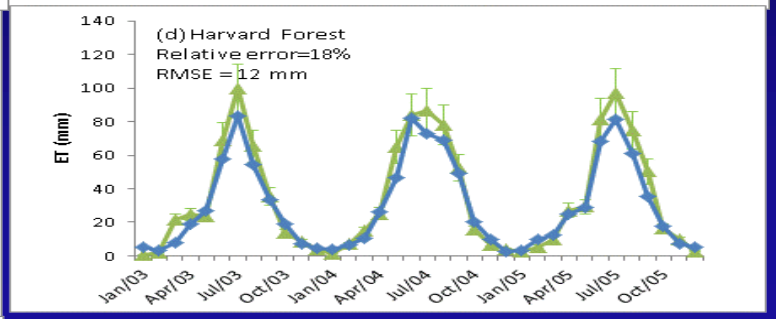
USGS

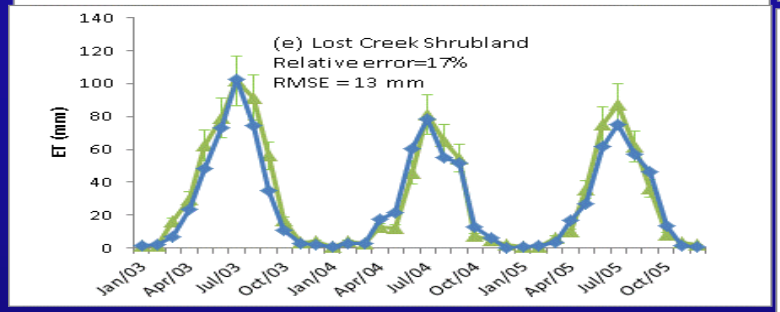
Model Validation: temporal traces

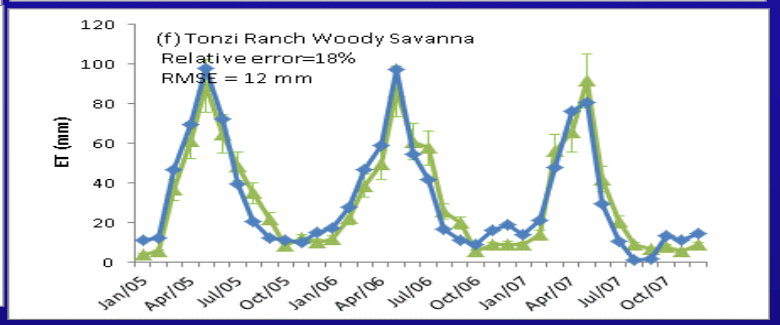










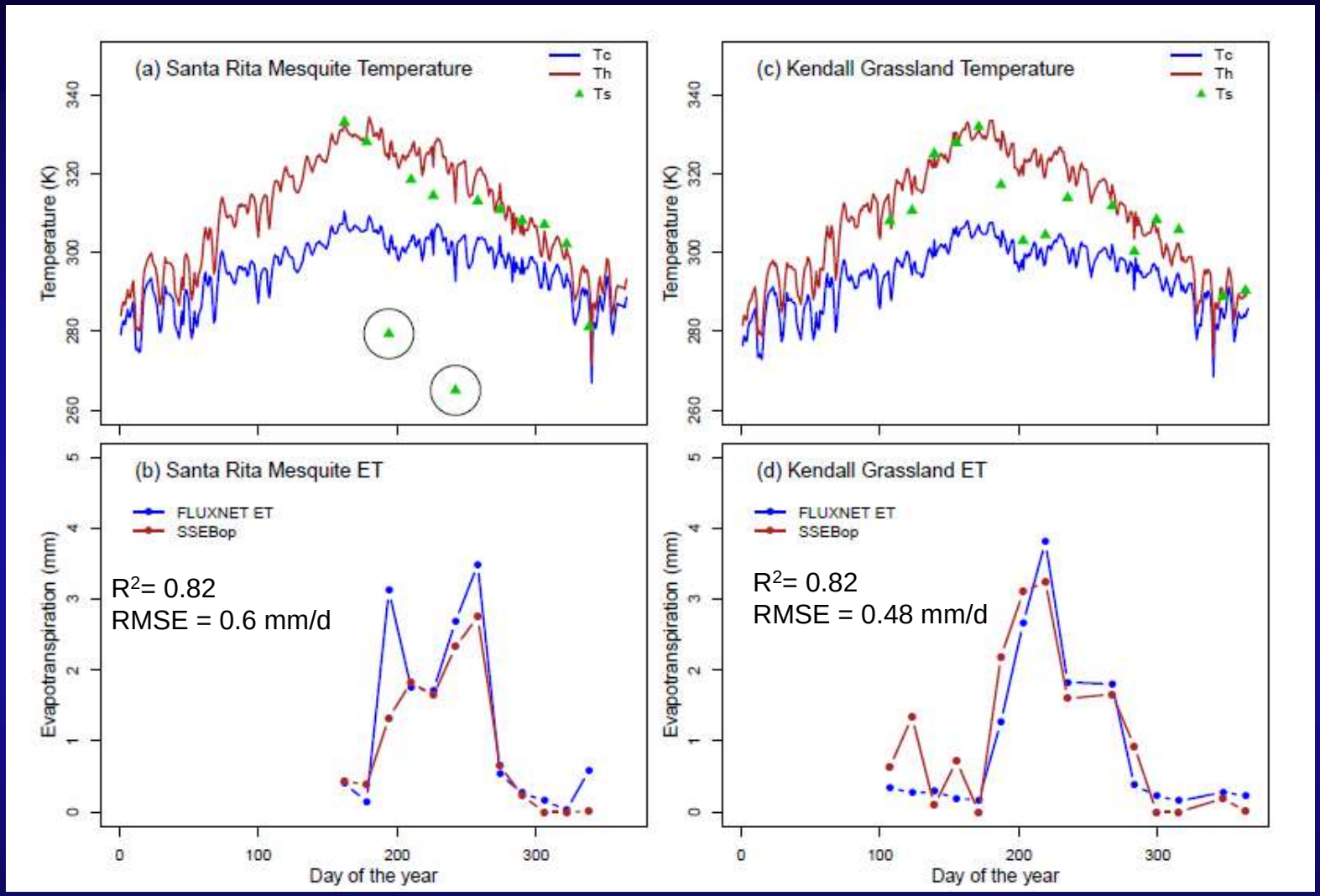


- **Comparison of ET ensemble means by Monte Carlo and SSEBop to ET measurements by eddy covariance method at six Ameriflux stations during a period from 2001 to 2007. The error bars indicate standard divisions of the ET estimates by the SSEBop model.**

MODIS-based

USGS

Evaluation using 2013 EC tower in semiarid shrub and grassland, AZ



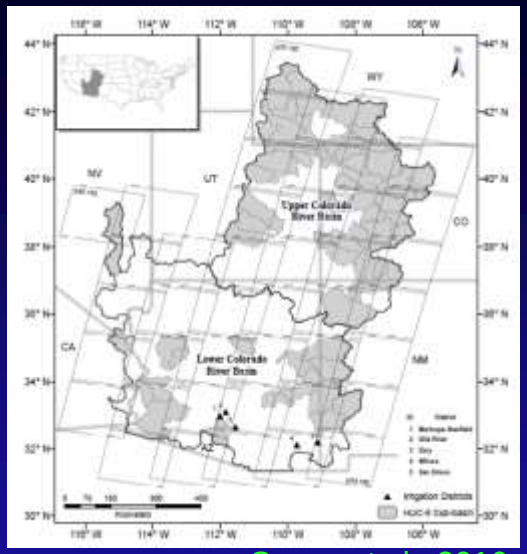
Senay et al., 2016, RSE

Landsat 8

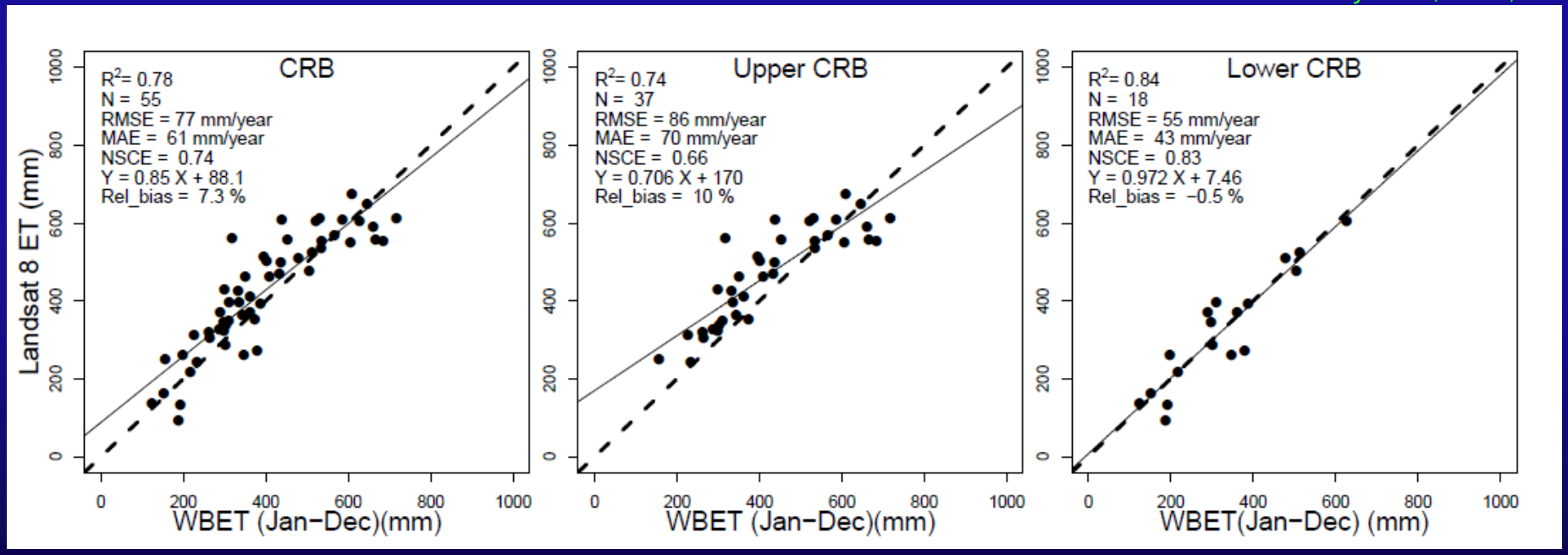
USGS

Landsat ET Evaluation using Annual Water Budget ET at HUC-8 level

PPT= PRISM
Runoff = USGS Runoff

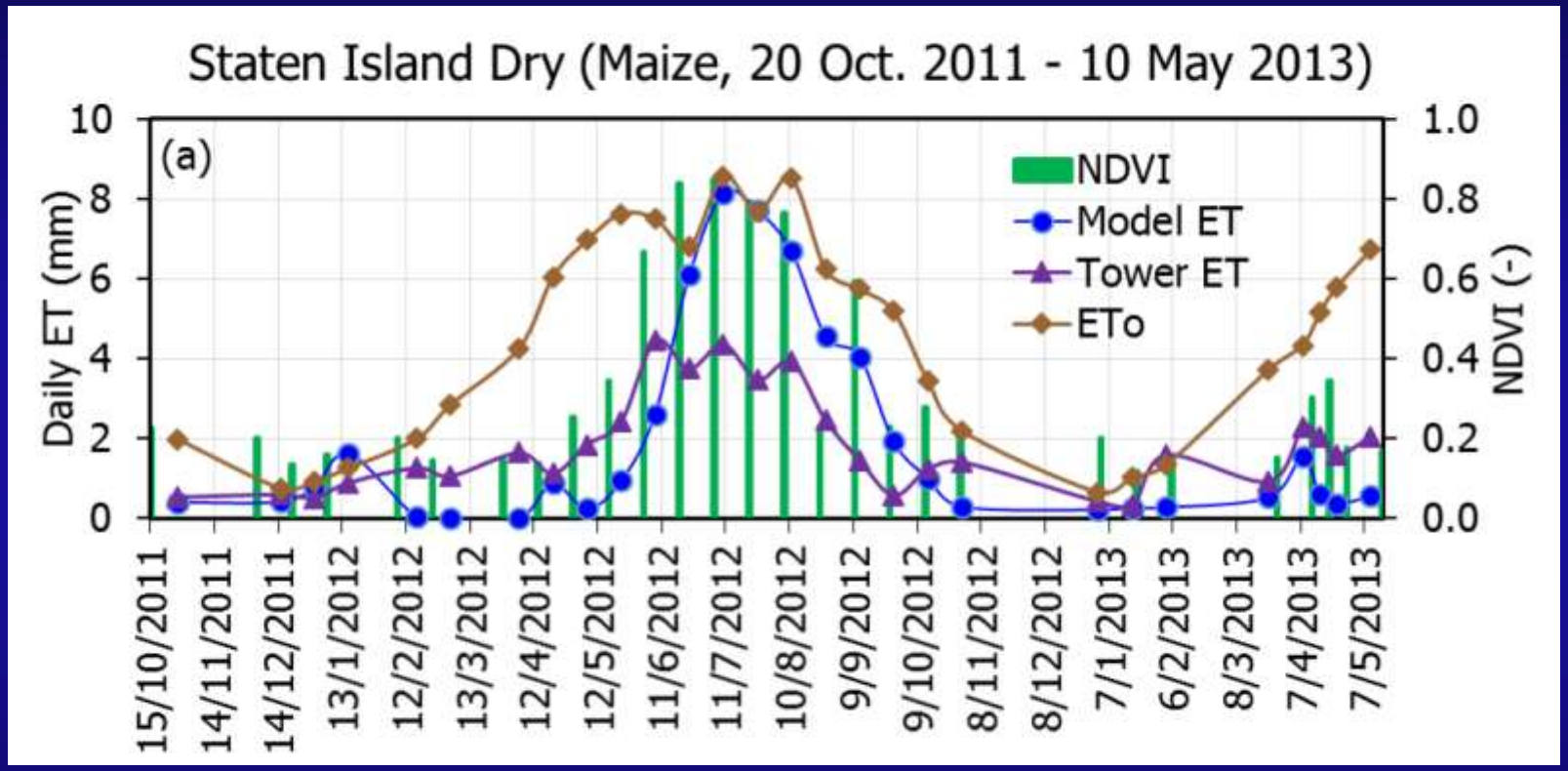


Senay et al., 2016, RSE



USGS

Evaluation using EC Tower at Staten Island, CA (Maize Crop)



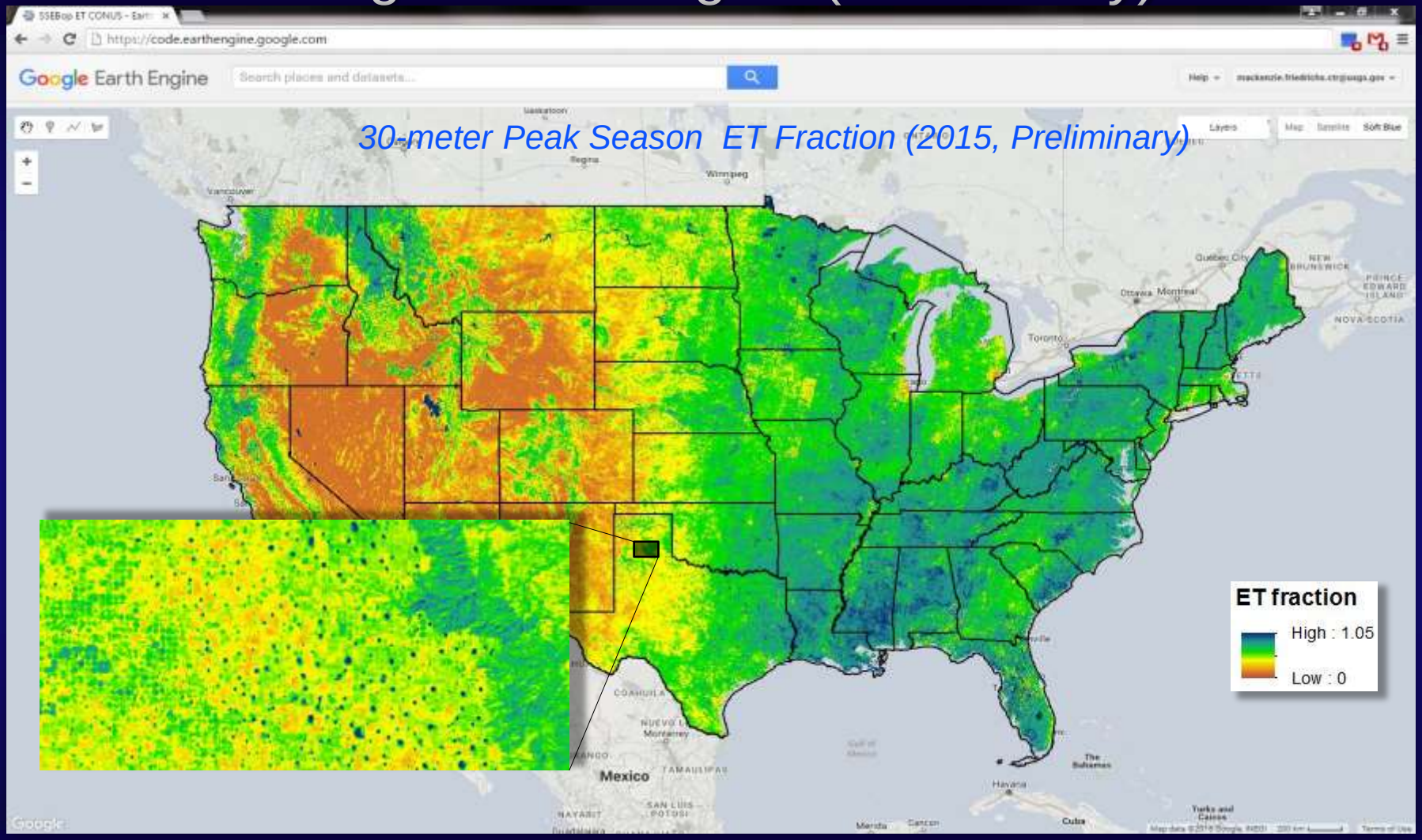
R2 = 0.58, but large “discrepancy” during peak ET

Landsat

Under Review with RSE

USGS

Landsat SSEBop ET Fraction
Google Earth Engine (Preliminary)



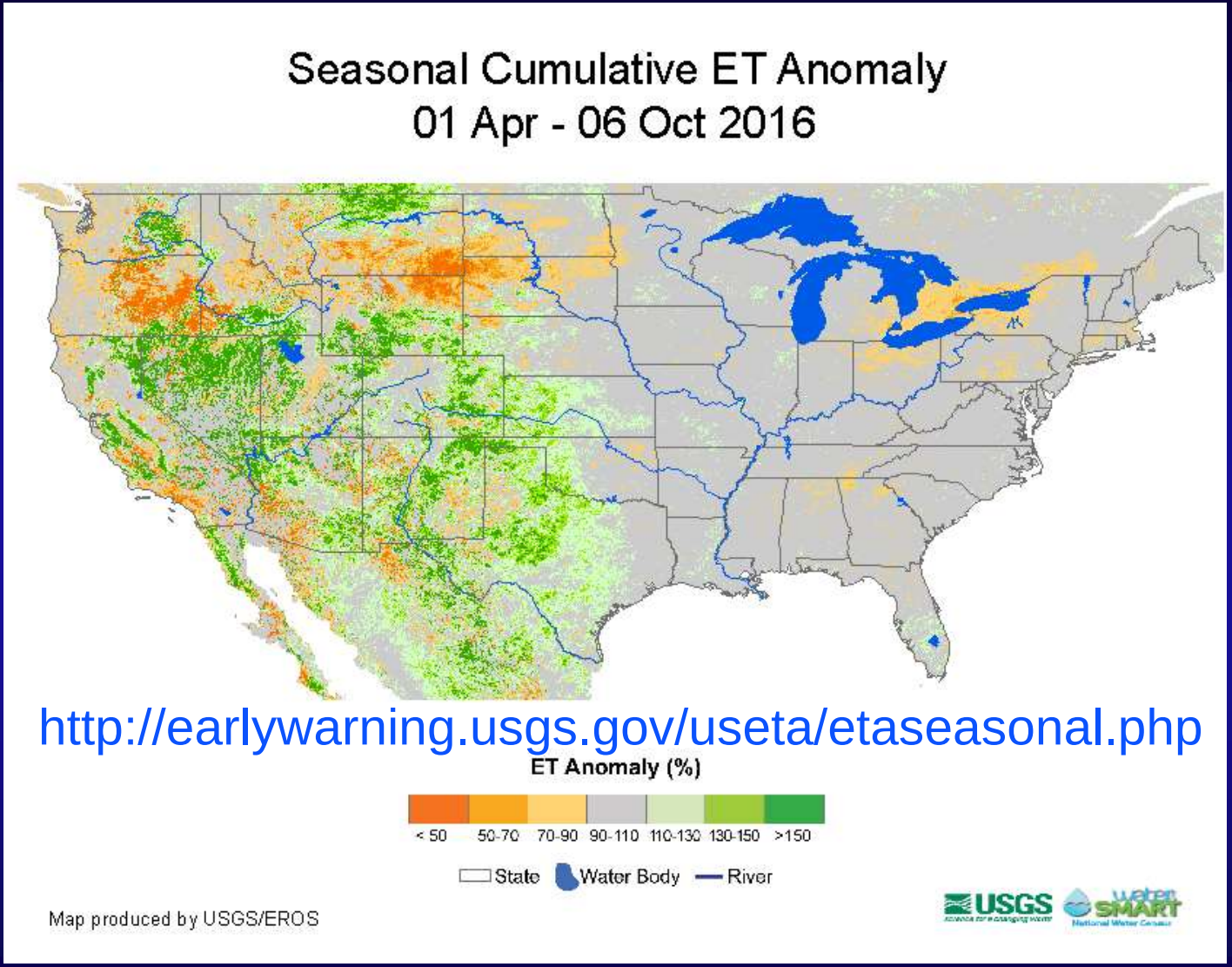
USGS

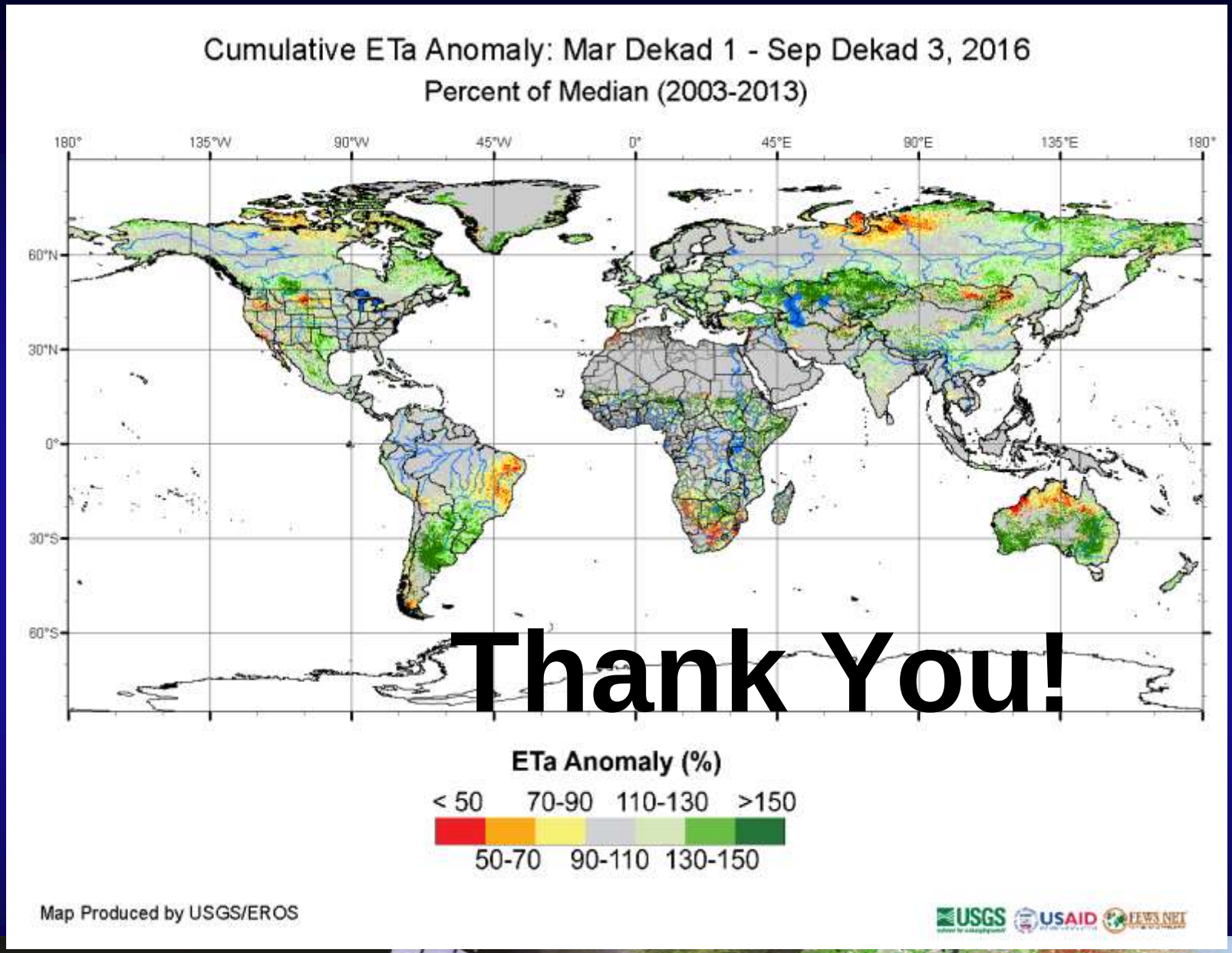
Remarks on SSEBop Approach

- SSEBop ET is a physically-based ET model that relies on LST for spatial variability and ETo for seasonality.
- SSEBop uses air temperature and clear-sky energy balance for model parameterization.
- SSEBop ET anomaly is currently used for operational drought monitoring and early warning.
- SSEBop absolute accuracy stands around 70-80% for monthly and around 80-90% for seasonal estimates.
- At least a one-time validation with independent data is recommended on new hydro-climatic region for bias removal
- SSEBop does not solve for sensible or ground heat flux

USGS

Operational Drought Monitoring Using ET




Cumulative ETa Anomaly: Mar Dekad 1 - Sep Dekad 3, 2016
Percent of Median (2003-2013)
180°
135°W
90°W
45°W
0°
45°E
90°E
135°E
180°
60°N
30°N
0°
30°S
60°S
Thank You!
ETa Anomaly (%)
< 50
50-70
70-90
90-110
110-130
130-150
>150
Map Produced by USGS/EROS
USGS
USAID
FEWS NET