Remote Sensing for Estimating Regional ET and Modeling Basin Water Balance

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

Outline

- Summary
- Background on ET
- Actual ET and Remote Sensing
  - Water Balance
    - Applications: CONUS
  - Energy Balance
    - Applications
      - Columbia Plateau
      - High Plains
      - CONUS
- Conclusion

Summary

- Global ETo available on a daily basis at USGS EROS
- With remotely sensed data, landscape actual ET (ETa) is generated for large scale applications:
  - Water balance and energy balance approach
- Case studies in the US and other parts of the world have shown its usefulness to monitor relative crop production performance, drought and estimate regional water balance components

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Why ET?

- An important component of the hydrologic budget
  - Rainfall = ET + Runoff
  - ET = 62% of terrestrial rainfall
  - ET is an Essential Climate Variable (ECV)
- Involves the exchange of both mass and energy between soil/ vegetation and atmosphere
  - Rn = ET + H + G
- Directly related to plant biomass
  - Carbon budget
  - crop production monitoring
  - Irrigation water use and groundwater withdrawal
  - Land cover change monitoring

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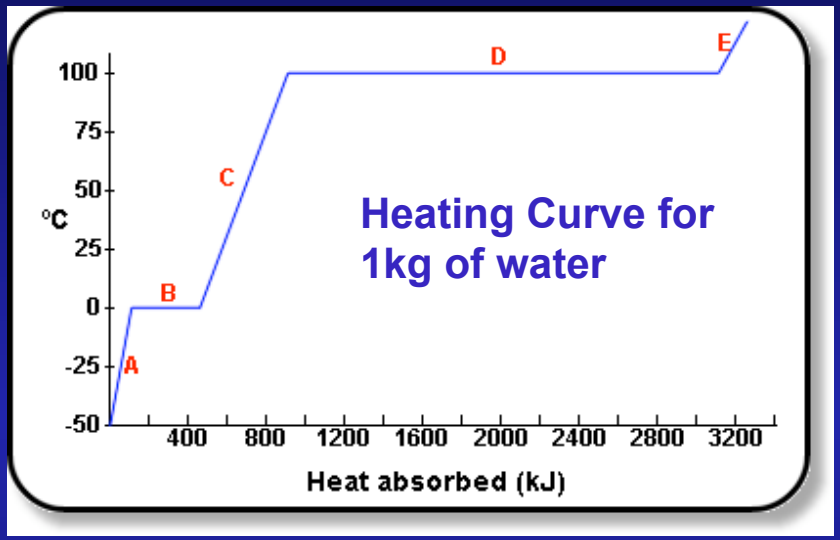
ET Facts

- ET requires a lot of energy

  More energy to change state (liquid to gas at 100^0c, 2.45 MJ/kg) than to warm water from 0^0c to 100^0c (0.45 MJ/kg)



http://www.physchem.co.za/Heat/Latent.htm#vaporization

- ET involves a large amount of water movement in the landscape
  - 1 kg grain = 1000 kg of water
  - 1 calorie = 1 kg of water (1 lit or ~ 1 quart)

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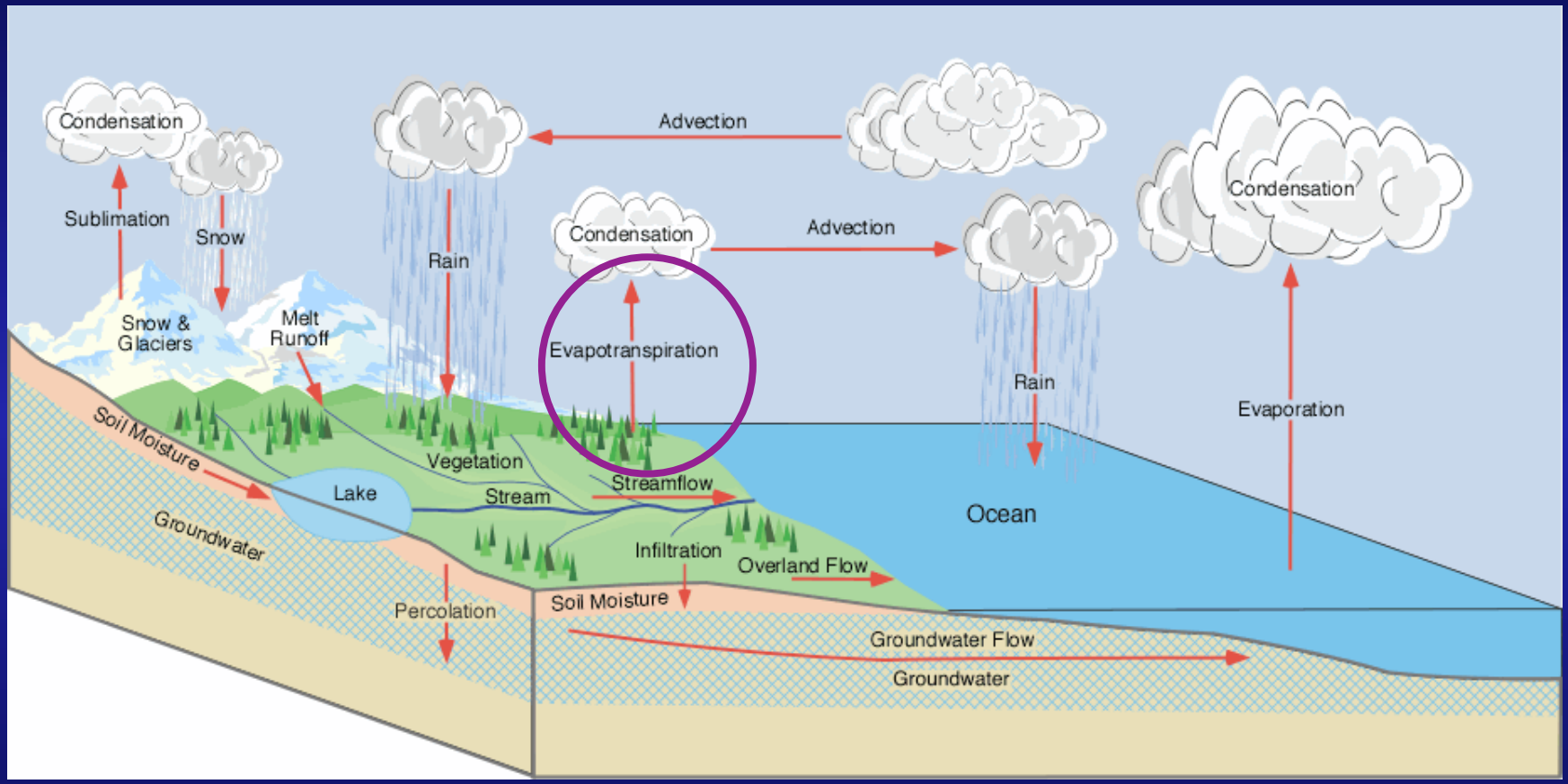
Hydrologic cycle



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Evapotranspiration (ET) = Water Use

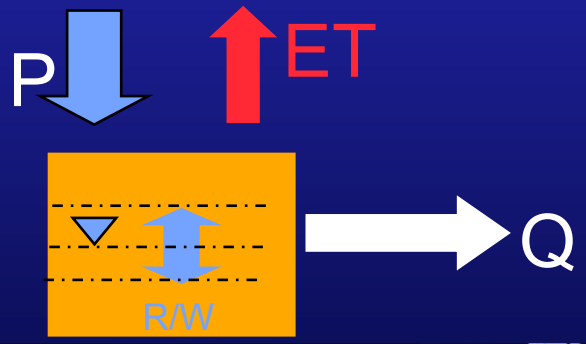
Simplified Water Balance

Precipitation (P) – ET = River Flow (Q) + X

Climate

Climate + Mang't (LULC)

+Recharge / -Withdrawal



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ETa Modeling Methods

- 1. Water Balance
  - SWAT, SWAP, Hydrus, Daisy, FAO-WRSI, etc
    - EROS: phenology-based water-use coefficient
      - VegET
- 2. Full Energy Balance
  - ALEXI (Anderson et al.); METRIC (Allen et al.); SEBAL (Bastiaanssen et al.); SEBS (Su et al.)
    - EROS: Simplified Surface Energy Balance Approach
      - SSEB/SETI (Senay et al.)

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Role of Remote Sensing

- Land Surface Temperature (LST) from thermal imagery
  - Landsat (~100-m)
  - MODIS (1-km)
  - AVHRR (1-km)
  - GOES (10-km)

- Precipitation Estimate
  - NOAA NEXRAD (5-km)
  - METEOSAT RFE (10-km)
  - NASA TRMM (25-km), etc

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Water Balance Approach for ET

VegET Modeling: Background and Objective

- Background
  - VegET is a new modeling approach that integrates Land Surface Phenology (LSP) and commonly used water balance modeling algorithms to estimate actual vegetation ET (water use) in primarily non-irrigated crop and grassland environments for agro-hydrological applications. (Senay, 2008)
- Key inputs to the model
  - 1) Rainfall
  - 2) Reference ET
  - 3) LSP from NDVI
  - 4) Soil water holding capacity

- Objective
  - Produce daily ETa and soil moisture to monitor crop and grassland performance for early assessment of yield reduction and onset of drought.

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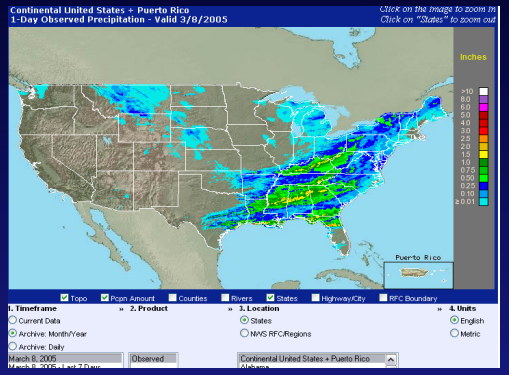
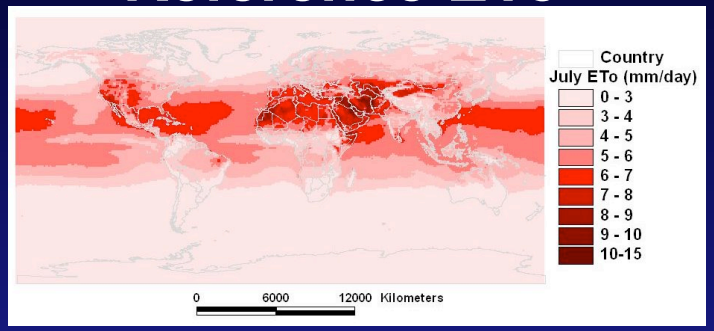
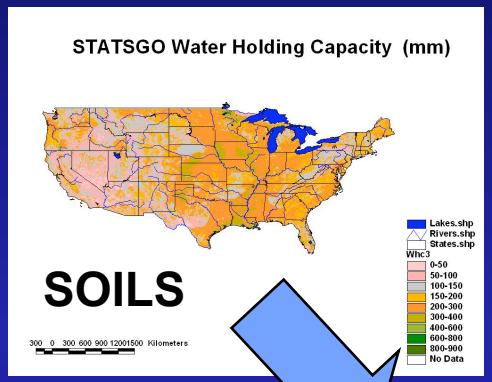
PRECIPITATION



Reference ETo





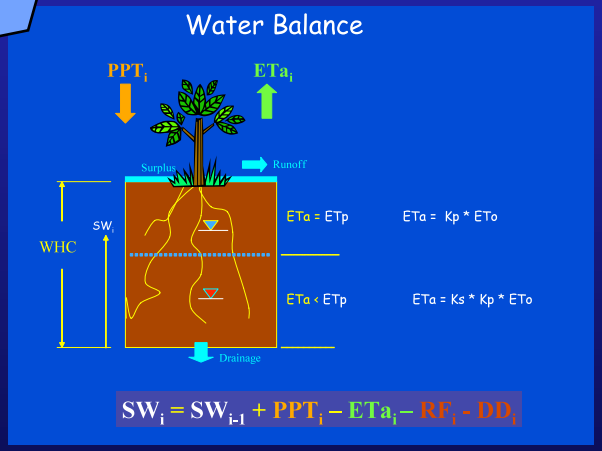
VegET

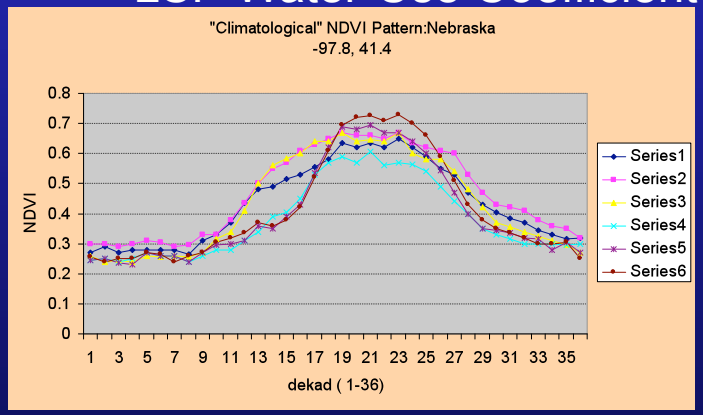
$$ETa = Ks * Kcp * ETo$$

Soil Stress Coefficient

LSP Water-Use Coefficient

Water Balance Model





Land Surface Phenology (LSP)

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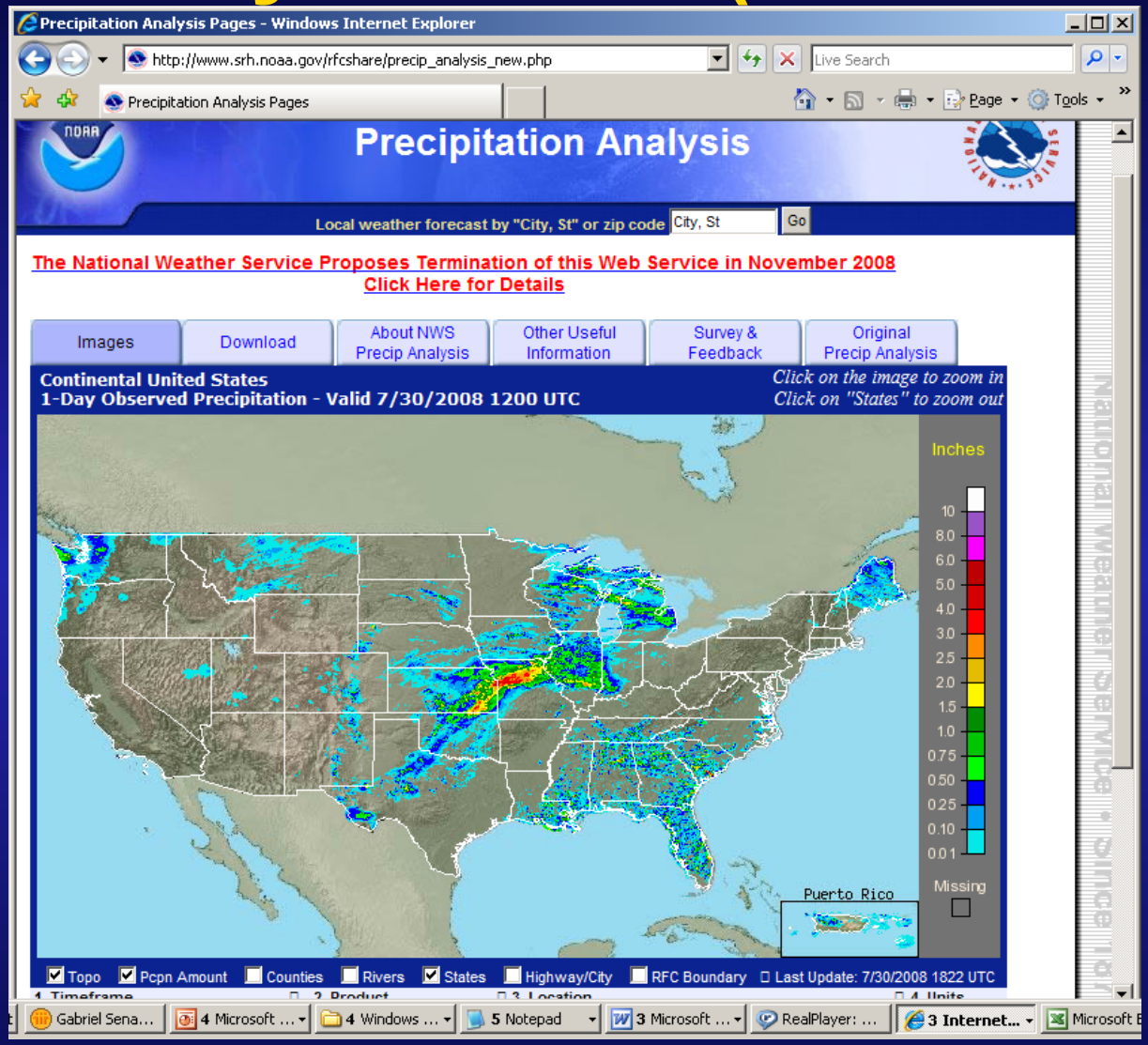
Daily Rainfall ("US" at ~ 4 km)



Hourly precipitation estimates from WSR-88D NEXRAD are compared to ground rainfall gauge reports, and a bias (correction factor) is calculated and applied to the radar field.

NOAA 2-source
-4km
-daily
Available
2005-current

-25 km
-daily
1996-current

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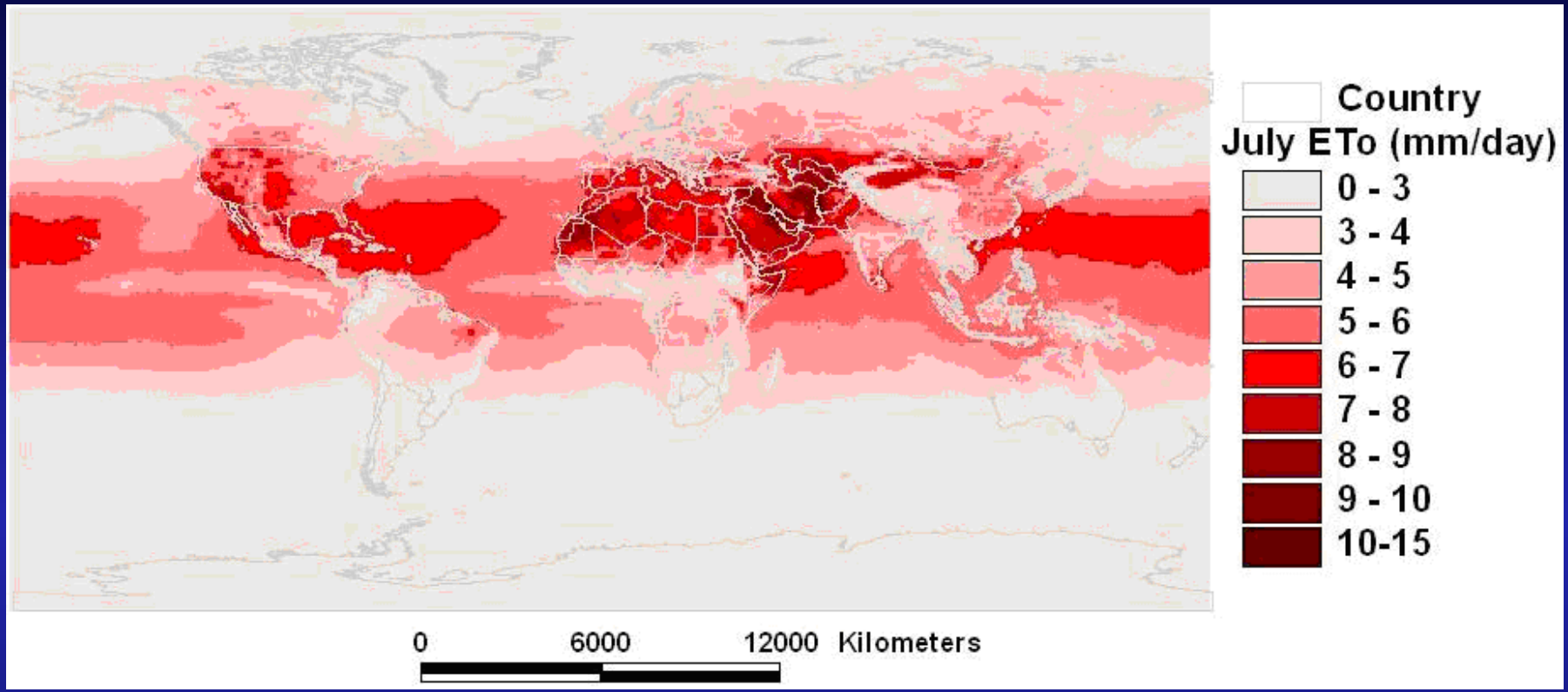
Daily Global GDAS ETo for July 2004



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

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

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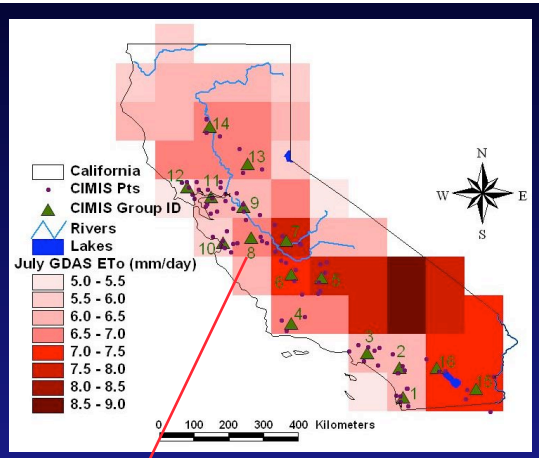
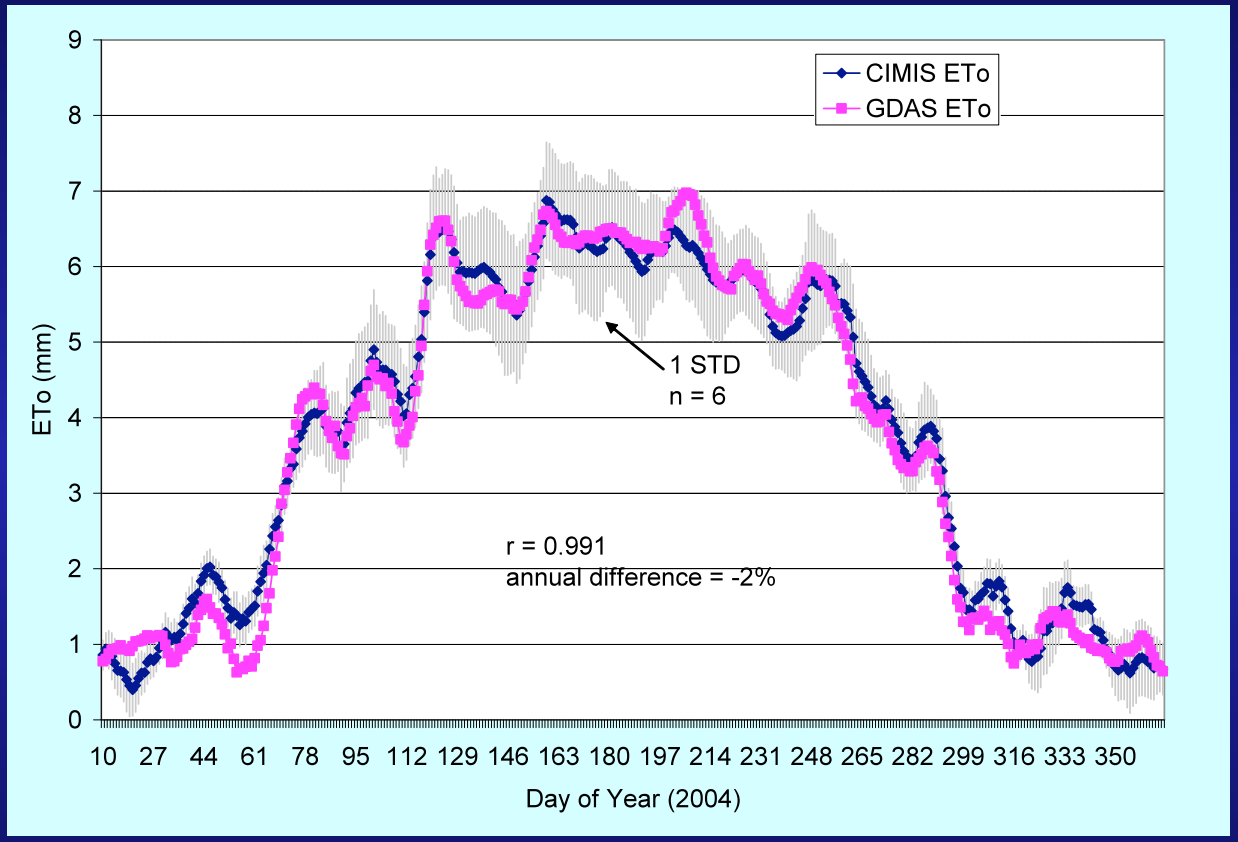
GDAS ETo Validation Using CIMIS Station Data (San Benito: 2004)





Senay, Verdin, Lietzow and Melesse, 2008. JAWRA.

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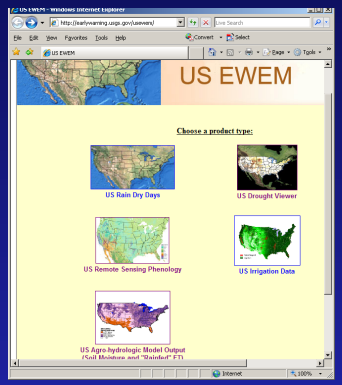
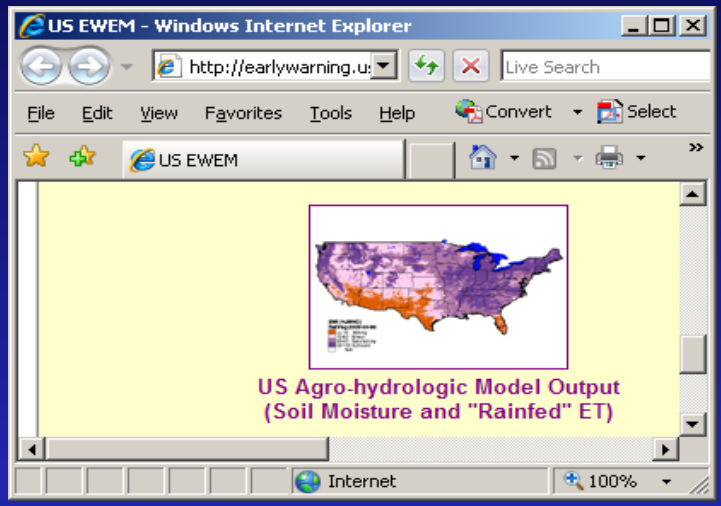
VegET Model Outputs





Operational Products

http://earlywarning.usgs.gov/usewem/swi.php

Current: April – present, 2009
Anomaly: based on 2000-2008 data
Season: April 1 – October 31

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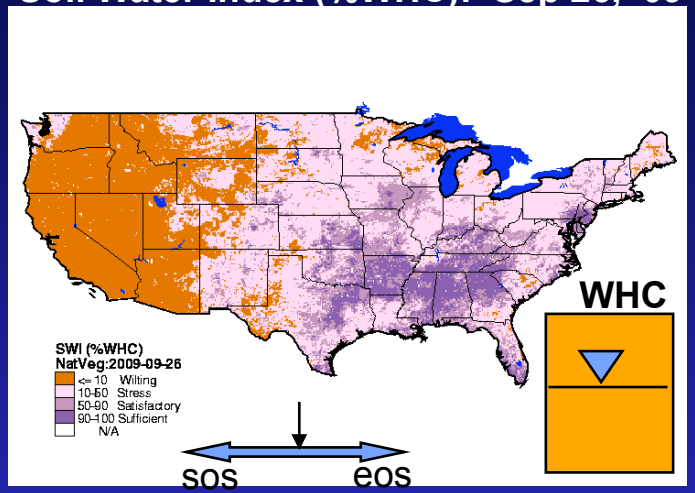
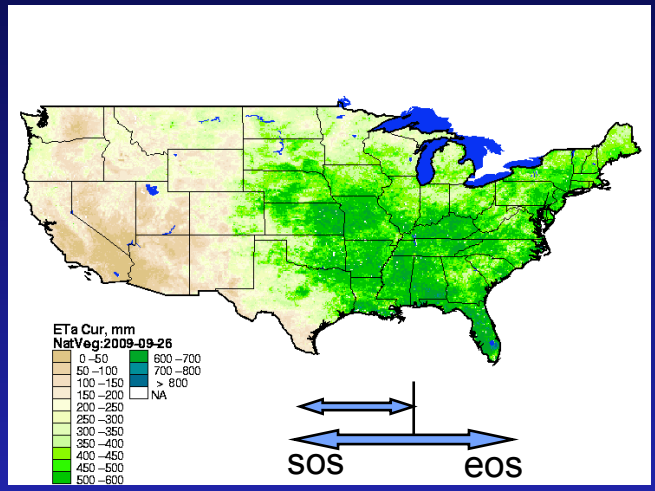
Daily VegET Output, Sep 26, 2009

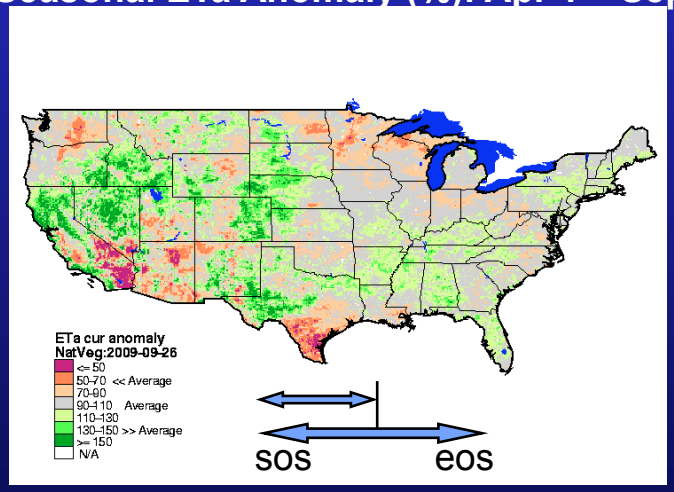
Soil Water Index (%WHC): Sep 26, '09



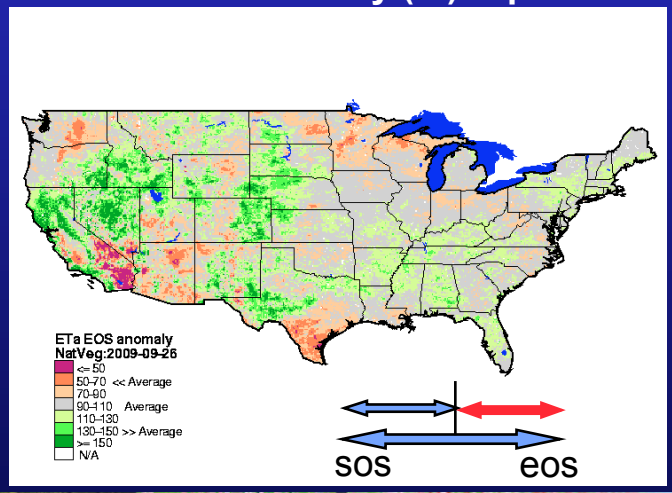
Seasonal ETa (mm): Apr 1 – Sep 26, '09



Seasonal ETa Anomaly (%): Apr 1 – Sep 26, '09



Forecast ETa Anomaly (%): Apr 1 – Oct 31, '09



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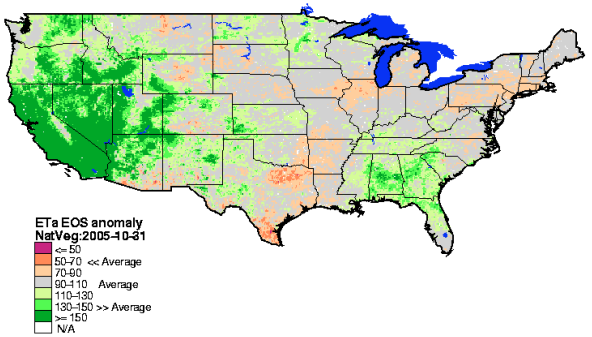
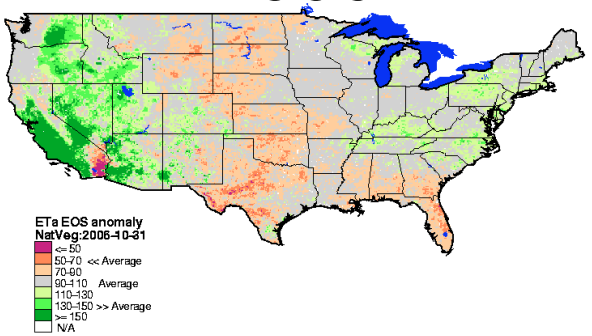
Historical EOS ETa Anomaly Products

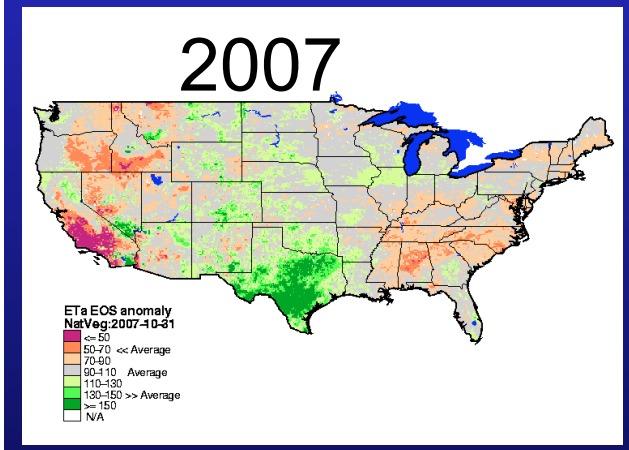
2005



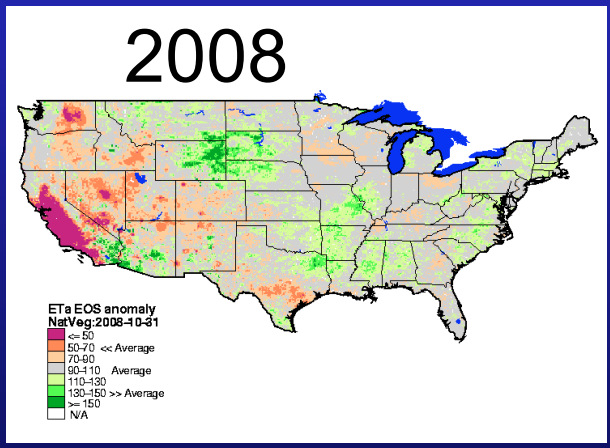
2006



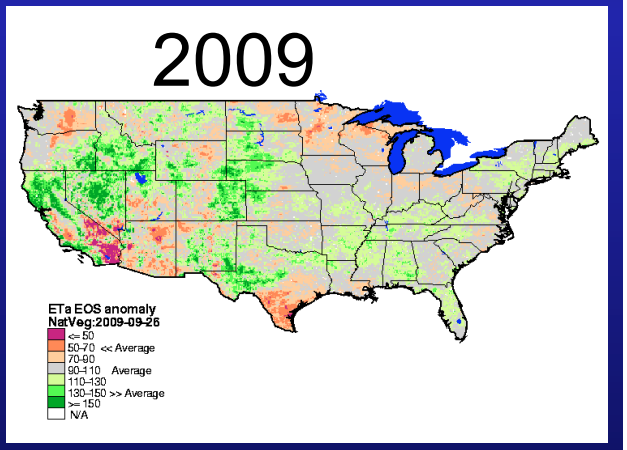
2007



2008



2009



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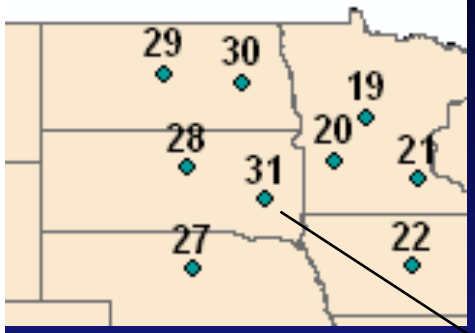
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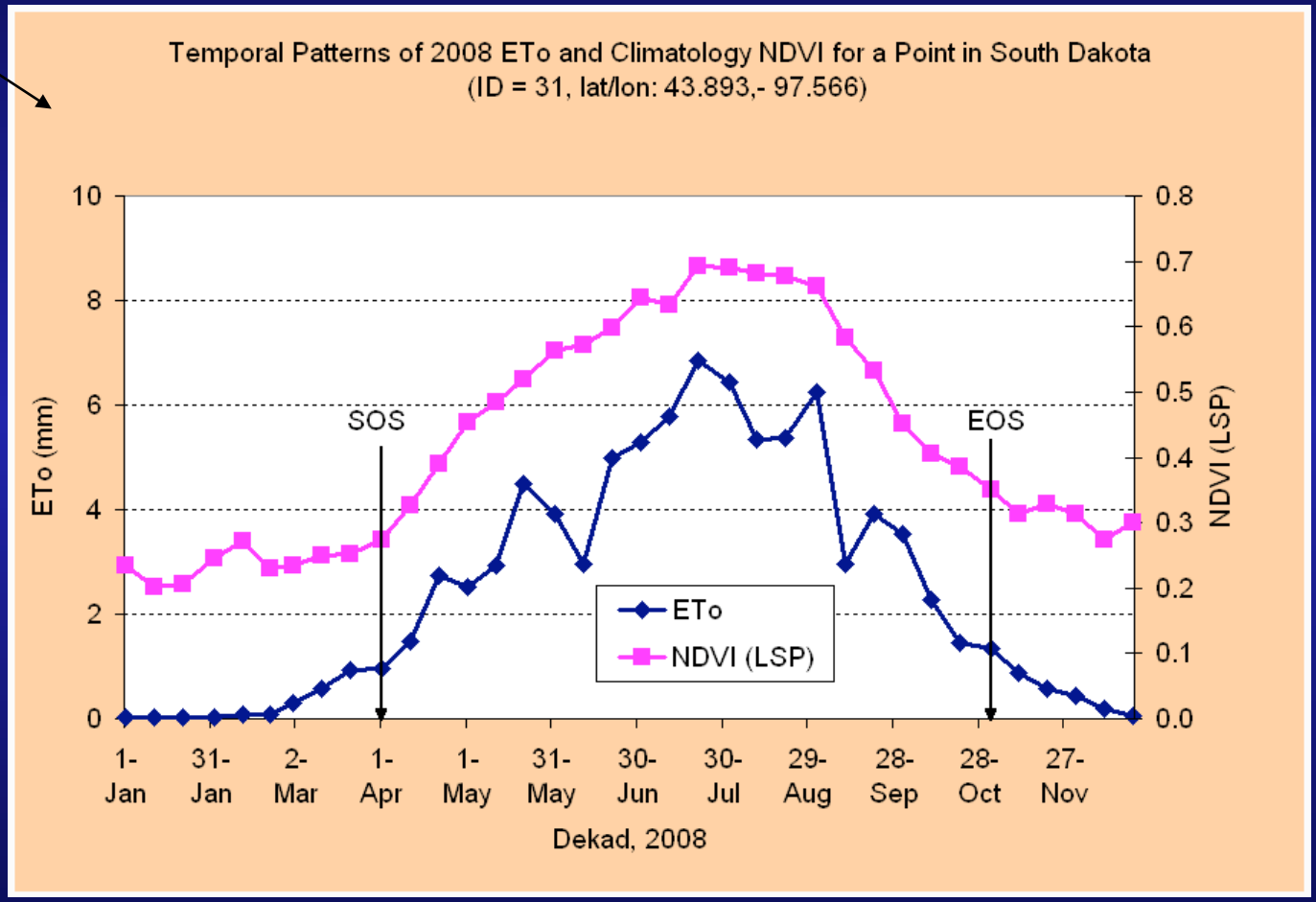
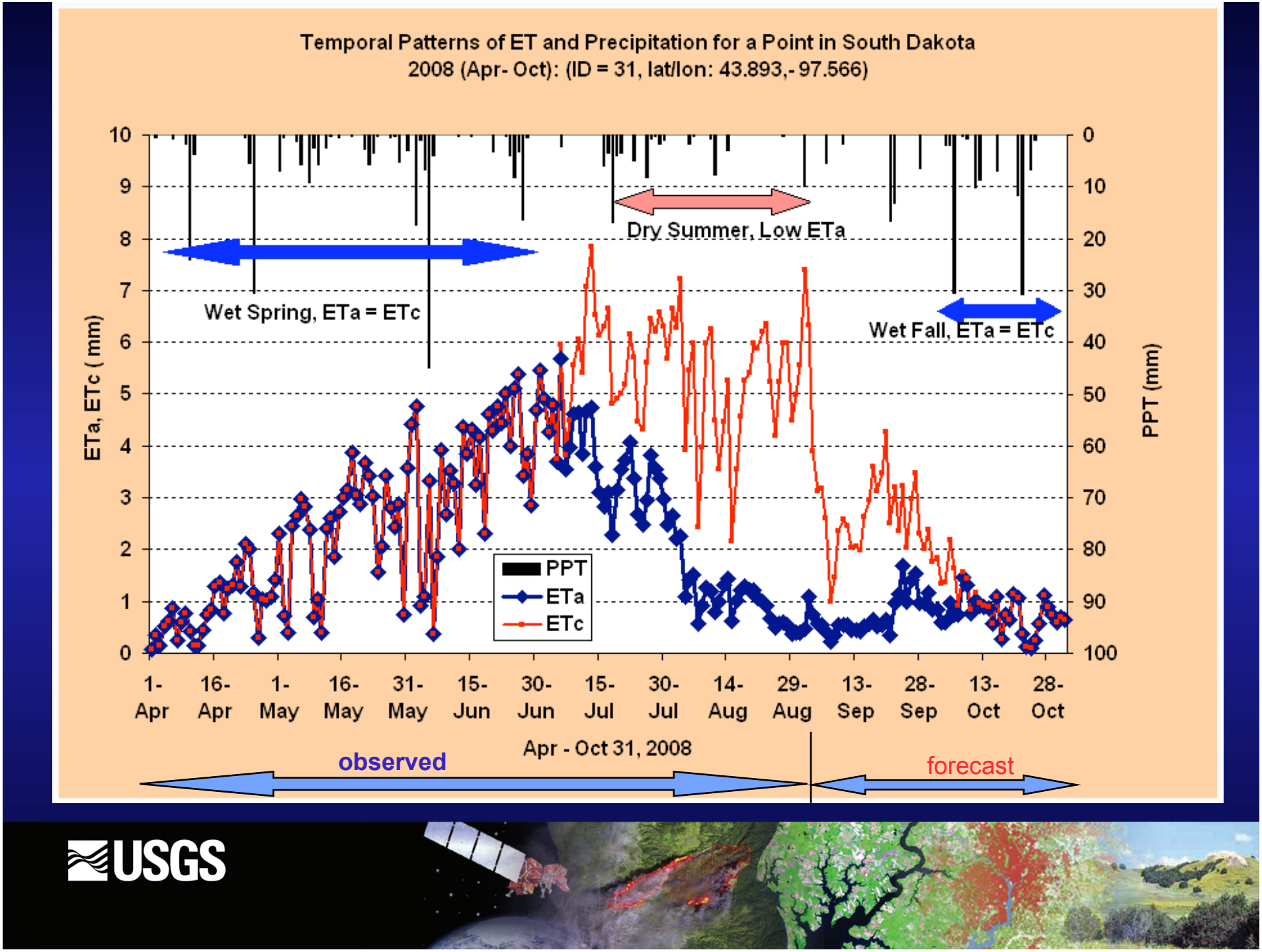
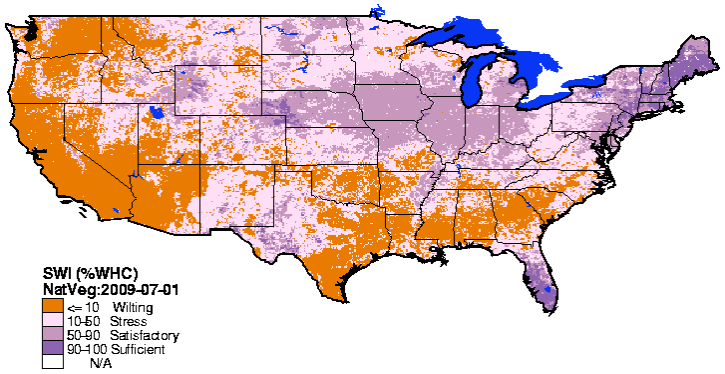

Temporal Patterns of 2008 ETo and Climatology NDVI for a Point in South Dakota
(ID = 31, lat/lon: 43.893,- 97.566)
ETo (mm)
NDVI (LSP)
SOS
EOS
ETo
NDVI (LSP)
1-Jan
31-Jan
2-Mar
1-Apr
1-May
31-May
30-Jun
30-Jul
29-Aug
28-Sep
28-Oct
27-Nov
Dekad, 2008

USGS

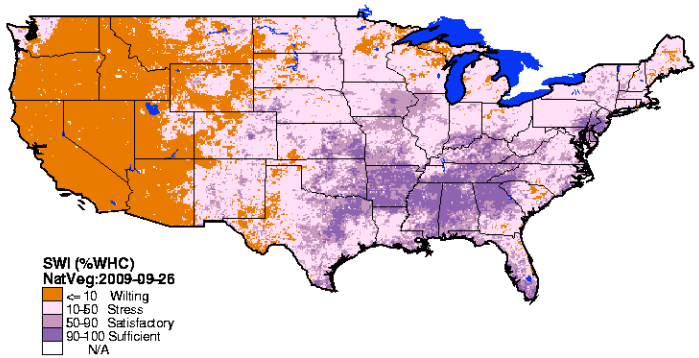

Temporal Patterns of ET and Precipitation for a Point in South Dakota
2008 (Apr- Oct): (ID = 31, lat/lon: 43.893,- 97.566)
Dry Summer, Low ETa
Wet Spring, ETa = ETc
Wet Fall, ETa = ETc
ETa, ETc (mm)
PPT (mm)
PPT
ETa
ETc
1-Apr
16-Apr
1-May
16-May
31-May
15-Jun
30-Jun
15-Jul
30-Jul
14-Aug
29-Aug
13-Sep
28-Sep
13-Oct
28-Oct
Apr - Oct 31, 2008
observed
forecast

Seasonal Evolution, 2009

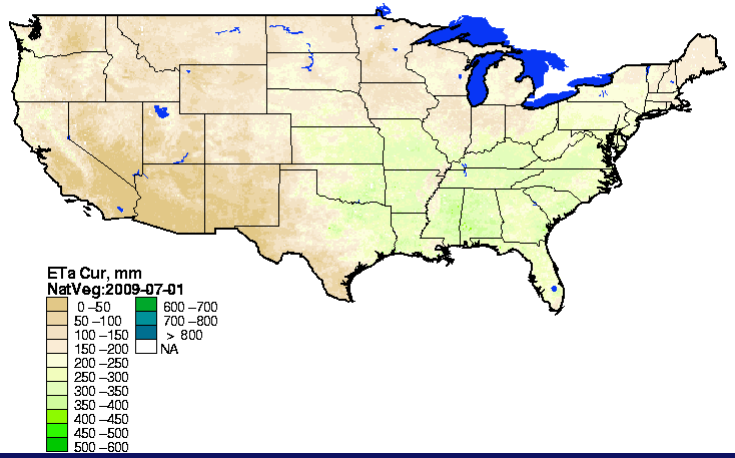
SWI, Jul 1



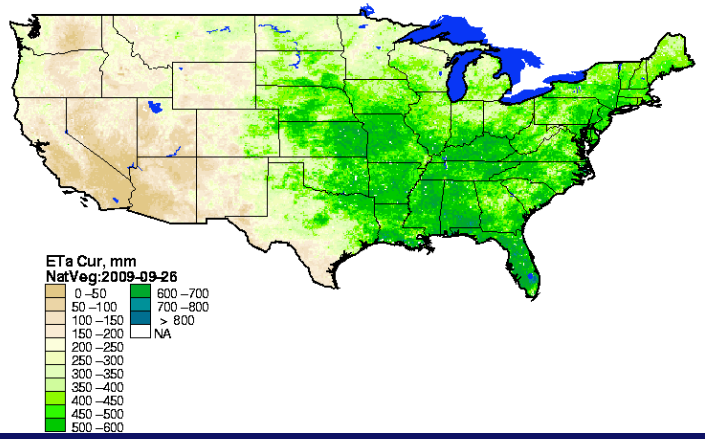
SWI, Sep 26



Cumulative ETa, Jul 1



Cumulative ETa, Sep 26



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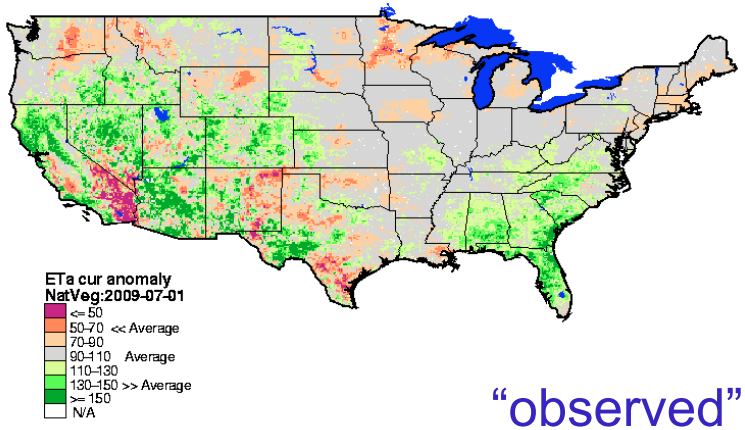
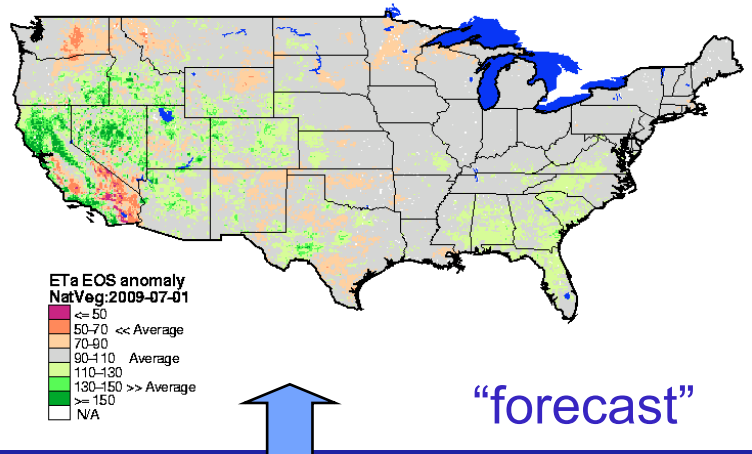
EOS Seasonal Forecast, 2009

ETa Anomaly (Apr 1 – Jul 1)



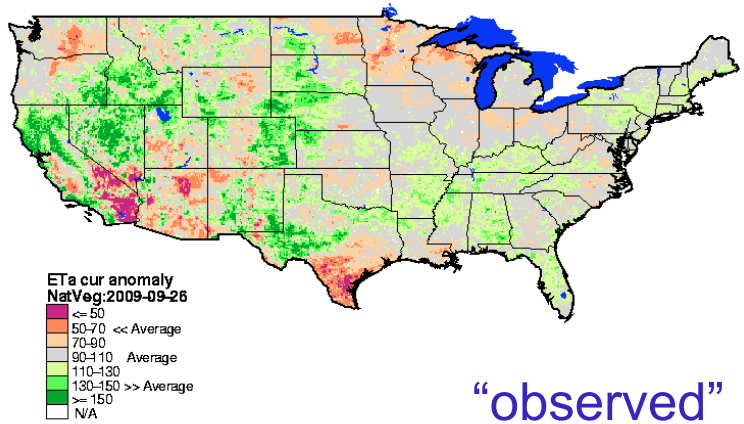
"observed"

ETa Anomaly (Apr 1 – Oct 31)



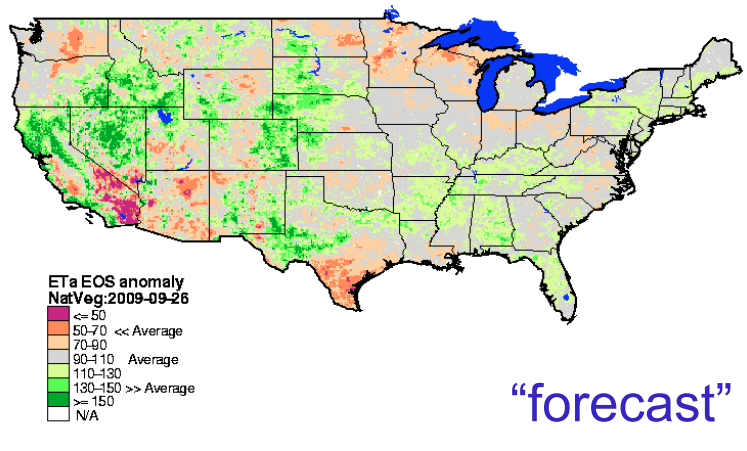
"forecast"

ETa Anomaly (Apr 1 – Sep 26)



"observed"

ETa Anomaly (Apr 1 – Oct 31)



"forecast"

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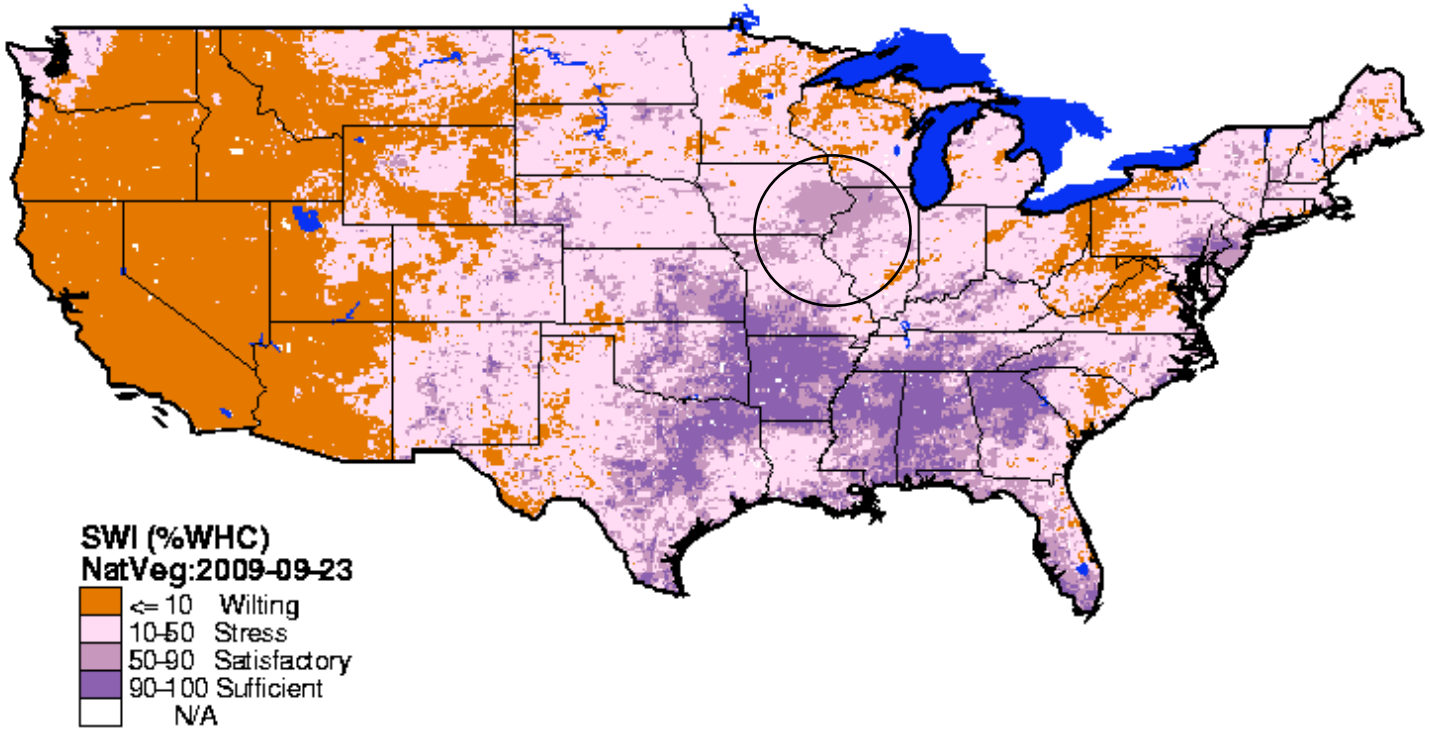
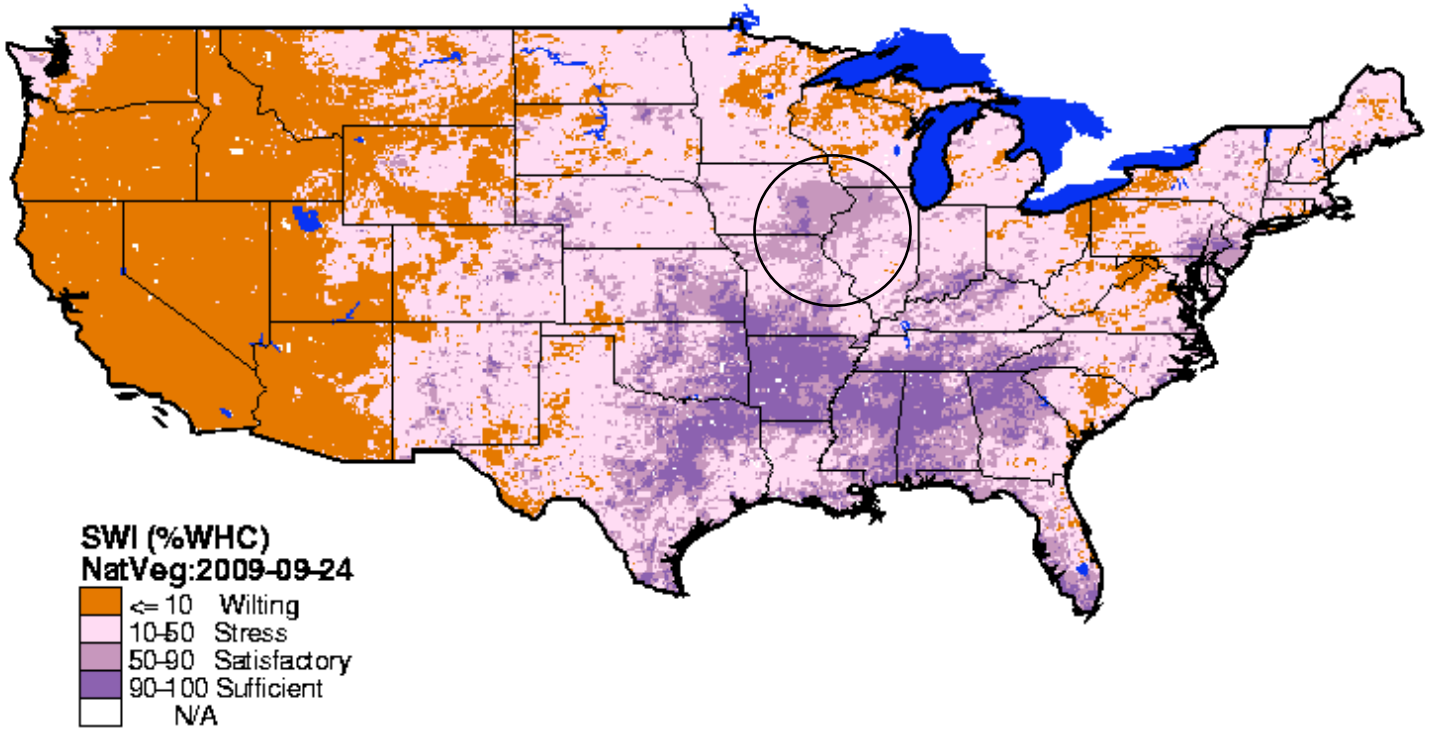
Daily Soil Water Index Maps

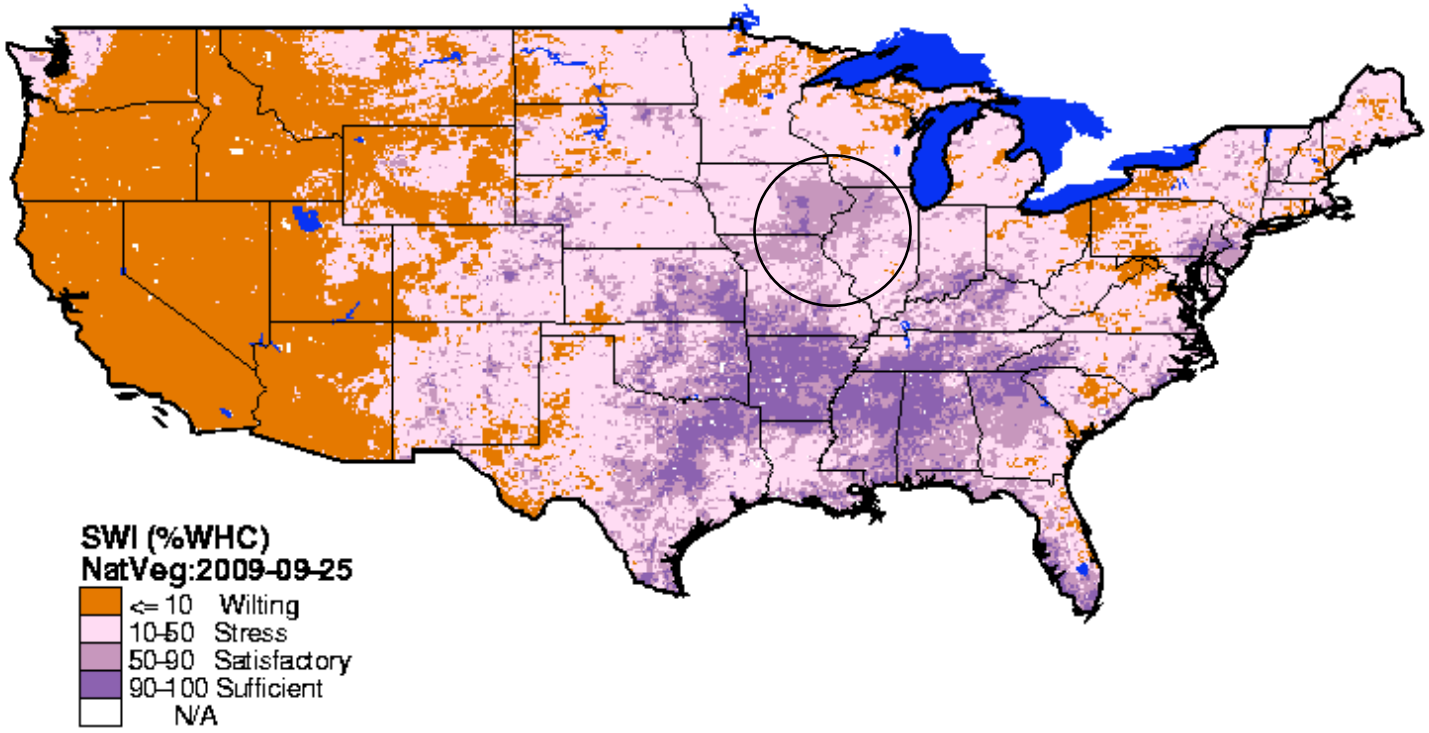
USGS


SWI (%WHC)
NatVeg:2009-09-23
<= 10 Wilting
10-50 Stress
50-90 Satisfactory
90-100 Sufficient
N/A

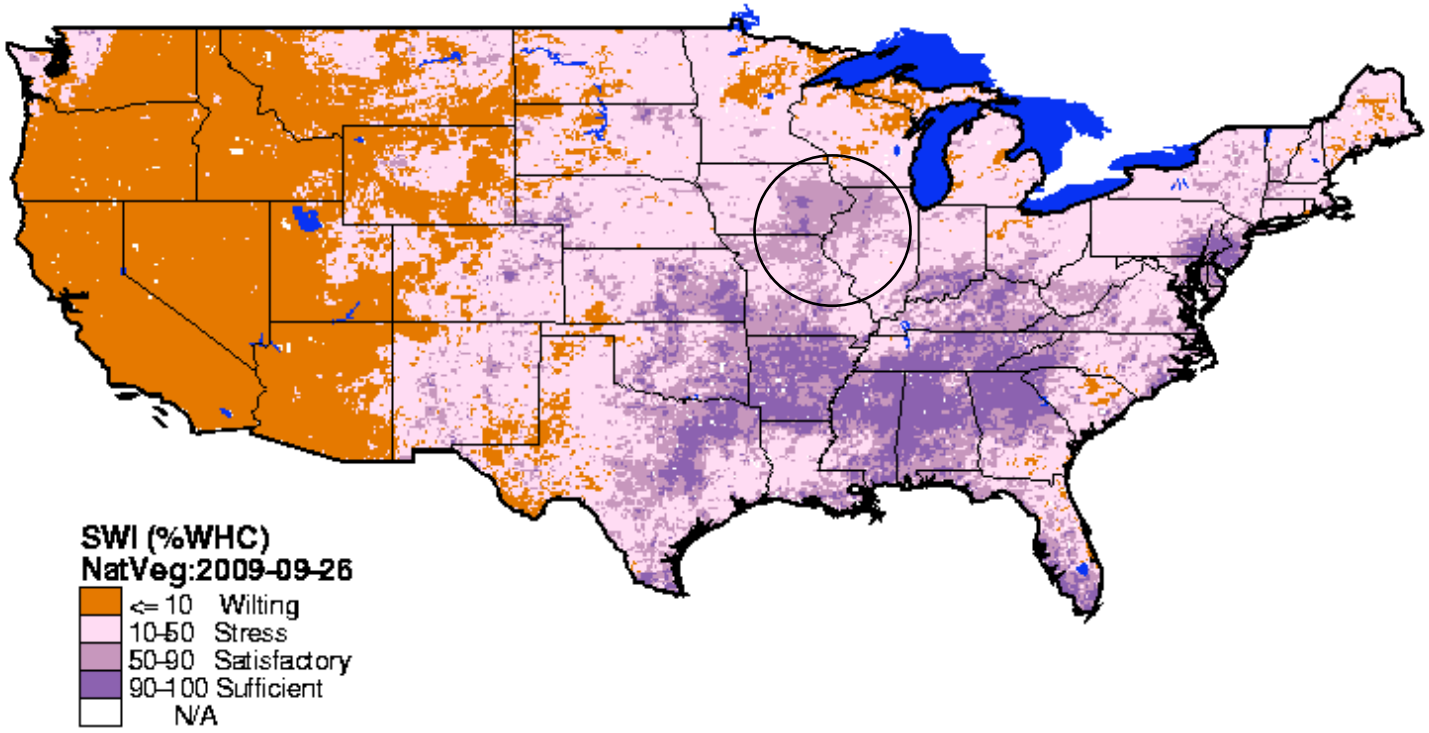
USGS


SWI (%WHC)
NatVeg:2009-09-24
<= 10 Wilting
10-50 Stress
50-90 Satisfactory
90-100 Sufficient
N/A

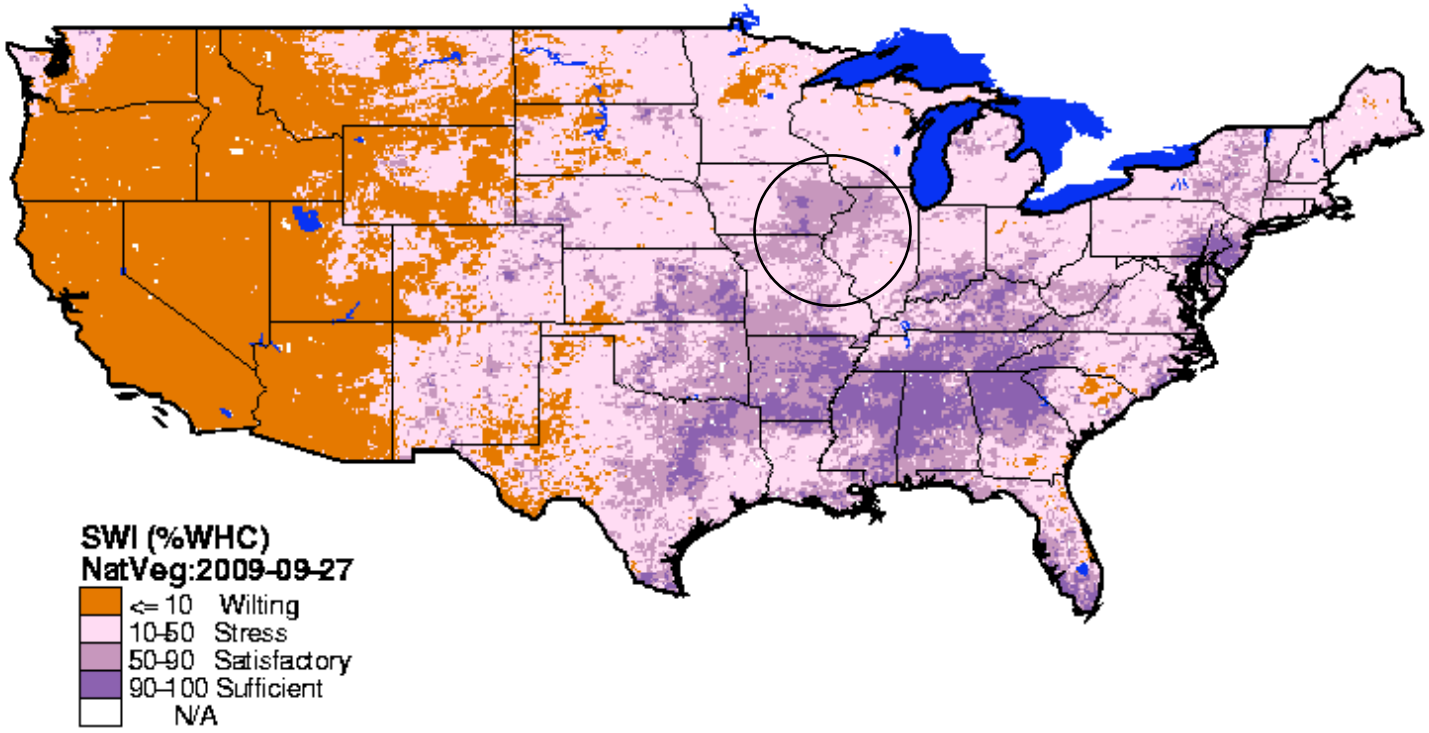
USGS


SWI (%WHC)
NatVeg:2009-09-25
<= 10 Wilting
10-50 Stress
50-90 Satisfactory
90-100 Sufficient
N/A

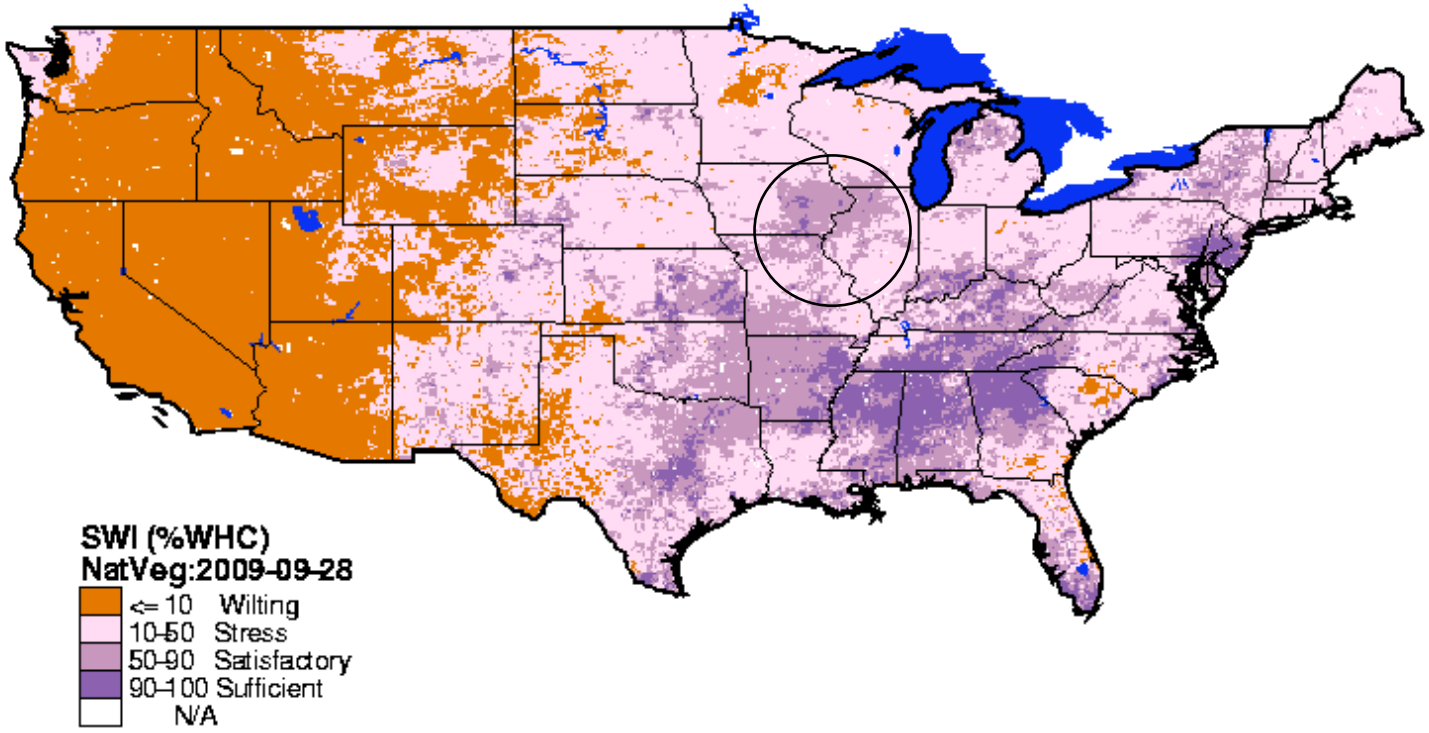
USGS


SWI (%WHC)
NatVeg:2009-09-26
<= 10 Wilting
10-50 Stress
50-90 Satisfactory
90-100 Sufficient
N/A

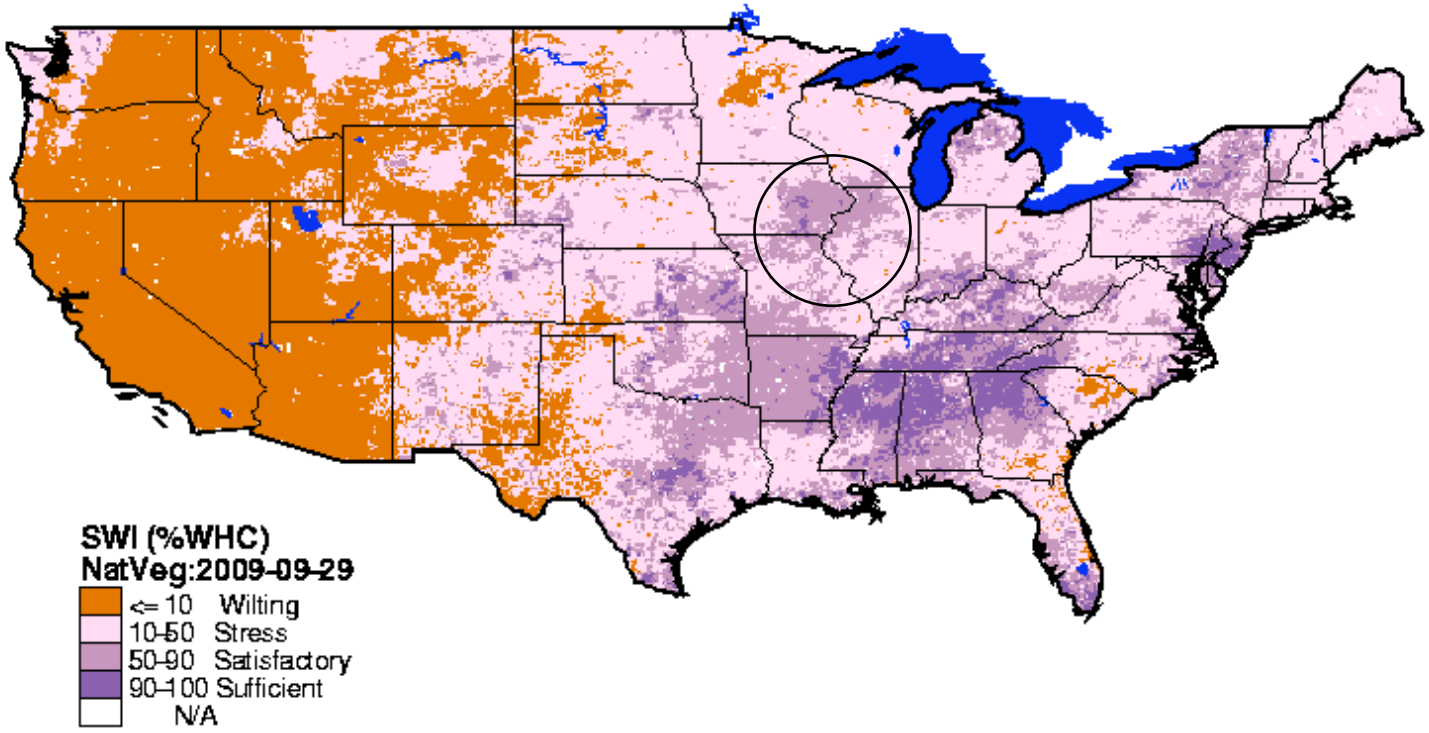
USGS


SWI (%WHC)
NatVeg:2009-09-27
<= 10 Wilting
10-50 Stress
50-90 Satisfactory
90-100 Sufficient
N/A

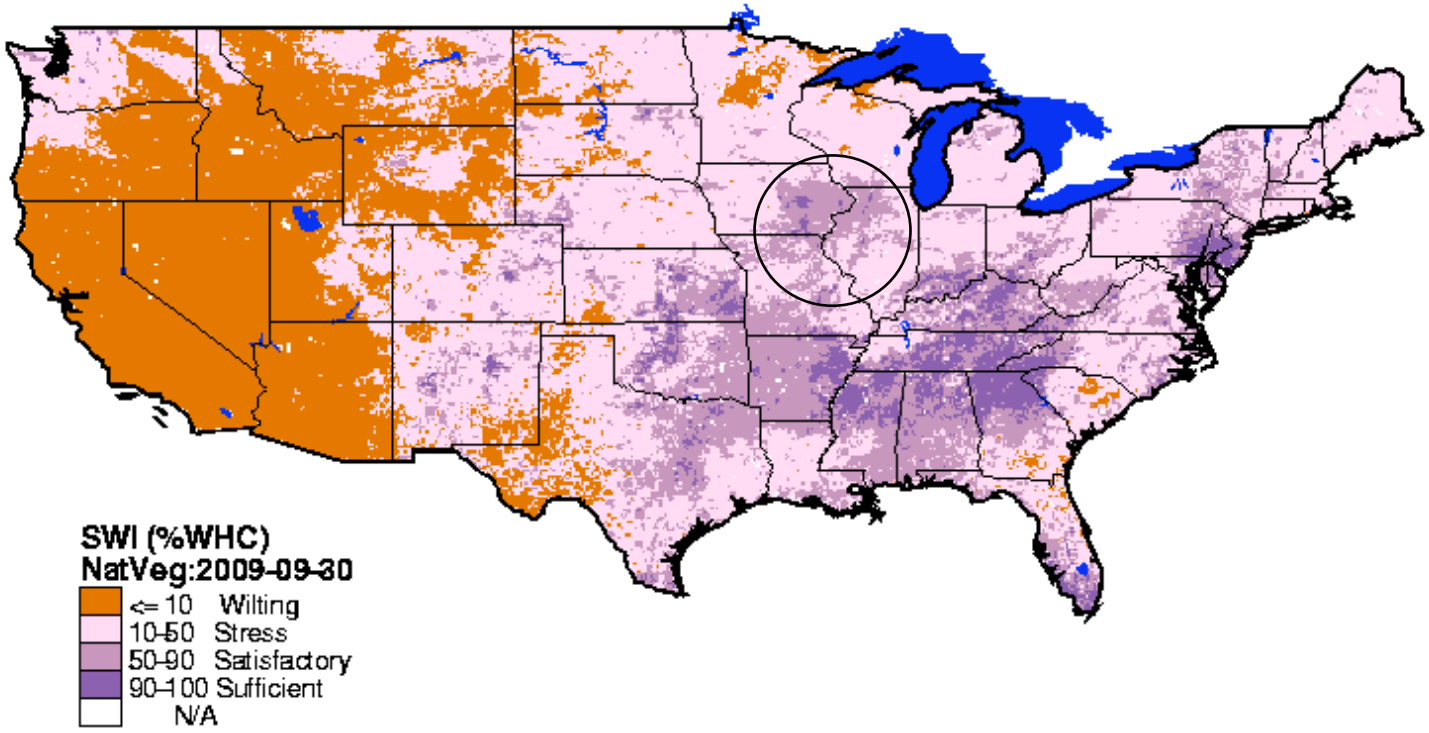
USGS


SWI (%WHC)
NatVeg:2009-09-28
<= 10 Wilting
10-50 Stress
50-90 Satisfactory
90-100 Sufficient
N/A

USGS


SWI (%WHC)
NatVeg:2009-09-29
<= 10 Wilting
10-50 Stress
50-90 Satisfactory
90-100 Sufficient
N/A

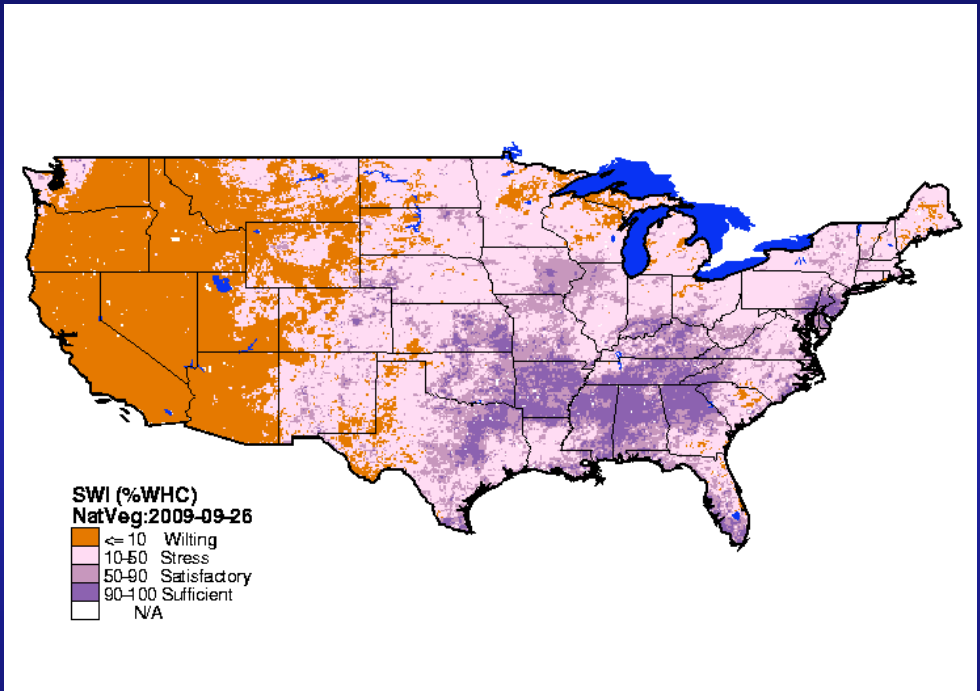
USGS


SWI (%WHC)
NatVeg:2009-09-30
<= 10 Wilting
10-50 Stress
50-90 Satisfactory
90-100 Sufficient
N/A

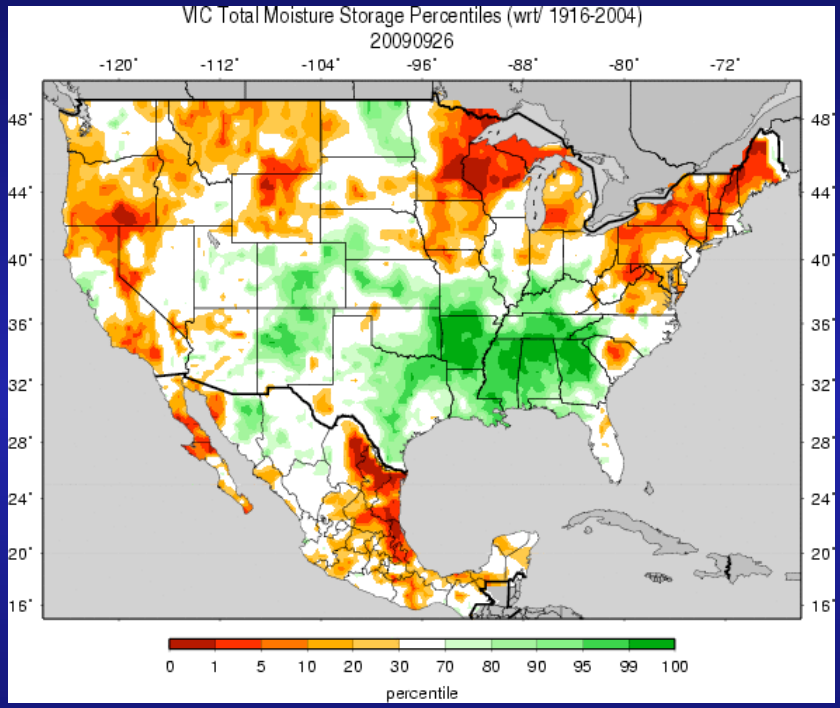
USGS

Comparison with other drought monitoring products:

VegET SWI vs VIC Output
Sep 26, 2009



Daily estimate as % of WHC



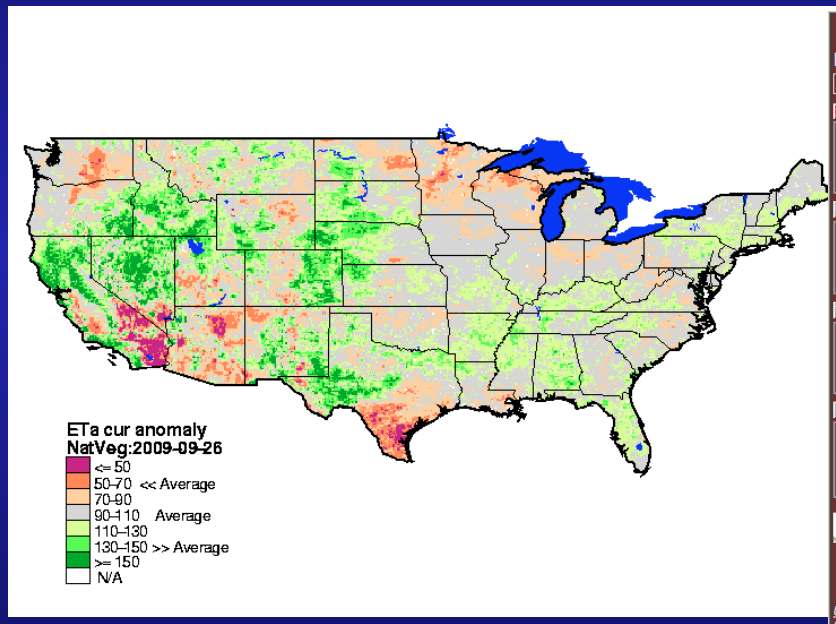
Daily estimate as % of climatology
(89 years: 1916-2004)

http://www.hydro.washington.edu/forecast/monitor/

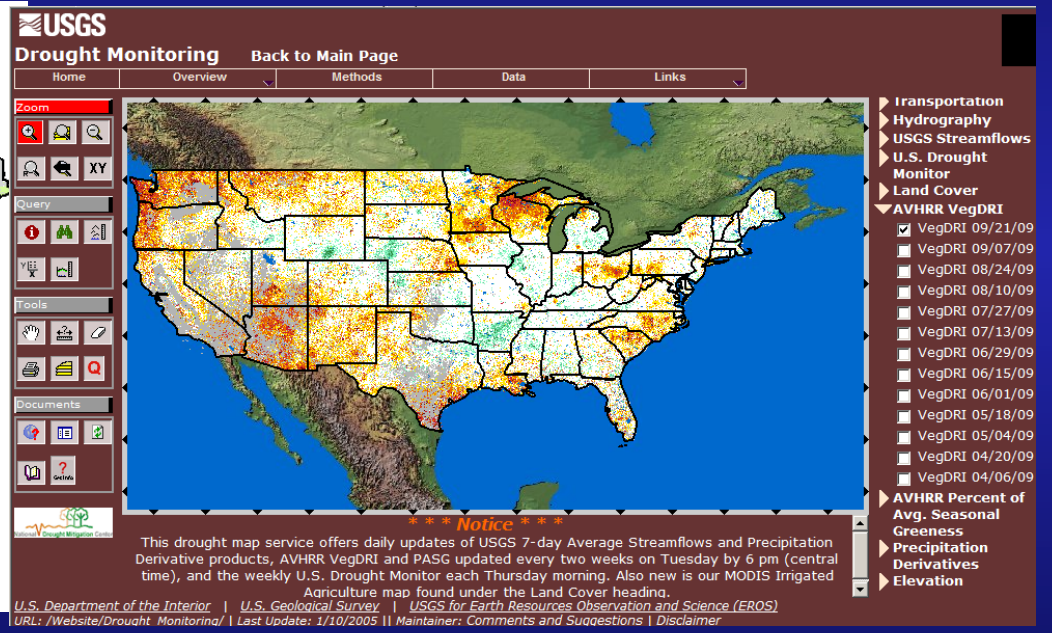
USGS

VegET SWI vs VegDRI Output

Sep 26, 2009



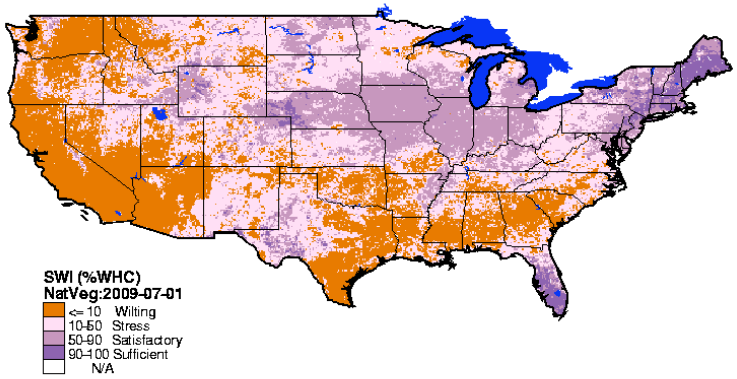
Sep 21, 2009



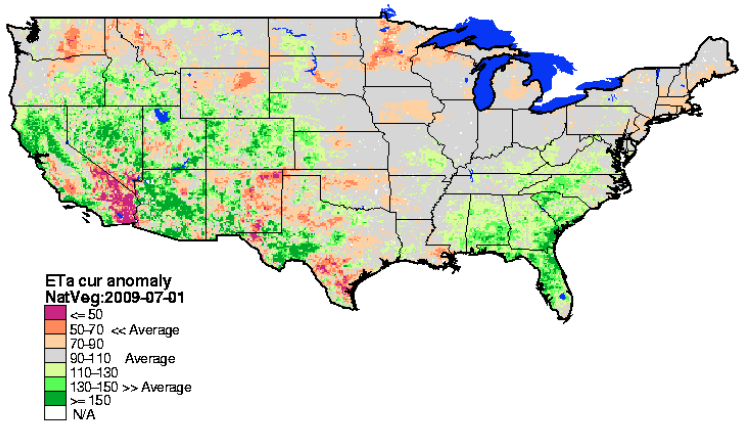
http://gisdata.usgs.gov/website/Drought_Monitoring/viewer.php

USGS

Soil Water Index (Jul 1, ’09)

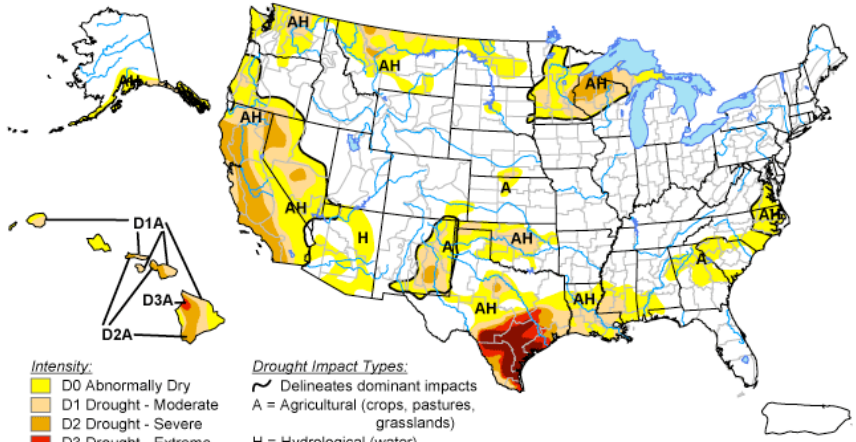


ETa Anomaly (Apr 1 – Jul 1, ’09)



U.S. Drought Monitor

July 7, 2009
Valid 8 a.m. EDT



Intensity:
- D0 Abnormally Dry
- D1 Drought - Moderate
- D2 Drought - Severe
- D3 Drought - Extreme
- D4 Drought - Exceptional

Drought Impact Types:
- ~ Delineates dominant impacts
- A = Agricultural (crops, pastures, grasslands)
- H = Hydrological (water)

The Drought Monitor focuses on broad-scale conditions. Local conditions may vary. See accompanying text summary for forecast statements.

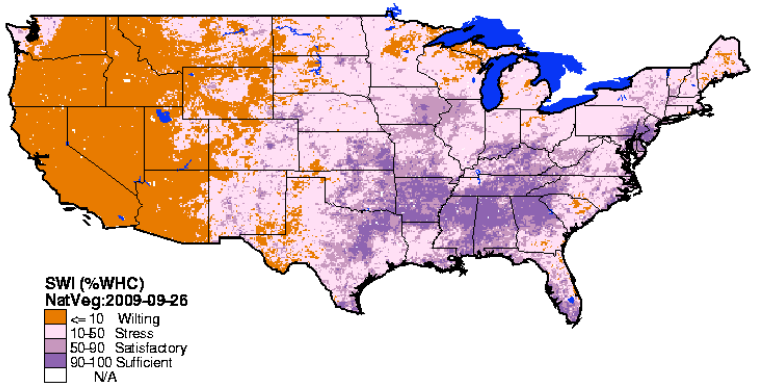
http://drought.unl.edu/dm

USDA National Drought Mitigation Center

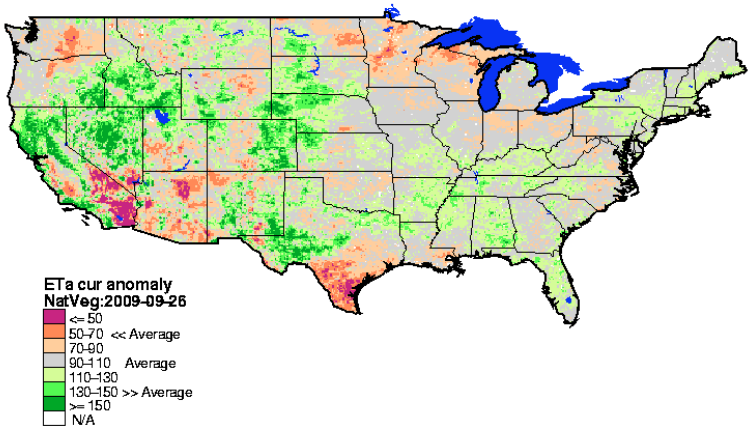
Released Thursday, July 9, 2009
Author: Rich Tinker, CPC/NCEP/NWS/NOAA

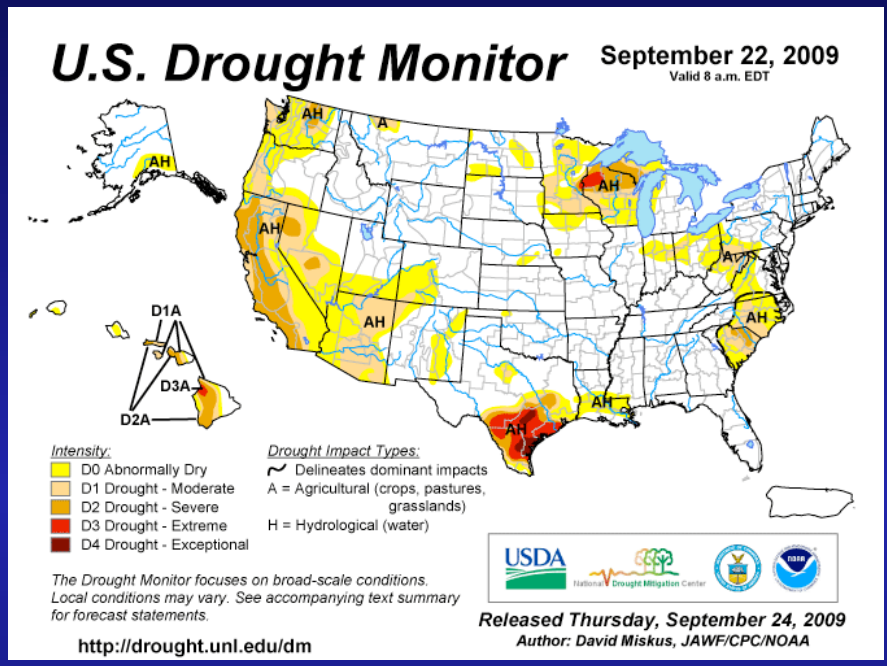
USGS

Soil Water Index (Sep 26, ’09)



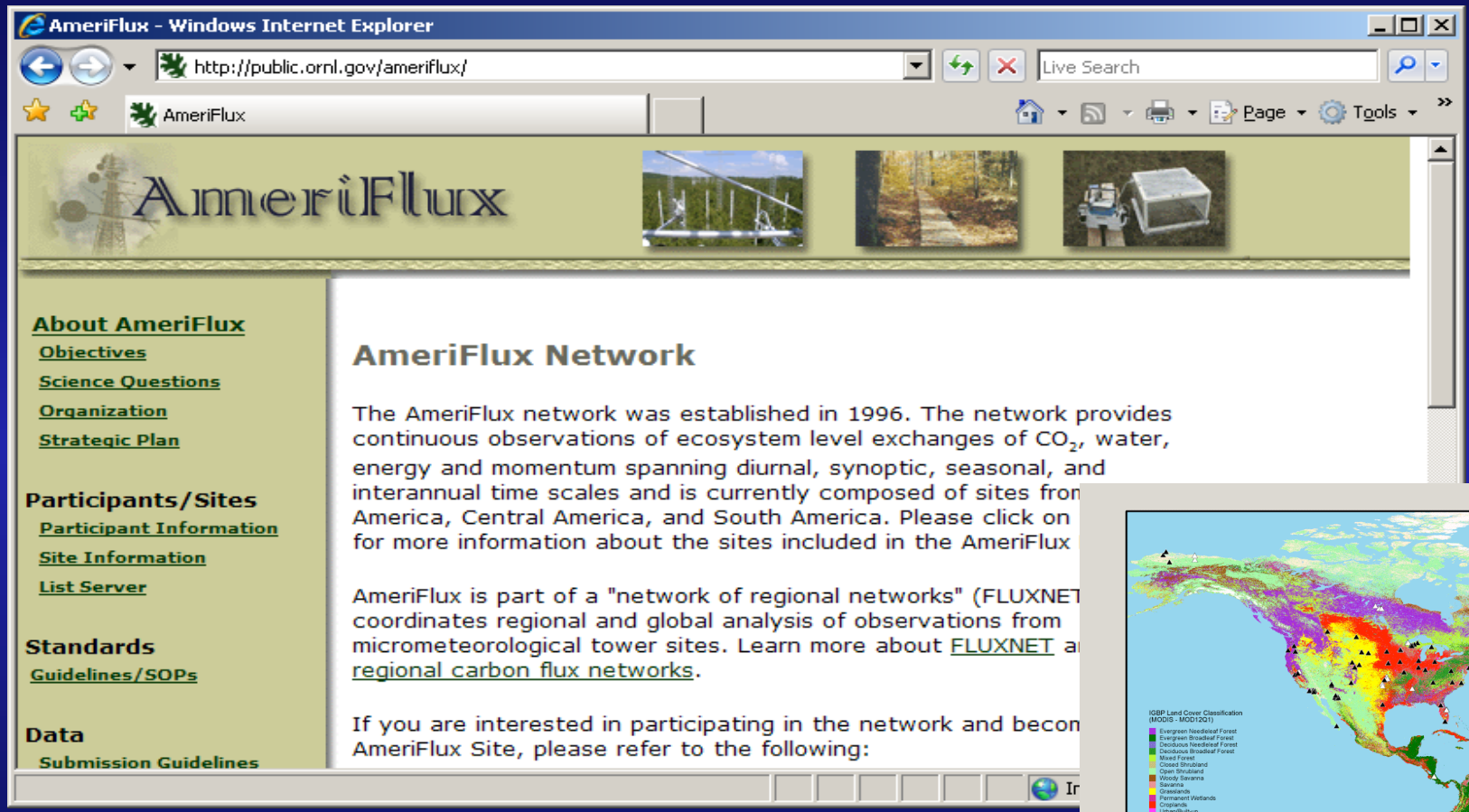
ETa Anomaly (Apr 1 – Sep 26, ’09)





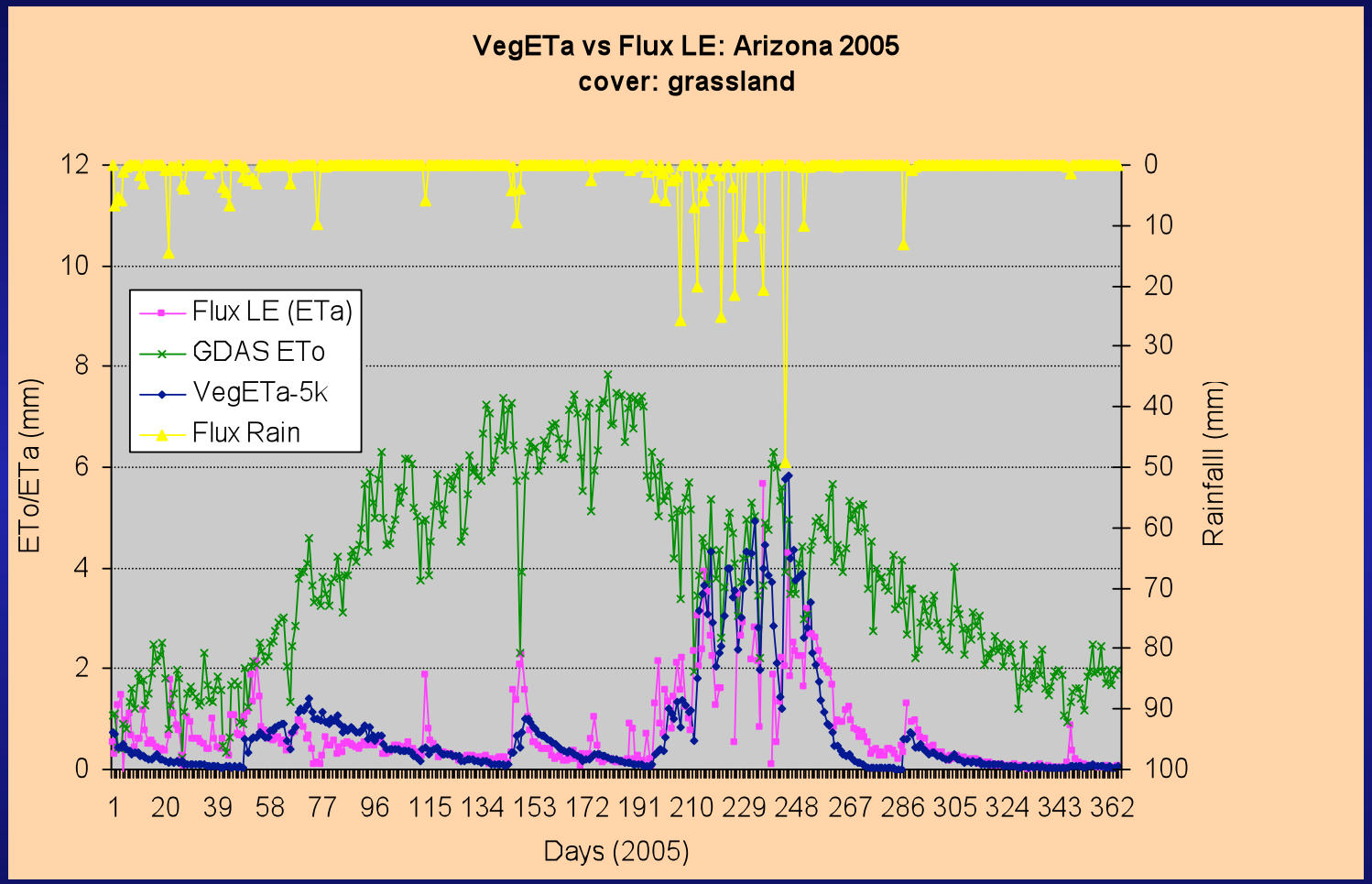
USGS

Evaluation: Latent Heat Flux (ET)
AmeriFlux Data



USGS

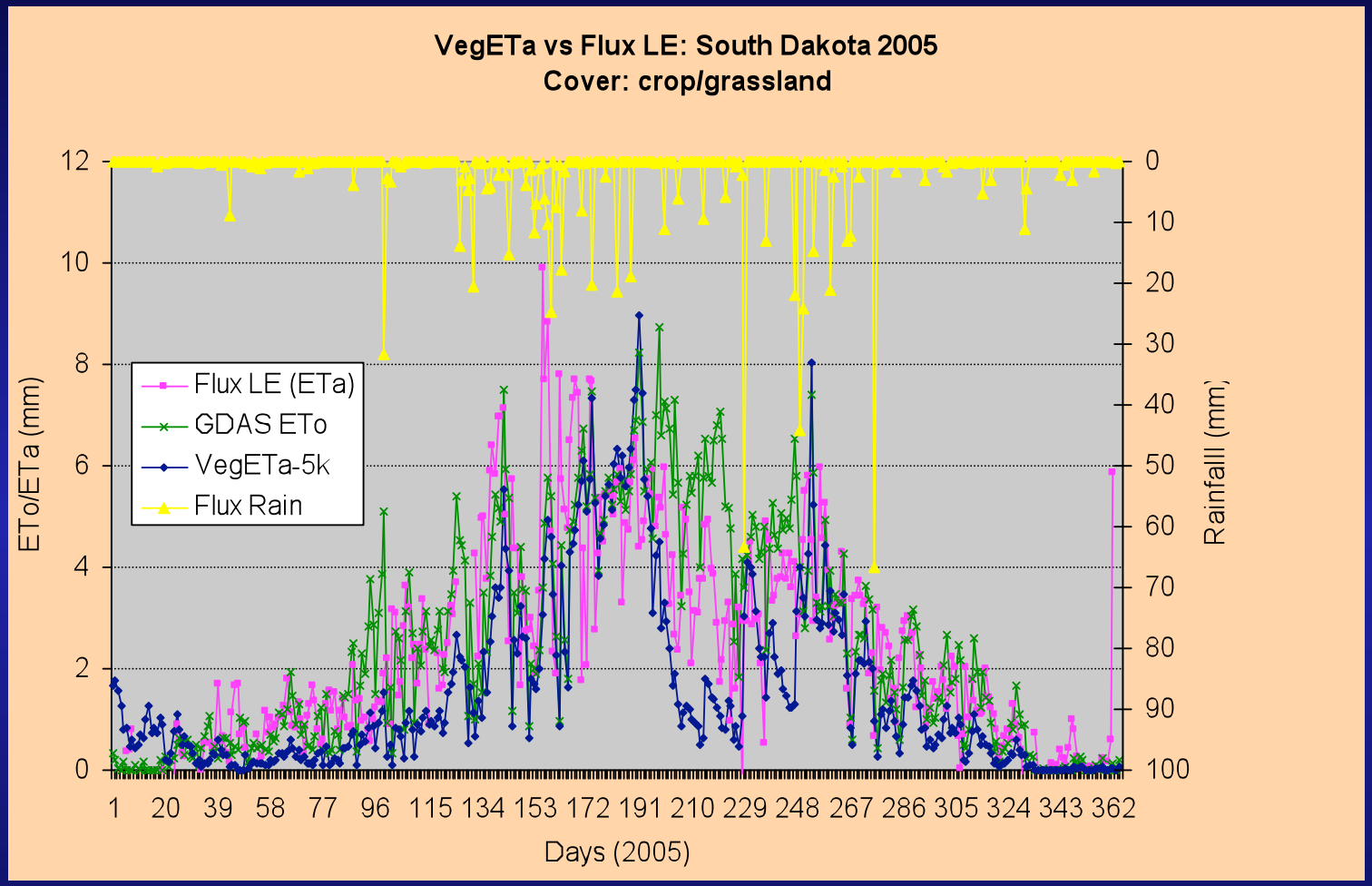
Latent heat flux (ET) from AmeriFlux tower and VegET ETa
Audubon, Arizona, 2005: water limiting environment



A stronger correspondence between VegETa and tower latent heat flux.

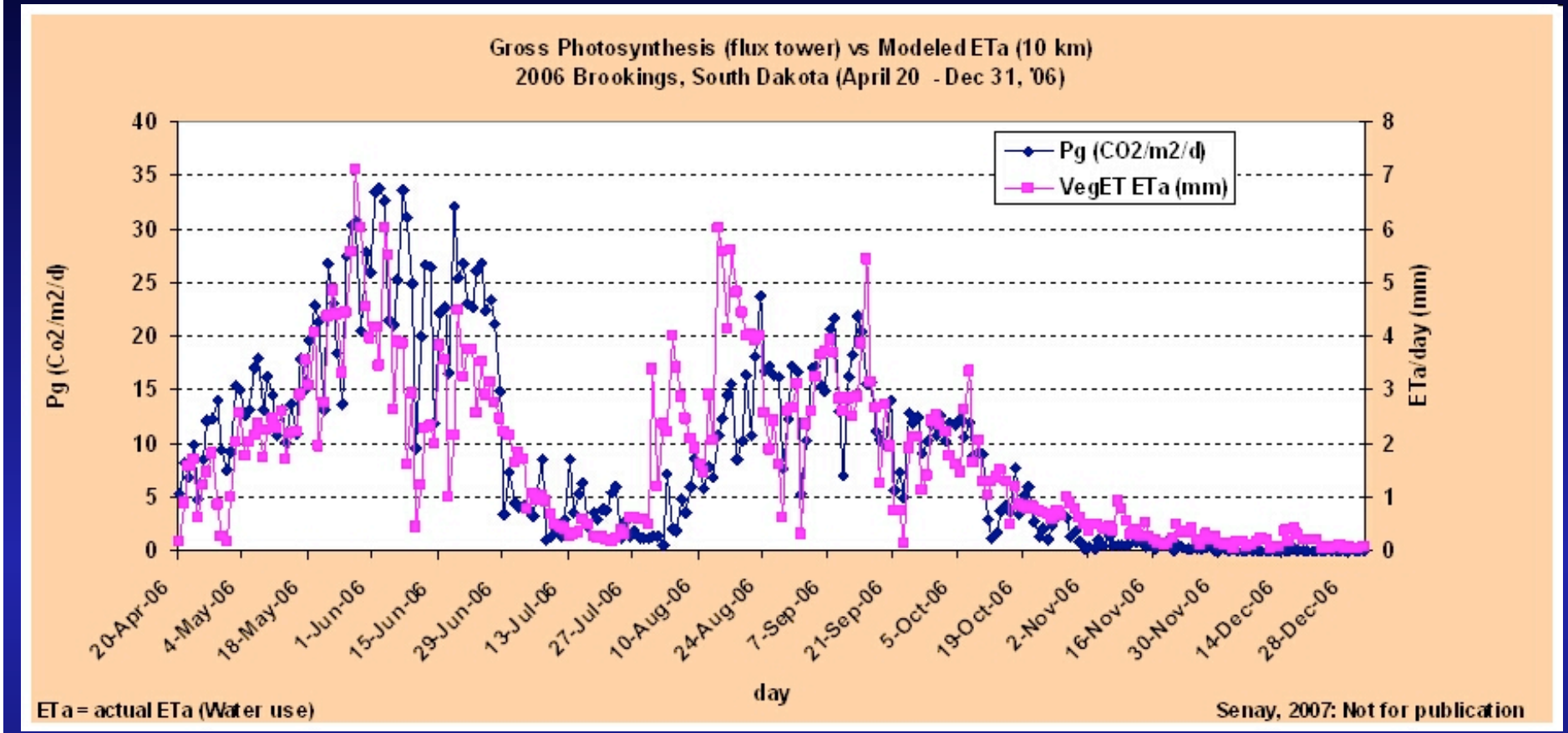
USGS

Latent heat flux (ET) from AmeriFlux tower and VegET ETa
South Dakota, Brookings: energy limiting environment



VegETa captured both the magnitude and temporal variations of measured flux at the tower site, including gross primary production (data not shown)

USGS

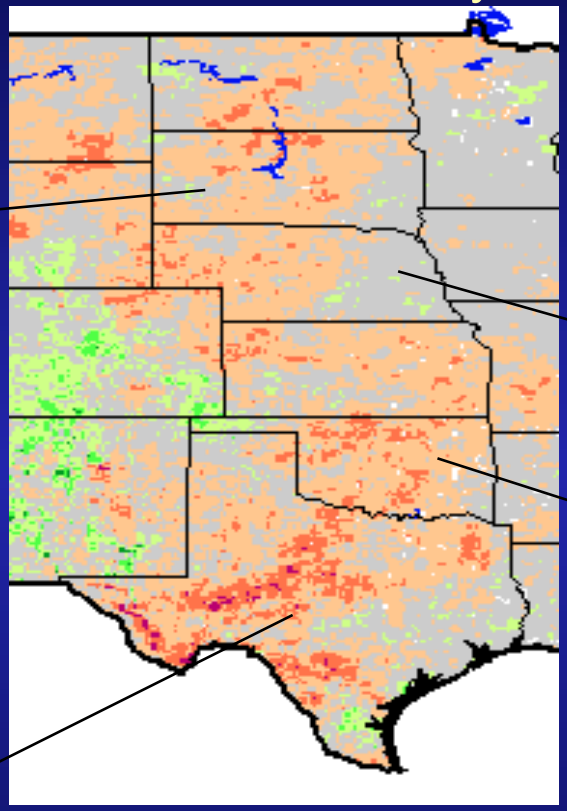


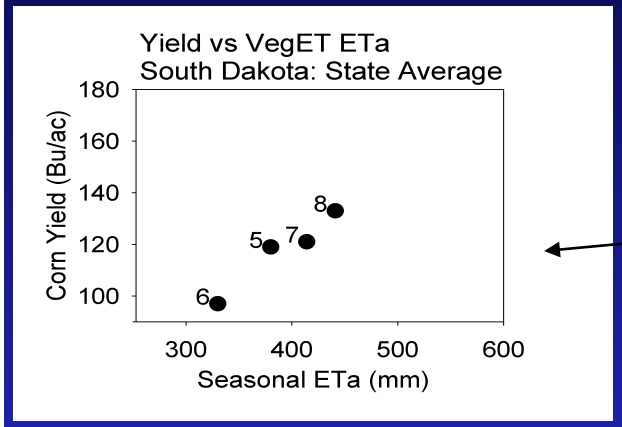
Pg: Gross Photosynthesis
Units: g/m^2/d

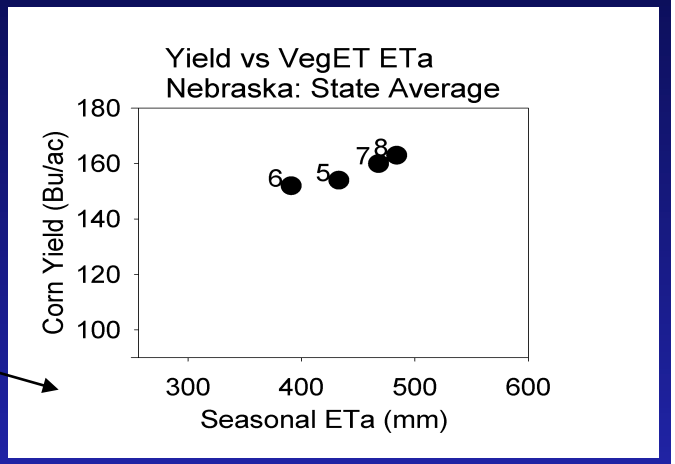
USGS

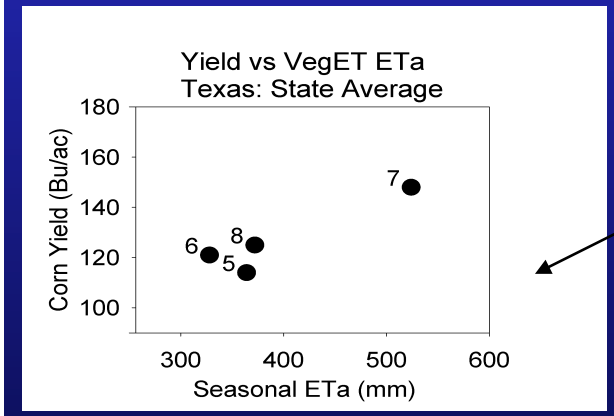
Validation with statewide NASS Yield Data

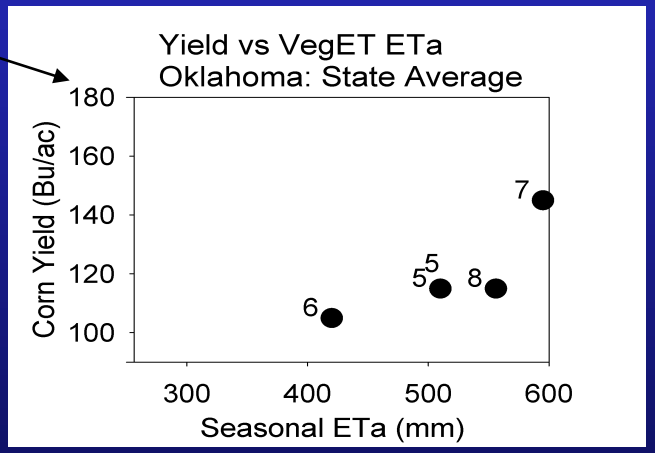
2006 ETa Anomaly











USGS

Water Balance Limitations

- Requires or depends on accuracy of…
  - rainfall data
  - characterization of vegetation water-use patterns
  - information on soils

- Difficult to estimate
  - irrigation applications
  - sub-surface extraction in wetlands and by deep rooted plants
  - The impact of pest and diseases on ET

USGS

Energy Balance Approach for ET

Energy balance gives us "actual" ET

Therefore, we can account for impacts on ET caused by:

- water shortage
- disease
- crop variety
- planting density
- cropping dates
- salinity
- management

$$ETa = Kc * Ks * ETo$$

- *(these effects can be converted directly into a crop coefficient)*

$$Kc * Ks$$

(ETf)

University of Idaho

USGS

Energy Balance Based ET

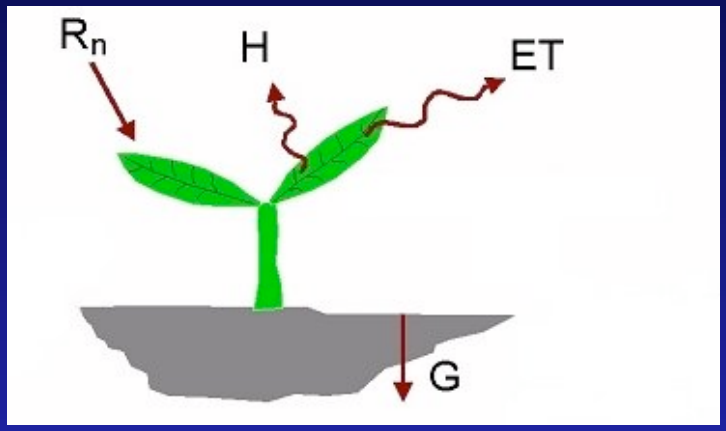
ET = residual of other energy terms

Rn = ET + H + G

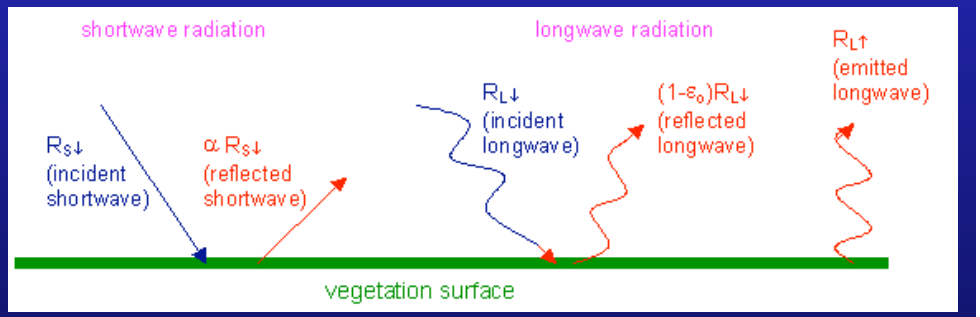
H = f(DT, wind speed, roughness)

G = f(Rn, surface type)

ET = Rn - H - G



$$R_n = R_{S\downarrow} - \alpha R_{S\downarrow} + R_{L\downarrow} - R_{L\uparrow} - (1 - \varepsilon_0) R_{L\downarrow}$$



Graphics: Rick Allen

Remote Sensing

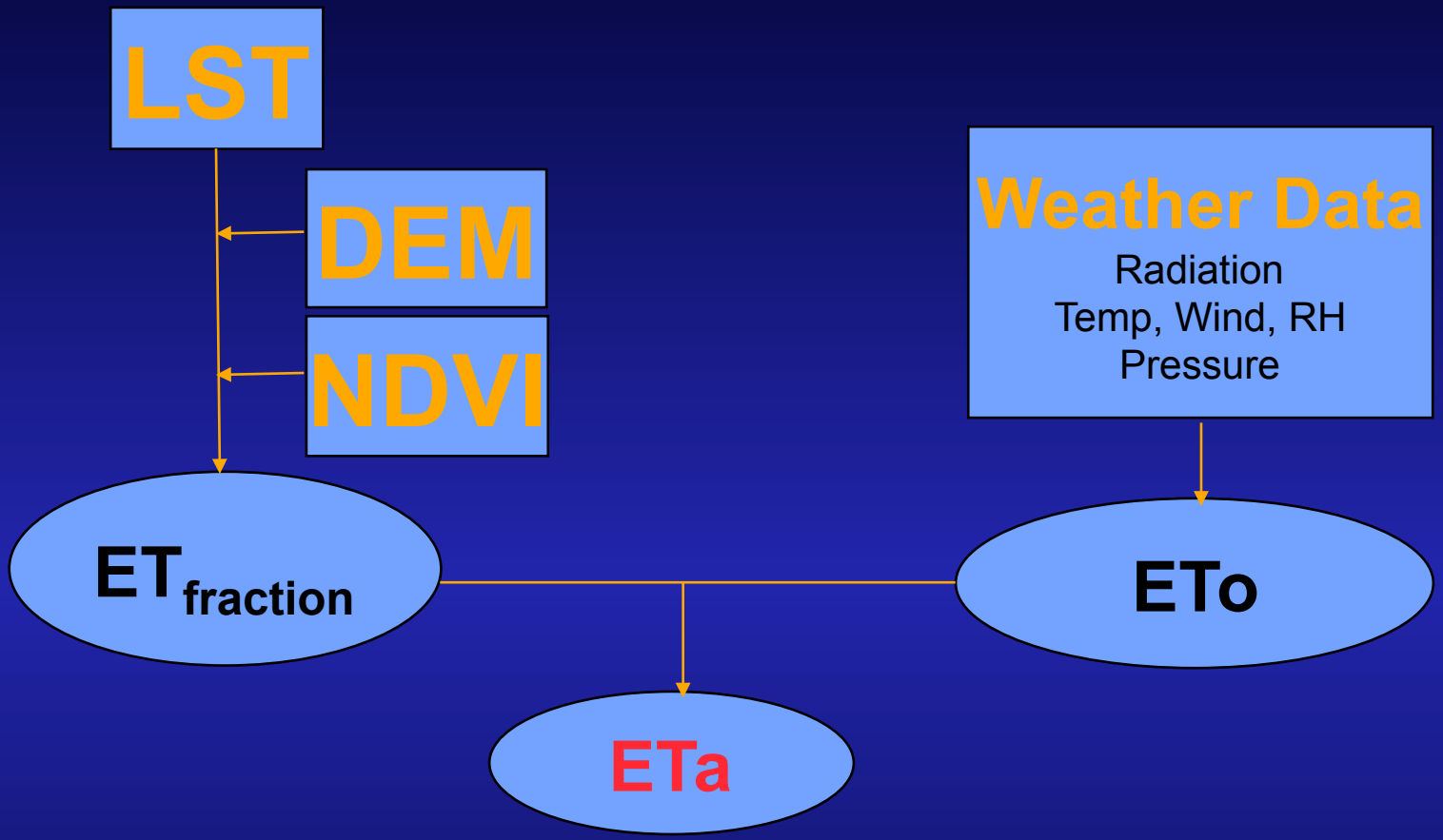
α = albedo

R_L = f(LST)

USGS

Geographic Information Science Center of Excellence
South Dakota State University

Simplified Surface Energy Balance (SSEB) Approach

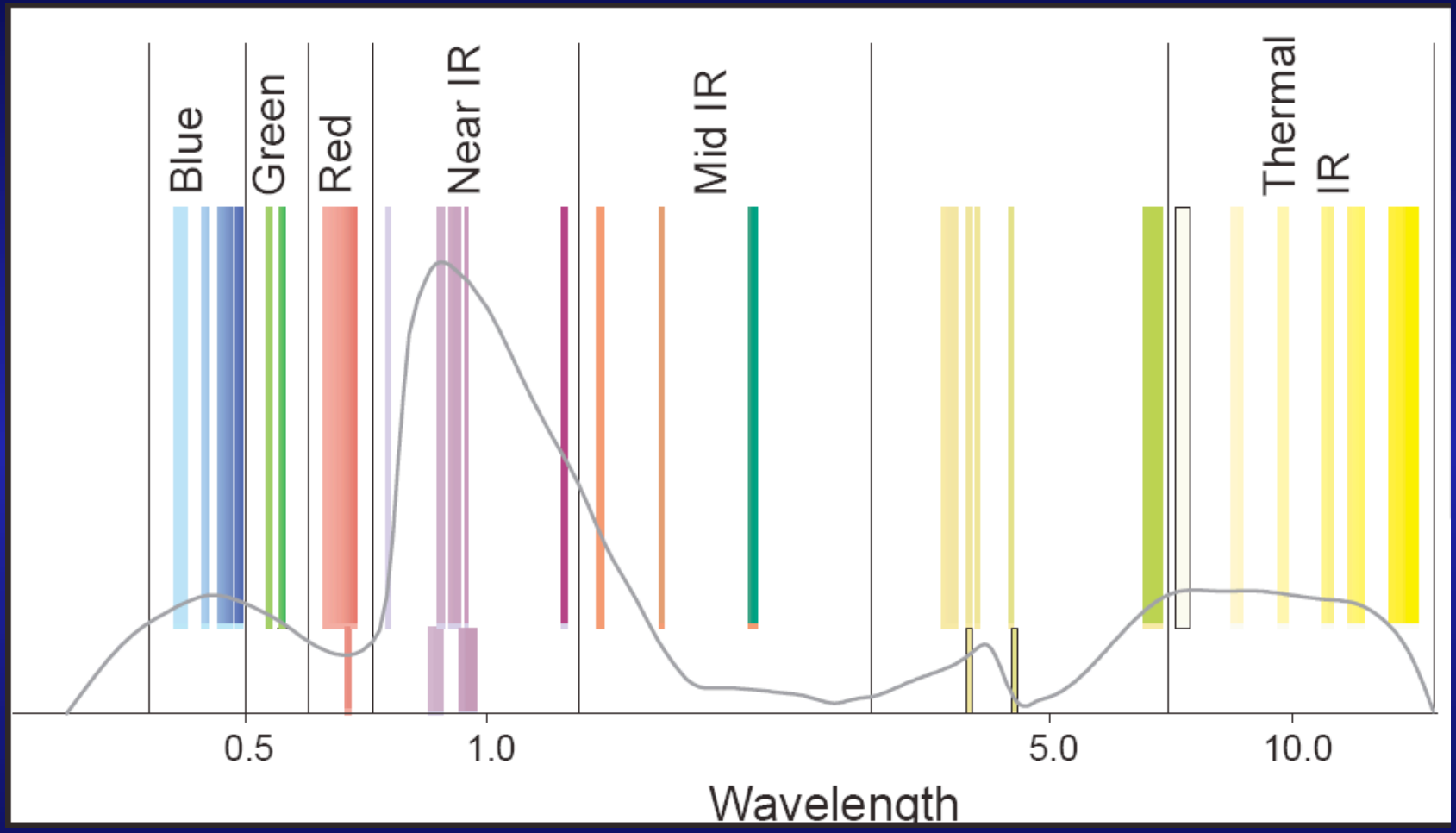


Adapted the "hot" and "cold" pixel concept from SEBAL (Bastiaanssen et al., 1998) and METRIC (Allen et al., 2005) to calculate ET fraction and combine it with ETo.

Senay, et al., 2007. Sensors, 7, 979-1000.

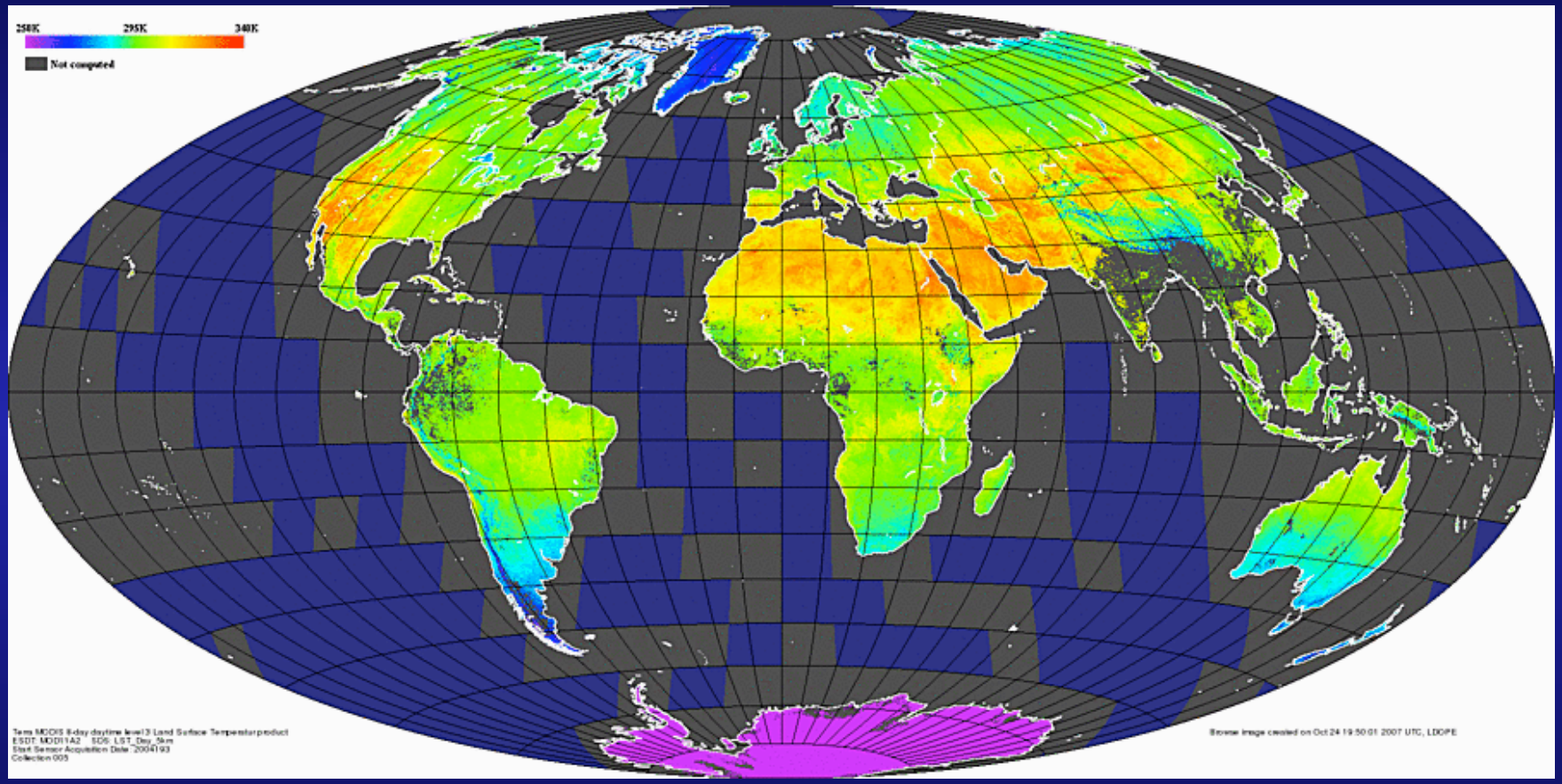
USGS

MODIS Spectral Bands (36)



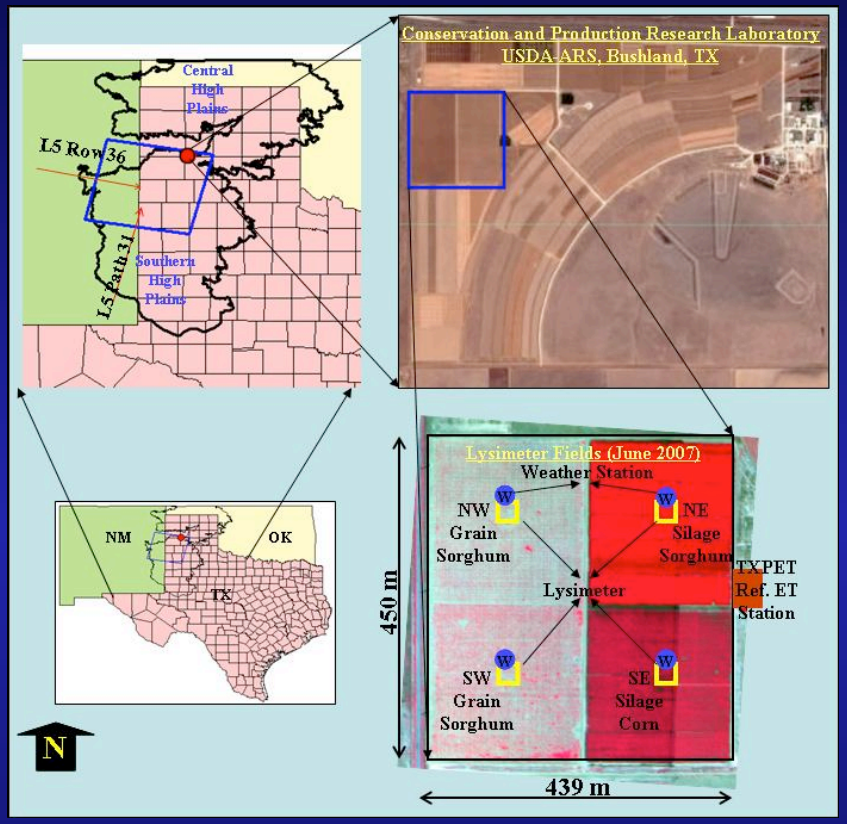
USGS

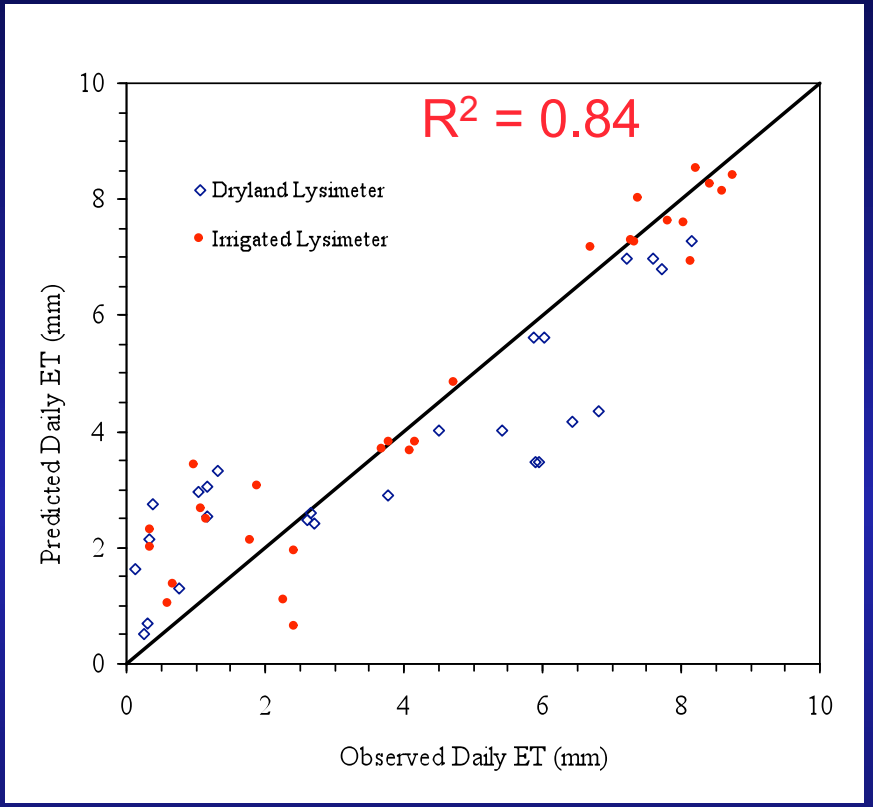
MODIS 8-day Land Surface Temperature (1-km spatial resolution)



USGS

Validation of SSEB/SETI against Lysimeter ET Data

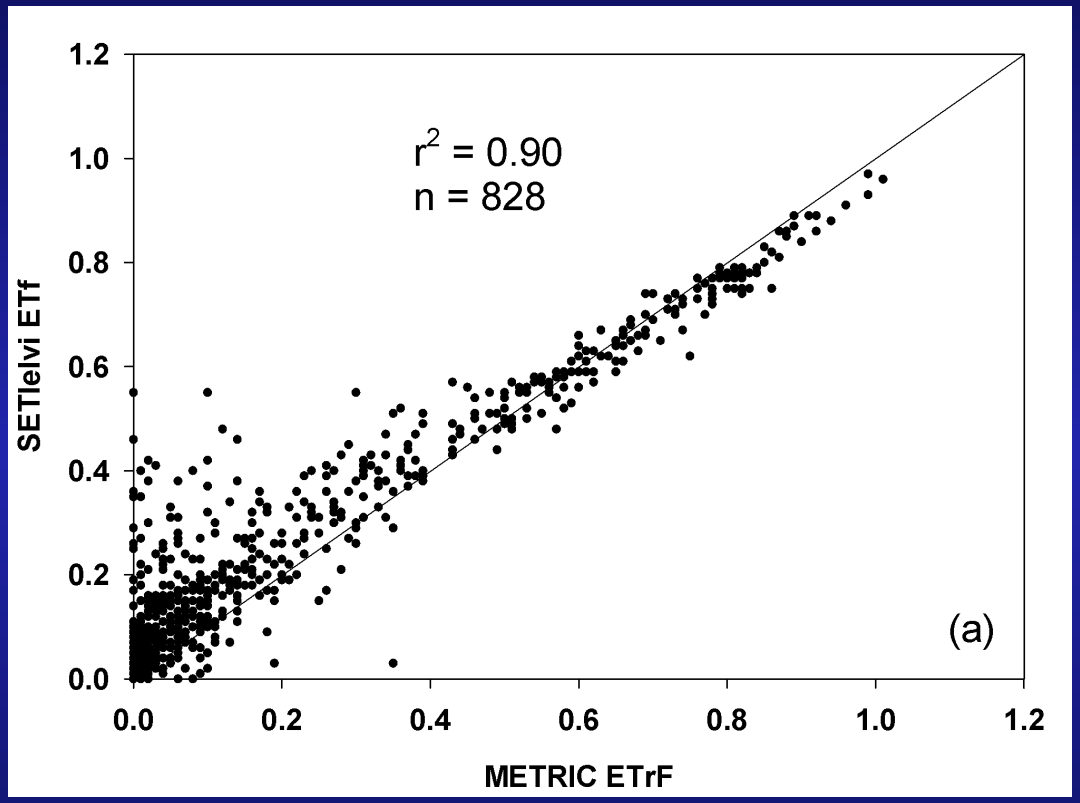




SSEB ETa versus observed daily ET on four large Lysimeters in Bushland, Texas.
Thermal Data: Landsat TM; 14 images; March – August, 2006/2007.
(Gowda et al., 2009, in Press)

USGS

Comparison: METRIC ETrF vs SSEB/SETI ETf



The Washington Post

Water Measured From the Sky

Satellites Track Land's Consumption

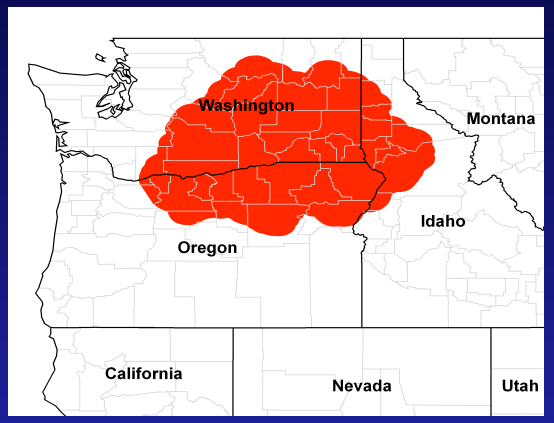
By Kari Lydersen
Washington Post Staff Writer
Monday, September 14, 2009

Senay, Allen, Budde and Verdin, 2009. Under Internal Review.

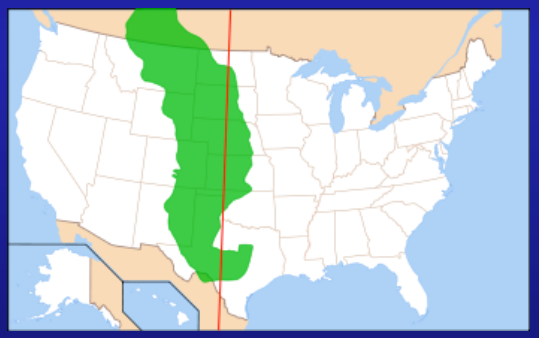
USGS

Case Studies:

- Columbia Plateau:
  - Ground Water Availability Study



- Great Plains:
  - High Plains Aquifer
  - New CONUS effort



USGS

Methods

- Model:
  - Simplified Surface Energy Balance (SSEB) Approach, renamed as Simplified ET Index (SETI)
- Data
  - MODIS 1-km Land Surface Temperature and NDVI (8-day average)
  - GDAS ETo ~10-km (daily)
  - Years: 2000 - 2008
  - NOAA/NEXRAD Precipitation for annual water budget
  - HYDRO1K for elevation-correction of LST

USGS

Columbia Plateau Ground-Water Availability

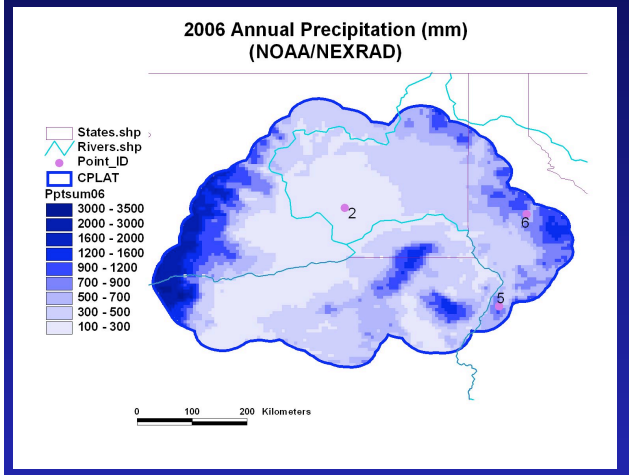
- Part of the USGS "Ground-Water Resources Program"

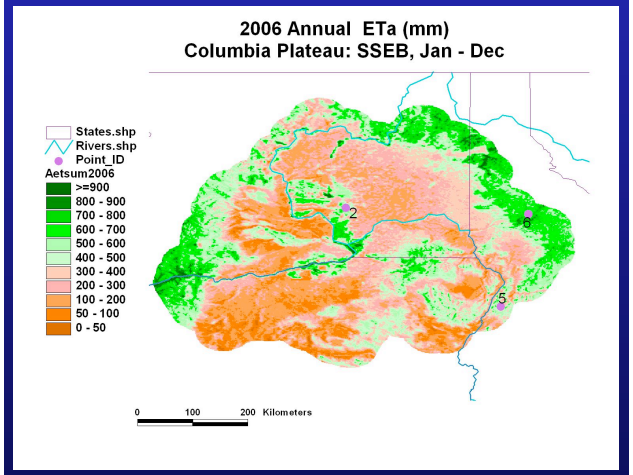
- A collaborative work between Oregon Water Science Center and USGS/EROS

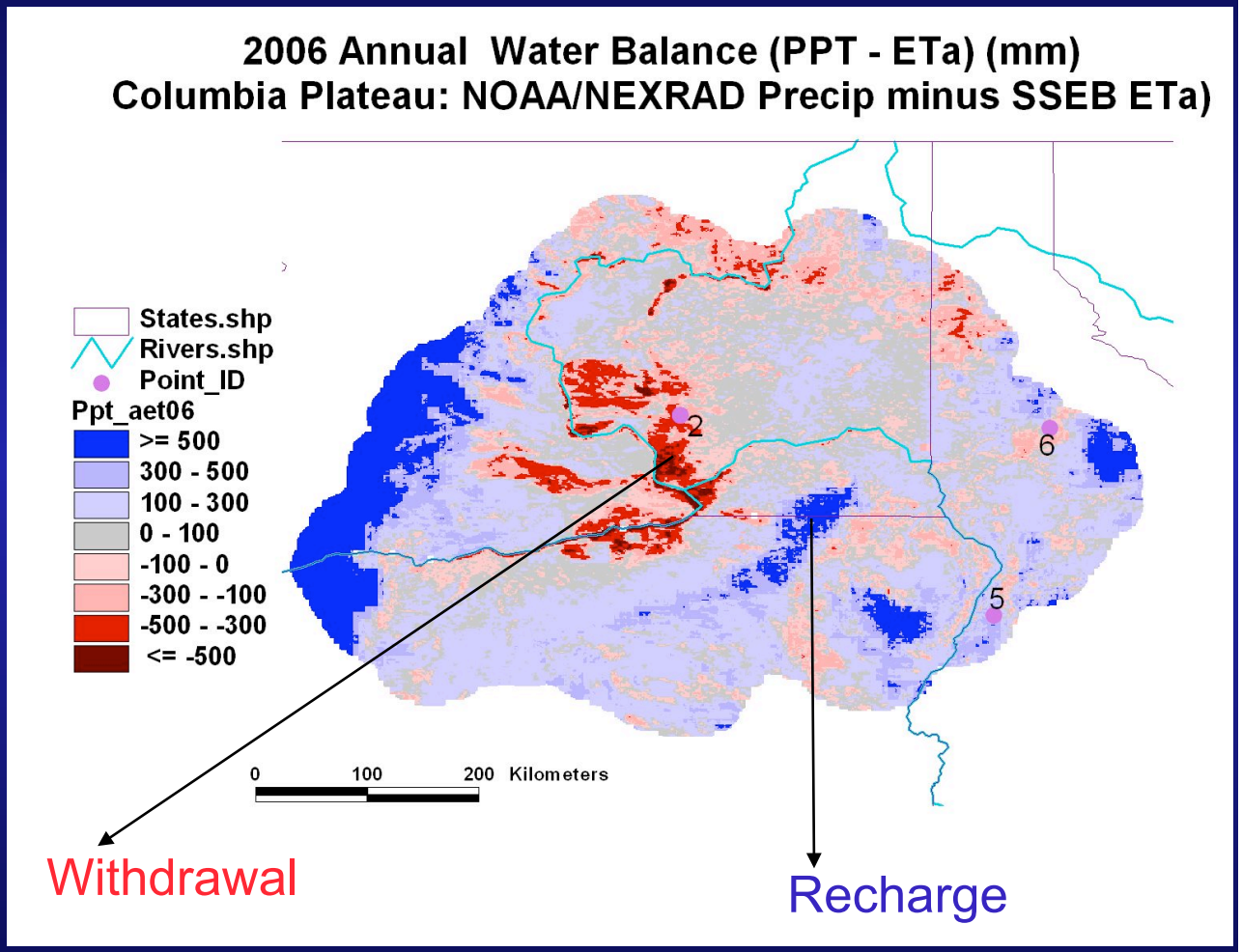
- Objective:
- To quantify and assess historical (1989 – 2007) irrigation water use rates and general landscape ET as part of the "Columbia Plateau Ground Water Budget" study.

USGS

Annual Water Balance



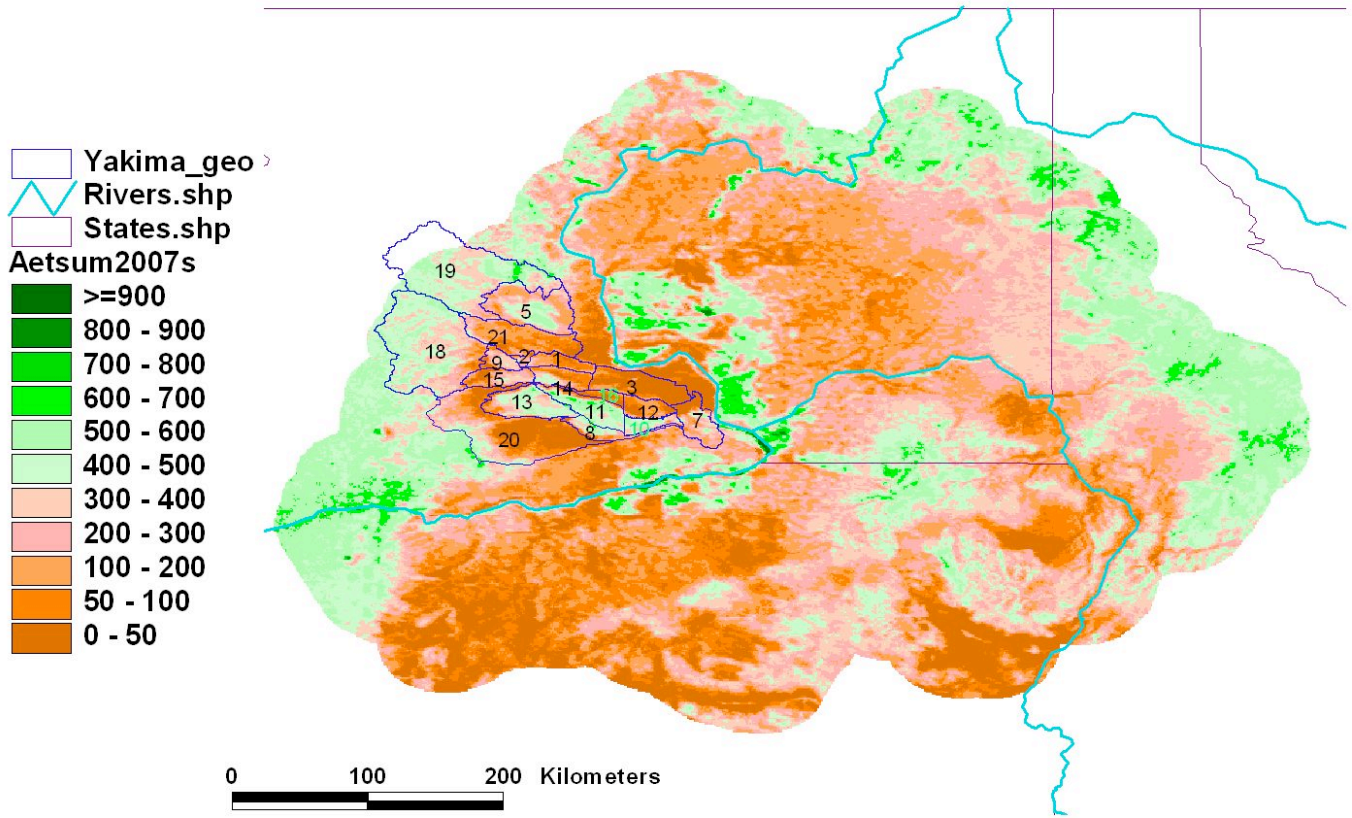




USGS

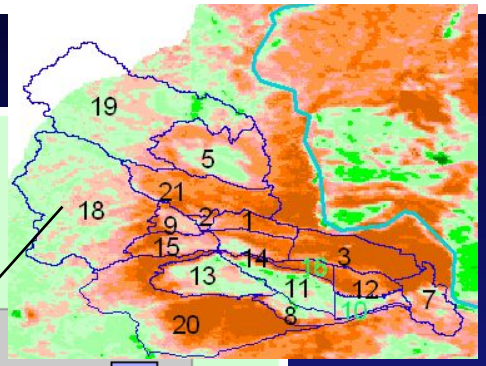
Field Validation using irrigation data

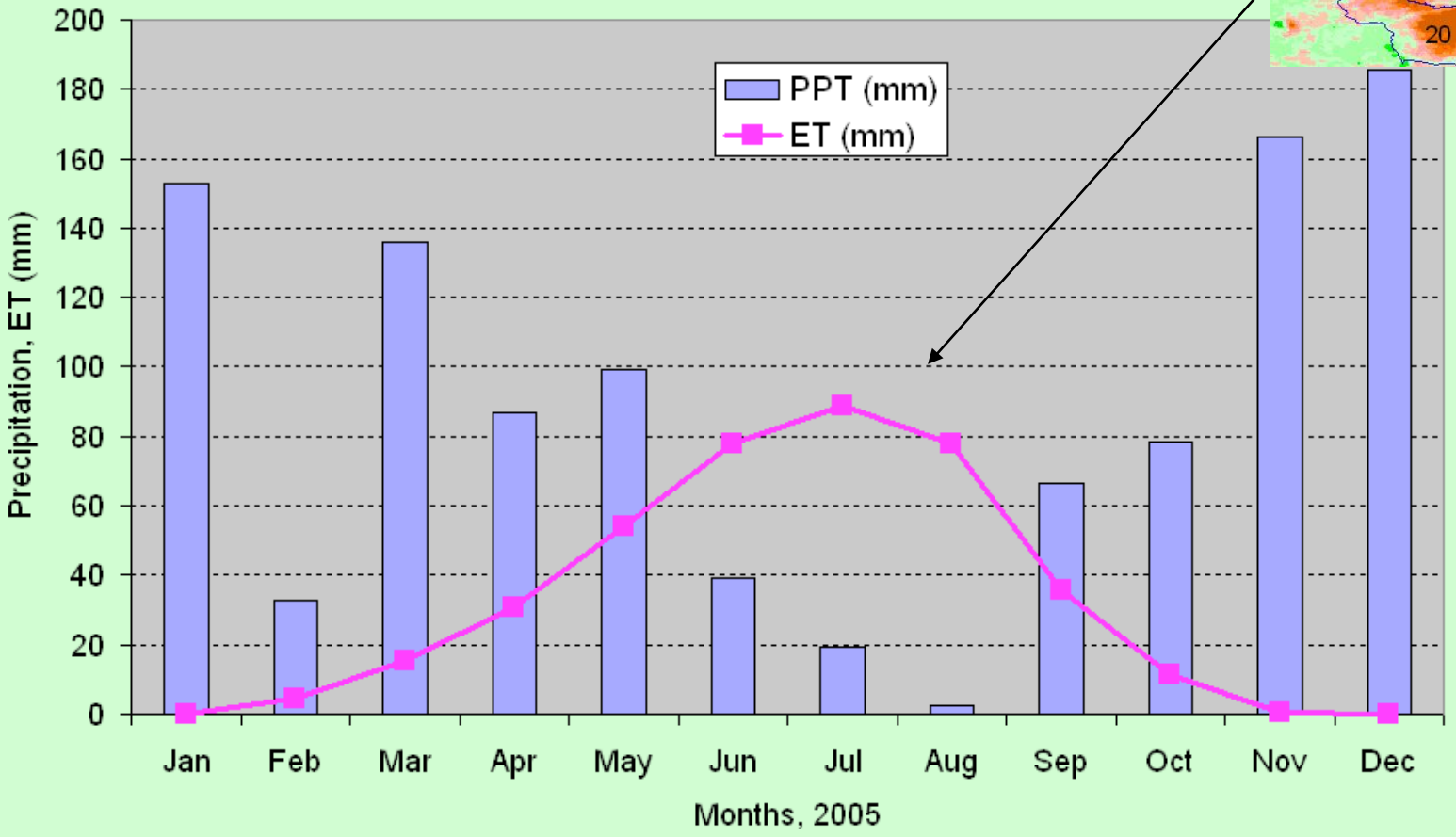
Yakima Basin with 2007 Seasonal ETa



USGS

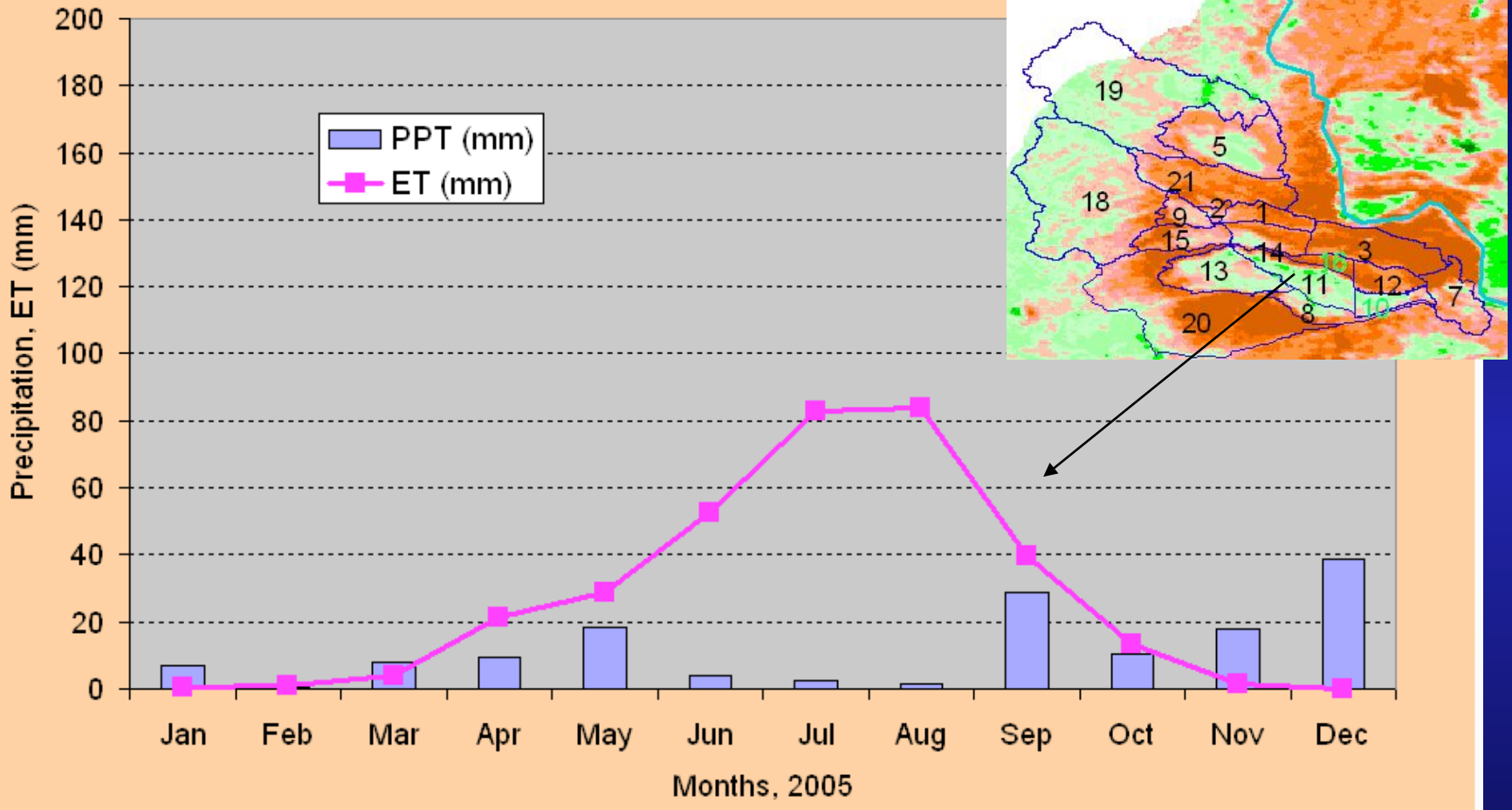
Monthly Traces of Precipitation and ET for 2005
Rainfed Basin, ID 18





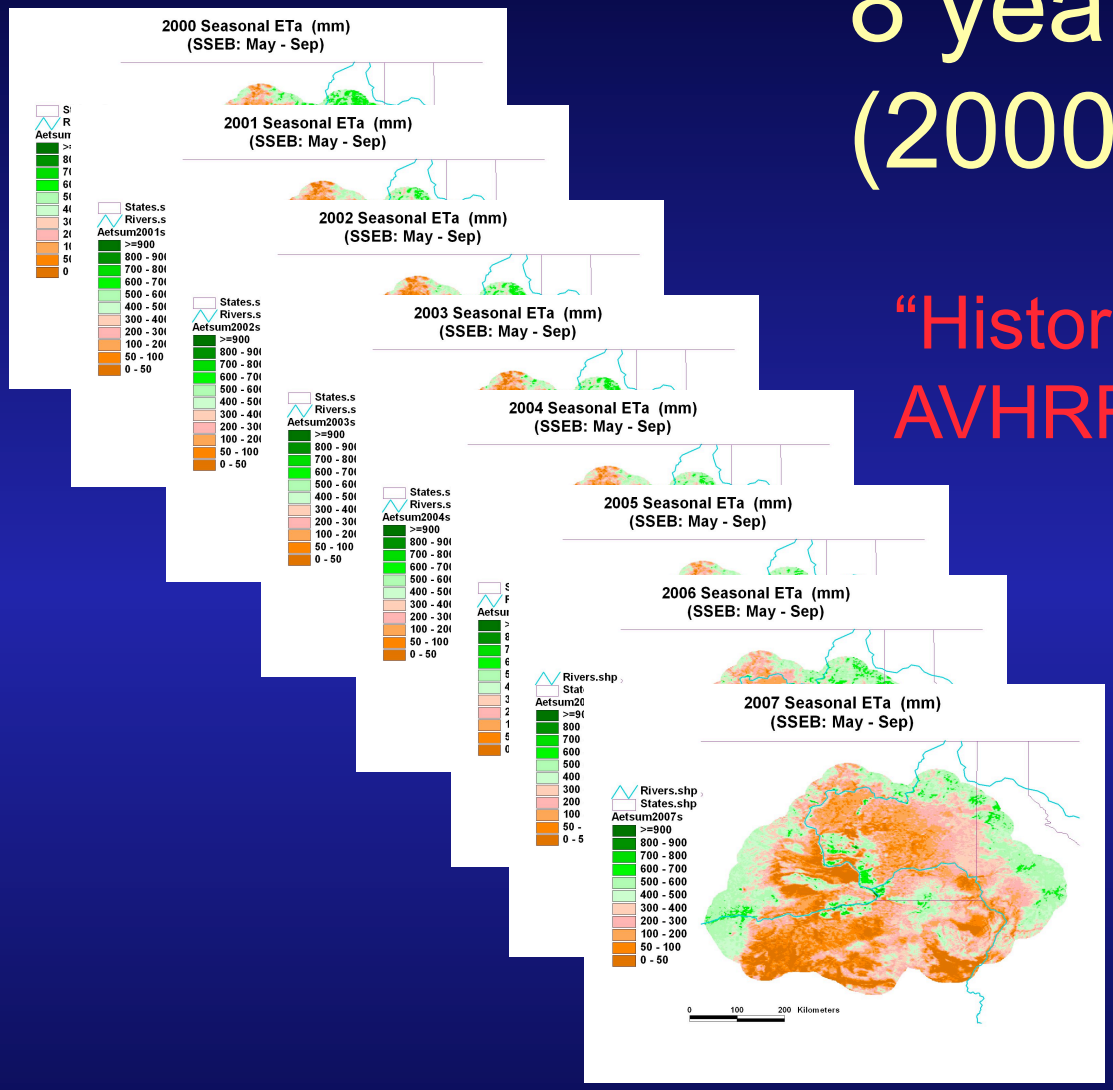
USGS

Monthly Patterns of Precipitation and ET for 2005
Irrigated Basin, ID 11



USGS

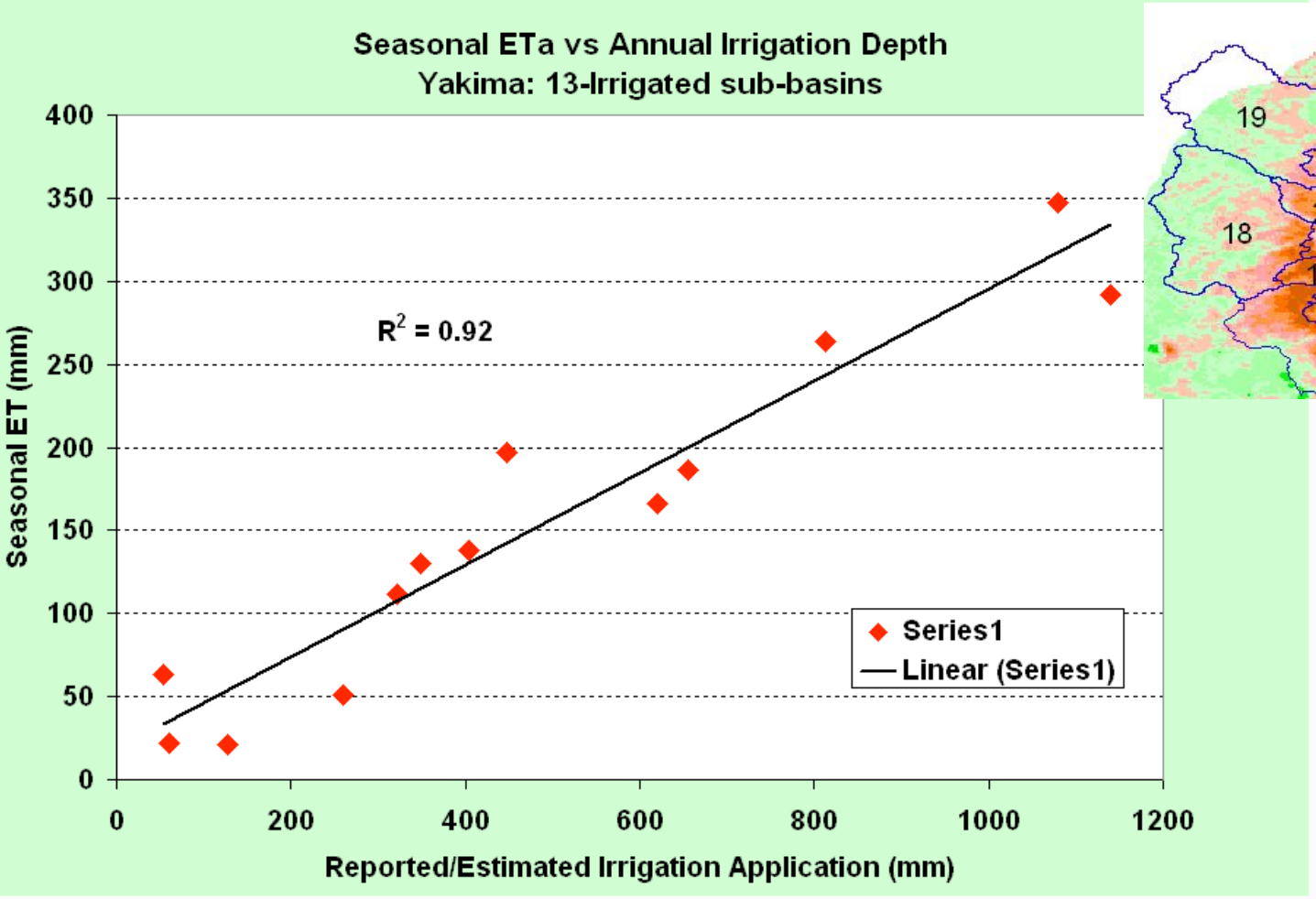
8 years of ETa (2000-2007)

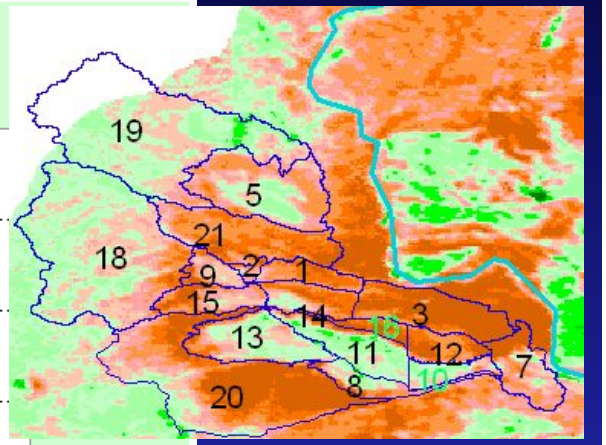


"Historical" ET
AVHRR1989-current

USGS

All basins: spatial pattern





~1/3 "Irrigation" is ET

? = return flow

? = recharge

I = ET + R + r/w

Strong correlation between ETa and irrigation application estimates

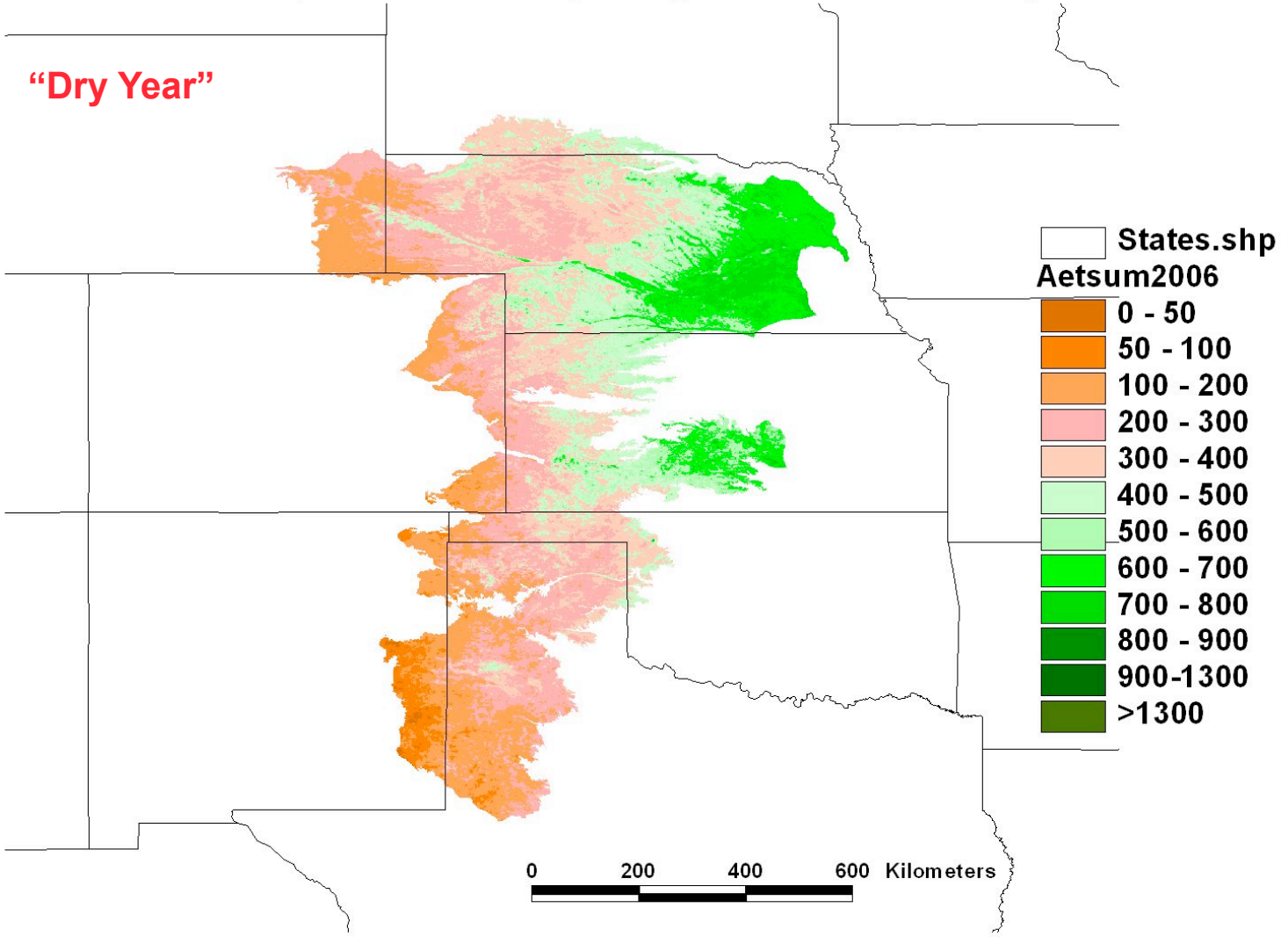
Irrigation data: Vaccaro & Olsen, 2007

USGS

High Plains Aquifer ET:

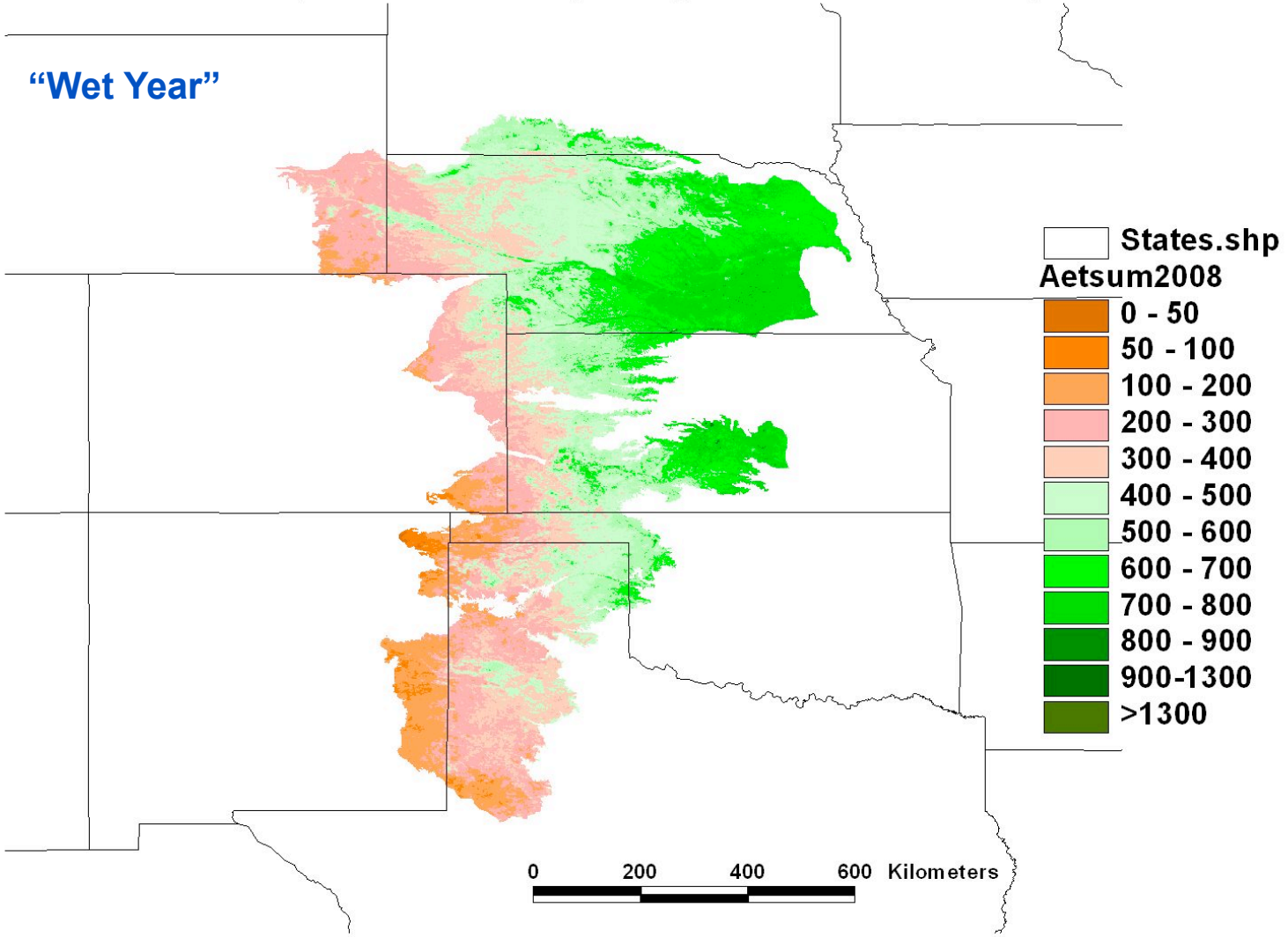
Plan to provide 10-year (2000-2009) Monthly and season ET to New Mexico Water Science Center

Annual ETa (mm) from the SSEB (SETI) model output for 2006 (using MODIS & GDAS)



USGS

Annual ETa (mm) from the SSEB (SETI) model output for 2008 (using MODIS & GDAS)



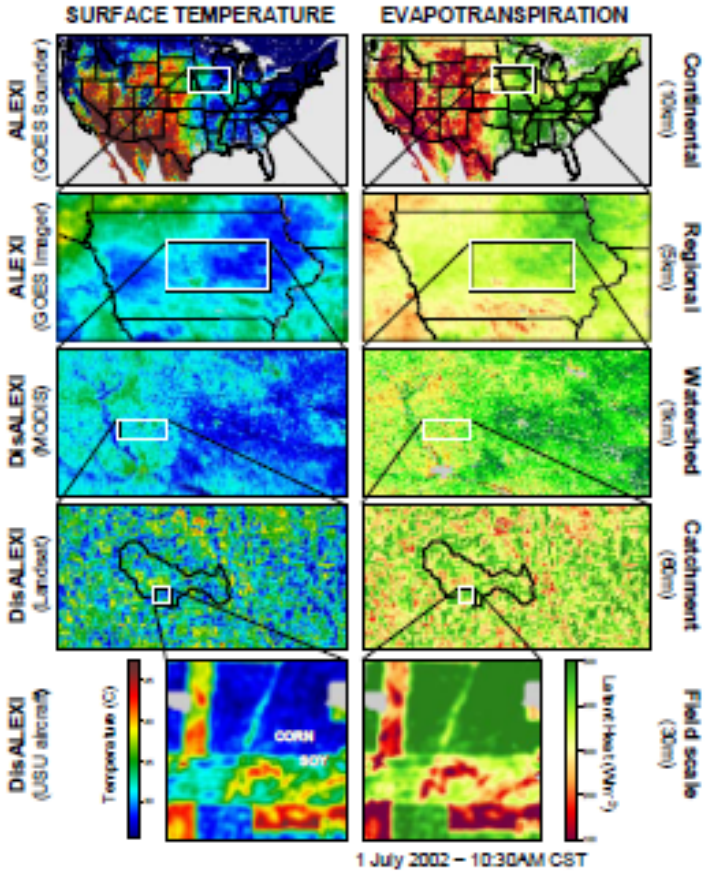
USGS

Preliminary CONUS ET Results:

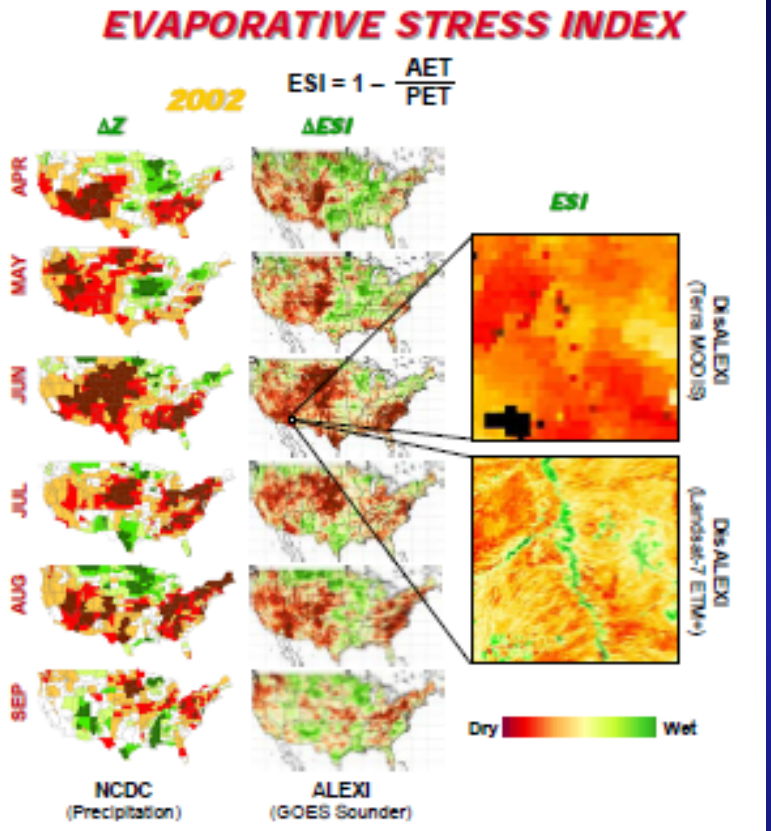
Exploratory Application of SSEB/SETI for Operational Use

USGS

ALEXI: GOES-based ET Products at 10-km



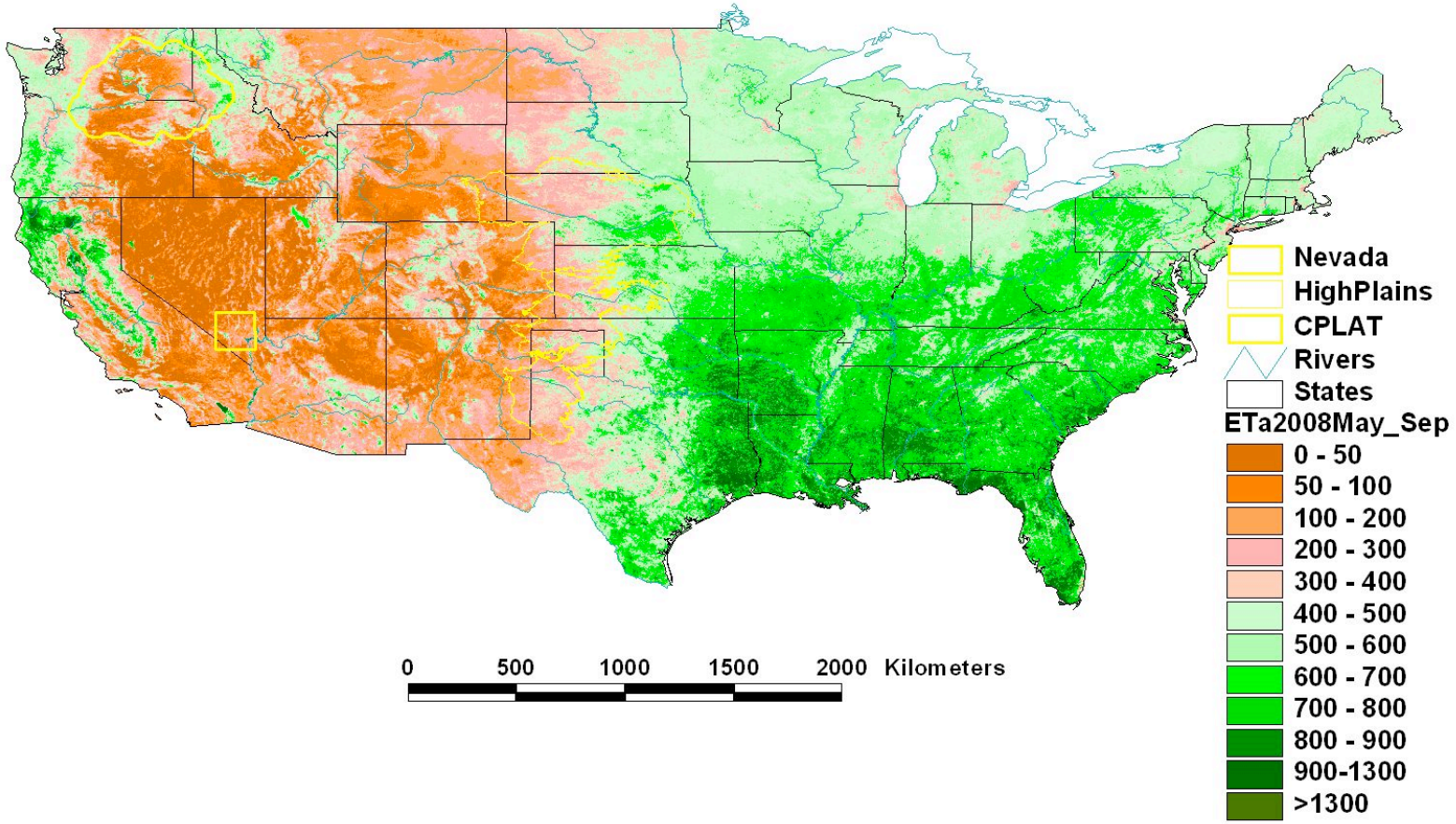
Multi-scale ET maps for 1 July 2002 produced using surface temperature data from aircraft (30-m resolution), Landsat-7 ETM+ (60-m), Terra MODIS (1-km), and GOES Imager (5-km) instruments (Anderson and Kustas (2008), Eos, 89, 233-234)



Monthly anomalies in a GOES-based Evaporative Stress Index (ESI=1-ET/PET) and in the Palmer Z index (Z), a precipitation-based metric of short-term meteorological drought, computed with respect to 4-year (2002-2005) mean monthly conditions. Also shown are ESI values over the San Pedro River basin in Arizona using TIR data from MODIS (1-km resolution) and Landsat 8 (60-m). (Anderson et al.(2007) J. Geophys. Res, 112, D11112, doi:11110.11029/12006JD007507.)

USGS

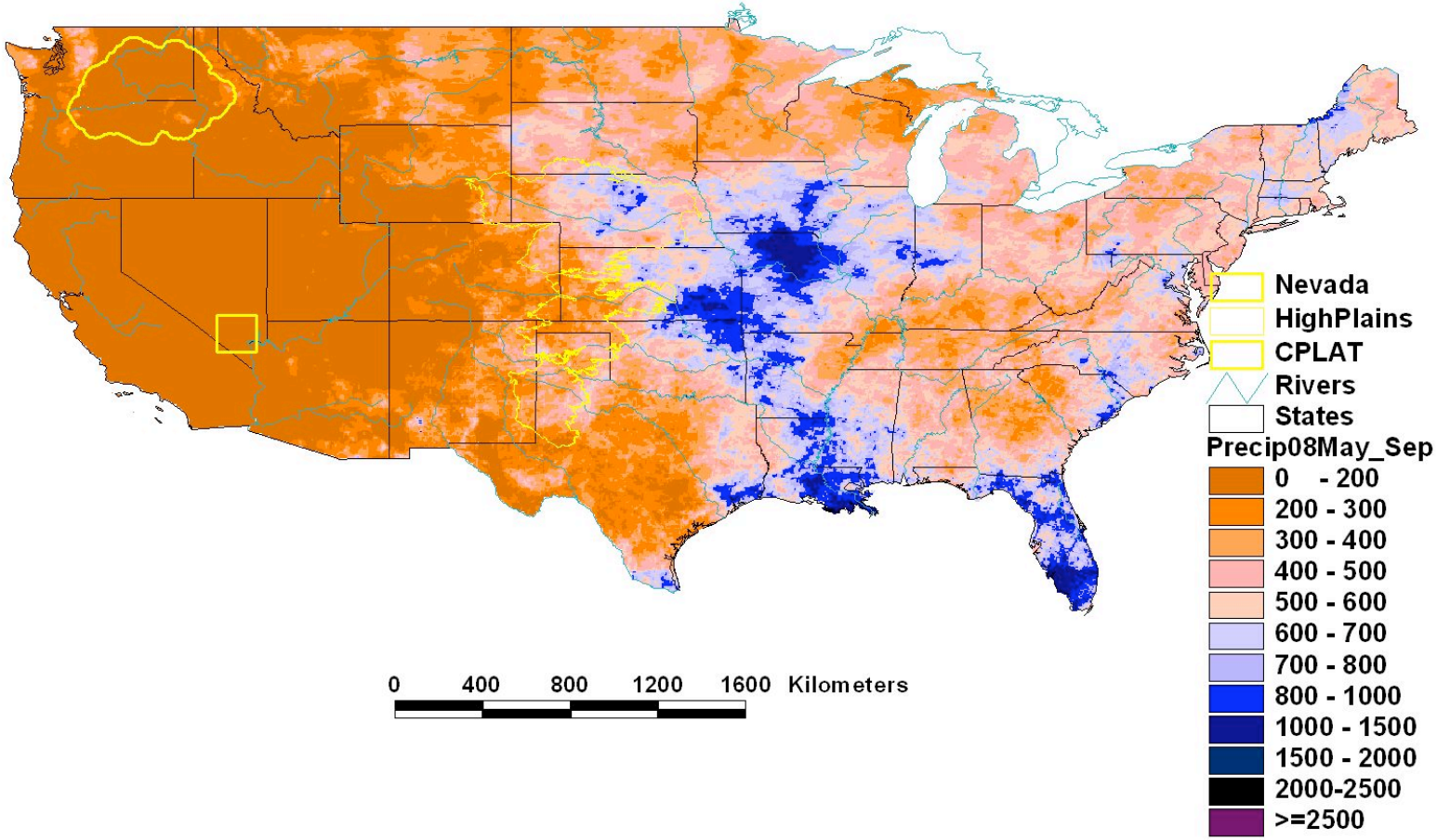
Seasonal (May-Sep) Actual ET Estimate (mm) for 2008
(SSEB/SETI: Preliminary CONUS Result)



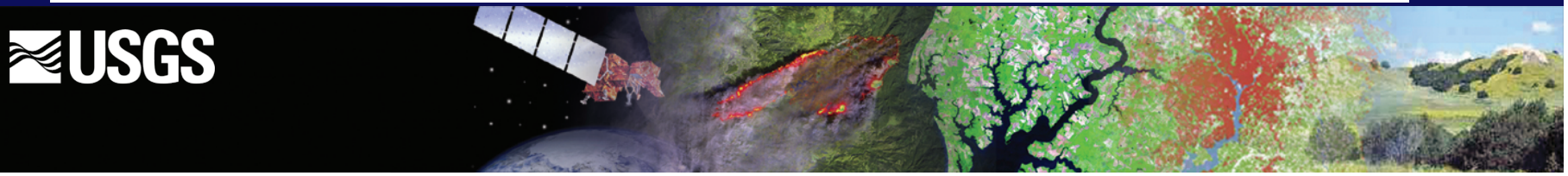
Spatial Resolution = 1-km

USGS

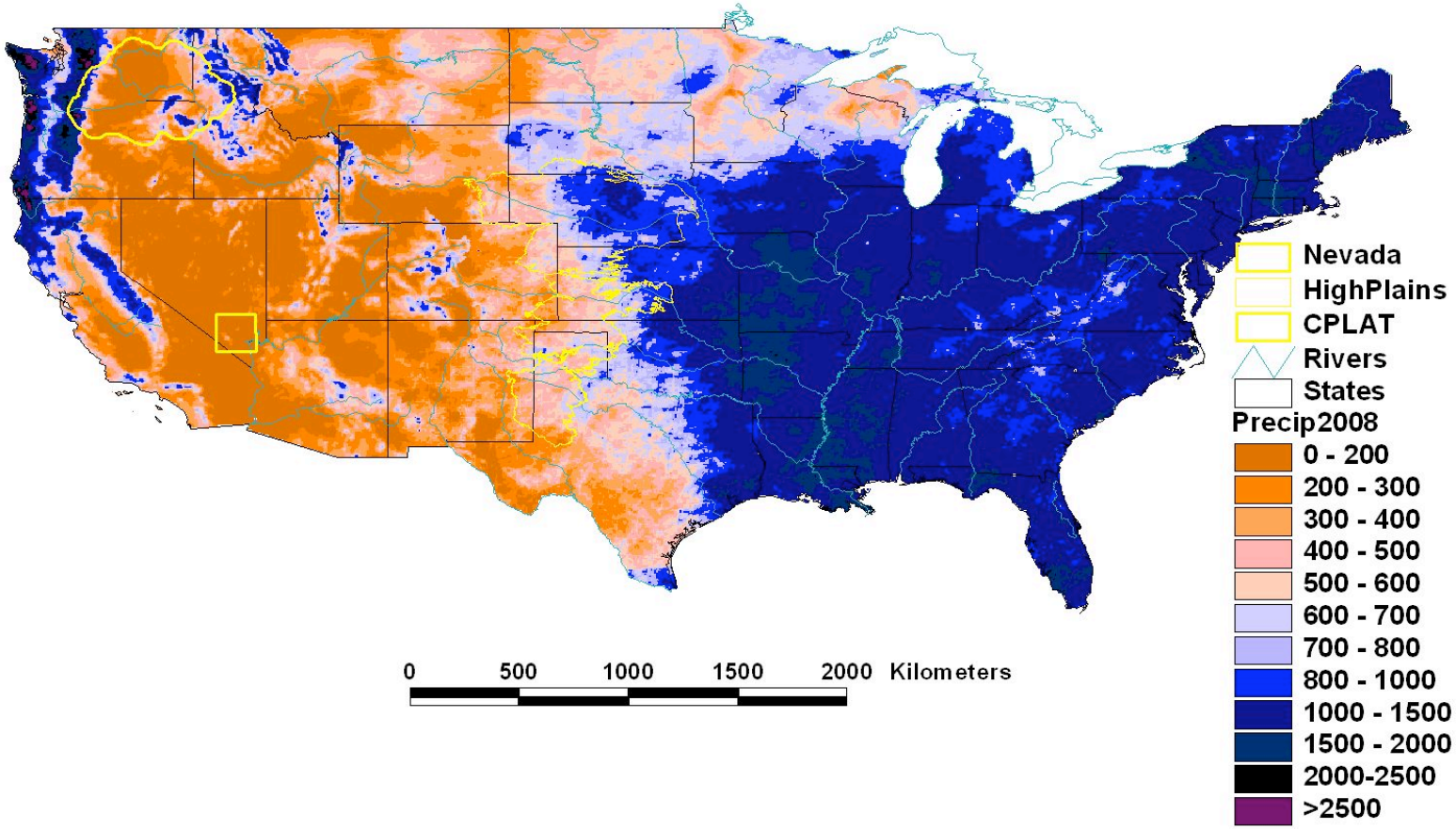
Seasonal (May-Sep) Precipitation (mm) for 2008
(NOAA: NEXRAD-Station Blend)



Spatial Resolution = 5-km



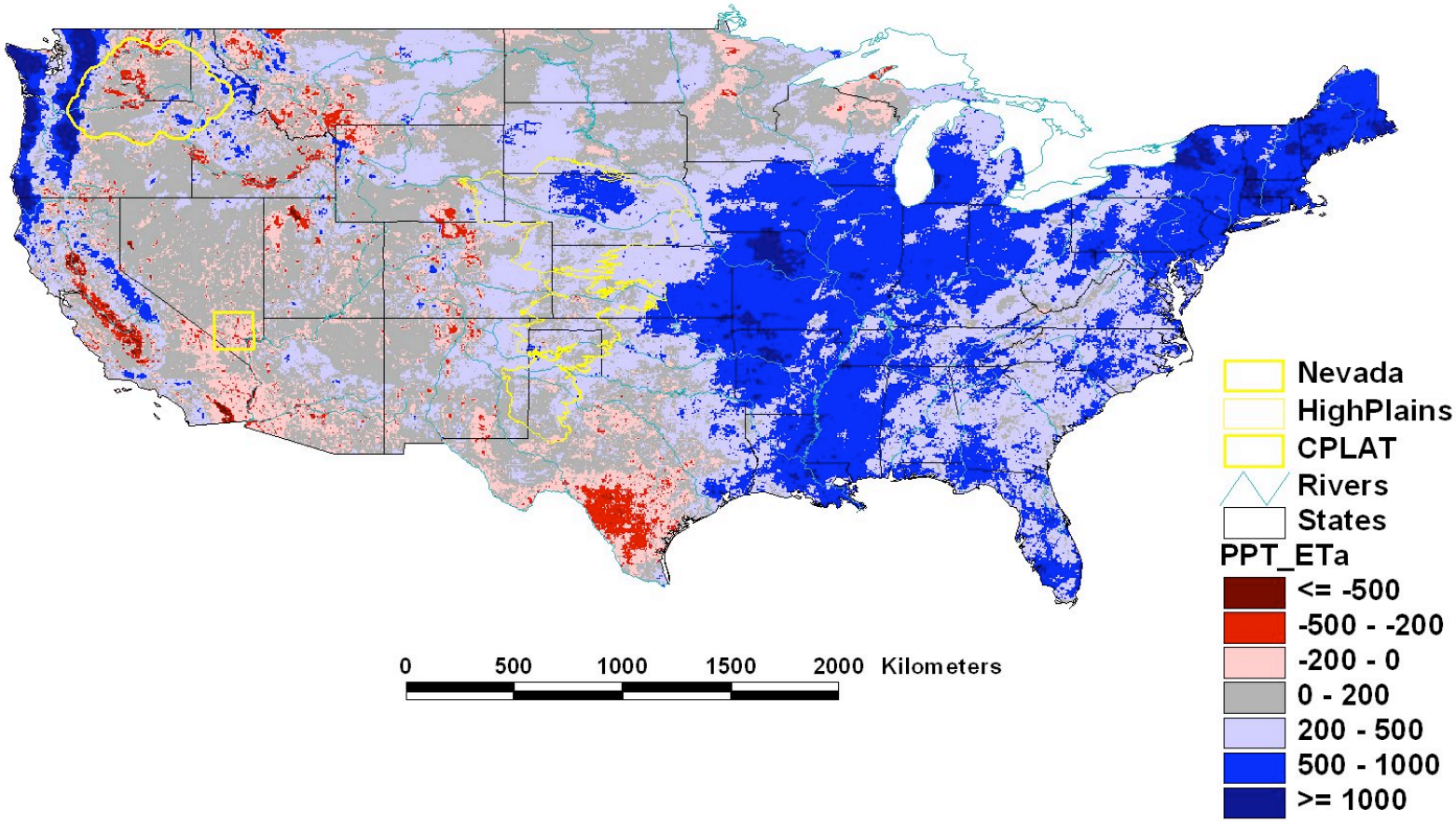
Annual Total Precipitation (mm) for 2008
(NOAA: NEXRAD-Station blend)



Spatial Resolution = 5-km

USGS

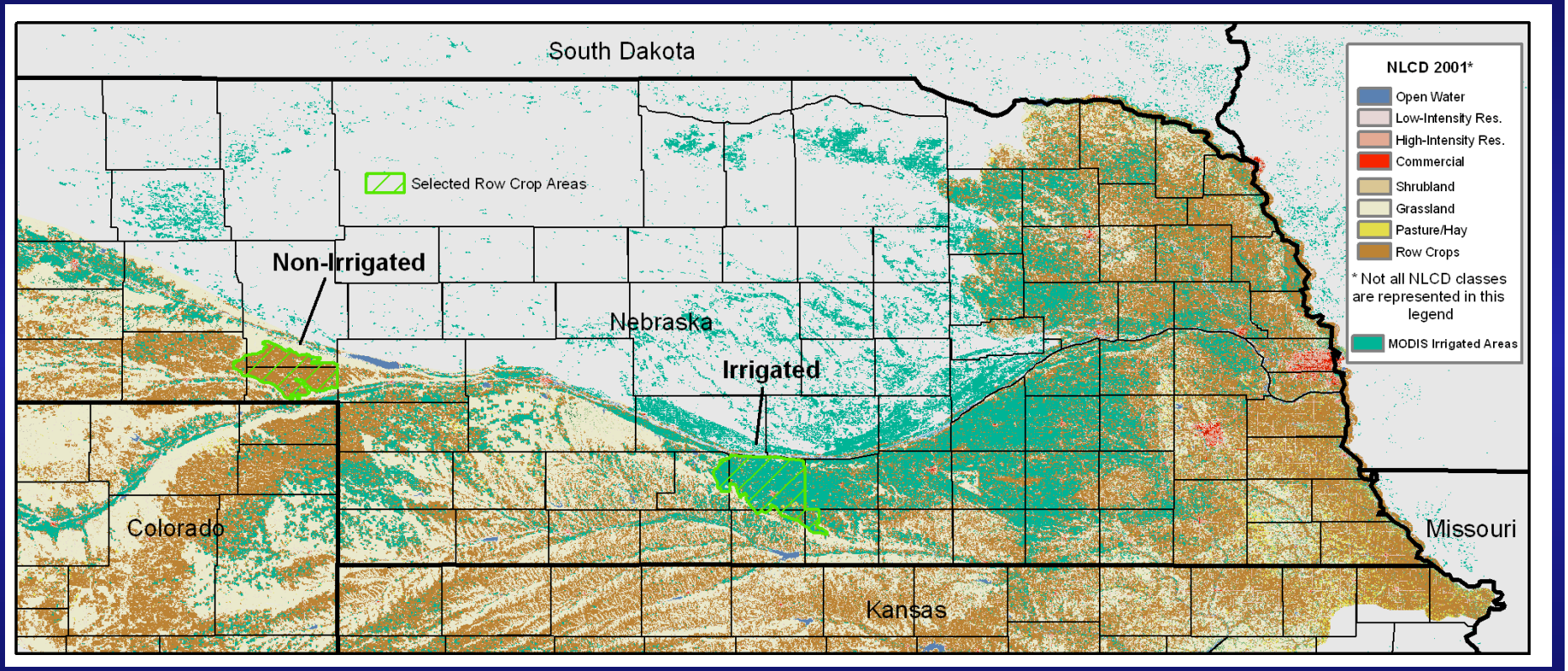
Seasonal Water Balance (mm) for 2008
(Pixel-based: Precipitation minus ETa; Preliminary Result)



Does the annual precipitation meet the peak water use demand?

USGS

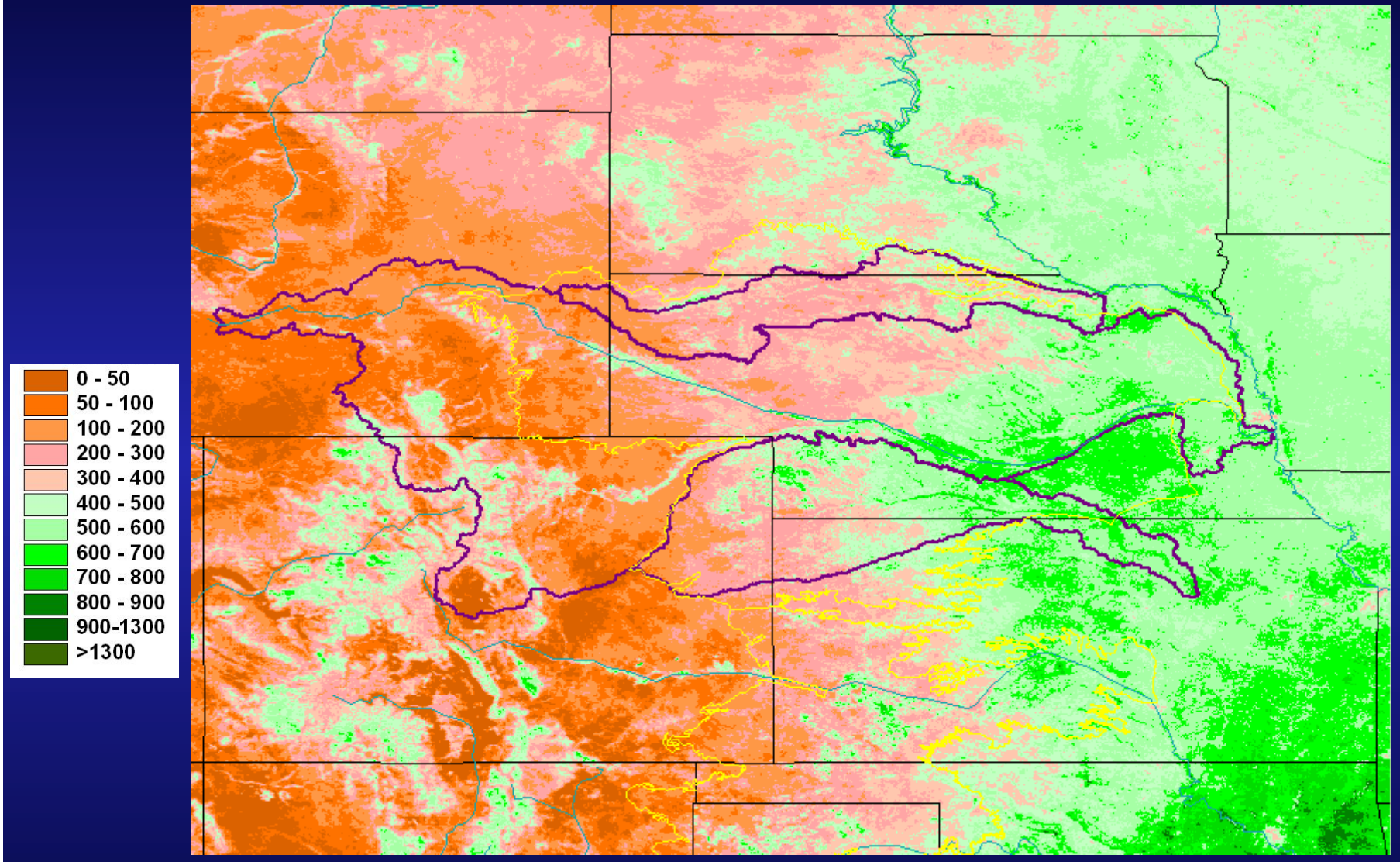
Identifying Irrigated vs Rainfed Areas (Nebraska)



Source: J. Brown, EROS

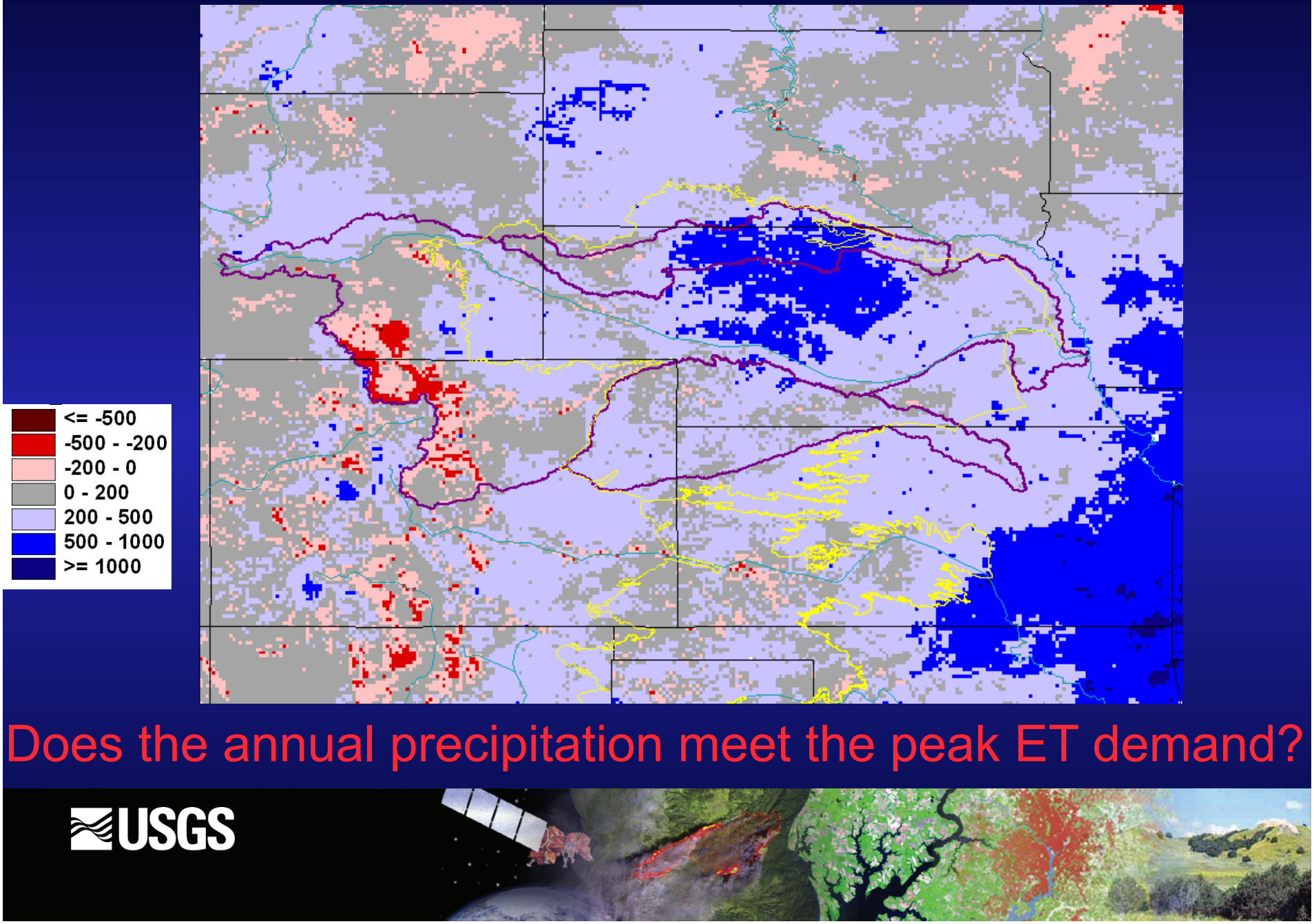
USGS

Regional Seasonal 2008 ETa (mm)



USGS

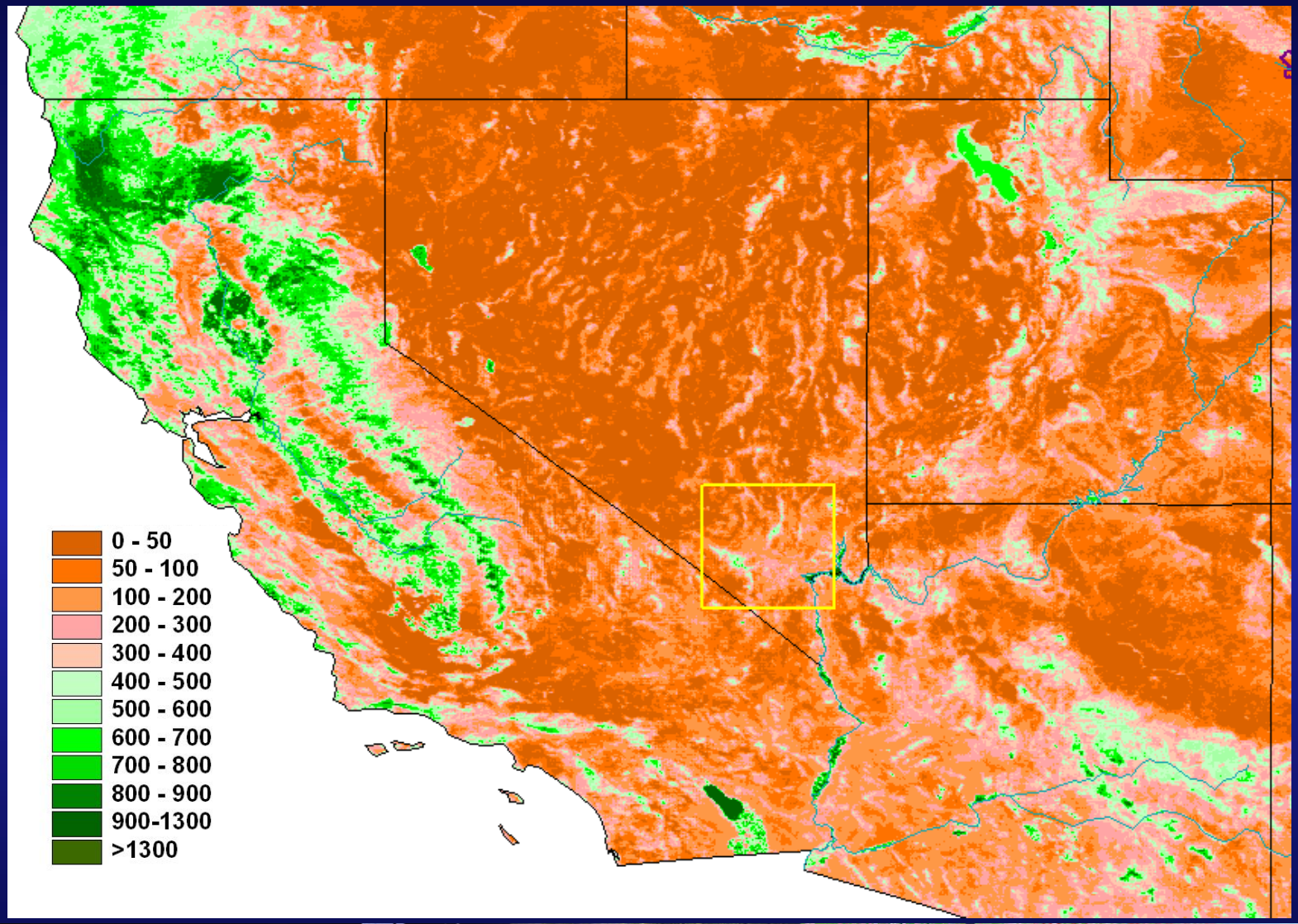
Regional Water Balance 2008 (PPT – ETa, mm)



Does the annual precipitation meet the peak ET demand?

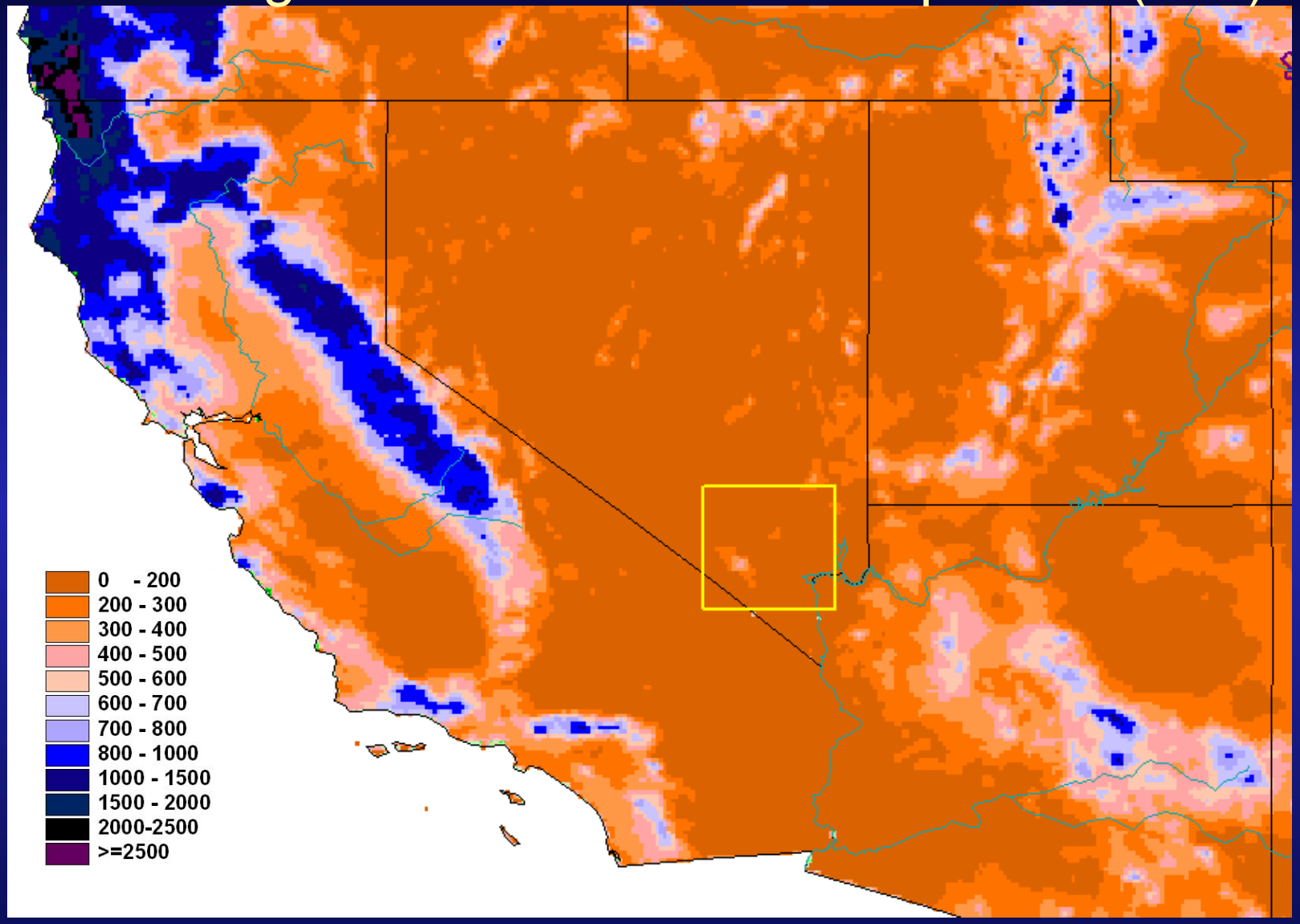
USGS

Regional Seasonal 2008 ETa (mm)



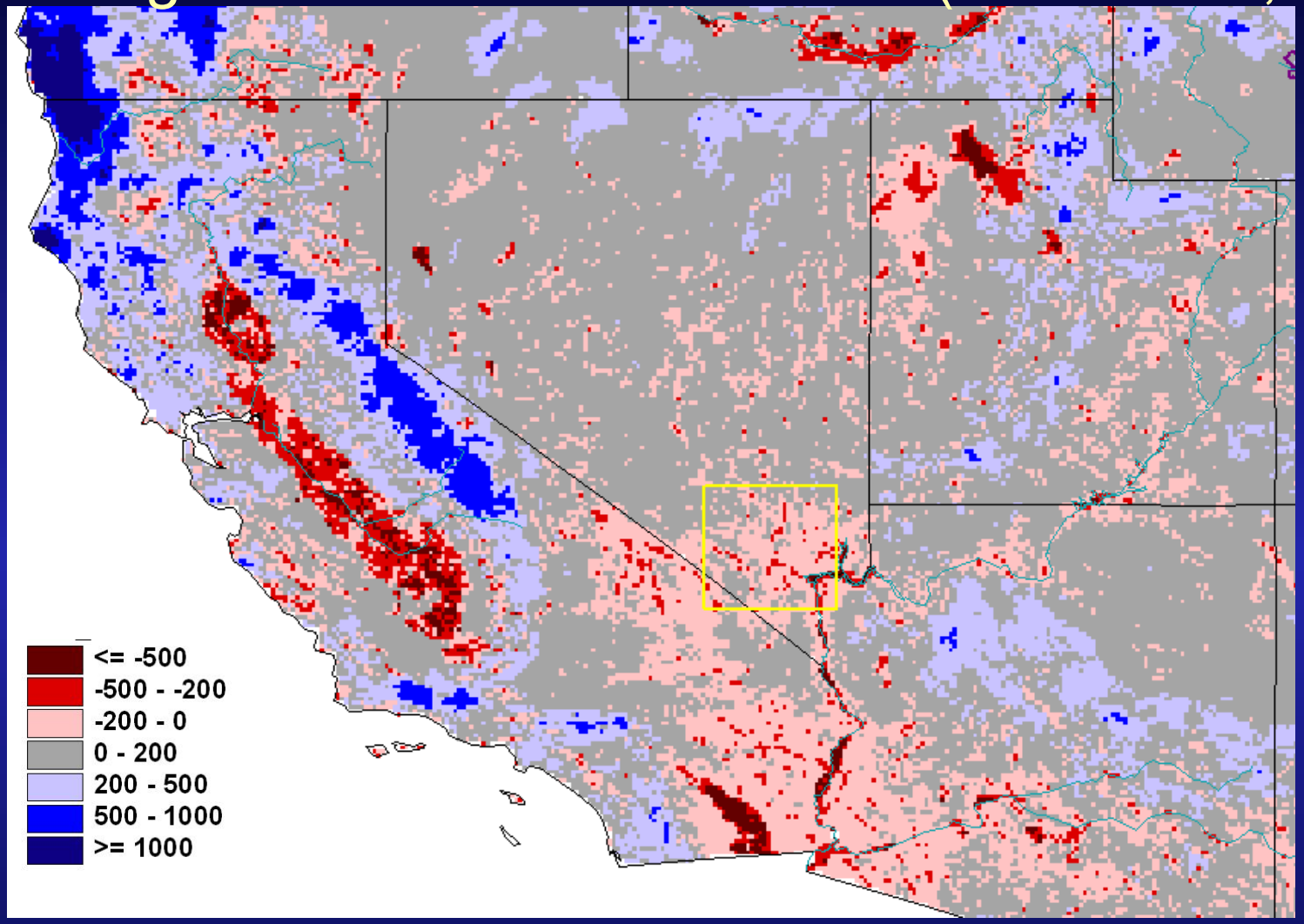
USGS

Regional Annual 2008 Precipitation (mm)



USGS

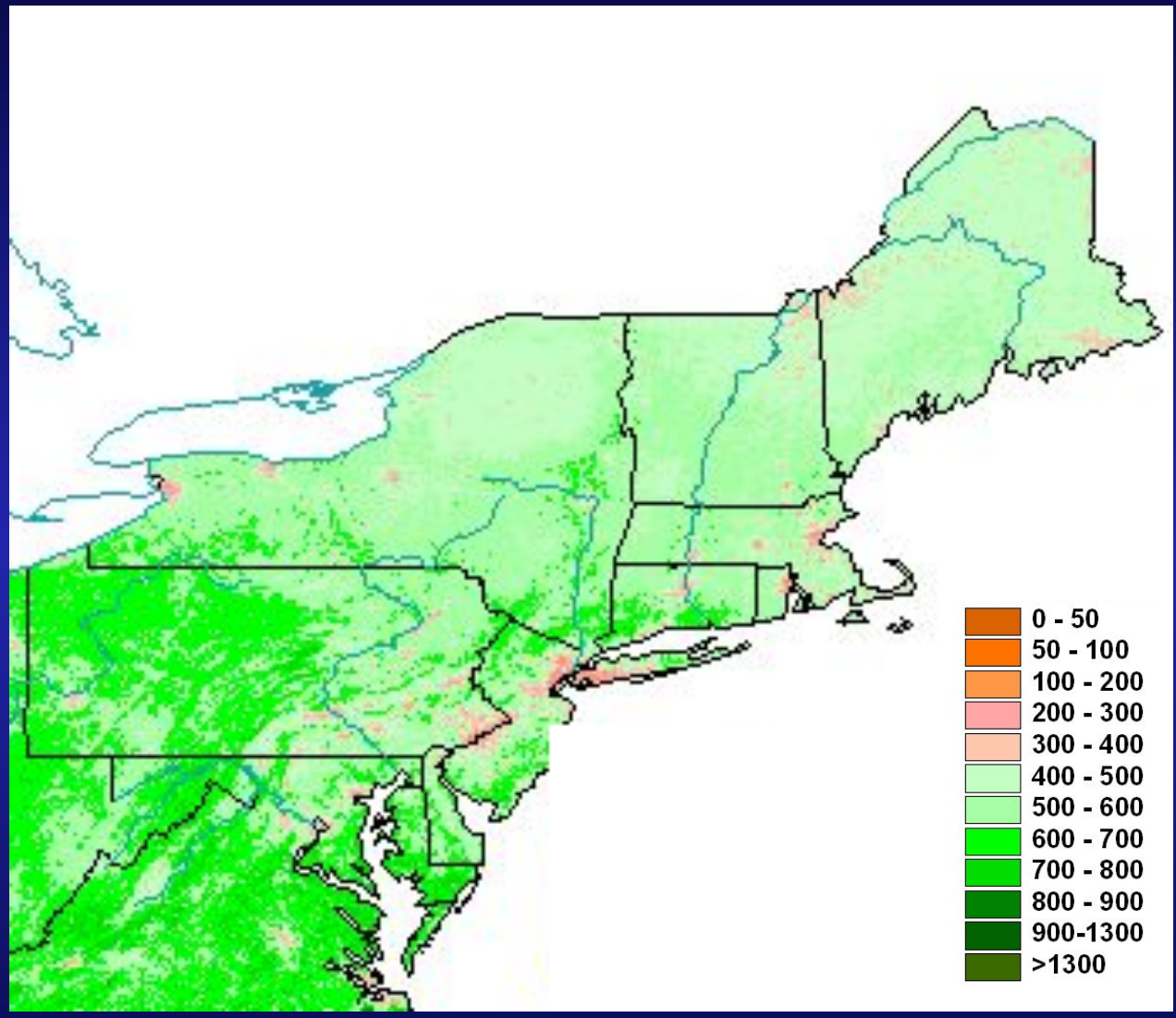
Regional Water Balance 2008 (PPT – ETa, mm)



Does the Annual Precipitation meet the peak ET demand?

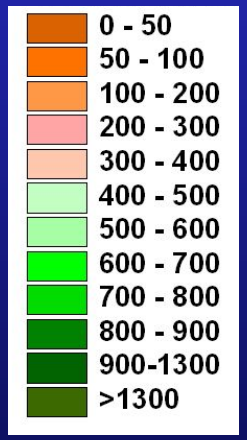
USGS

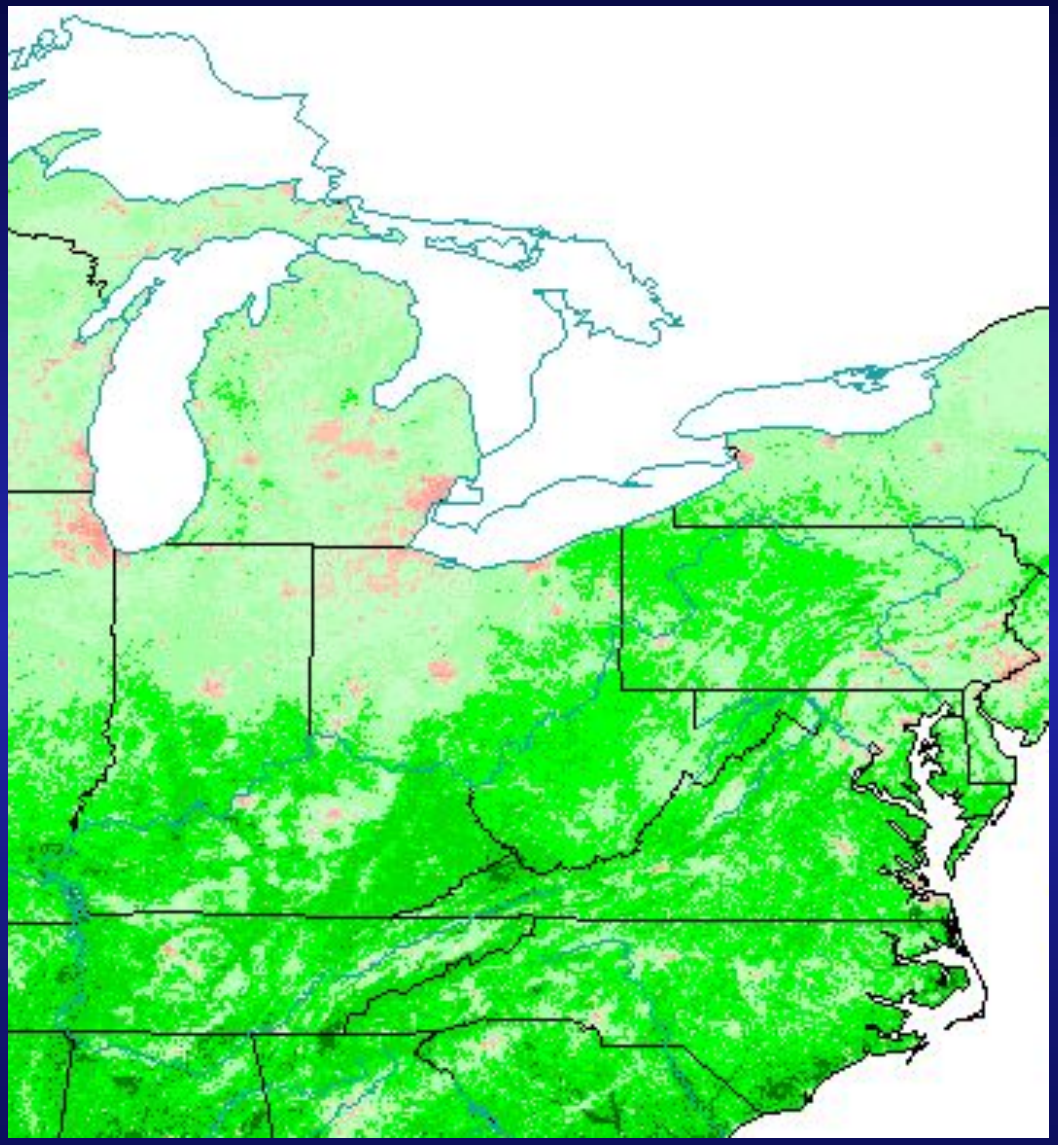
Regional Seasonal 2008 ETa (mm)



USGS

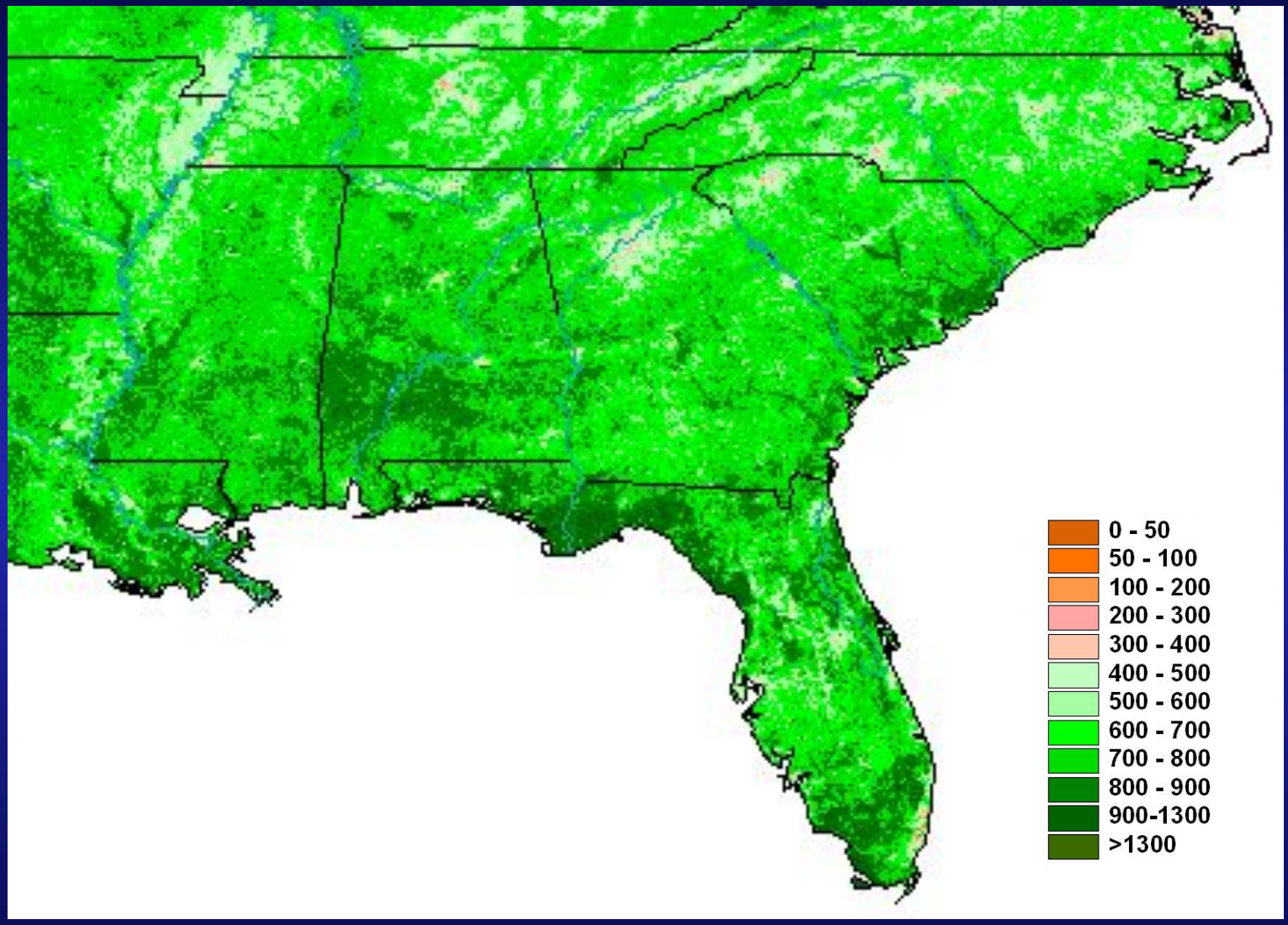
Regional Seasonal 2008 ETa (mm)





USGS

Regional Seasonal 2008 ETa (mm)



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Conclusion

- Successful monitoring of water use is possible
- Integrated application of both energy and water balance approaches for drought monitoring and hydrologic studies may provide insight on ET water sources
- Future Direction
  - More validation
  - Historical water use estimation
  - Basin-wide water balance estimation
  - Global application
  - Climate change scenario

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Thank You!

Operational Products

http://earlywarning.usgs.gov/usewem/swi.php