Mapping Evaporation and Moisture Stress from Space Using Thermal Remote Sensing

M.C. Anderson, W.P. Kustas
USDA-ARS, Hydrology and Remote Sensing Laboratory

J.M. Norman
U Wisconsin-Madison

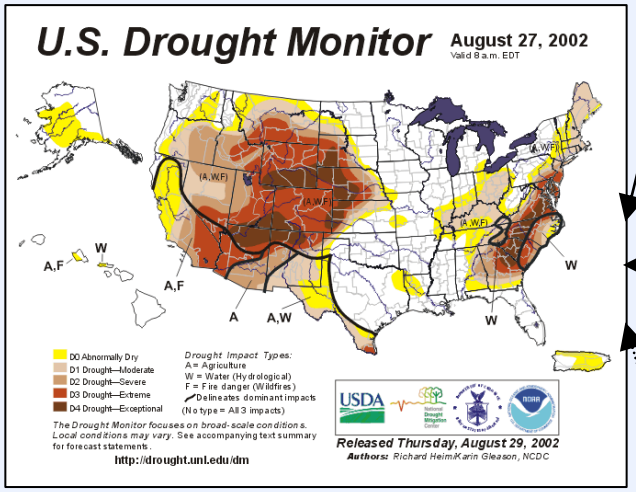
OBJECTIVE

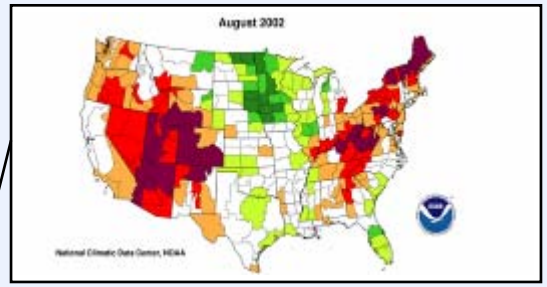
Map ET and moisture stress (drought) using thermal infrared (TIR) and vegetation index (VI) remote sensing data.

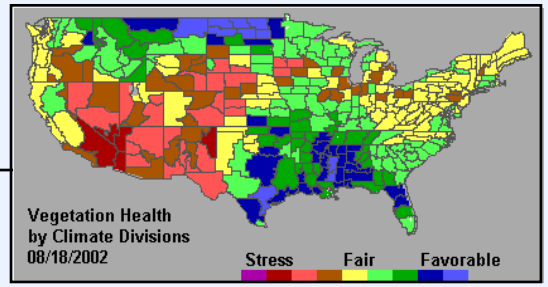
Varying soil moisture conditions yield distinctive thermal signatures:

- depletion of water from the **soil surface** layer causes the soil component of the scene to heat up rapidly.
- moisture deficiencies in the **root zone** lead to vegetation stress and elevated canopy temperatures

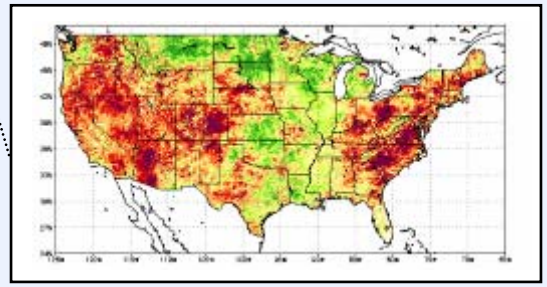
Operational Drought Monitoring







?



Palmer Drought Index

Antecedent precipitation

Vegetation Health Index

$$VCI = \frac{NDVI - NDVI_{min}}{NDVI_{max} - NDVI_{min}}$$

$$TCI = \frac{T_{max} - T}{T_{max} - T_{min}}$$

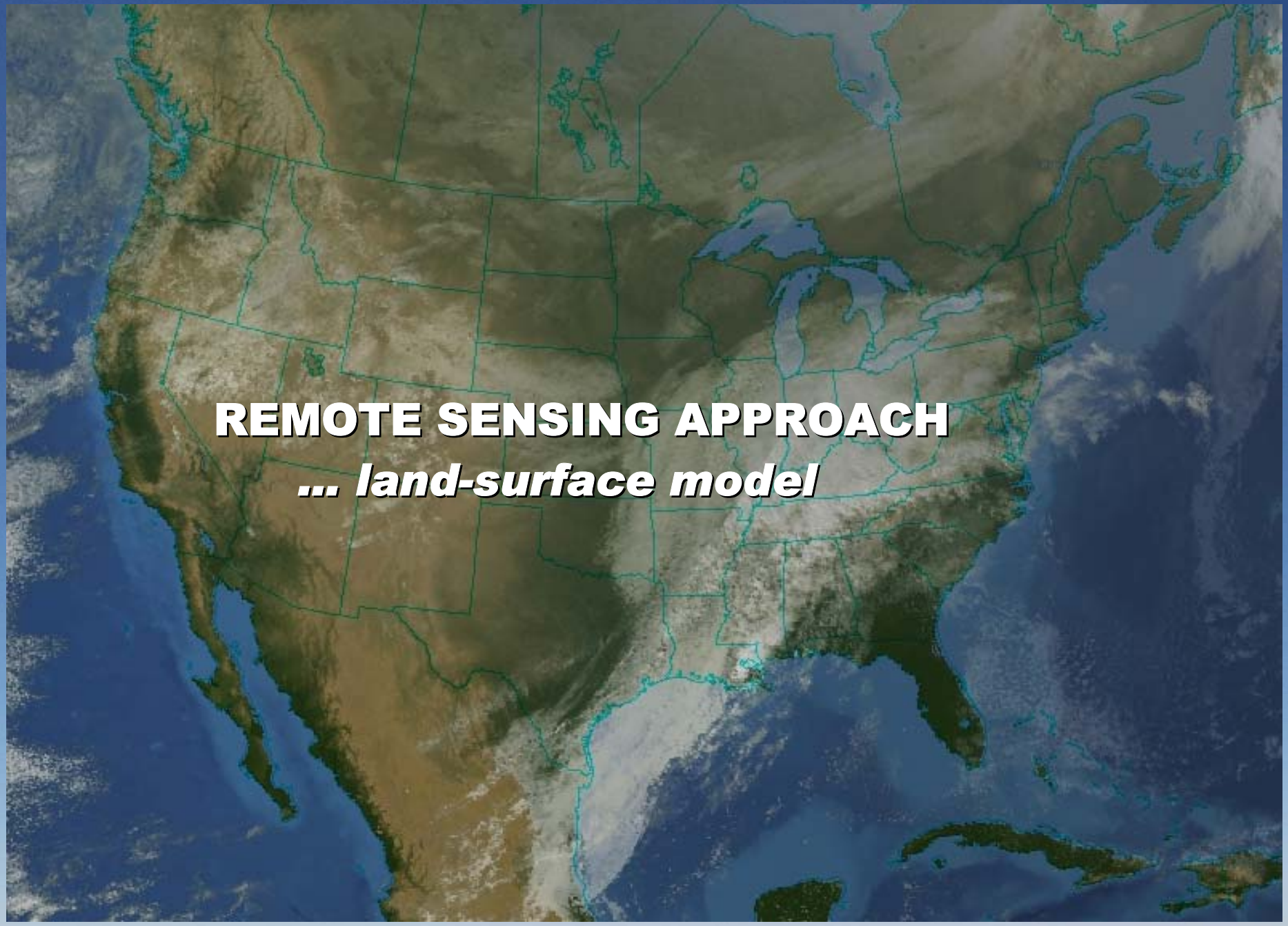
$$VHI = aVCI + (1-a)TCI$$

Evaporative Stress Index

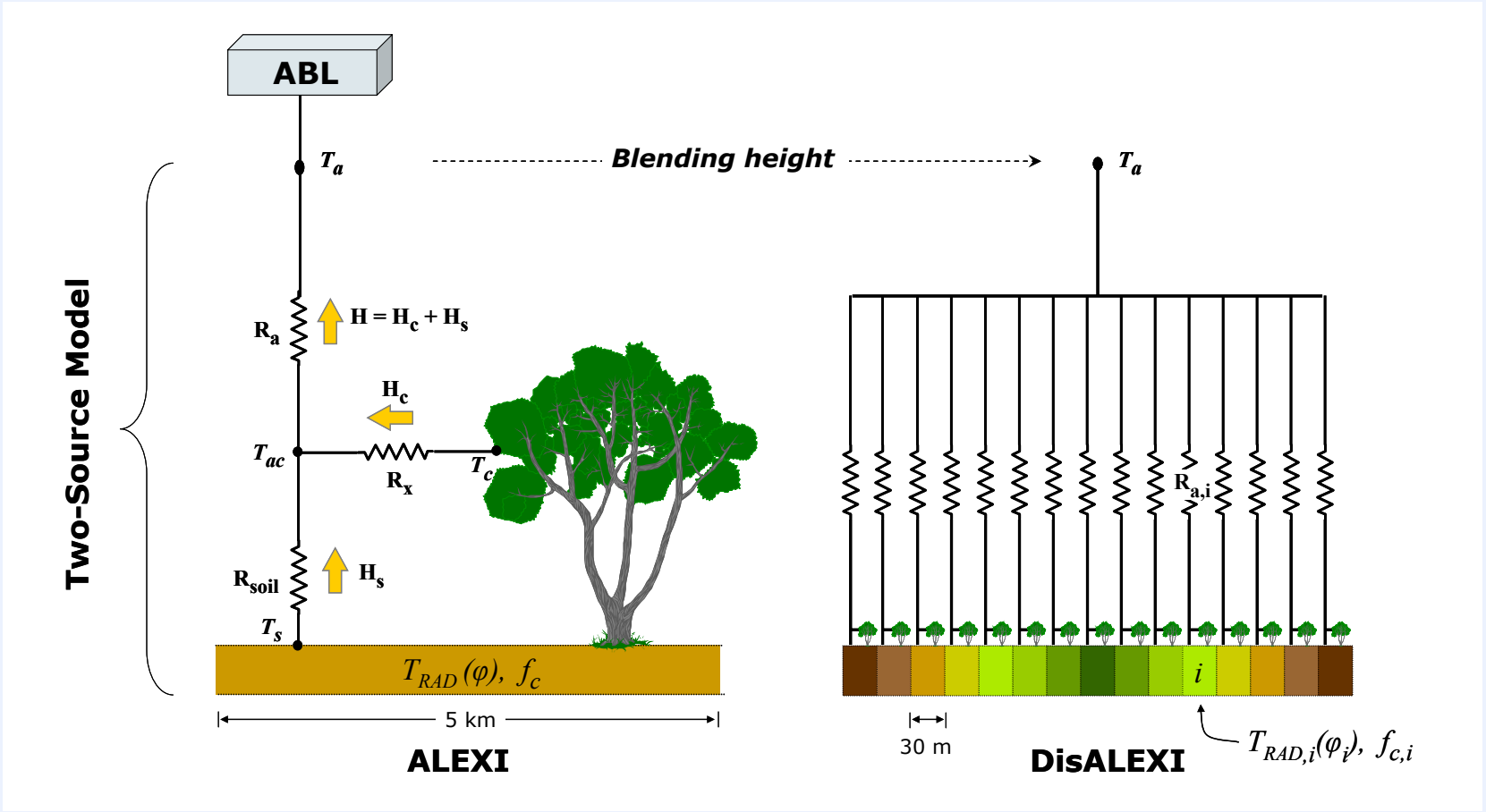
$$ESI = 1 - AET/PET$$

OUTLINE

- **REMOTE SENSING APPROACH**
  - *... land-surface model*
  - *... validation*
- **FLUX CLIMATOLOGY**
  - *... evaporative stress index*
- **NEED FOR HIGH-RES THERMAL**
  - *... impending data gap*


REMOTE SENSING APPROACH
... land-surface model

Atmosphere-Land Exchange Inverse Model (ALEXI)



Regional scale

ΔT_{RAD} - GOES

f_c - AVHRR, MODIS

Landscape scale

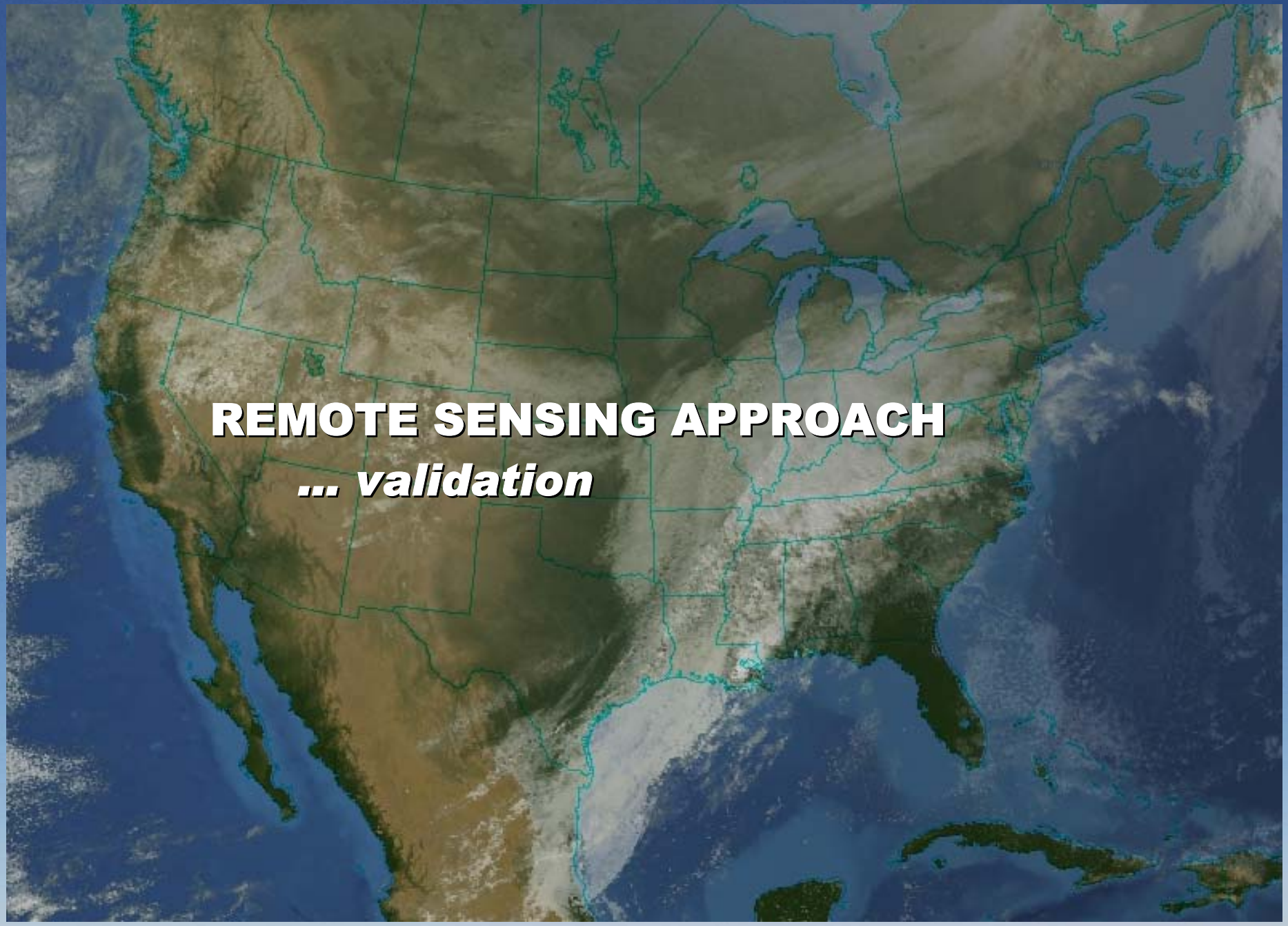
T_{RAD} - TM, ASTER, MODIS

f_c - TM, ASTER, MODIS

Input data requirements

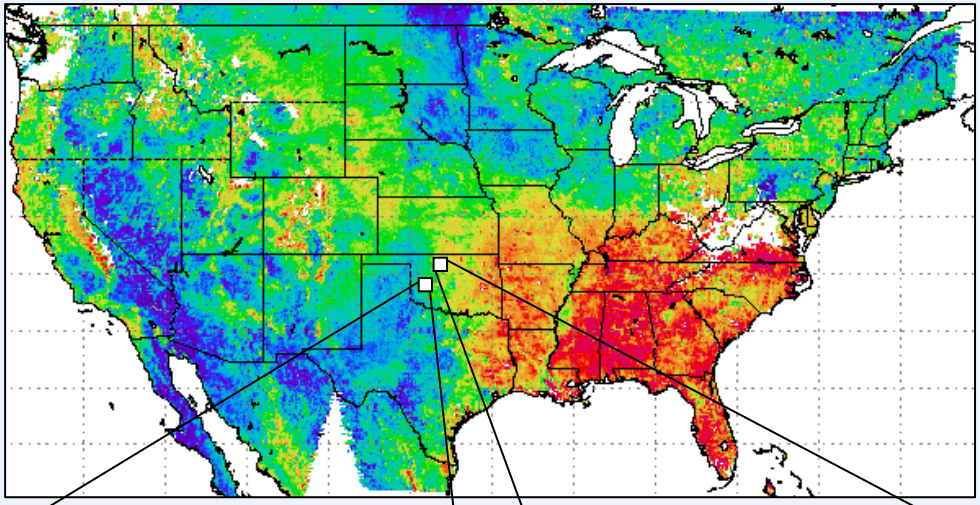
DATA	ALEXI	DisALEXI
THERMAL IR	GOES (5-10km)	TM/ASTER/air (1-90m)
LAI - COVER FRACTION	AVHRR/MODIS (1km)	TM/ASTER/air (1-90m)
LANDCOVER TYPE	AVHRR/MODIS (1km)	TM/ASTER/air (1-90m)
WINDSPEED	Synoptic wx network	Synoptic wx network
SW/LW RADIATION	GOES (20km)	GOES (20km)
AIR TEMPERATURE BOUNDARY	Radiosonde network	ALEXI (5-10km)

SURFACE TEMPERATURE
EVAPOTRANSPIRATION
ALEXI
(GOES Sounder)
Continental
ALEXI
(GOES Imager)
Regional
DisALEXI
(Landsat)
Watershed
DisALEXI
(USU aircraft)
Field scale
CORN
SOY
45
40
35
30
600
500
400
300
200
100
0

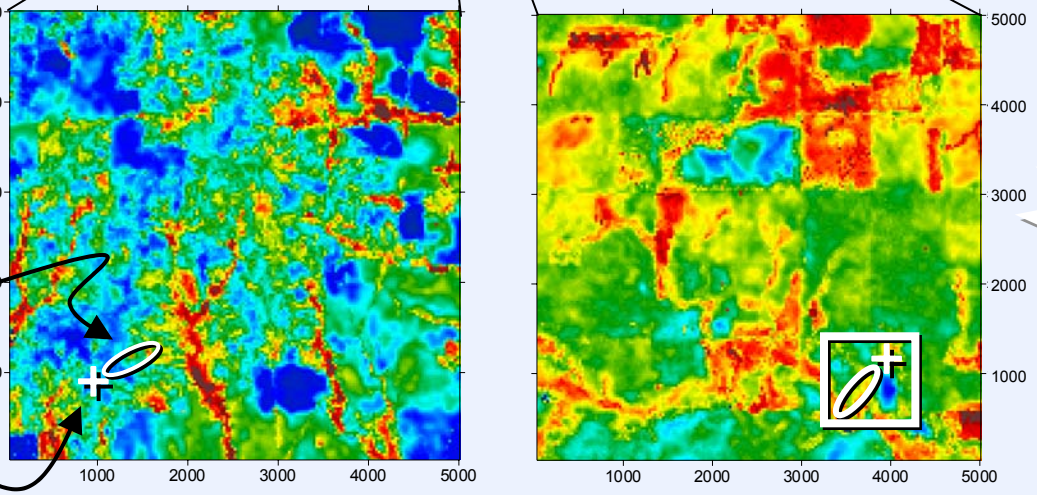

REMOTE SENSING APPROACH
... validation

Validation through disaggregation

GOES-DERIVED FLUXES (5-10 km)

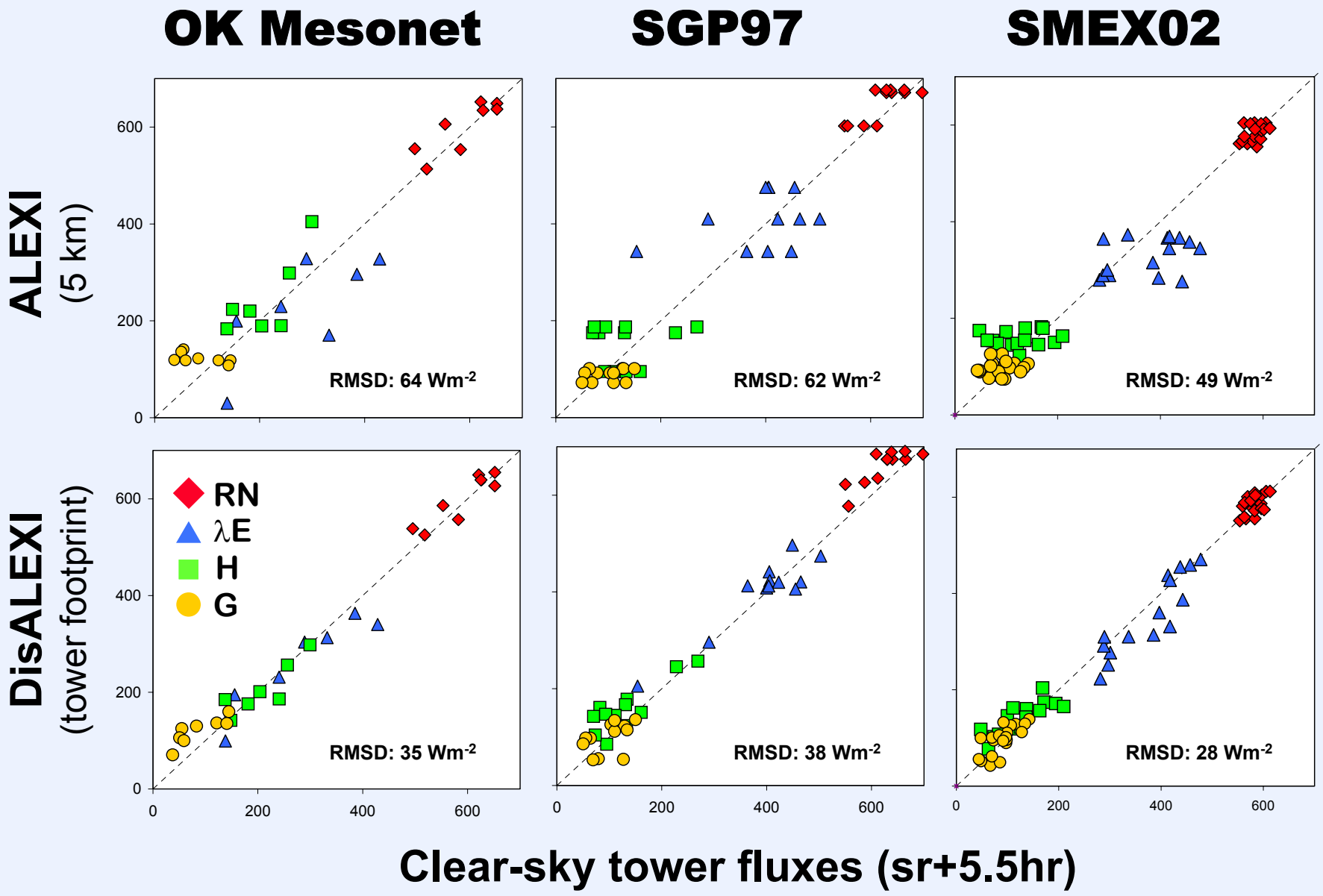


ALEXI

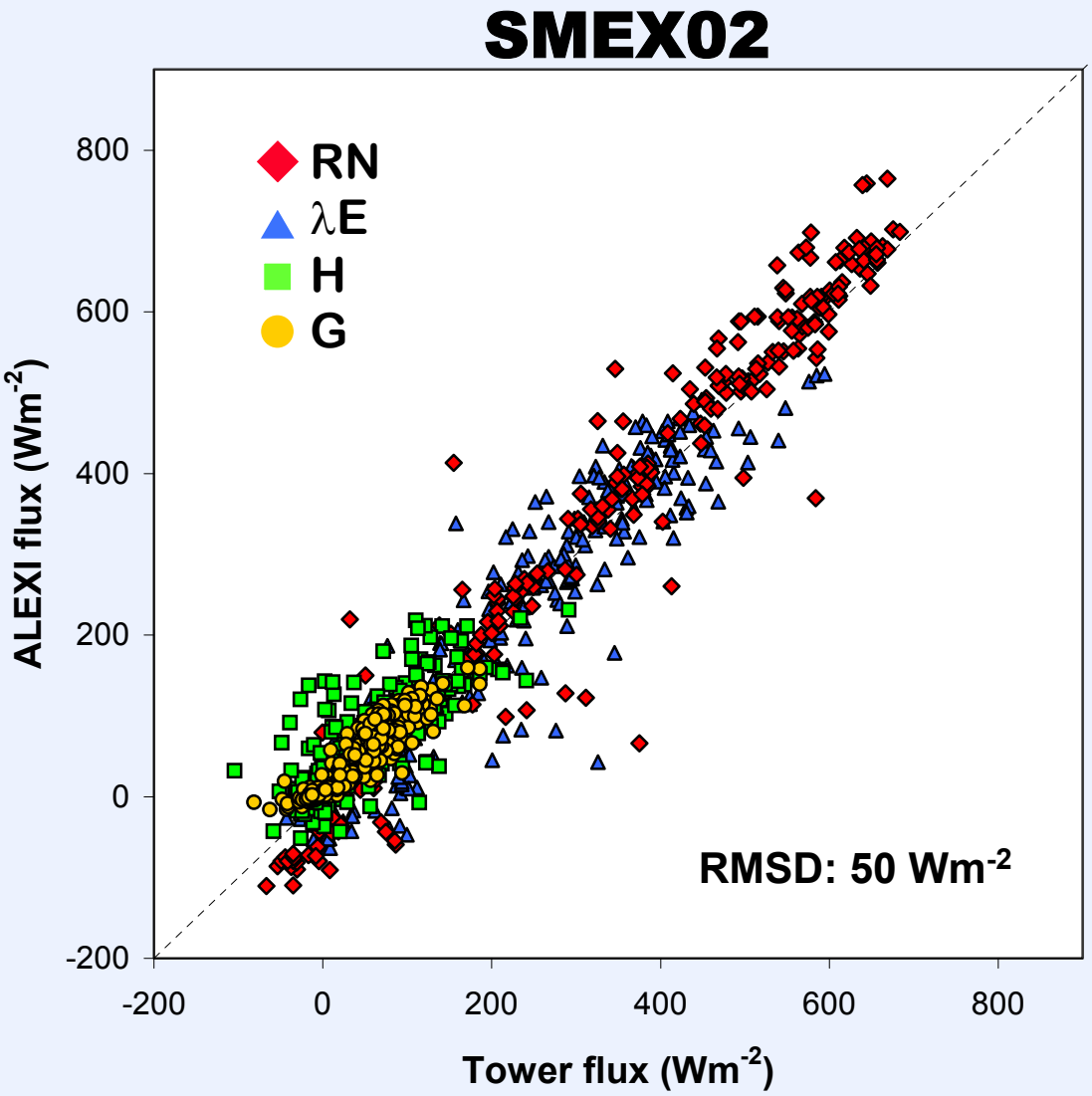


DisALEXI

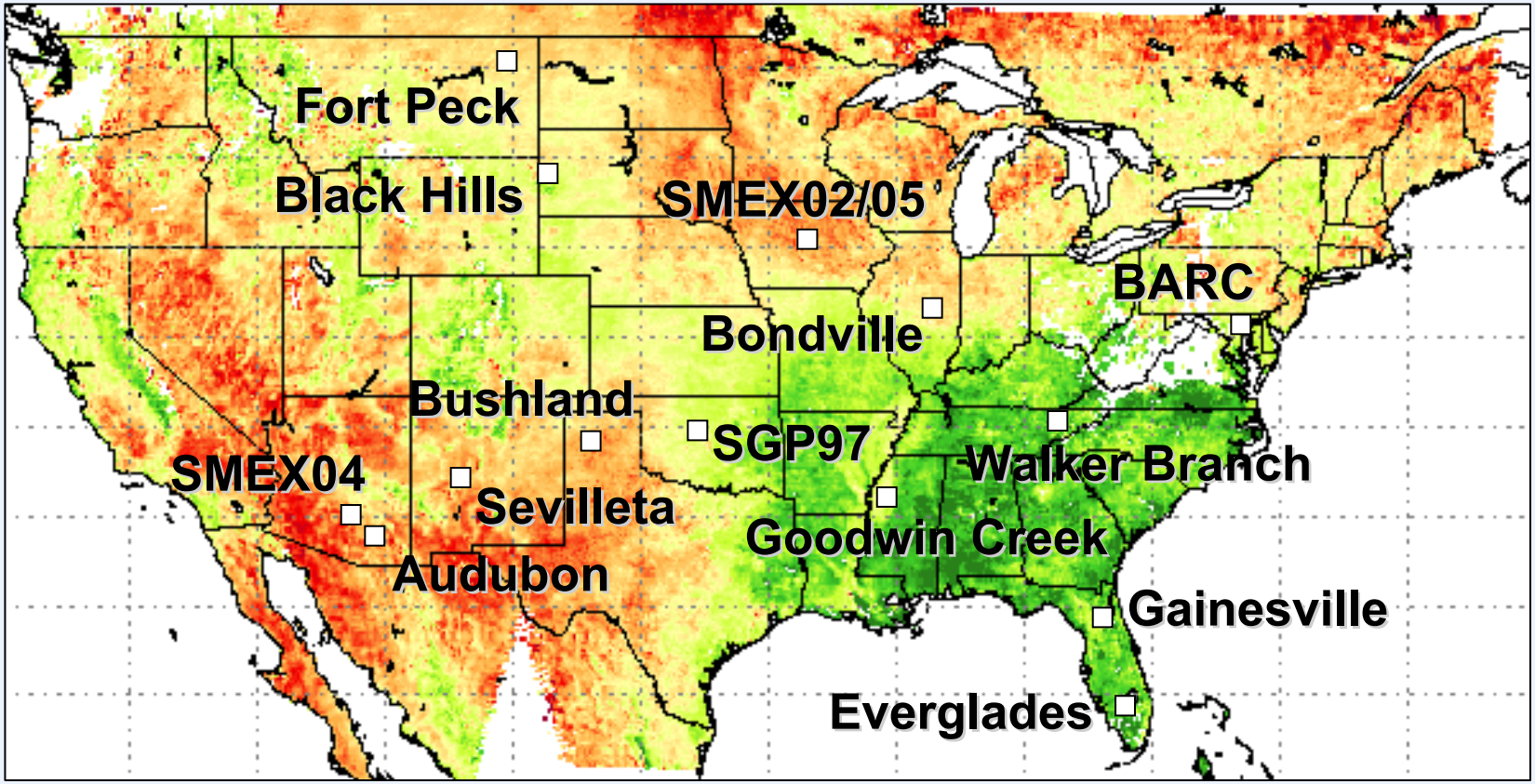
LANDSAT-DISAGGREGATED FLUXES

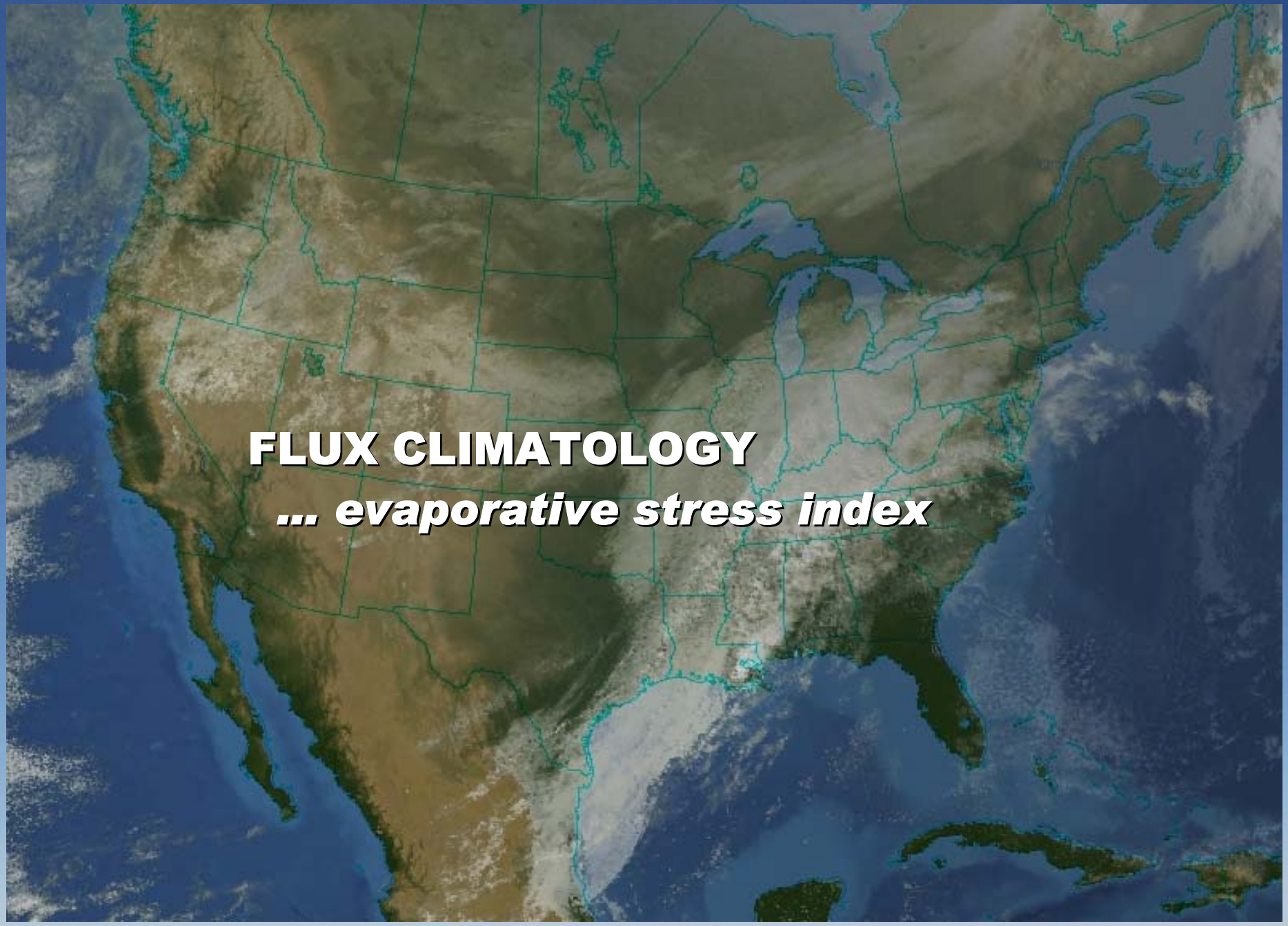

OK Mesonet
SGP97
SMEX02
ALEXI
(5 km)
DisALEXI
(tower footprint)
RN
λE
H
G
RMSD: 64 Wm-2
RMSD: 62 Wm-2
RMSD: 49 Wm-2
RMSD: 35 Wm-2
RMSD: 38 Wm-2
RMSD: 28 Wm-2
0
200
400
600
Clear-sky tower fluxes (sr+5.5hr)

Hourly daytime fluxes (watershed average)

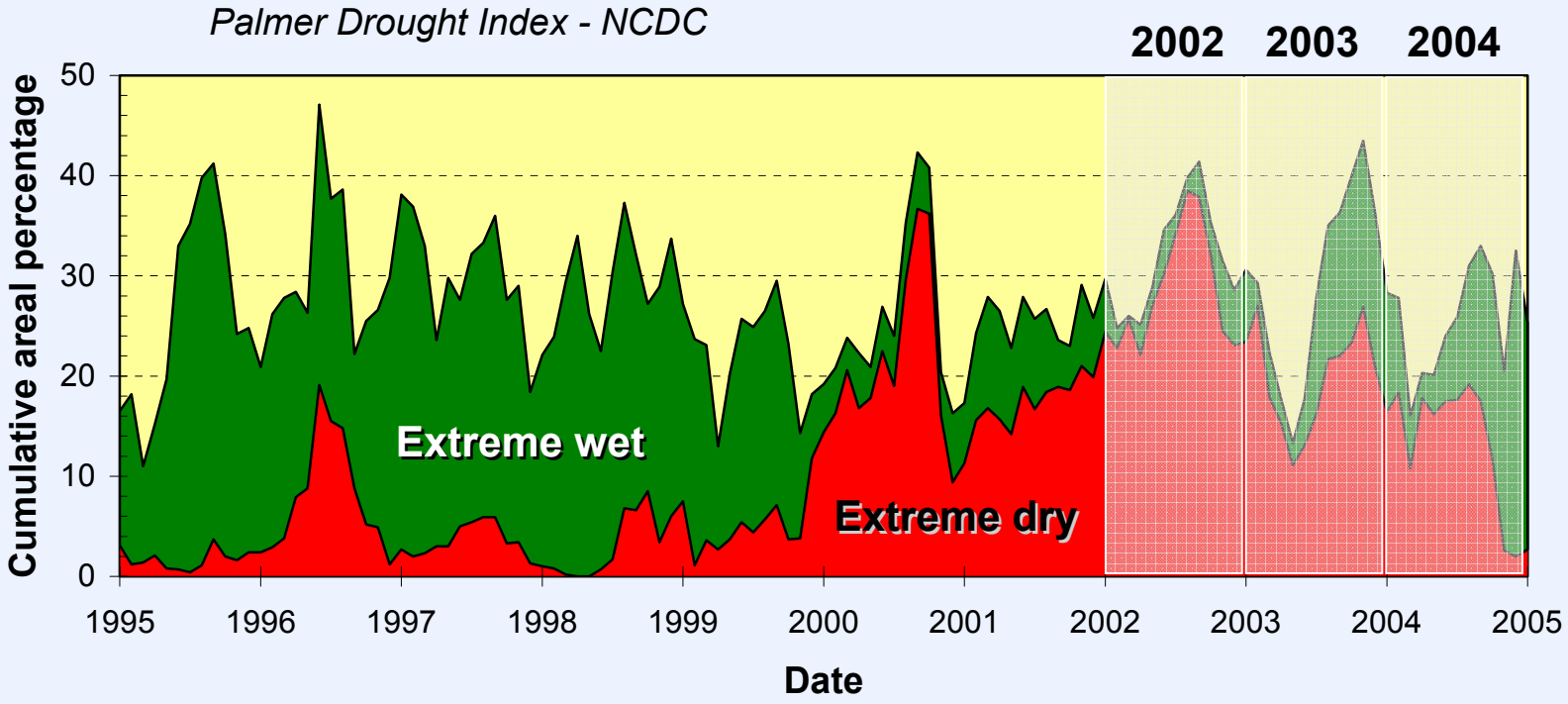


ALEXI validation sites



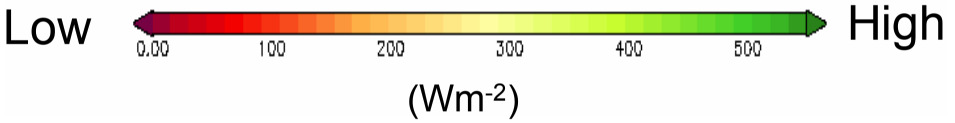

FLUX CLIMATOLOGY
... evaporative stress index

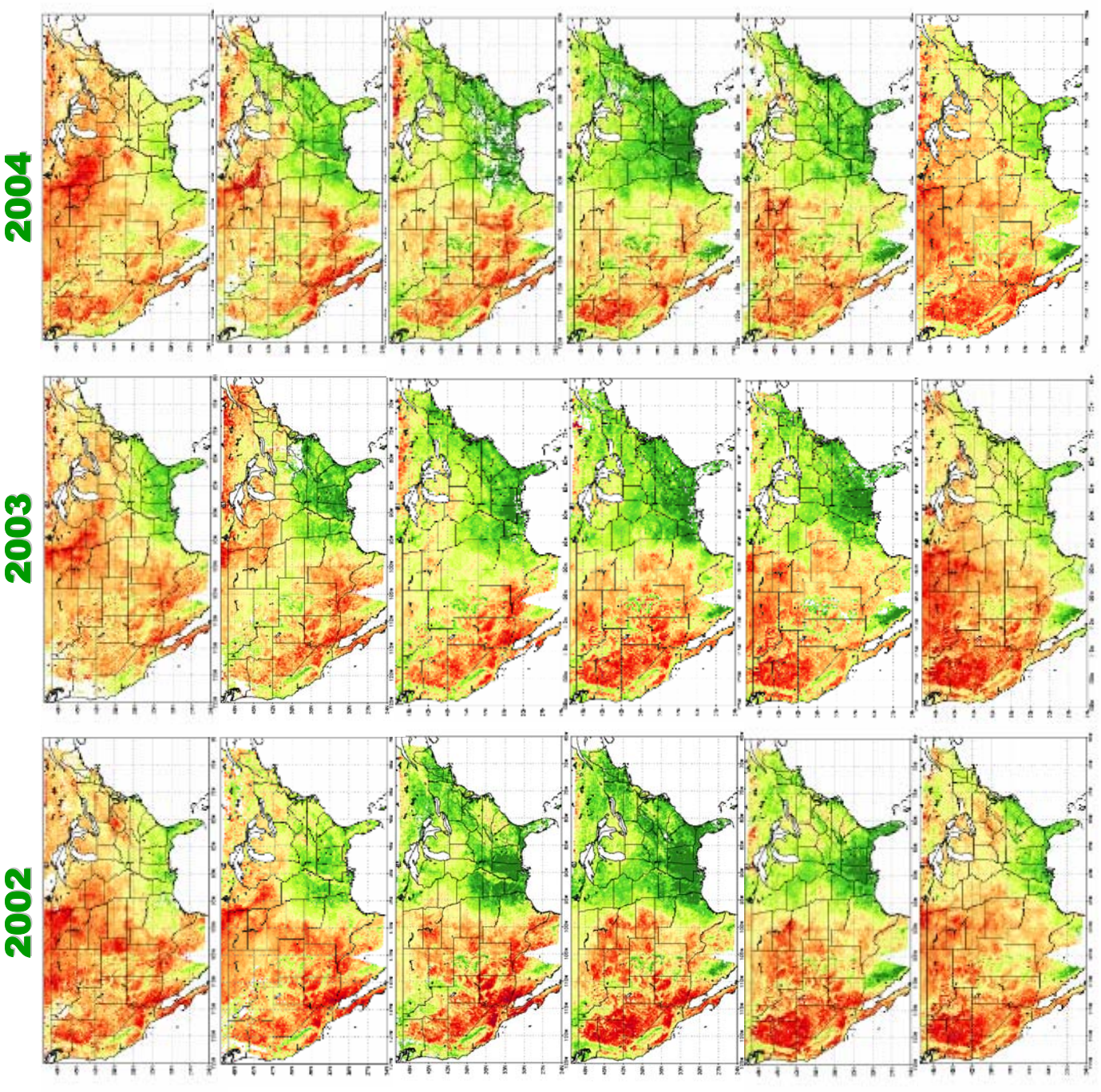
Climatological Study: 2002-2004

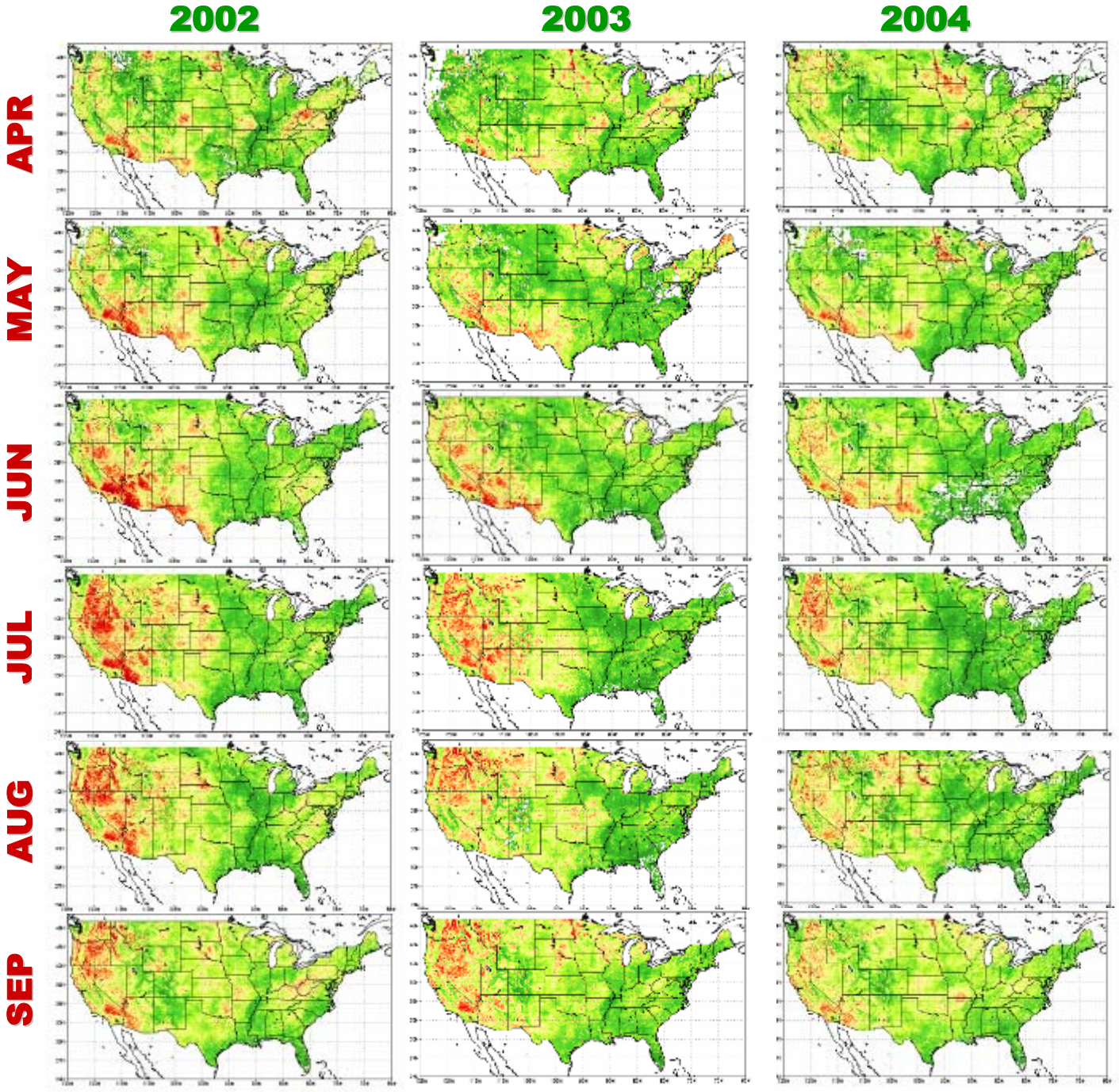


- **2002**: extreme-severe drought conditions covering 40% of the US in July
- **2003**: some improvement (10-25% extreme-severe drought coverage)
- **2004**: extreme drought coverage falls < 5% due to increased late rainfall

EVAPOTRANSPIRATION





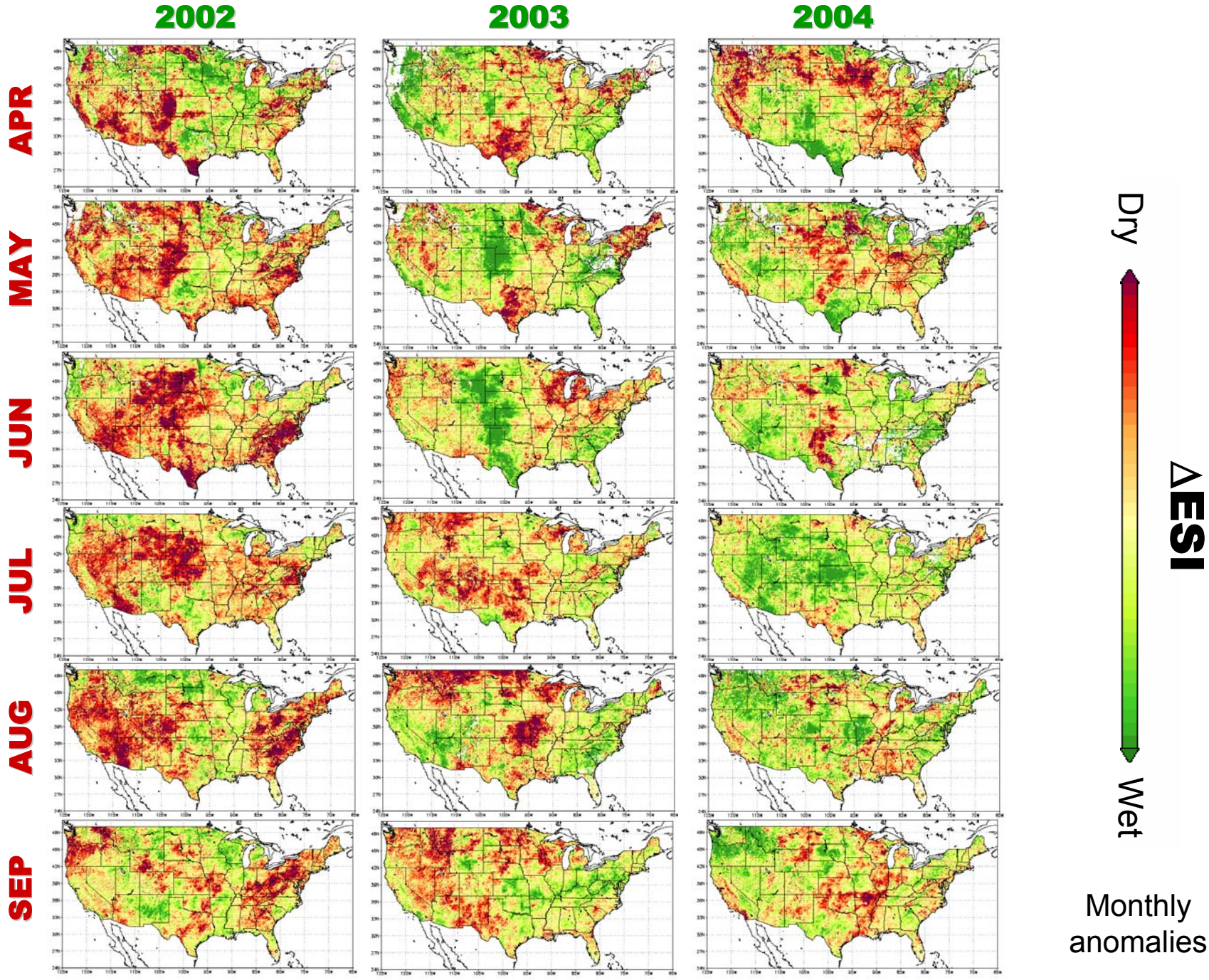


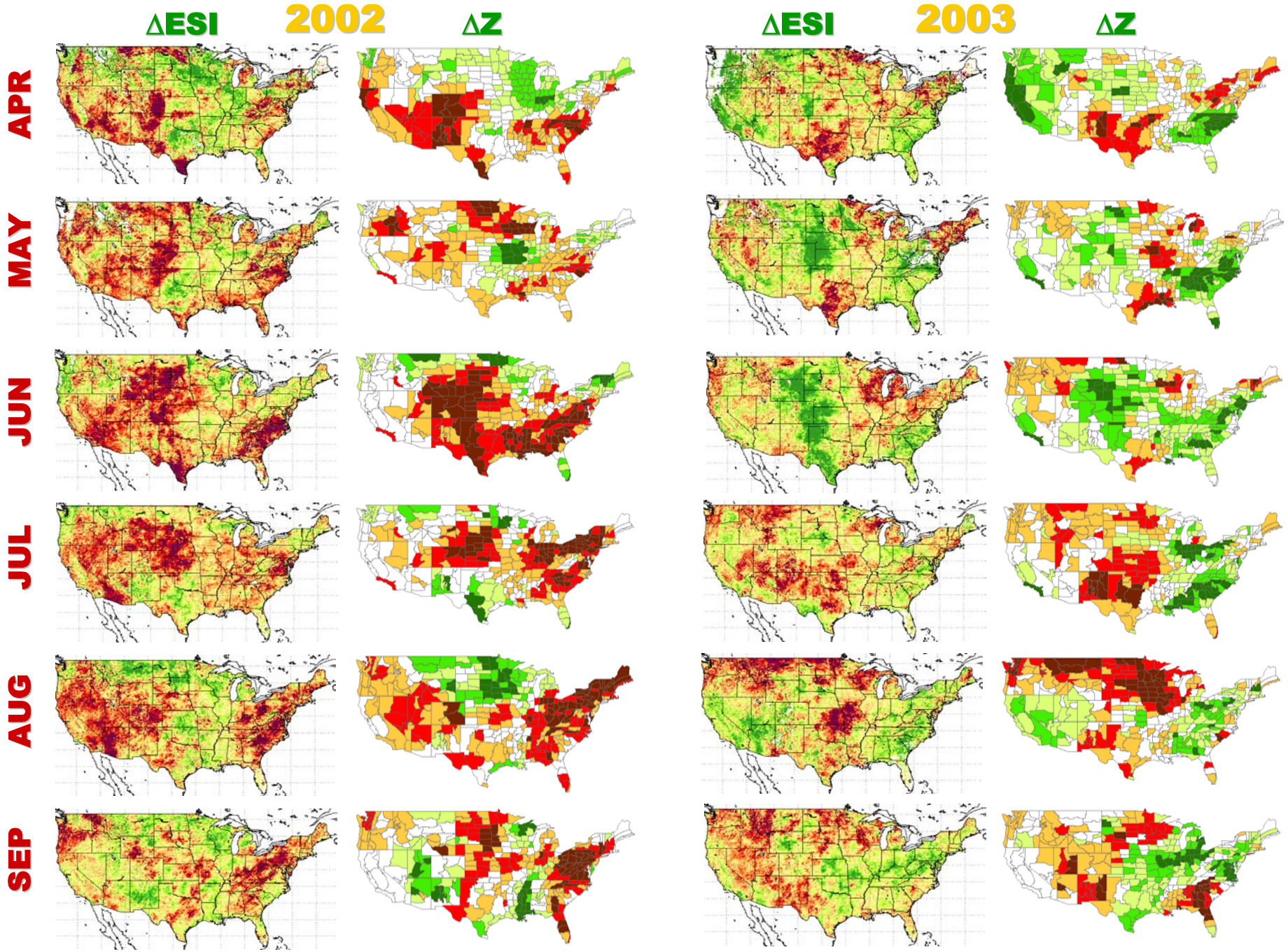
Evaporative Stress Index

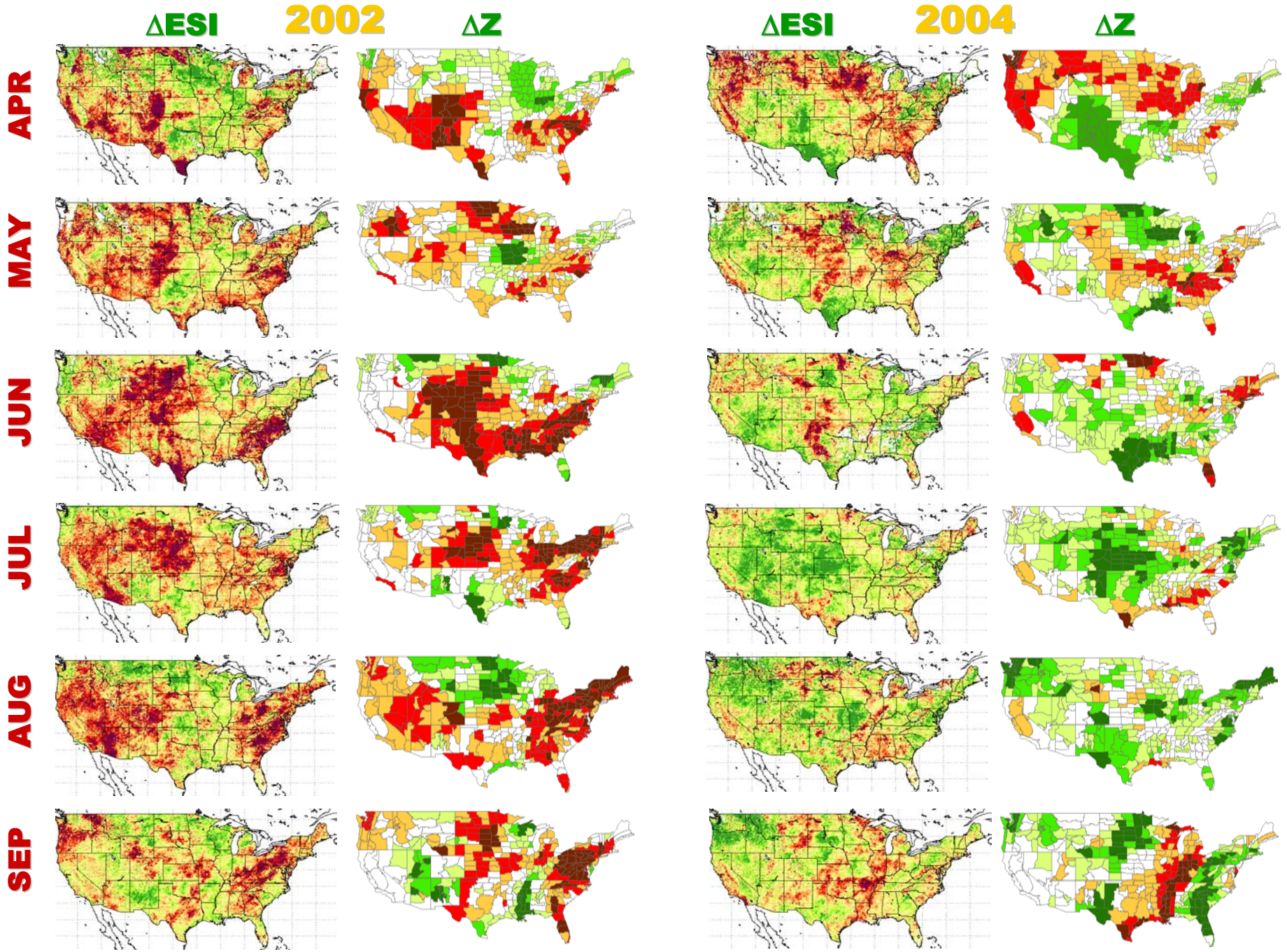
Dry

Wet

$$ESI = 1 - \frac{AET}{PET}$$


2002
2003
2004
APR
MAY
JUN
JUL
AUG
SEP
Dry
Wet
ΔESI
Monthly anomalies


ΔESI
2002
ΔZ
ΔESI
2003
ΔZ
APR
MAY
JUN
JUL
AUG
SEP


ΔESI
2002
ΔZ
ΔESI
2004
ΔZ
APR
MAY
JUN
JUL
AUG
SEP

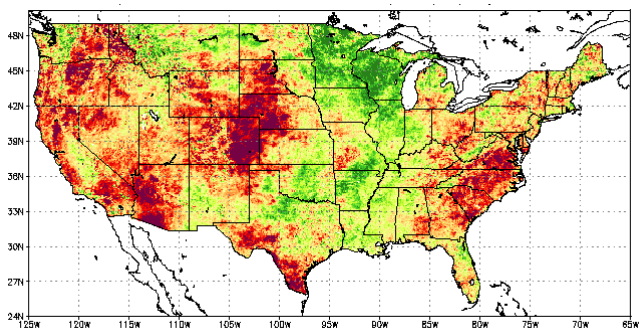
ALEXI

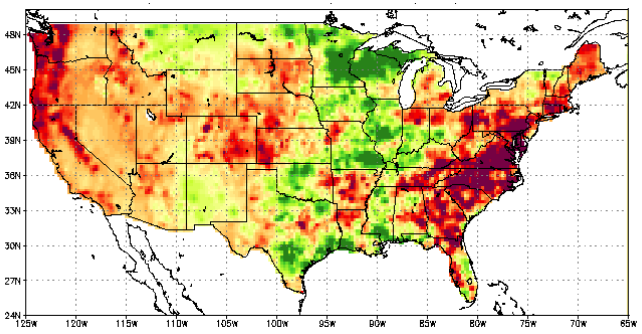
Precipitation

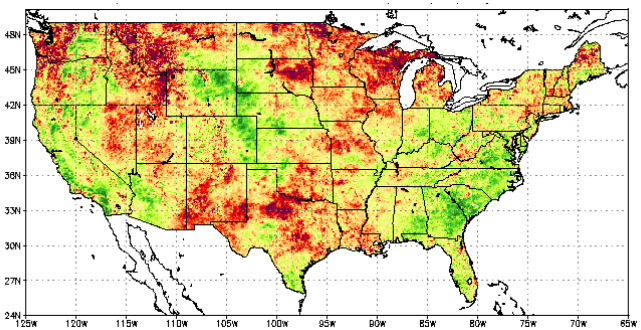
2002

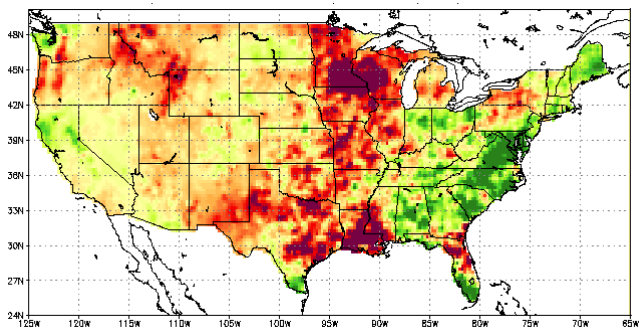
2003

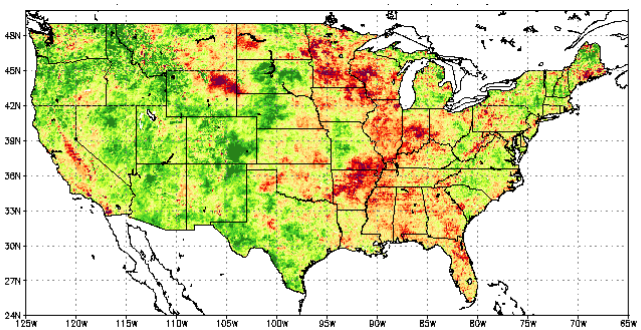
2004

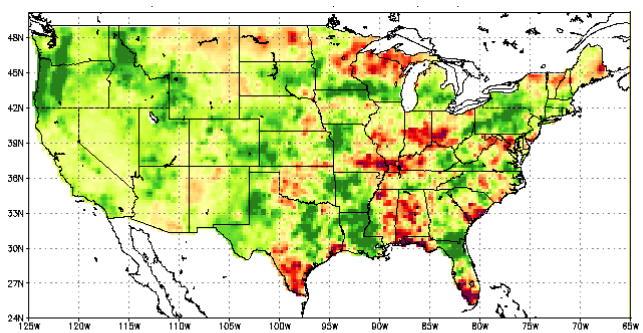












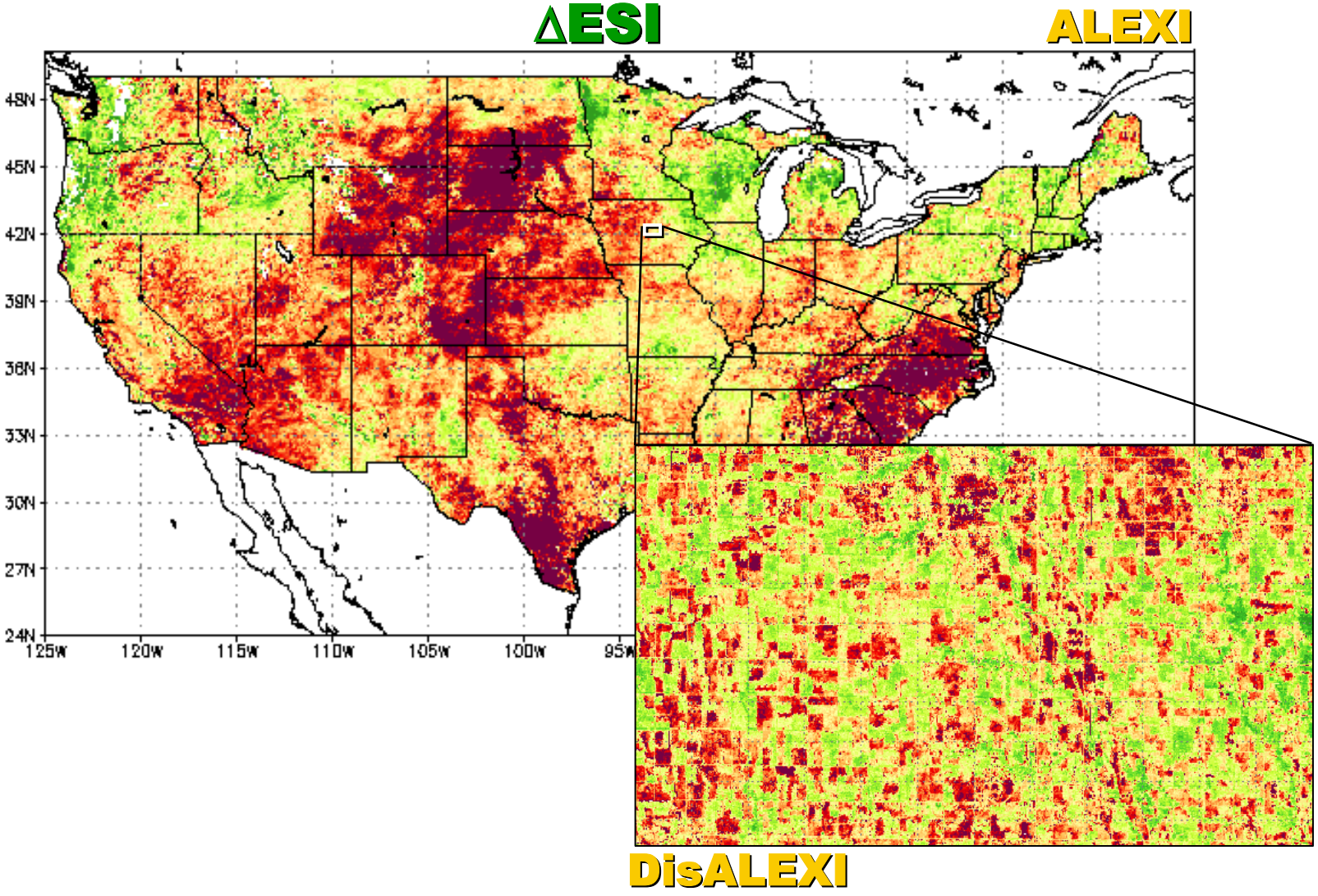
Dry — Wet

ESI anomaly

−20.00 −15 −10 −5 0 5 10 15 20

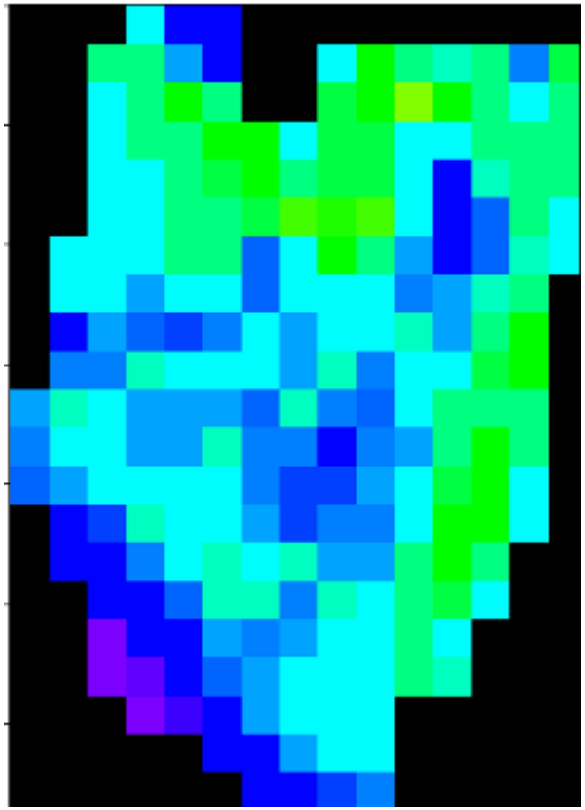
Precipitation anomaly (mm)

Multi-scale Drought Monitoring



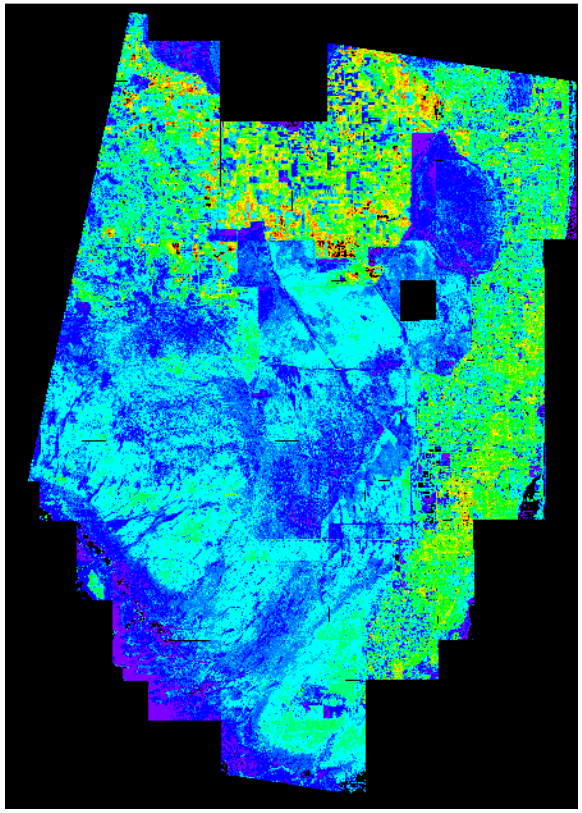
Multi-scale Ecosystem Health Monitoring

MODIS resolution (1km)
Evapotranspiration



(weekly)

L7 resolution (60m)
Evapotranspiration



(monthly)

L7 resolution (60m)
ESI

(monthly)

Florida Everglades


NEED FOR HIGH RESOLUTION
THERMAL IMAGING
... Impending data gap

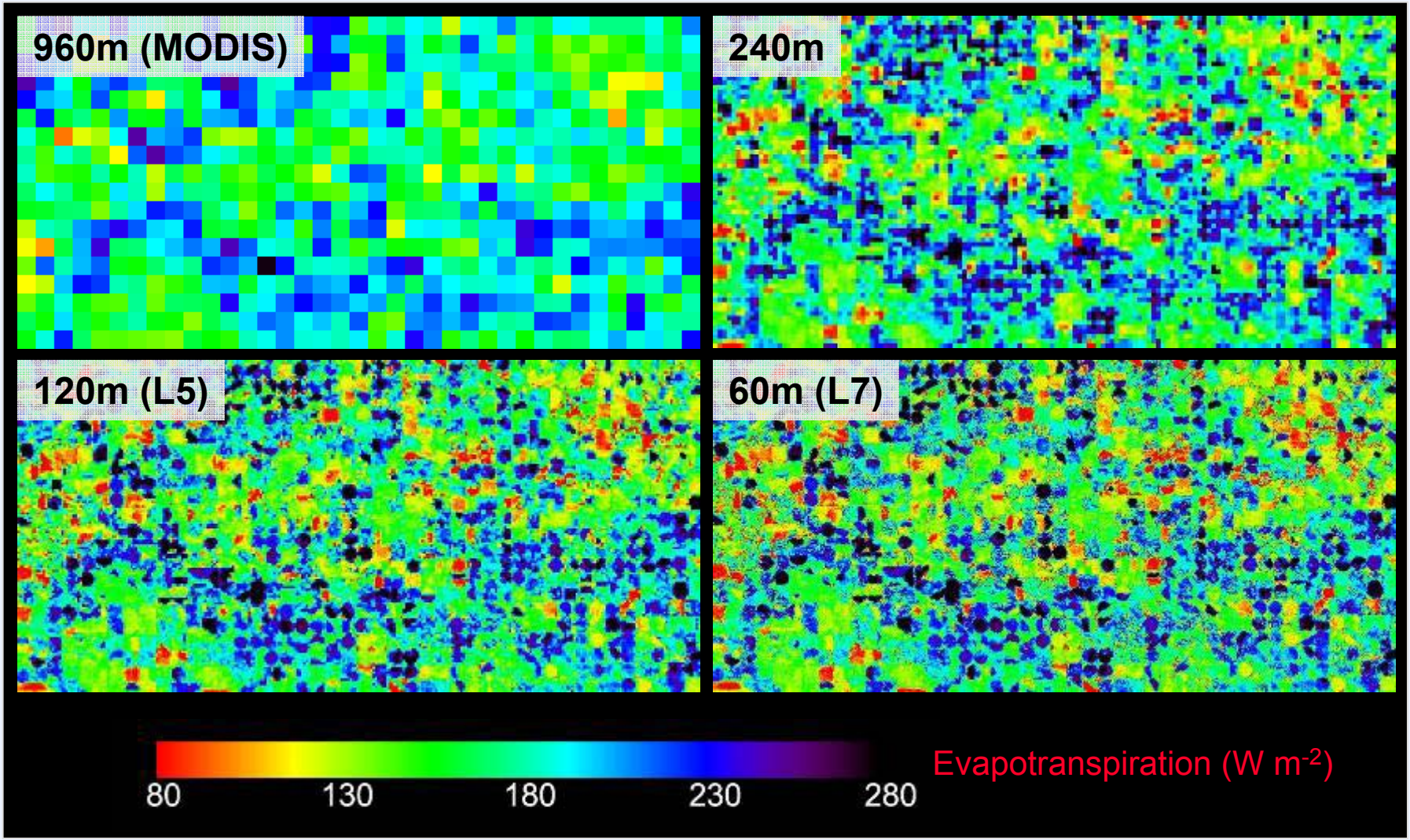
IMPENDING THERMAL DATA GAP

Land Surface Temperature and Emissivity Earth System Data Record (LSTE-ESDR)

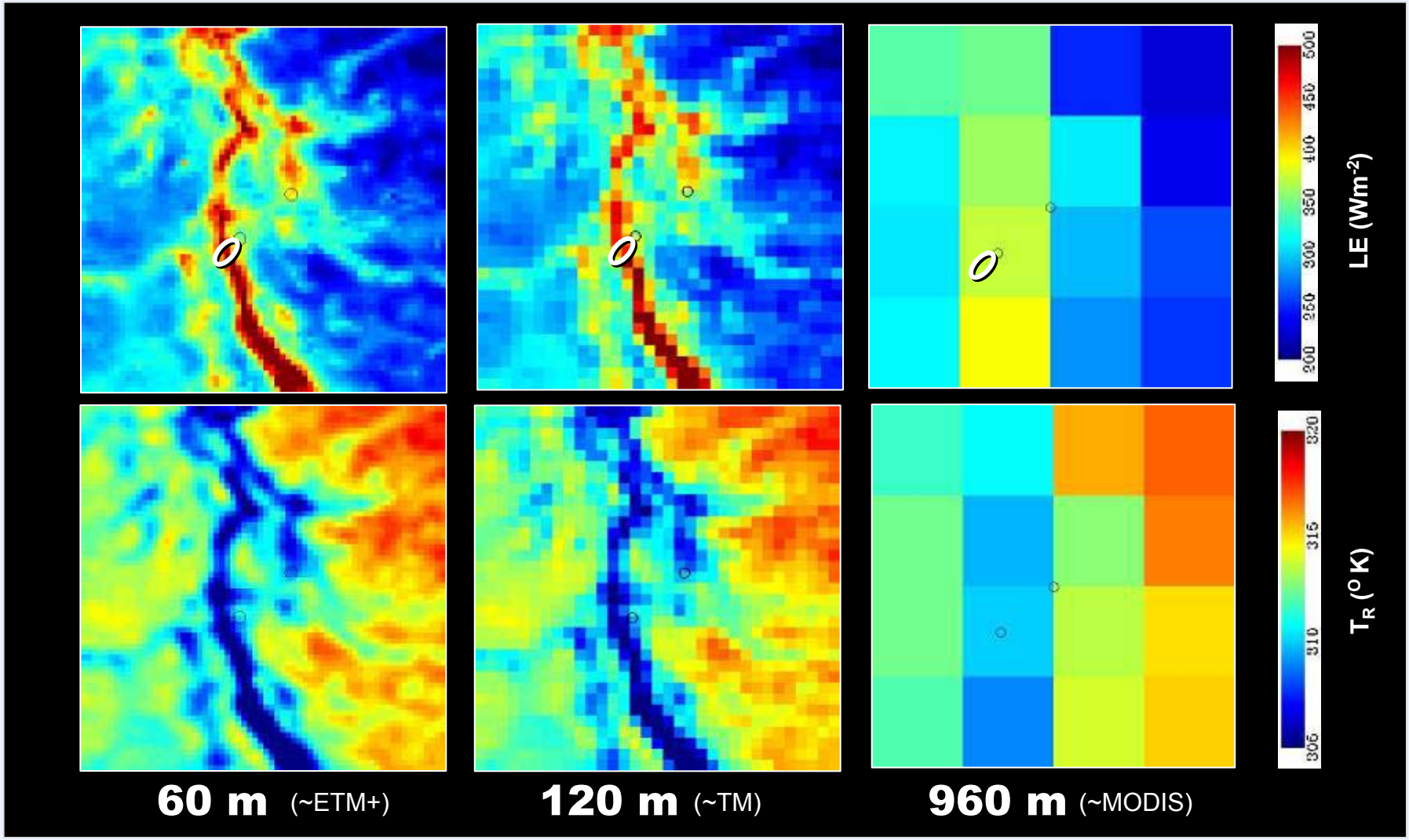
Coverage	Spatial Resolution	Temporal Resolution	Current Data Sources	Future Data Sources
Global	10-20 km	Hourly	AIRS GOES MSG	CrIS GOES MSG
Regional	1-5 km	2-4 times daily	MODIS AVHRR ATSR	VIIRS AVHRR ATSR
Local	30–100 m	Once every 8-16 days	ASTER Landsat	!!

Table from S. Hook

The importance of Landsat-resolution thermal data



The importance of Landsat-resolution thermal data



29 July 2004 – Southern Arizona (San Pedro River Basin)

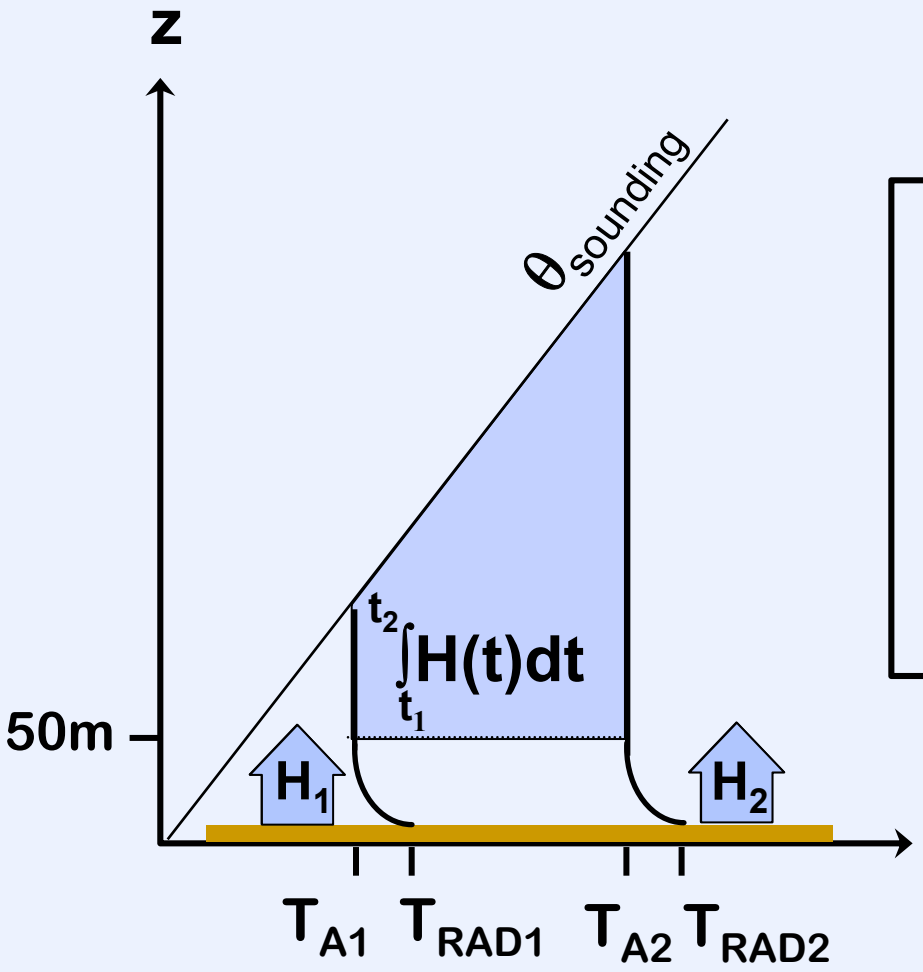
CONCLUSIONS

- **THERMAL REMOTE SENSING DATA HAVE GREAT UTILITY:**
  - ***... ET mapping***
  - ***... drought monitoring***
  - ***... soil moisture mapping***

NEED TO MAINTAIN MULTI-SCALE THERMAL DATA SOURCES

manderson@hydrolab.arsusda.gov

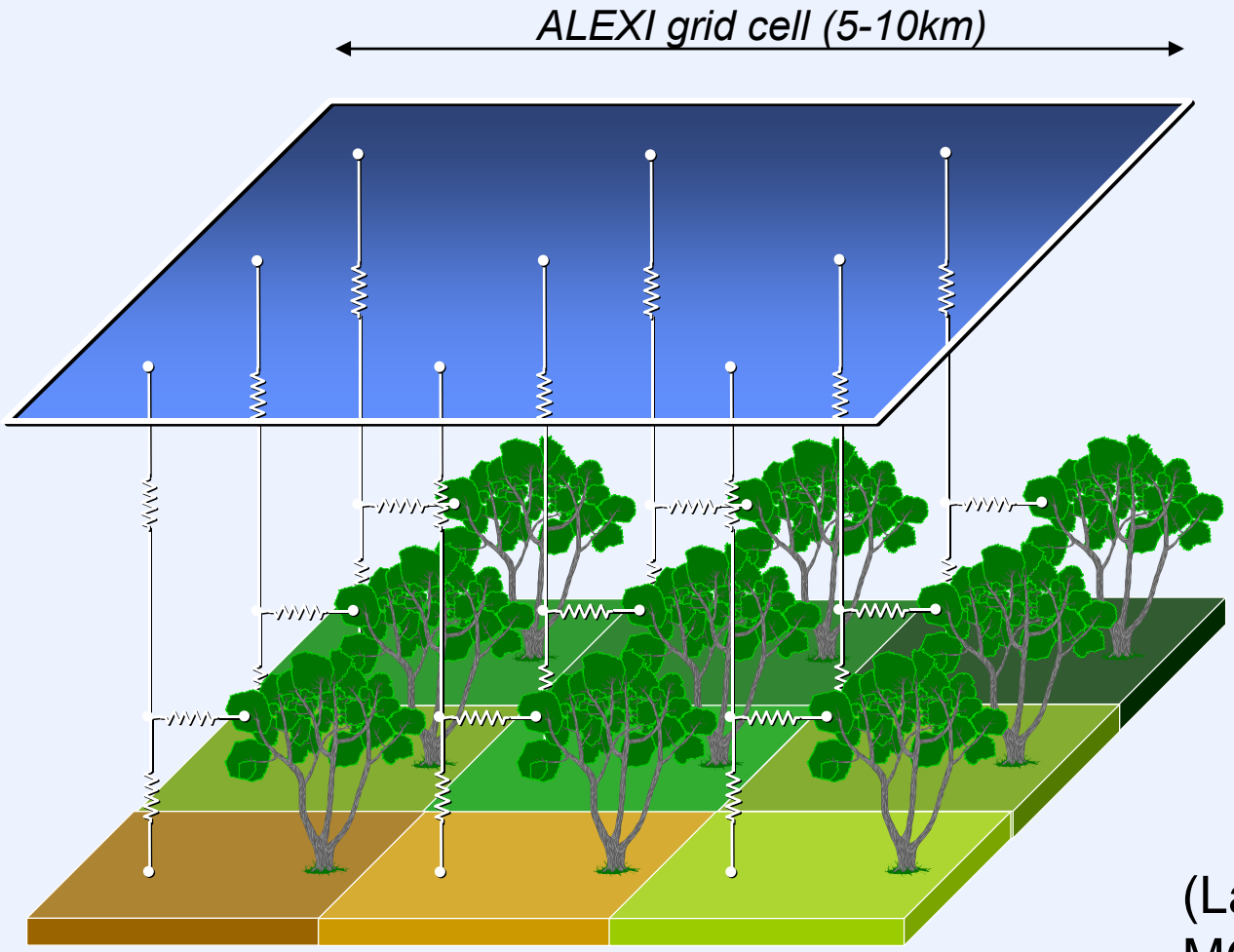
Atmosphere-Land Exchange Inverse Model (ALEXI)



PROCEDURE:

- Apply TSM at 2 times during morning
- Estimate T_{A1} & T_{A2} at blending height
- Compute required $\int_{t_1}^{t_2} H(t)dt$
- Revise H_1 & H_2

Disaggregated ALEXI (DisALEXI)

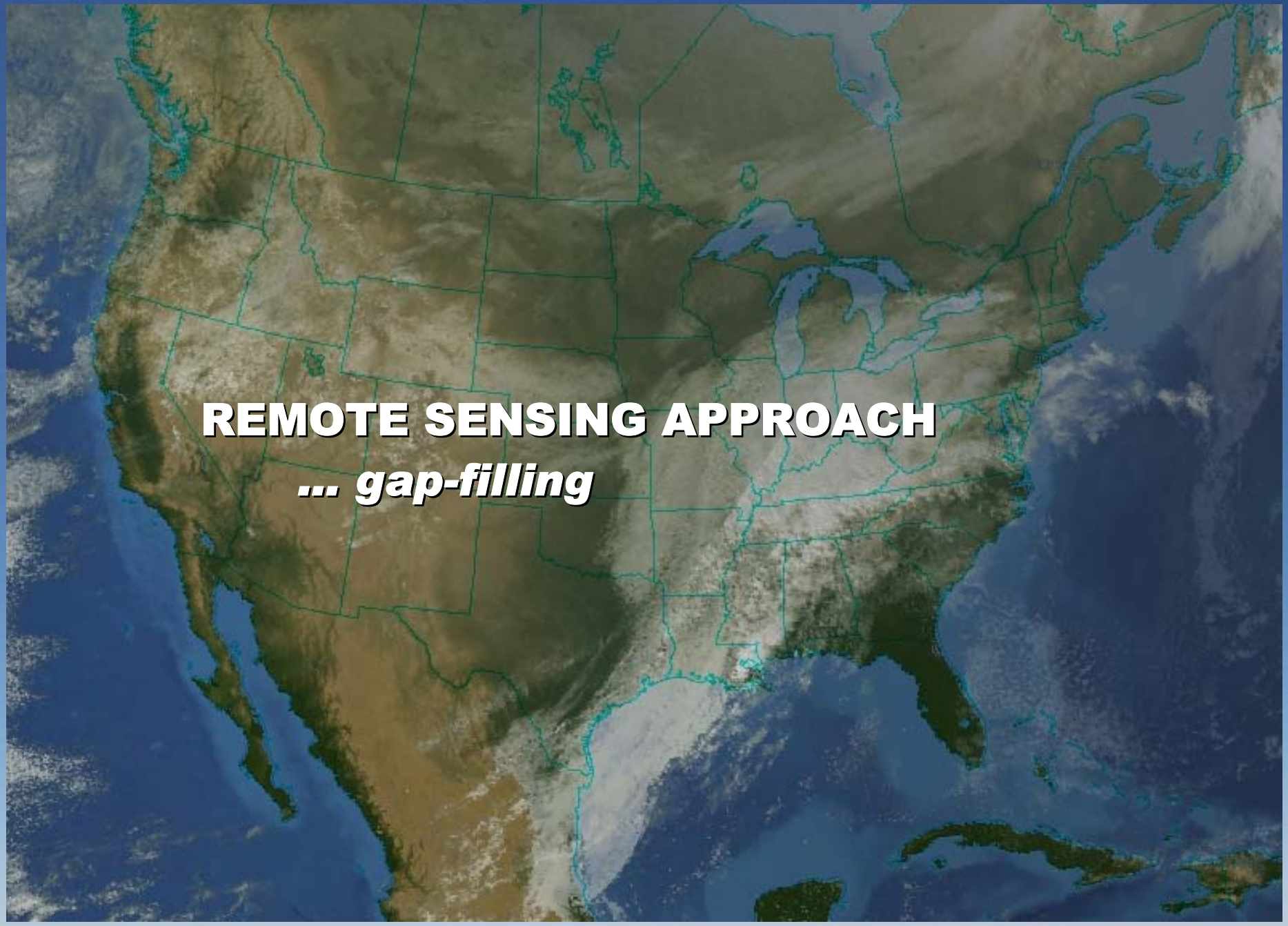


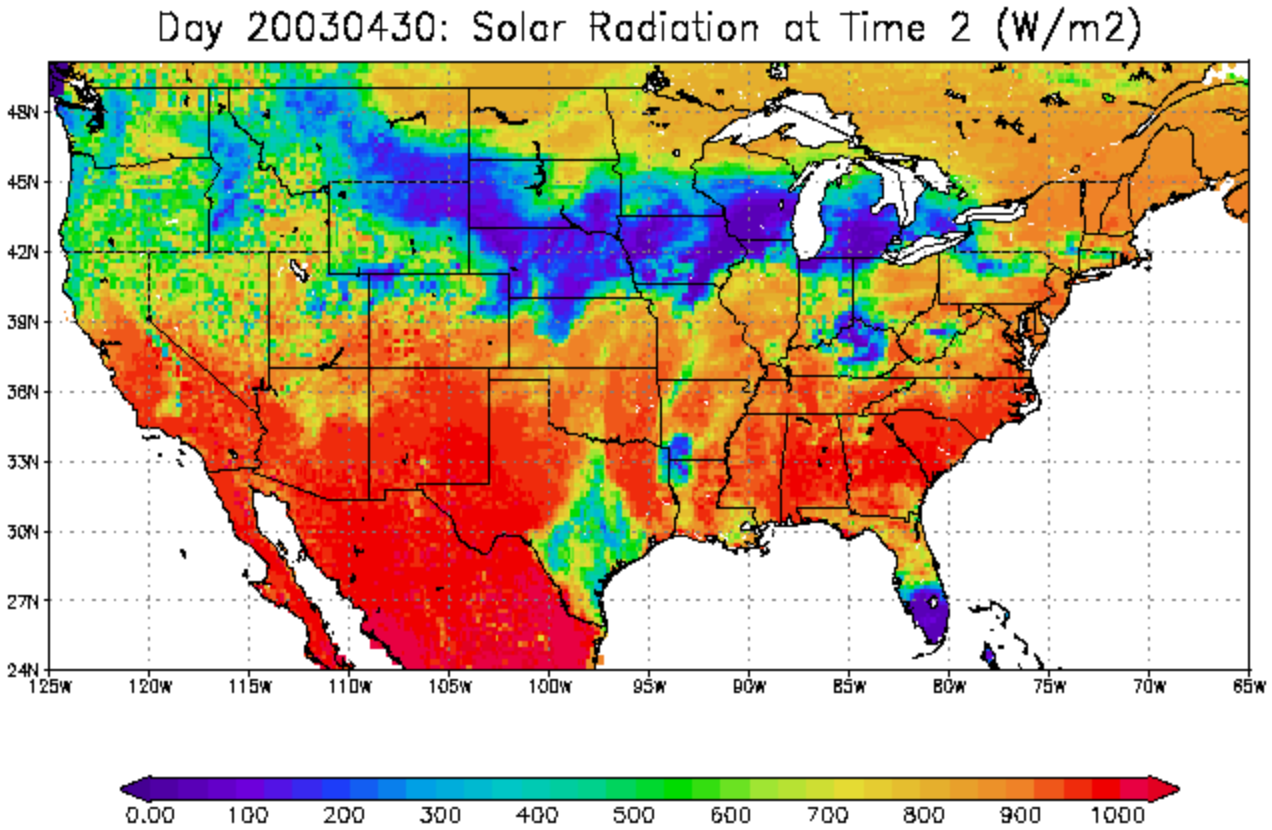
T_A (ALEXI)

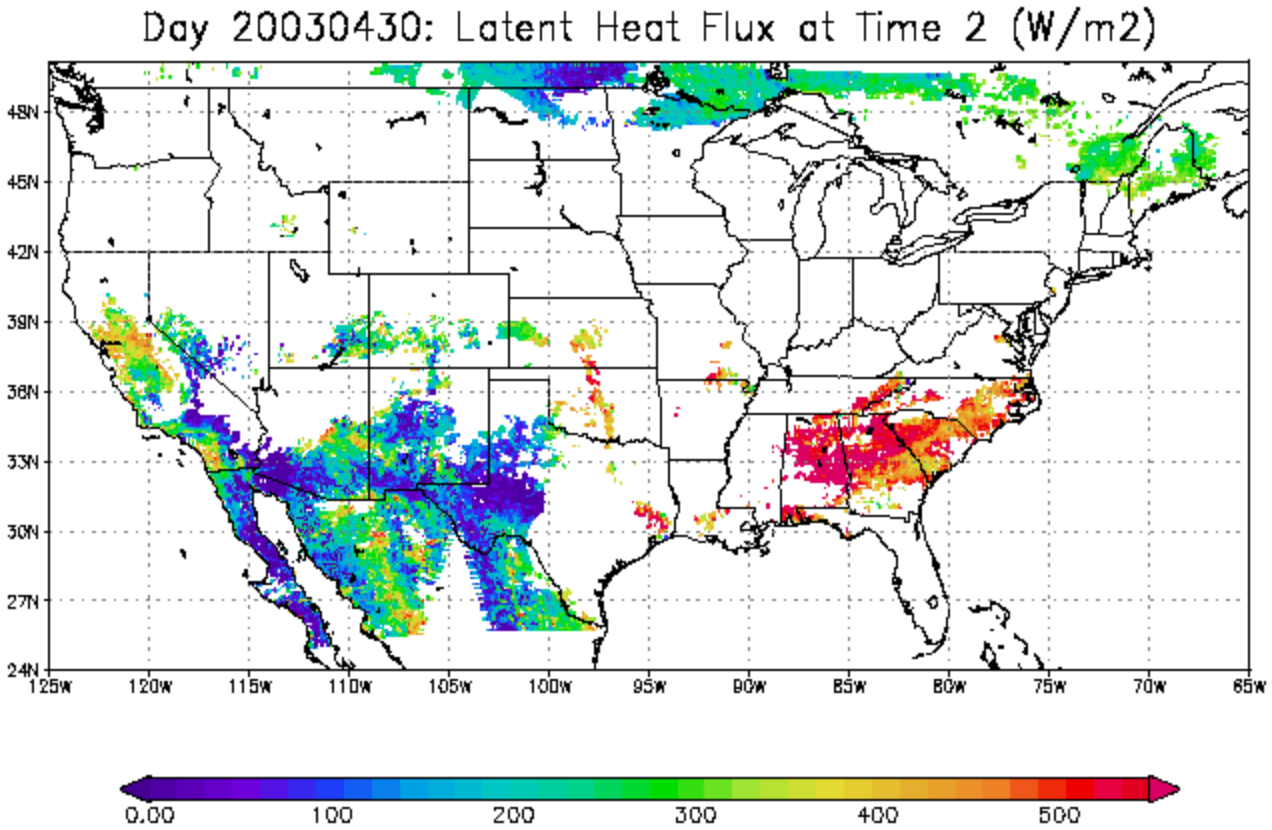
$H_{bulk} = H_{ALEXI}$

T_{RAD}, f_c

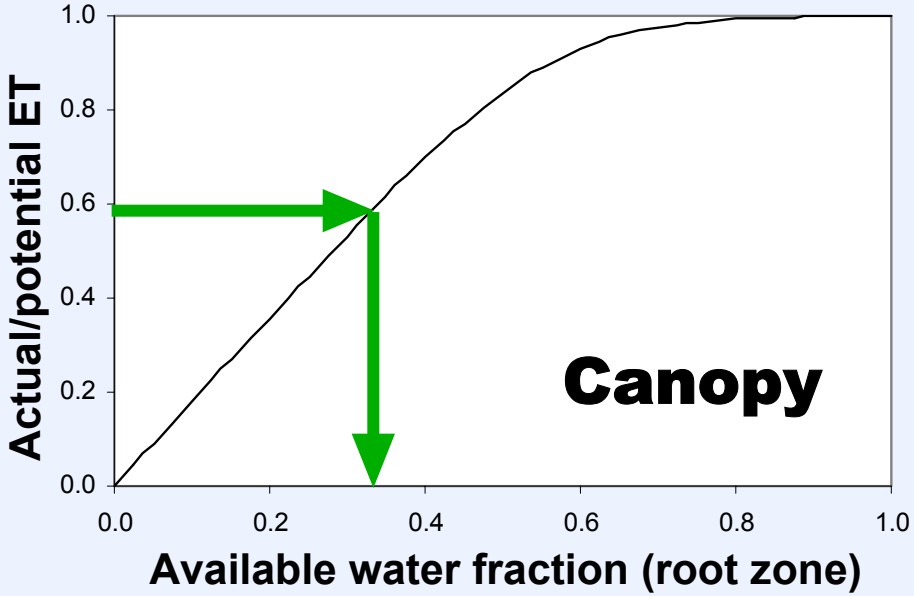
(Landsat, ASTER MODIS, aircraft)

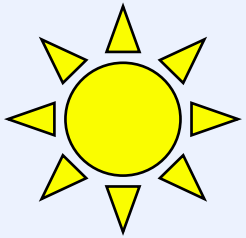

REMOTE SENSING APPROACH
... gap-filling


Day 20030430: Solar Radiation at Time 2 (W/m2)
48N
45N
42N
39N
36N
33N
30N
27N
24N
125W
120W
115W
110W
105W
100W
95W
90W
85W
80W
75W
70W
65W
0.00
100
200
300
400
500
600
700
800
900
1000

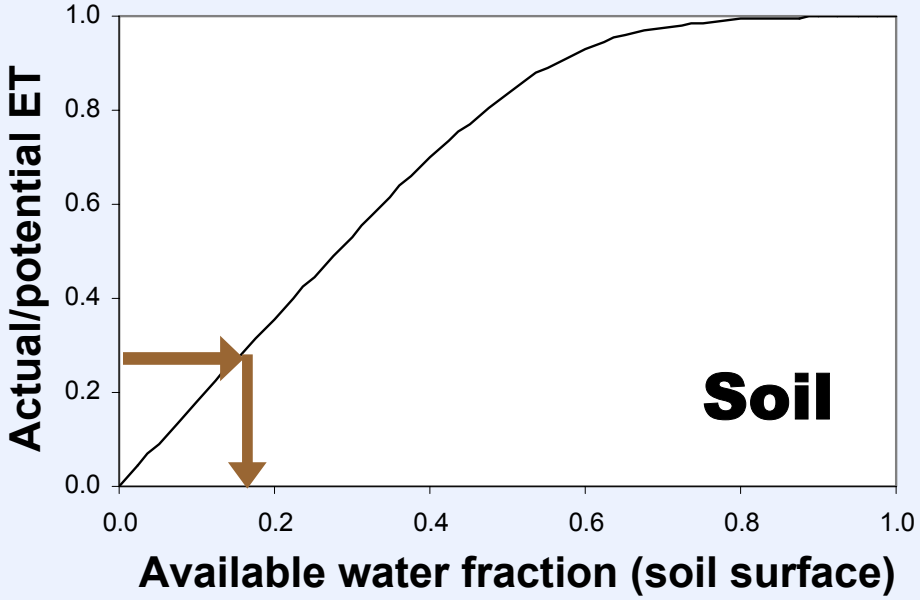

Day 20030430: Latent Heat Flux at Time 2 (W/m2)
48N
45N
42N
39N
36N
33N
30N
27N
24N
125W
120W
115W
110W
105W
100W
95W
90W
85W
80W
75W
70W
65W
0.00
100
200
300
400
500

Transpiration

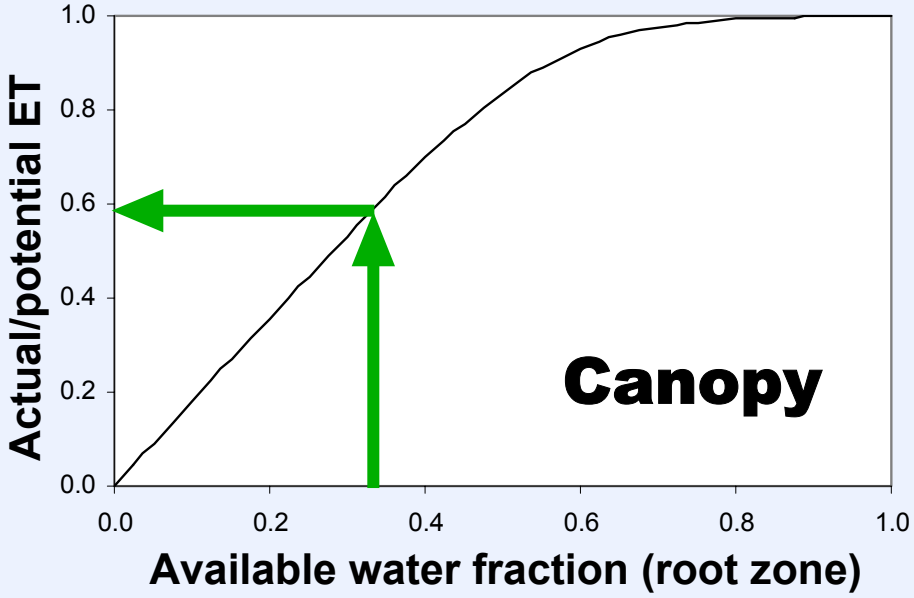




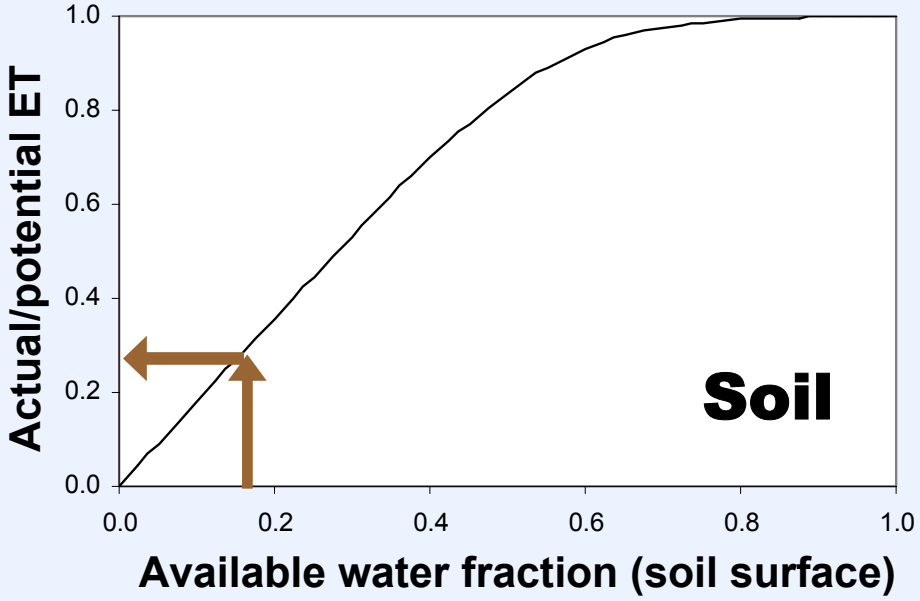
Soil evaporation

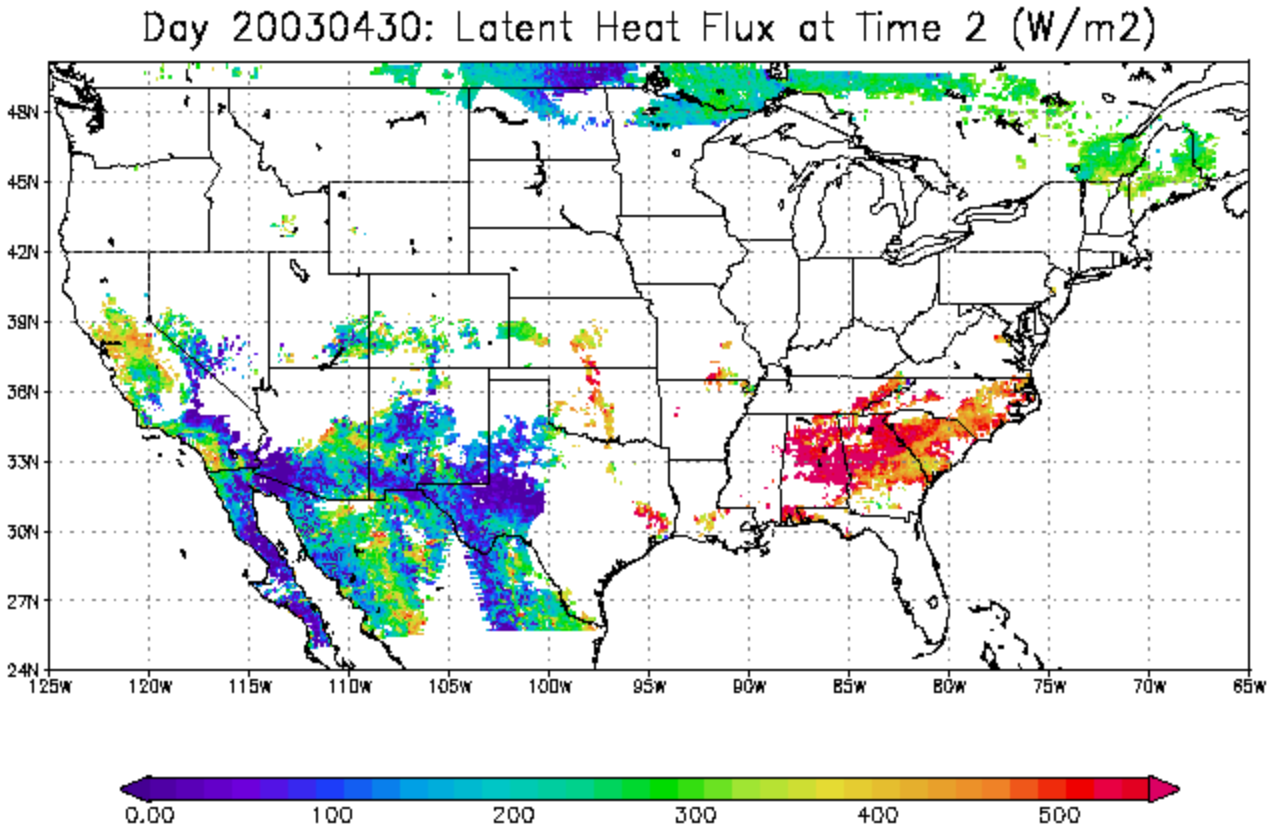


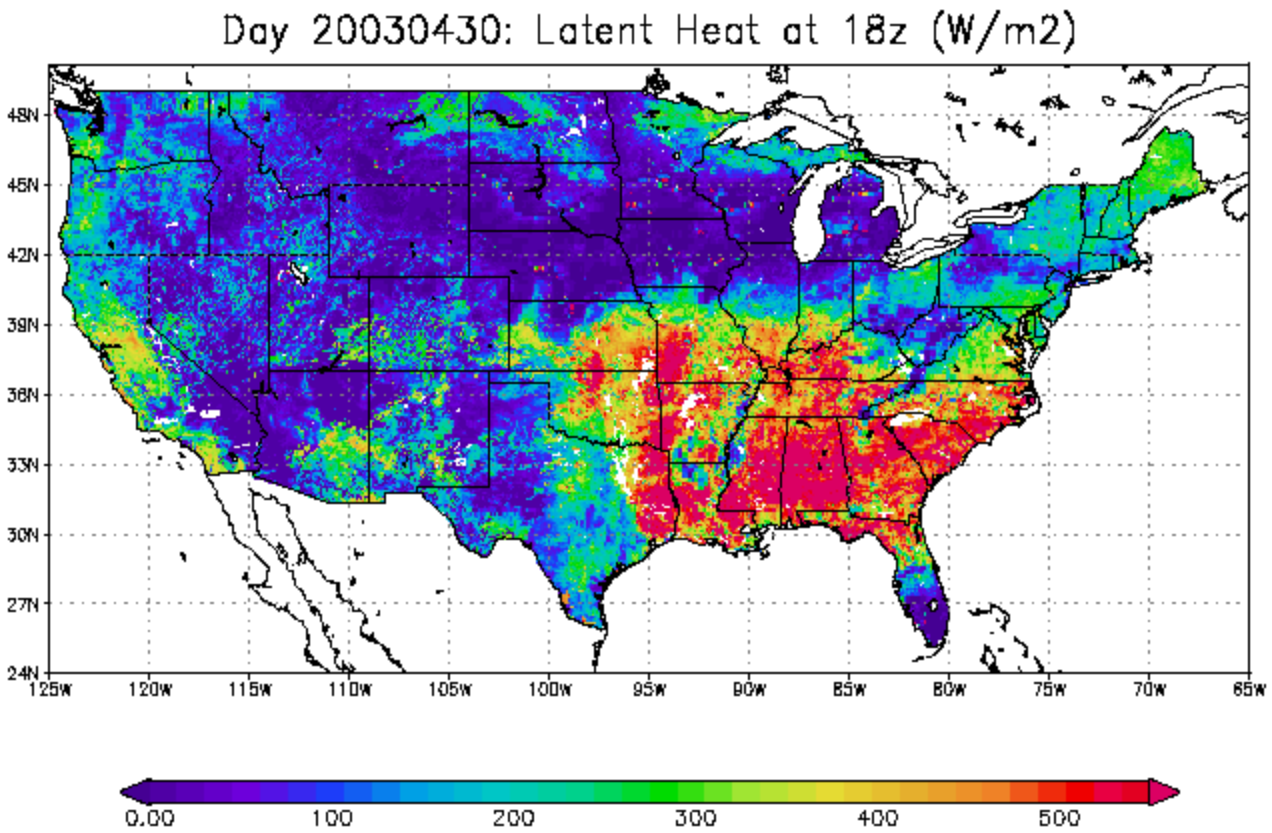
Transpiration



Soil evaporation

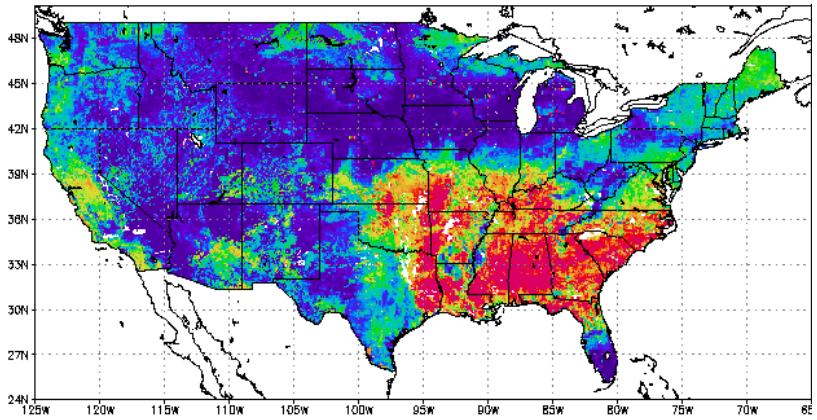



Day 20030430: Latent Heat Flux at Time 2 (W/m2)
48N
45N
42N
39N
36N
33N
30N
27N
24N
125W
120W
115W
110W
105W
100W
95W
90W
85W
80W
75W
70W
65W
0.00
100
200
300
400
500

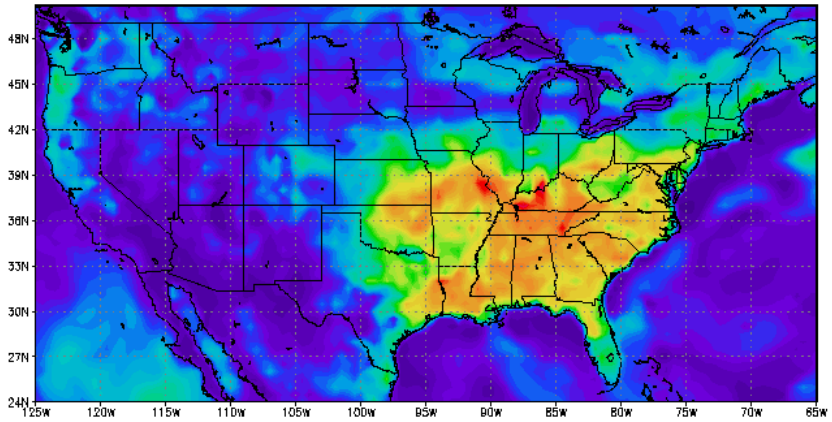

Day 20030430: Latent Heat at 18z (W/m2)
48N
45N
42N
39N
36N
33N
30N
27N
24N
125W
120W
115W
110W
105W
100W
95W
90W
85W
80W
75W
70W
65W
0.00
100
200
300
400
500

Latent heat intercomparison

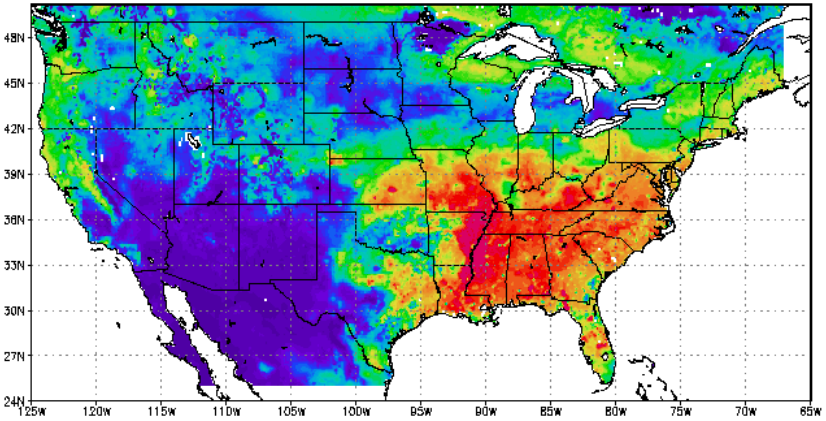
ALEXI



Eta



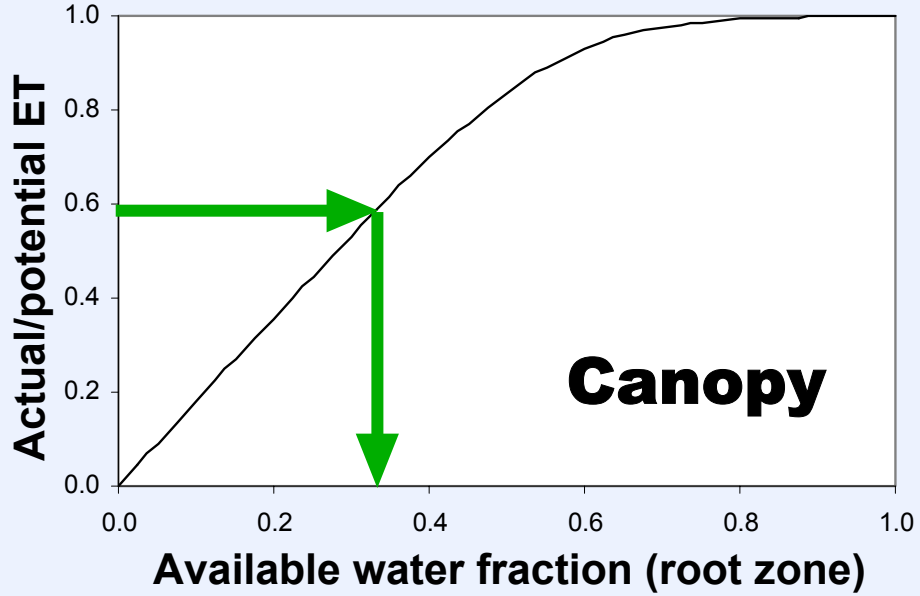
Mosaic



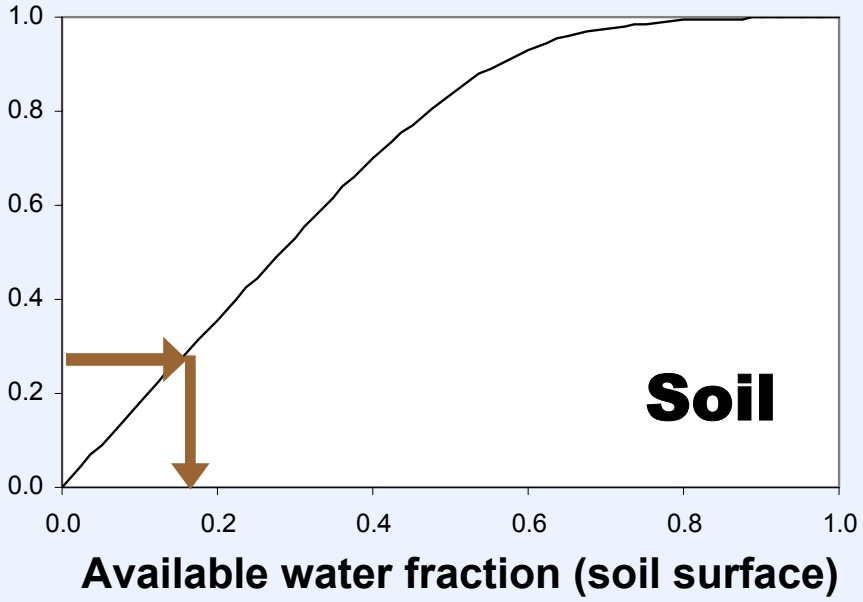
Latent Heat

30 April 2003 (18z)

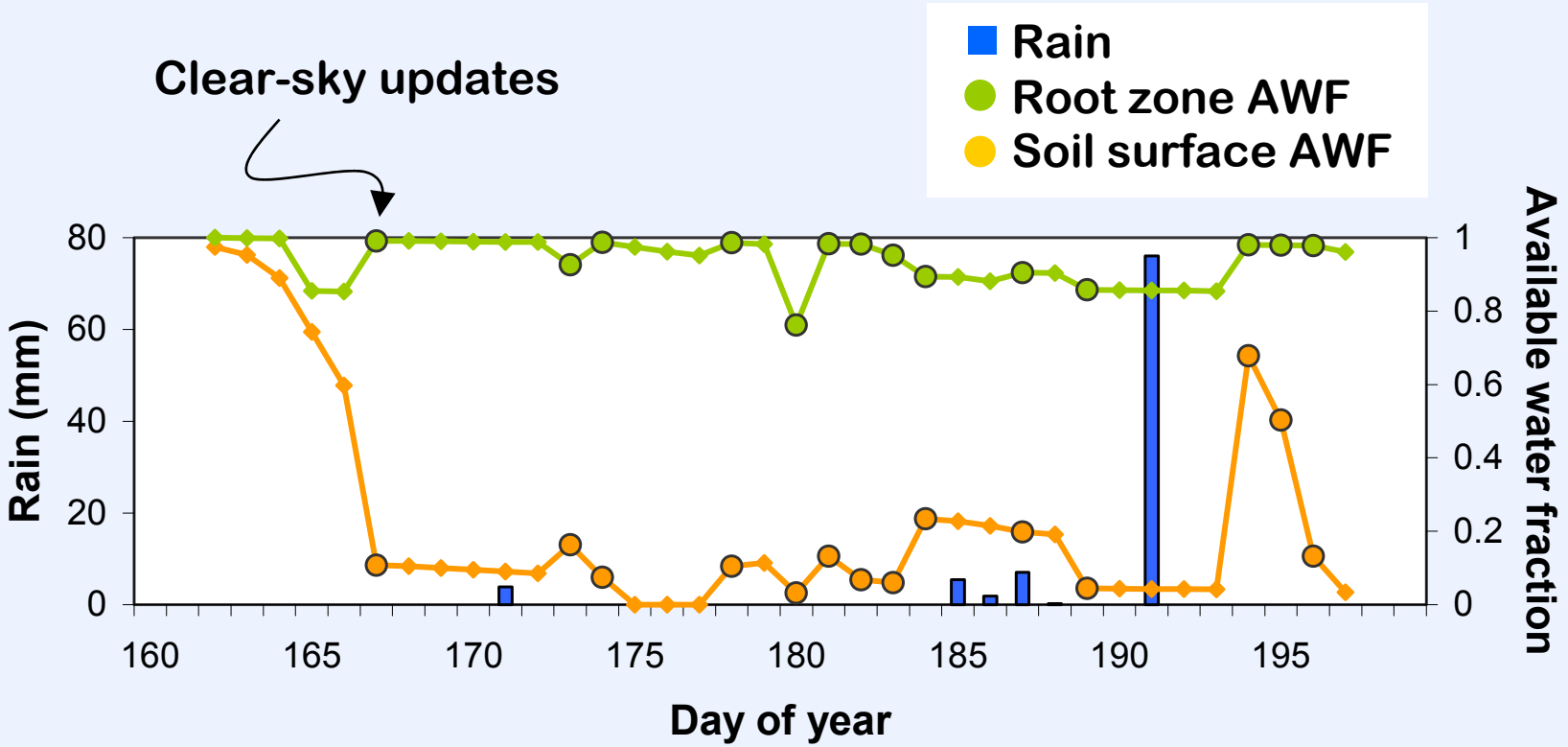
Transpiration



Soil evaporation



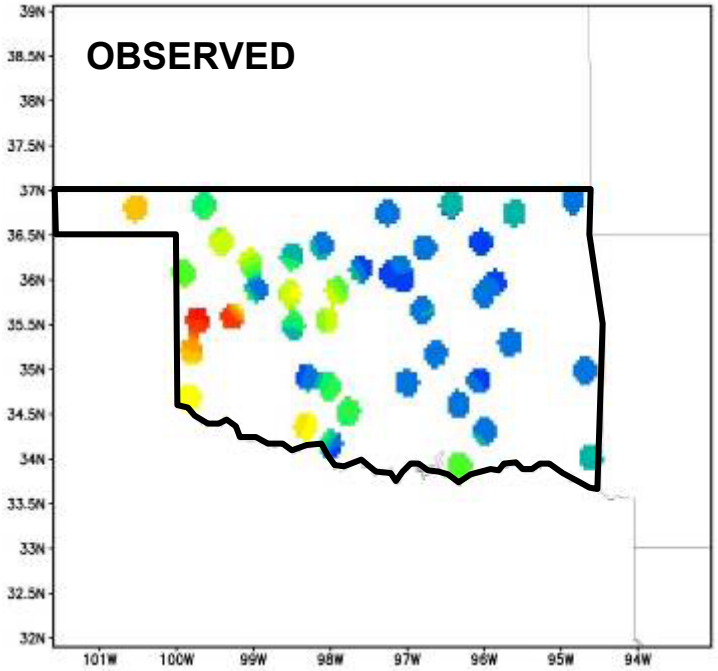
Available water response to rainfall (SMEX02)

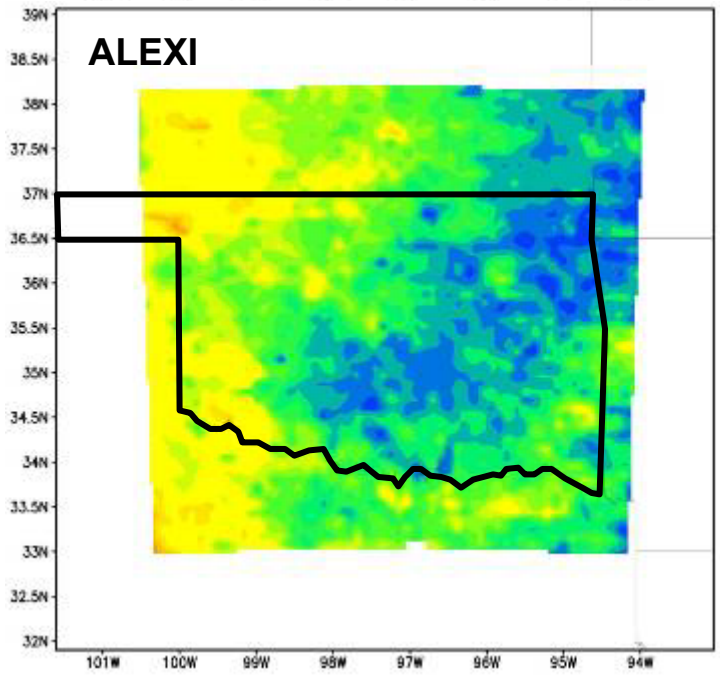


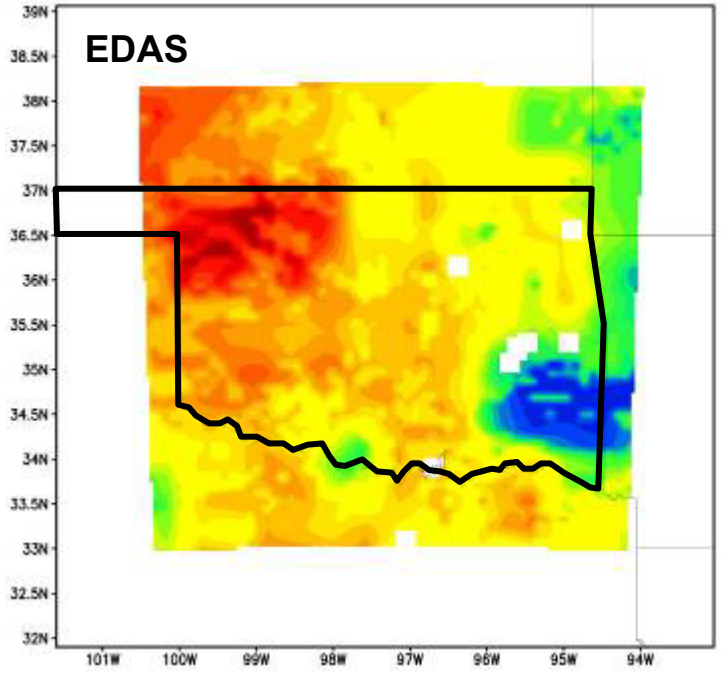
Available Water Fraction

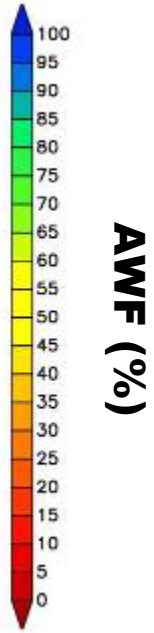
June 19, 2002

ALEXI	EDAS
MAE = 12.06%	MAE = 38.84%
Bias = -0.86%	Bias = -36.90%





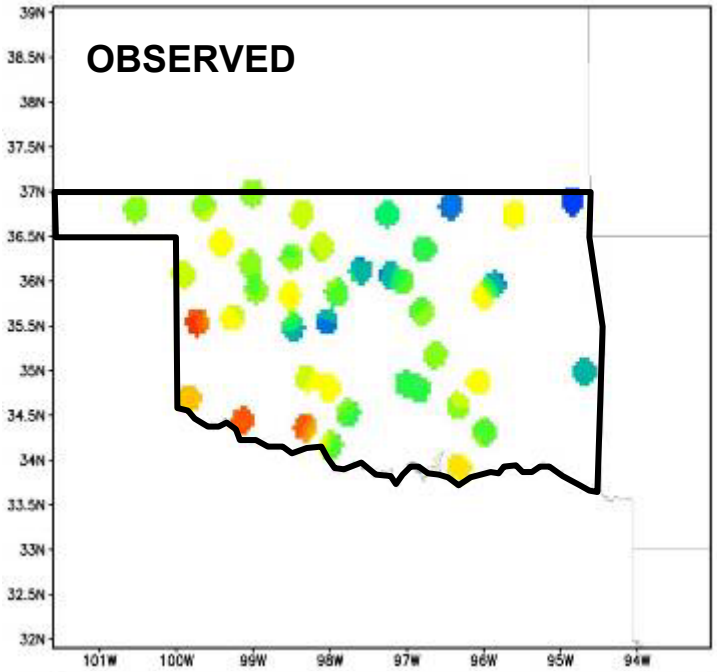


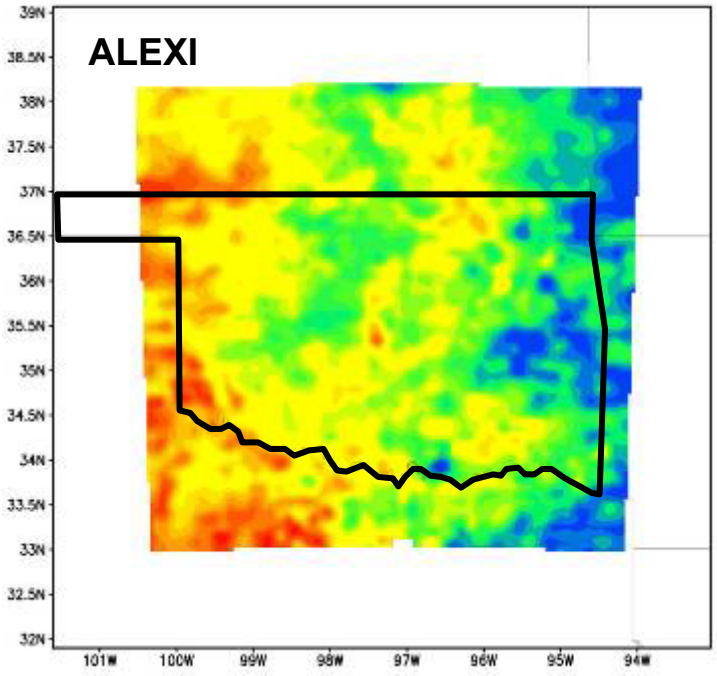


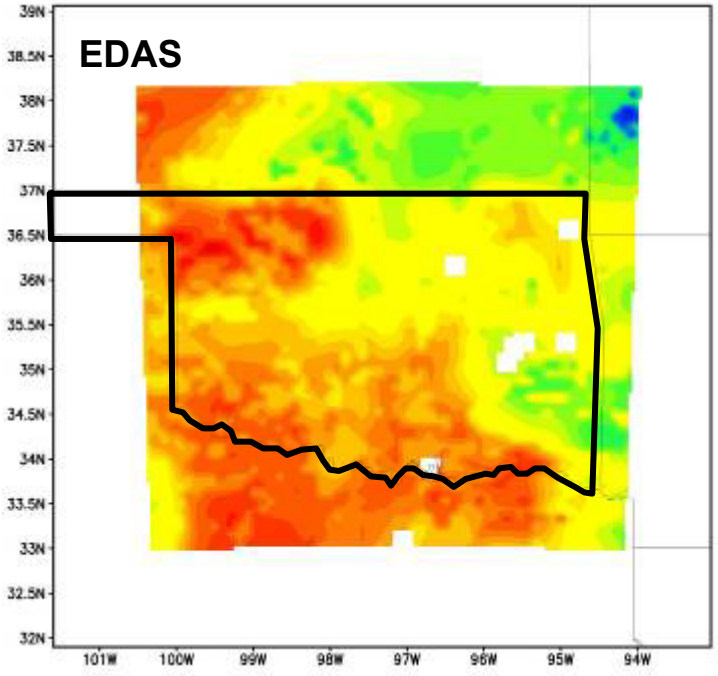
Available Water Fraction

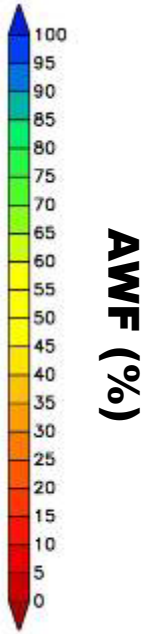
May 12, 2003

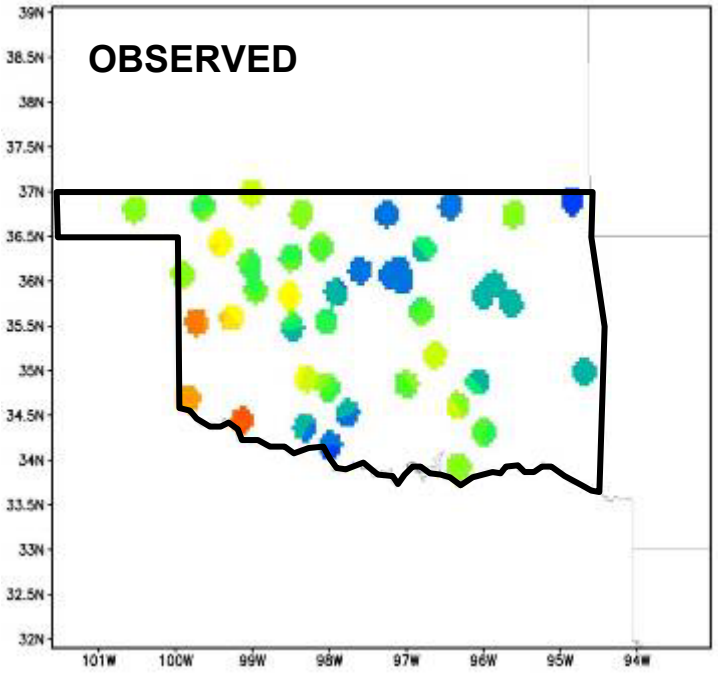
ALEXI	EDAS
MAE = 15.70%	MAE = 27.13%
Bias = -5.47%	Bias = -25.85%







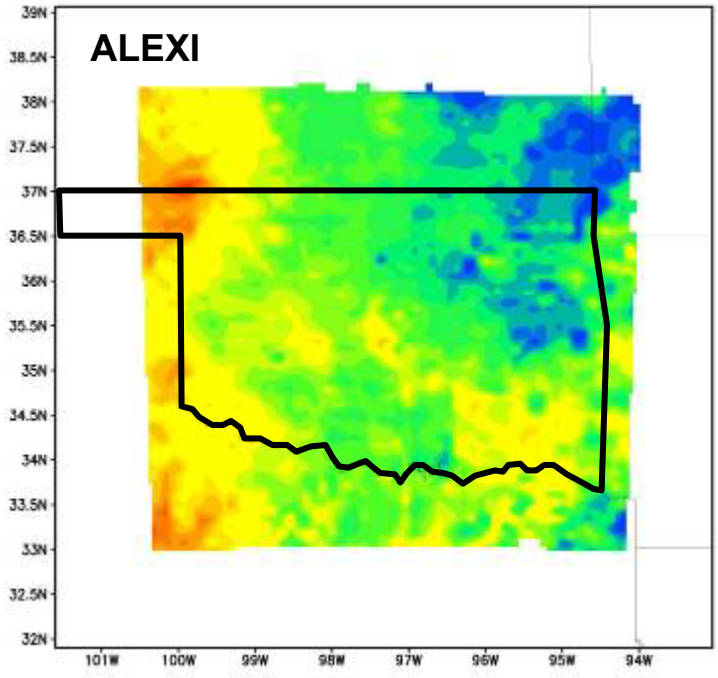


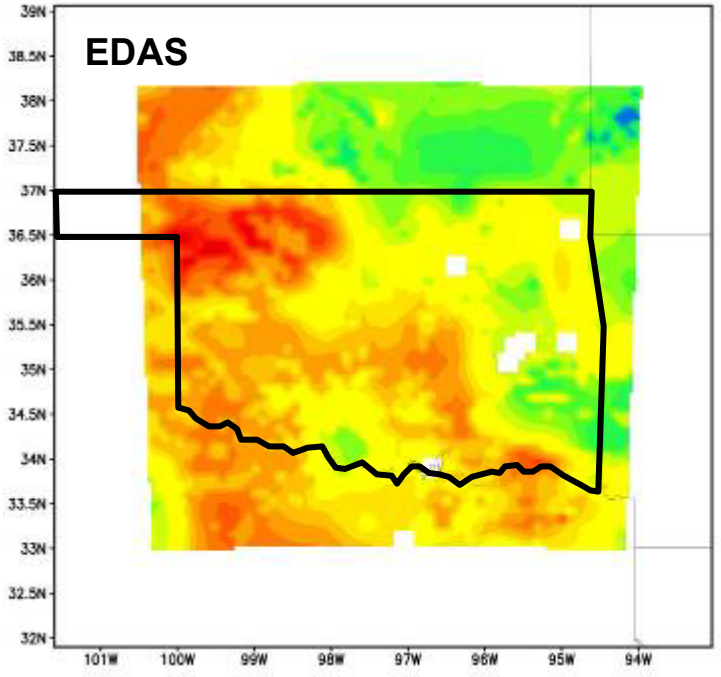


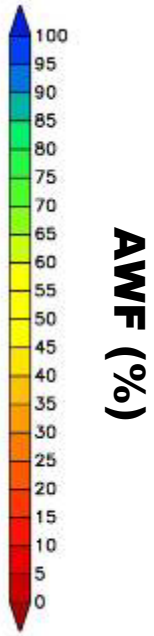
Available Water Fraction

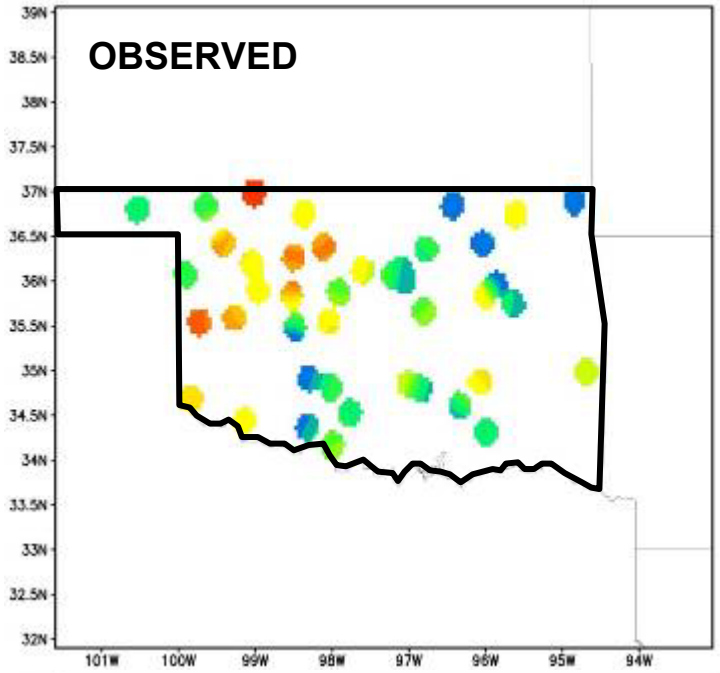
May 29, 2003

ALEXI	EDAS
MAE = 13.36%	MAE = 31.30%
Bias = -4.55%	Bias = -30.15%





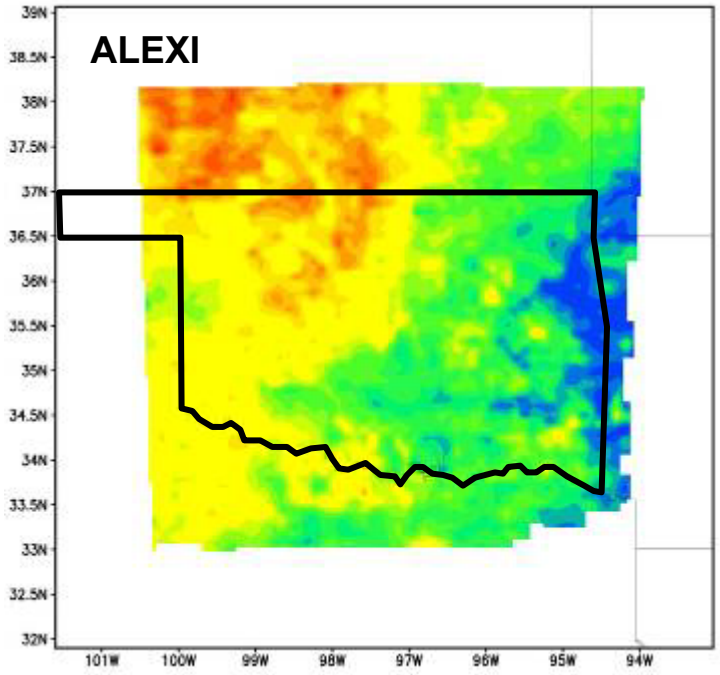


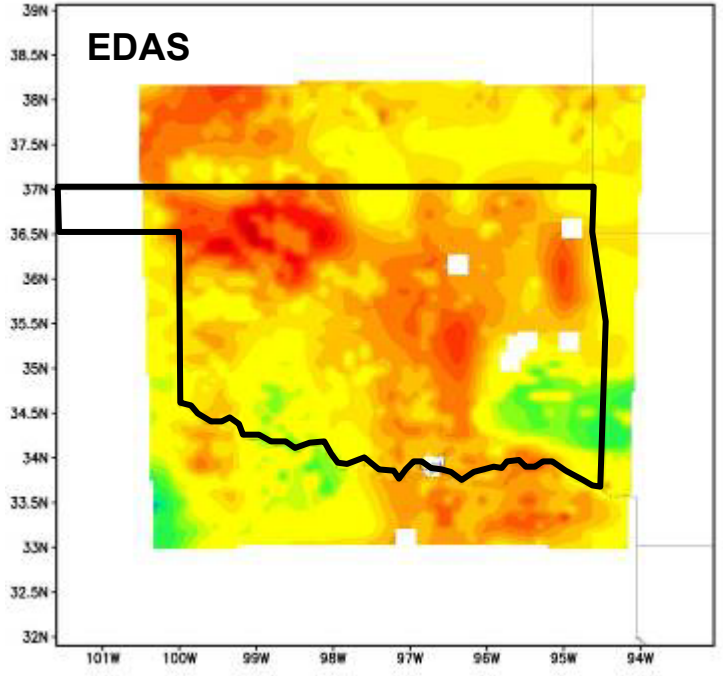


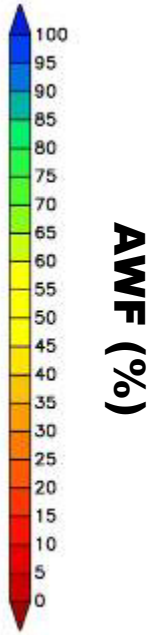
Available Water Fraction

July 5, 2003

ALEXI	EDAS
MAE = 16.45%	MAE = 30.52%
Bias = -3.75%	Bias = -28.06%



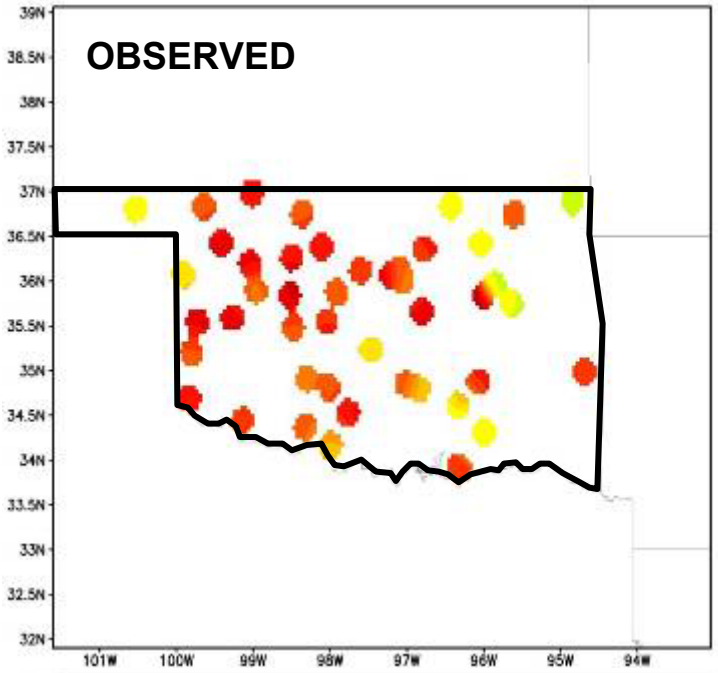


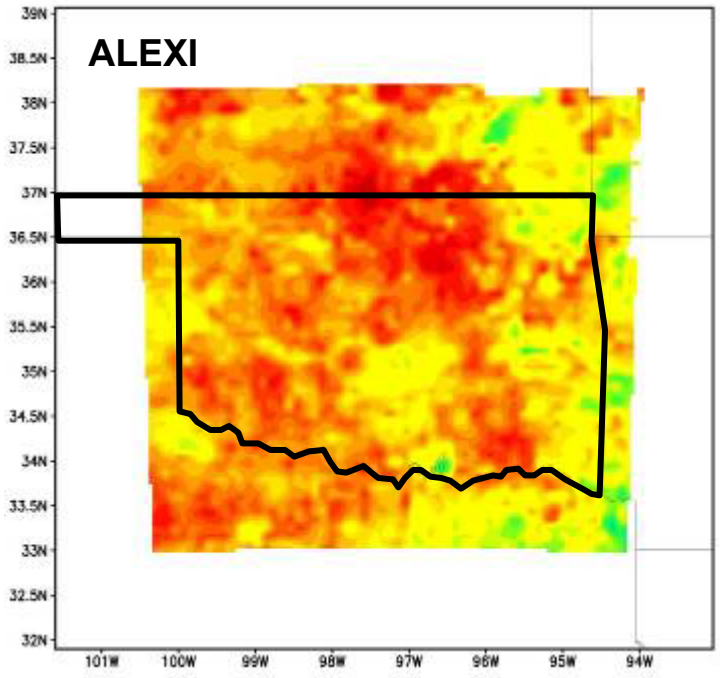


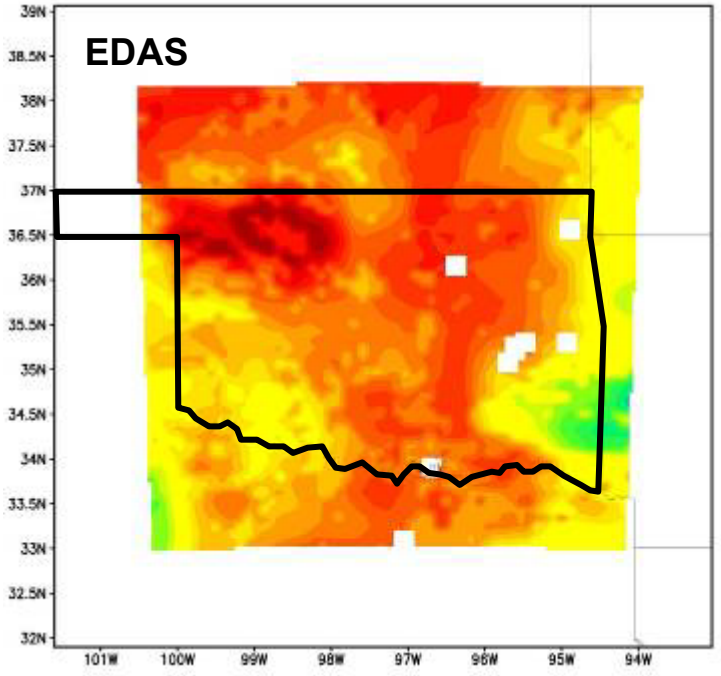
Available Water Fraction

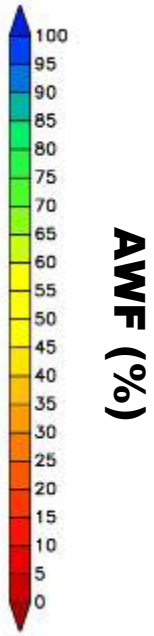
August 1, 2003

ALEXI	EDAS
MAE = 16.15%	MAE = 15.43%
Bias = 7.75%	Bias = 1.34%





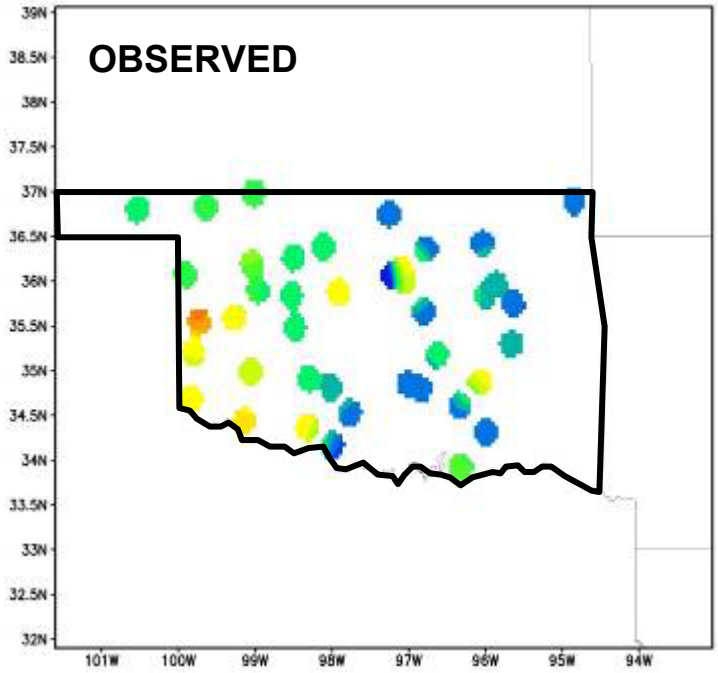


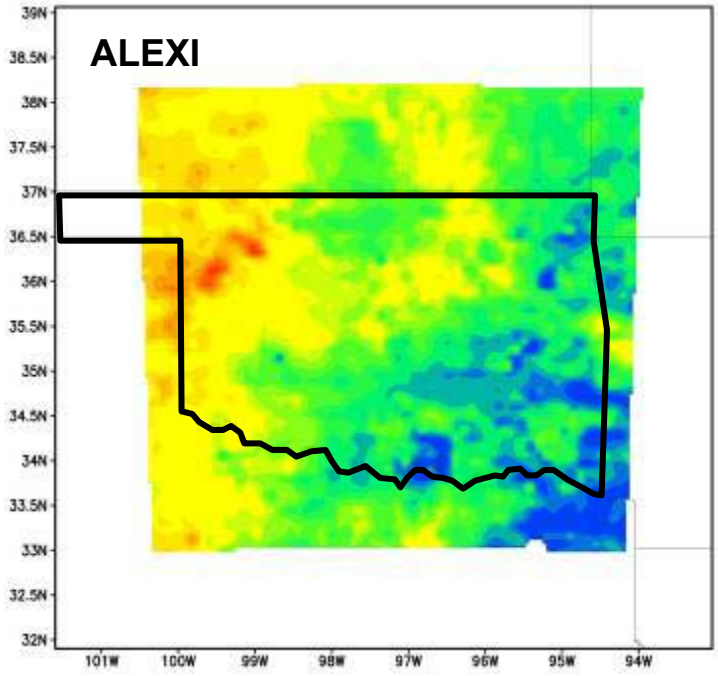


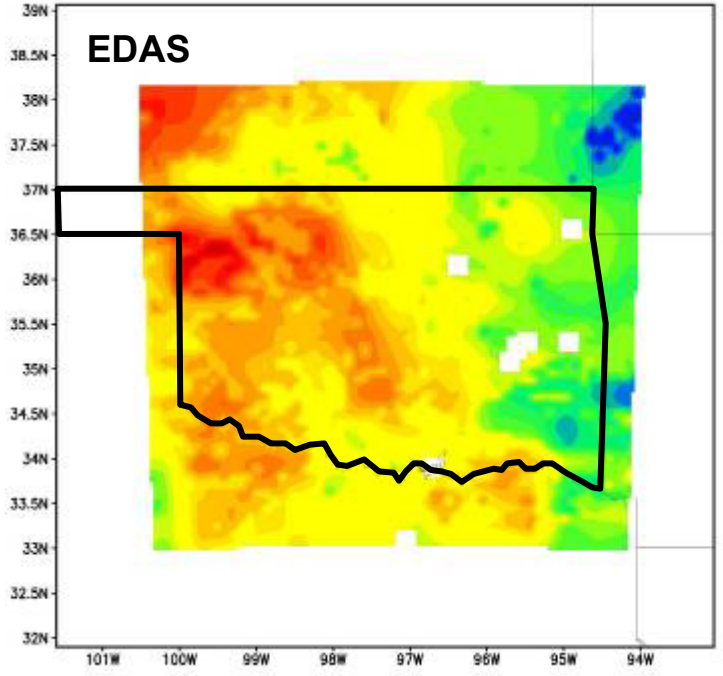
Available Water Fraction

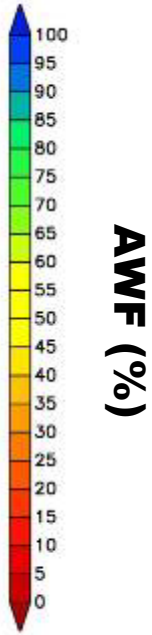
May 7, 2004

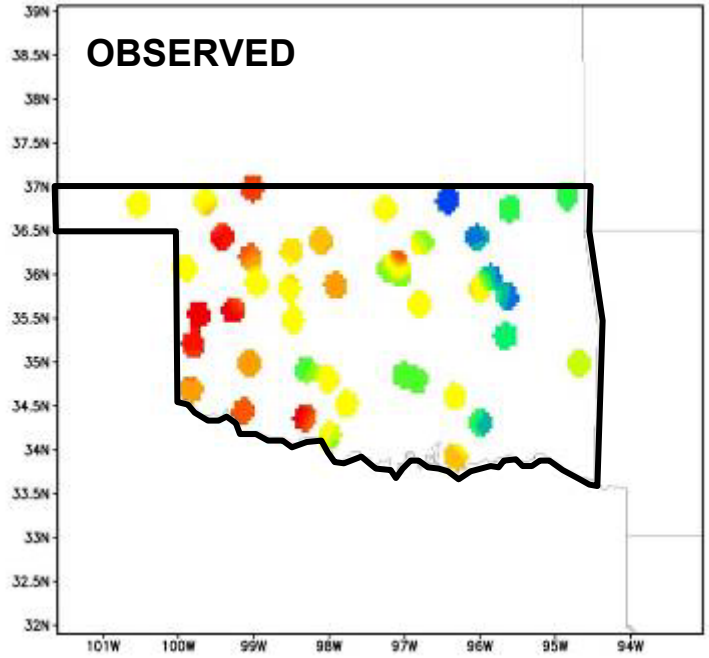
ALEXI	EDAS
MAE = 16.85%	MAE = 33.68%
Bias = -12.12%	Bias = -33.30%







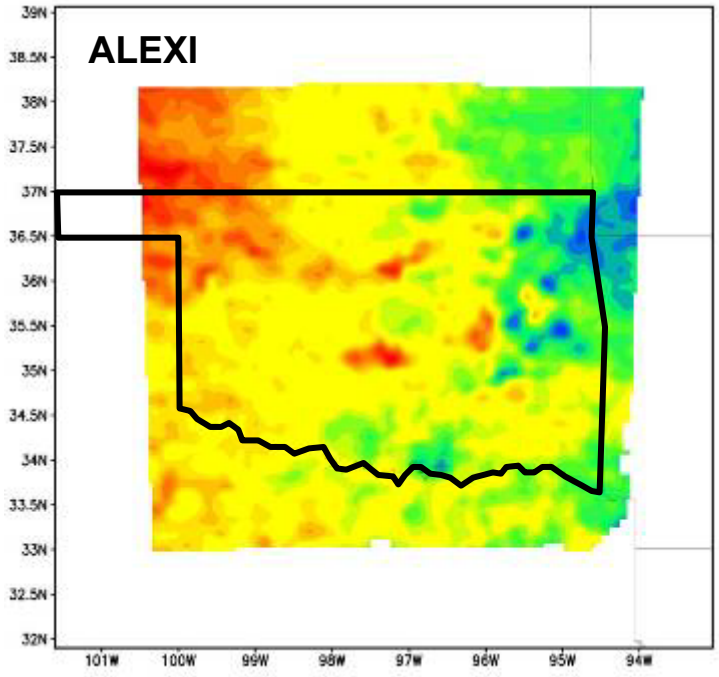


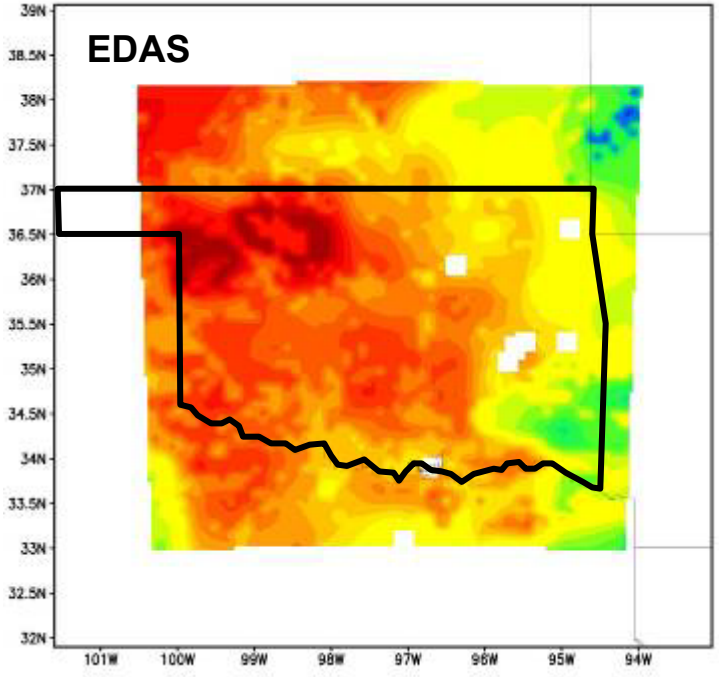


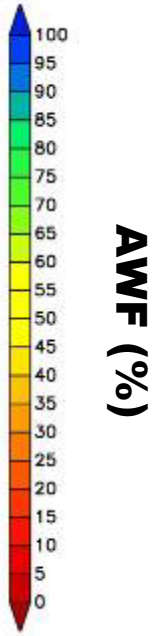
Available Water Fraction

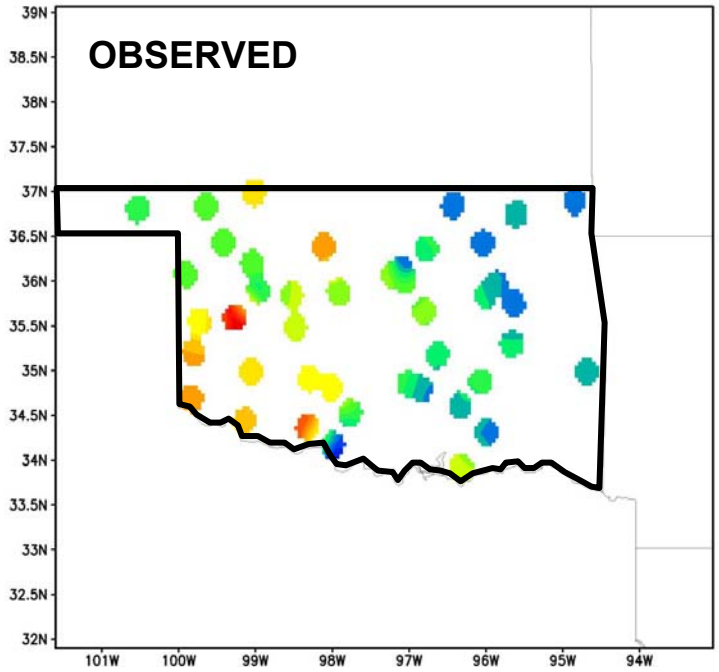
June 2, 2004

ALEXI	EDAS
MAE = 16.47%	MAE = 26.69%
Bias = 0.16%	Bias = -23.73%





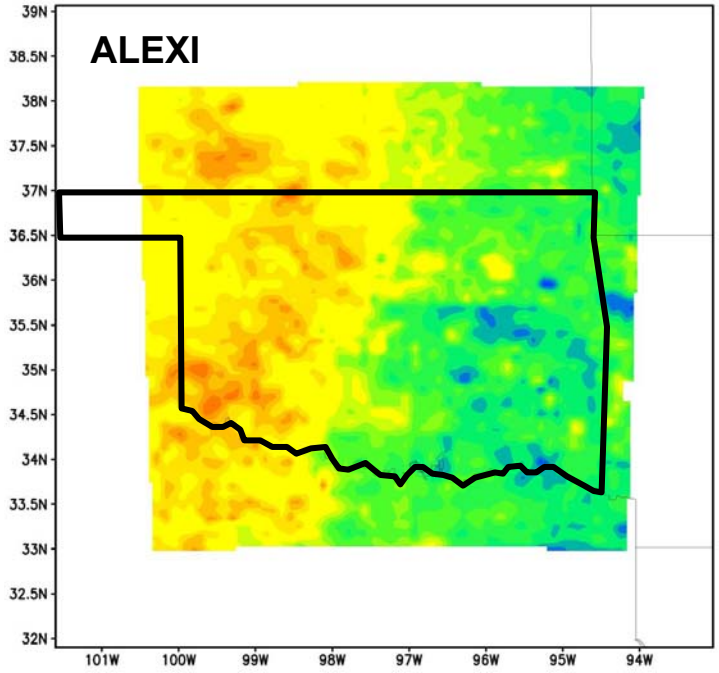


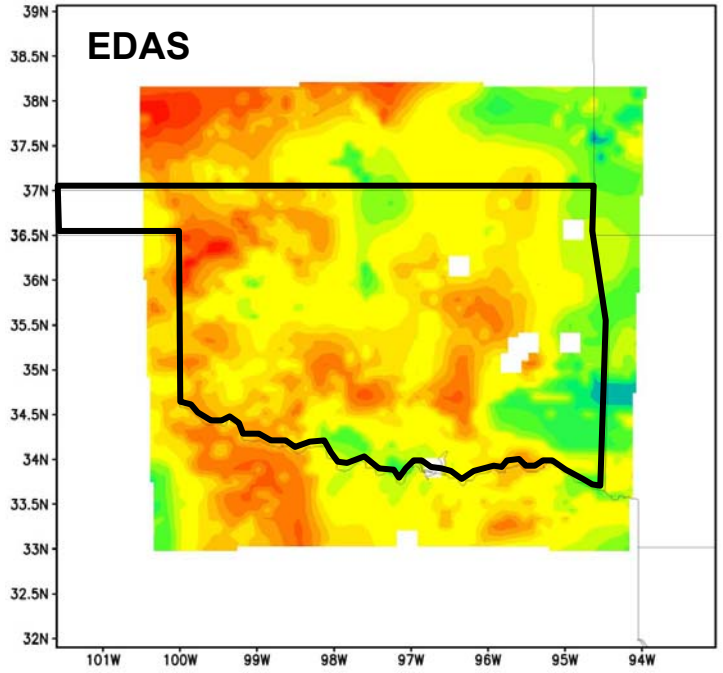


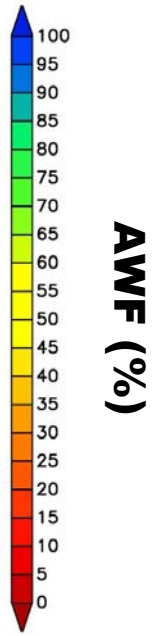
Available Water Fraction

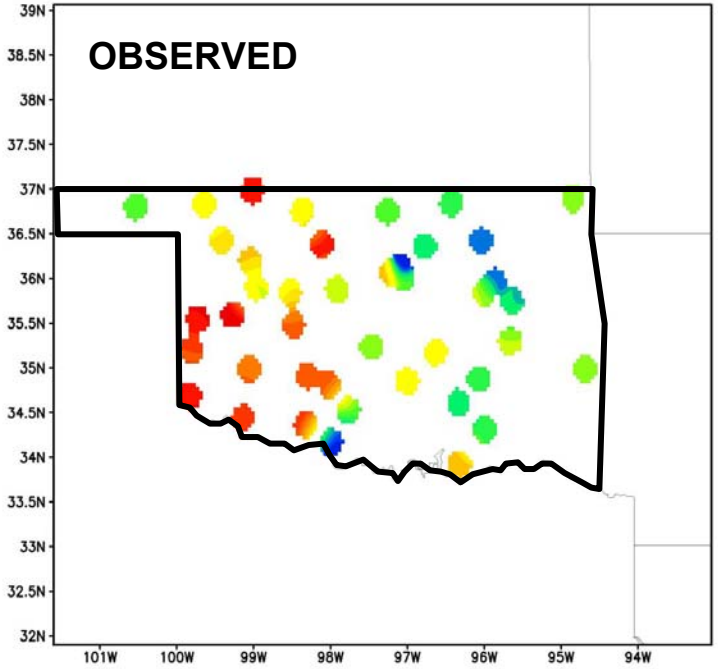
July 16, 2004

ALEXI	EDAS
MAE = 14.69%	MAE = 28.26%
Bias = -9.25%	Bias = -24.95%





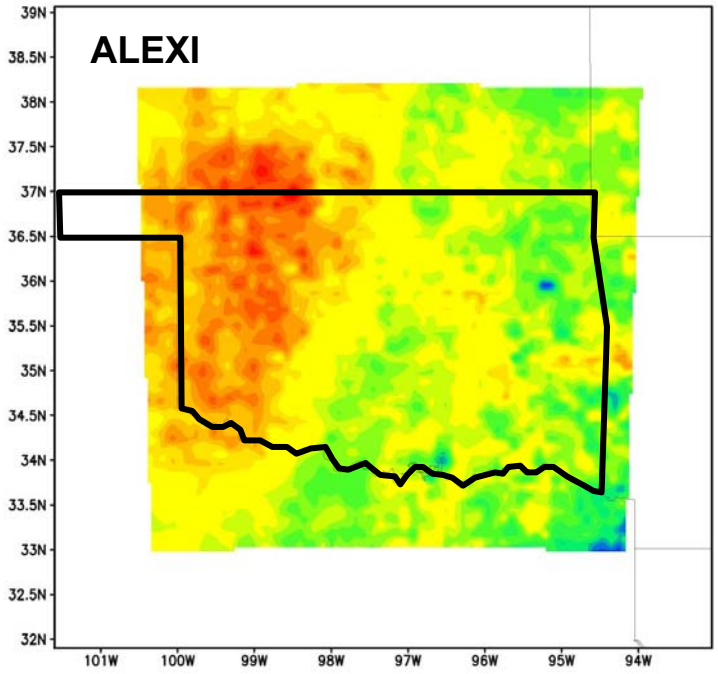


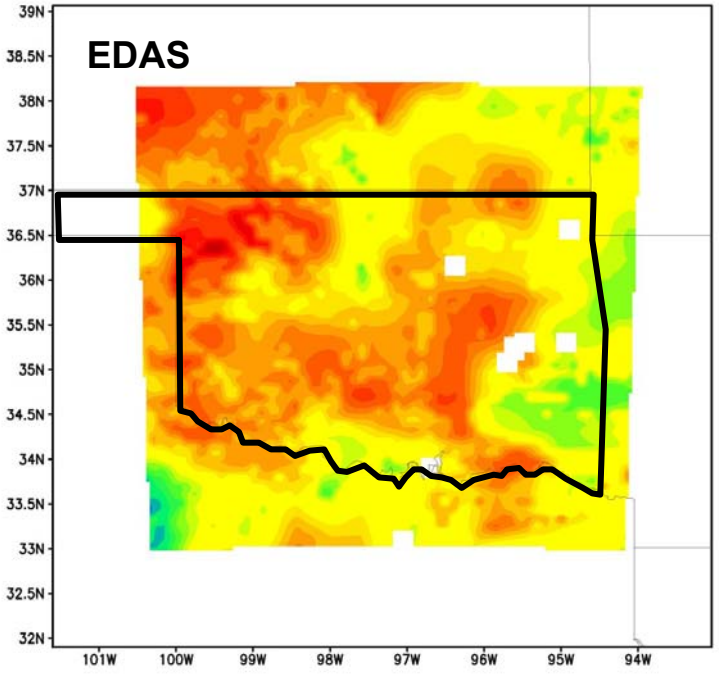


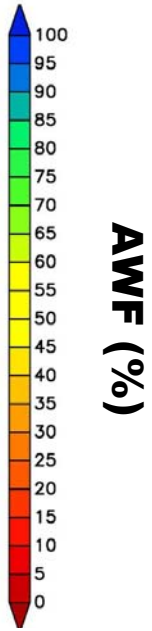
Available Water Fraction

August 3, 2004

ALEXI	EDAS
MAE = 18.71%	MAE = 25.34%
Bias = -5.14%	Bias = -17.31%







Volumetric Soil Moisture Retrievals