Combined Use of Vis/IR and Microwave Remote Sensing Data to Diagnose the Closure Relationship Between Land-Surface Water and Energy Balance

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Land Surface Analysis SAF
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The EUMETSAT Network of Satellite Application Facilities

LSA SAF
Land Surface Analysis

Outline

I. Land-atmosphere coupling and land-atmosphere interaction: An observation-based case example

II. A key pathway of coupling: Closure of water and energy balance at the land-surface (*the question*)

III. Current state of knowledge of the closure

IV. Estimation of closure function: Mapping using remotely sensed observations

V. Future enhanced observing systems

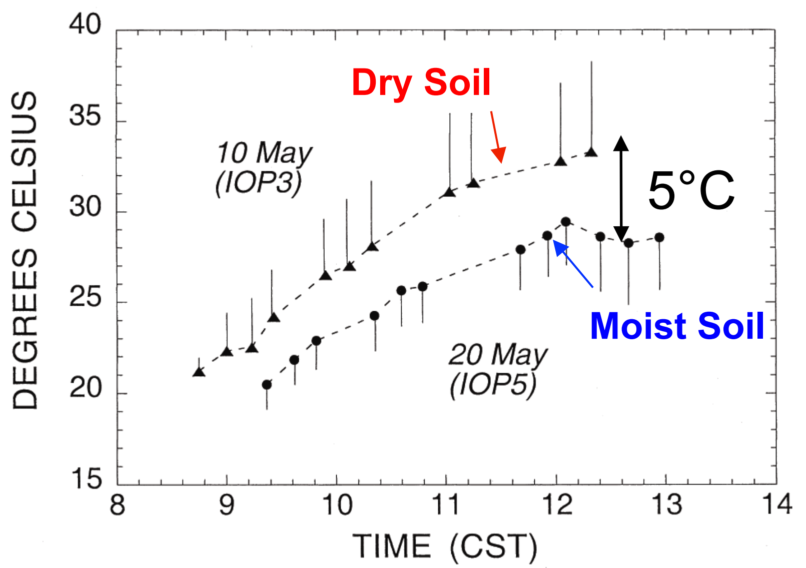
Land-Atmosphere Interaction: An Observation Case Example

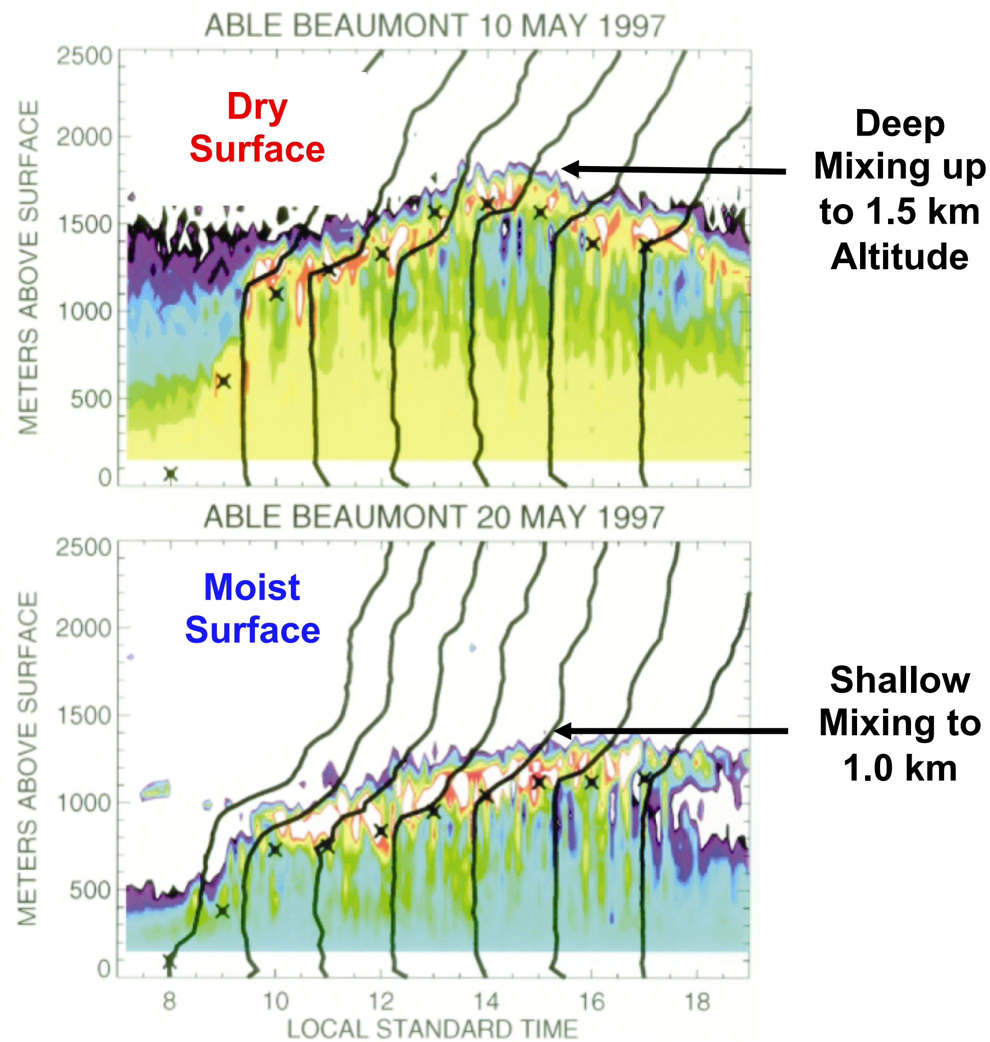
CASES' 97 Field Experiment,
BAMS, 81(4), 2000.

May 10 Dry soil, clear, mild winds. ($L{\cdot}E \approx H$)

May 18 90 mm Rain

May 20 Moist soil, clear, mild winds. ($L{\cdot}E > H$)





H is the conduction of heat from land to atmosphere (turbulent sensible heat flux).
$L{\cdot}E$ is the latent heat flux due to evaporation E. $L = 2.5\times10^{6}\ \left[J\ kg^{-1}\right]$

Coupling of Land Moisture and Temperature Dynamics in Models

Land states θ, T_s

Temperature:

$$c\frac{\partial T}{\partial t} + \frac{\partial G}{\partial z} = 0$$

$$G(0,t) = -\kappa \frac{\partial T}{\partial z}\bigg|_{(z=0,t)} = R_n(T_s) - L \cdot E(\theta, T_s) - H(T_s)$$

$$T_s = T(0,t)$$

Moisture:

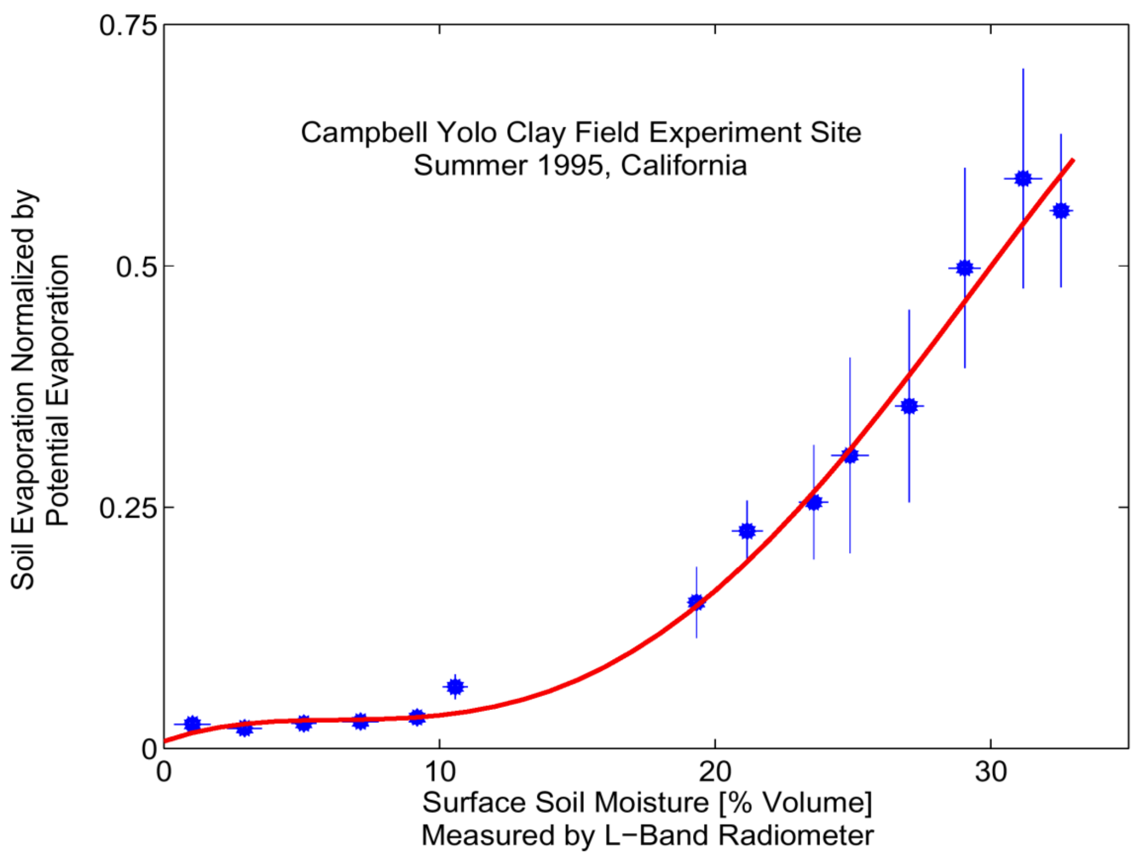
$$\frac{\partial \theta}{\partial t} + \frac{\partial q}{\partial z} = 0$$

$$q(0,t) = -K\left[\frac{\partial \psi}{\partial z} + 1\right]\bigg|_{(z=0,t)} = P - E(\theta, T_s)$$

Coupling:

Soil heat capacity $c(\theta)$
Soil thermal conductivity $\kappa(\theta)$
Liquid water viscosity $K(\theta, T_s)$ and $\psi(\theta, T_s)$
Surface evaporation $E(\theta, T_s)$ ⬅

Key Determinants of Land Evaporation



Cahill et al., JAM(38), 1999.

Latent heat flux (evaporation) links the water, energy, and carbon cycles at the surface.

All meteorological and hydrological models with land water and energy balance (LSM or SVATs) include (explicitly or implicitly) a form for the closure:

e.g., $\beta(\theta)=E/E_p$ or $r_g(\theta)$ …

Parameterized Closure Functions But Without Strong Evidence

NOAH

model grid cell and

$$\beta = \left(\frac{\Theta_1 - \Theta_w}{\Theta_{\text{ref}} - \Theta_w} \right)^f \qquad (7)$$

represents a normalized soil moisture availability term where Θ_w is the wilting point and Θ_{ref} is the field capac-

$$F_4 = \sum_{i=1}^{n} \frac{(\Theta_i - \Theta_w) d_{z_i}}{(\Theta_{\text{ref}} - \Theta_w)\left(\sum_{j=1}^{n} d_{z_j} \right)},$$

CLM

functional type and the soil water potential of each soil layer

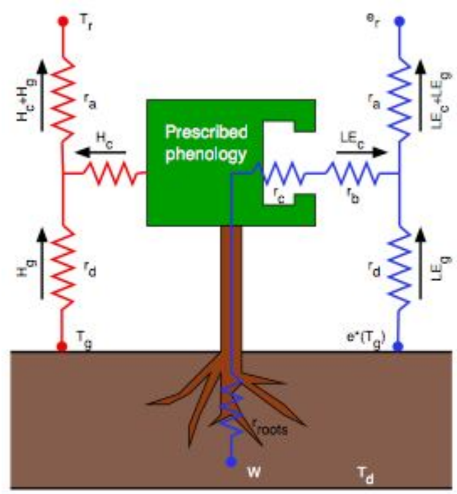
$$\beta_t = \sum_i w_i r_i \geq 1 \times 10^{-10} \qquad (8.10)$$

where w_i is a soil dryness or plant wilting factor for layer i, and r_i is the fraction of roots in layer i.

The plant wilting factor w_i is

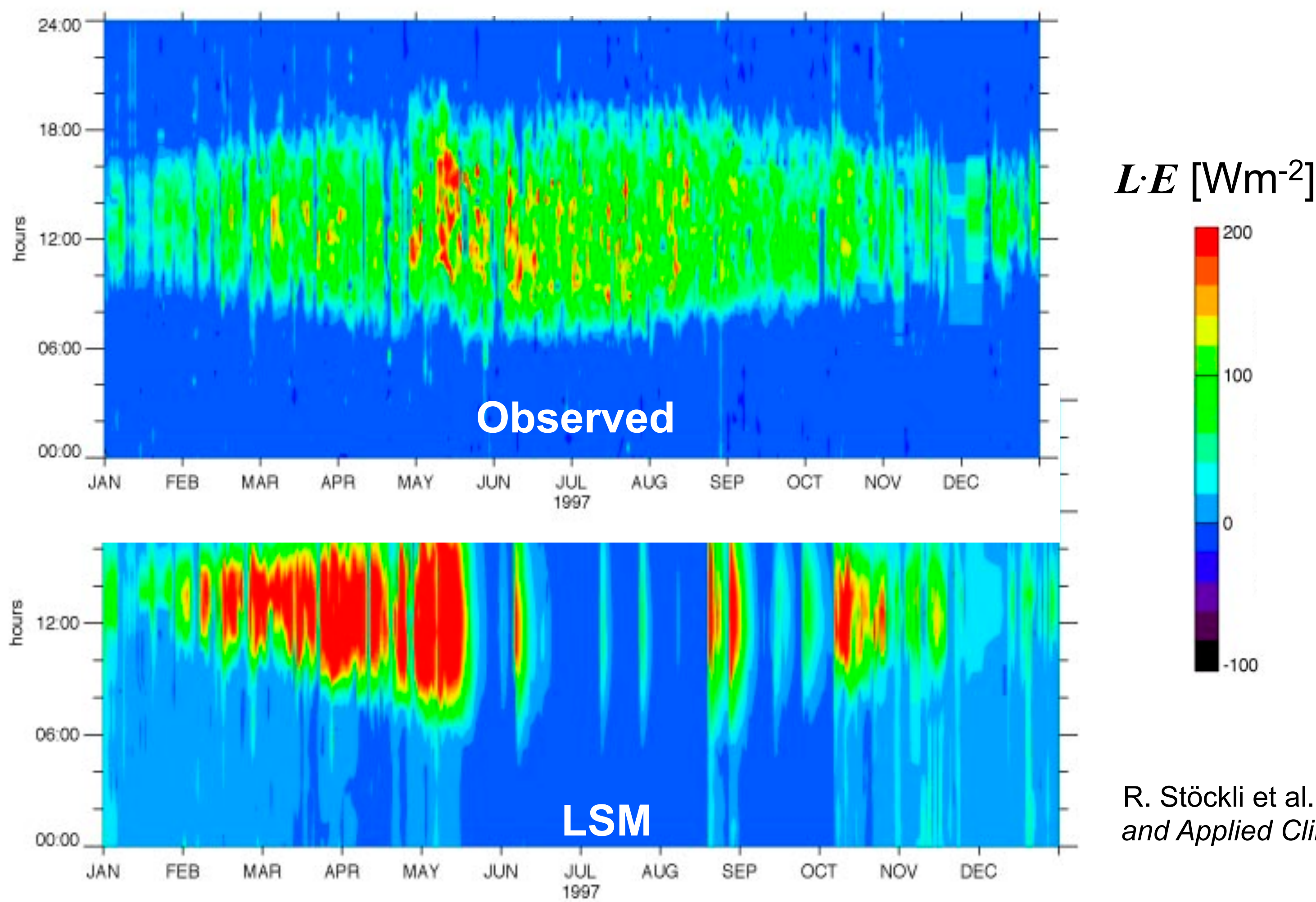
$$w_i = \left\{ \frac{\psi_{\max} - \psi_i}{\psi_{\max} + \psi_{sat,i}} \quad \text{for } T_i > T_f \right\} \qquad (8.11)$$

$$\beta = \begin{cases} \frac{1}{4}\left[1 - \cos\left(\frac{\theta_1}{\theta_{fc}}\pi\right)\right]^2 & \theta_1 < \theta_{fc} \\ 1 & \theta_1 \geq \theta_{fc} \quad \text{or} \quad q_{air} > \alpha q_{sat}(T_g) \end{cases}, \qquad (5)$$



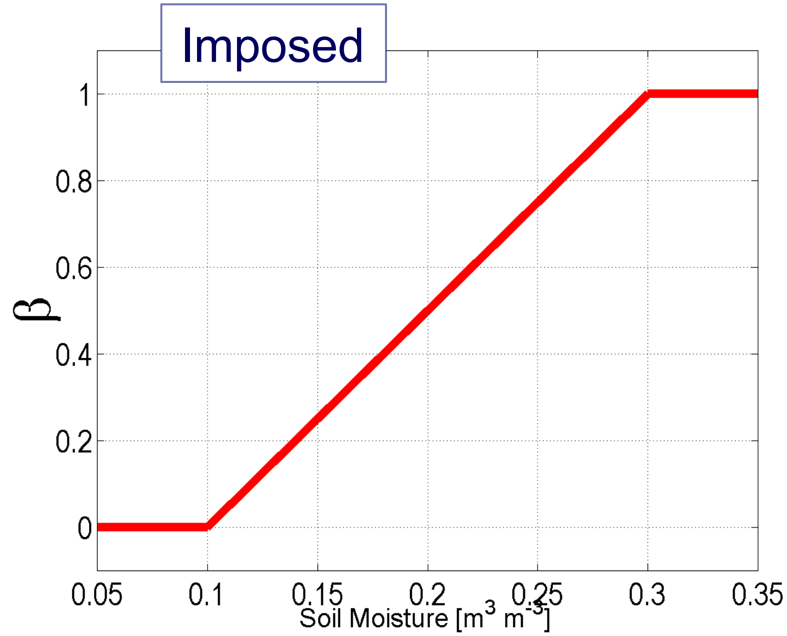
R. Stöckli and P. L. Vidale (ETH)

Consequences for LSMs

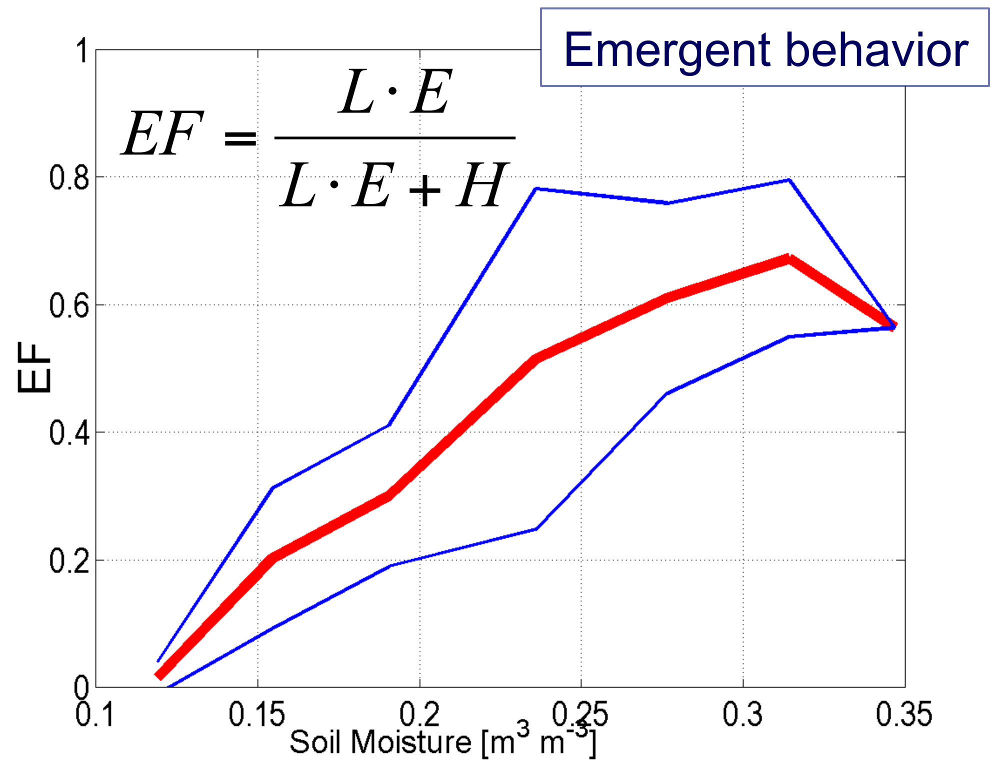


R. Stöckli et al., 2005: *Theoretical and Applied Climatology* , 80(1-2).

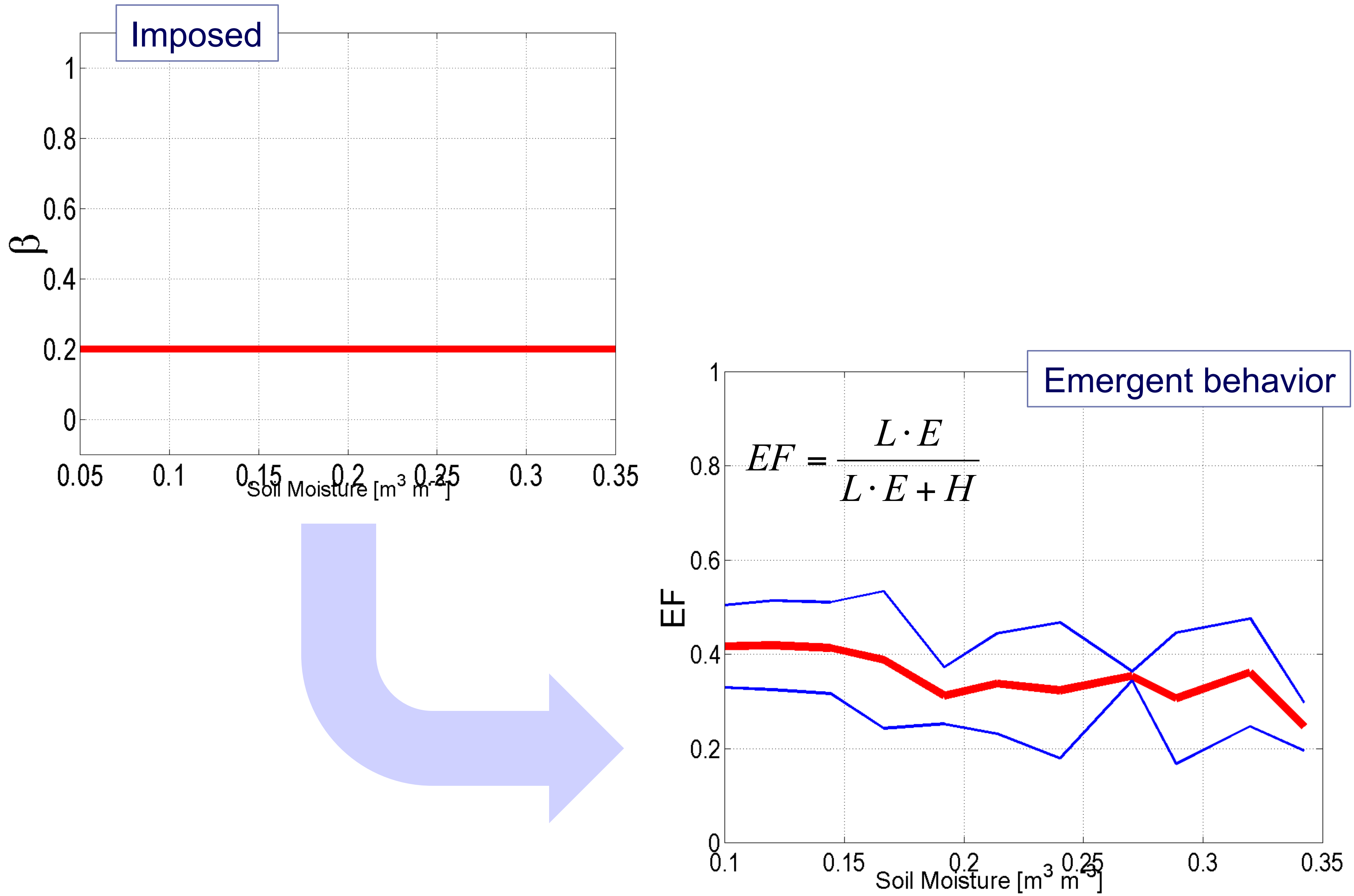
Shape of Closure Function: A Modeling Sensitivity Example



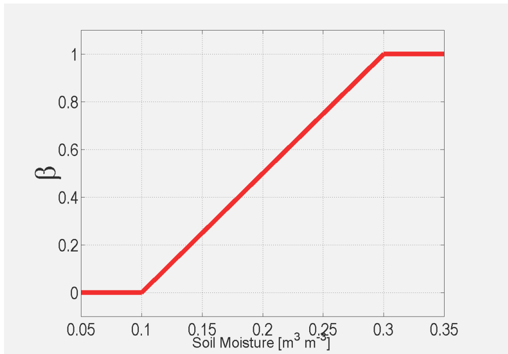
- Numerical model of soil heat and moisture diffusion (SHAW)
- 5 years of JJA simulations
- Durant, Oklahoma Mesonet micrometeorology

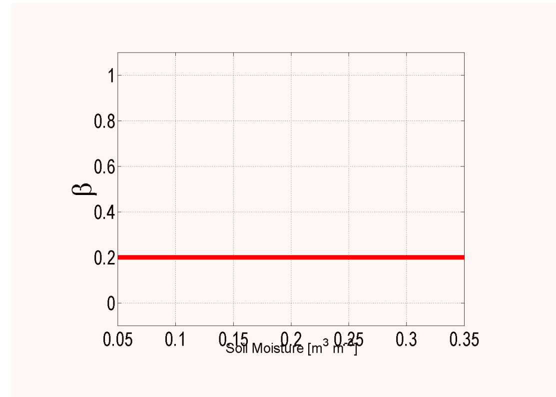


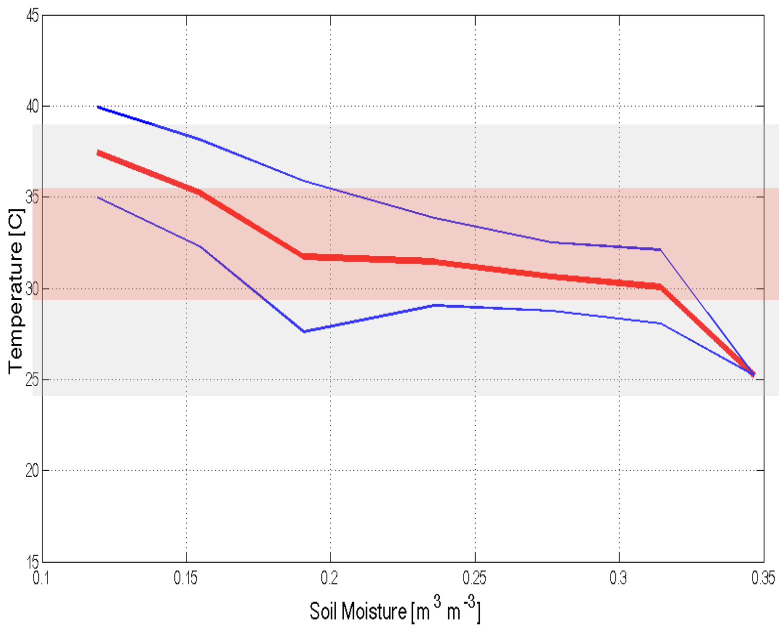
Without a Closure Function

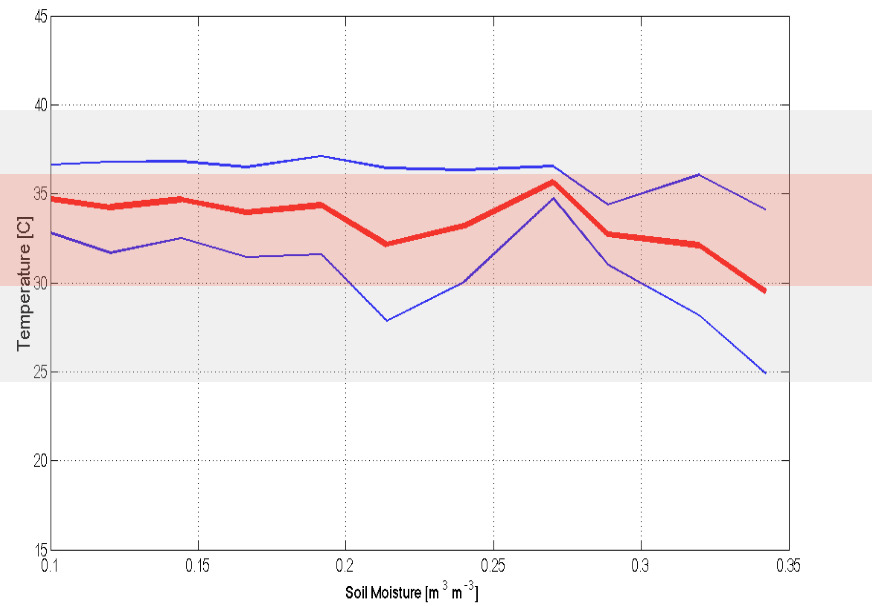


Consequences Land-Surface States (θ, T_s) Coupling

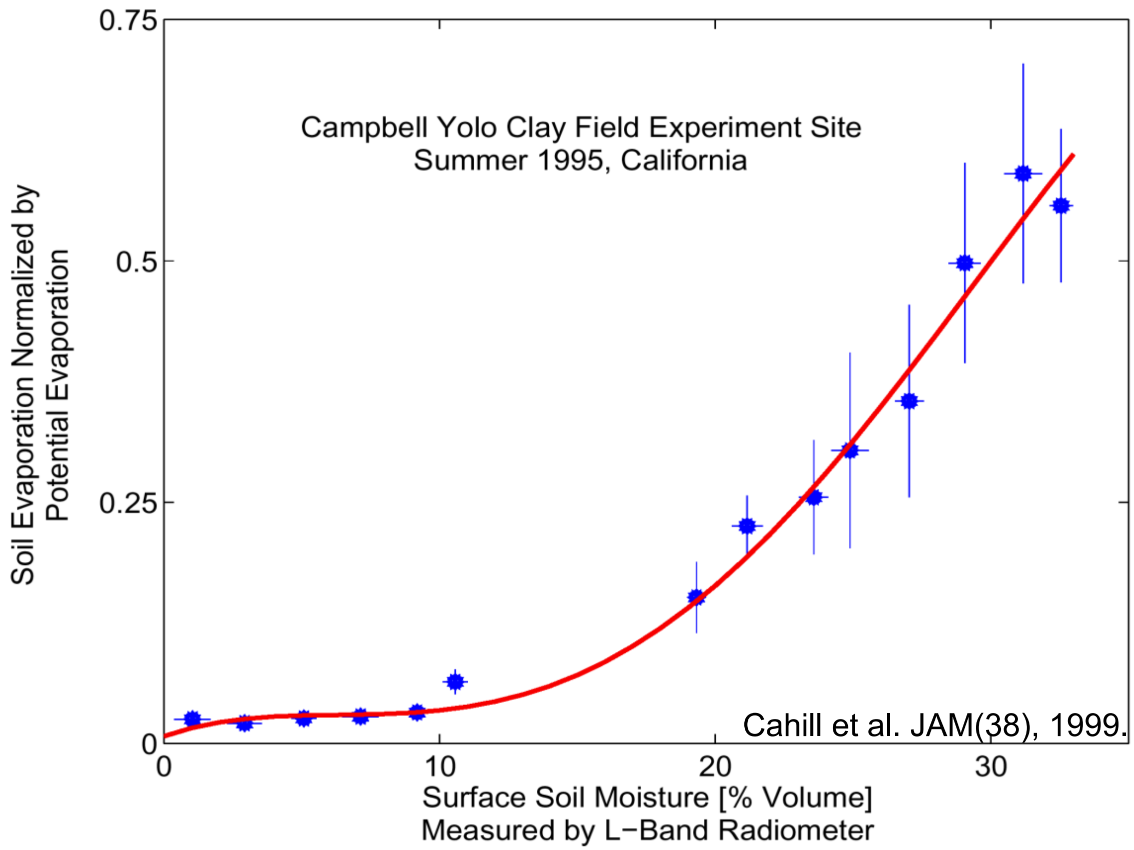








Key Determinants of Land Evaporation



To estimate this closure function, **independent** observations of

soil moisture state

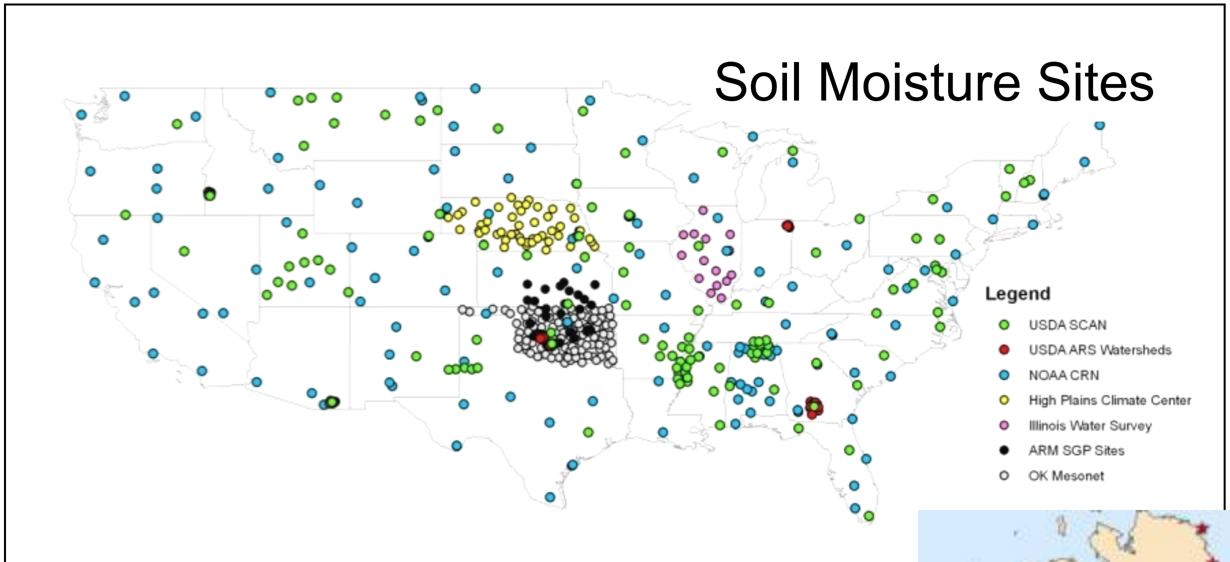
and

evaporation flux

are required.

…the objective

Surface Observing Networks



Note: Sites map may not be up-to-date. Purpose here is to show representative network density: North America example.

Need *independent* observations of the two variables.

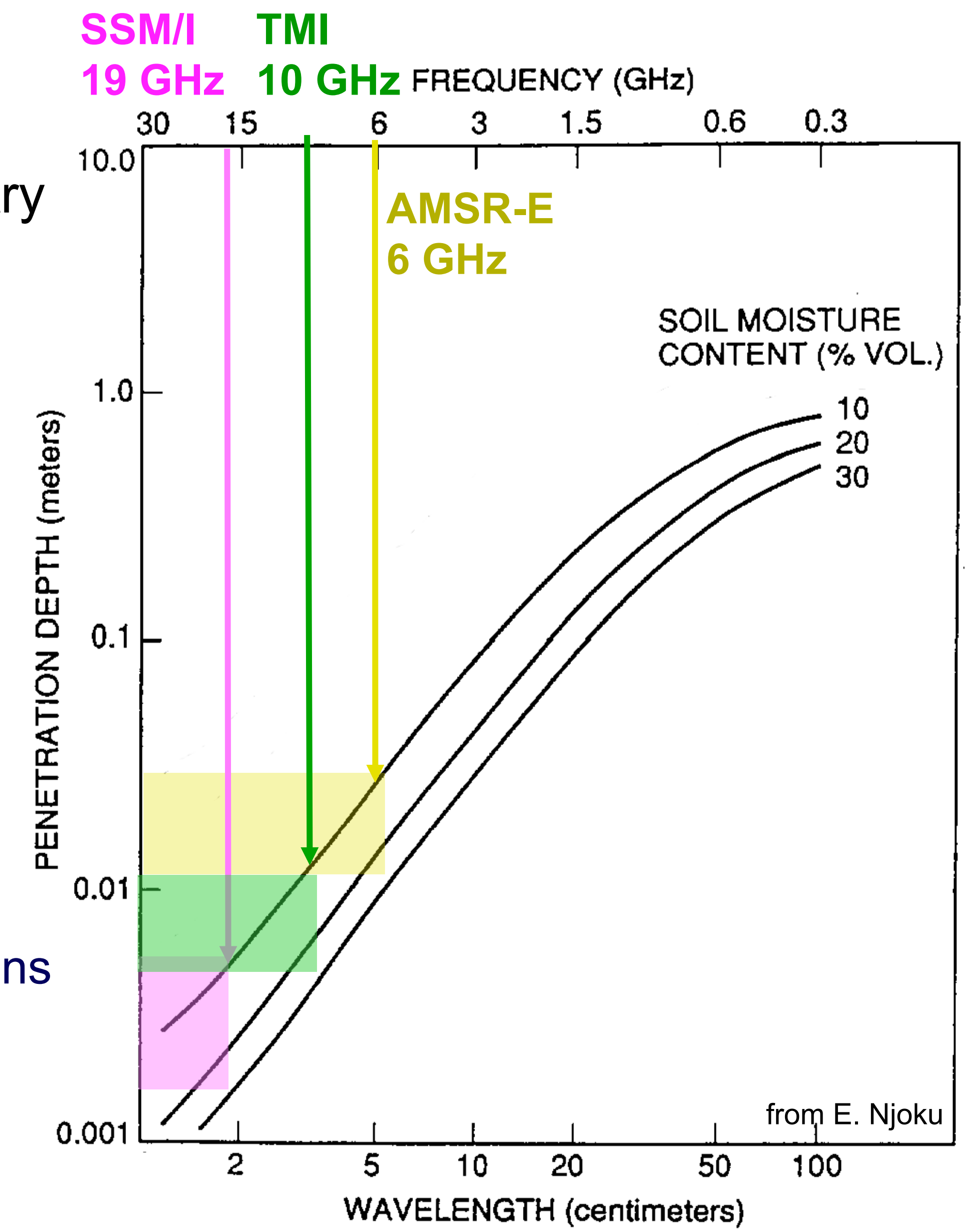
To cover diverse vegetation, soil and seasonal conditions, remotely sensed observations need to be used.

Remote Sensing of Key Variables

1. Surface soil moisture <u>state</u> through low-frequency microwave radiometry

2. Evaporation <u>flux</u> or through Vis/IR LST products

How to map the <u>flux</u> without:
- empirical relations
- use of soil and vegetation specifications
- precipitation, vegetation index, etc.



Signature of Moisture Constraints in Land Temperature Dynamics

1. Soil heat transport

Conceptual

$$c\frac{\partial T_s}{\partial t}+\frac{\partial G}{\partial z}=0 \qquad \text{and} \qquad G=-\kappa\frac{\partial T_s}{\partial z}$$

2. Surface energy balance

$$G(0,t)=R_s^{\downarrow}(1-a)+R_l^{\downarrow}-R_l^{\uparrow}(T_s)-H(T_s)-L\cdot E(\theta,T_s)$$

3. Fluxes:

$$R_l^{\uparrow}(T_s)=\varepsilon\sigma T_s^4 \qquad H(T_s)=\frac{\rho c_p}{r_a}(T_s-T_a) \qquad L\cdot E(\theta,T_s)=\frac{\rho L}{r_a}\beta(\theta)\left[q(T_s)-q_a\right]$$

↑ soil moisture

Lead to linear T_s perturbation analysis result:

$$\frac{d\delta T_s}{d\tau}=-\left(\frac{r_a}{r_o}+1+\beta\frac{\Delta}{\gamma}+\frac{r_a}{r_g}\right)\cdot\delta T_s$$

where:

$$\tau=t/\left(P\cdot r_a/\sqrt{\omega}\cdot\rho\cdot c_p\right)$$

$$r_o=\rho\cdot c_p/4\cdot\varepsilon\cdot\sigma\cdot T_a^3$$

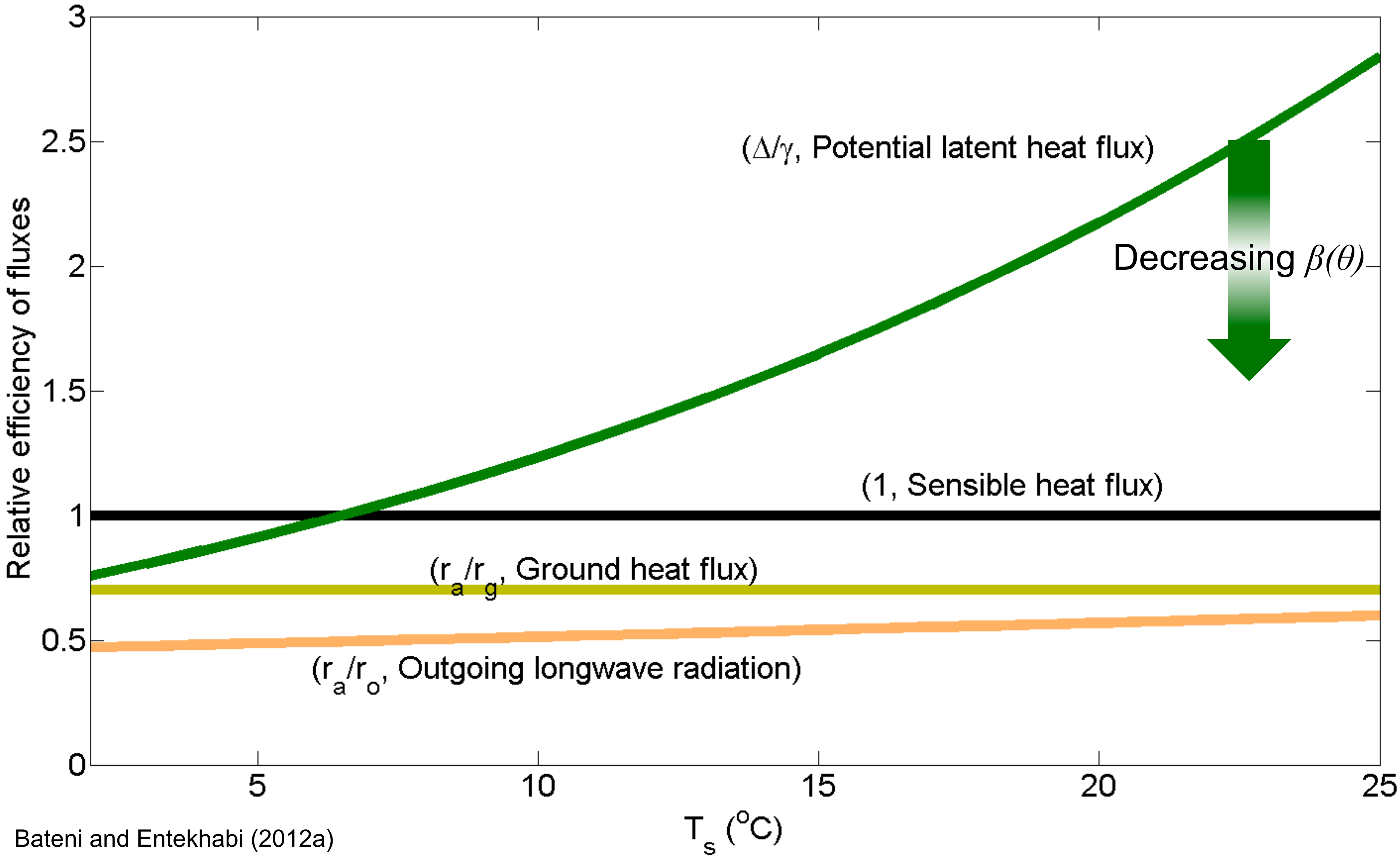
$$r_g=\rho\cdot c_p/P\cdot\sqrt{\omega}$$

$$\Delta/\gamma=\left(de_s/dT\right)/\left(c_p\cdot P/\left(R_d/R_v\right)\cdot L\right)$$

Terms are **time-scales** of restoration to equilibrium.

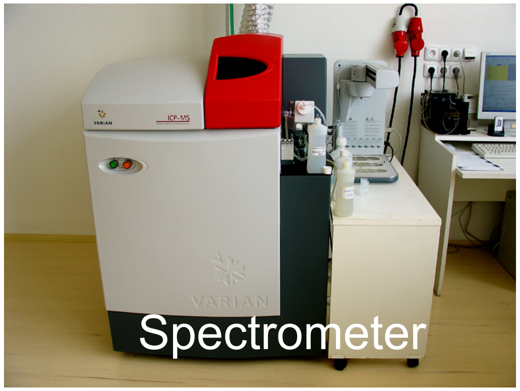
Bateni and Entekhabi (2012a)

Relative Heat Transport Efficiencies

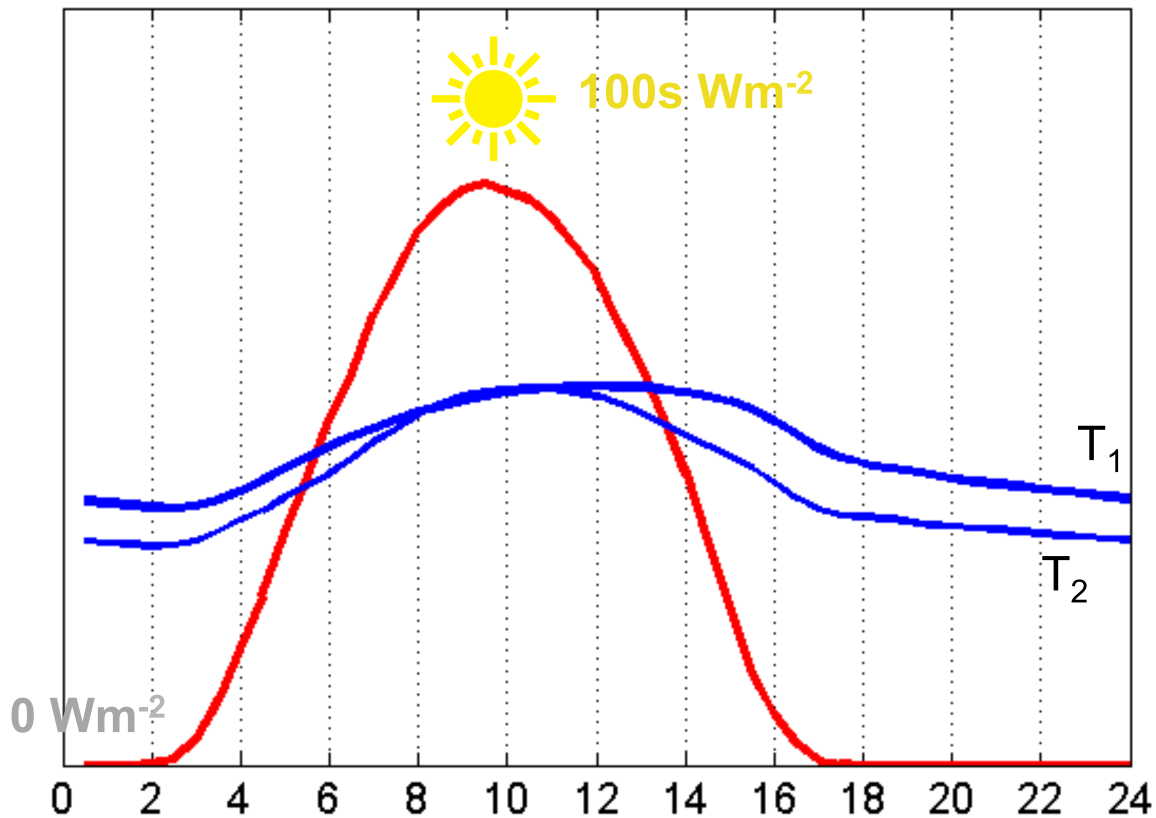


Bateni and Entekhabi (2012a)

Instrumentation



A Natural and Global Energy-Excitation and Thermal-Response Instrument



The Evaporation Estimation Problem

State Equation:

Soil heat transport

$$c\frac{\partial T_s}{\partial t} + \frac{\partial G}{\partial z} = 0$$

Surface energy balance

$$G(0,t) = -\kappa \frac{\partial T}{\partial z}\bigg|_{(z=0,t)} = R_n - L \cdot E - H = R_n - \frac{1}{1-EF}H$$

$$= R_n - \frac{1}{1-EF}\rho c_p C_H U\left(T_s - T_a\right)$$

Observation Equation:

$$\mathbf{T}_{satellite} = \mathbf{M} \cdot \mathbf{T}_s + \boldsymbol{\varepsilon}$$

Multiple platforms and resolutions

Unknowns (dimensionless):

C_H Turbulent transfer coefficient scales $LE+H$ varies seasonally.

EF Evaporative fraction partitions $LE/(LE+H)$ varies daily.

- Does not require information about **land cover, soil and vegetation or precipitation**.
- Driven principally by remotely sensed diurnal cycle of land-surface temperature.

Variational Adjoint-State Data Assimilation

Observation equation:

$$\mathbf{T}_{obs} = \mathbf{M} \cdot \mathbf{T}_s + \boldsymbol{\varepsilon}$$

Multiple satellite platforms and resolutions
(GOES and AVHRR LST products)

Minimize least-squares penalty function:

Remote sensing

$$\underset{EF, C_H}{Minimize} \quad J = \left[\mathbf{T}_{obs} - \mathbf{M} \cdot \mathbf{T}_s \right]^T \mathbf{G}_{\mathbf{T}_s}^{-1} \left[\mathbf{T}_{obs} - \mathbf{M} \cdot \mathbf{T}_s \right] +$$

Measurement misfit penalty

$$+ \left[EF - \overline{EF} \right]^T G_{EF}^{-1} \left[EF - \overline{EF} \right] + \left[C_H - \overline{C_H} \right]^T G_{CB}^{-1} \left[C_H - \overline{C_H} \right]$$

Priors penalty

$$+ \int_{\upsilon} \Lambda^T \left[\frac{d\mathbf{T}_s}{dt} - \mathbf{F}\left(\mathbf{T}_s, EF, C_H \right) \right] dt$$

Adjoined physical constraint

Forcing: $T_a \quad \|U\| \quad R^{\downarrow}$

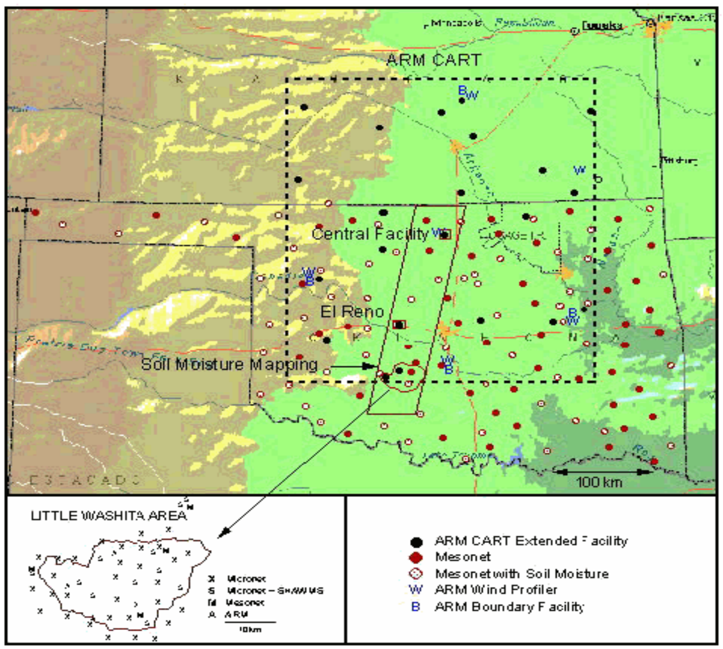
EF varies **daily.**
$\boldsymbol{C_H}$ varies **monthly**.

Bateni and Entekhabi (2012b)

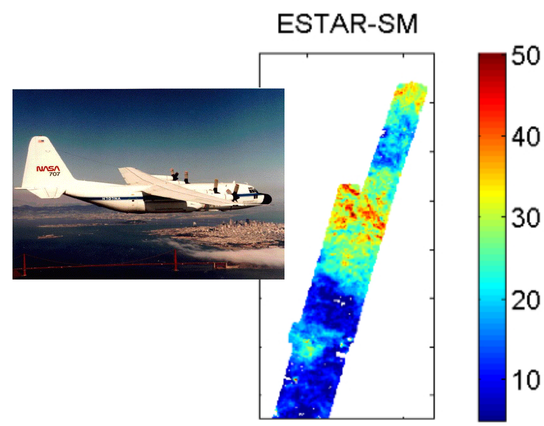
ARM/CART Site Application

Well-instumented DoE's Atmospheric Radiation Measurement (ARM) Cloud and Radiation Testbed (CART)

Mid-April to mid-October 1997

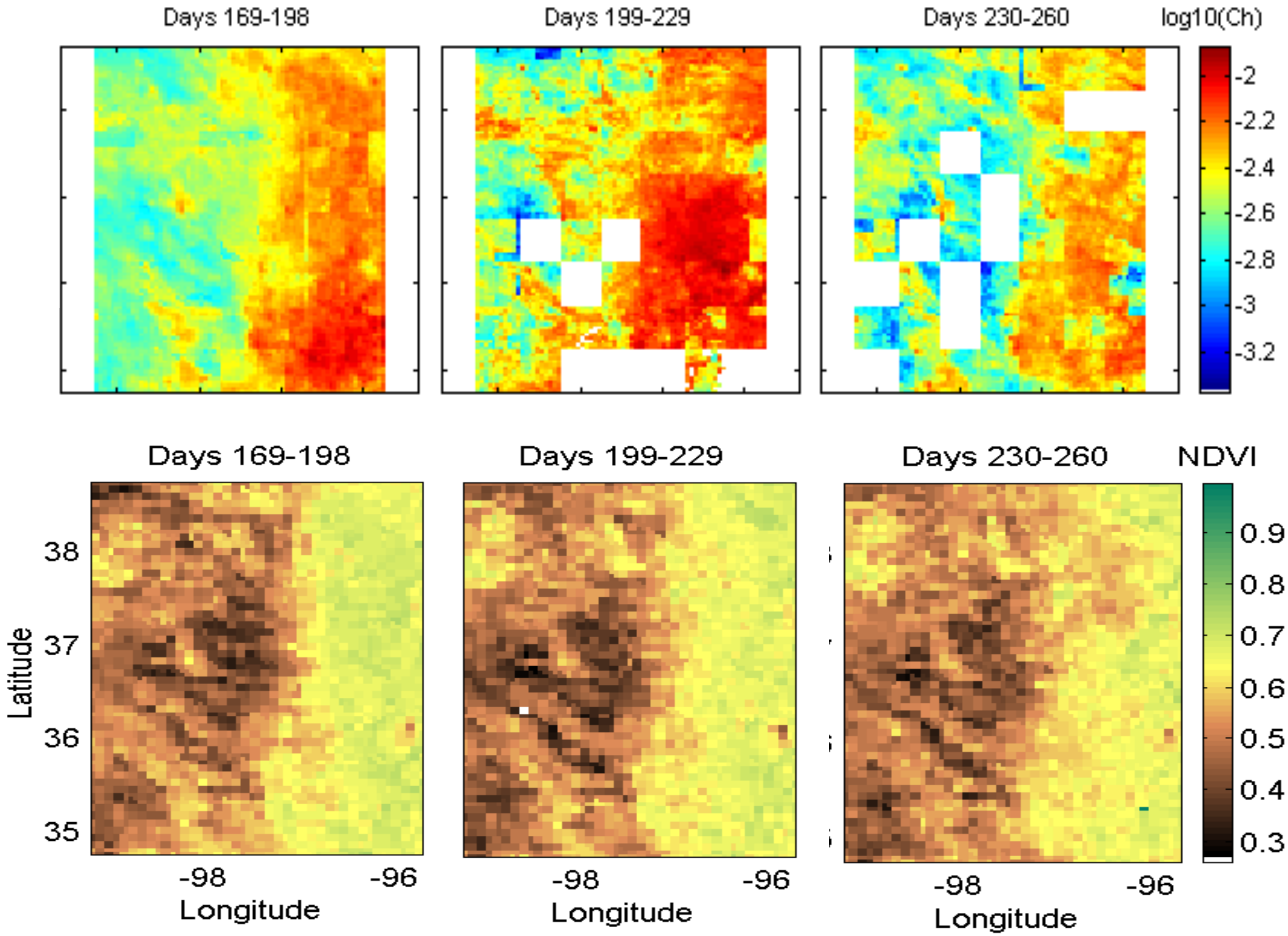


Southern Great Plain (SGP97)



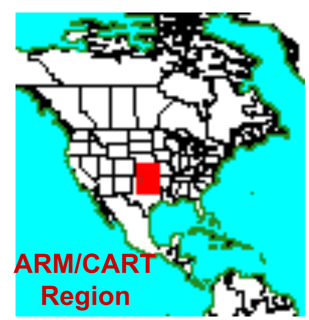
Airborne L-Band Radtiometer ESTAR (Electronically Scanned Thinned Array Radiometer)

Estimation of Turbulent Transfer Coefficient



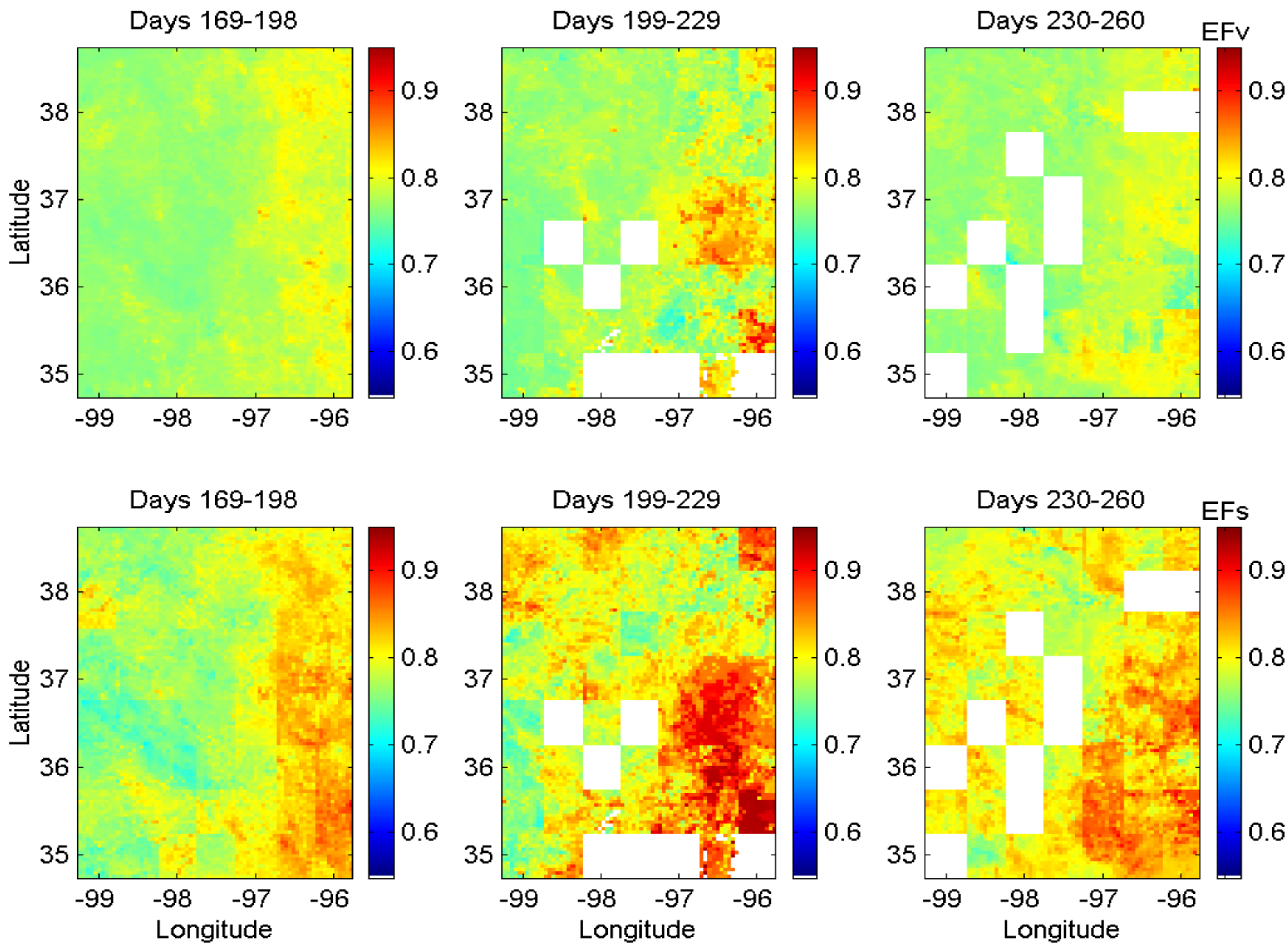
C_{H_N}

NDVI (withheld from estimation)



Bateni and Entekhabi (2012b)

Components of Evaporative Fraction

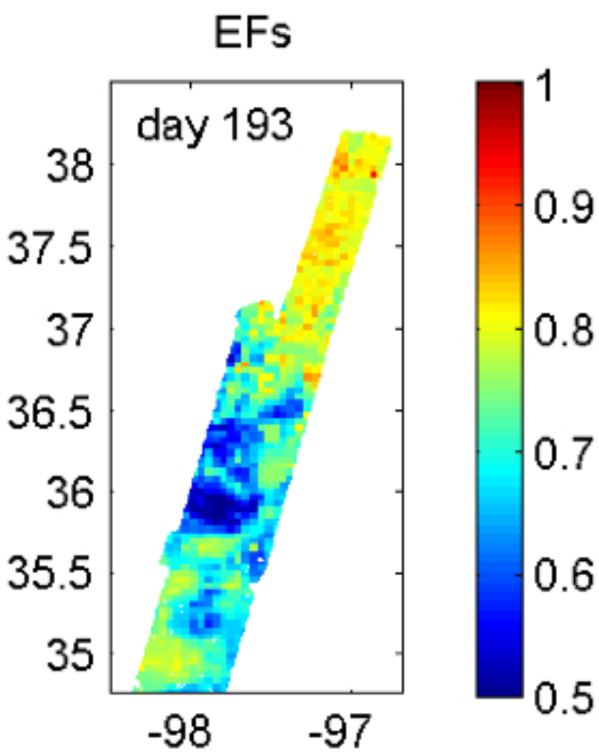


EF_v

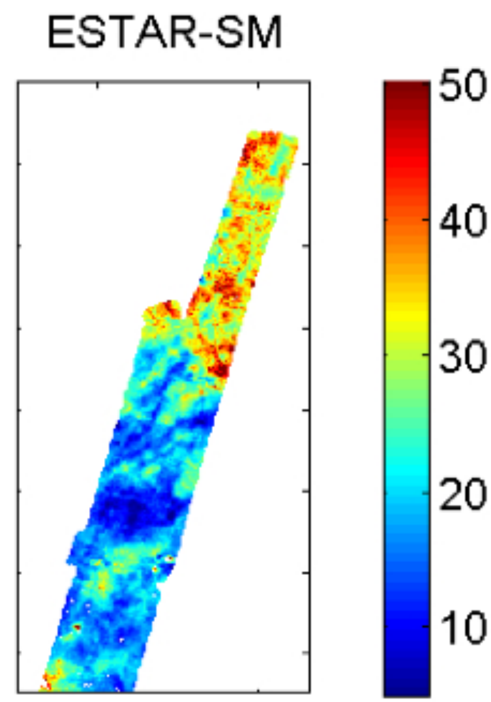
EF_s

Bateni and Entekhabi (2012b)

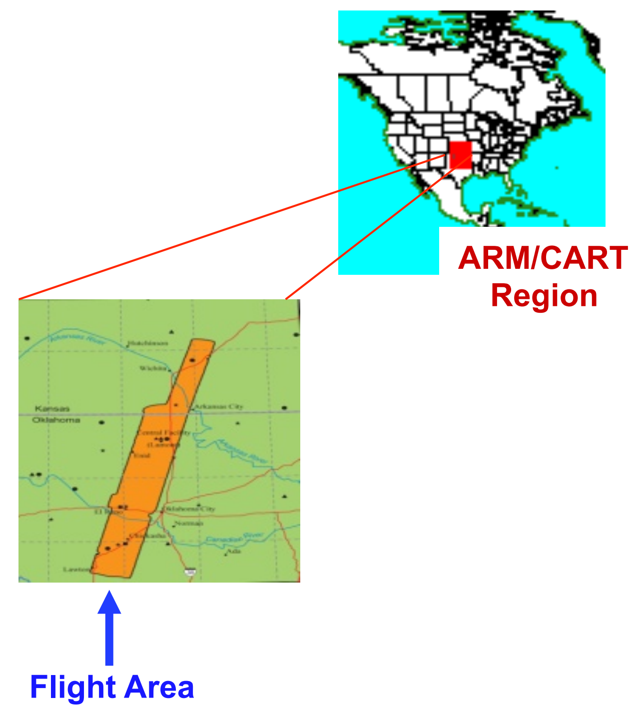
Pair With Independent Airborne Soil Moisture Measurements



EF from multiplatform remotely-sensed surface temperature

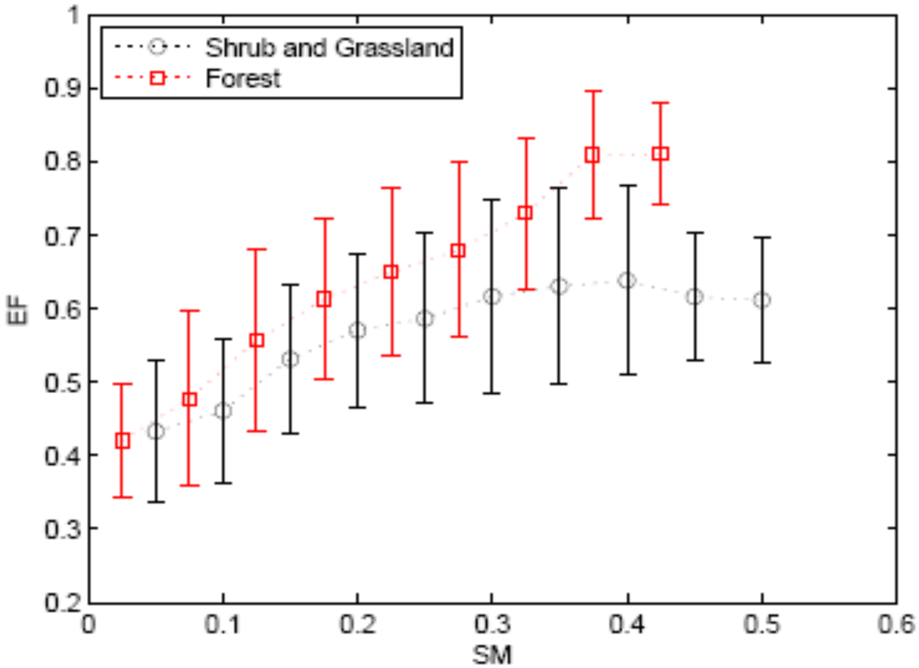


Volumetric surface soil moisture θ from airborne μwave

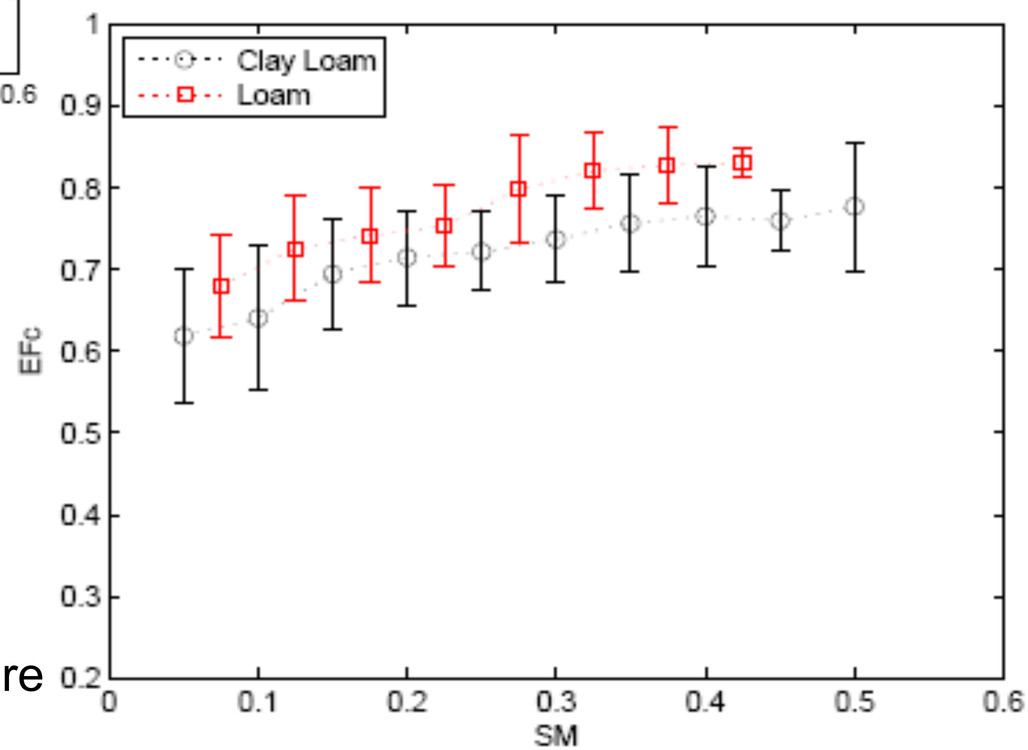


Bateni and Entekhabi (2012b)

Example $EF(\theta)$ Closure Relationship Estimation



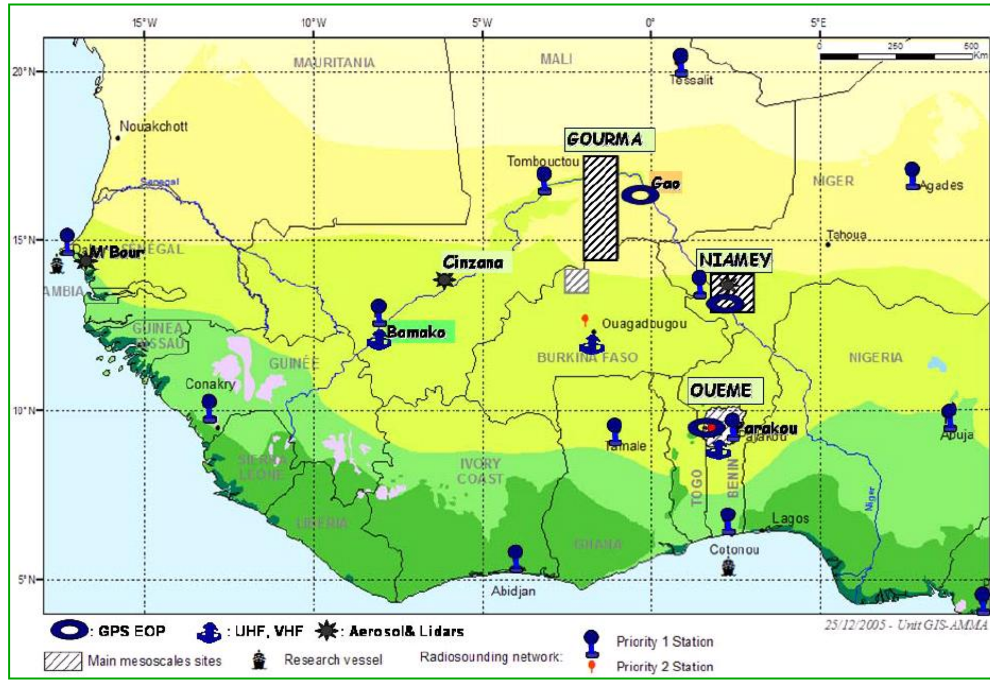
Vegetation type



Soil texture

Bateni and Entekhabi (2012b)

Scaling to Satellite Application



AMMA

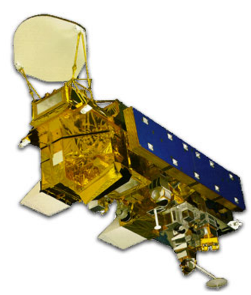
Satellites:

Meteosat Second Generation (MSG)
SEVIRI vis/IR instrument

SEVIRI Disc:
4 vis/NIR and 8 IR channels
(geostationary; 15 mins interval)

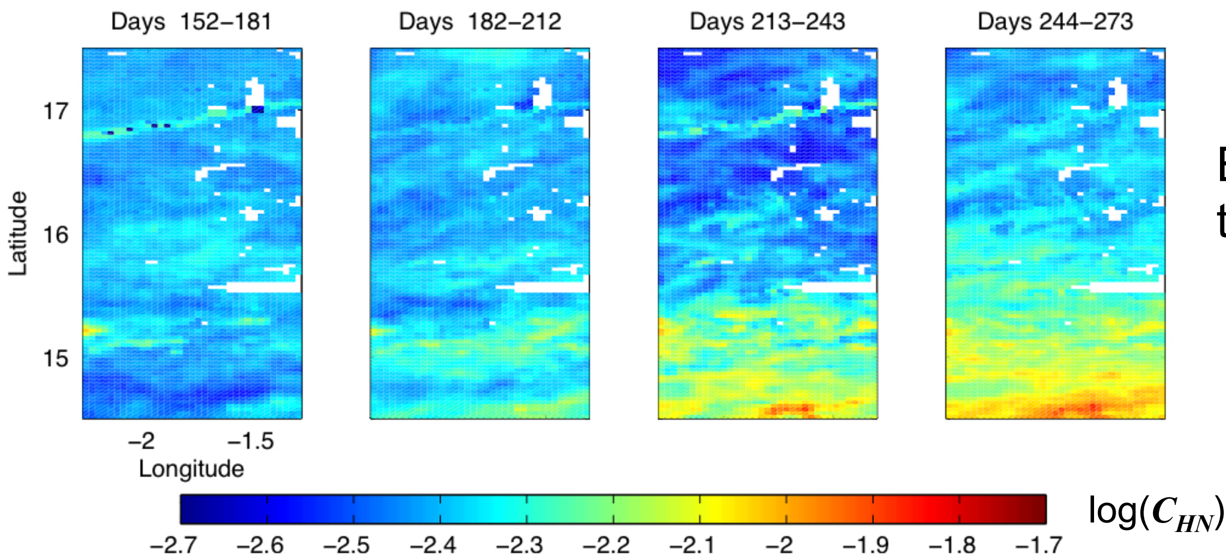
LSA SAF LST Product

AQUA's AMSR-E microwave imaging radiometer



AMSR-E microwave
6.9 GHz (56 km)
10.6 GHz (38 km)

Retrievals Examples



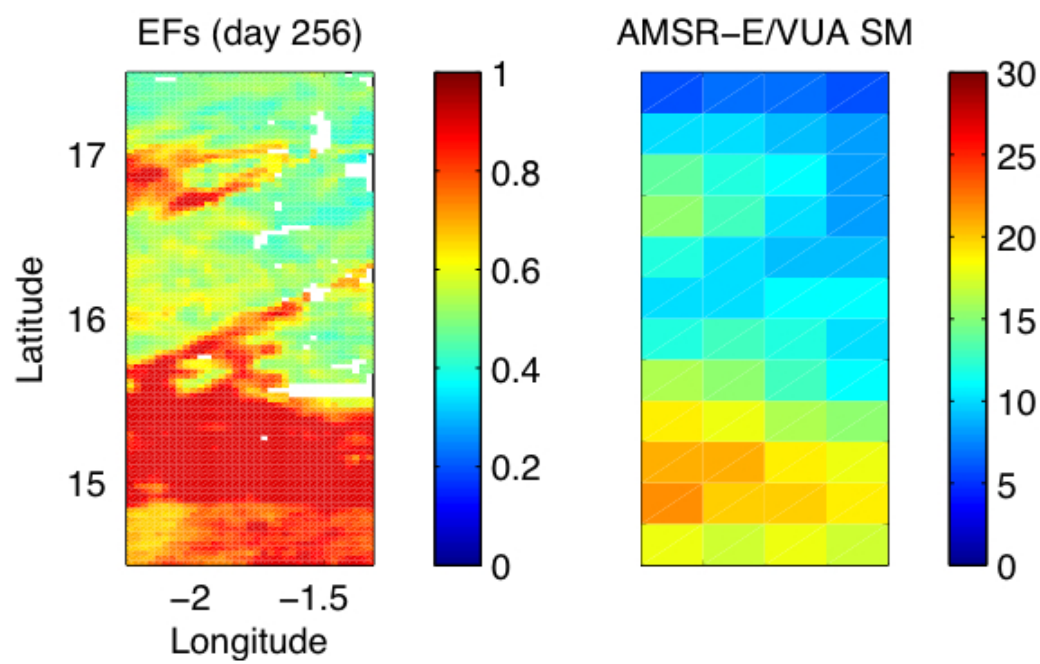
Estimated neutral turbulent transfer coefficient C_{H_N}

Example of one day's paired

estimated evaporative fraction EF

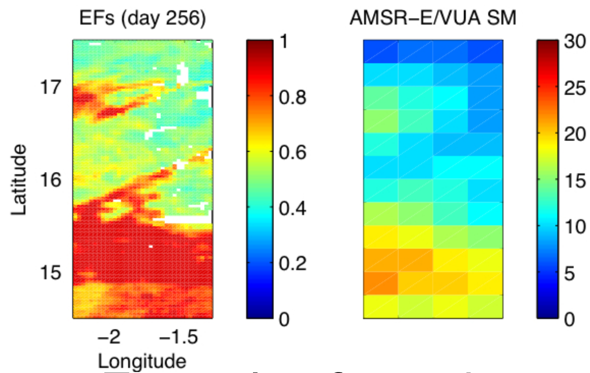
and

AMSR-E soil moisture



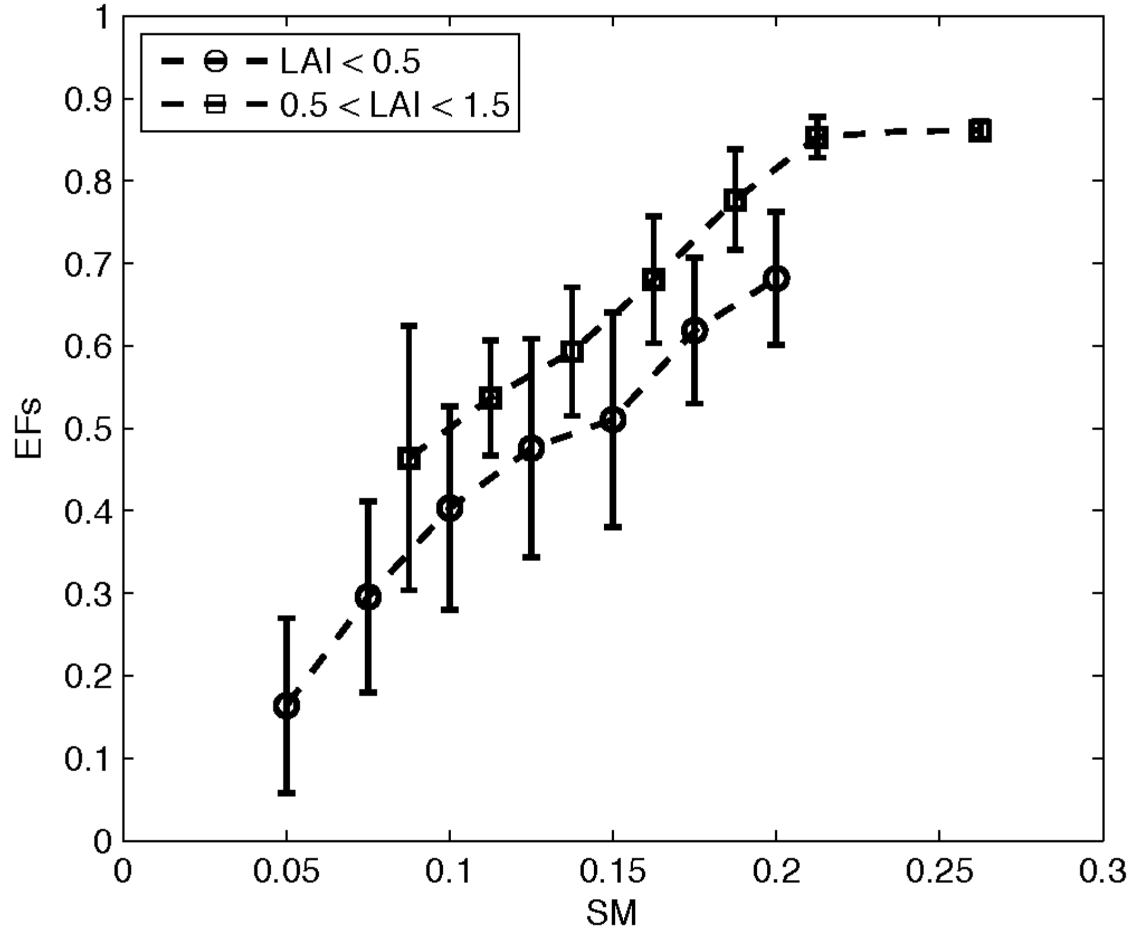
Bateni and Entekhabi (2012c)

EF_s Retrievals

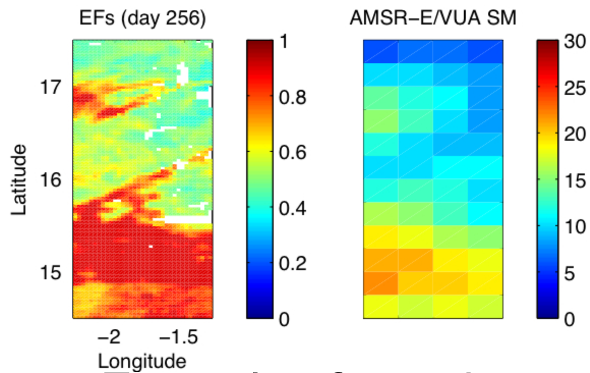


Example of one day

Closure Function

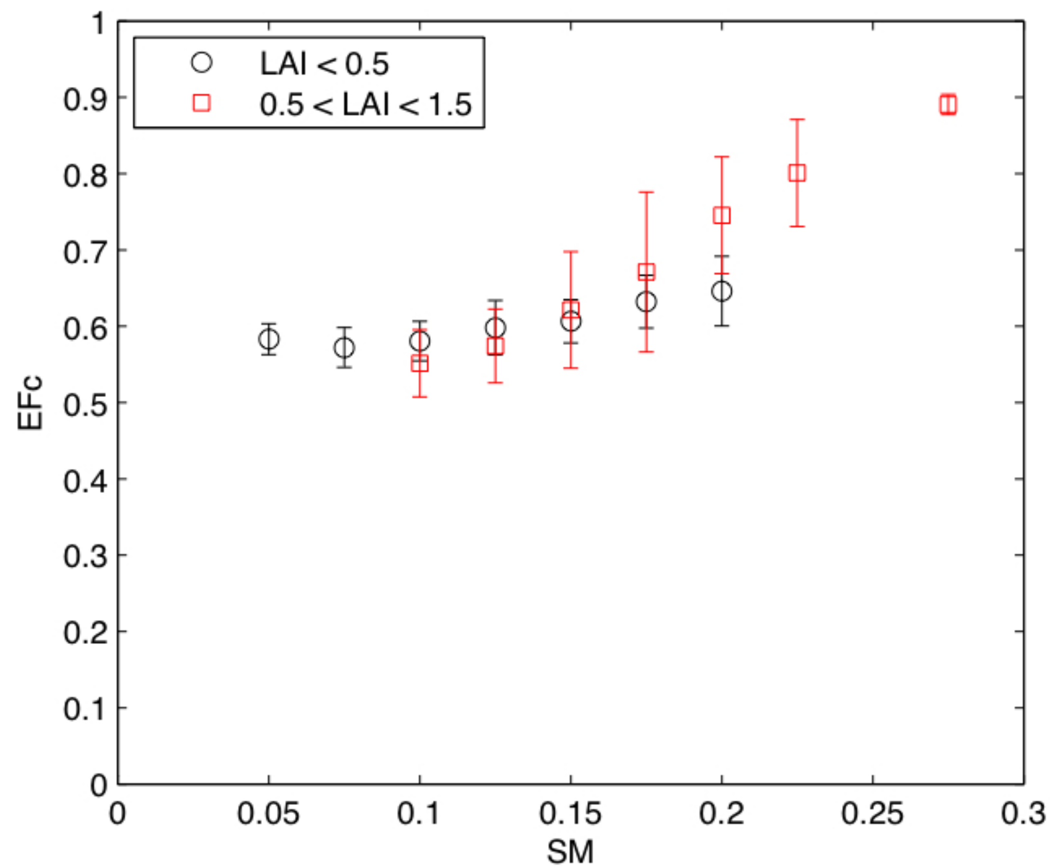


EF_c Retrievals



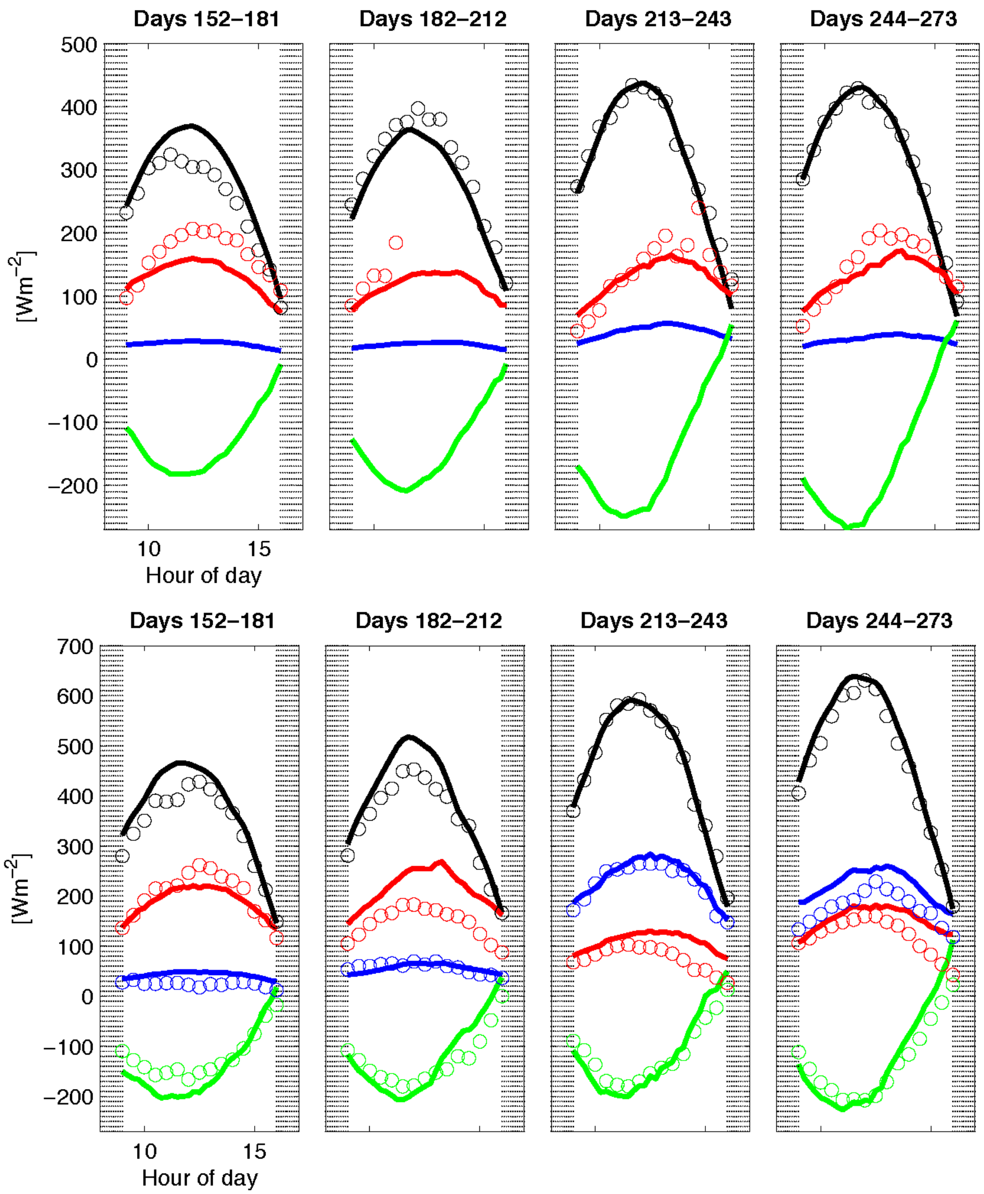
Example of one day

Closure Function



Test With AMMA Observations: Diurnal Cycle

Bamba (top) and Agoufou (Bottom)



FIFE
22 Flux Stations in 15 km x 15 km Area

Daily average fluxes

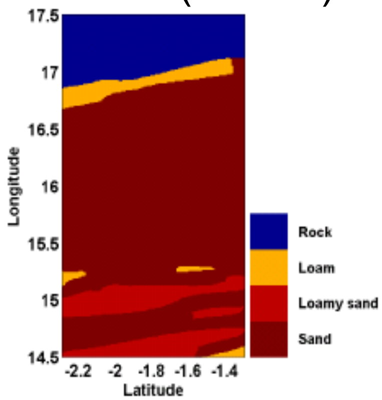
	ρ	RMSE [Wm^{-2}]
LE	0.98	19.77
H	0.99	9.87

Half-hour fluxes

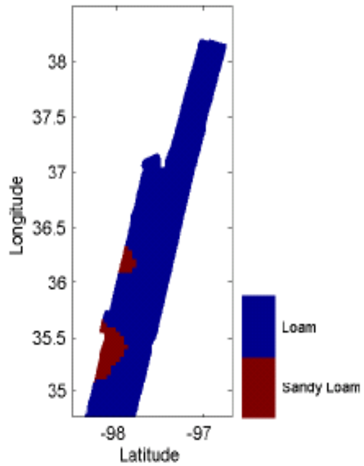
	ρ	RMSE [Wm^{-2}]
LE	0.92	56.19
H	0.90	31.18

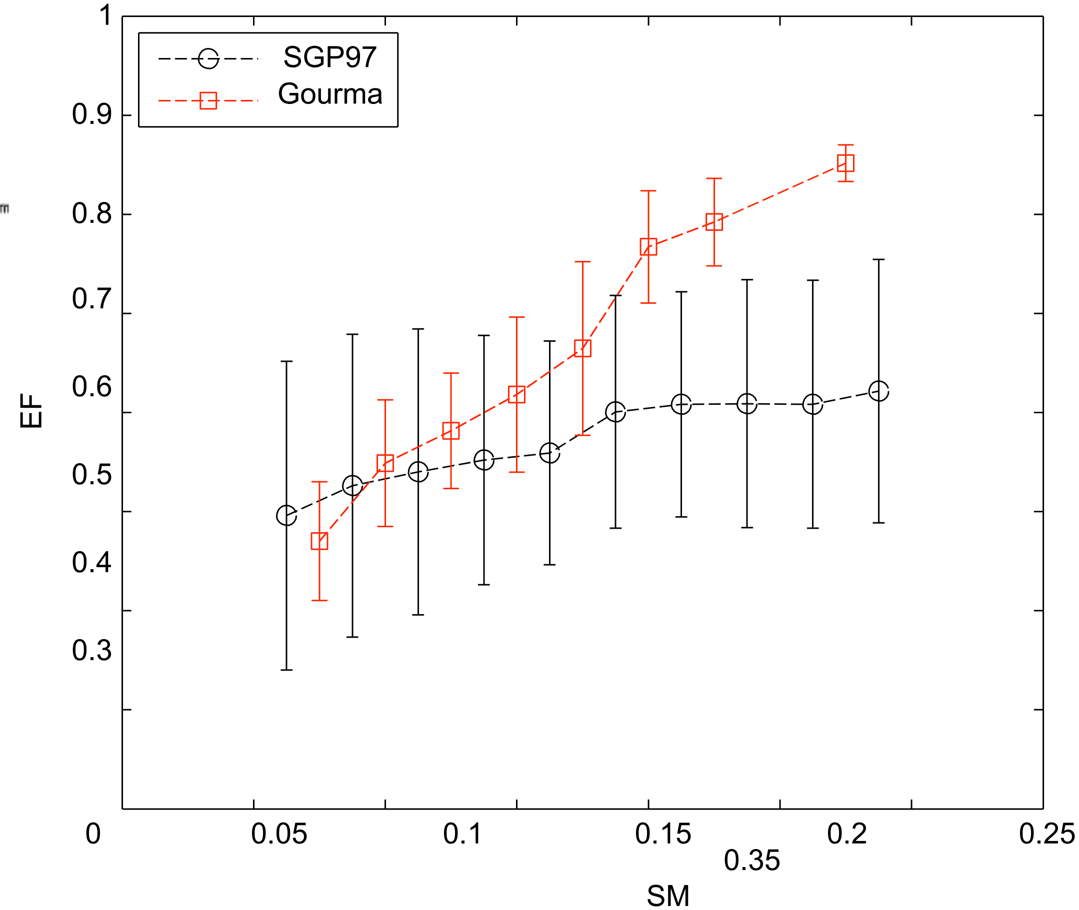
EF_s versus Soil Moisture for W. Africa and US

West Africa (AMMA)



Southern Great Plains (ARM/CART)





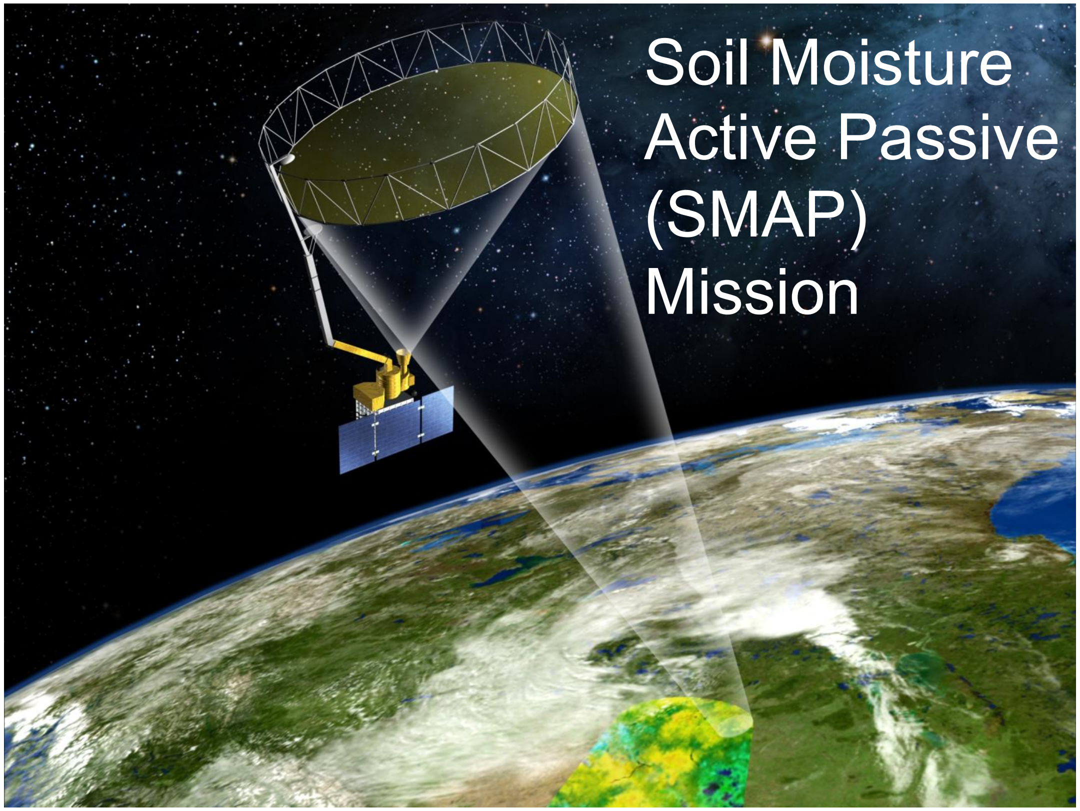
Bateni and Entekhabi (2012c)

Improved Observing Systems

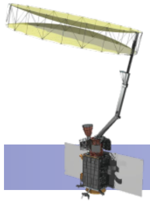
Soil moisture with:

- Finer spatial resolution
- Increased vegetation penetration
- Deeper sensing depth
- Great soil moisture sensitivity
- Global coverage
- RFI detection and mitigation

is the rate-limiting information.



Development of next-generation sensing systems and data-sets

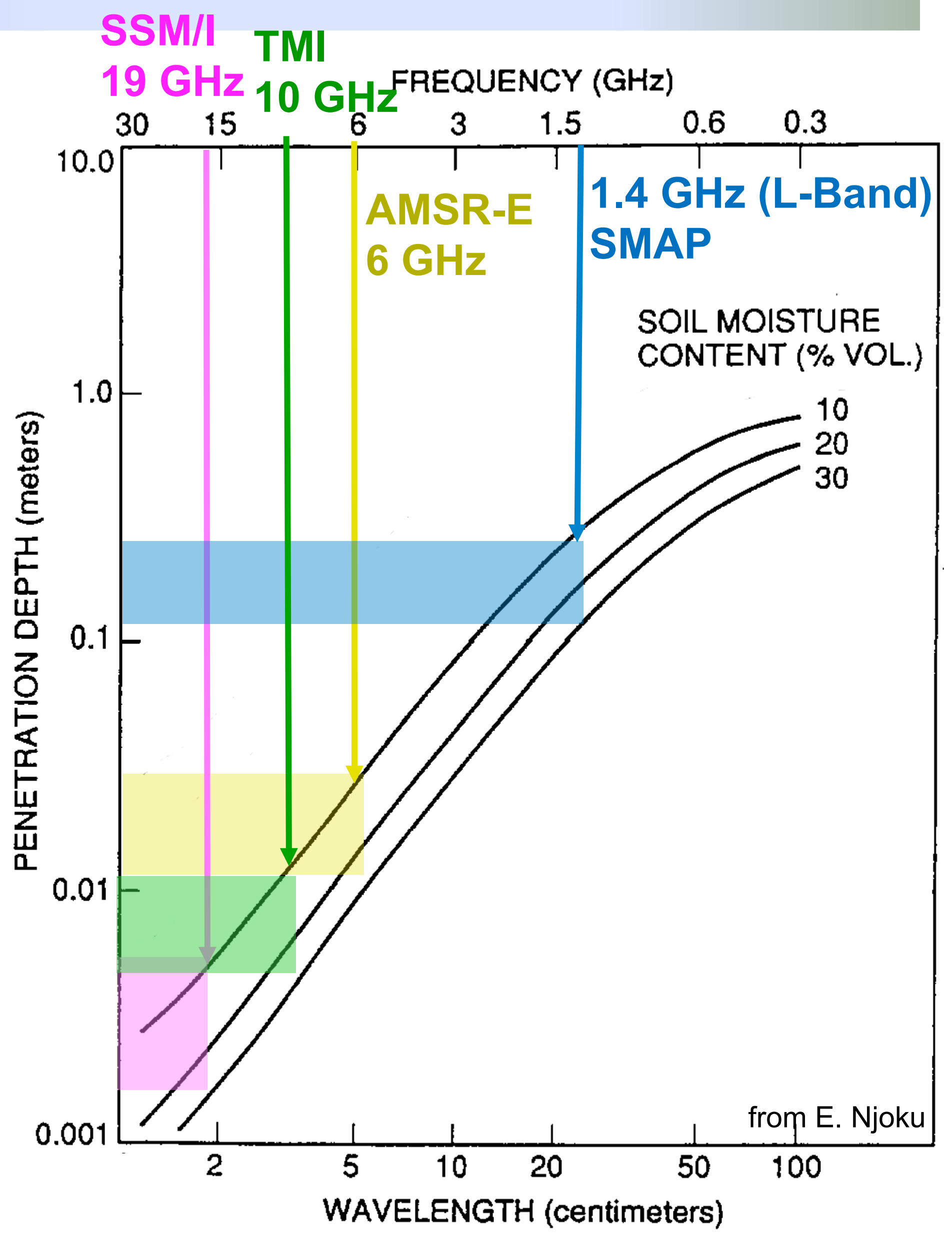


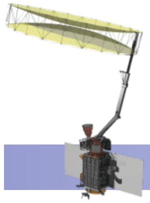
Comparison Across Microwave Frequencies

λ = Wavelength
n’’ =**Im**{Refractive Index}
Power Attenuates as $e^{-z/d}$

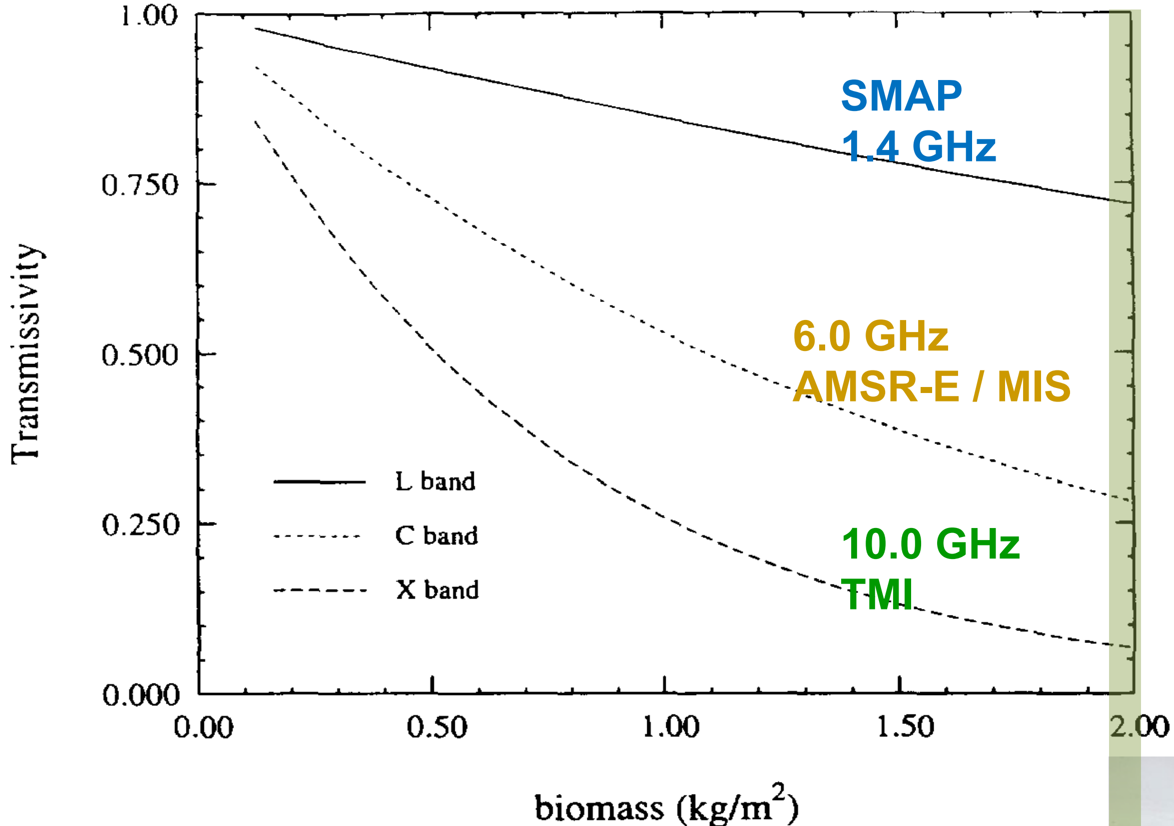
$$d = \frac{\lambda}{4 \cdot \pi \cdot n''}$$

Existing Sensors	**SSM/I**	**19 GHz (50 km)**	**~1 mm**
	TMI	**10 GHz (38 km)**	**~ 1 mm**
	AMSR-E MIS	**6 GHz (56 km)**	**~ 10 mm**
Future	**SMAP**	**1.4 GHz (9 km)**	**~ 50 mm**





Vegetation Opacity at Microwave Frequencies



For Example:

SSM/I	(19 GHz)	100% Loss
TMI	(10 GHz)	95% Loss
AMSR-E / MIS	(6 GHz)	75% Loss
SMAP	(1.4 GHz)	25% Loss

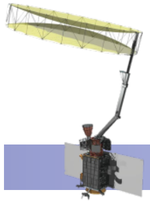
Project Development

US National Research Council Report: *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond*

SMAP is one of four missions recommended by the NRC "Decadal Survey" for launch in the 2010–2013 time frame

Tier 1: 2010–2013 Launch
Soil Moisture Active Passive (SMAP)
ICESAT II
DESDynI
CLARREO
Tier 2: 2013–2016 Launch
SWOT
HYSPIRI
ASCENDS
GEO-CAFE
ACE
Tier 3: 2016–2020 Launch
LIST
PATH
GRACE-II
SCLP
GACM
3D-WINDS

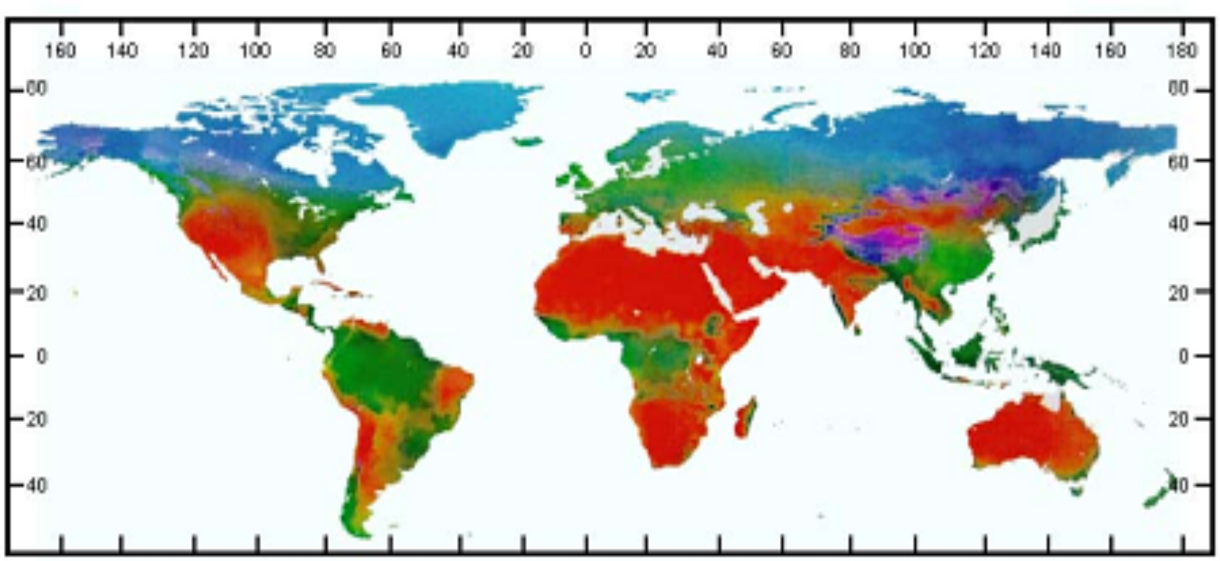
- Feb 2008: NASA announces start of SMAP project
- SMAP is a directed-mission with heritage from HYDROS
- HYDROS risk-reduction performed during Phase A
  Cancelled 2005 due to NASA budgetary constraints
- SMAP now in Phase D (System Integration and Testing)



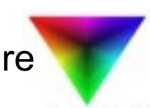
Mission Science Objectives

Global mapping of soil moisture and freeze/thaw state to:

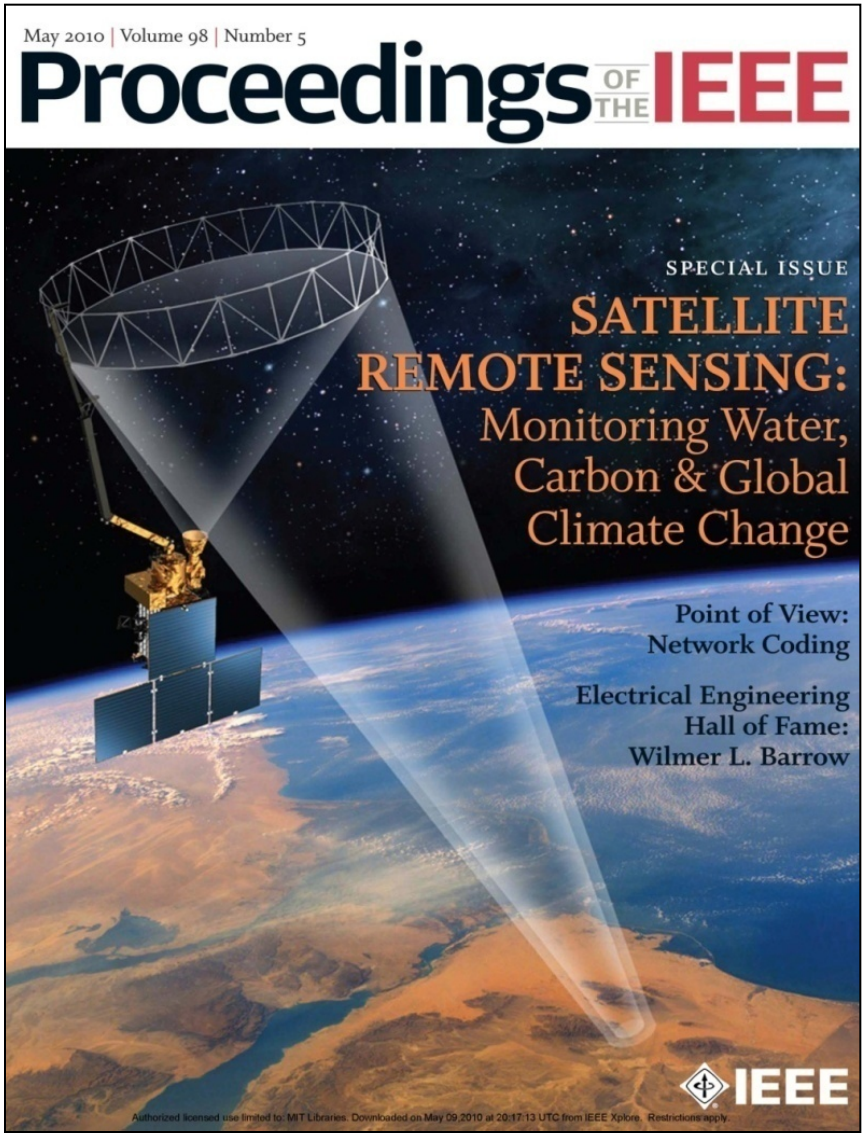
1. Understand processes that *link* the terrestrial water, energy and carbon cycles
2. Estimate global water and energy fluxes at the land surface
3. Quantify net carbon flux in boreal landscapes
4. Enhance weather and climate forecast skill
5. Develop improved flood prediction and drought monitoring capability



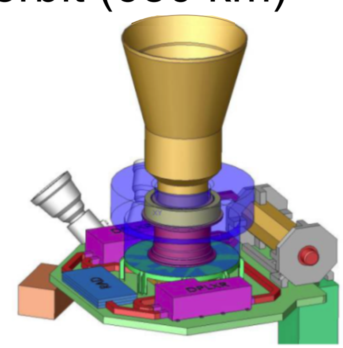
Primary controls on land evaporation and biosphere primary productivity



SMAP Mission Concept



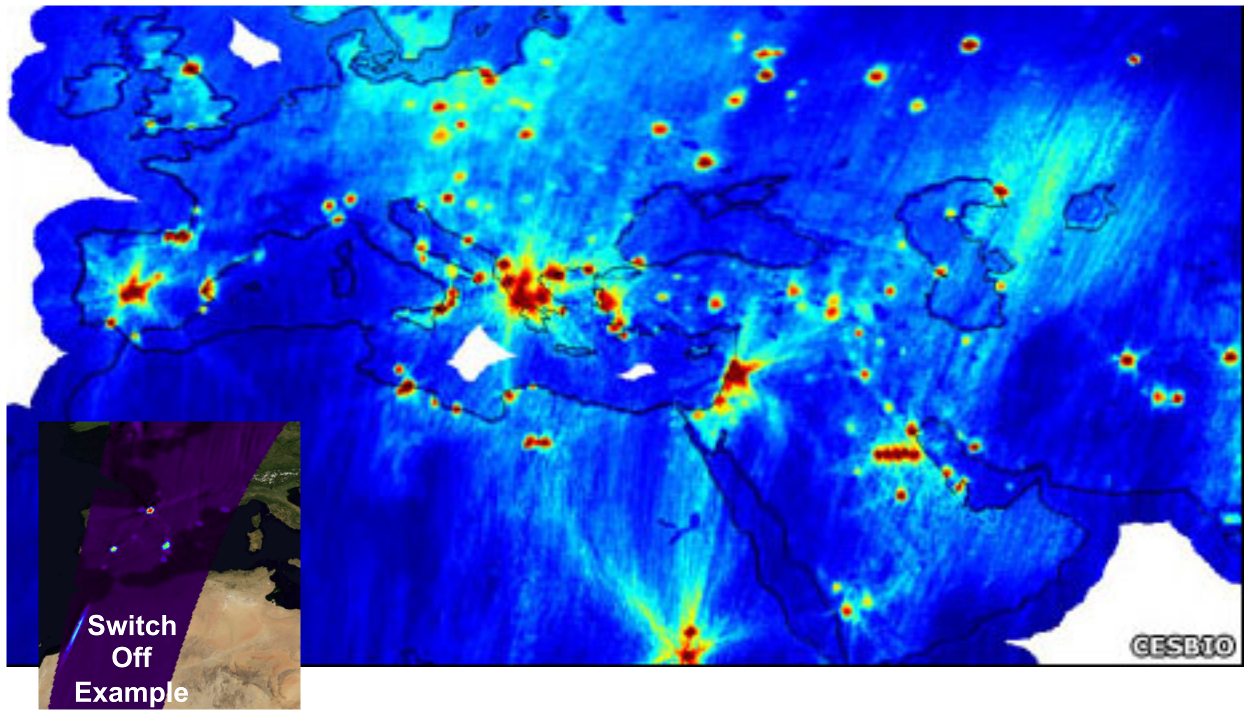
- L-band unfocused SAR and radiometer system, offset-fed 6 m light-weight deployable mesh reflector. Shared feed for
  - 1.26 GHz HH, VV, HV
    Radar at 1-3 km (30% nadir gap)
  - 1.4 GHz H, V, 3rd and 4th Stokes
    Radiometer at 40 km
- Conical scan, fixed incidence angle across swath
- Contiguous 1000 km swath with 2-3 days revisit (8 day repeat)
- Sun-synchronous 6am/6pm orbit (680 km)
- Launch October 31, 2014
- Mission duration 3 years



SMAP Approach to RFI Detection-Mitigation

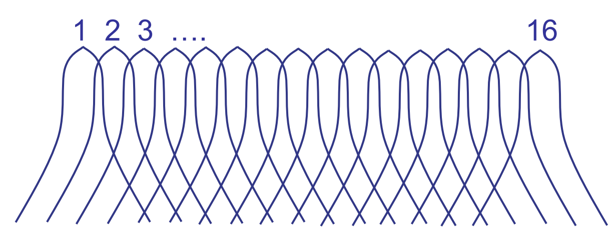
SMOS 1.4 GHz RFI

Aggressive approach to Radio-Frequency Interference (RFI) detection and mitigation



SMAP's Multi-layer defense:

- Spectral and temporal resolution
- Acquire 3rd and 4th Stokes parameters
- Temporal kurtosis



L-band Active/Passive Soil Moisture Mapping

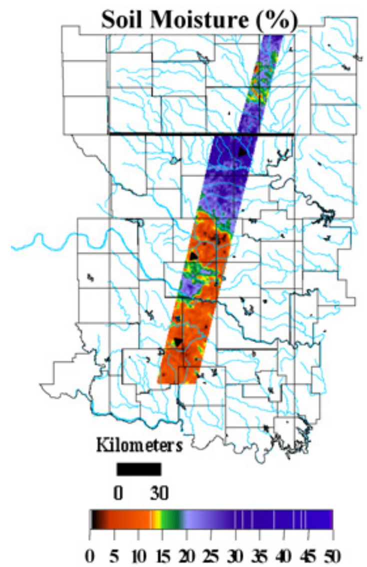
- Soil moisture retrieval algorithms are derived from a long heritage of microwave modeling and field experiments

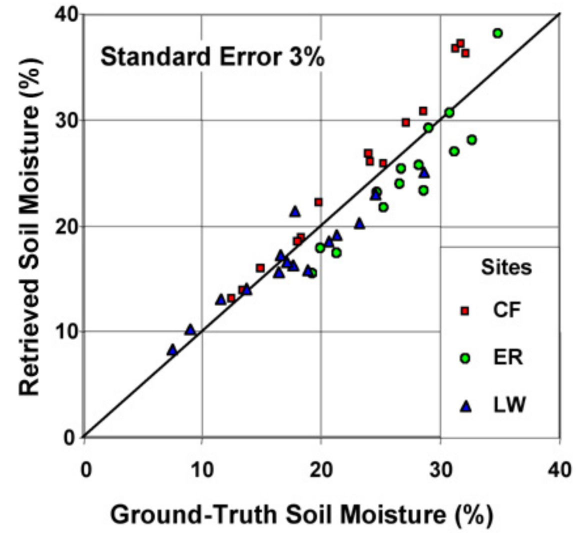
    MacHydro'90, Monsoon'91, Washita92, Washita94, SGP97, SGP99, SMEX02, SMEX03, SMEX04, SMEX05, CLASIC, SMAPVEX08, CanEx10, SMAP-Ex3

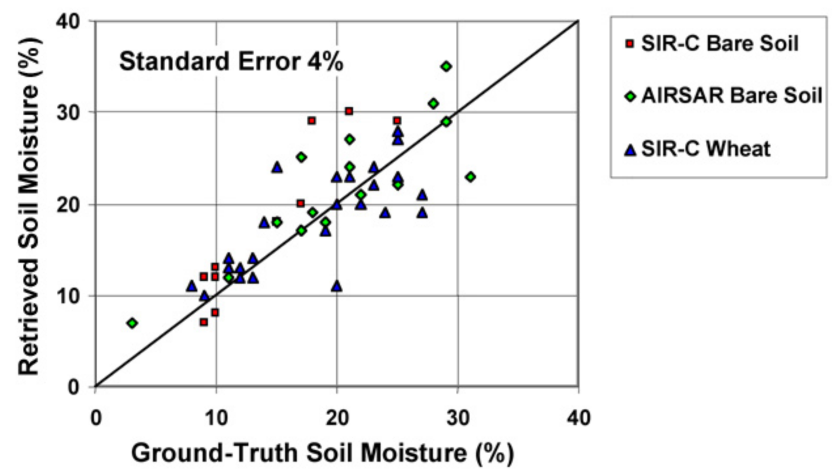
- ***Radiometer*** - High accuracy (less influenced by roughness and vegetation) but coarser spatial resolution (40 km)

- ***Radar*** - High spatial resolution (1-3 km) but more sensitive to surface roughness and vegetation

- **Combined Radar-Radiometer** product provides intermediate resolution and intermediate accuracy to meet science objectives







Summary

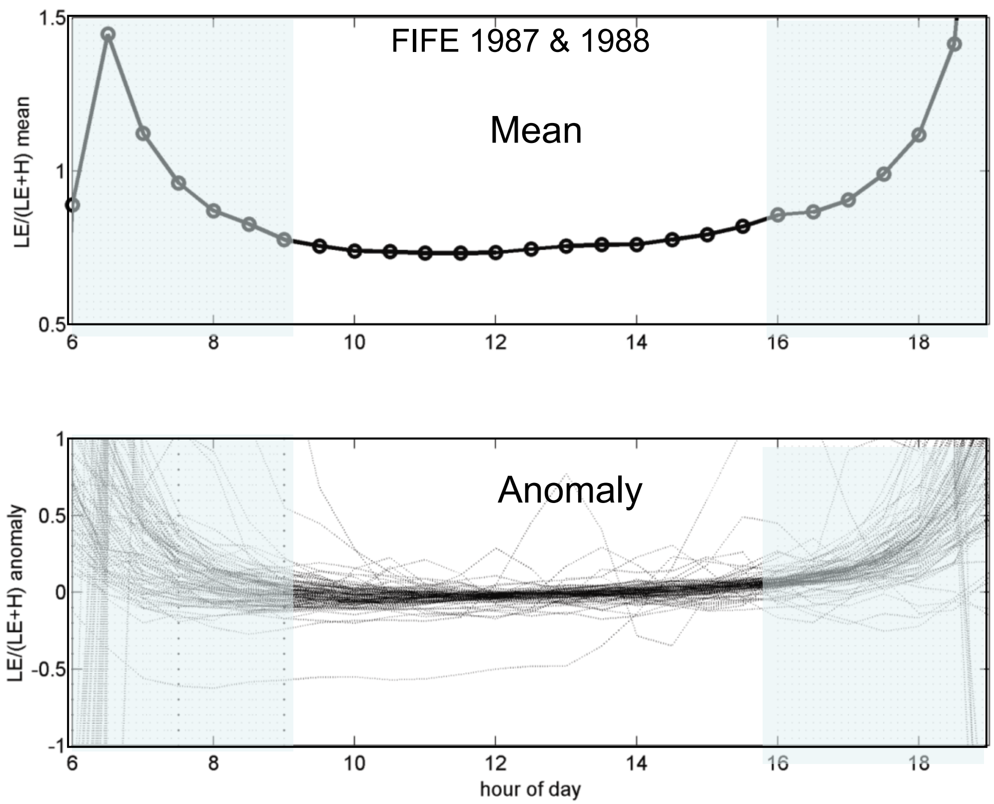
- The strength of land-atmosphere coupling is critically dependent on the surface closure function in the land water and energy balance – Here $EF(\theta)$
- The shape of this function and its dependence on vegetation, soil and climate are largely unknown
- Lack of observation of this function can result in misleading representation and diagnosis of land-atmosphere interaction in NWP and climate models
- Way forward is independent and – as much as possible – model-free and observations-based estimation
- Synergy of microwave and LSA SAF LST products to address a critical science application/question

Self-Preservation of Evaporative Fraction (EF)

Convenient to estimate evaporation from **evaporative fraction** :

$$EF = \frac{LE}{LE + H}$$

- $0 \le EF \le 1$ depends on soil moisture θ
- **Transferrable** across models
- Separates diurnal (radiative) cycle from longer-term soil moisture variations
- Observed to be **approximately constant during daytime**

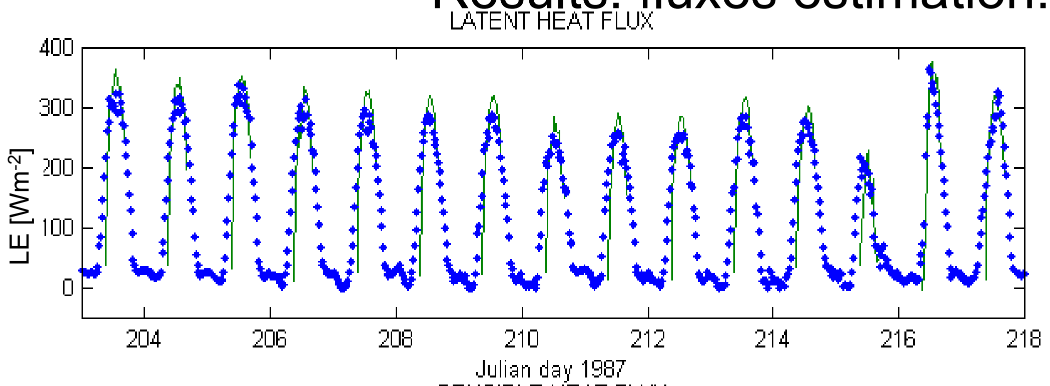


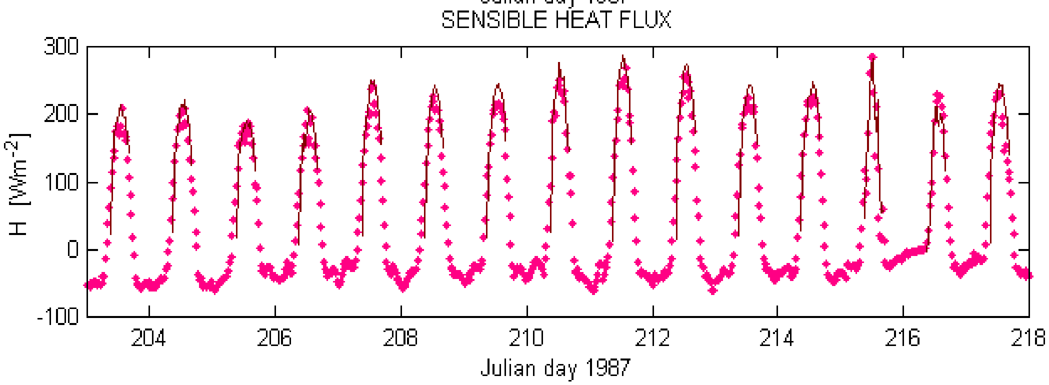
Shuttleworth et al., (1989) IAHS Pub. 186.
Nichols & Cuenca, (1993) WRR 29.
Crago & Brutsaert, (1996) JH 178.
Crago, (1996) JH 180.
Gentine & Entekhabi (2007), AFM 143.

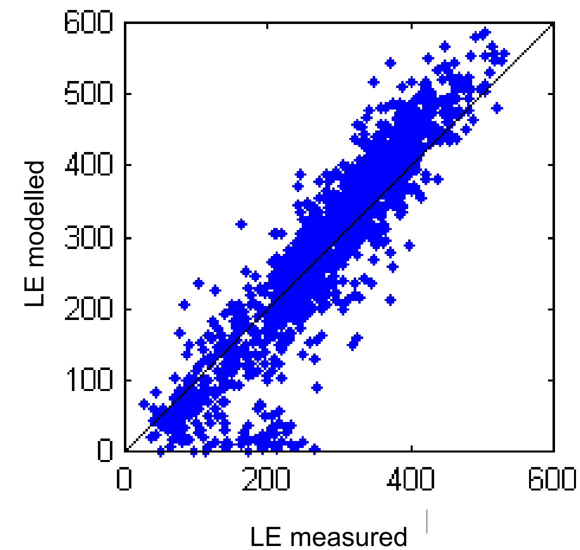
Test With FIFE 1987 Observations: Hourly

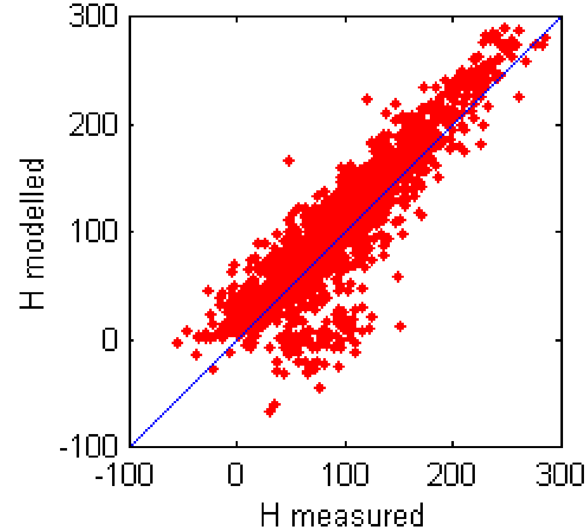
22 Flux Stations in
15 km x 15 km Area

Results: fluxes estimation:





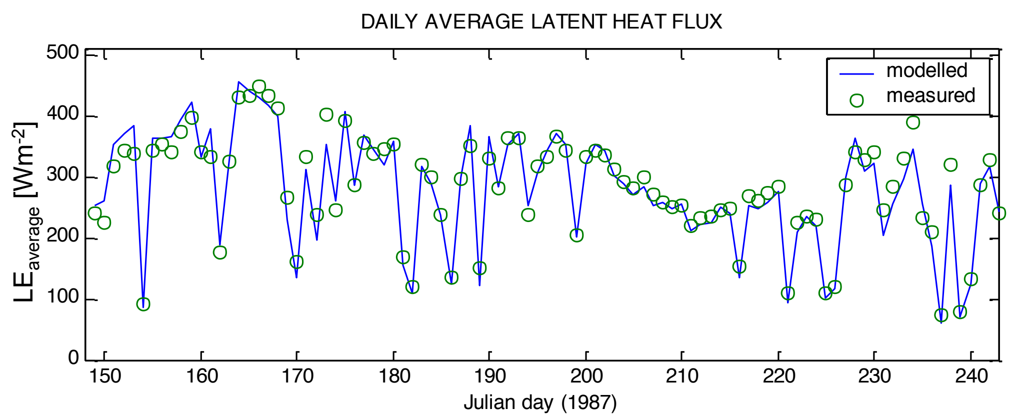


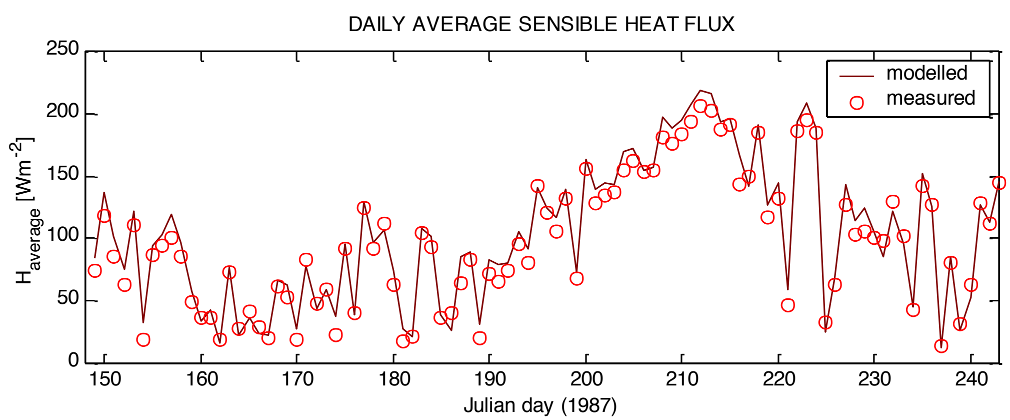


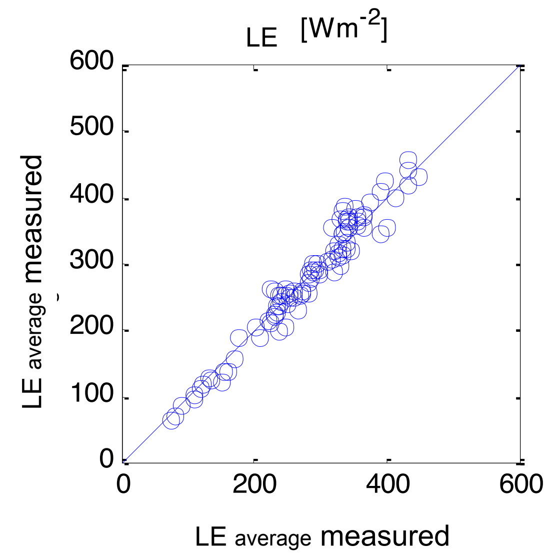
Half-hour fluxes

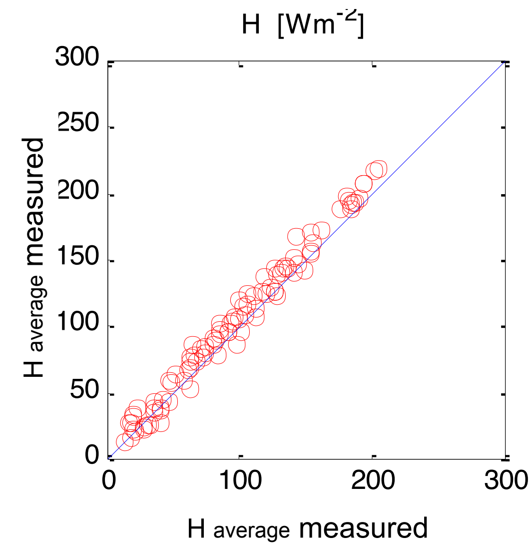
	ρ	RMSE [Wm^{-2}]
LE	0.92	56.19
H	0.90	31.18

Test With FIFE 1987 Observations: Daily









Daily average fluxes

	ρ	RMSE [Wm^{-2}]
LE	0.98	19.77
H	0.99	9.87