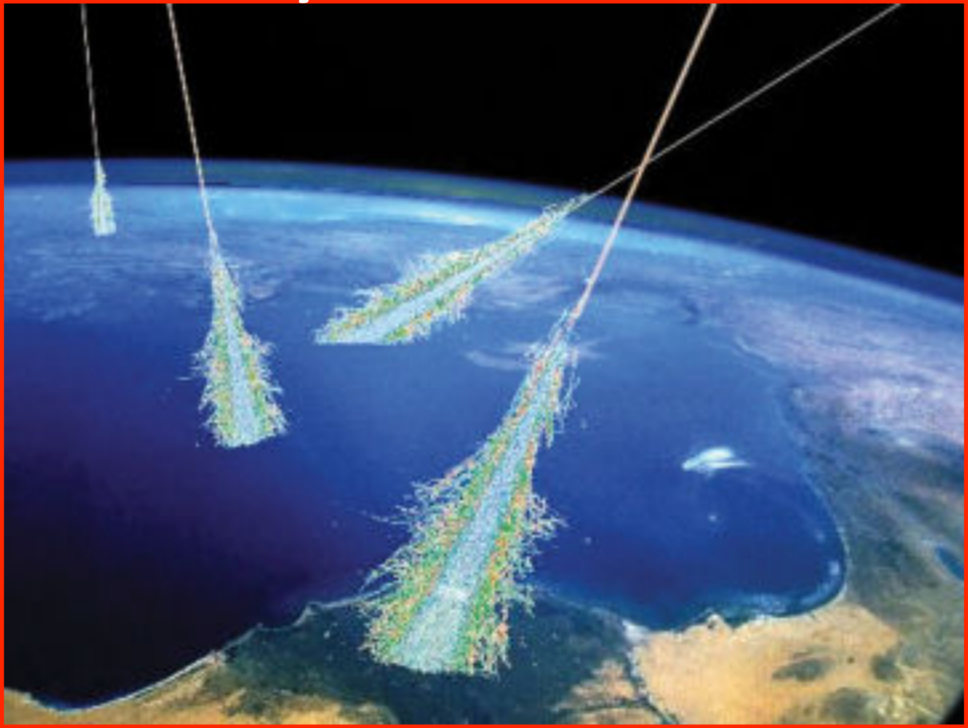
# Cosmic-ray Neutron Probes for Regional-Scale Soil Moisture and Humidity Observations



## Potential Benefits for Atmospheric Sciences at the Regional Scale

Ankur R Desai, UW-Madison

# Collaborators

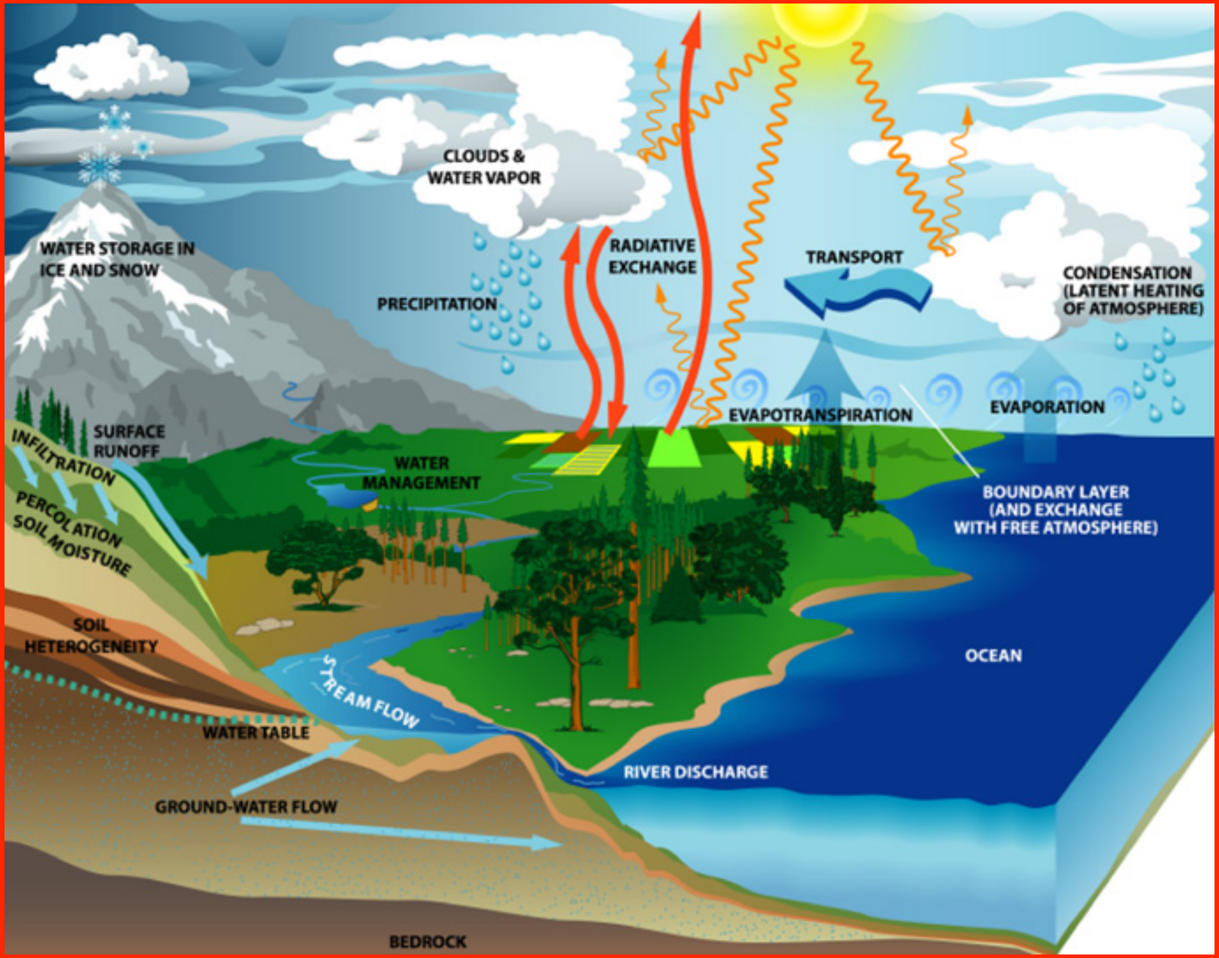
- COsmic-ray Soil Moisture Observing System (COSMOS) team (U. Arizona): **Trenton Franz, W. James Shuttleworth**, Marek Zreda, Xubin Zeng, Chris Zweck, Ty P.A. Ferré, **R. Rosolem**, and S. Stillman
- Hydroinnova Consortium: Hydroinnova, Zetetic Institute, Questa Instruments, General Electric, PDT
- WLEF tower: Arlyn Andrews (NOAA), Jonathan Thom (SSEC), Dan Baumann (USFS), Jeff Ayers (WI ECB)
- Funding: National Science Foundation, Dept of Energy

# Outline

- What is soil moisture?
- Land-atmosphere coupling: Importance of soil moisture in the land-atmosphere system
- Observing soil moisture
- Initial results from COSMOS
- Future applications

# What is Soil Moisture?

# Hydrologic Cycle

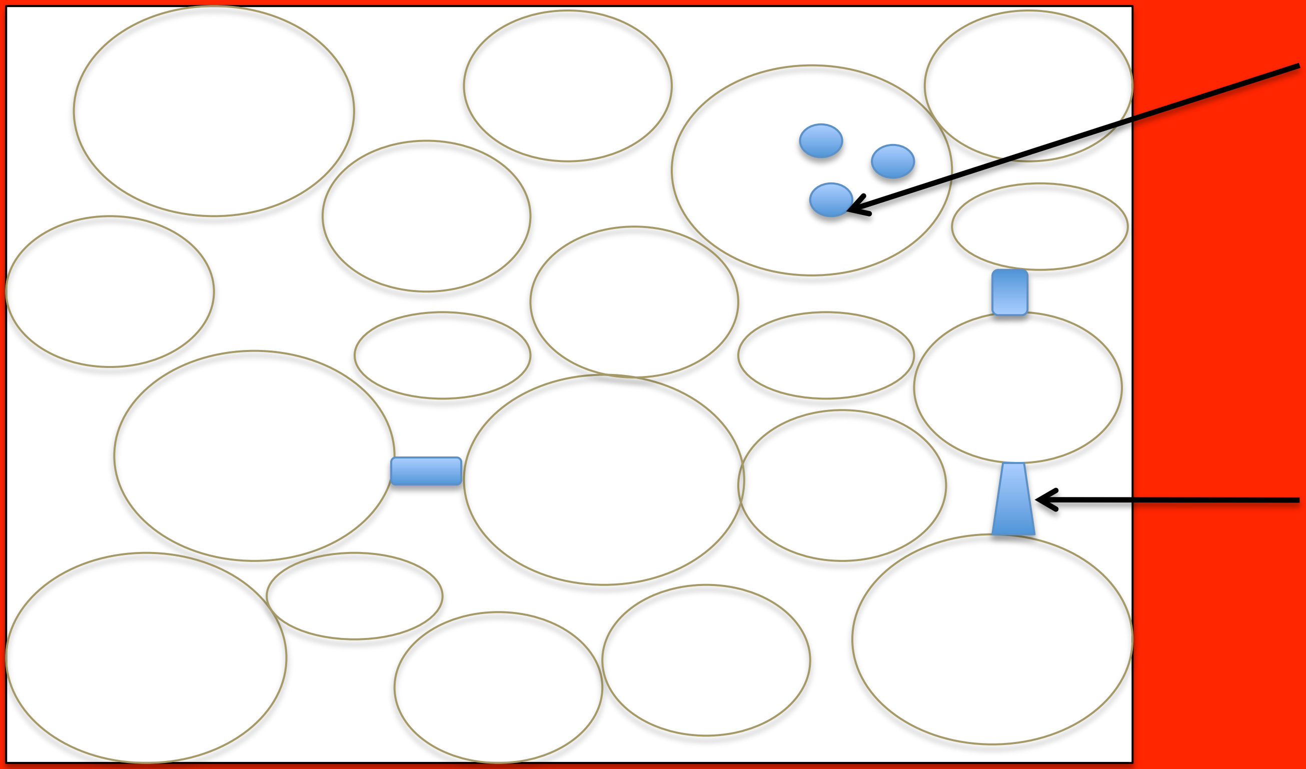


Source: NASA

# Soil Moisture

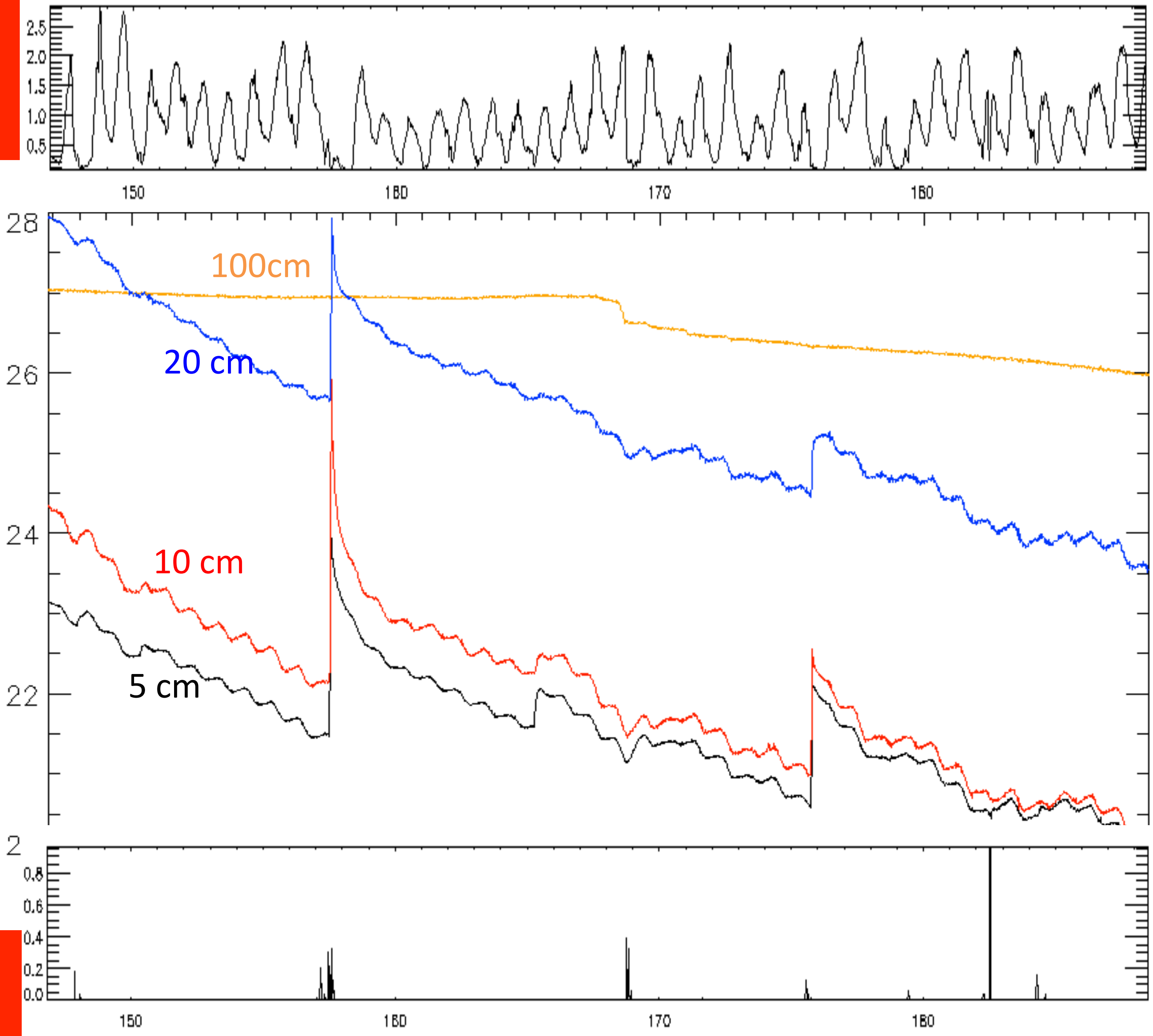
- Memory of precipitation in land system, source moisture for evaporation, reservoir for plant transpiration, conduit for longer term reserves (groundwater)
- Water fills pore space of soil, but capacity and ease of extraction/filling related to bulk density, texture, porosity, tortuosity, etc…
- Usually measured in percent VWC (Volumetric Water Capacity) or GWC (Gravimetric Water Capacity), but other units abound (matric potential, percent of field capacity, plant wilting point, vapor pressure deficit)

# Soil Moisture



Lattice Water
In physical structure
of grains

Pore Water
What hydrologists
care about


2.5
2.0
1.5
1.0
0.5
150
160
170
180
28
26
24
22
2
100cm
20 cm
10 cm
5 cm
0.8
0.6
0.4
0.2
0.0
150
160
170
180

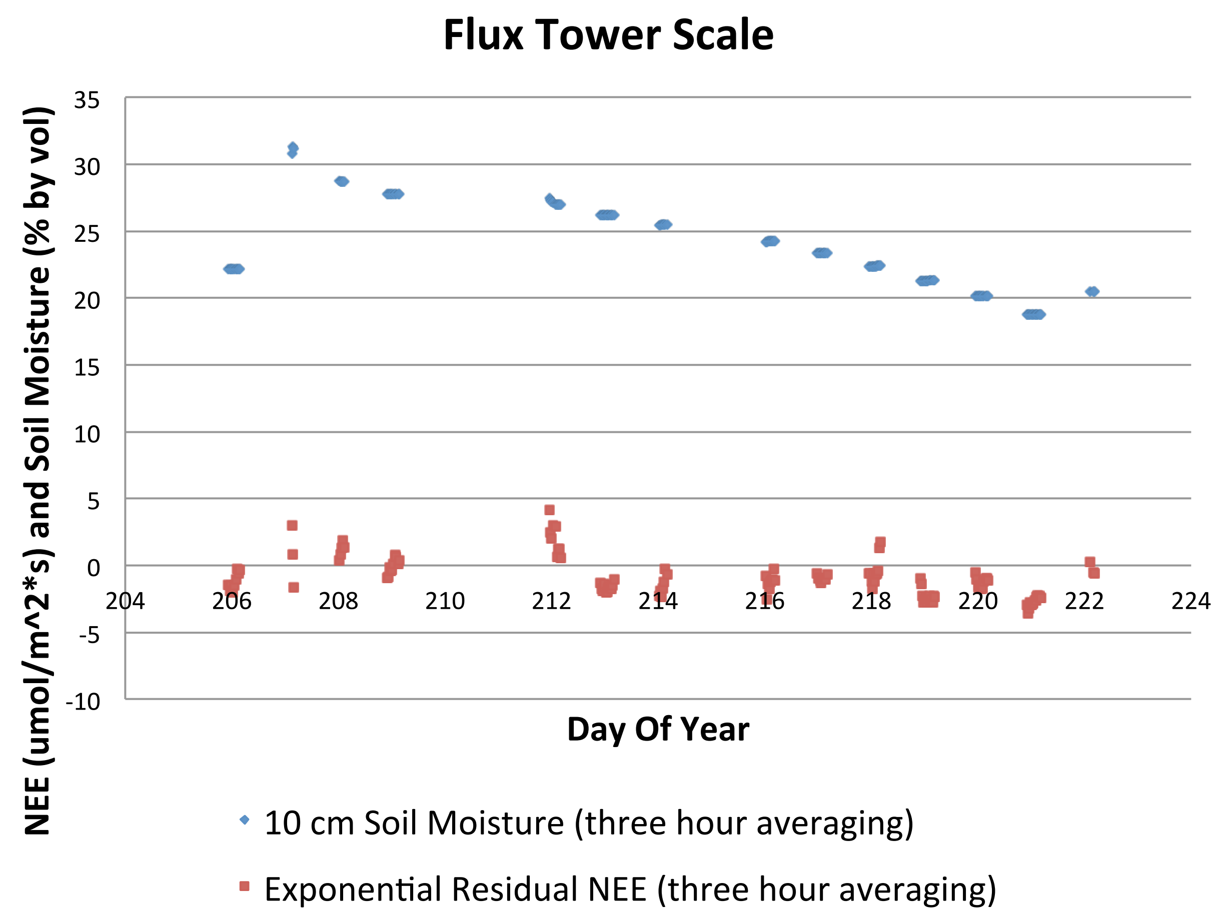
# Land-Atmosphere Coupling

# Land-Atmosphere Coupling

- Improving the understanding of soil moisture improves our ability to better predict or understand:
  - weather and climate
  - ecological processes and phenomenon
  - hydrological flow processes in catchments
  - water storage on/in vegetation canopies and as frozen precipitation
  - remotely sensed measurements of surface wetness

# Land-Atmosphere Coupling

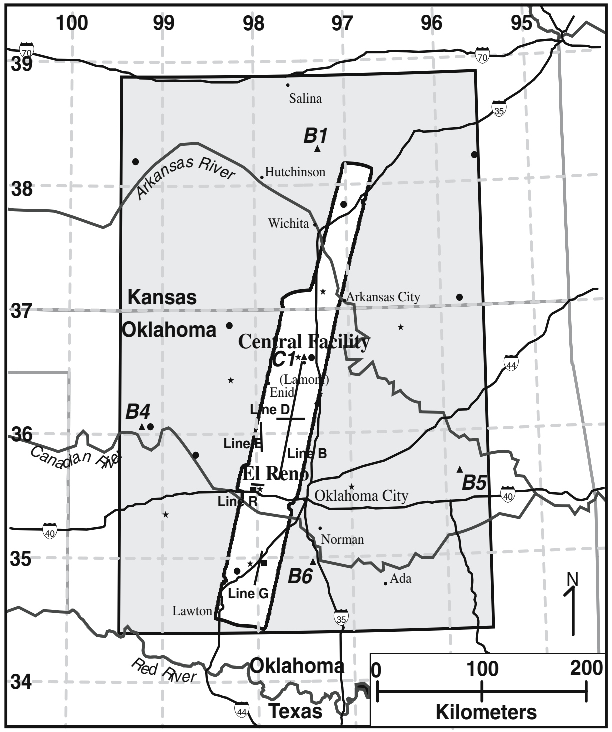
Microscale

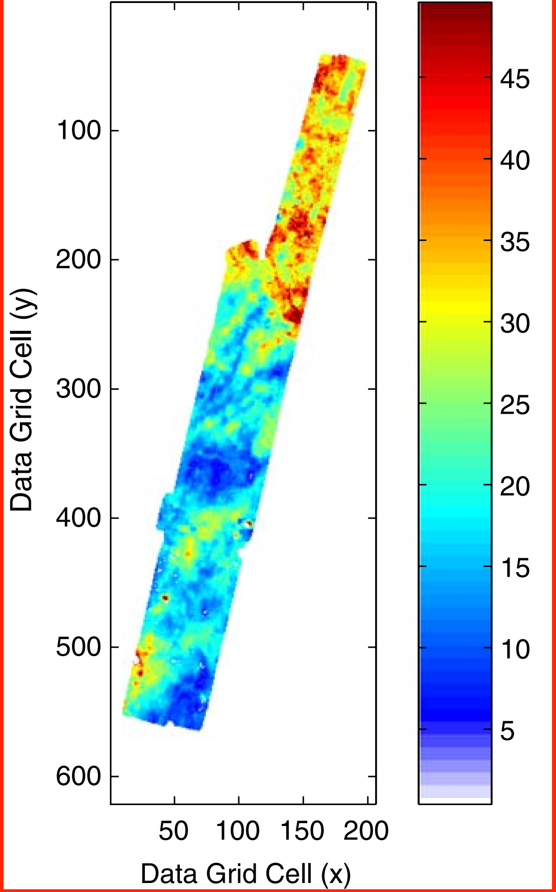


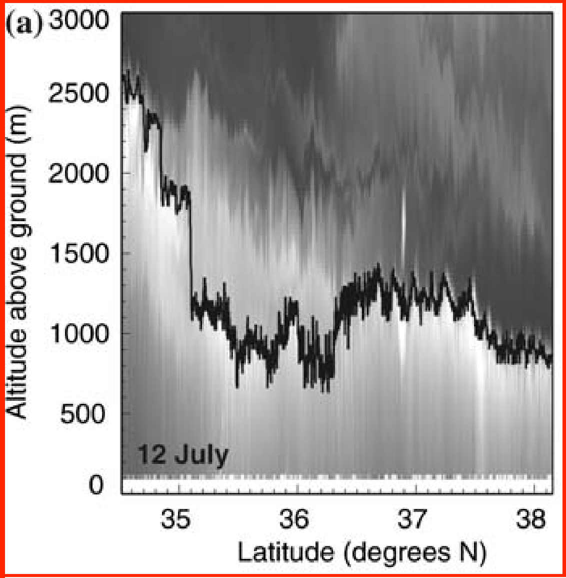
Source: Ryan Harp

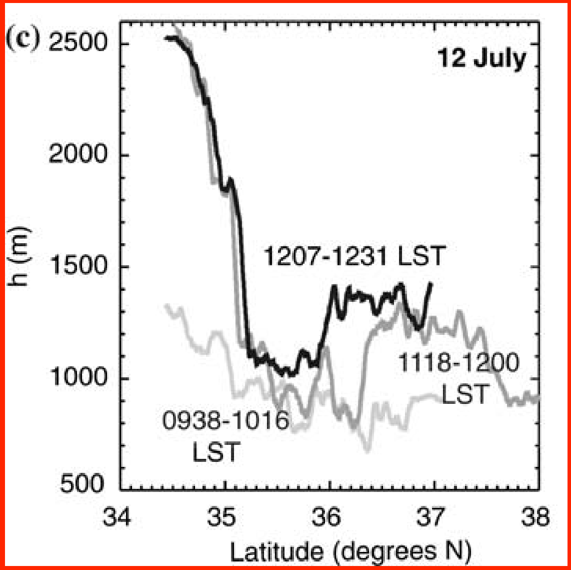
# Land-Atmosphere Coupling

Mesoscale



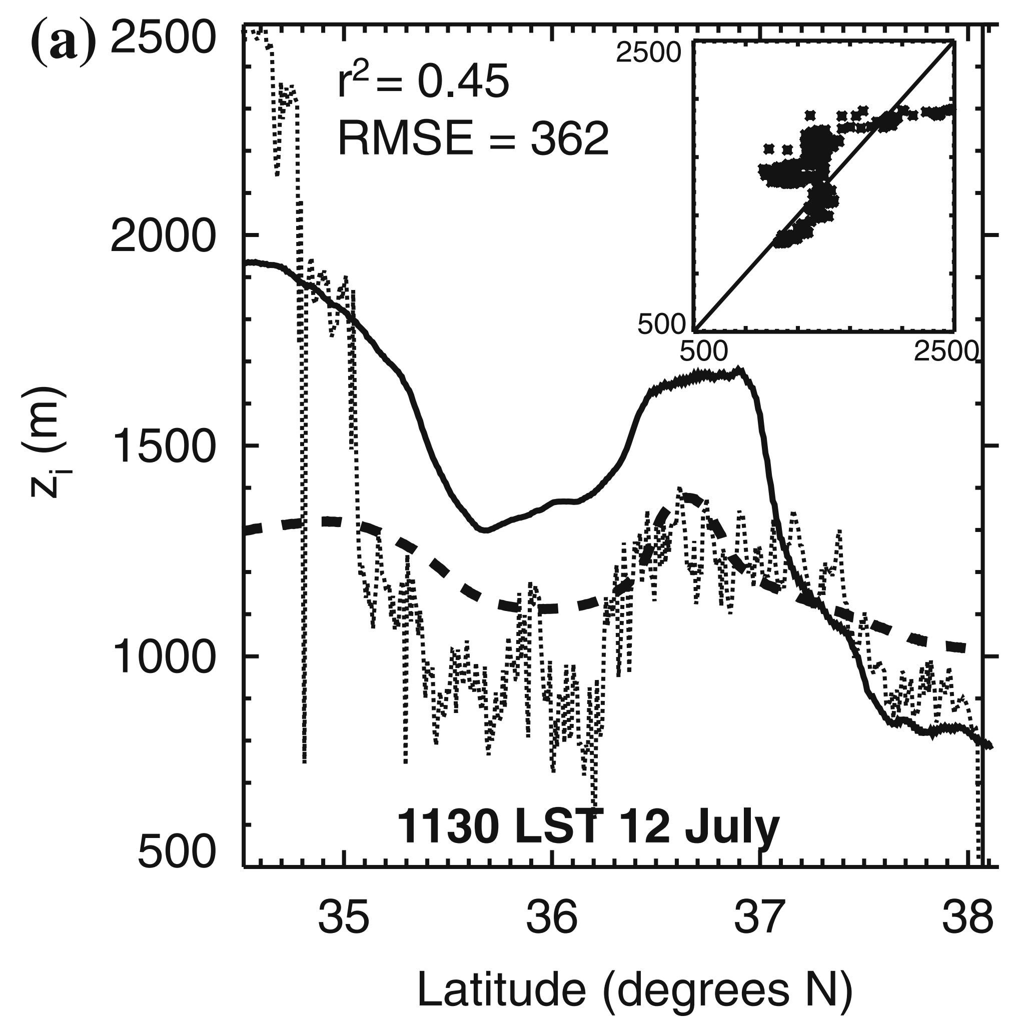






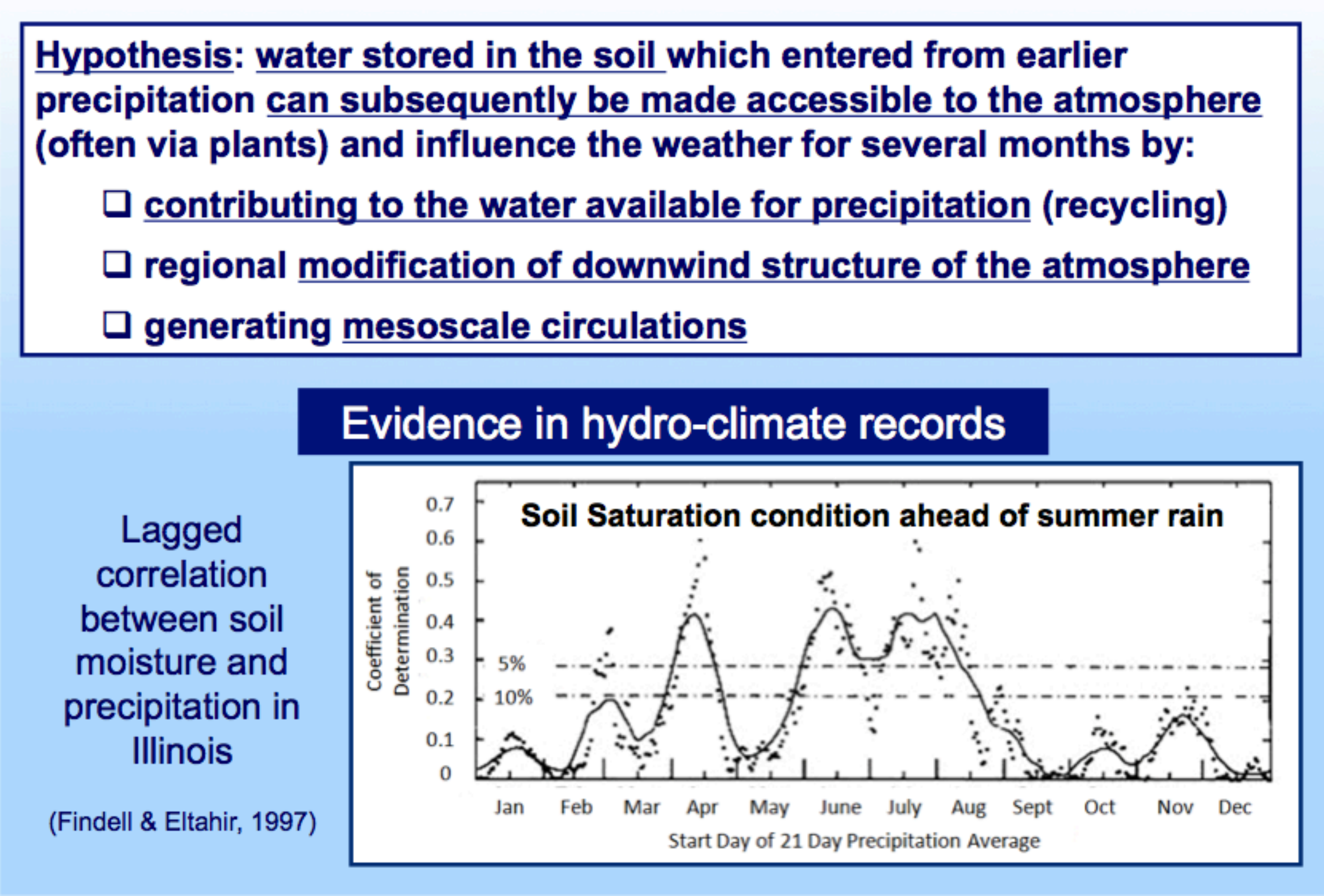
Desai et al (2006); Reen et al (2006)

# Land-Atmosphere Coupling



# Land-Atmosphere Coupling

Mesoscale/Synoptic



**Hypothesis**: **water stored in the soil which entered from earlier precipitation can subsequently be made accessible to the atmosphere (often via plants) and influence the weather for several months by:**

- ☐ **contributing to the water available for precipitation (recycling)**
- ☐ **regional modification of downwind structure of the atmosphere**
- ☐ **generating mesoscale circulations**

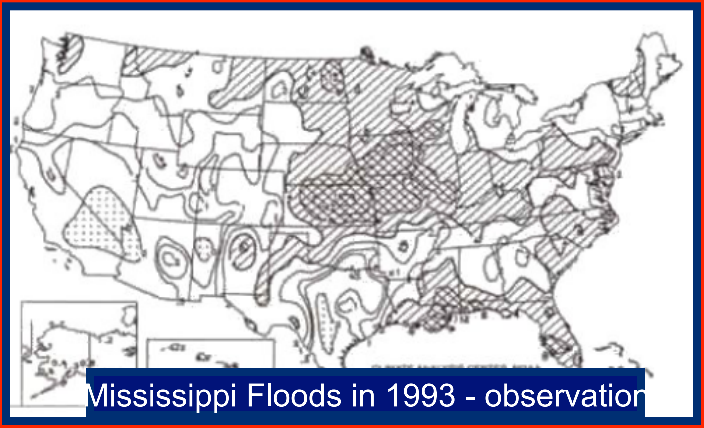
**Evidence in hydro-climate records**

Lagged correlation between soil moisture and precipitation in Illinois

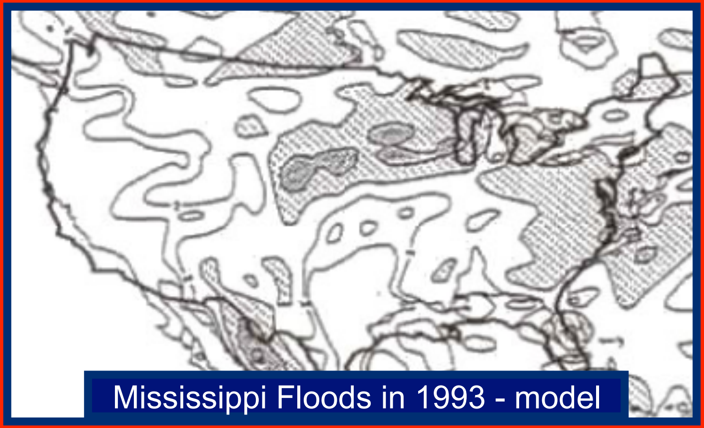
(Findell & Eltahir, 1997)

# Land-Atmosphere Coupling

Synoptic

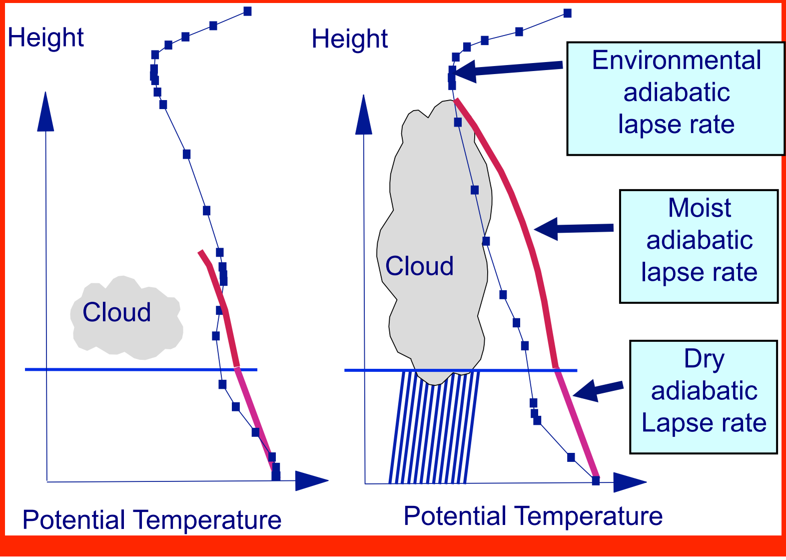


Mississippi Floods in 1993 - observation



Mississippi Floods in 1993 - model

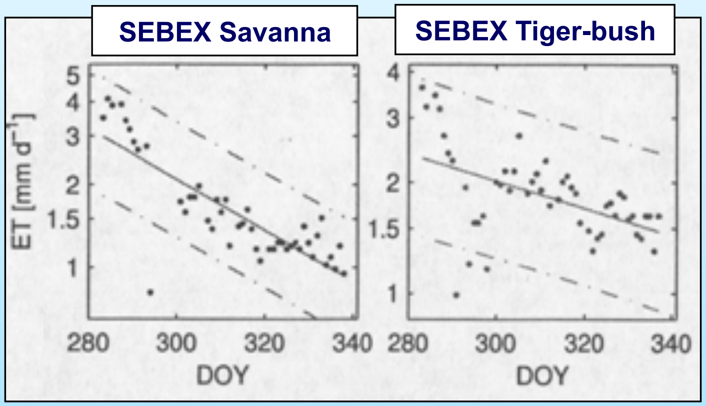
Influence not through recycling,
rather through modified
downwind lapse rate through
changes in upstream surface
flux partitioning
(Beljaars et al., 1996)



# Land-Atmosphere Coupling

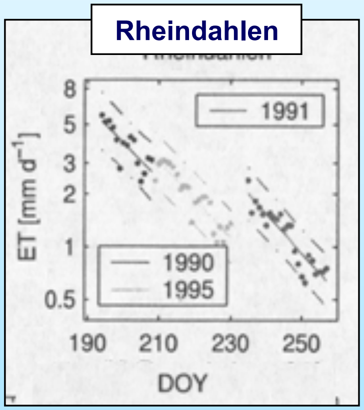
Climate

**Teuling et al (2006) and others observed decay time of evaporation as soil moisture fell during drying periods at selected sites, and compared these with modeled decay for the models used in GCMs**



**SEBEX Savanna**

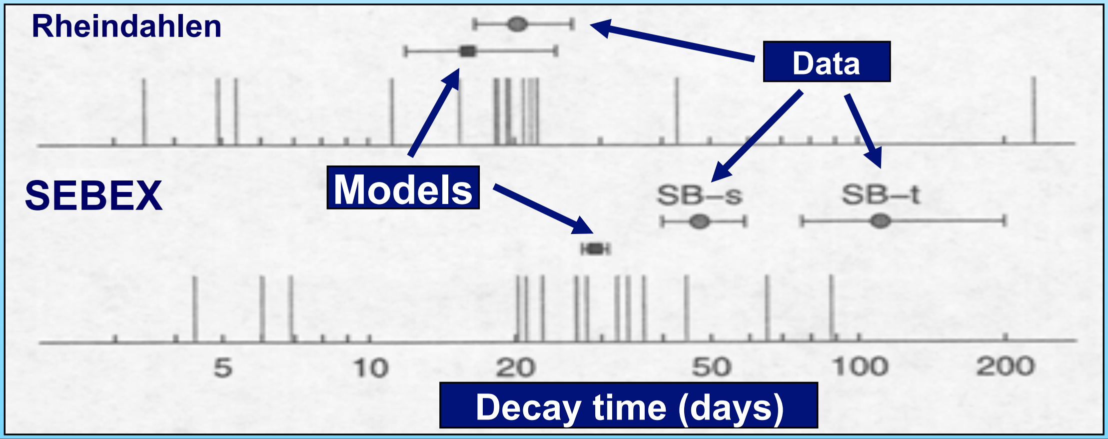
**SEBEX Tiger-bush**



**Rheindahlen**

$$E(t)=\frac{S(t)}{\lambda}$$

$$E(t)=E_0\exp\left(\frac{t}{\lambda}\right)$$



**Rheindahlen**

**Data**

**SEBEX**

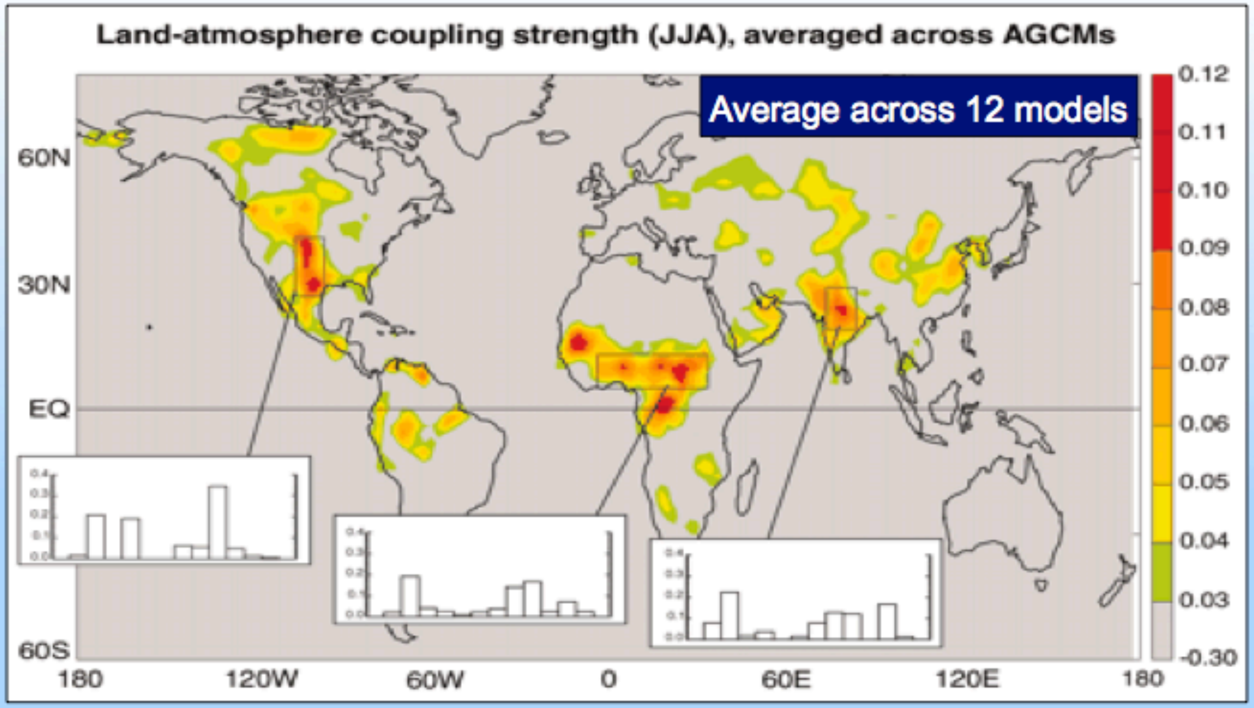
**Models**

**Decay time (days)**

**Modeling of the observed influence of soil moisture on evaporation in GCMs can be poor**

# Land-Atmosphere Coupling

Climate



Koster et al. (2004)

Land– atmosphere coupling strength: the degree to which anomalies in land surface state (e.g., soil moisture) can affect rainfall generation and other atmospheric processes.

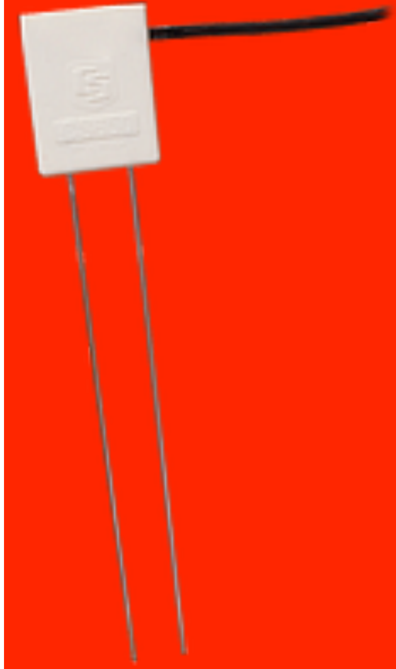
The plotted hot spots indicate where a successful initialization of soil moisture may enhance precipitation prediction skill during Northern Hemisphere summer.

# Observing Moisture

# Observing Soil Moisture

- Soil coring: Remove soil of known volume, measure mass before and after drying in oven

# Observing Soil Moisture

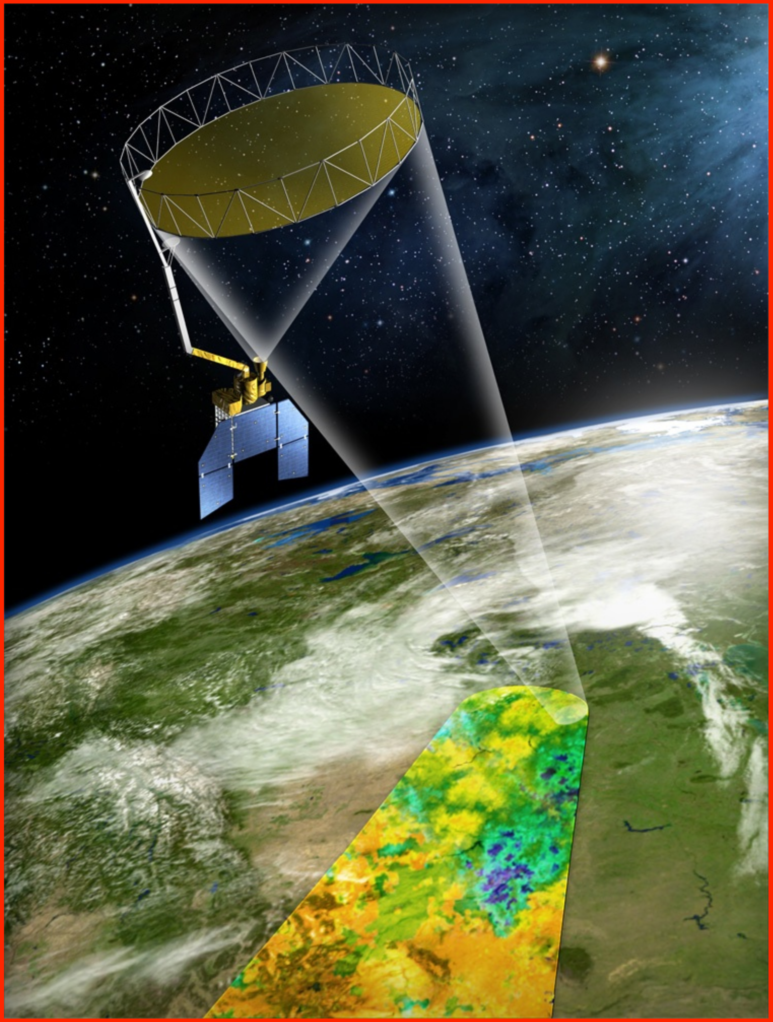


- Time-domain reflectometry (TDR)
  - Send electromagnetic pulse through waveguide, measure travel time = f(signal velocity and waveguide length)
  - Use velocity and length to determine permittivity (dielectric constant) of porous media, related to soil bulk density and moisture
  - Example: Campbell Scientific reflectometer (left). Picosecond voltage gain and time converted to MHz oscillation frequency

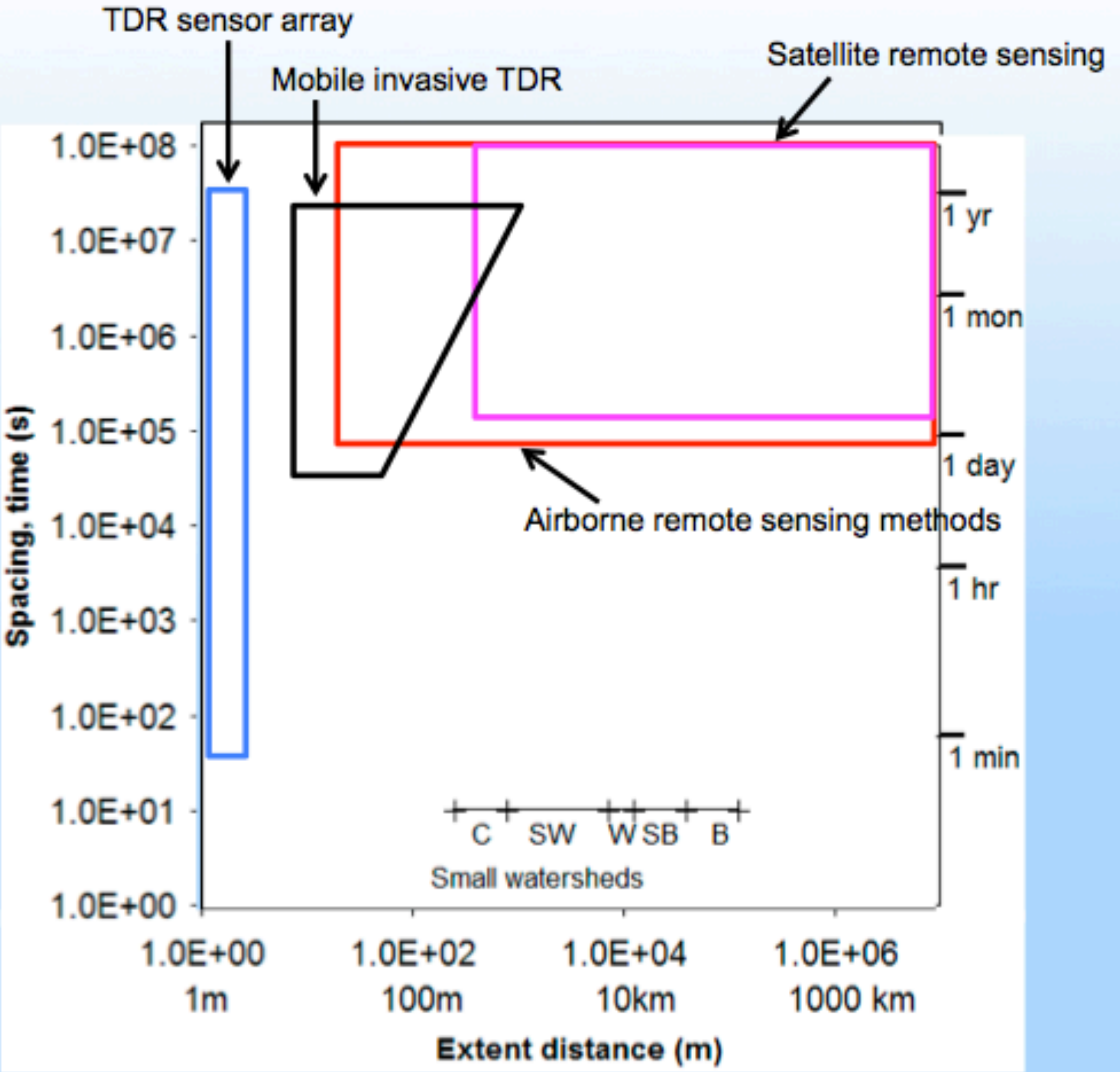
# Observing Soil Moisture

- By Satellite
  - Passive: Microwave (L-band or Microwave)
  - Active: Synthetic aperture radar (SAR)

- Example: NASA SMAP (smap.jpl.nasa.gov)
  - Polar orbit, L-band SAR (1.26 GHz) + passive L-band (1.41 GHZ)
  - Resolution: 10 km soil moisture, 3 km freeze/thaw
  - Swath: 1000 km , 3 day repeat
  - Launch expected in 2014



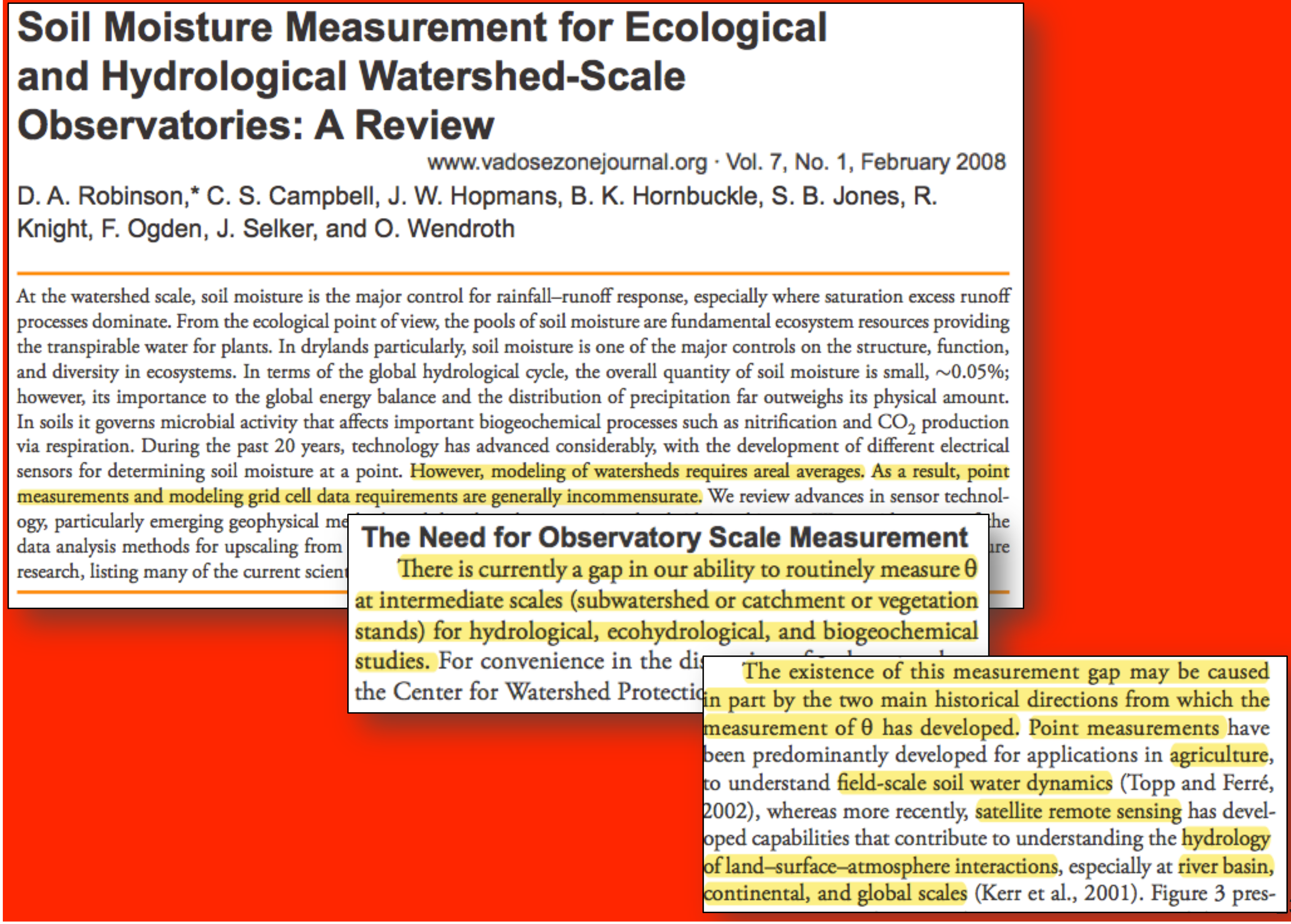
# Observing Soil Moisture



Adapted from Robinson et al. (2008)

Current technology is constrained to measuring processes with space and time scales consistent with boxes.

# Observing Soil Moisture



## Soil Moisture Measurement for Ecological and Hydrological Watershed-Scale Observatories: A Review

www.vadosezonejournal.org · Vol. 7, No. 1, February 2008

D. A. Robinson,* C. S. Campbell, J. W. Hopmans, B. K. Hornbuckle, S. B. Jones, R. Knight, F. Ogden, J. Selker, and O. Wendroth

At the watershed scale, soil moisture is the major control for rainfall–runoff response, especially where saturation excess runoff processes dominate. From the ecological point of view, the pools of soil moisture are fundamental ecosystem resources providing the transpirable water for plants. In drylands particularly, soil moisture is one of the major controls on the structure, function, and diversity in ecosystems. In terms of the global hydrological cycle, the overall quantity of soil moisture is small, ~0.05%; however, its importance to the global energy balance and the distribution of precipitation far outweighs its physical amount. In soils it governs microbial activity that affects important biogeochemical processes such as nitrification and $CO_2$ production via respiration. During the past 20 years, technology has advanced considerably, with the development of different electrical sensors for determining soil moisture at a point. However, modeling of watersheds requires areal averages. As a result, point measurements and modeling grid cell data requirements are generally incommensurate. We review advances in sensor technology, particularly emerging geophysical me

the

data analysis methods for upscaling from

ure

research, listing many of the current scien

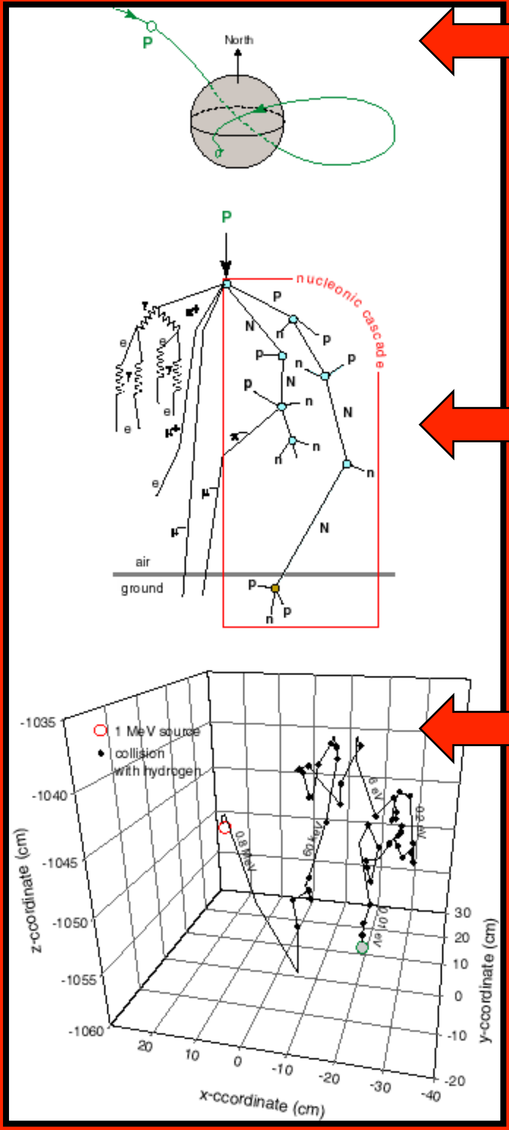
### The Need for Observatory Scale Measurement

There is currently a gap in our ability to routinely measure θ at intermediate scales (subwatershed or catchment or vegetation stands) for hydrological, ecohydrological, and biogeochemical studies. For convenience in the di

the Center for Watershed Protecti

The existence of this measurement gap may be caused in part by the two main historical directions from which the measurement of θ has developed. Point measurements have been predominantly developed for applications in agriculture, to understand field-scale soil water dynamics (Topp and Ferré, 2002), whereas more recently, satellite remote sensing has developed capabilities that contribute to understanding the hydrology of land–surface–atmosphere interactions, especially at river basin, continental, and global scales (Kerr et al., 2001). Figure 3 pres-

# Cosmic-rays & Soil Moisture



IN SPACE: there are incoming high-energy cosmic-ray protons

Their intensity changes slowly with time, and with geomagnetic latitude, (because they interact with the Earth's magnetic field). These both have to be corrected for in COSMOS

IN THE ATMOSPHERE: cascades of secondary cosmic rays are generated

The intensity of these cascades depends on barometric pressure. This has to be corrected for in COSMOS

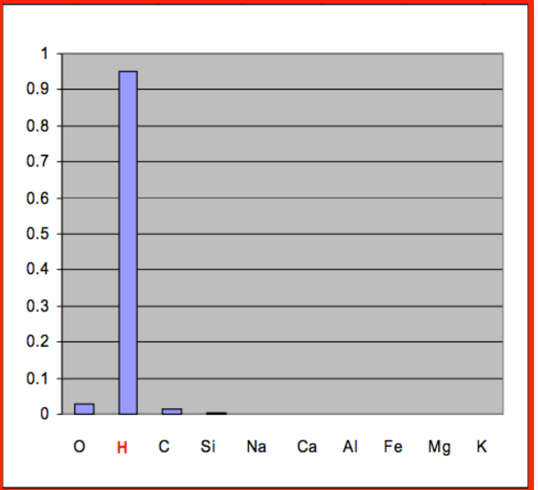
IN THE SOIL: the fast neutrons are scattered ("thermalized") and absorbed

BUT some escape back into the air above the ground, depending on the composition of the soil (thermal),

especially on its water content (fast neutrons)

(strictly hydrogen content)

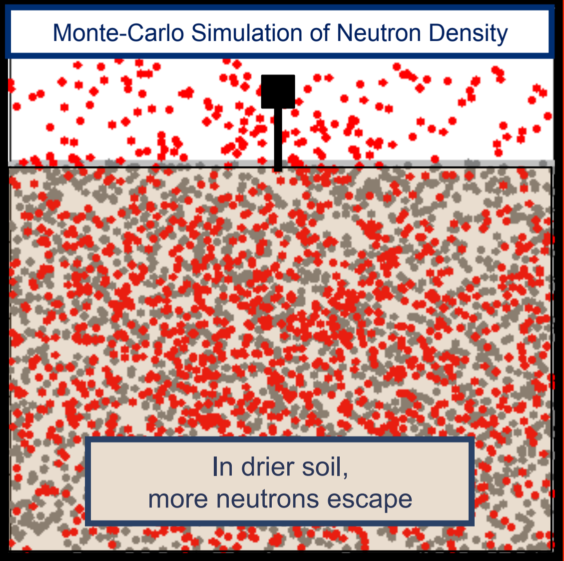
Secondary cosmic-ray particles produced in copper plates in a large cloud chamber. [D. Skobeltzyn, 1927]



# Observing Soil Moisture

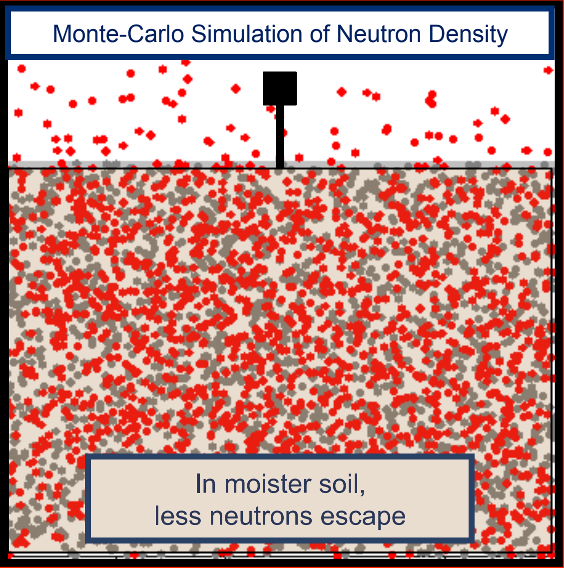
- Neutron detection has been around since the 1950s
  - Surface moisture alteration of neutron rate was considered a nuisance at the time (Hendrick and Edge, 1966)
- Inexpensive off-the-shelf $^3$He gas proportional neutron counters for fast and thermal neutrons and remote power/data logging/ communications are now available

# Going from Neutron Count Rate to Soil Moisture



Monte-Carlo Simulation of Neutron Density

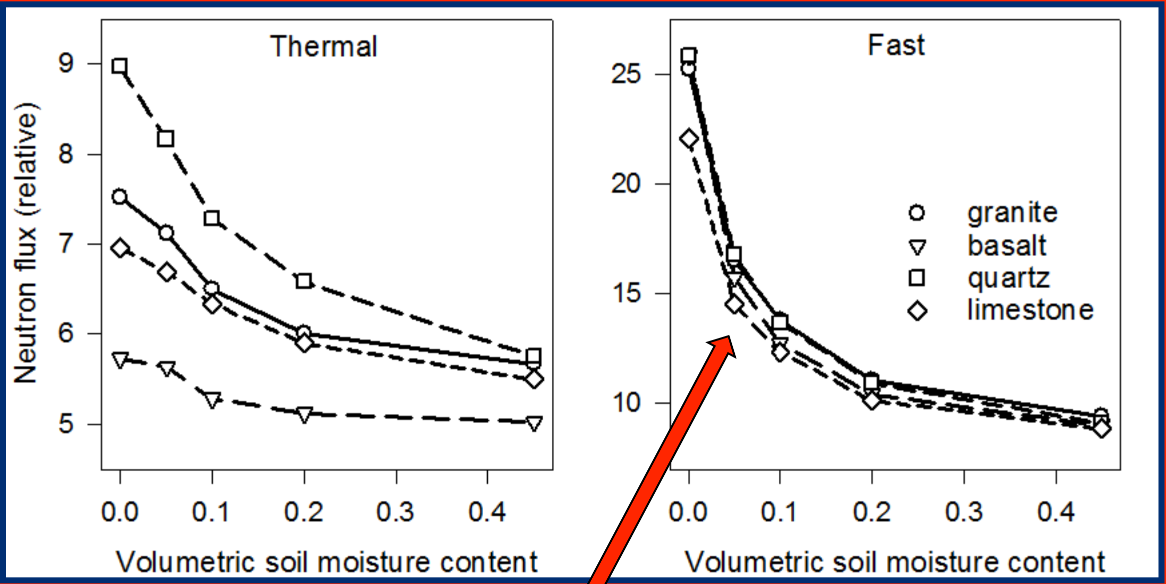
In drier soil, more neutrons escape



Monte-Carlo Simulation of Neutron Density

In moister soil, less neutrons escape

Zreda et al. (2008)

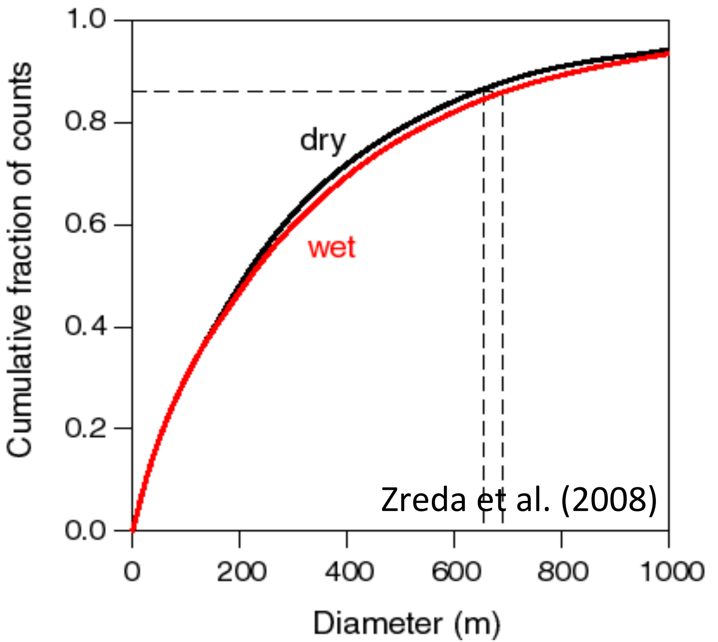


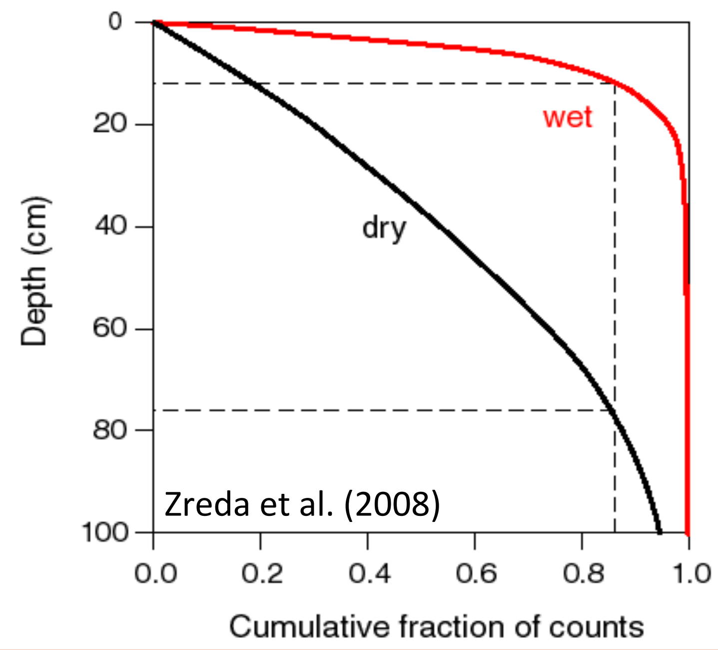
COSMOS probes detect neutrons at two energies, but <u>use "fast" neutrons for soil moisture detection because calibration is less sensitive to the chemistry of the soil</u>

(thermal neutrons give information on above-ground water, e.g. snow cover)

# Measurement Volume

Use a Monte-Carlo simulation of the random path of neutrons (including their collisions in the moist soil and air above) and count the proportion passing through the detector from each source position.





86% of neutrons from within 350 m radius

Independent of soil moisture

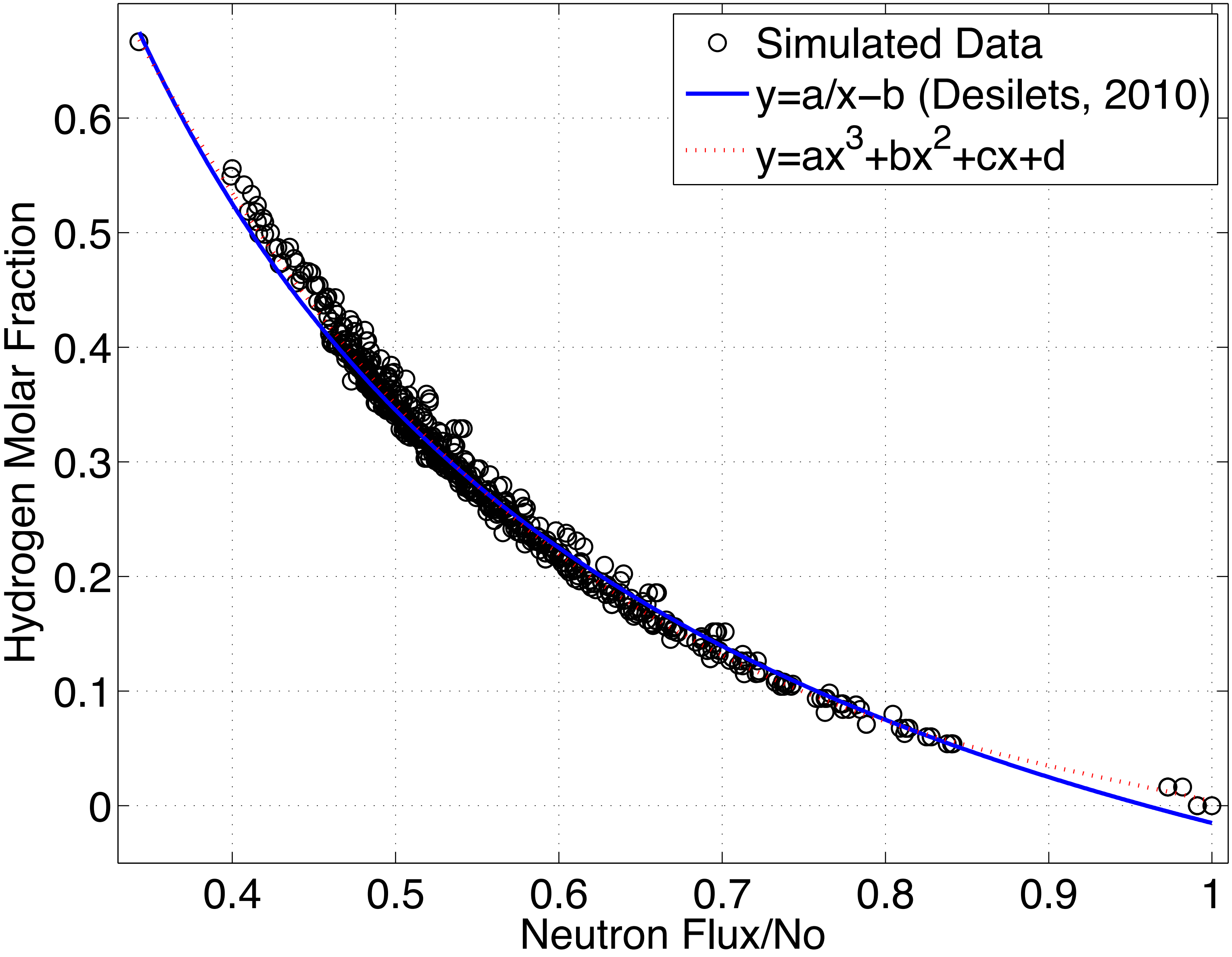
Increases with increasing altitude (decreasing pressure)

86% of neutrons from within a depth of 70 cm (dry)

Depth decreases to 12 cm in wet soils

Independent of altitude (and pressure)

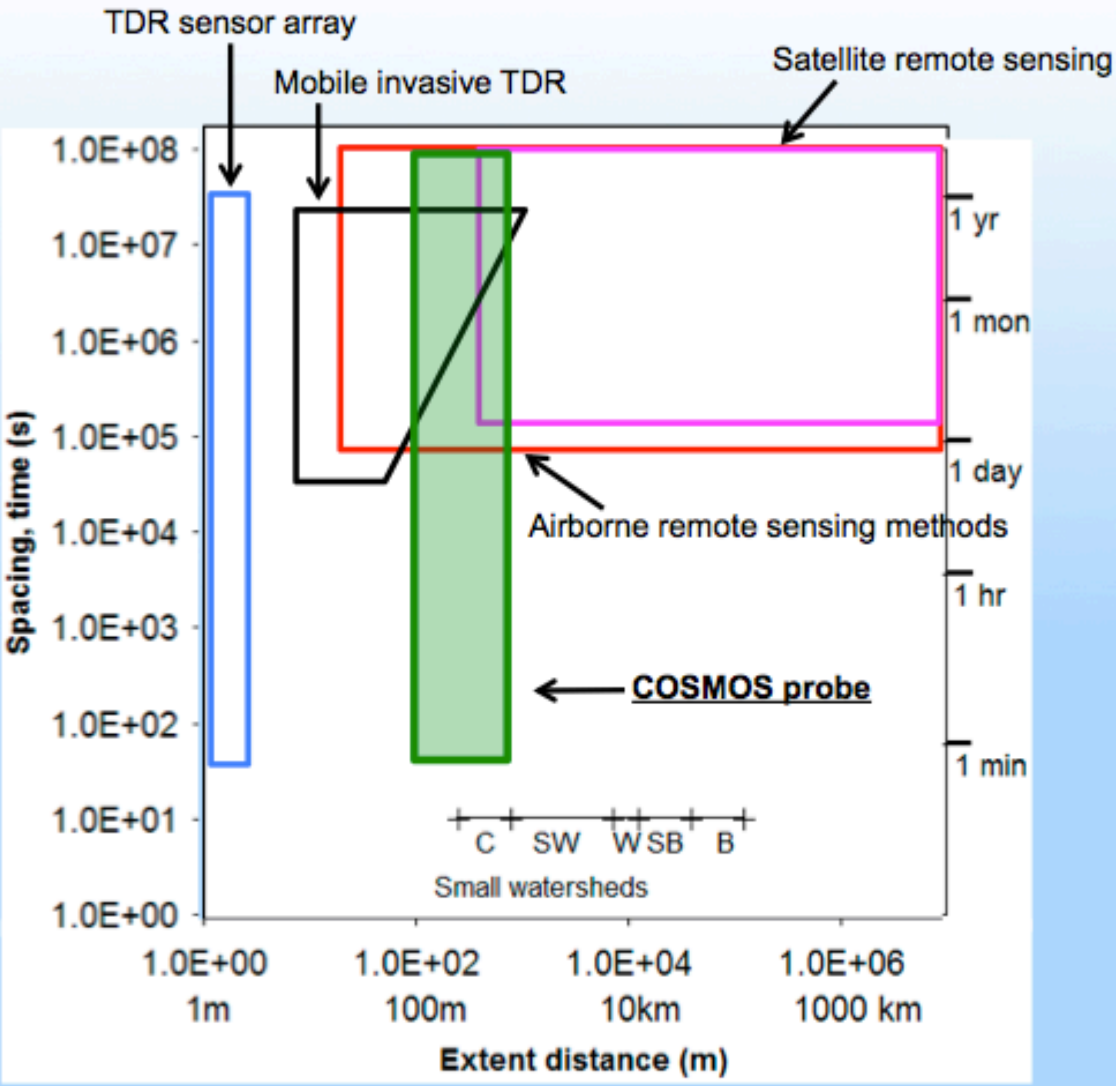
# A Universal Calibration Function But…



# A Working Universal Calibration Function

- Still need local estimates of bulk density and lattice water
- Bulk density not very sensitive in expected range of 1.4 g/cm3 with s.d of 0.1-0.2 g/cm3 (except rare volcanic soils 0.7 g/cm3)
    - Maps and data readily available
- Lattice water requires full chemistry analysis (~$200 per sample)
- Not sure of spatial variation (more samples being analyzed)
- Surprisingly little data on full soil chemistry analysis (typically macro or micro nutrients not both, saves $)
- Working solution, local soil chemistry or two VWC calibrations at different mean VWC to back calculate lattice water

# Soil Moisture Measurements

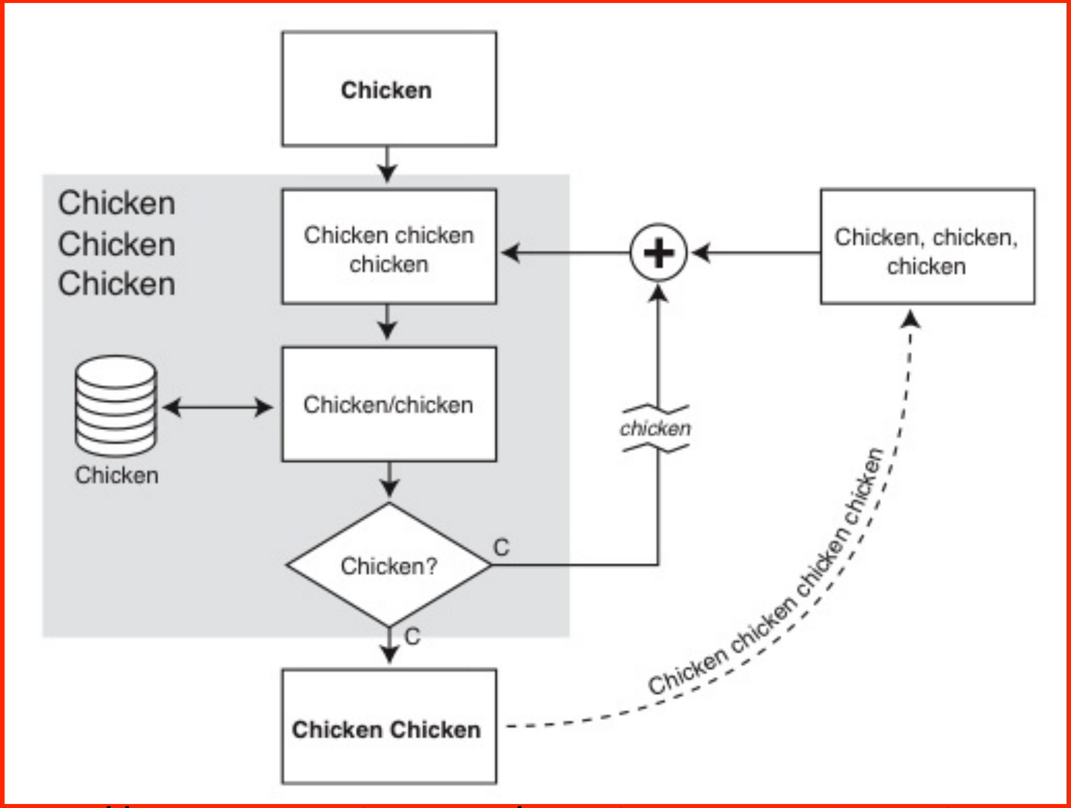


Adapted from Robinson et al. (2008)

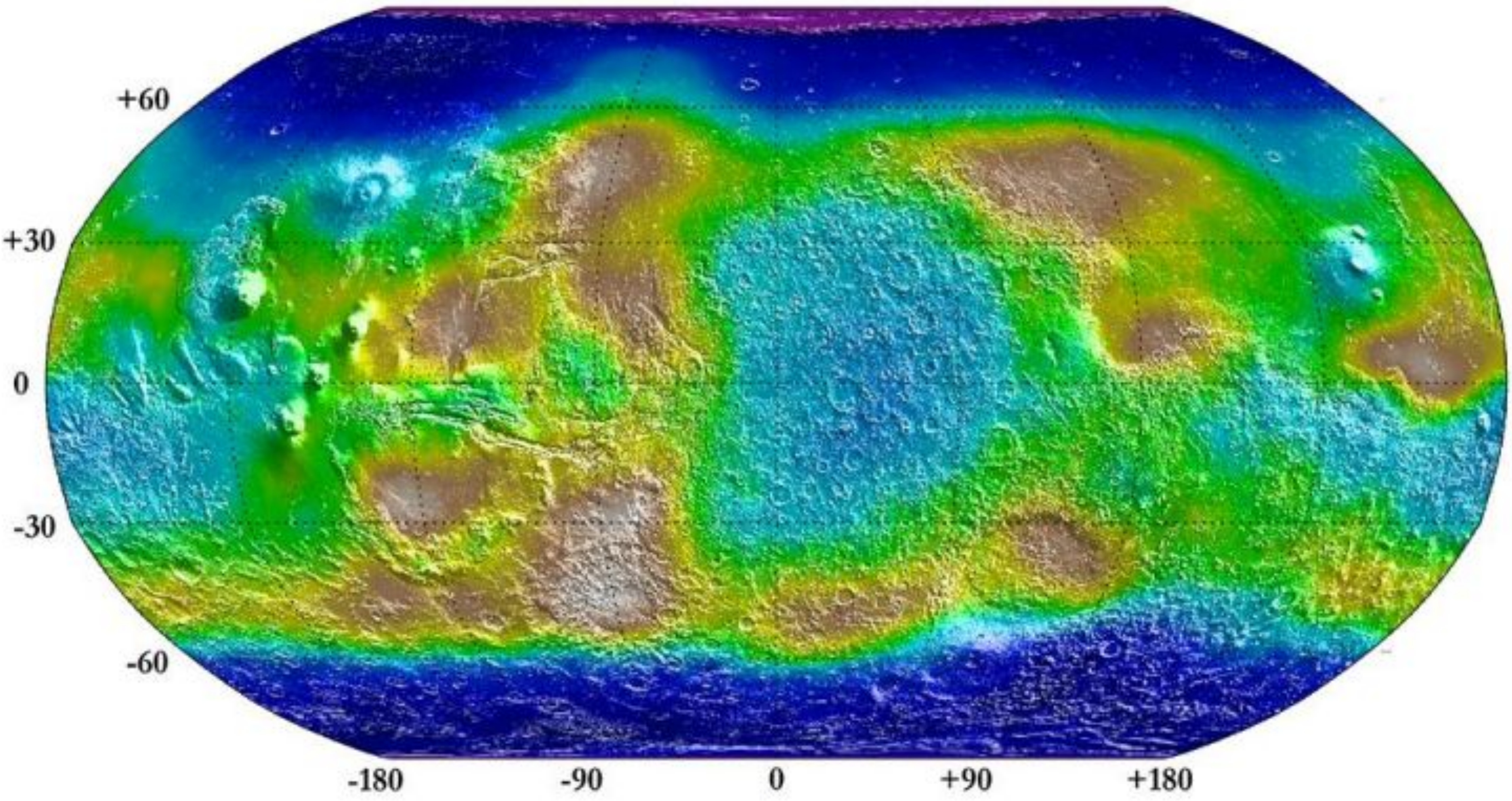
Current technology is constrained to measuring processes with space and time scales consistent with boxes.

Need to form a bridge between current sensor and remote sensing capabilities.

# Initial Results



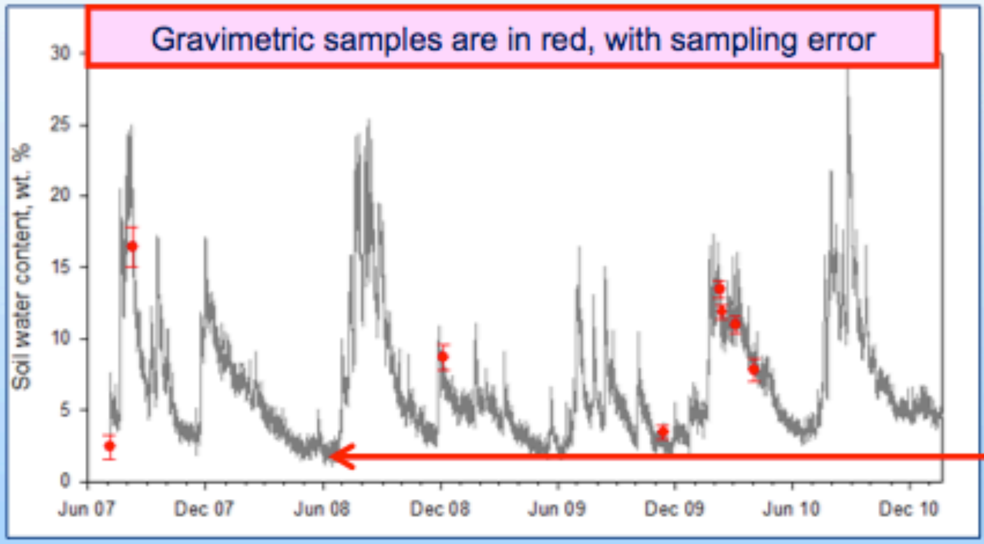
http://www.youtube.com/watch?v=yL_-1d9OSdk



Source: NASA, LANL (Mars Odyssey)

# Initial Results

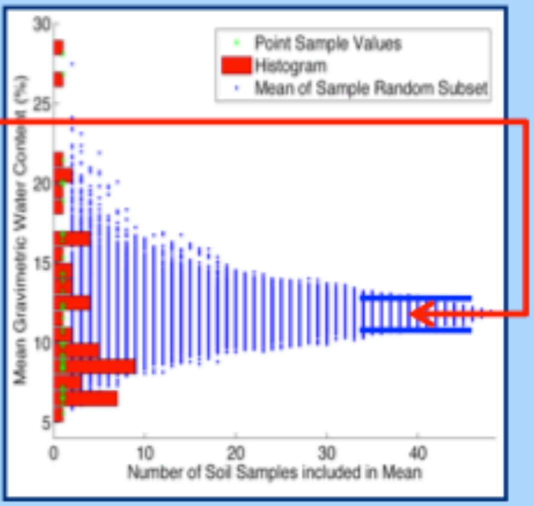
## Example COSMOS Data for the San Pedro Basin



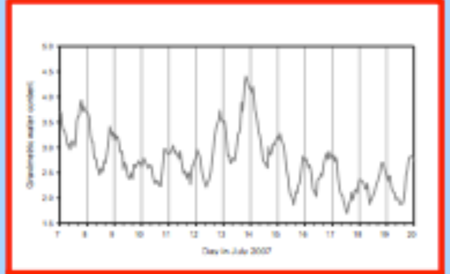
Gravimetric samples are in red, with sampling error

**Soil moisture from cosmic-ray neutron data compared with gravimetric samples**

How many point measurements are needed to get a similar (2%) precision in area-average soil moisture?



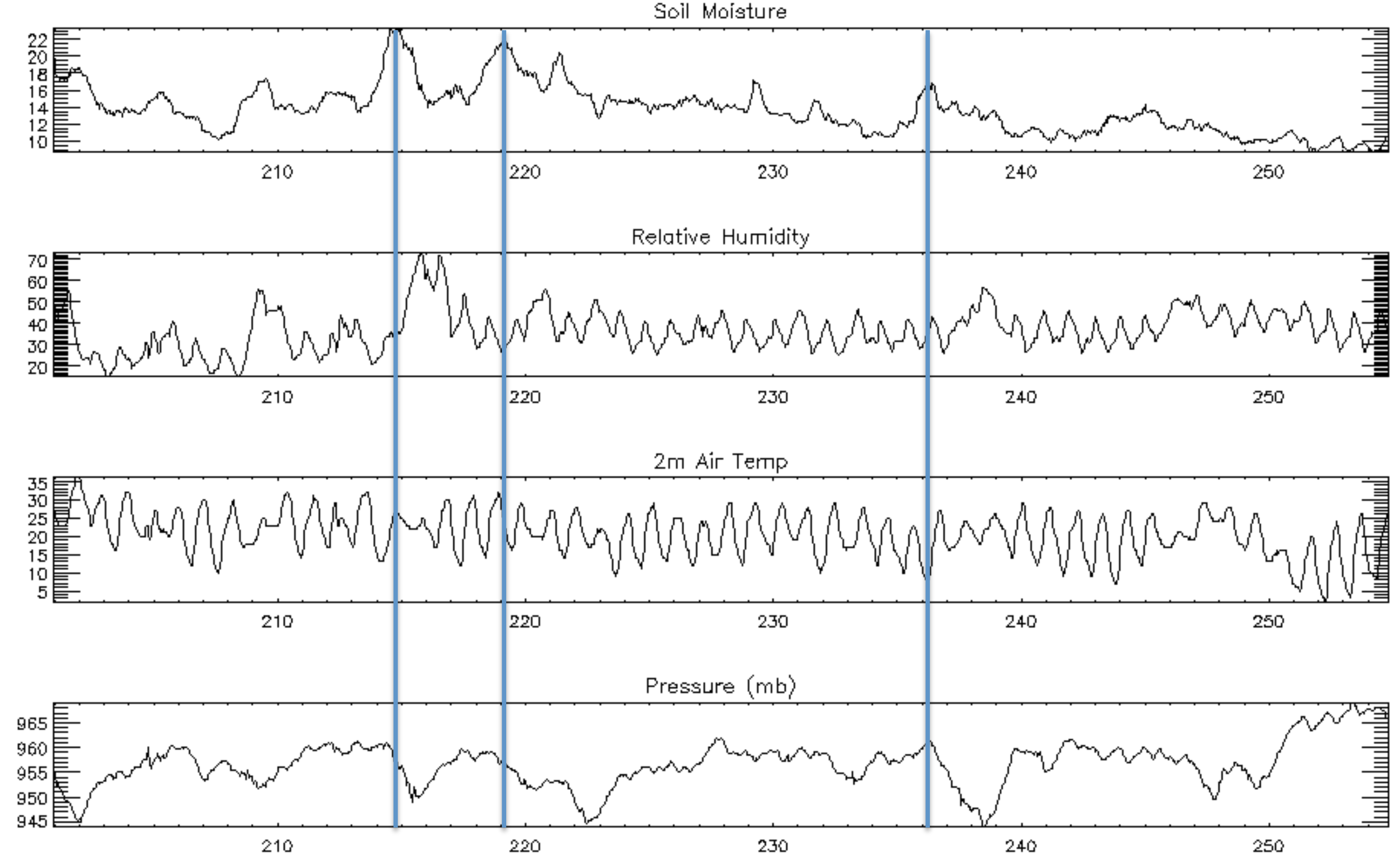
For the (single) calibration of a COSMOS probe (made at installation), soil will be sampled at 3 depths, 8 directions, and 3 radii around the probe (i.e., 72 samples).



Diurnal Cycles
(moisture redistribution)

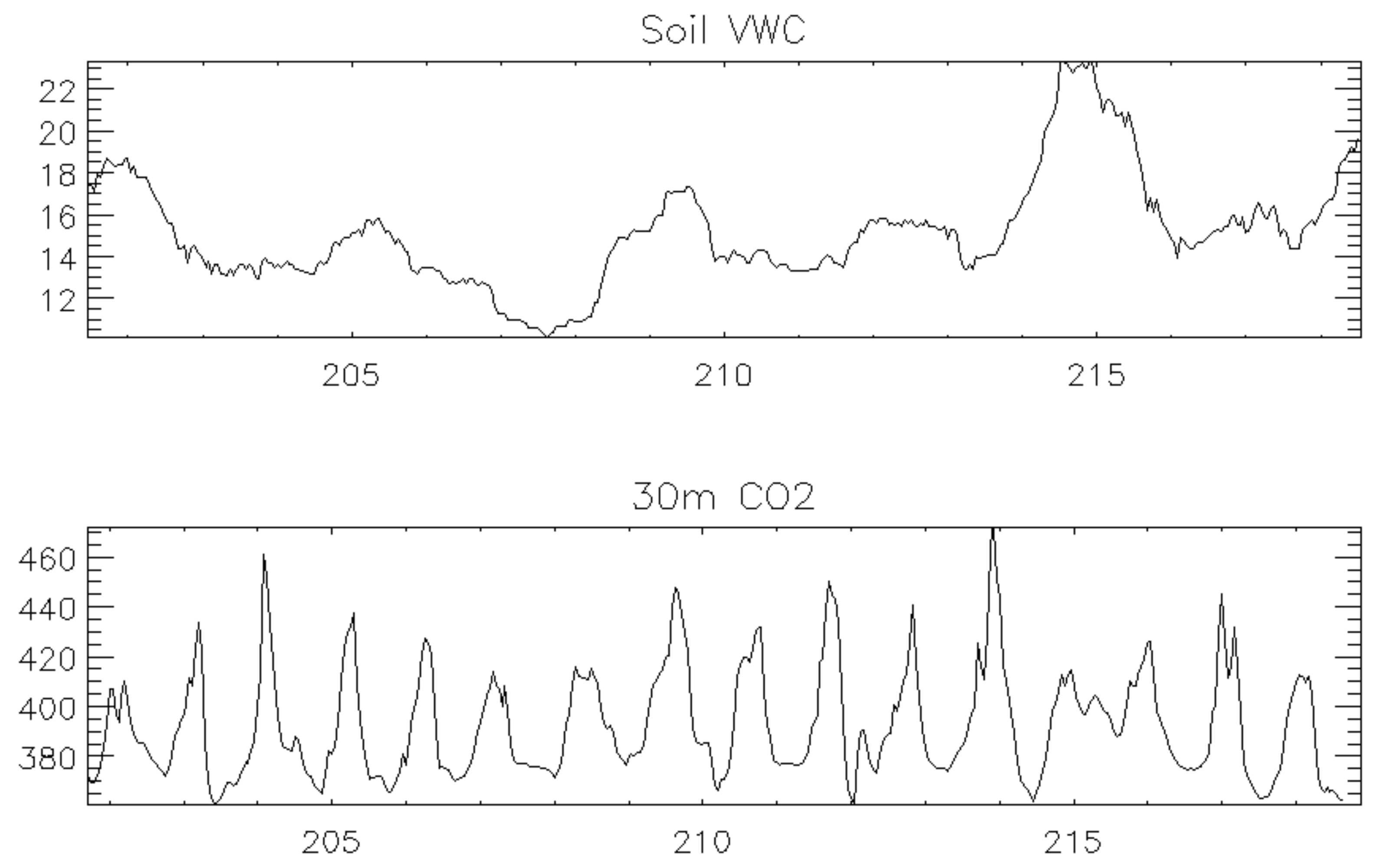
# Initial Results: WLEF

# Initial Results: WLEF

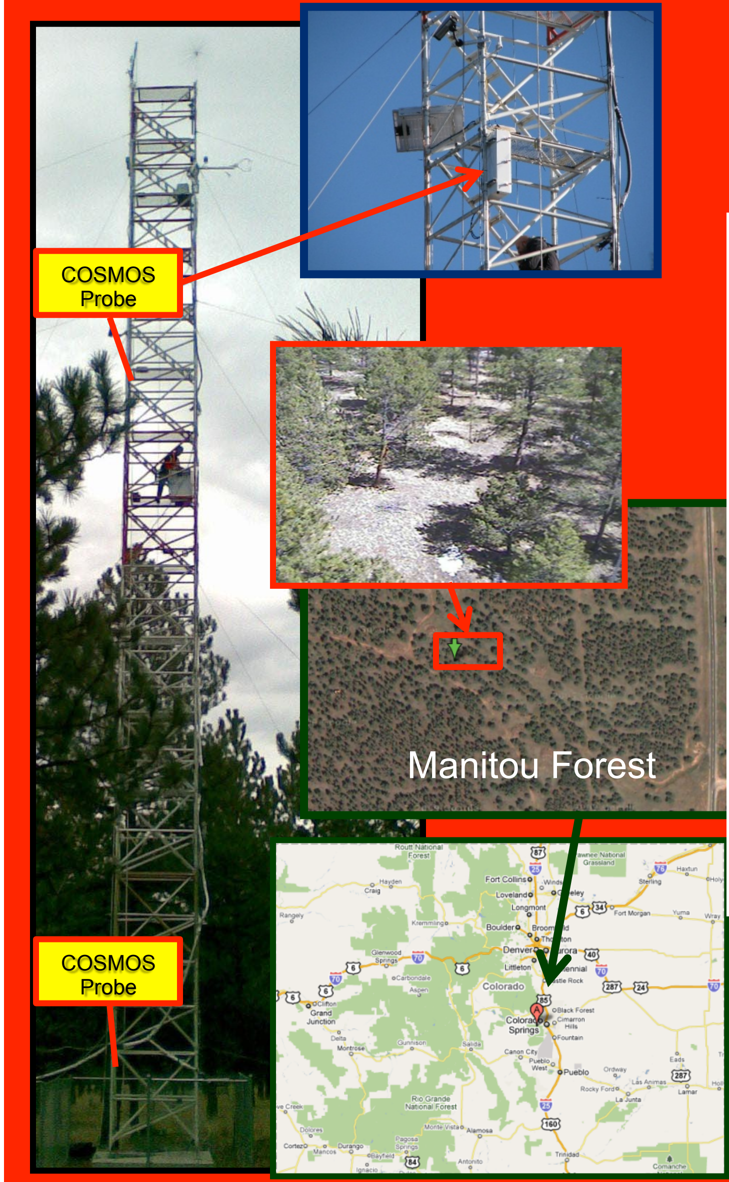


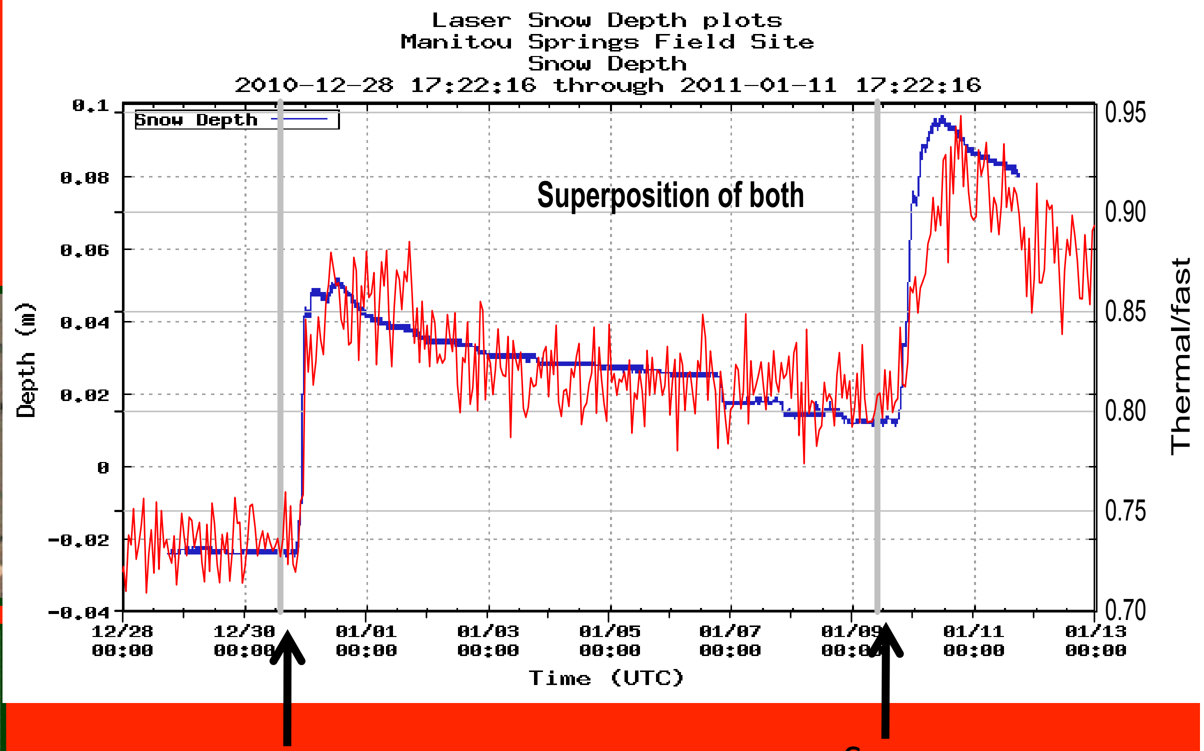
http://cosmos.hwr.arizona.edu/Probes/probemap.php

# Initial Results: WLEF



# Initial Results: Manitou Forest (CO)



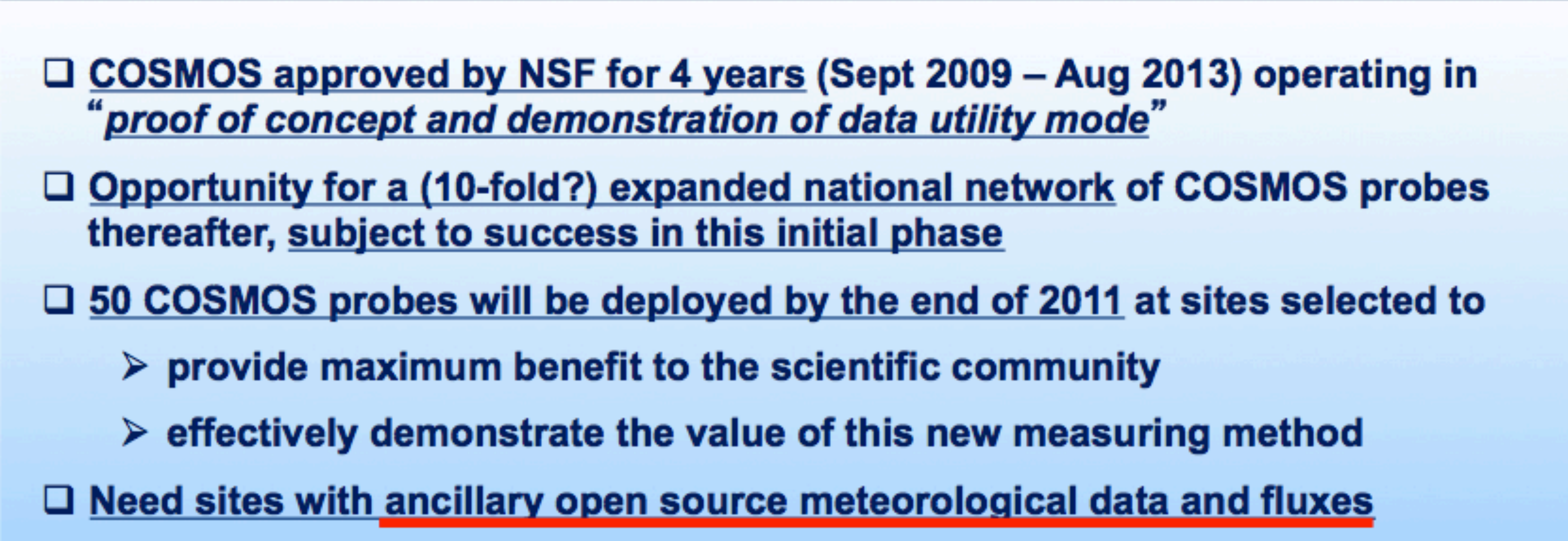


Snow event

Snow event

# Future Plans

# COSMOS Science Priorities



☐ COSMOS approved by NSF for 4 years (Sept 2009 – Aug 2013) operating in "*proof of concept and demonstration of data utility mode*"

☐ Opportunity for a (10-fold?) expanded national network of COSMOS probes thereafter, subject to success in this initial phase

☐ 50 COSMOS probes will be deployed by the end of 2011 at sites selected to

  ➢ provide maximum benefit to the scientific community

  ➢ effectively demonstrate the value of this new measuring method

☐ Need sites with ancillary open source meteorological data and fluxes

http://cosmos.hwr.arizona.edu/

# Summary

- ☐ New national soil moisture observatory network at novel spatial scales
- ☐ Instrument is easy to setup and calibrate with a lifespan of 500+ yrs
- ☐ Monotonic relationship between uniformly distributed soil moisture and fast neutrons
- ☐ Novel hydrological datasets for model parameterization and validation are theoretically possible with cosmos sensor

# More Data Possiblities with COSMOS Sensor

☐ Time series of average depth of ponded water on the surface (time resolution dependent on probe gas volume)

☐ Effects infiltration and runoff production, top boundary condition for Richard's Equation

☐ Quantify hillslope scale runoff in infiltration excess systems

# Theoretically Possible with COSMOS Sensor

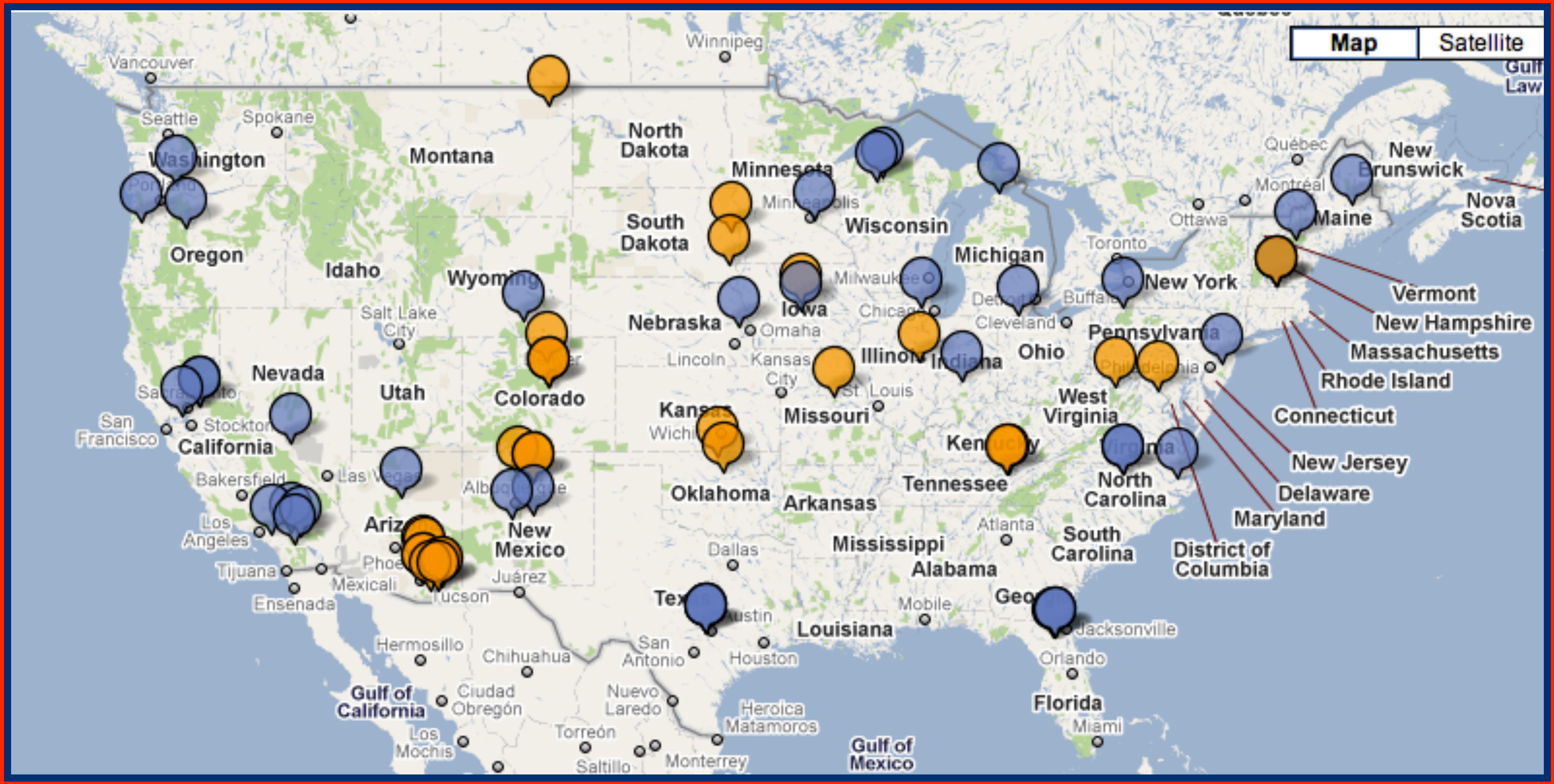
- ☐ Sensor does not “see” over steep elevation changes, fast and thermal neutrons are created in the soil and bounce around and may get reabsorbed in soil before hitting sensor

- ☐ Possible to map soil moisture in drainage basin only following contours with rover

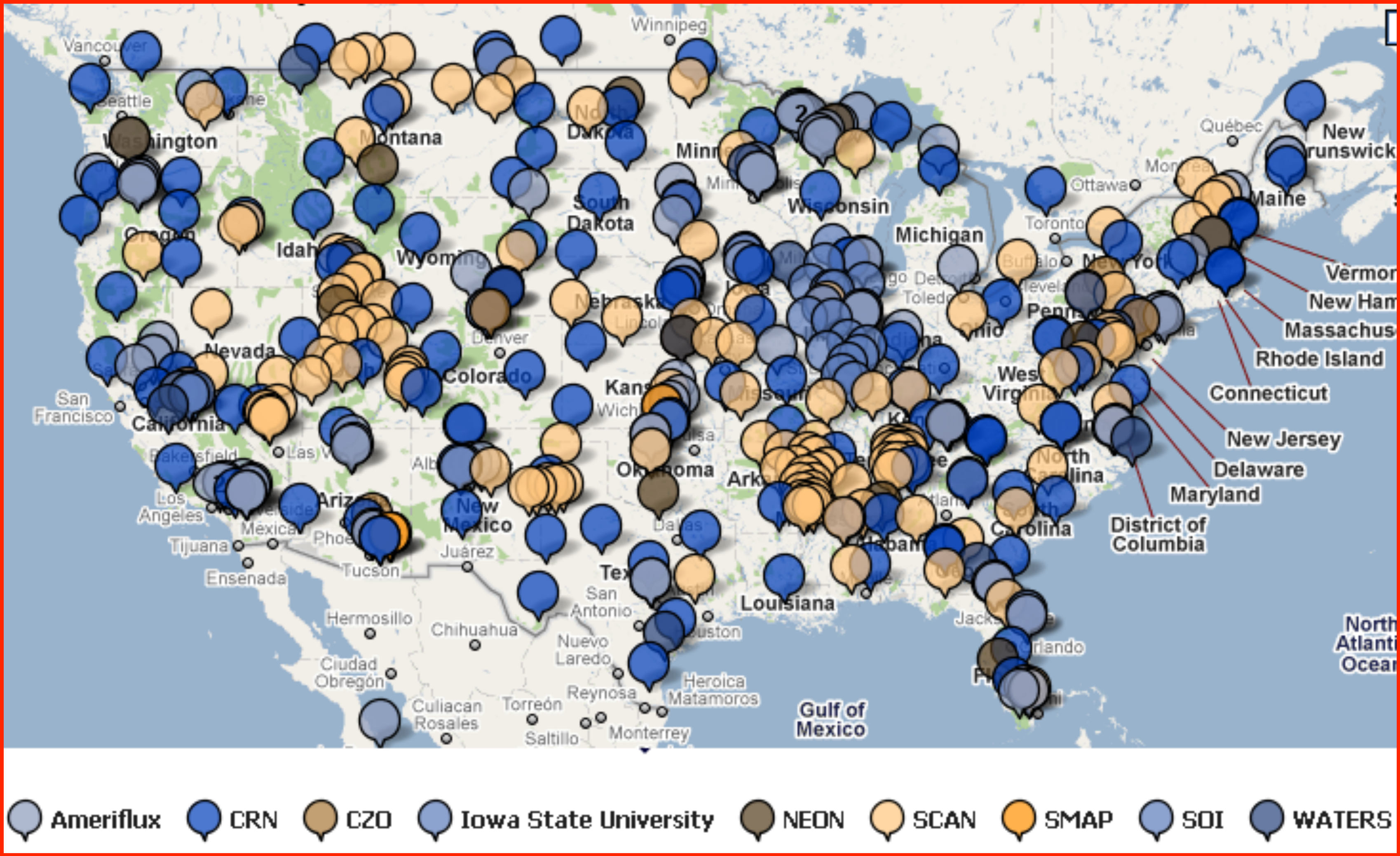
- ☐ Repeated surveys in basin before and after rain events would give you spatiotemporal look at changes in moisture at a novel scale

# Deployments

## AMERIFLUX Sites where COSMOS might be deployed this year



# And Beyond!



Vancouver
Seattle
Washington
Oregon
Idaho
Montana
Wyoming
Nevada
California
San Francisco
Los Angeles
Tijuana
Ensenada
Mexicali
Las Vegas
Arizona
Phoenix
Tucson
Utah
Colorado
Denver
New Mexico
Albuquerque
Juárez
Hermosillo
Chihuahua
Ciudad Obregón
Culiacan Rosales
Torreón
Saltillo
Monterrey
Reynosa
Nuevo Laredo
Heroica Matamoros
Winnipeg
North Dakota
South Dakota
Nebraska
Lincoln
Kansas
Wichita
Oklahoma
Tulsa
Texas
Dallas
San Antonio
Houston
Minnesota
Minneapolis
Wisconsin
Iowa
Missouri
Arkansas
Louisiana
Michigan
Detroit
Toledo
Ohio
Indiana
Kentucky
Tennessee
Alabama
Atlanta
Georgia
Jacksonville
Orlando
Florida
Miami
Gulf of Mexico
Toronto
Ottawa
Montreal
Québec
Buffalo
Cleveland
New York
Pennsylvania
West Virginia
North Carolina
South Carolina
Maine
New Brunswick
Vermont
New Hampshire
Massachusetts
Rhode Island
Connecticut
New Jersey
Delaware
Maryland
District of Columbia
North Atlantic Ocean
2
Ameriflux
CRN
CZO
Iowa State University
NEON
SCAN
SMAP
SOI
WATERS

# Thanks!