Theme of this AMS Meeting, "***Taking Predictions to the Next Level…***"

"In the next decade we will mine the meteorological predictability associated with measured storage of atmospherically accessible water on land surfaces"

Jim Shuttleworth

Department of Hydrology and Water Resources and Department of Atmospheric Science University of Arizona

Atmospheric Science, Hydrology, and Ecology Programs (grant ATM-0838491)

Robert E Horton (1875–1945)

An ecologist and soil scientist, he was:

"the father of modern hydrology"

AGU Horton Medal

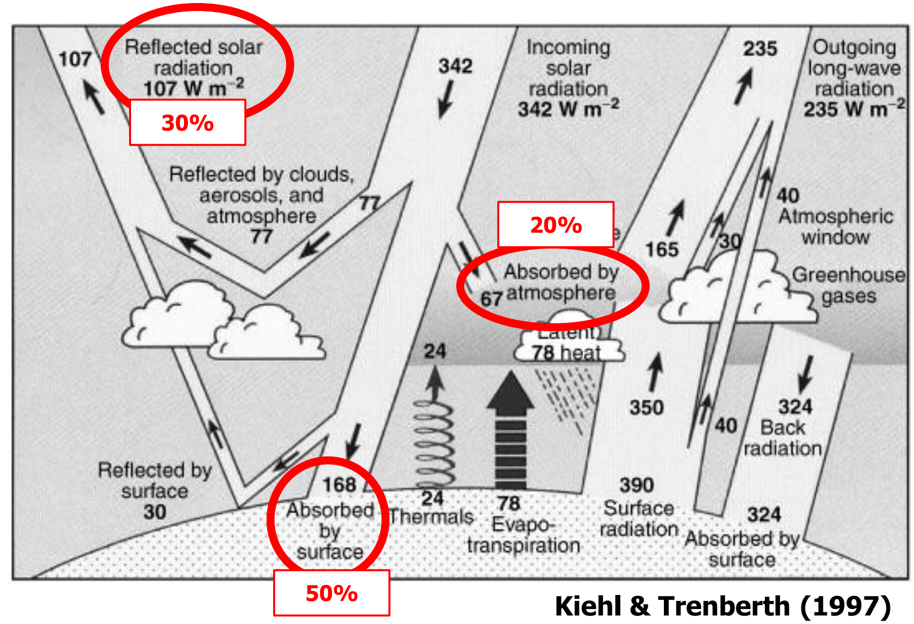
Horton's seminal publications in approximate chronological order from 1903 to 1945 include papers on:

base-flow analysis
snow
interception
history of hydrology
infiltration
ground-water levels
erosion
capillarity

evaporation
rainfall and estimates of water yield
transpiration
drainage-basin characteristics
overland flow
stream-channel storage
flood waves
the physics of rain and thunderstorms

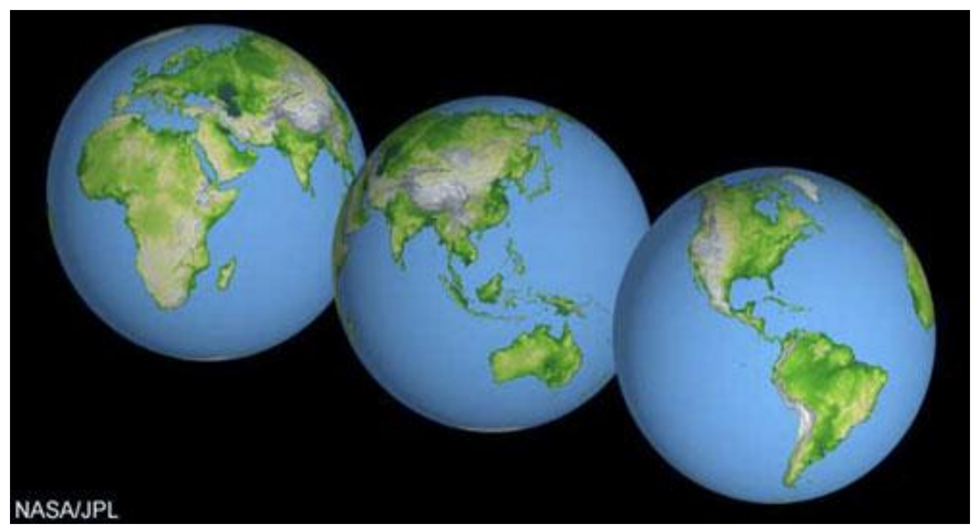
Context

- The atmosphere is largely powered from below



Kiehl & Trenberth (1997)

- Ocean cover 70% of the globe, but continents cover the other 30%



History

Success in discovering and implementing predictability from knowledge of <u>oceanic surfaces</u> involved:

1. **Recognizing sensitivity to the "oceanic influence"**
2. **Measuring the "oceanic influence"**
3. **Modeling the "oceanic influence"**
4. **Interpreting the consequences of the "oceanic influence"**

For oceanic surfaces, the relevant control providing influence is

Sea Surface Temperature (SST)

History

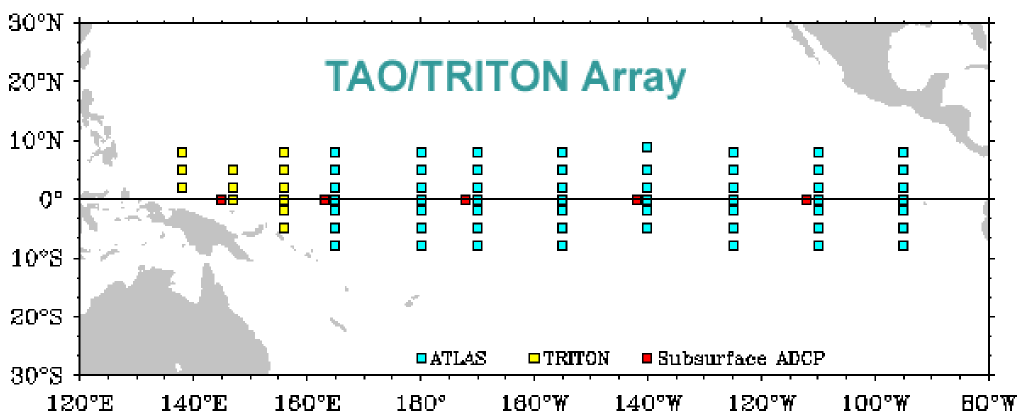
Recognizing the Oceanic Influence:

A powerful El Nino in 1982 and 1983 caused severe droughts in Australia and Indonesia, heavy rain in California, and rains and destructive floods in Ecuador and Peru

Measuring the Oceanic influence:

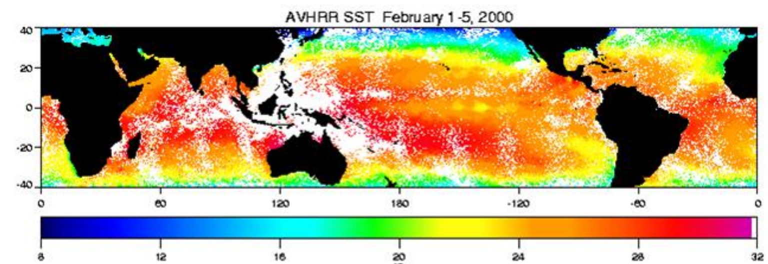
In Situ

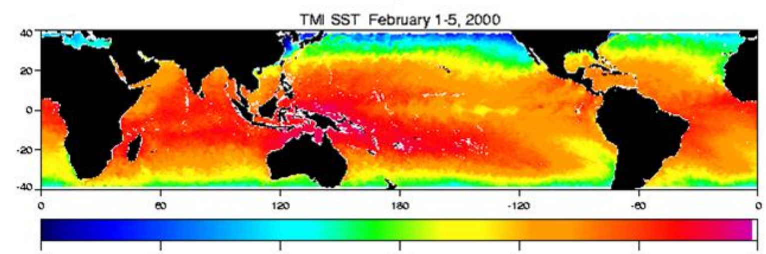
Remote sensing calibration, and information at depth



Remotely Sensed

Thermal Infrared

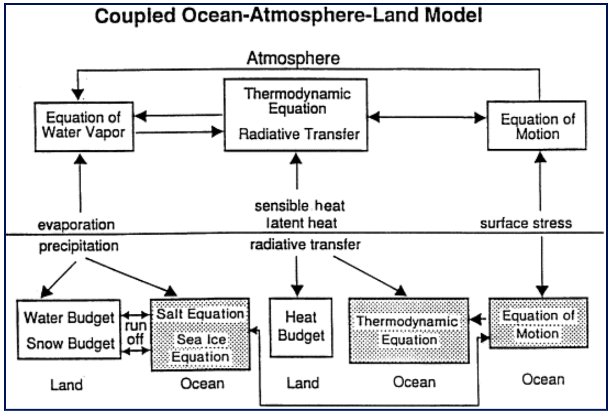




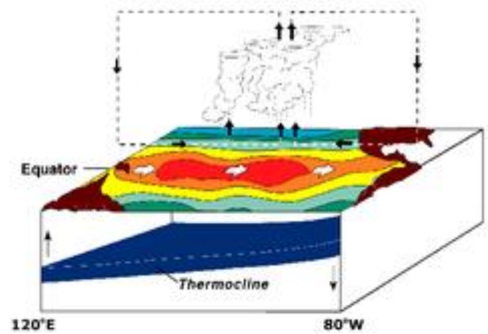
Passive Microwave

History

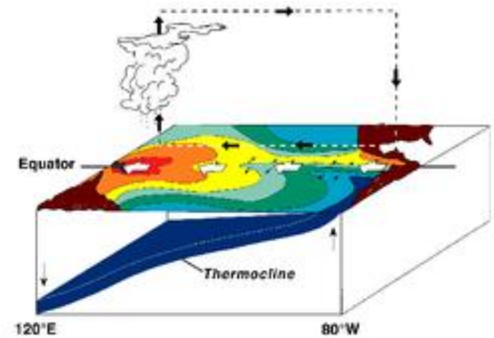
Modeling the Oceanic Influence:



El Niño

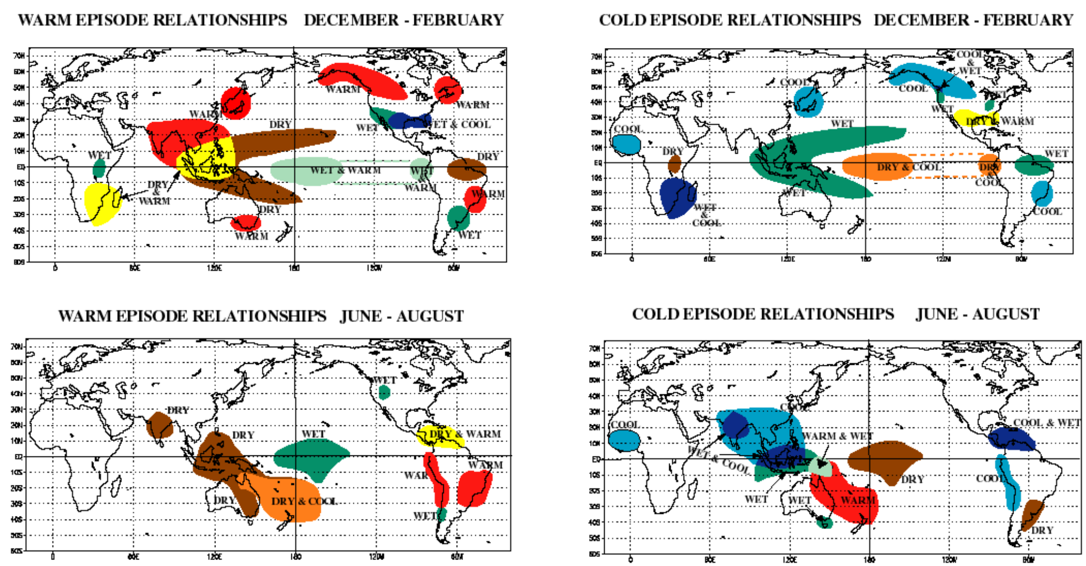


La Niña



Interpreting the Oceanic Influence:

(mainly through <u>observational</u> statistics)



The "Terrestrial Influence"

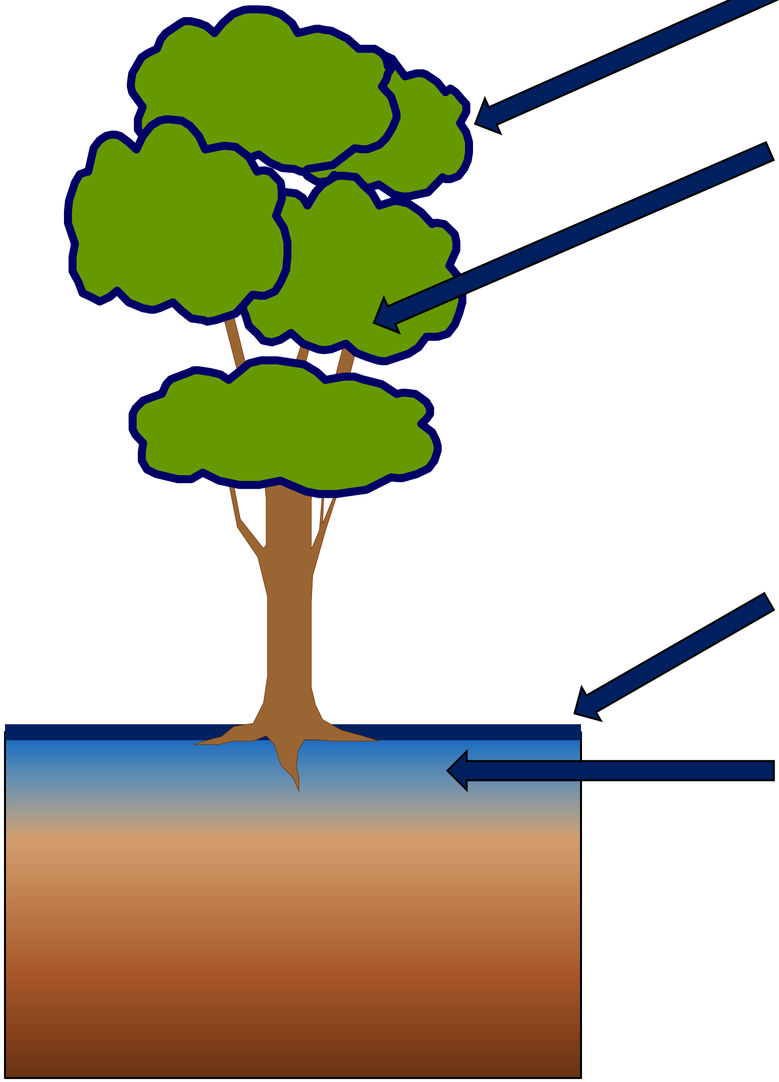
History suggests that discovering and implementing predictability from knowledge of <u>terrestrial surfaces</u> will <u>also</u> involve:

1. **Recognizing sensitivity to the "terrestrial influence"**
2. **Measuring the "terrestrial influence"**
3. **Modeling the "terrestrial influence"**
4. **Interpreting the consequences of the "terrestrial influence"**

For terrestrial surfaces, arguably the most important control providing influence is

"Atmospherically Accessible Water (AAW)"

“Atmospherically accessible” water



Water on vegetation

Water in vegetation

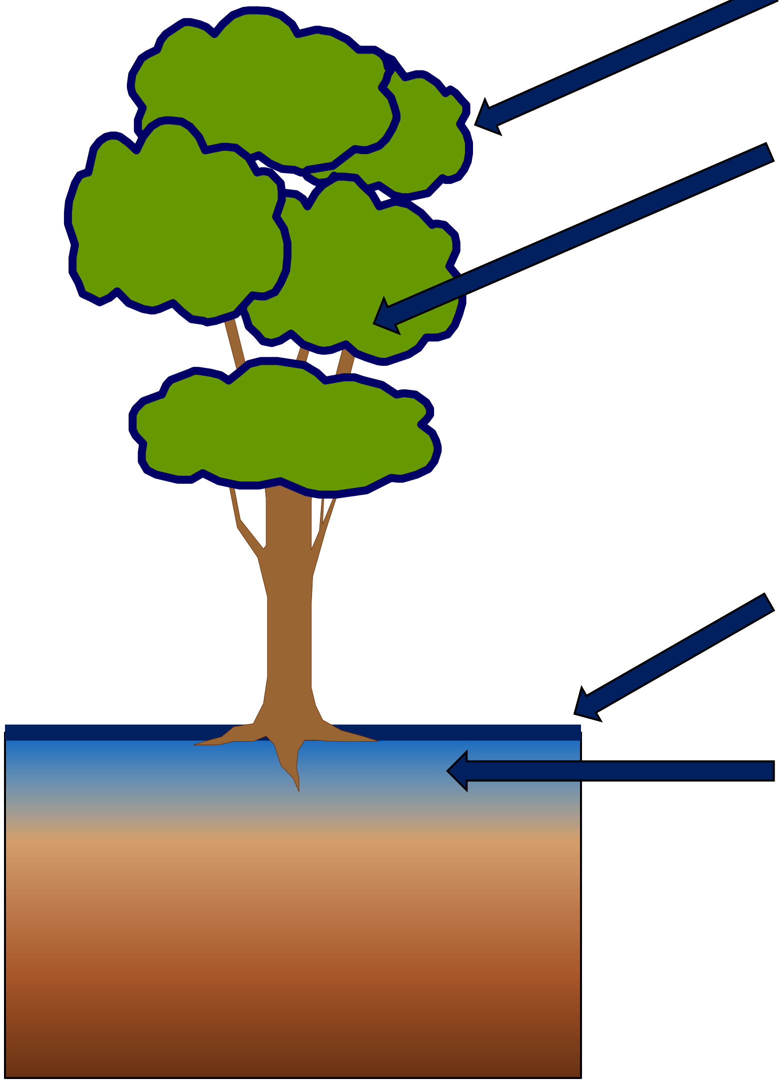
- in transit
- biologically bound

Water on soil

Water in soil

- pore water
- biologically bound
- chemically bound

"Atmospherically accessible" water



Water on vegetation — Hours to days

Water in vegetation

- in transit — Hours to days
- biologically bound — Seasons to years

Water on soil — Hours to days

Water in soil

- pore water — Days to months
- biologically bound — Seasons to years
- chemically bound — NOT ACCESSIBLE

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see, for example, the references in the review of *"Atmospheric Sensitivity to Land Surface Exchanges"* in Chapter 25 of *Terrestrial Hydrometeorology* (Shuttleworth; 2012)

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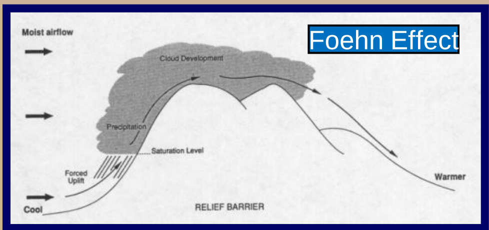
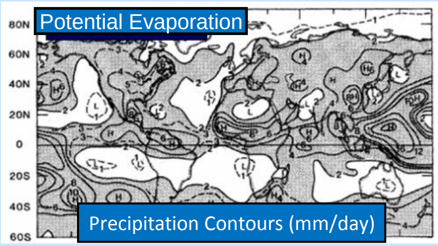
Recognizing the "terrestrial influence"

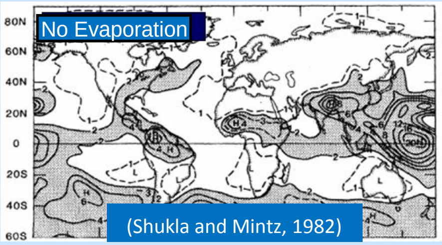
Many studies provide evidence for mechanisms of influence

Influence of topography



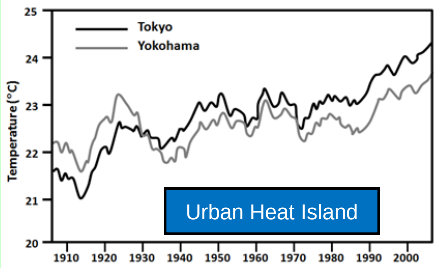
Moisture recycling



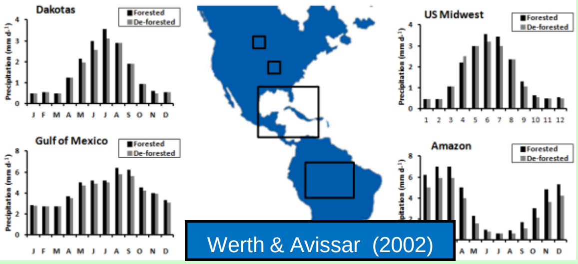


Imposed change of land cover

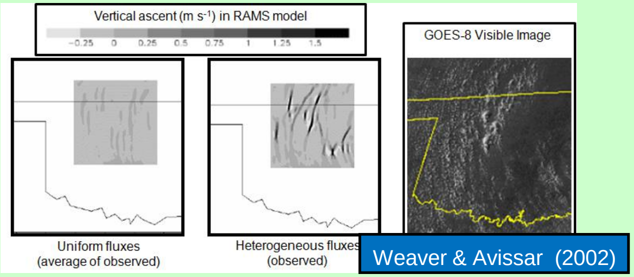
Local climate



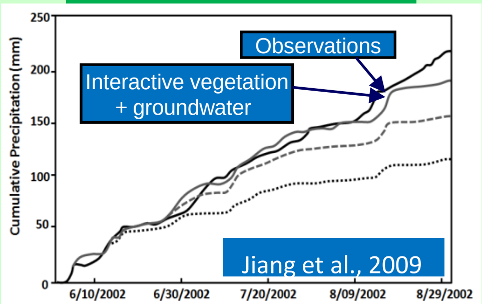
Regional



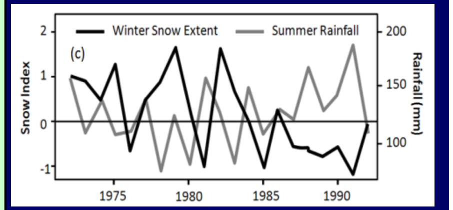
Heterogeneity



Seasonal vegetation



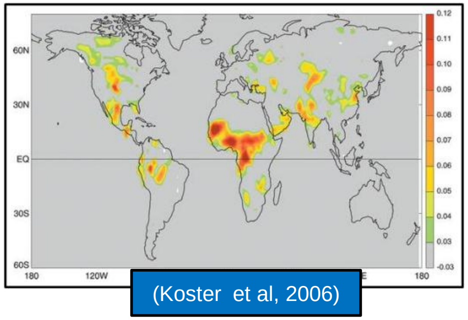
Changes in frozen precipitation



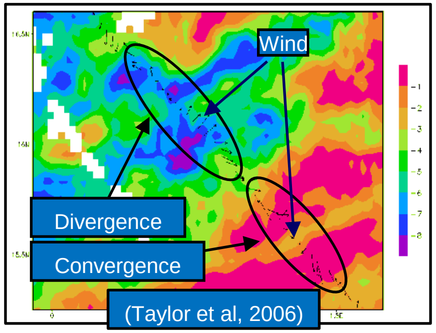
Gutzler & Preston (1997)

Changes in soil moisture

Regional



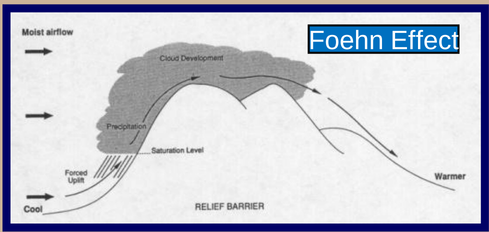
Mesoscale



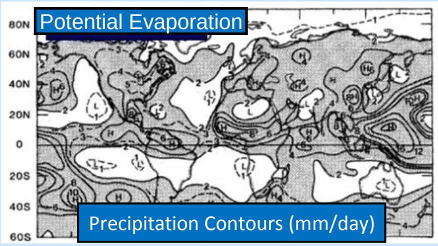
Recognizing the "terrestrial influence"

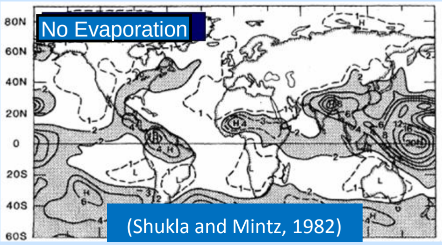
Many studies provide evidence for mechanisms of influence

Influence of topography



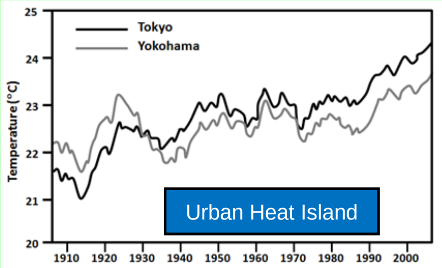
Moisture recycling



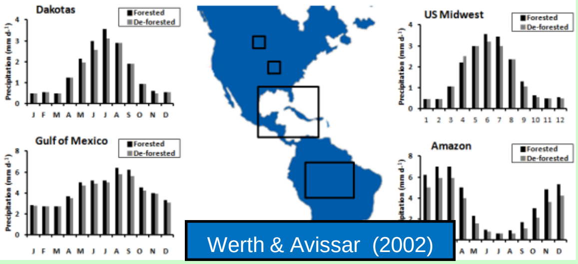


Imposed change of land cover

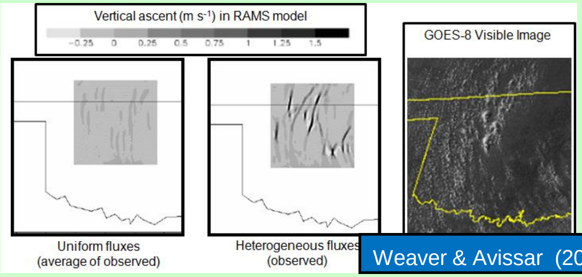
Local climate



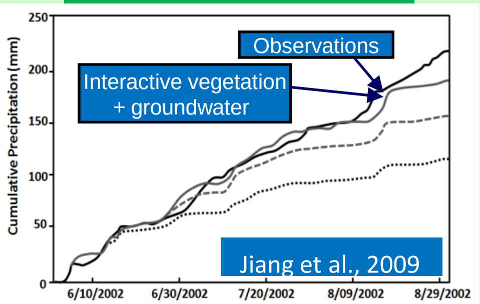
Regional



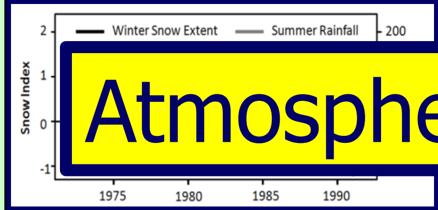
Heterogeneity



Seasonal vegetation

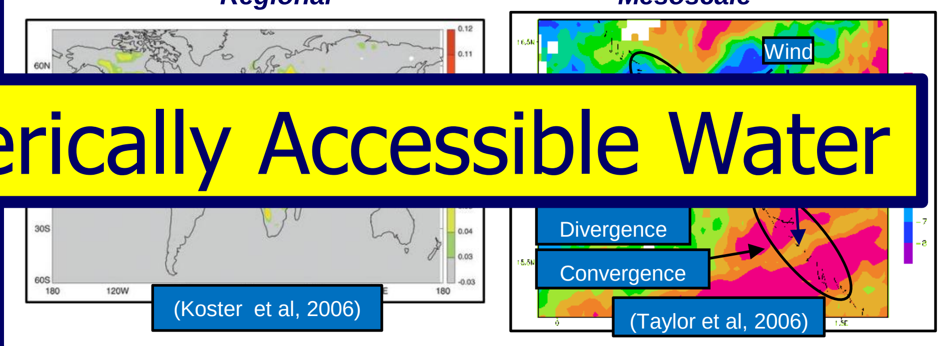


Changes in frozen precipitation



Gutzler & Preston (1997)

Changes in soil moisture



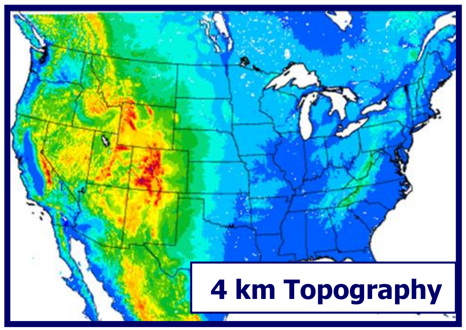
Atmospherically Accessible Water

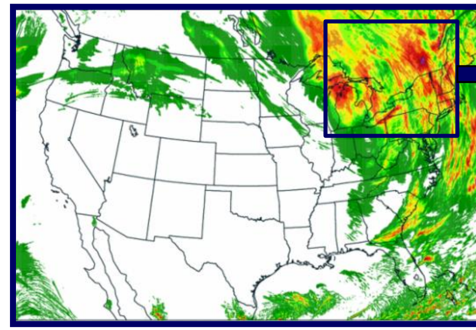
Modeling the "terrestrial influence"

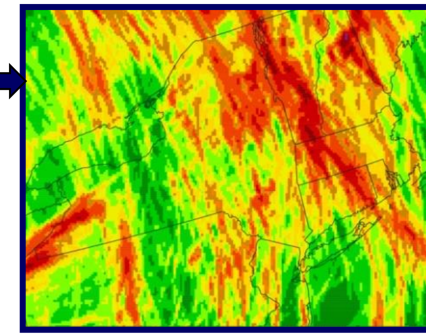
There has been very substantial progress in developing models of the terrestrial influence

- **Model grid resolution of regional and global models has reduced hugely**

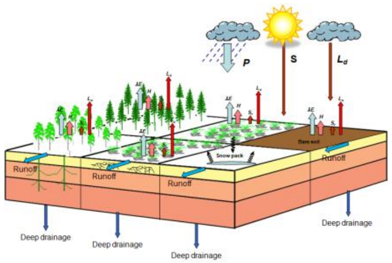
www.nssl.noaa.gov/wrf/



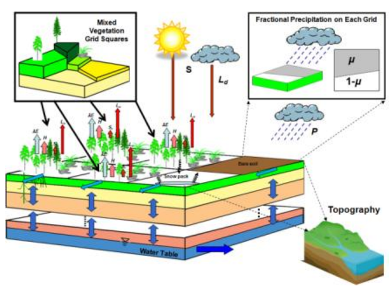




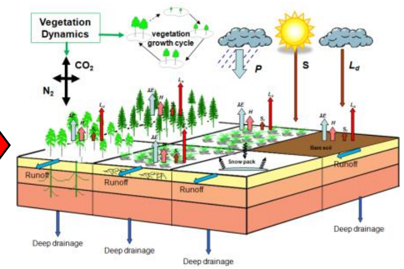
- **3.5 cycles of improvement in the realism of land surface models**



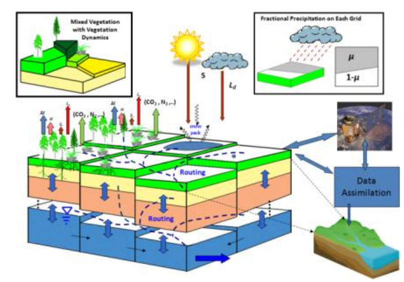
1. Plot-scale, 1-d models (e.g. BATS, SiB,...)



2. Improved hydrology (e.g. VIC,...)



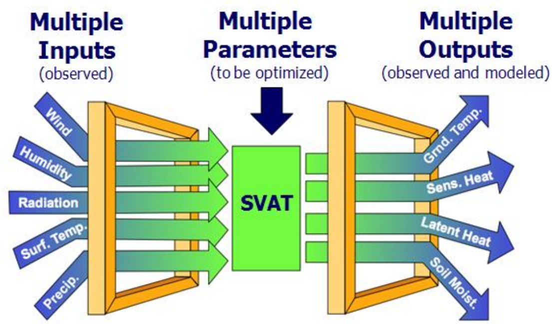
3. Improved CO_2 exchange (e.g. BATS2, SiB2/3, CLM)

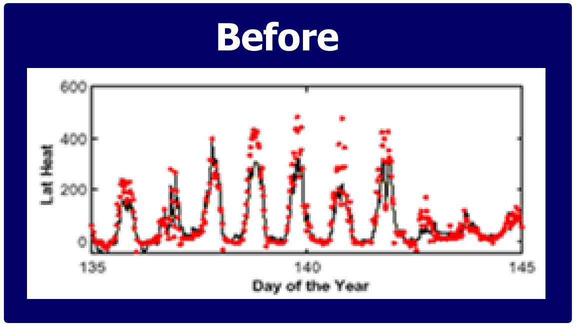


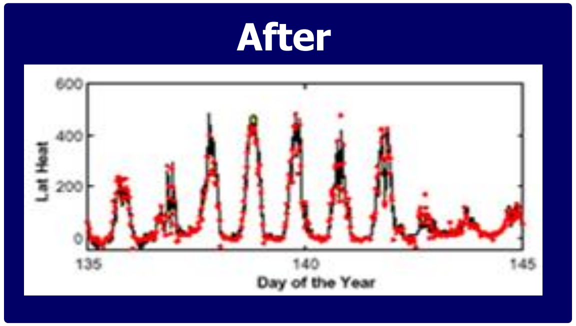
4. Ongoing (groundwater, hydraulic redistribution,..)

Modeling the "terrestrial influence"

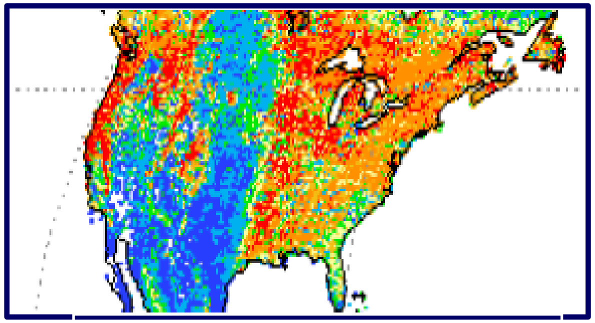
- Using field data with multi-criteria optimization to calibrate models



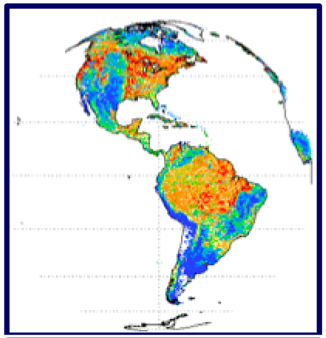




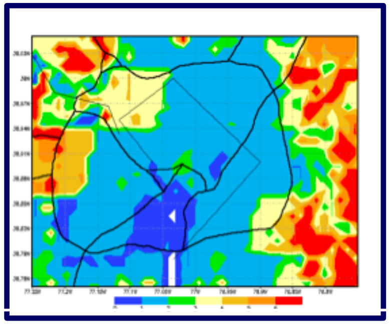
- Creation of *Land Data Assimilation Systems* (LDAS)



North American LDAS
0.125° resolution



Global LDAS 0.125° resolution



Land Information System (LIS)
Global, regional, point
(1km resolution, and finer)

BUT ALL MODELS NEED INITIATION AND CORRECTION

The "Terrestrial Influence"

"In the next decade we will mine the meteorological predictability associated with measured storage of atmospherically accessible water on land surfaces"

(Shuttleworth 2013)

HOW?

By creating the capability to measure the "atmospherically accessible water" (available in soil and vegetation) at the land surface.

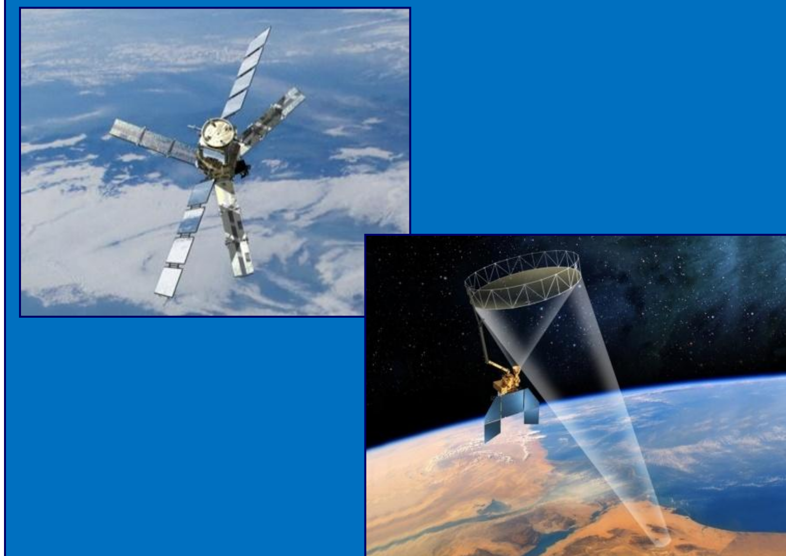
We are in the first stages of an observational revolution

"Taking Predictions to the Next Level..."

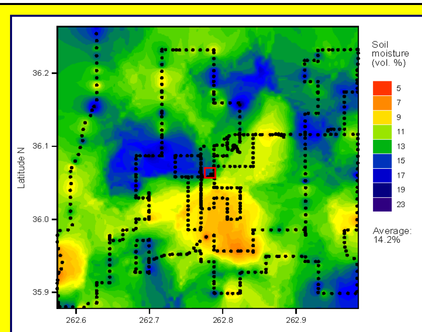
Measuring the "terrestrial influence"

Components of the upcoming observational revolution

Remotely Sensed
Large pixel-scale area-averages



In Situ
Stationary hectometer-scale area-averages



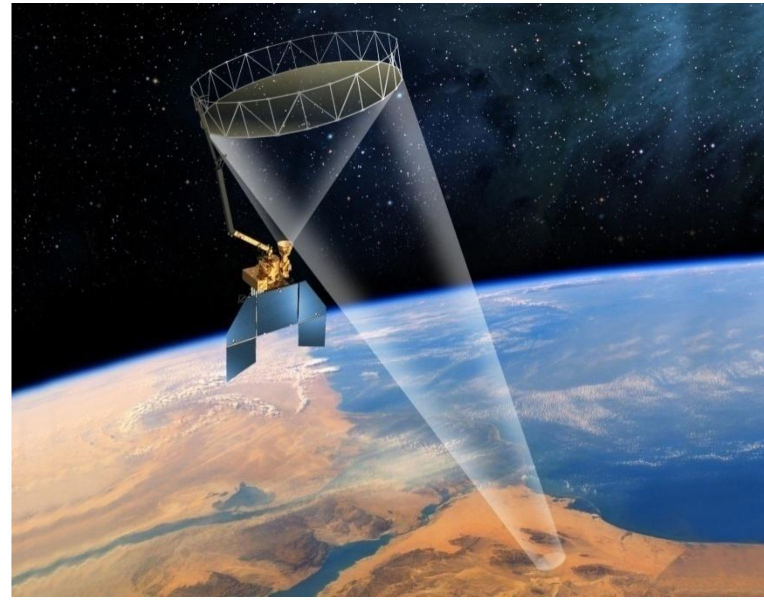
Mobile
hectometer-scale area-averages combined to large pixel scale

(e.g., SMAP Test Bed)

Measuring the "terrestrial influence"

Remote Sensing Platforms

Soil Moisture Ocean Salinity (SMOS)
(launched Nov 2, 2009)



Soil Moisture Active Passive (SMAP)
(projected launch 2114)

http://www.esa.int/esaLP/LPsmos.html

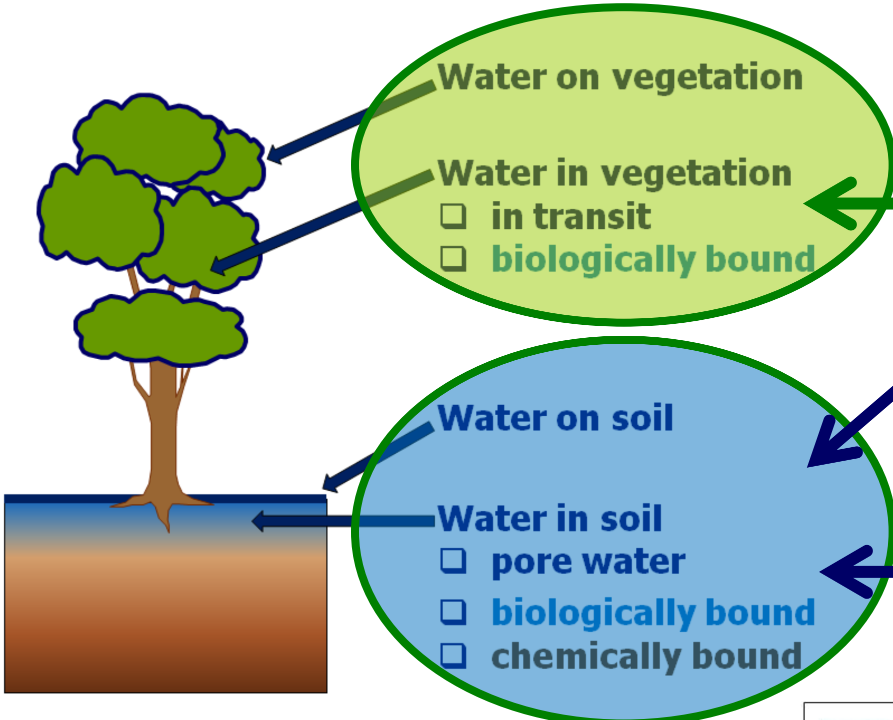
Images every 1.2 seconds
~~Altitude ~ 758 km~~
Field of view ~ 1000 km hexagon
Global coverage every 3 days

http://smap.jpl.nasa.gov/instrument/

Radiometer/SAR L-band (1.20-1.41 GHz)
~~Measures surface emission/backscatter~~
Measurement swath width ~1000 km
Global coverage 2-3 days

Measuring the “terrestrial influence”

Microwave Remote Sensing



One has to know or measure <u>THIS</u> in order to measure <u>THIS</u>

One can only measure <u>ALL OF THIS</u> <u>not its separate contributions</u>

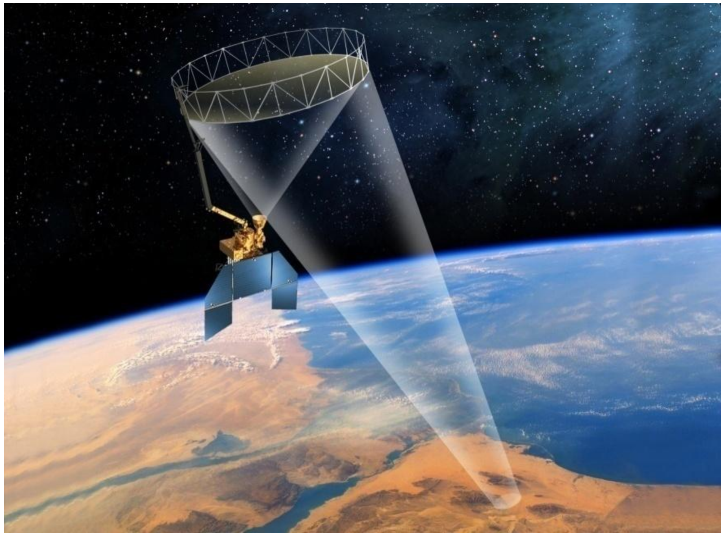
Microwave missions measure “Atmospherically Accessible water”

“Taking Predictions to the Next Level…”

Soil Moisture Ocean Salinity (SMOS)
(launched Nov 2, 2009)

Soil Moisture Active Passive (SMAP)

Expectations for the SMAP Platform



Soil Moisture Active Passive (SMAP)

Instrument:

- Includes a radiometer and a synthetic aperture radar operating at L-band (1.20-1.41 GHz).
- Will make coincident measurements of surface emission and backscatter, with the ability to sense the soil conditions through moderate vegetation cover.
- Measurements will be analyzed to yield estimates of soil moisture and freeze/thaw state.

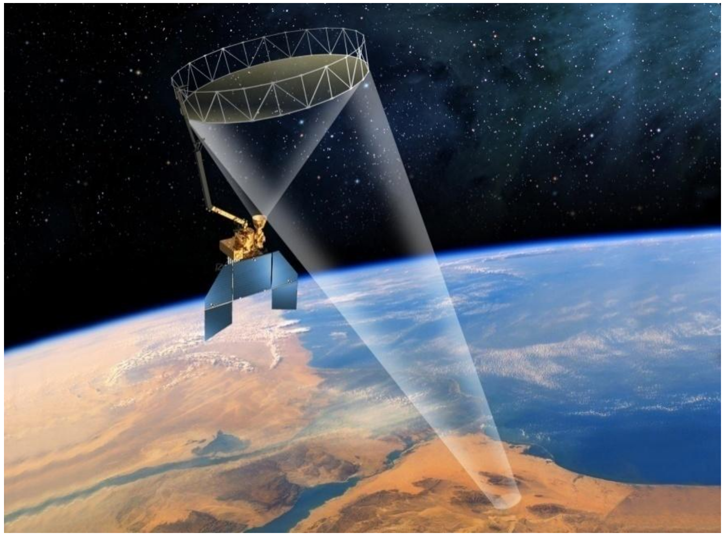
PRODUCTS (both SMAP and SMOS)

Primary observation-derived "soil moisture" product: soil moisture in the top 5 cm with accuracy ± 0.04 m^3 m^{-3} at ~10 km resolution

Additional model-derived "soil moisture" product: estimated soil moisture in top 1 m of soil (using EnKF to merge SMAP data with estimates from NASA Catchment model driven with observation-based surface meteorological forcing, including precipitation.)

Most relevant to meteorological prediction

Expectations for the SMAP Platform



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The true SMAP/SMOS product (cal/val reflects this)

Mainly depends on accurate ancillary data and a realistic, model of soil movement (does cal/val reflect this?)

Measuring the "terrestrial influence"

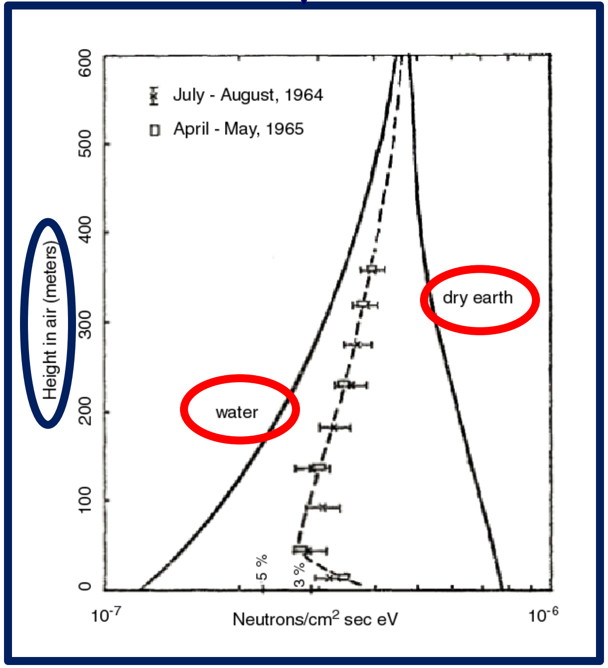
In Situ and Mobile Cosmic-ray Surface Moisture Sensors

The basic idea and sensor technology is not new:

- neutron detectors developed in the 1950s are available "off the shelf"
- it was known in the 1960s that above-ground neutron count rate depends on soil moisture

What is New?

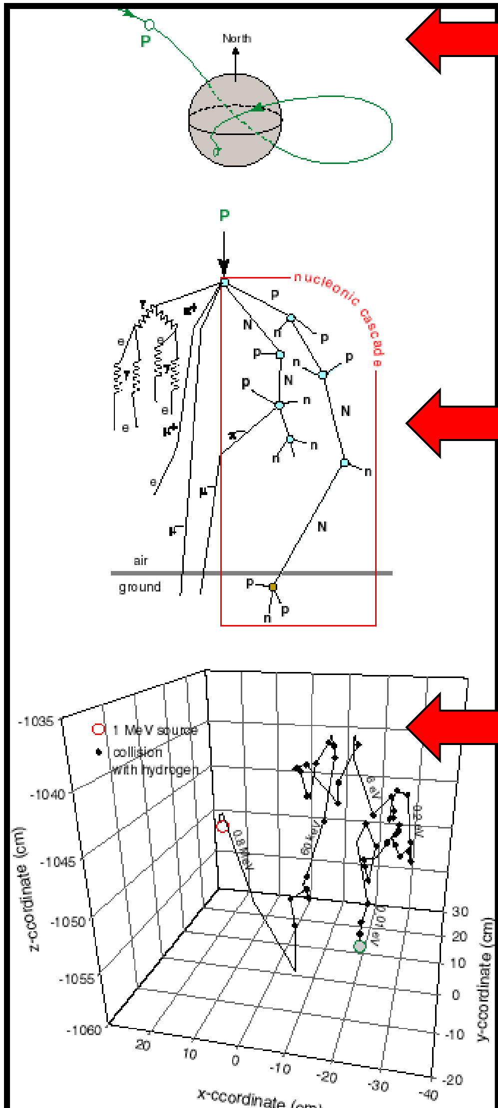
- **systematic understanding of cosmic-ray neutron interactions at the ground-atmosphere interface,** revealed near-surface above-ground fast neutron density has:
  - **a source footprint of hectometers**
  - **limited sensitivity to soil type**
- **improved and low power electronics** (for pulse shaping and amplification; remote detection and correction of sensor drift, and remote data capture); and better (solar) power systems



Hendrick and Edge (1966)

Cosmic-ray Surface Moisture Sensors

How are high energy neutrons created



IN SPACE:
There are incoming high-energy cosmic-ray protons whose intensity changes slowly with time and with geomagnetic latitude (they interact with the Earth's magnetic field).

Both corrected for

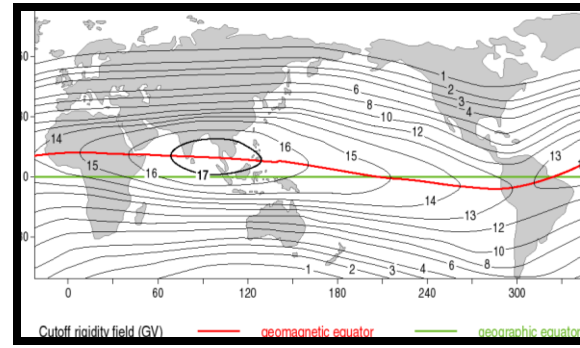
IN THE ATMOSPHERE:
Cascades of secondary cosmic rays generated whose intensity depends on barometric pressure.

Corrected for

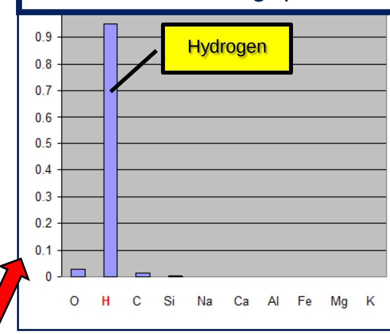
AT THE EARTH SURFACE:
the fast neutrons are scattered ("thermalized") and absorbed

A field of fast neutrons is created in the air above the ground whose strength depends on the composition of the interface,

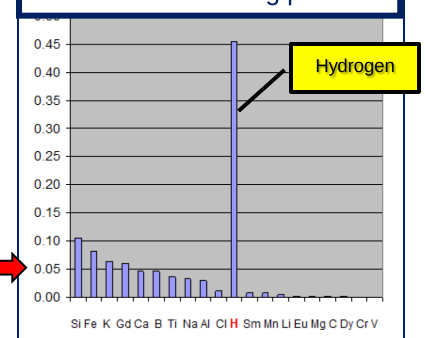
especially its water content
(strictly hydrogen content)



Relative "slowing" power



Relative absorbing power

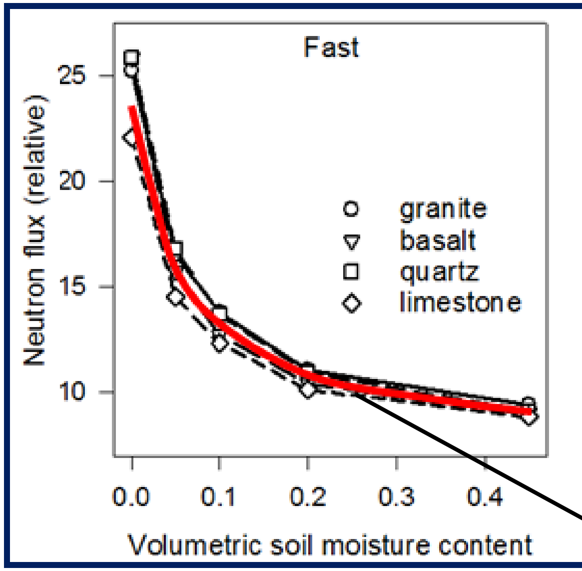


Cosmic-ray Surface Moisture Sensors

Instrument

Fast Neutron Detector

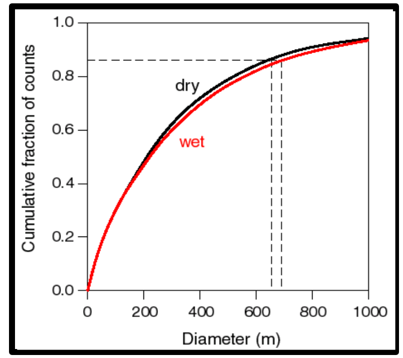
Calibration



(Zreda, et al; 2008)

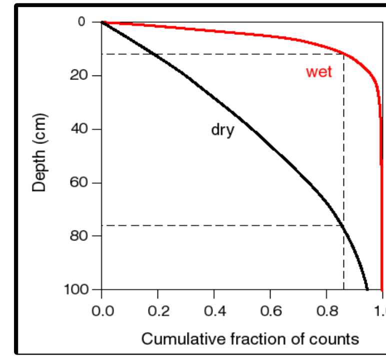
Soil Sample

Radius



86% of neutrons from within 350 m radius

Depth

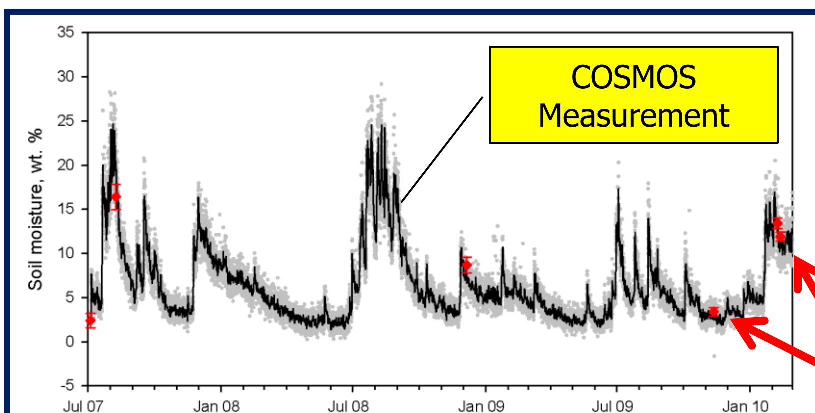


86% of neutrons from within a depth of 70 cm (dry); 12 cm (wet)

A "shift" related to the <u>fixed</u> chemistry of the soil and (perhaps) vegetation, (including chemically bound hydrogen)

SO REQUIRES ONE FIELD CALIBRATION AT INSTALLATION

<u>Allows measurement of varying water content, e.g. soil pore water</u> (with a small, correction for atmospheric humidity)

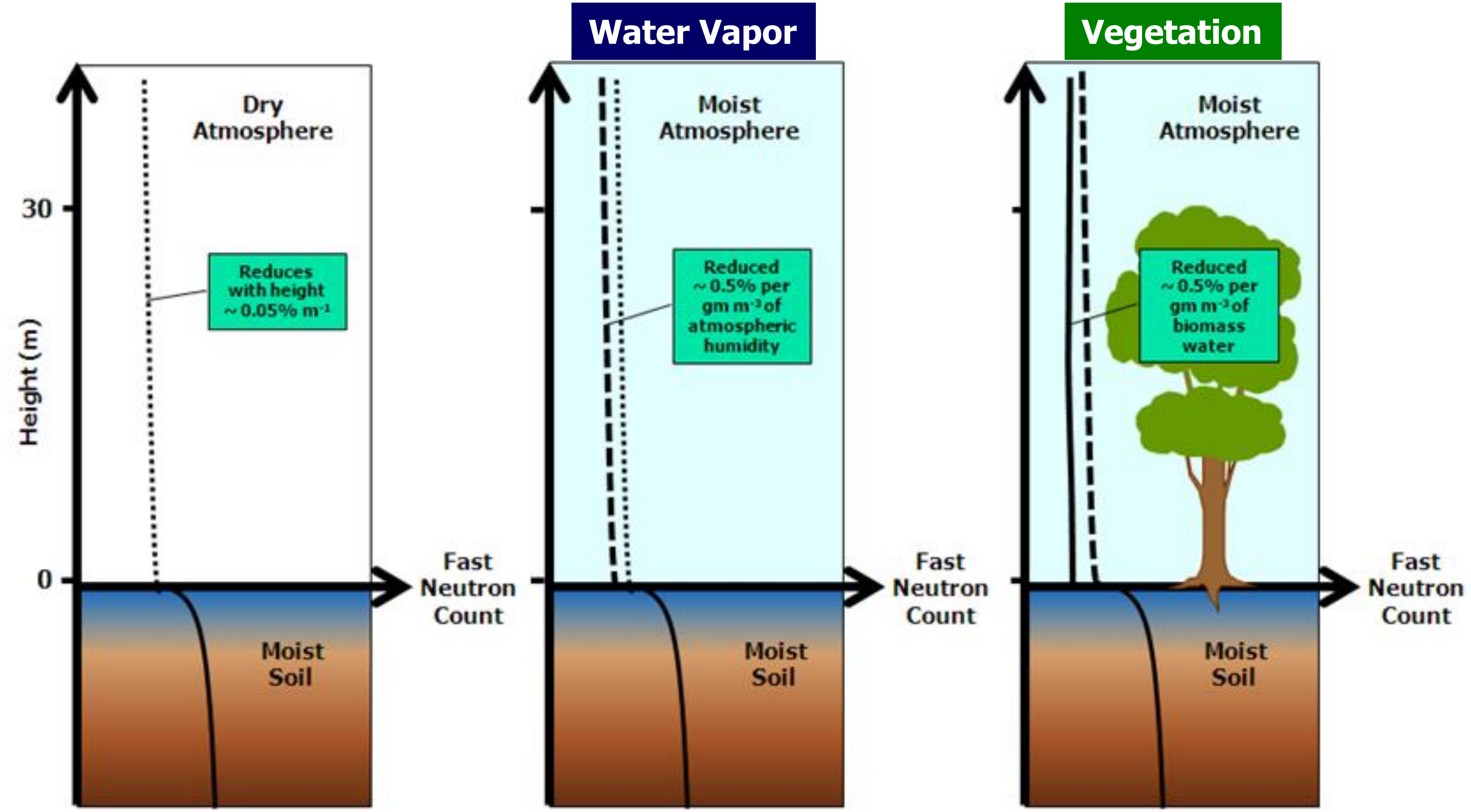


Gravimetric Comparisons

University of Arizona

Cosmic-ray Surface Moisture Sensors

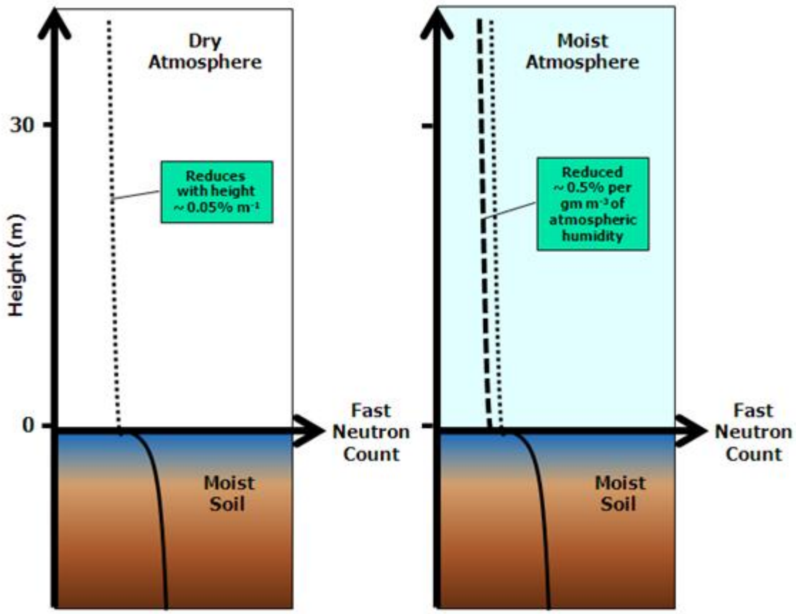
Effect of additional water stores near the land surface

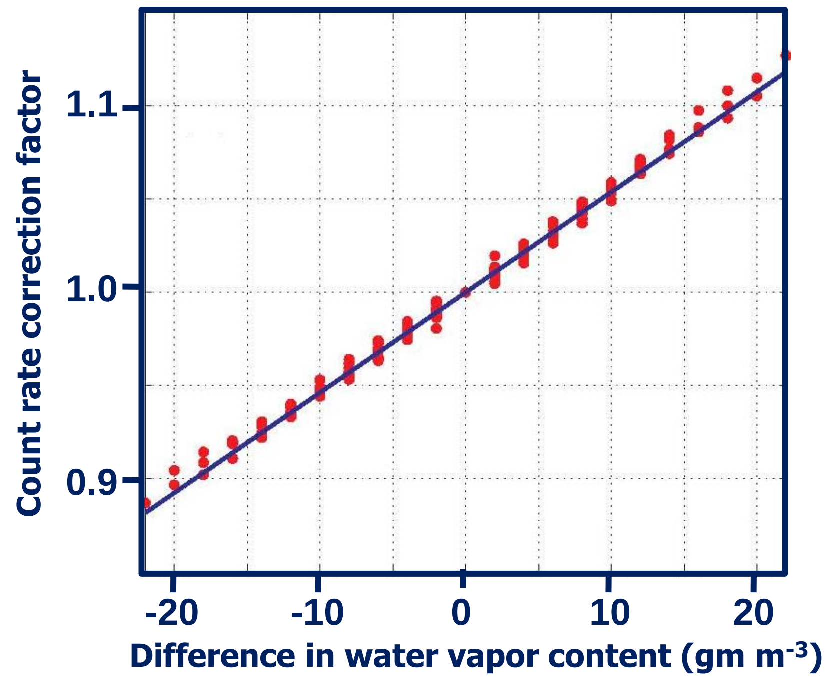


Calibration gives correction for fixed additional sources

Cosmic-ray Surface Moisture Sensors

A simple correction for <u>changes</u> in atmospheric moisture





$$N_{corr} = N_{meas}\left[1 + 0.0054(\Delta\rho)\right]$$

(Rosolem at al, 2013)

where: N_{corr} **is the corrected sensor count rate**

N_{meas} **is the measured sensor count rate**

$(\Delta\rho)$ **is the difference (in gm m^{-3}) between the water vapor content of the air relative to that on the day of sensor calibration**

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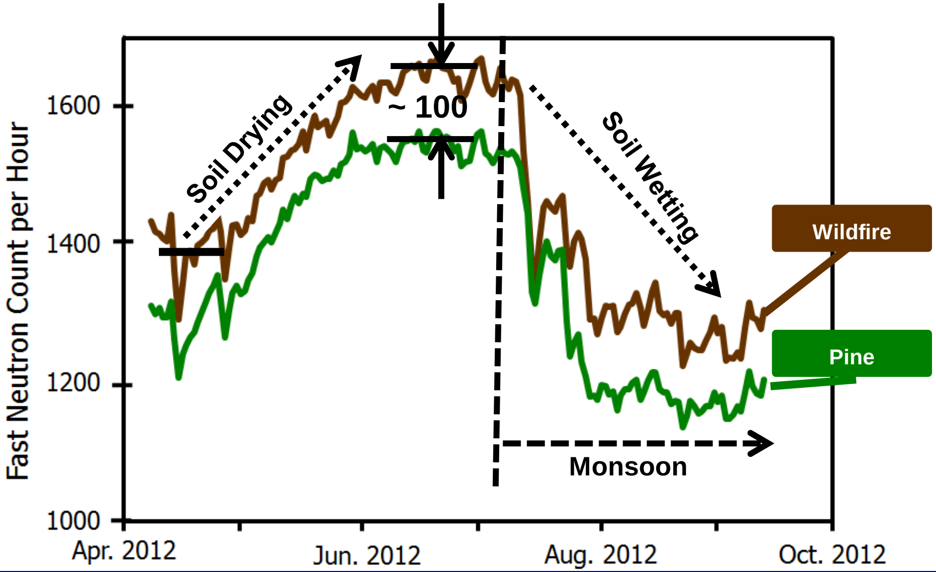
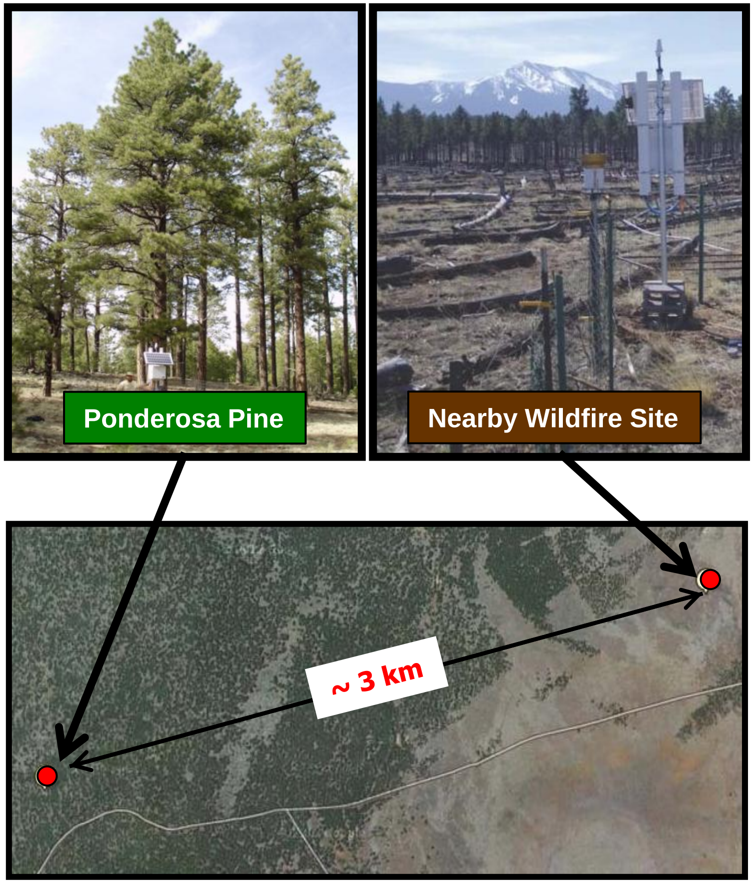
Cosmic-ray Surface Moisture Sensors

Effect of "slow" biowater at two sites near Flagstaff, AZ





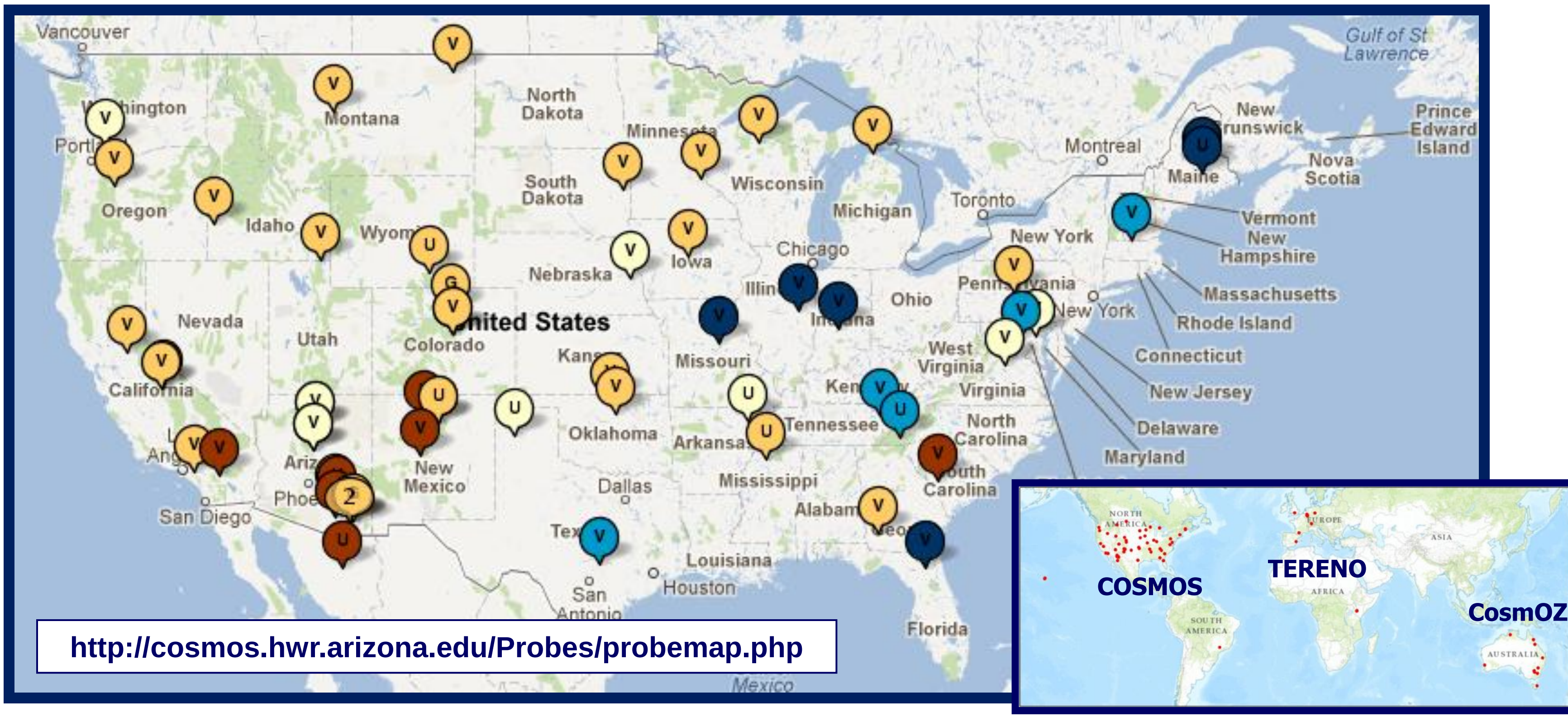
- ❑ **Reduction of ~100 counts due to the (fairly constant) forest biowater**
- ❑ **Corresponds to biowater equivalent of 17.1 ± 0.6 mm of water**
- ❑ **Three independent allometric estimates give biowater in the range 18-25 mm The difference may be due to:**
  - **remnant trunks at the wildfire site**
  - **hydrogen "clumping" in tree trunks**

(Frantz et al, 2012)

University of Arizona

Cosmic-ray Surface Moisture Sensors

Current in situ COSMOS Probe deployment in the USA and beyond



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

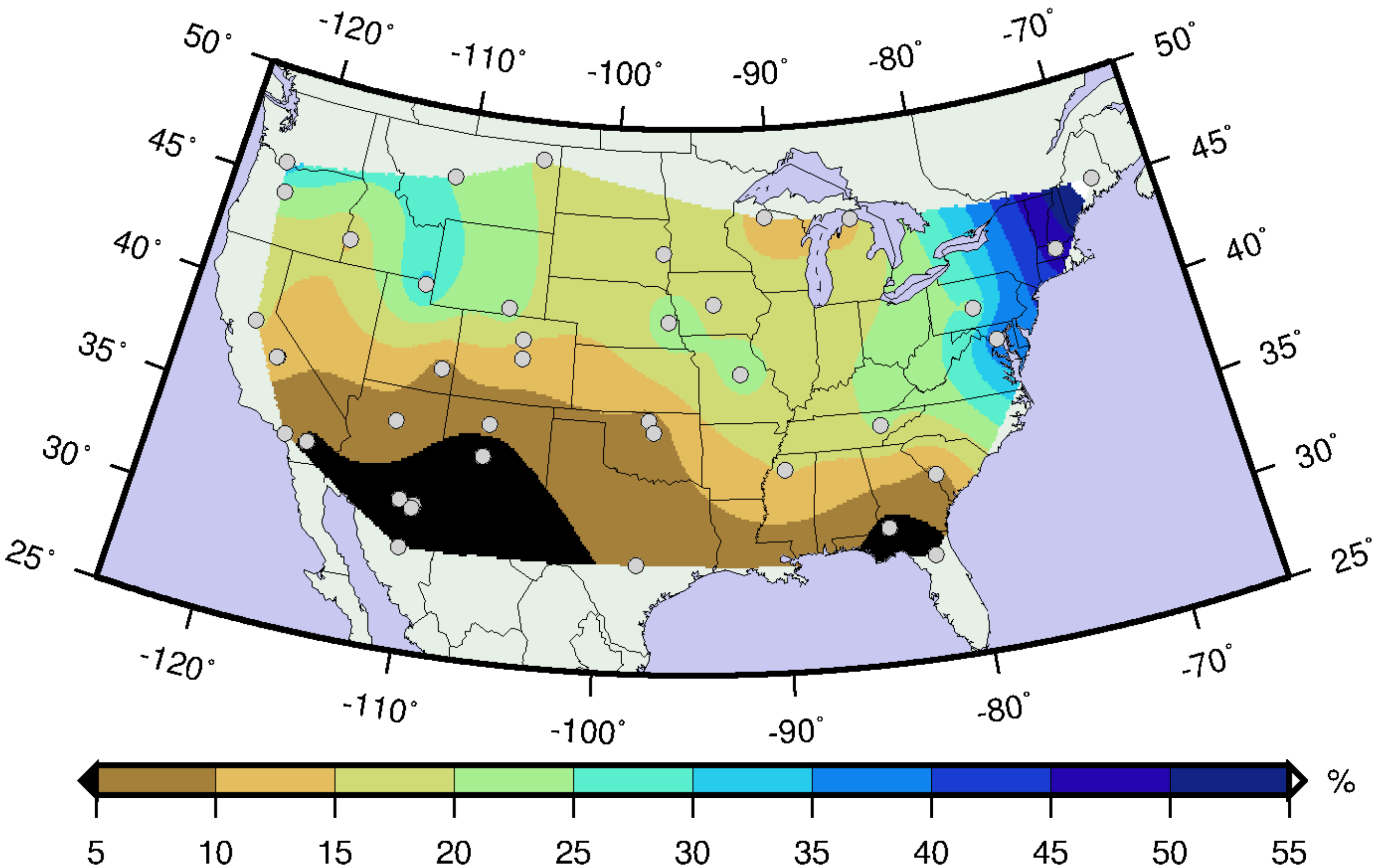
Soil Moisture (V=volumetric, G=gravimetric, U=uncalibrated)

0 - 05% | 05 - 15% | 15 - 25% | 25 - 35% | > 35% | mixed

University of Arizona

Cosmic-ray Surface Moisture Sensors

The aftermath of Hurricane "Sandy" on Oct 30, 2012



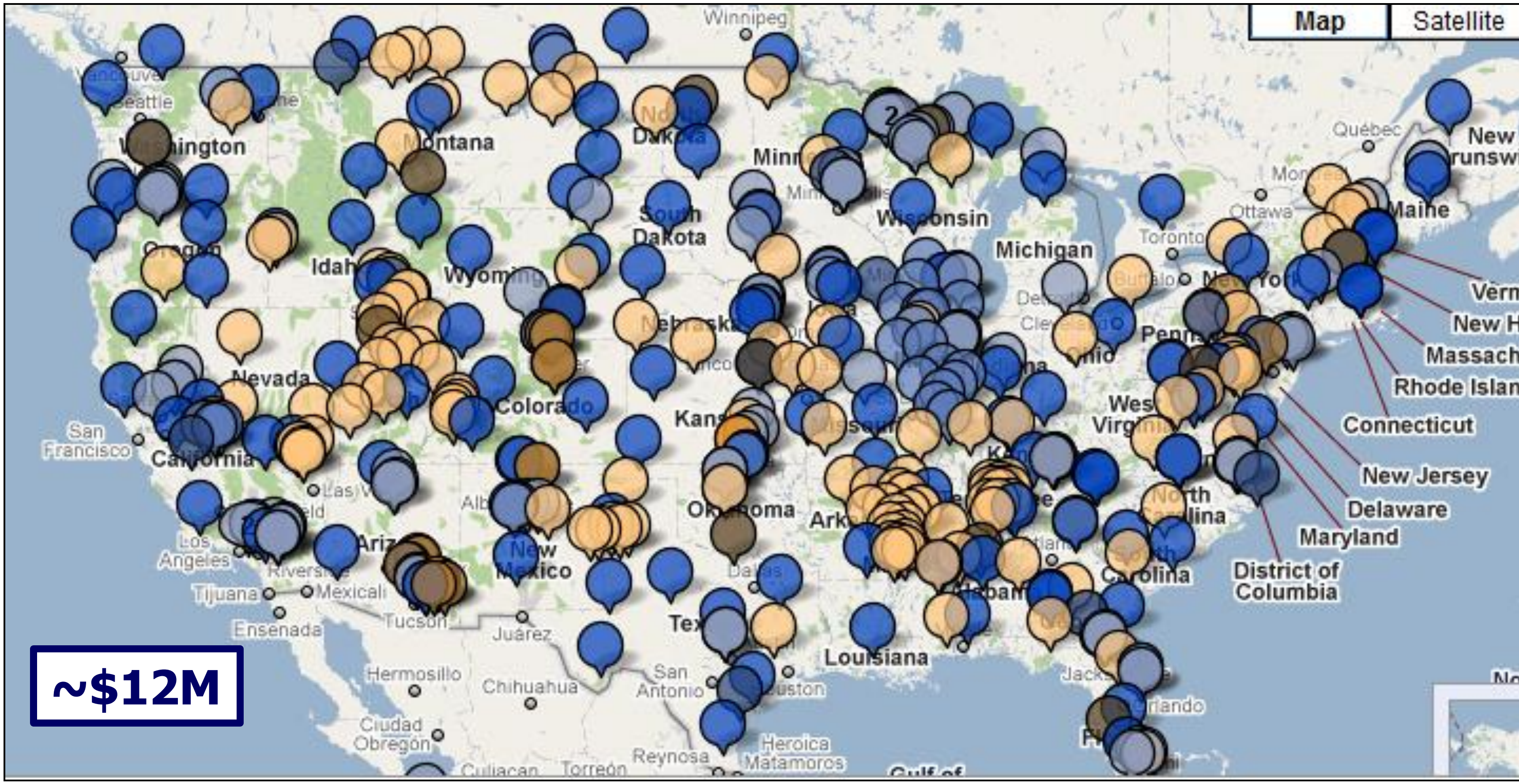
Soil Moisture (% volumetric)

[Interpolation following Smith and Wessel (1990)]

University of Arizona

Cosmic-ray Surface Moisture Sensors

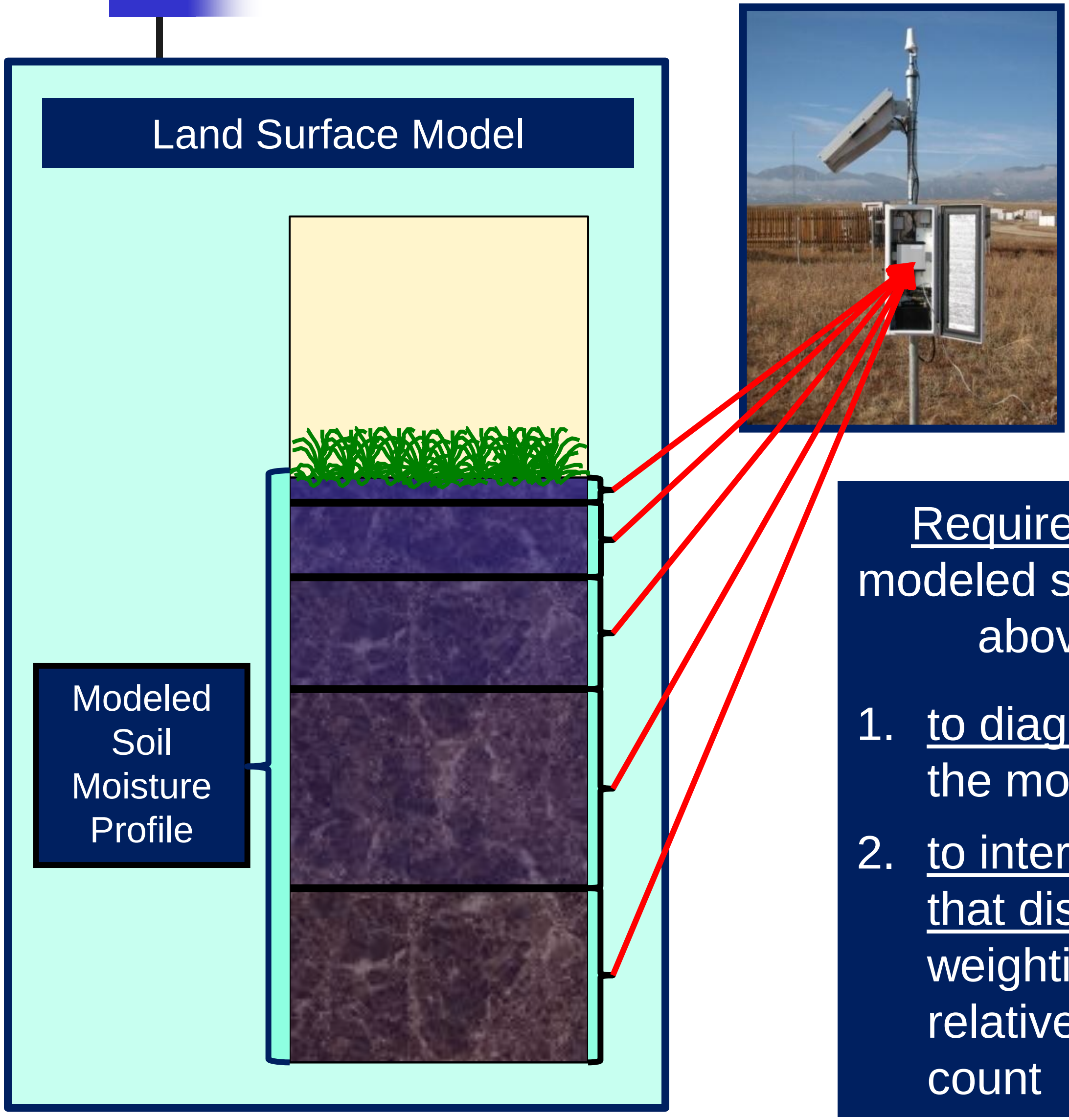
Potential US COSMOS Deployments at up to 500 Sites



Ameriflux | CRN | CZO | NEON | SCAN | SMAP

University of Arizona

Assimilating COSMOS data into LDAS and LSPs



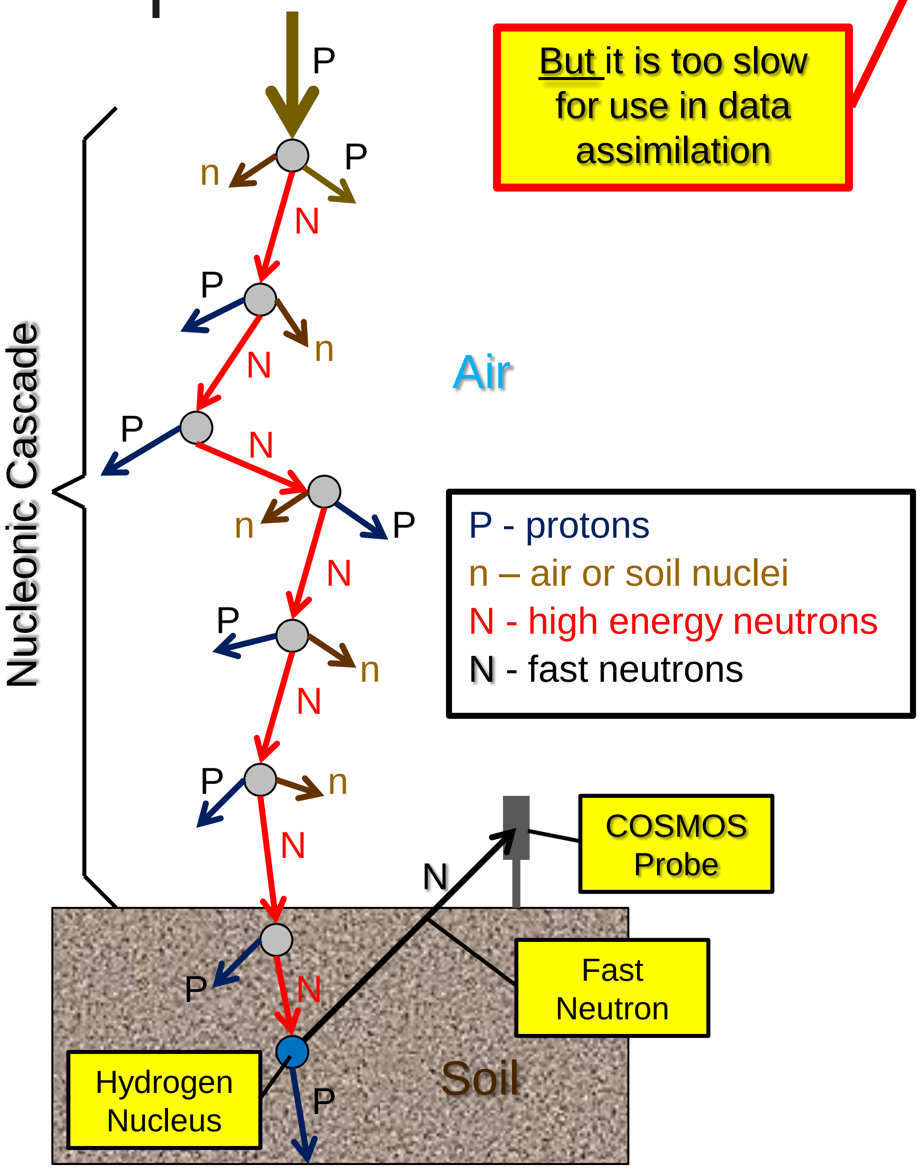
GOAL

to update soil moisture profiles by assimilating the cosmic-ray fast neutron count

Requires an accurate model to interpret modeled soil moisture profiles in terms of the above-ground fast neutron count:

1. to diagnose if there is a discrepancy in the modeled soil moisture status
2. to interpret knowledge of the extent of that discrepancy back into the LSP, with weighting between layers reflecting their relative influence on the fast neutron count

In Principle, the Needed Model Already Exists



But it is too slow for use in data assimilation

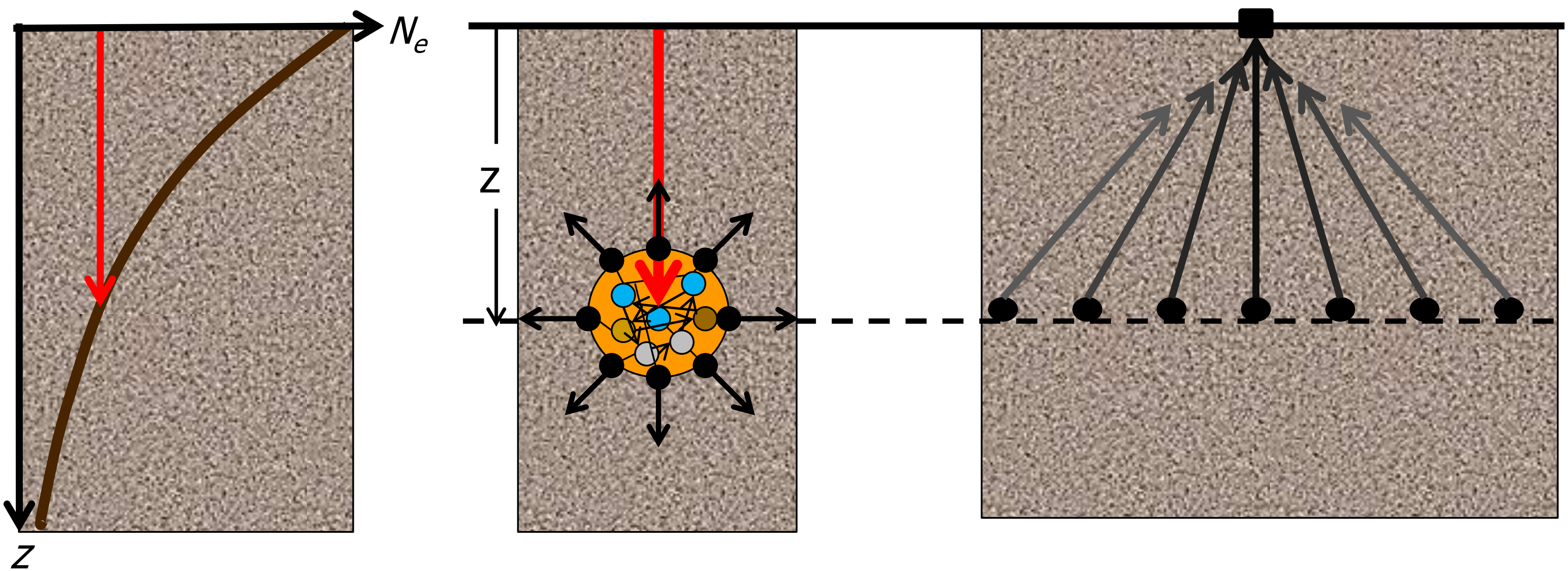
The *Monte Carlo* *N-Particle eXtended* (MCNPX) model
(created to design nuclear bombs!)

- requires specified chemistry for the atmosphere and soil, including hydrogen.
- uses measured nuclear collision cross sections for all constituents
- tracks the life history of randomly selected, individual cosmic rays and their collision products
- counts the "fast neutrons" that pass through the detector volume of the COSMOS probe

The COsmic-ray Soil Moisture Interaction Code (COSMIC)

COSMIC is a simple analytic model which:

- captures the essential below-ground physics that MCNPX represents
- can be calibrated by optimization against MCNPX so that the nuclear collision physics is re-captured in parametric form



Exponential reduction in the number of high energy neutrons with depth

Isotropic creation of fast neutrons from high energy neutrons at level "z"

Exponential reduction in the number of the fast neutrons created at level "z" before their surface measurement

high energy neutrons — fast neutrons

University of Arizona

The COsmic-ray Soil Moisture Interaction Code (COSMIC)

The resulting analytic function that describes the total number of fast neutrons reaching measurement point is:

A few meters will do!

Exponential reduction in the number of high energy neutrons with depth

Isotropic creation of fast neutrons from high energy neutrons at "z"

Exponential reduction in the number of the fast neutrons created at level "z" before their surface measurement

$$N_{COSMOS} = N \int_0^{\infty} \left[\exp\left(-\left[\frac{m_s(z)}{L_1} + \frac{m_w(z)}{L_2} \right] \right) \cdot \left[\alpha \rho_s(z) + \rho_w(z) \right] \cdot \left(\frac{2}{\pi} \right) \int_0^{\pi/2} \exp\left(\frac{-1}{\cos(\theta)} \left[\frac{m_s(z)}{L_3} + \frac{m_w(z)}{L_4} \right] \right) . d\theta \right] . dz$$

(Shuttleworth et al, 2013)

Six parameters to be defined:

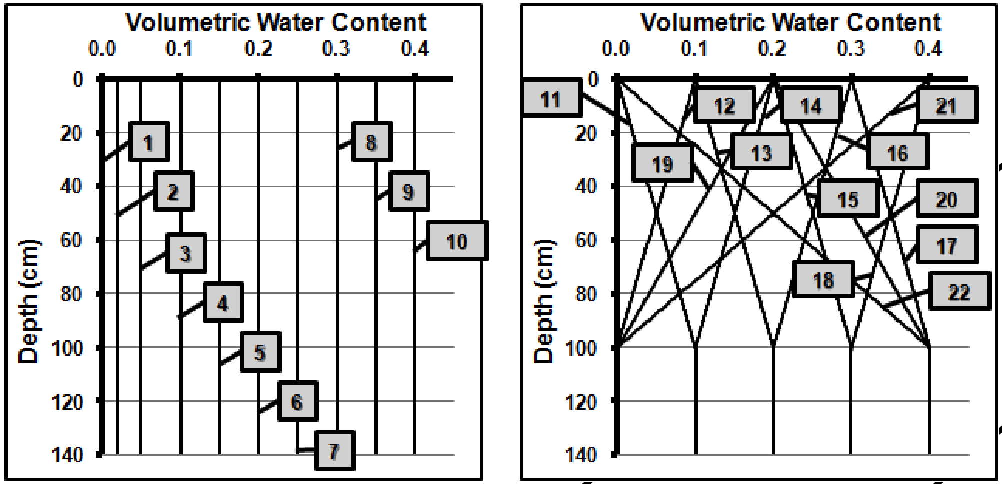
- L_1, L_2 and L_4 are site-independent and are easily determined from MCNPX

  L_1 = 162.0 gm per unit area
  L_2 = 129.1 gm per unit area
  L_4 = 3.61 gm per unit area

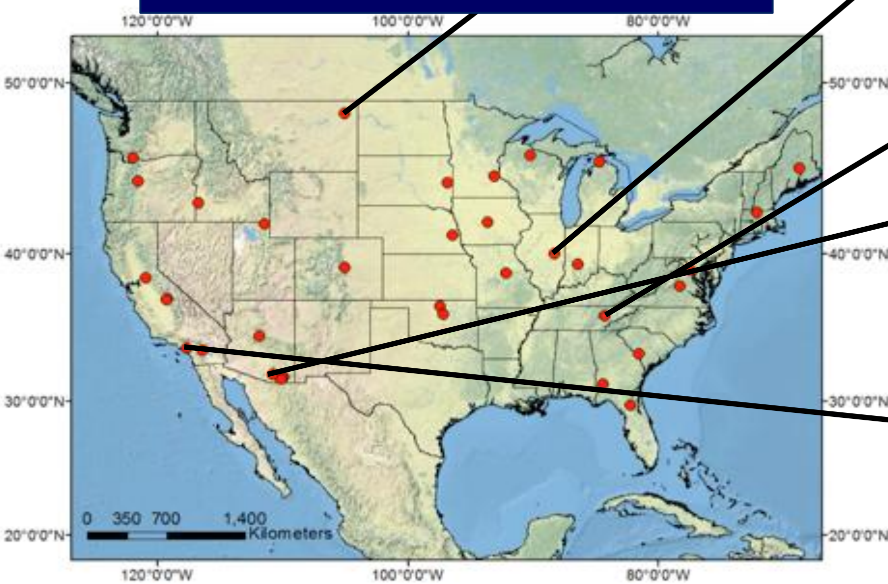
- N, α and L_3 require multi-parameter optimization against site specific-specific runs of MCNPX for a range of hypothetical soil moisture profiles

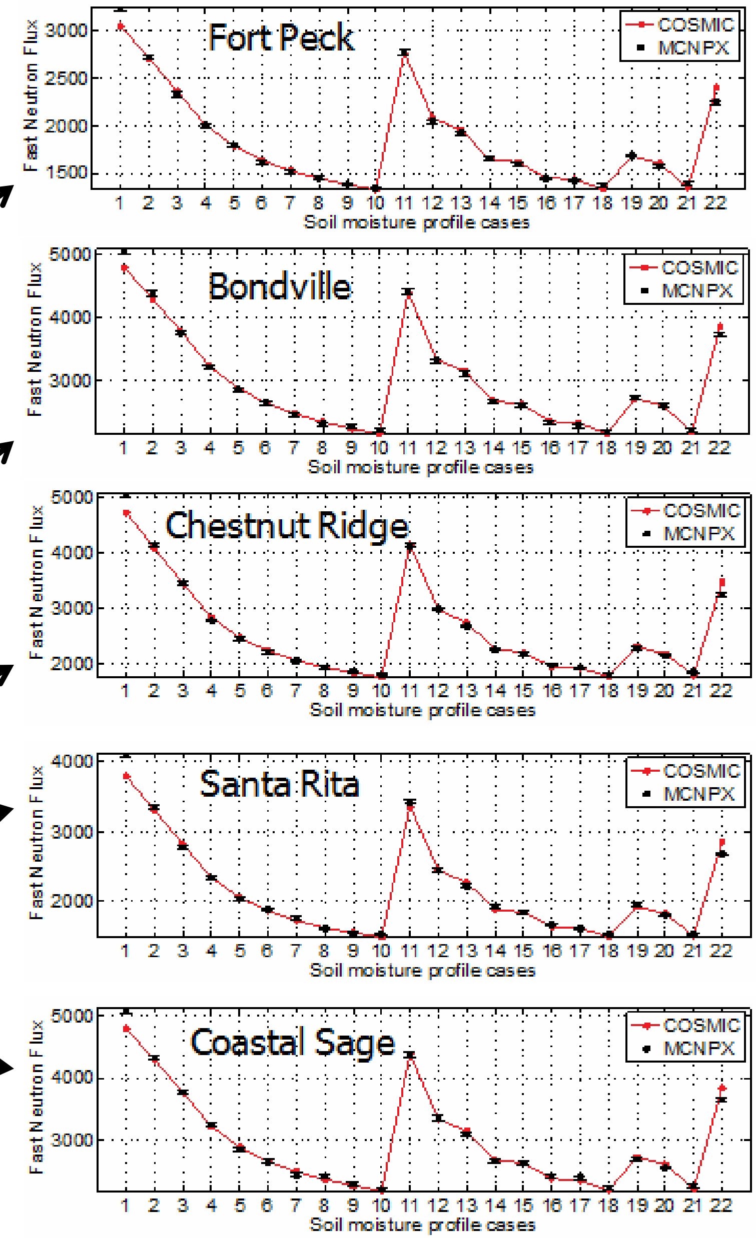
Calibrating COSMIC

Hypothetical soil water profiles



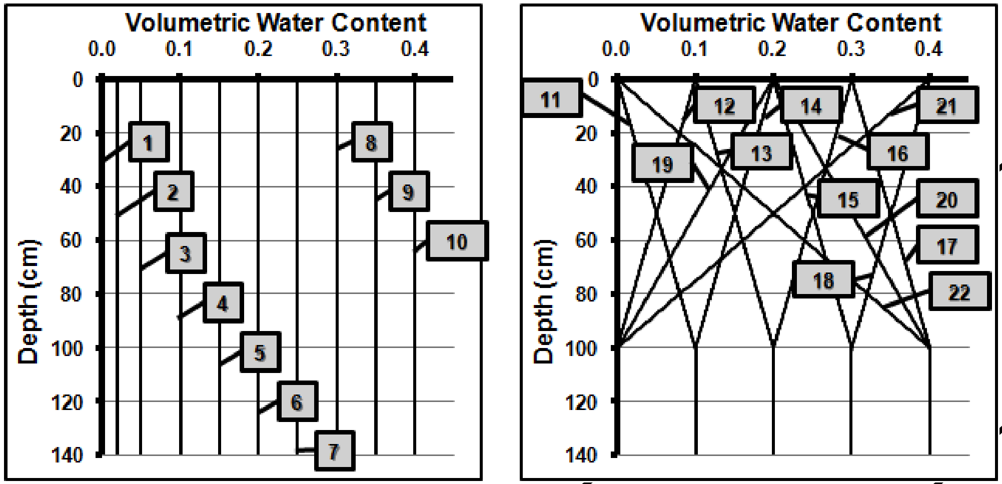
42 COSMOS Probe Sites



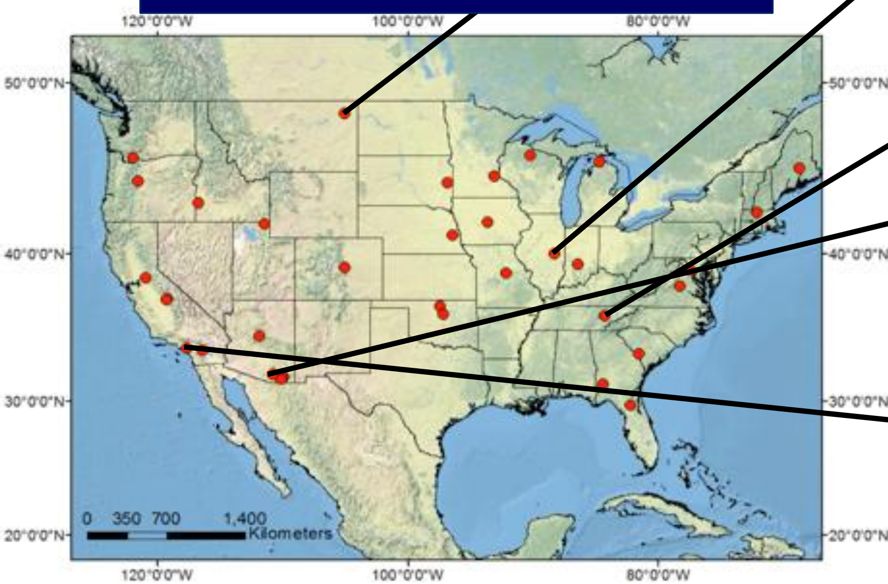


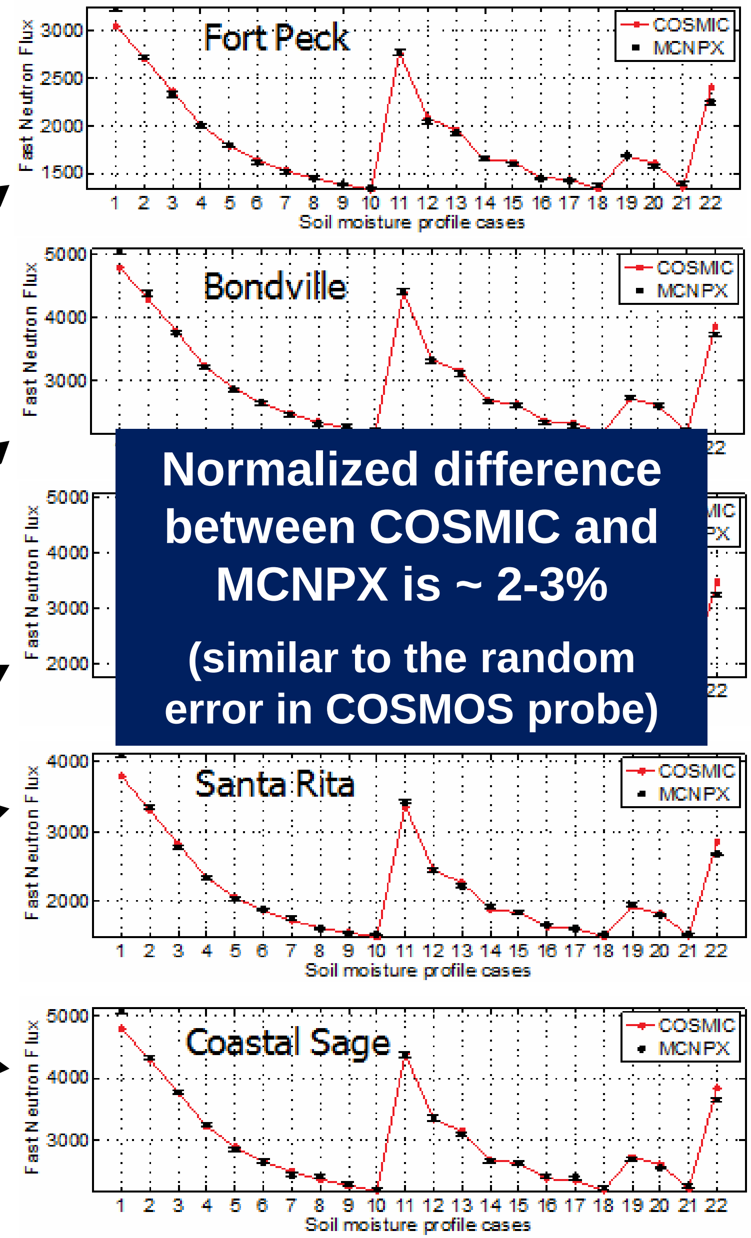
Calibrating COSMIC

Hypothetical soil water profiles



42 COSMOS Probe Sites



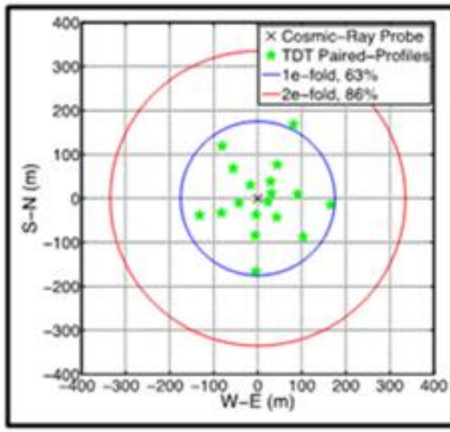


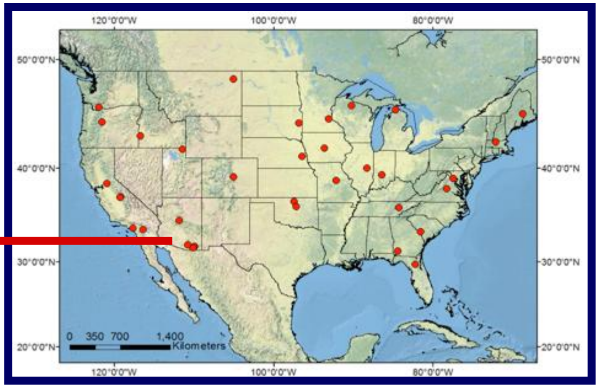
Normalized difference between COSMIC and MCNPX is ~ 2-3%

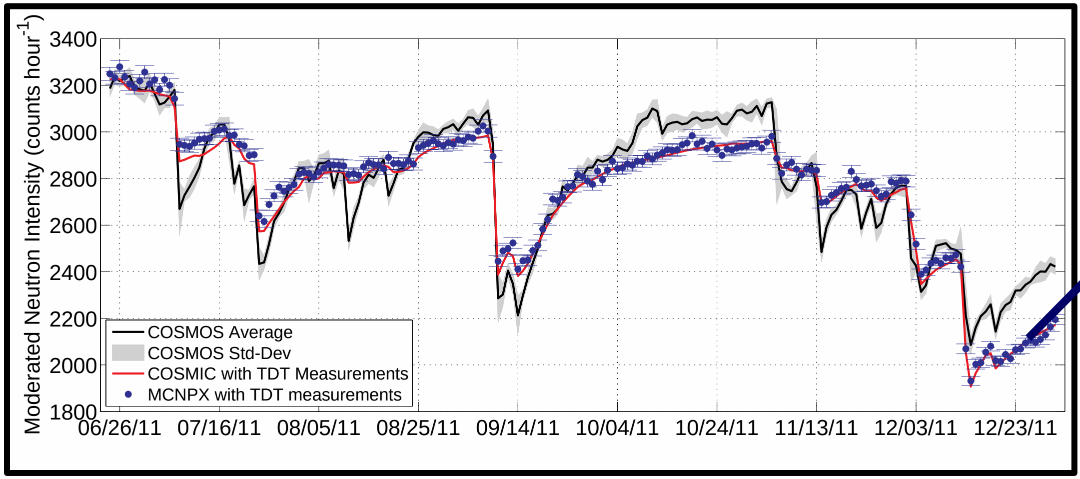
(similar to the random error in COSMOS probe)

Using COSMIC: Calculating COSMOS Probe Count

Estimating COSMOS Probe counts from measured soil moisture profiles at the Santa Rita site







Area-average from the TDT sensors doesn't sample the near-surface (above 10 cm depth), so both the MCNPX & COSMIC calculations based on TDT data do not recognize the faster rate of drying of surface soil moisture

(Shuttleworth et al, 2013)

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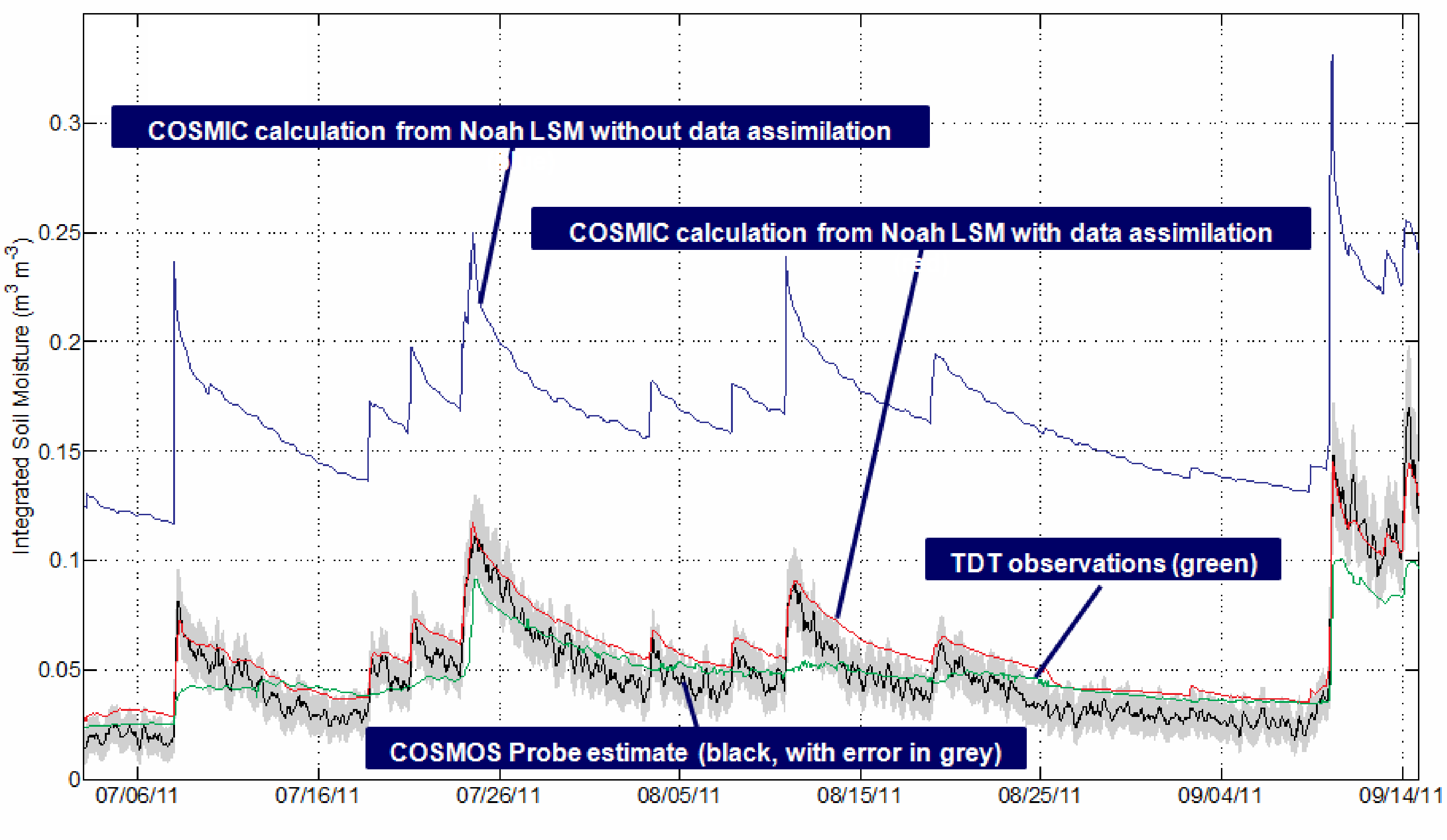
The COsmic-ray Soil Moisture Interaction Code (COSMIC)

Using COSMIC to assimilate COSMOS probe counts into the Noah model at the Santa Rita site



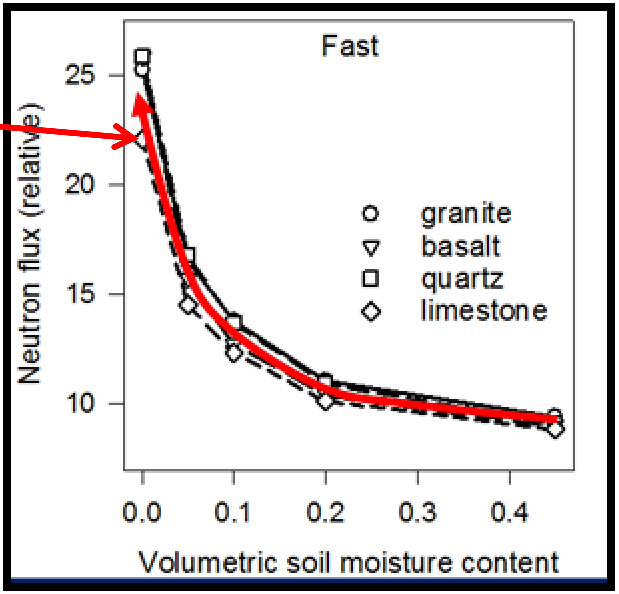
(Shuttleworth et al, 2013)

University of Arizona

Mobile Measurement of Near Surface Water

The COSMOS "Rover"

- Mounted in a vehicle
- Large detectors (to increase sample volume and count rate)
- Includes GPS
- Assumes area-average value for calibration
- Driven for a day, to sample a selected area systematically
- Interpolation of the soil moisture values measured while driving the sample route



(Zreda, et al; 2013)

Mobile Measurement of Near Surface Water

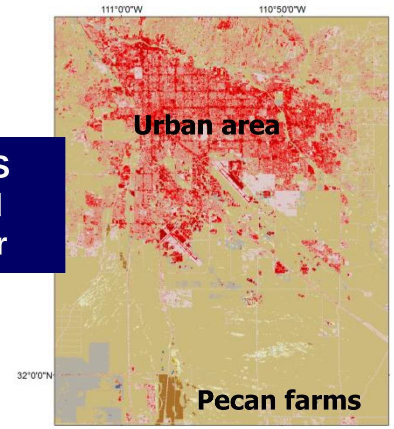
Experimental Mapping of Near Surface Water with the COSMOS Rover in the Tucson Basin

(Chrisman, 2012)

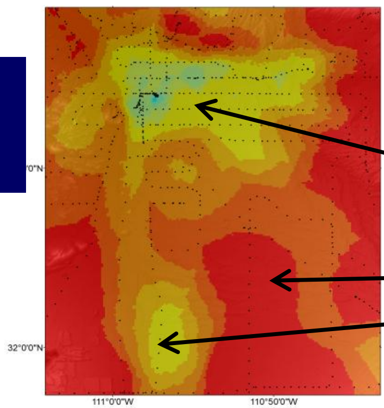
PRELIMINARY

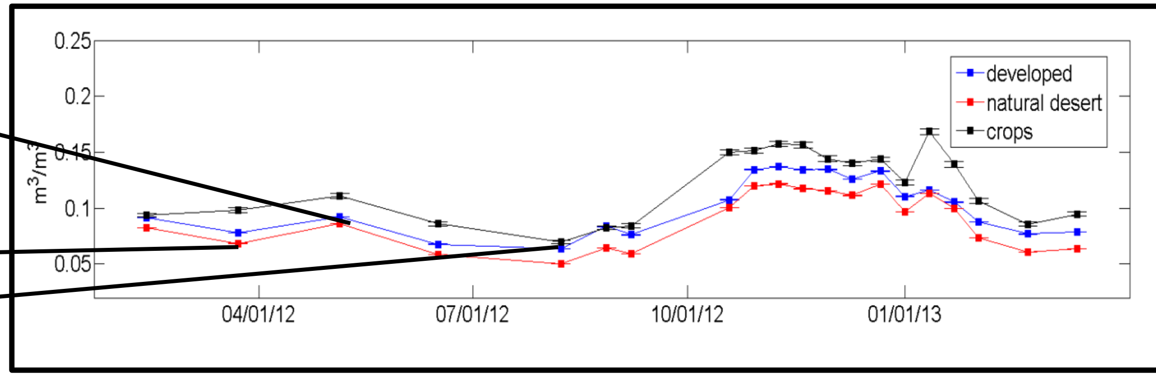
City Map

USGS Land cover



Pre-monsoon 6/15/2012

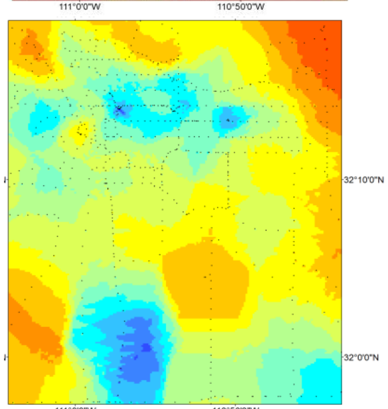


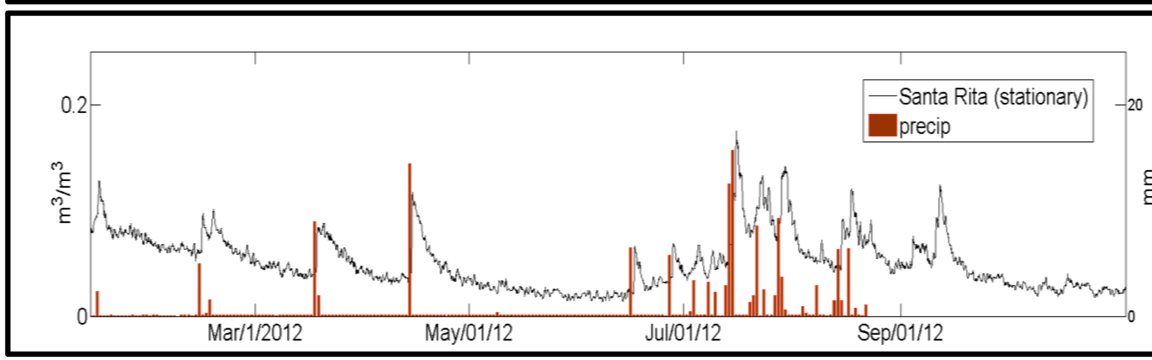


Surface Moisture (% Vol)

- 6 - 6
- 7
- 8
- 9
- 10
- 11
- 12
- 13
- 14
- 15
- 16
- 17
- 18

Post-monsoon 7/13/2012

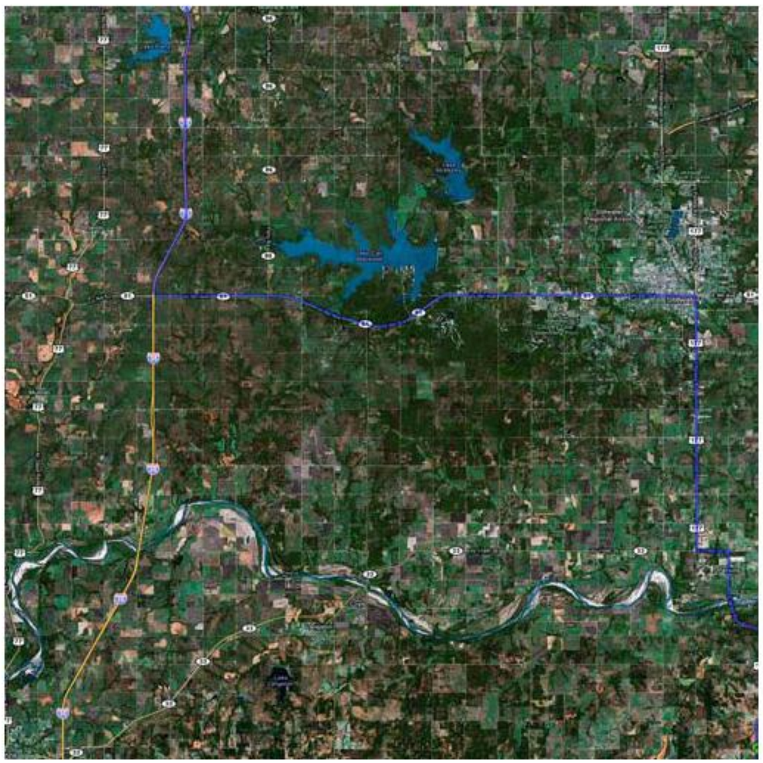


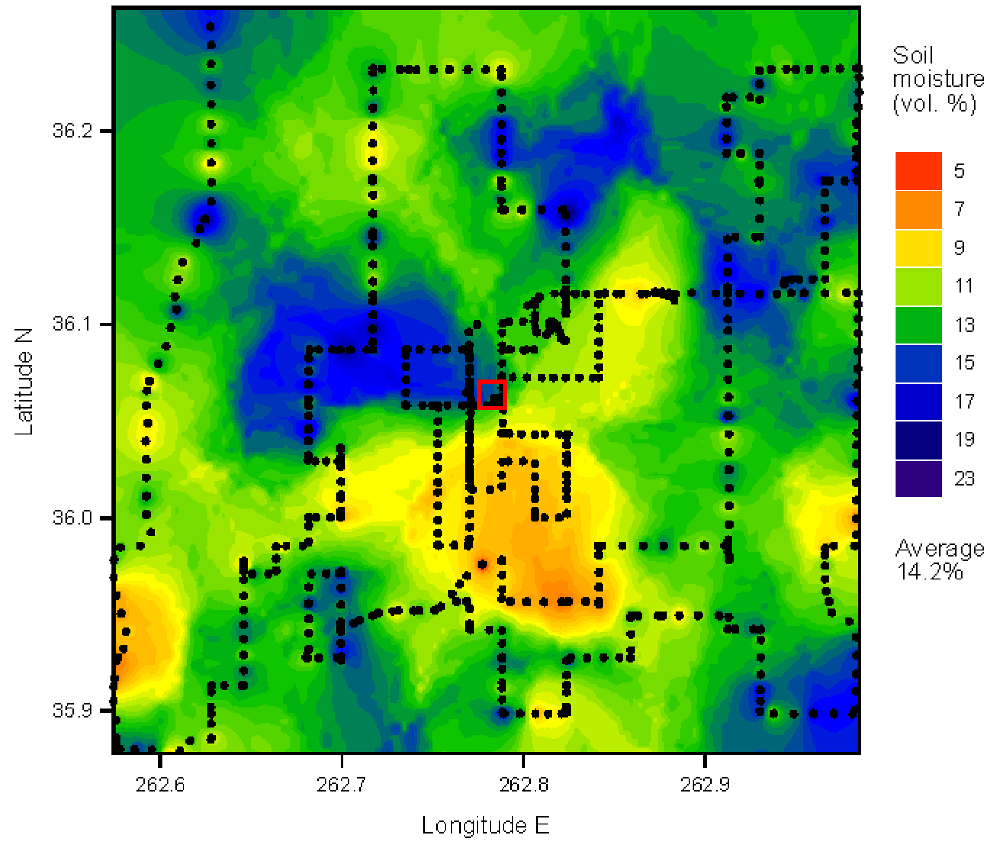


University of Arizona

Mobile Measurement of Near Surface Water

Experimental Mapping of Near Surface Water with the COSMOS Rover at the "SMAP" Test Bed in Oklahoma





PRELIMINARY

University of Arizona

New Measurements Bring New Challenges

1. **Measured near-surface water won't help if the LSP is wrong!**
   (It might make predictions worse!)

2. **Measurement is only of part of the near-surface water profile!**
   ("Equifinality" is a potential challenge!)

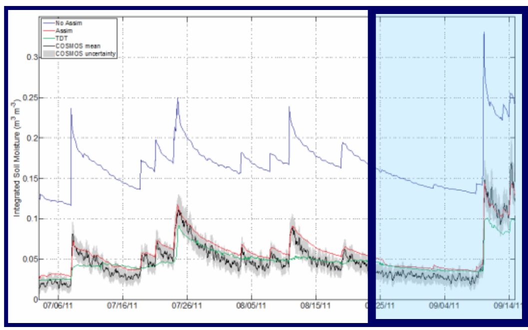
3. **Biological water is also "atmospherically accessible water"!**
   (Vegetation dynamics are needed in <u>all</u> LSMs/LDAS)

4. **Some of the near-surface soil water is not accessible!**
   (empirical estimates?, use <u>rate of change</u> of total surface water?)

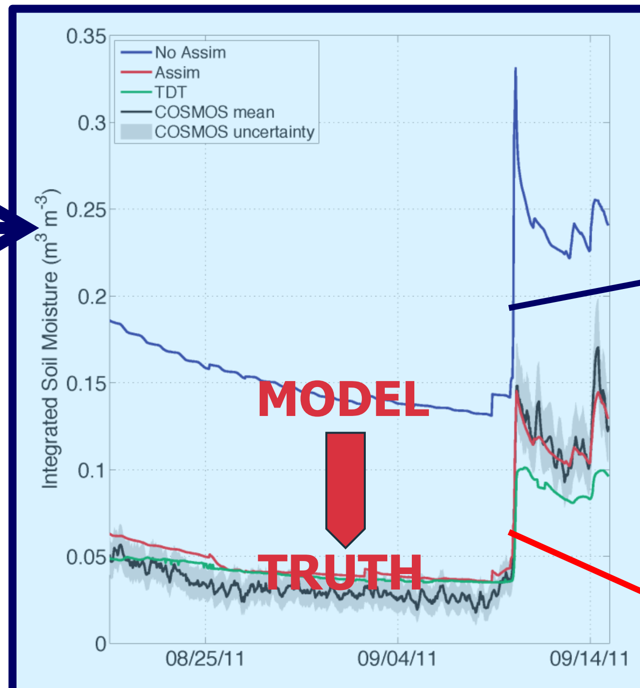
New Measurements Bring New Challenges

1. **New measurements of near surface water can only improve meteorological prediction if LSPs correctly describe its influence on surface exchanges**

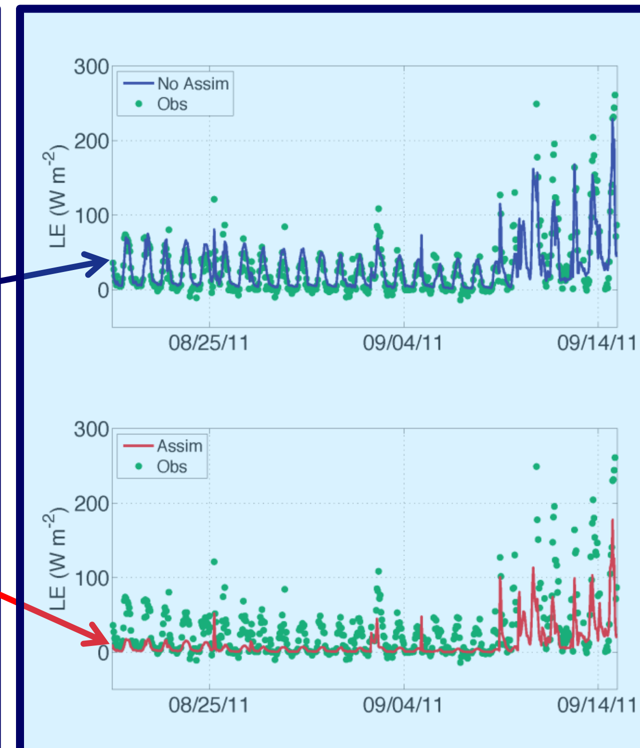
Pending re-parameterization, they can make predictions worse!



Inserting the TRUTH into the MODEL without re-parameterization kills the transpiration



Santa Rita Site, Southern Arizona



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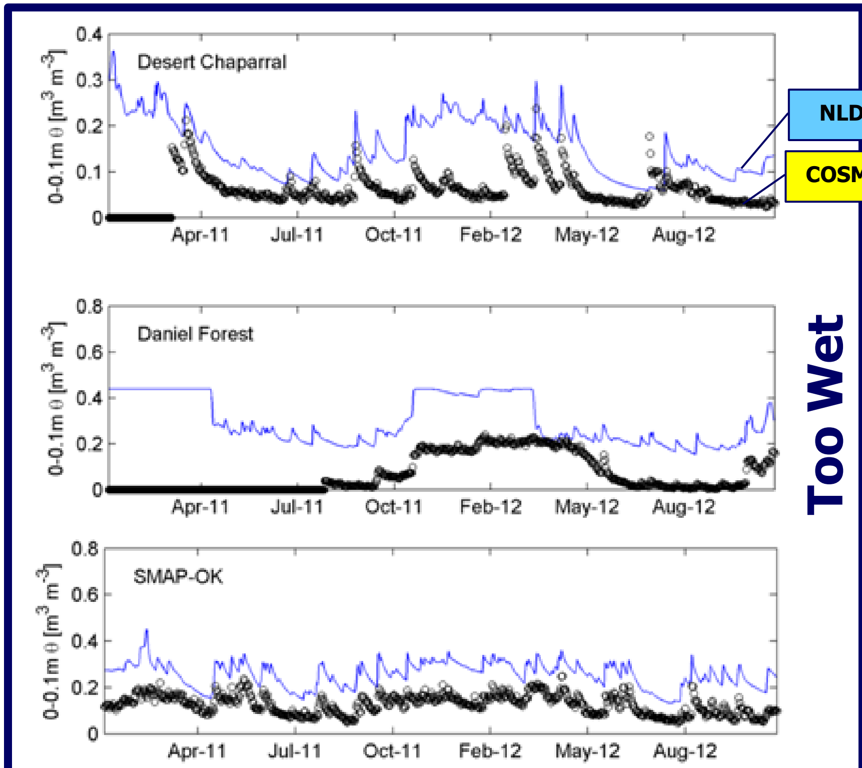
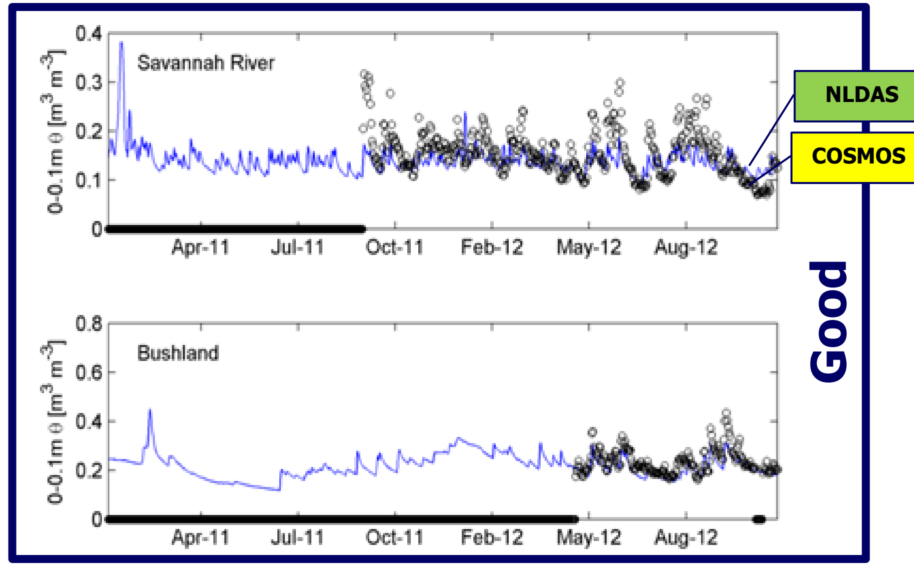
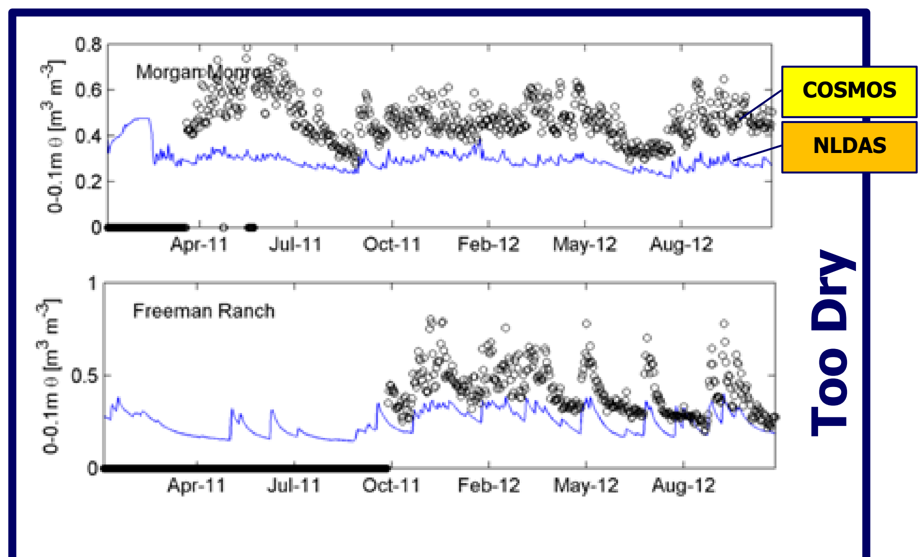
New Measurements Bring New Challenges

COSMOS Data versus NLDAS

Caldwell (2013)





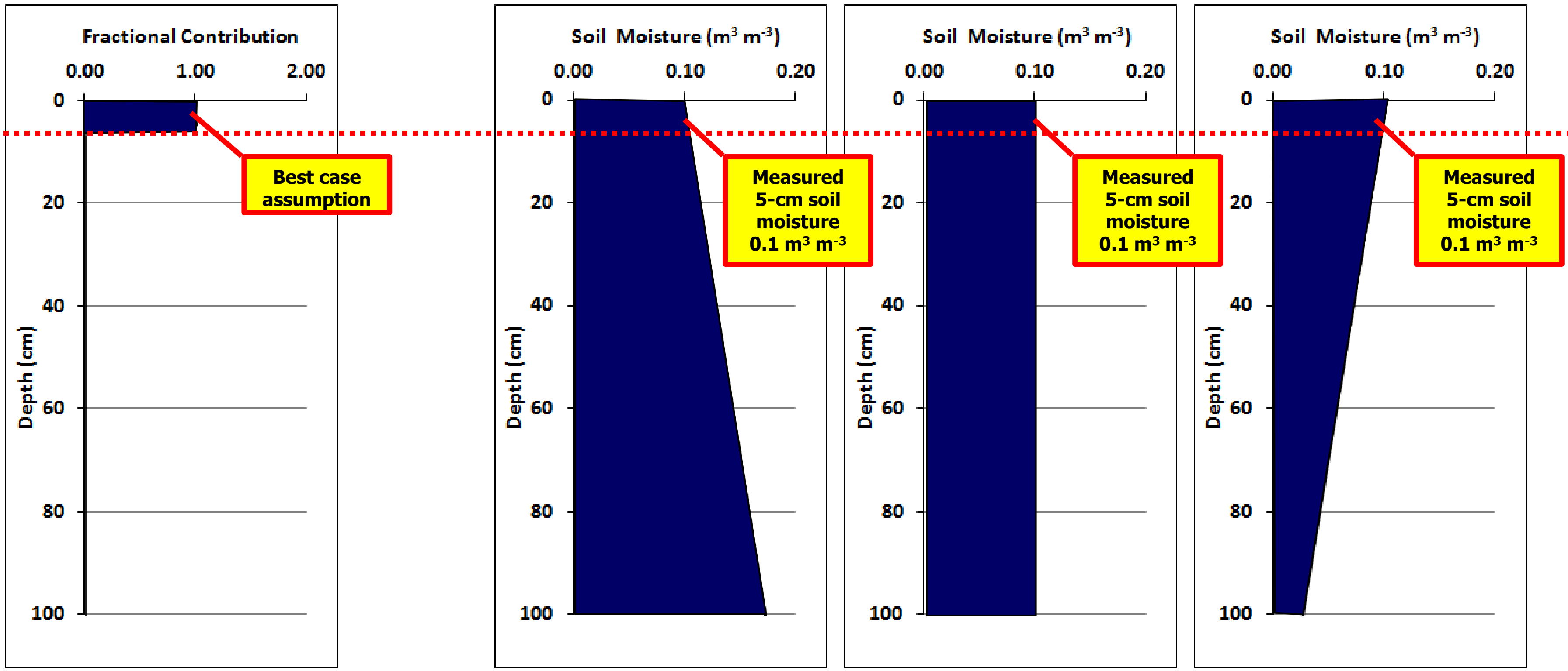


Bureau of Economic Geology

New Measurements Bring New Challenges

2. Measurement is only of part of the near-surface water profile, the accuracy of the remainder depends on the accuracy of the ancillary forcing and model used to describe water movement

With a Remote Sensing Product

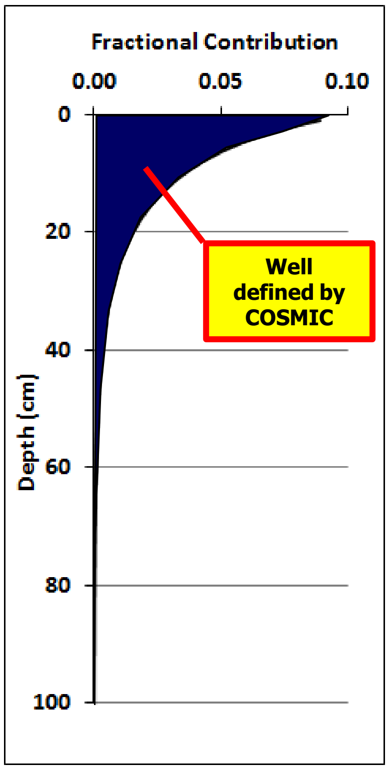


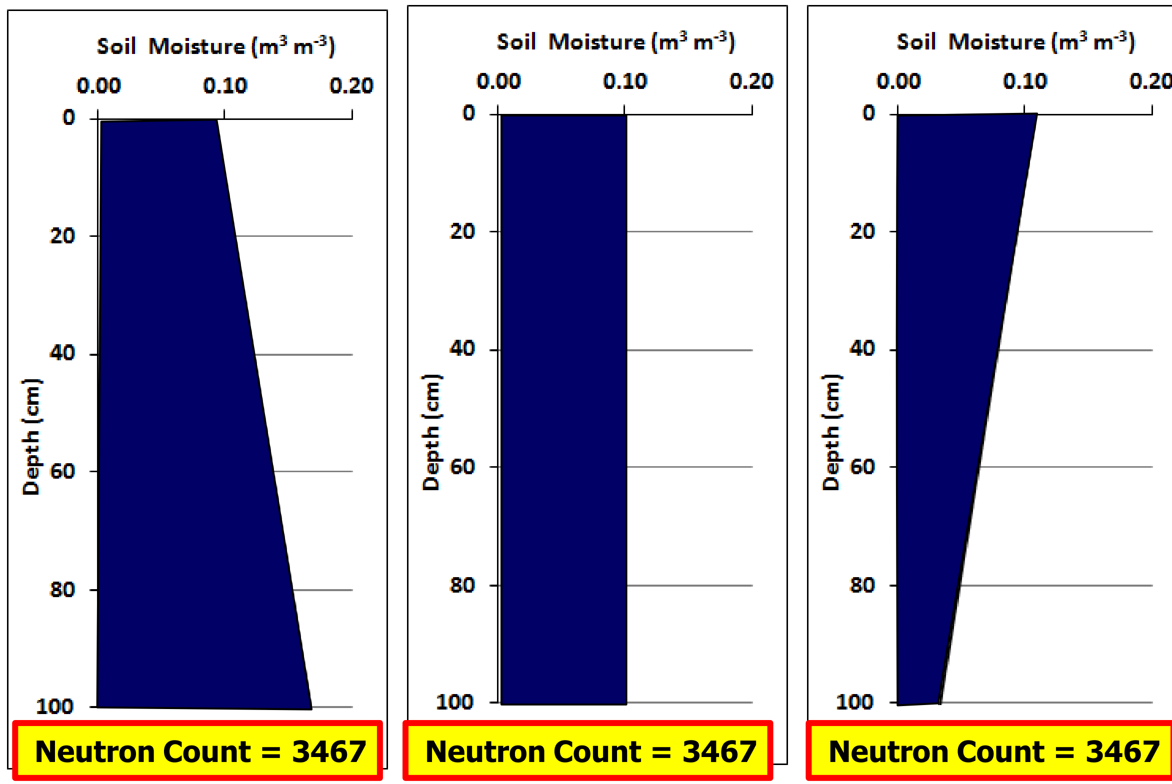
"Equifinality" is a potential challenge!

New Measurements Bring New Challenges

2. **Measurement is only of part of the near-surface water profile, the accuracy of the remainder depends on the accuracy of the ancillary forcing and model used to describe water movement**

With a COSMOS Probe





Modern data assimilation methods and the fact we have a time series of data should help with this, providing the LSP is good

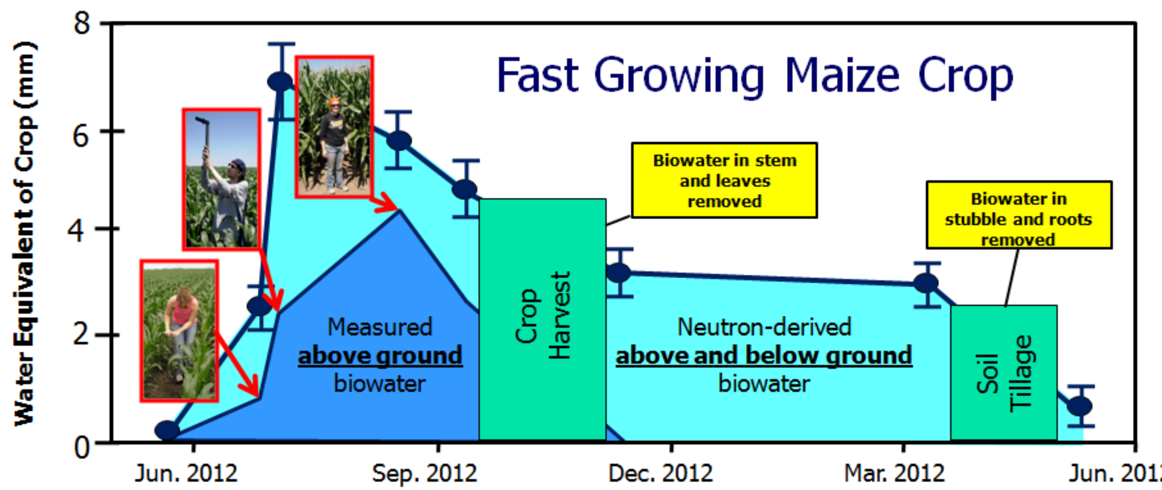
New Measurements Bring New Challenges

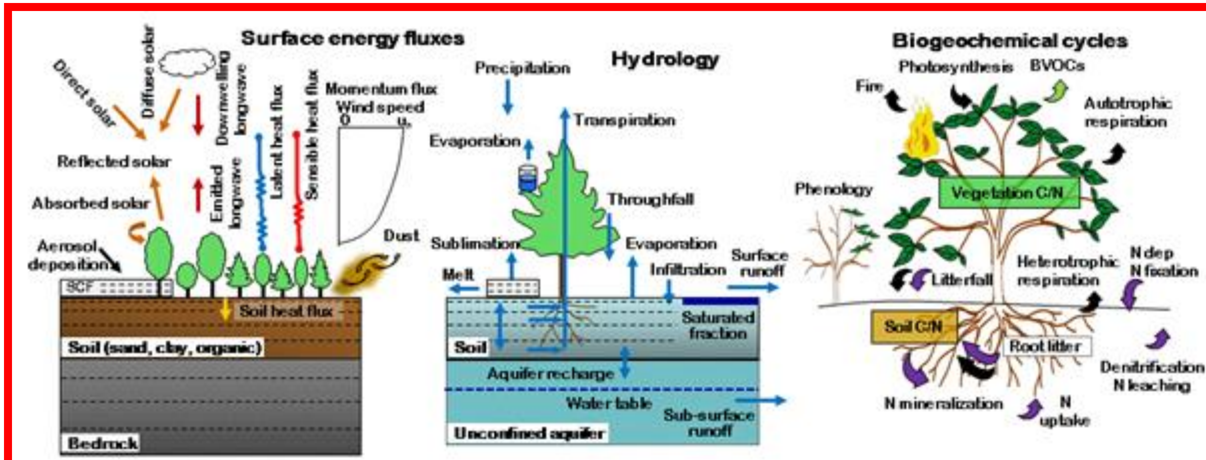
3. Biological contributions are part of the measured near surface water and changes in them must also be modeled in LSPs or LDAS

Extreme Example:

Seasonal changes in the above and below ground biowater of fast growing Maize in Iowa

(Hornbucke et al, 2013)

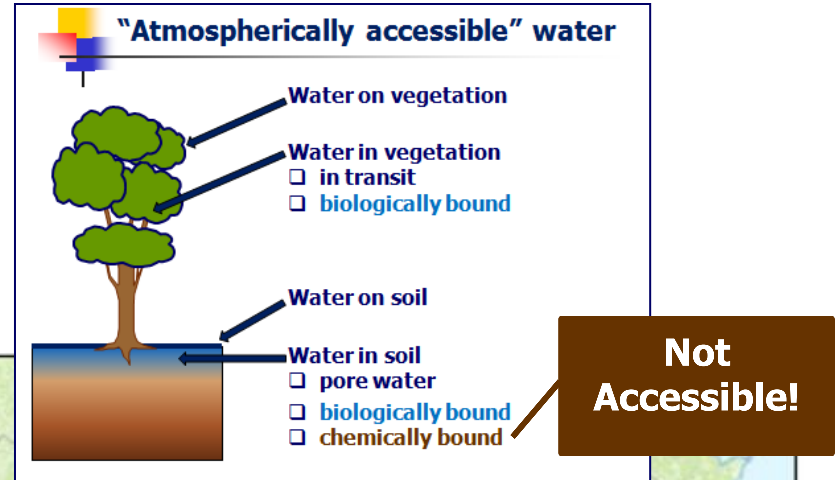


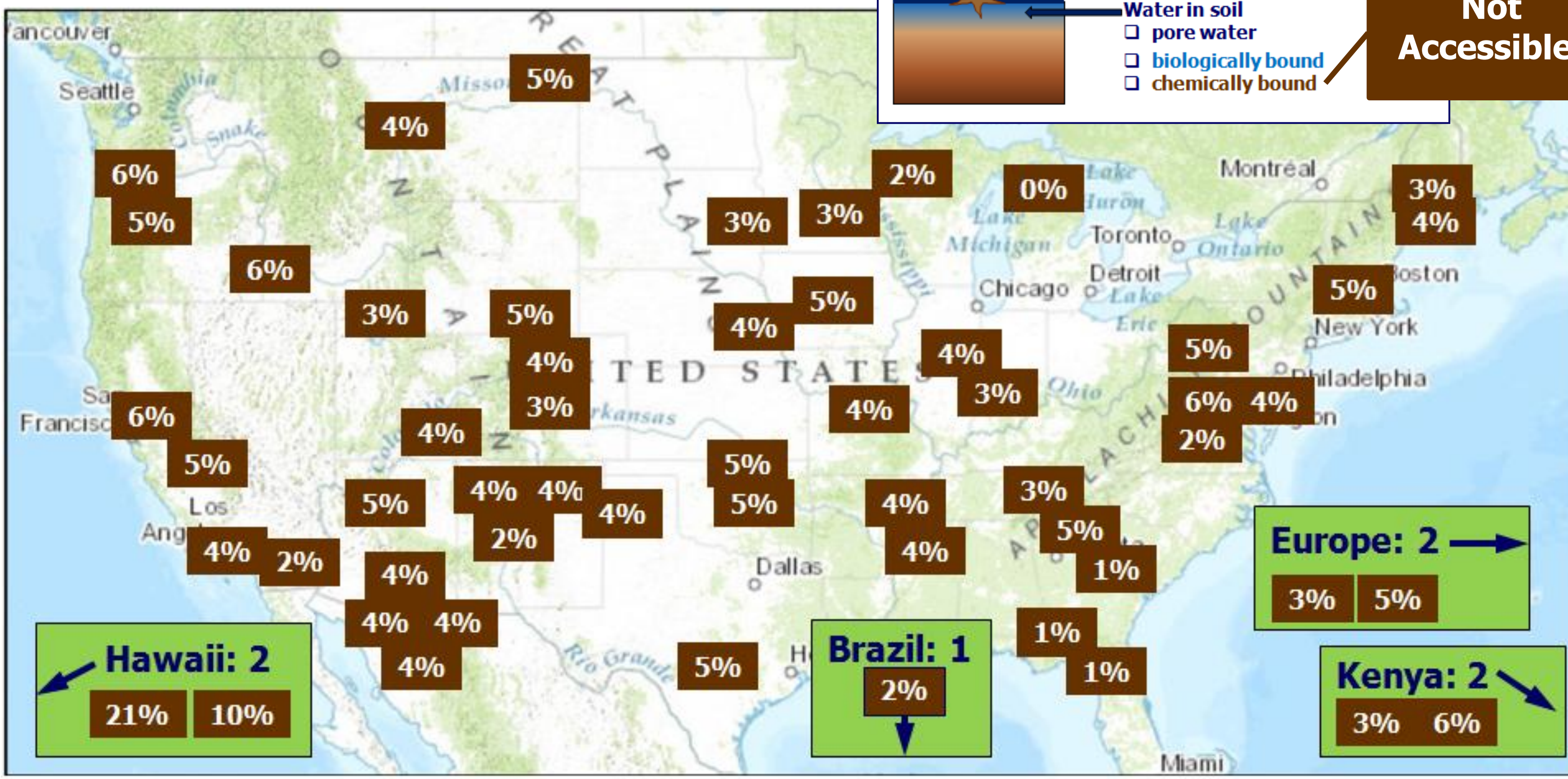


Representing vegetation dynamics is needed in LSMs <u>even when only concerned with modeling energy flux exchanges</u>

New Measurements Bring New Challenges

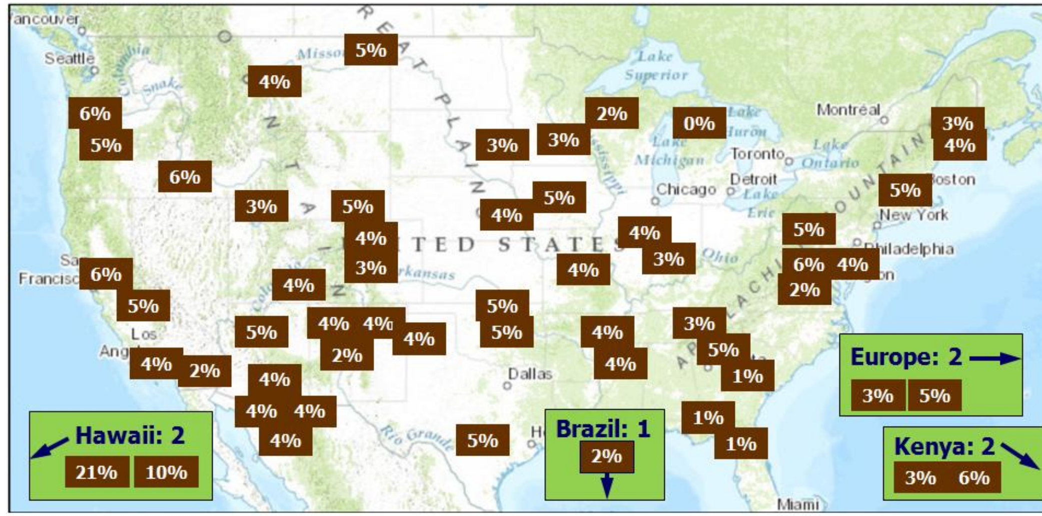
4. **A significant portion of the the measured near-surface water is <u>not accessible</u> to the atmosphere**





New Knowledge Bring New Challenges

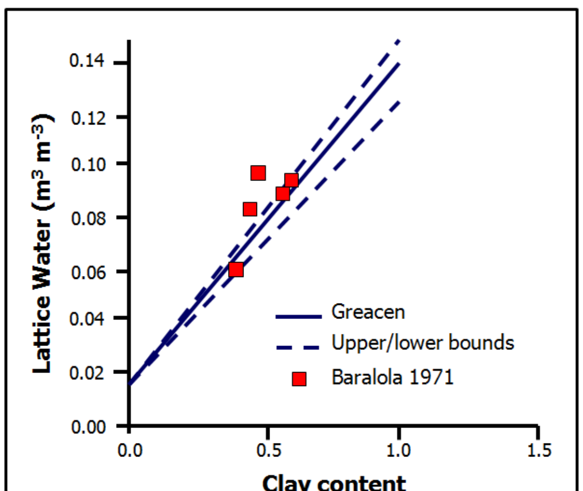
4. **A significant portion of the the measured near-surface water is "lattice water" and <u>not accessible</u> to the atmosphere**

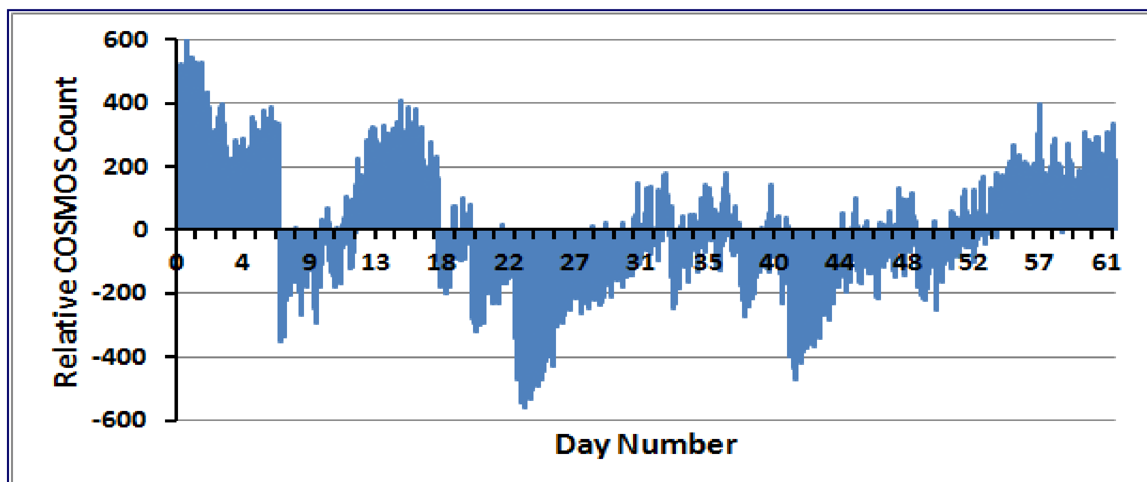


Can we live with assuming an average value?

Can we build empirical relationships?

Can we assimilate the <u>relative change in total water</u>?





Summary

1. We are in the first stages of an observational revolution which will give routine measurement of atmospherically accessible water as:
    a. Remotely sensed large pixel-scale area-averages
    b. Stationary hectometer-scale area-averages
    c. Mobile hectometer-scale area-averages combined to large pixel scale

2. New measurements bring new challenges:
    a. Measured near-surface water won't help if the LSP is wrong
    b. Measurement is only of a part of the near-surface water profile
    c. Biological water is also "atmospherically accessible water"!
    d. Some of the near-surface soil water is not accessible

3. We are being given the tools, we have a duty to use them effectively; and the hydrology section of AMS is the most appropriate community to do this

4. If we accept this challenge,
   "in the next decade we will mine the meteorological predictability associated with measured storage of atmospherically accessible water on land surfaces"

Questions

For a copy of this presentation, please email: shuttle@email.arizona.edu>