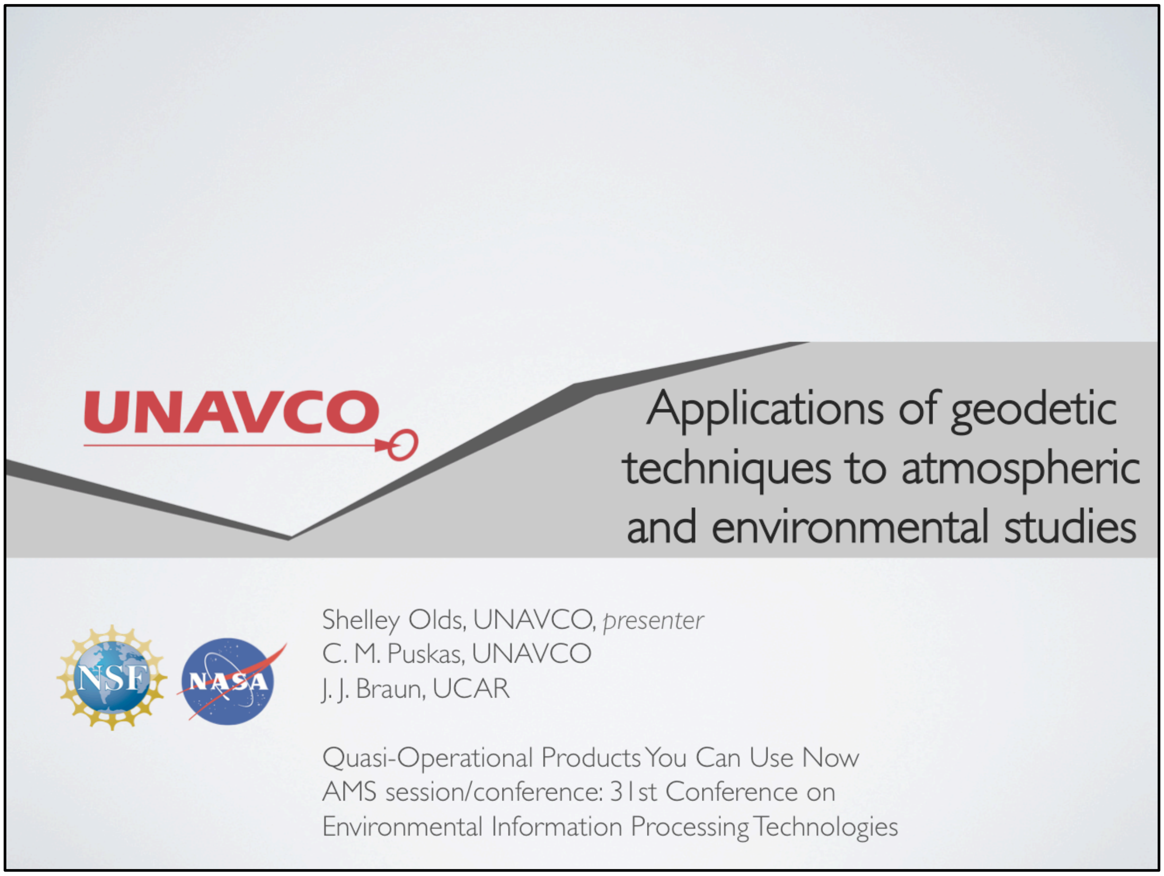


Abstract: Precipitable water vapor (PWV), surface soil moisture, snow depth, hydrologic loading, vegetation growth, and total canopy water storage are important properties for climate studies and are often measured with many different instruments. Today, these can be measured with GPS/GNSS technology and are freely available as data products through UNAVCO, UCAR, and PBO H2O. UNAVCO, a National Science Foundation funded Earth Science Geodetic Facility, manages the EarthScope Plate Boundary Observatory (PBO) with ~1100 GPS stations and analyzes an additional 600+ stations from other public networks. Originally installed to measure the strain and deformation of the western United States, data from PBO and the GPS satellite radio signals are used to derive atmospheric and environmental data products. This presentation will focus on the suite of products and tools freely available and include examples of applications to real world research and data exploration. We welcome input on the products usefulness and suggestions for improving the products and tools to explore and display the data.

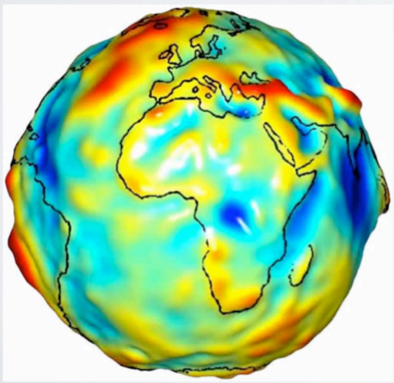
Tuesday, 6 January 2015: 2:45 PM

131C (Phoenix Convention Center - West and North Buildings)

UNAVCO

Applying Geodesy

Geodesy is the science of …
accurately measuring the Earth's
size, shape, orientation,
gravitational field and
the variations of these **with time**.

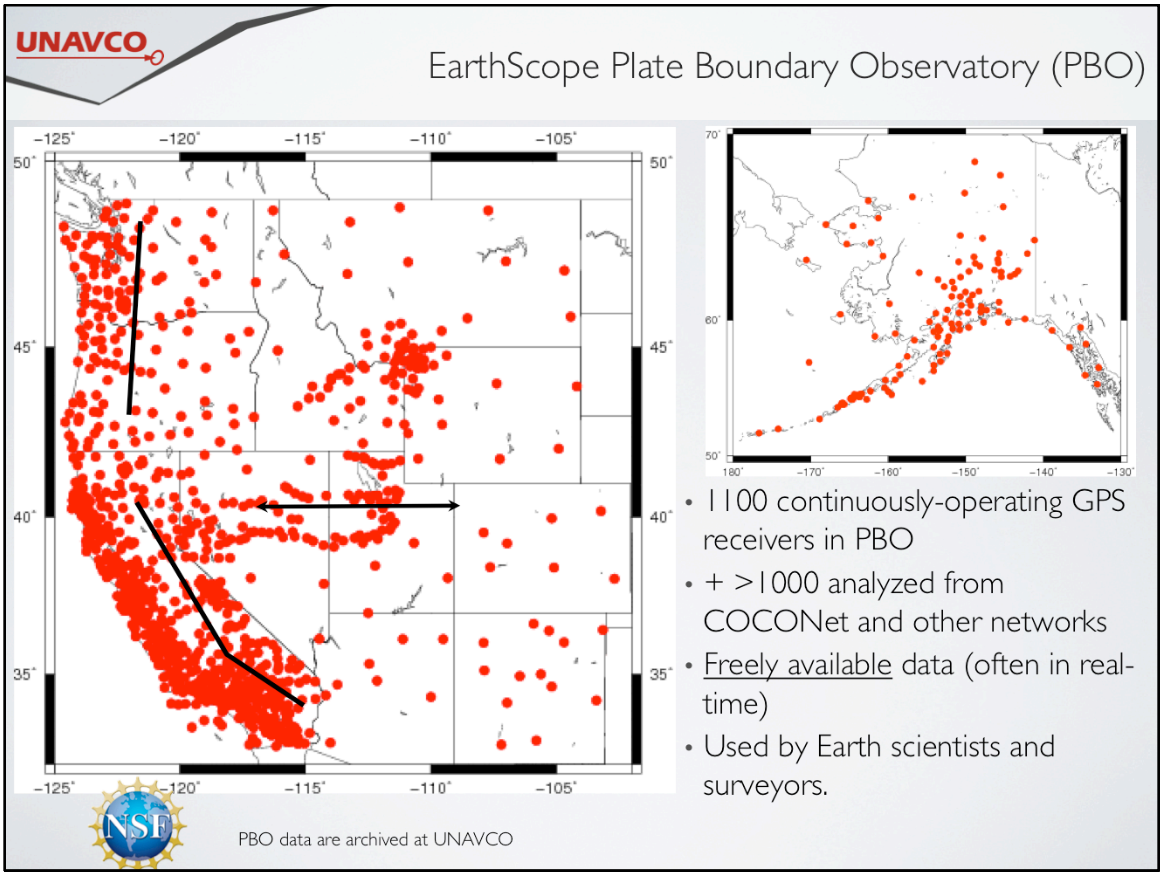


Source: NASA GRACE

Applications:

- Making maps: Precise positioning of points on the surface of the Earth
- Measuring plate movement & deformation
- *Measuring water load*

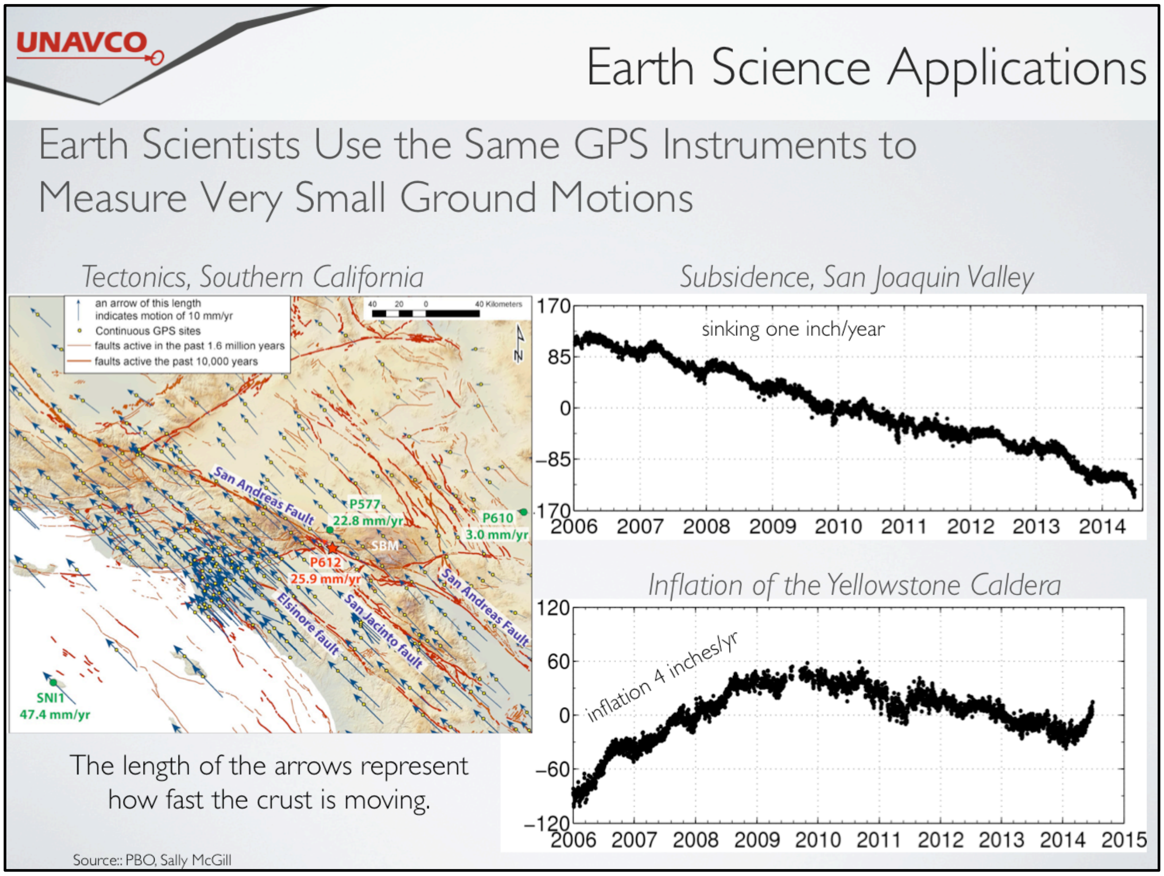
While making maps and finding precise positions are important outputs of geodesy; Geodesy has moved beyond these are have been environmental applications



UNAVCO operates the EarthScope Plate Boundary Observatory (PBO) on behalf of National Science Foundation (NSF) as part of Geodesy Advancing Geosciences and EarthScope (GAGE) Facility operations.

PBO was installed to measure the strain field in the Western United States and Alaska. Each red dot is the location of a permanent high-prevision GPS. The black lines are areas of different types of strain and plate deformation (extension – Nevada & Utah), transform (side by side plate movement in California), and subduction causing compression (Pacific Northwest, Washington, Oregon, Northern California, up to Vancouver Island, Canada)

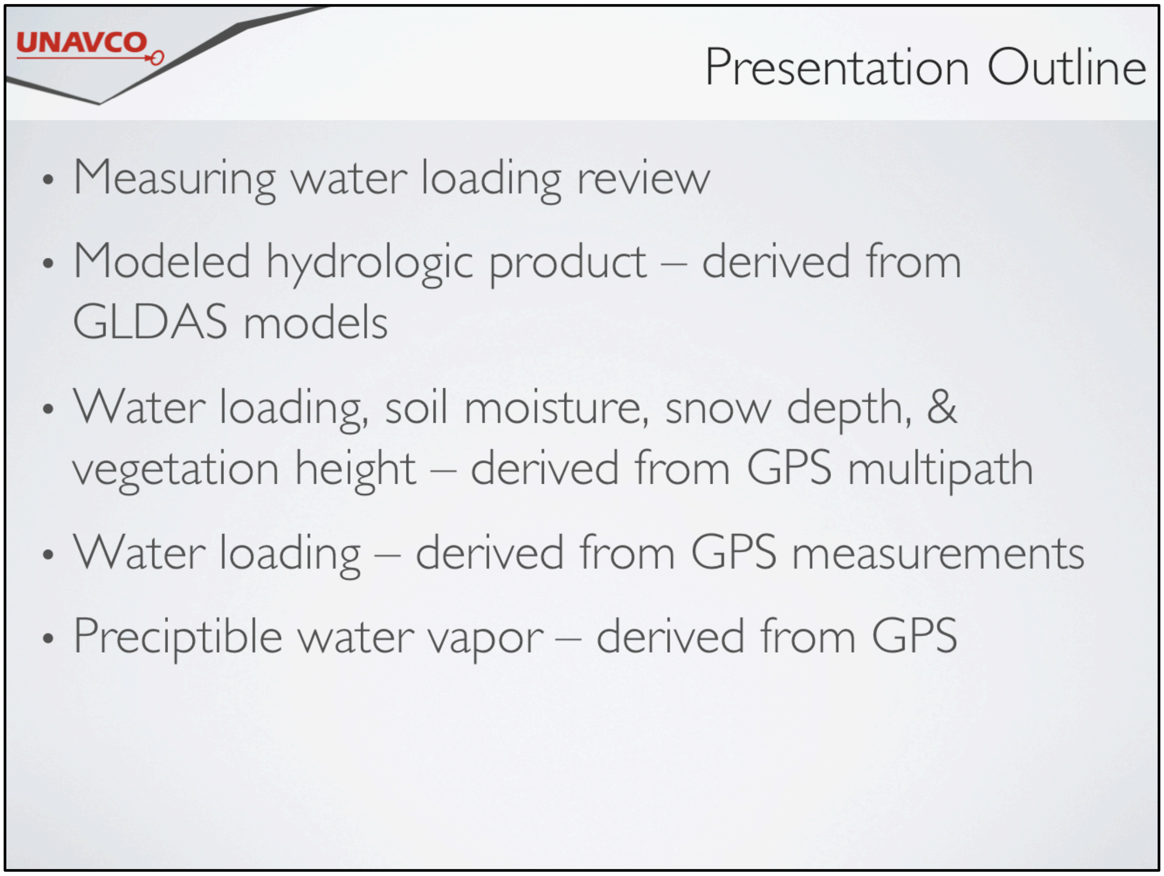
Other networks include COCONet (Continuously Operating Caribbean GPS Observational Network), TLALOCNet (Mexico), and other GPS stations analyzed by the GAGE Analysis Centers.



Using the high-revision GPS stations of these networks, Earth Scientists measure plate motion, regional motion, and plate deformation in high detail. The left image shows southern California. Each vector is associated with a single GPS station. The length represents how fast the station is moving, the length points in the direction of movement.

Relevant to environmental studies, the top right image shows how GPS is directly measuring the subsidence of San Joaquin Valley and other areas due to drought and heavy groundwater pumping. Bottom right shows inflation and deflation of the Yellowstone Caldera from 2006 to present.

http://www.unavco.org



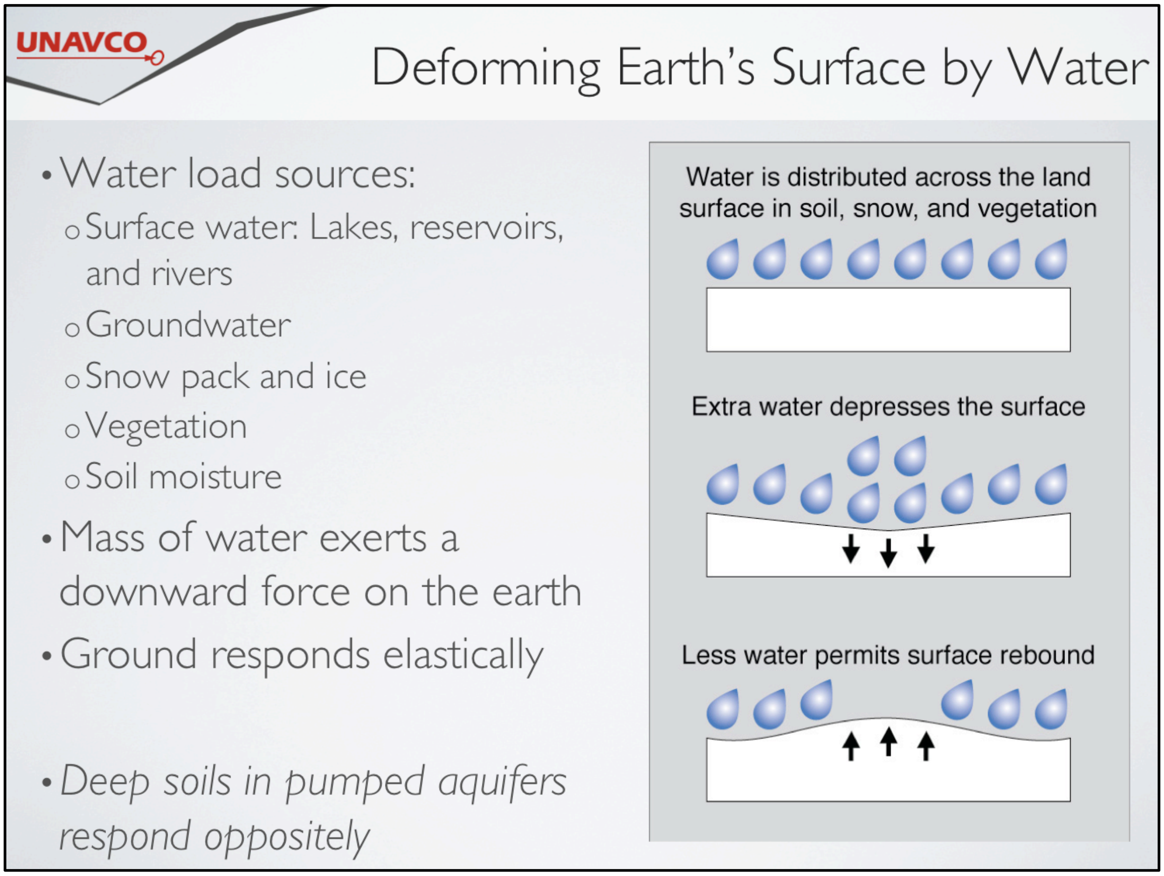
Today I am going to introduce a suite of data products that are in different stages of being quasi-operational or have the potential for being integrated into operational atmospheric and environmental forecasting models. These products are all derived from applying geodetic techniques to measure the changes in these different parameters.

First we will take a look at a modeled hydrologic product that calculates the ground displacement due to water loading.

Then we take a look at three environmental data products: vegetation height, snow depth, and surface loading through a different technique, GPS multipath

A quick detour to look at direct measurement of water loading, still in research stage

Finally we move on to the atmosphere and take a look at precipitable water vapor derived from GPS signal



The mass of the water exerts a downward force on the earth, which responds elastically

There are many sources of water on earth's surface – more than just streams and rivers … groundwater, snow pack, ice, water in the vegetation, and moisture locked in the soils.

When more water is added to the surface, surface is elastically pressed downward

When there's less water on the surface, the surface rebounds.

Now, about areas with deep soils, such as the Central Valley, that are under heavy pumping, the soils respond oppositely due to poroelastic deformation. For this reason, many examples that I show remove the GPS influence of the Central Valley of California.

…more about poroelastic deformation…

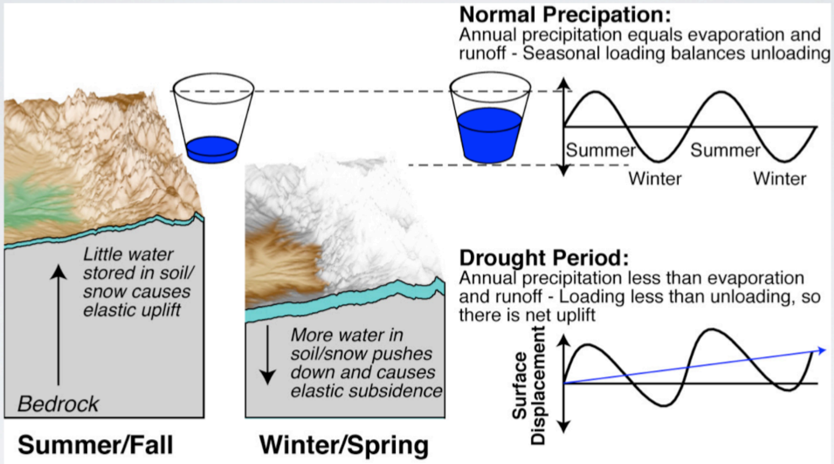
Poroelastic deformation is driven by heavy groundwater pumping to create changes in water stored in aquifer.

Local hydrologic pumping effects

Poroelastic effects in deep soil regions (valleys)

Lakes, reservoirs, and other large bodies of water

Local Loading Impacts



- Seasonal changes
  - Winter: snow load → pushes down
  - Summer: low water storage → elastic uplift
- Drought
  - Gradual uplift

Two scenarios shown here in the mountains

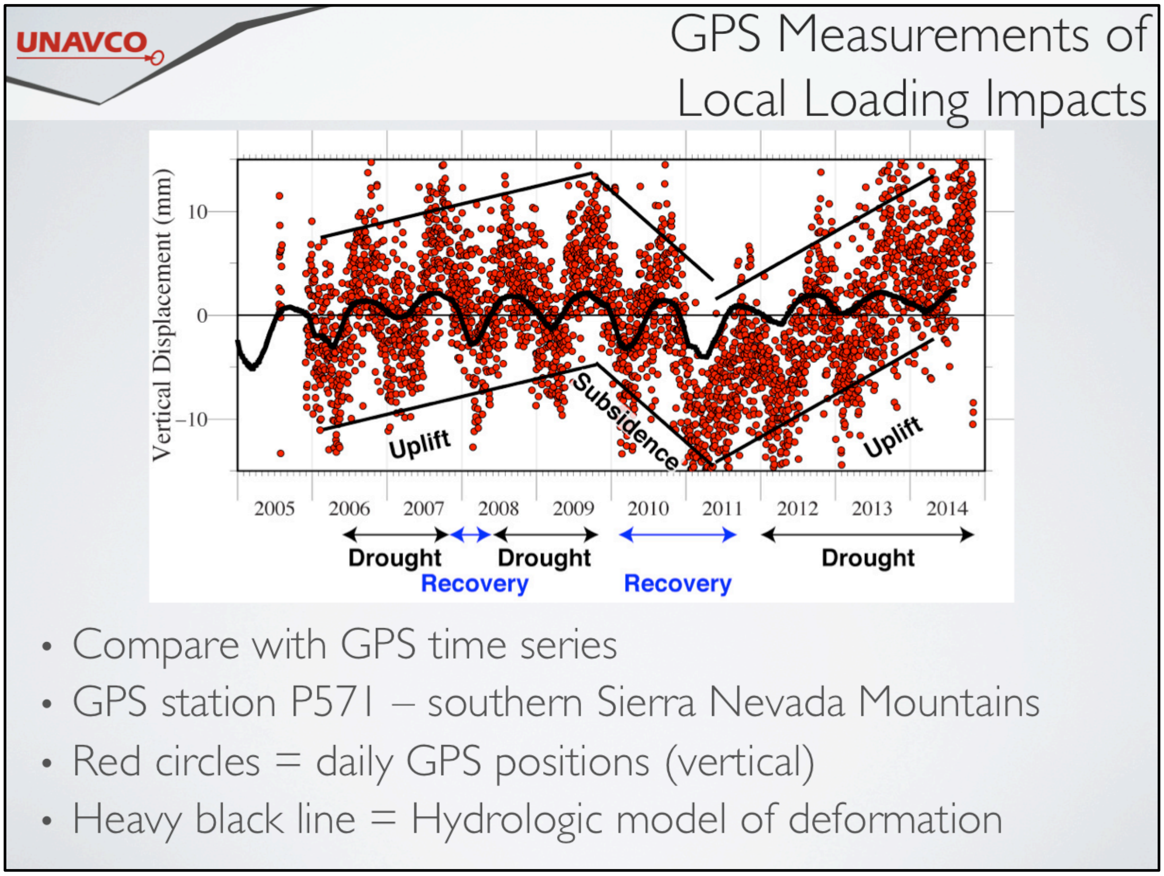
Winter and spring when snowpack and soil moisture is high, the ground surface is depressed by the load. (see graph)

Summer, low storage of water, elastic uplift

readily observed in mountainous regions, where bedrock predominates, soil thickness is less than ~1 meter, and poroelastic effects are minimized.

In a drought, the overall trend is a gradual uplift.

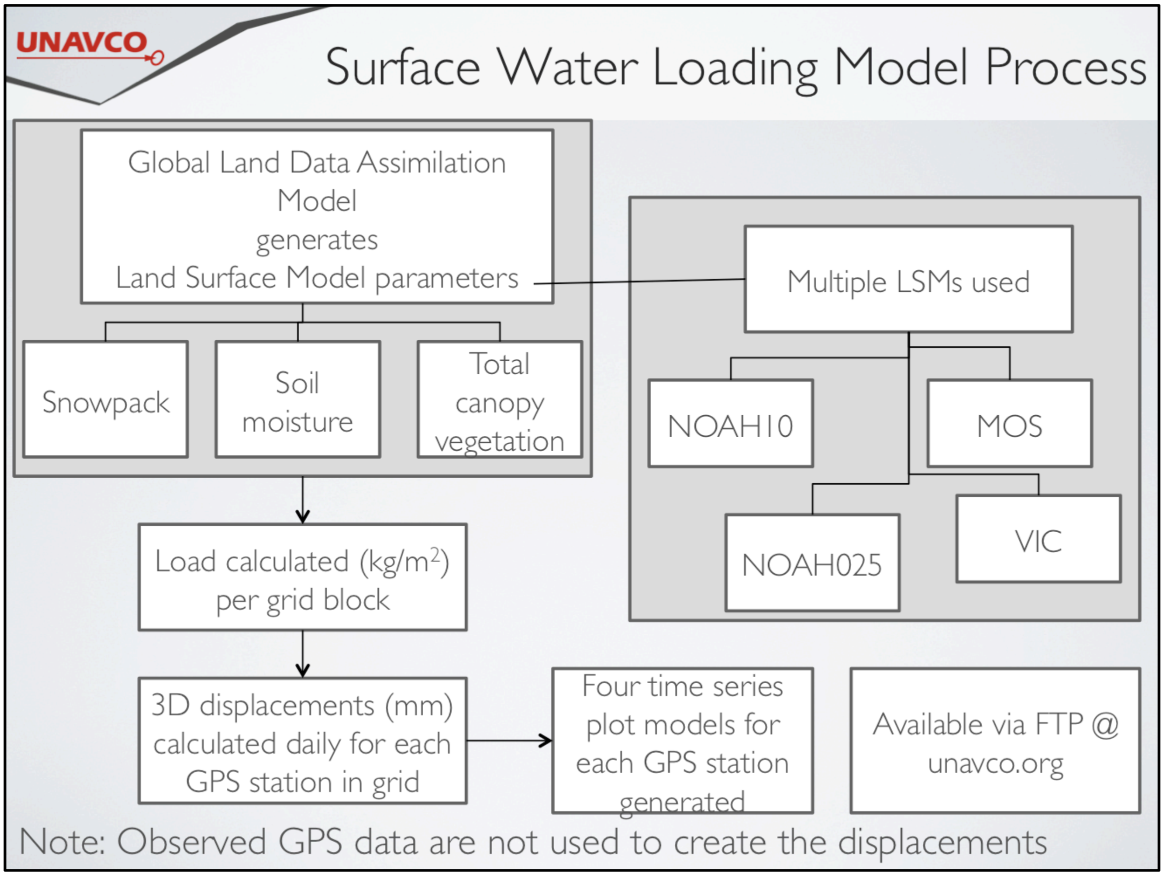
That’s theory, let’s look at reality



In periods of drought, water loss exceeds precipitation and storage, so elastic rebound exceeds load-induced subsidence and there is net uplift. This effect can be seen at station P571, in the southern Sierra Nevada mountains.

general uplift from 2006 to 2009, corresponding to drought at this time. A brief period of recovery in winter 2007/2008 is not enough to offset the uplift trend, though the minimum seasonal amplitude has a greater amplitude than the previous and following years, corresponding to a greater water load that winter. Recovery begins in late 2009, and there is subsidence through 2011 as more water is accumulated at the surface. Starting in 2011, uplift resumes with the advent of another drought. The higher uplift rate indicates that this is a more severe drought.

Vertical motion recorded at station P571 (red circles) and hydrologic model of deformation (heavy black line). The observed and modeled seasonal deformation both have the same trends of uplift and subsidence corresponding to periods of drought and recovery. The GPS time series has much larger seasonal amplitudes than the hydrologic model partly because the PBO realization of the North America-fixed reference frame (NAM08) exaggerates the seasonal signal.



Process to create the hydrologic displacement model

- Starts with Land Surface Model parameters from the Global Land Data Assimilation System (GL DAS) …
- These parameters include snowpack, soil moisture and total canopy vegetation
- The total surface water load is calculated for each grid block (1 degree by 1 degree) in kg/m2
- From the load of water, the three dimensional displacement is calculated for each GPS station. (using **Green's functions (Farrell, 1972)** using the algorithms of van Dam et al. (2001) and Wahr et al. (2013). Contributions from loads at all grid squares are summed at coordinates corresponding to GPS station locations. The result is a displacement time history in millimeters at the GPS site.)
- There are four different LSMs used (NOAH10, NOAH025, MOS, and VIC models) so four modeled time series plots are generated

ftp://data-out.unavco.org/pub/products/hydro/

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The Global Land Data Assimilation System (GLDAS) is a project to generate sets of environmental parameter values by incorporating satellite and ground observations into land surface models using data assimilation techniques (Rodell et al., 2004). GLDAS was developed through the collaboration between the National Aeronautics and Space Administration (NASA) Goddard Space Flight Center (GSFC) and the National Oceanic and Atmospheric Administration National Centers for Environmental Prediction (NOAA NCEP). GLDAS oversees multiple LSMs, developed and contributed by different groups.

Modeled product, can be used as a baseline
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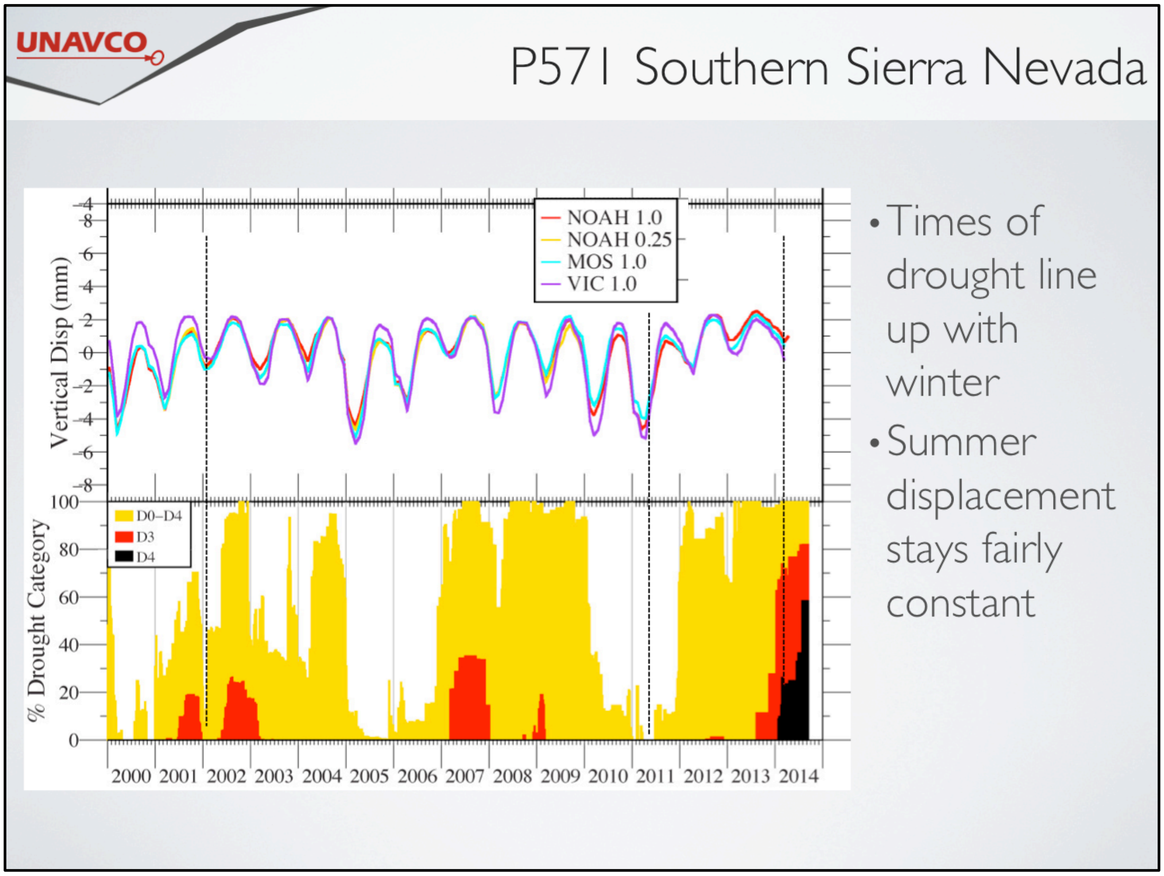


Taking a look at the GPS station P571 in Southern Sierra Nevadas, this image shows the modeled displacements in the vertical direction over time.

Displacements from different land surface models are represented by different colors.

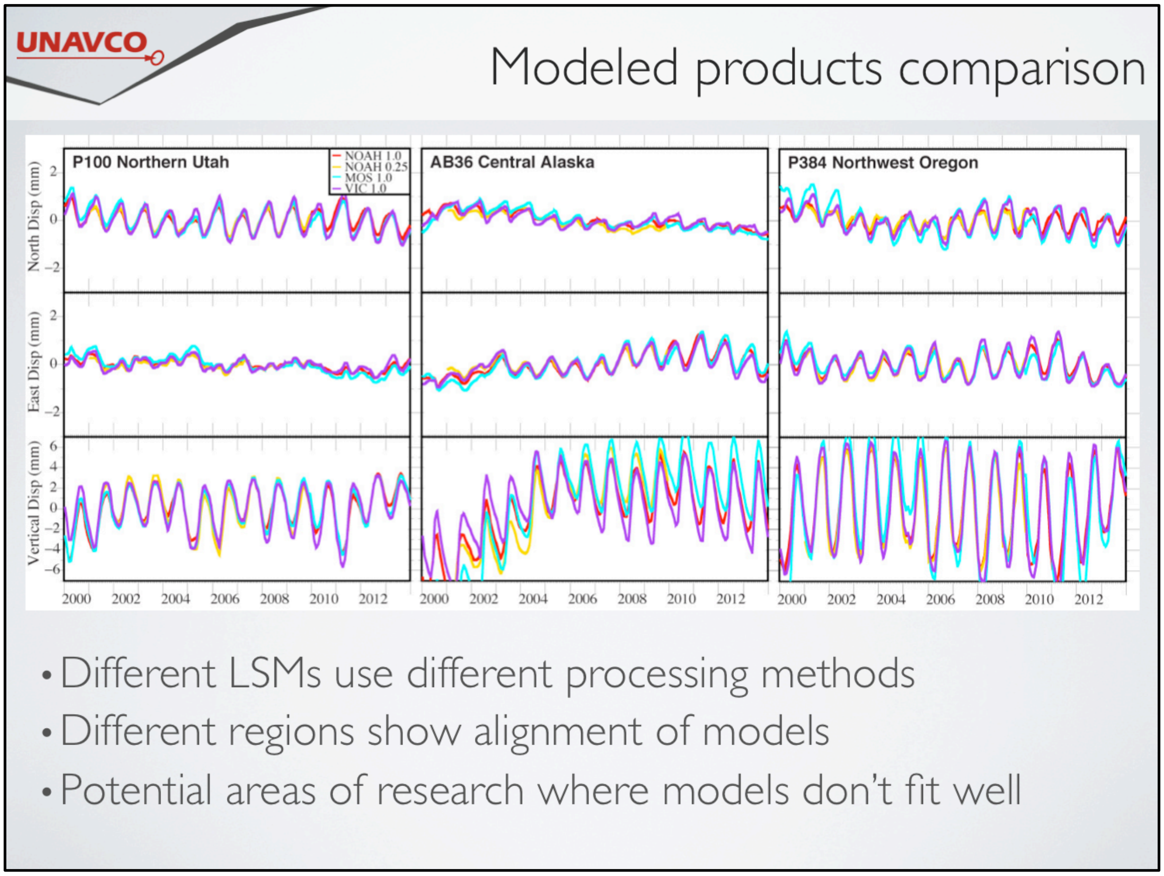
The lower graph shows the percentages of drought

all categories of drought (gold),

the percentage of the state in extreme drought (D3, red) and

exceptional drought (D4, black).

Components of hydrologic displacement and the percentage of California experiencing some level of drought.



The primary differences relevant to UNAVCO's hydrologic modeling are due the number and thicknesses of the soil layers (Fang et al., 2009) and to the availability of vegetation storage

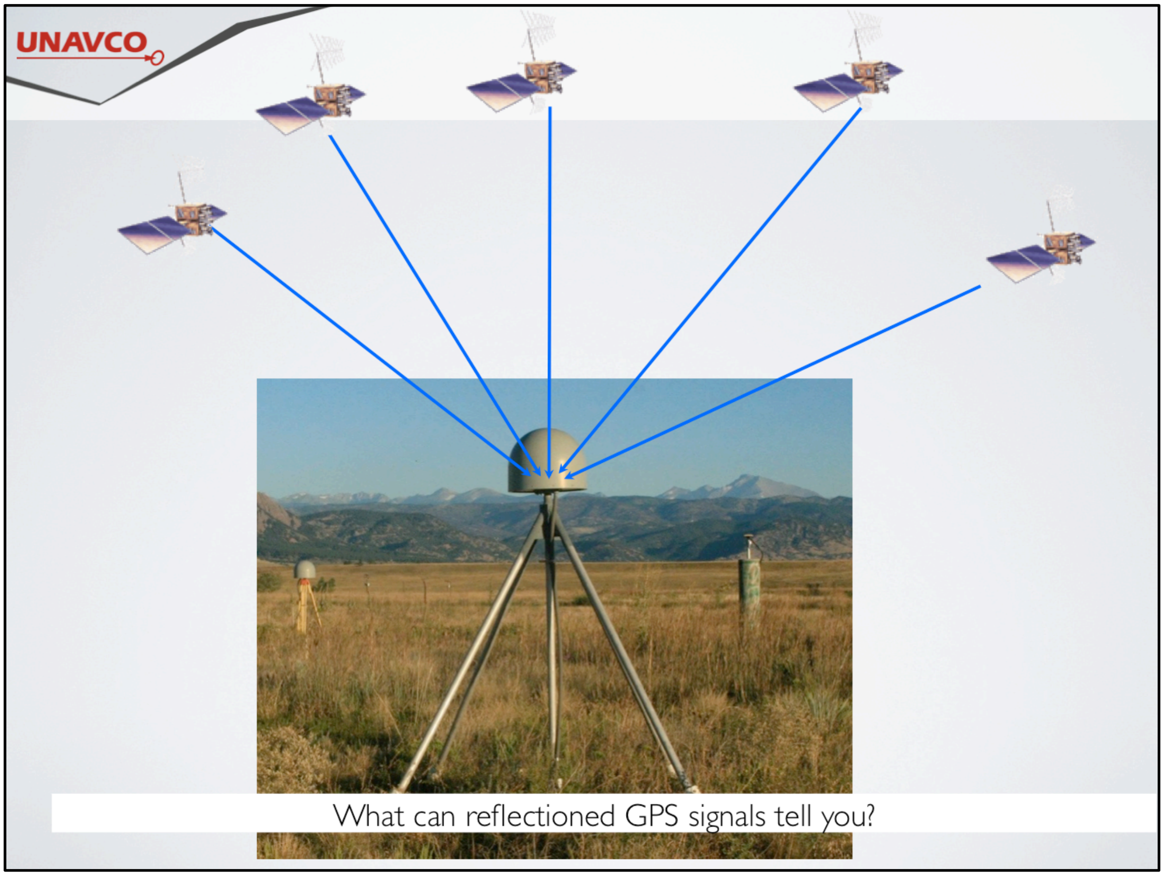
LSMs use different methods for processing observations and modeling parameters

surface environmental parameters for water, temperature, atmospheric pressure, radiation, fluxes, and other measures of the transfer of mass and energy at the Earth's surface

Examples of hydrologic time series in different regions.

- Station P100 in Utah is located in the arid to semi-arid Basin and Range province.
- Station AB36 is located in Alaska south of the Arctic Circle, in a region with discontinuous permafrost (e.g., Abraham, 2011).
- Station P384 in northwest Oregon is located in the marine west coast climate zone.
- Notice how the models have the most differences in the Arctic. Why? What could we learn from these differences? An area of potential research.

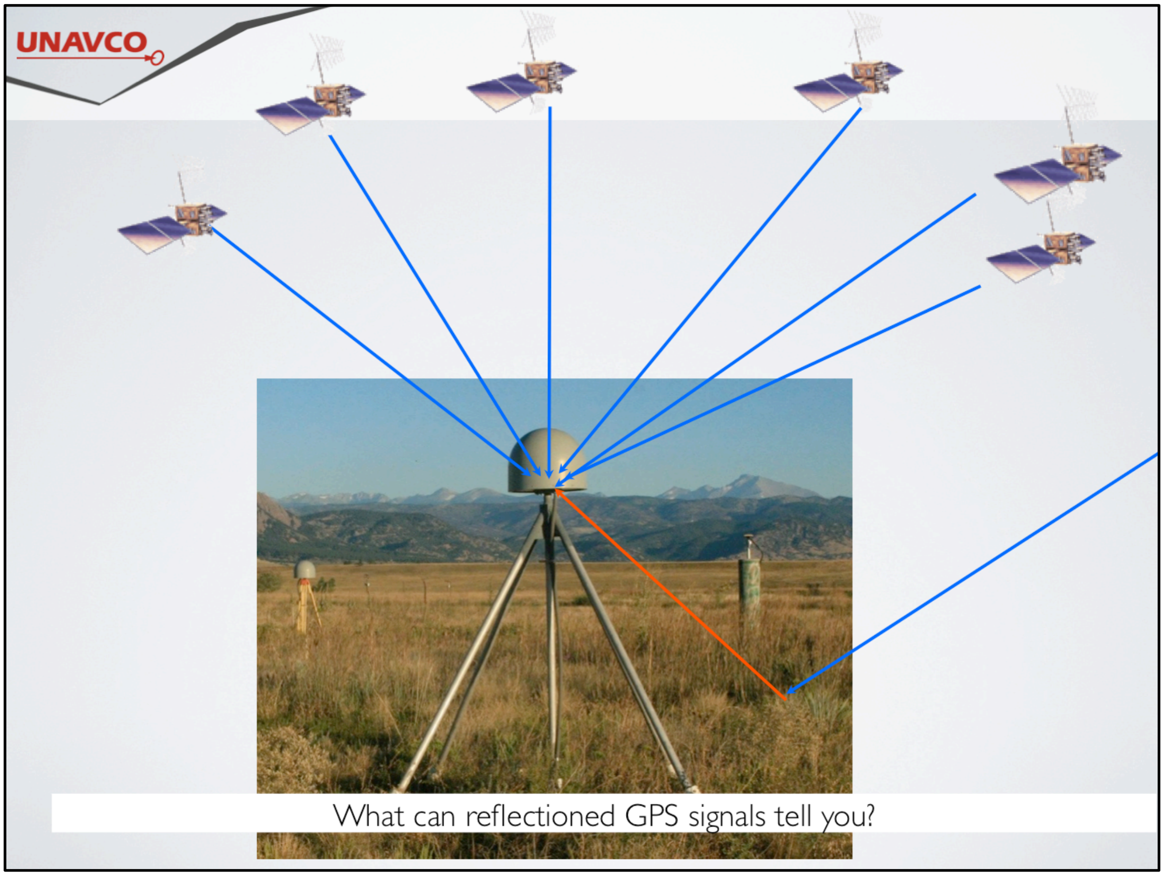
NOAH (Noah) 1.0, NOAH 0.25, MOS (Mosaic) 1.0, and VIC (Variable Infiltration Capacity) 1.0



Moving on to using the reflected signals that reach the GPS station.

When data is collected from GPS satellites, the signal to noise ratio is also collected. One source of noise is multipath, the reflection of the GPS signal against the ground and other surfaces before reaching the GPS antenna. And it turns out, these reflected signals provide lots of information about the ground surface conditions.

The footprint that the permanent GPS stations can measure is around 30 x 30 meters, every hour.



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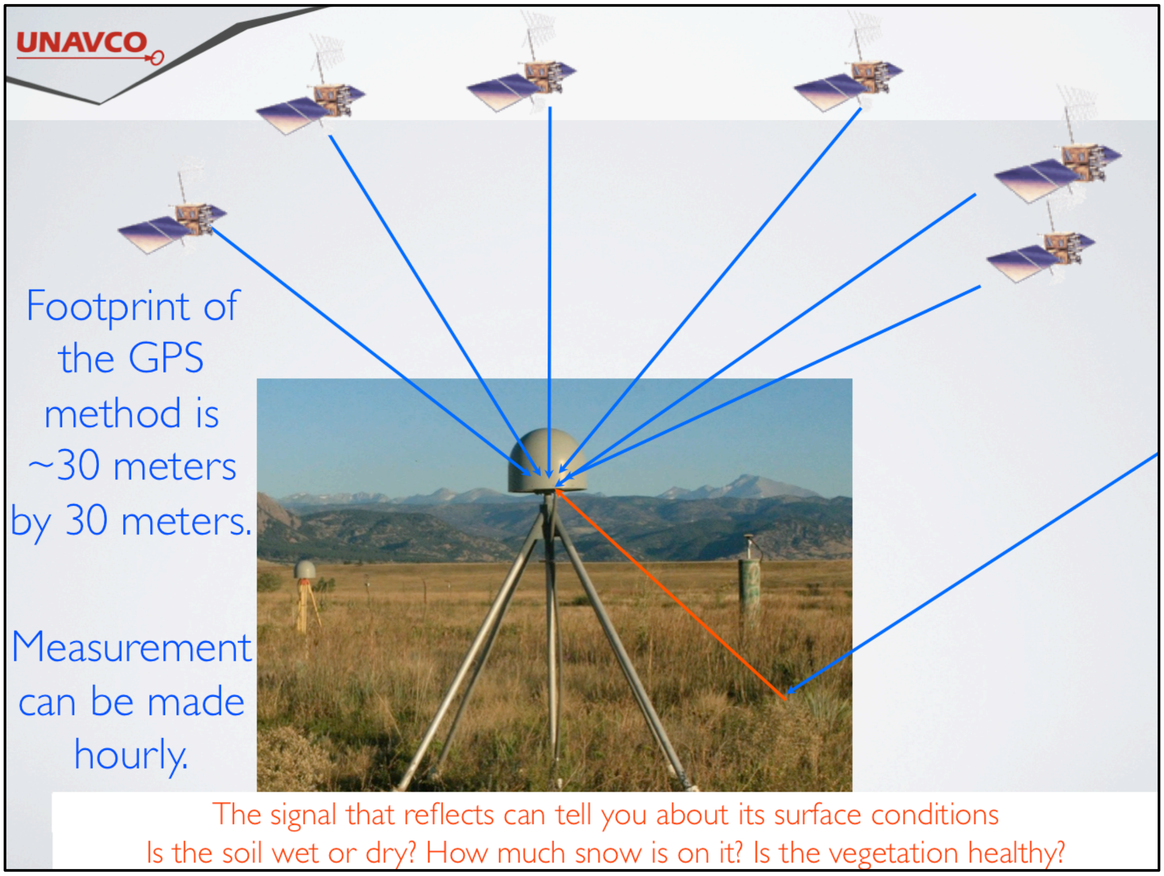

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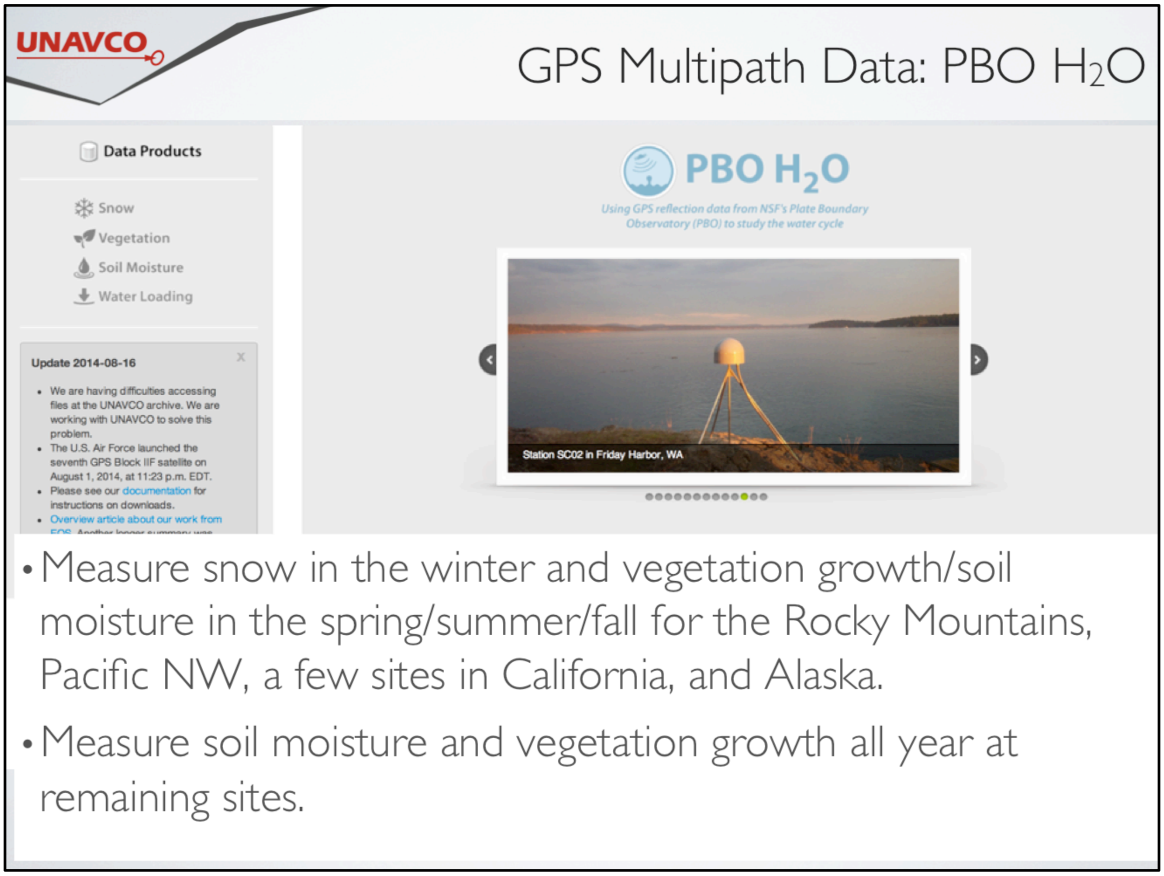


PBO H2O is a data portal created by Kristine Larson and the Reflection Group at University of Colorado.

The group won the 2014 Prince Sultan Bin Abdulaziz Creativity Prize for Water!

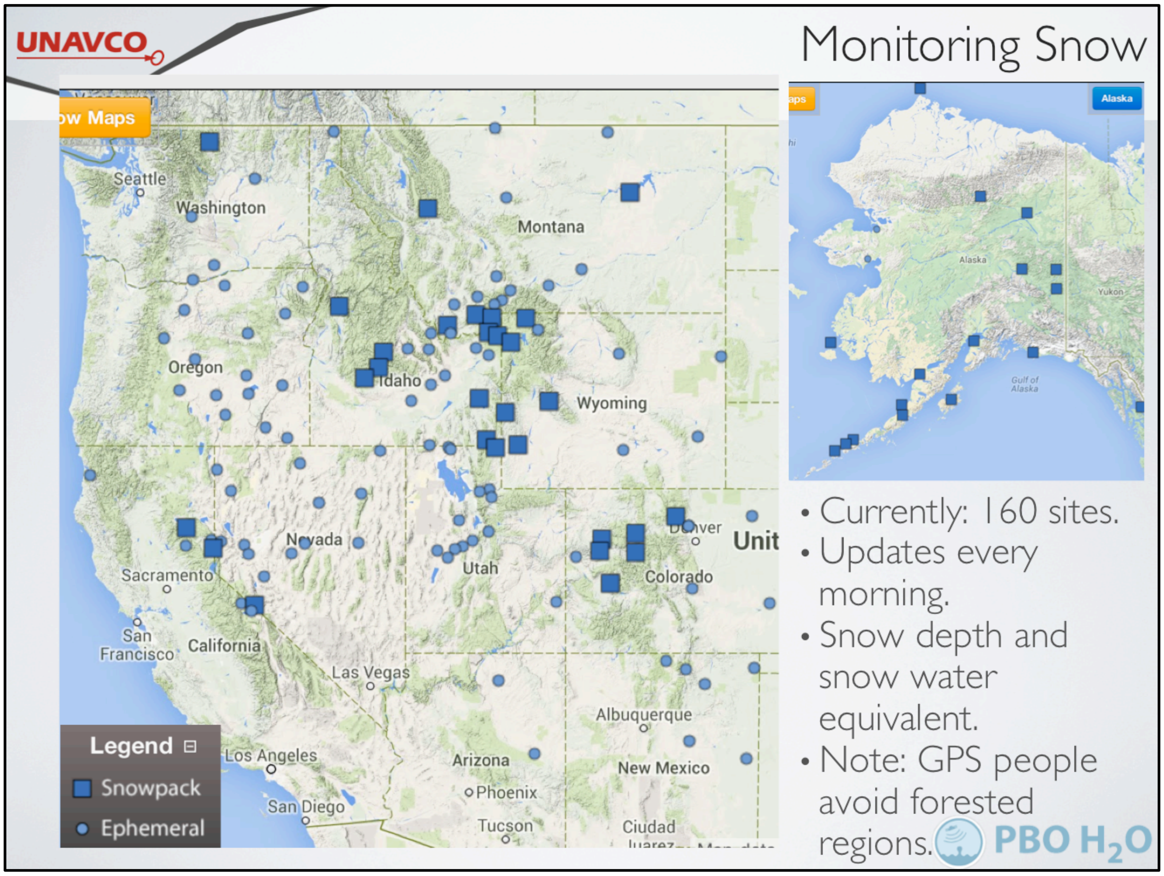
For their work on these data products:

Soil moisture

Vegetation height

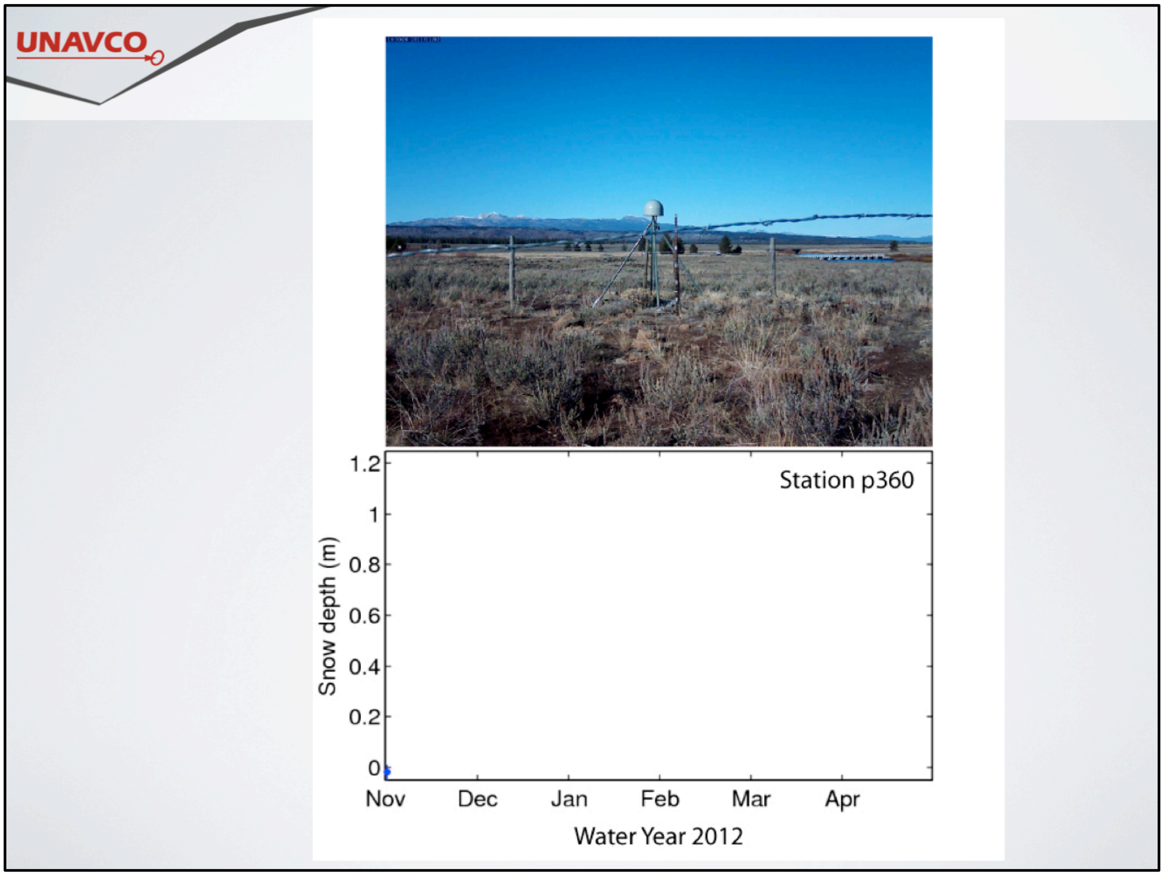
Snow depth (winter)

http://xenon.colorado.edu/portal/



GPS stations located where significant snow accumulates. These are typically open areas – not forested.

This animation in the top frame shows photos of the GPS station over a snow season. The bottom frame shows a graph of time vs snow depth (in blue) in meters as measured by the GPS station. The next image shows with red dots, the snow depth as measured by a yard stick from the still images. Very close correlation between the two.



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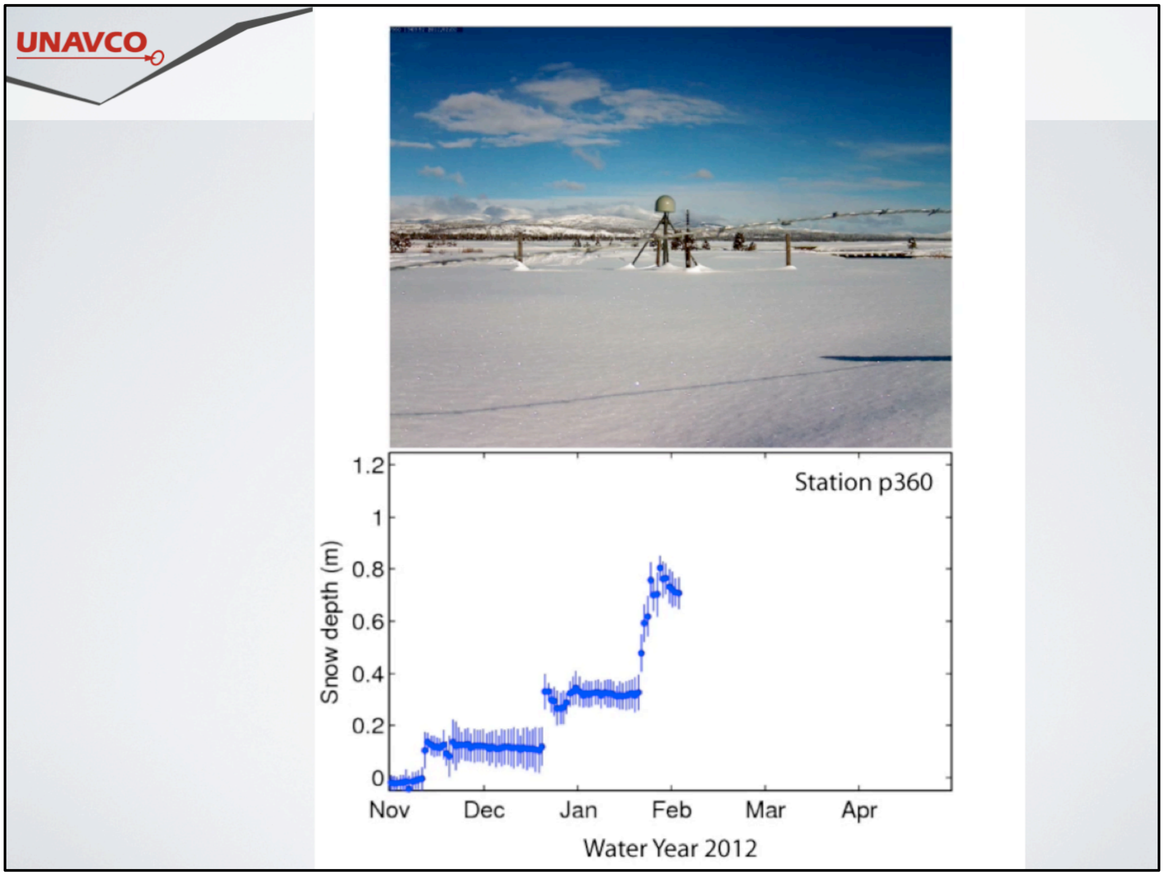

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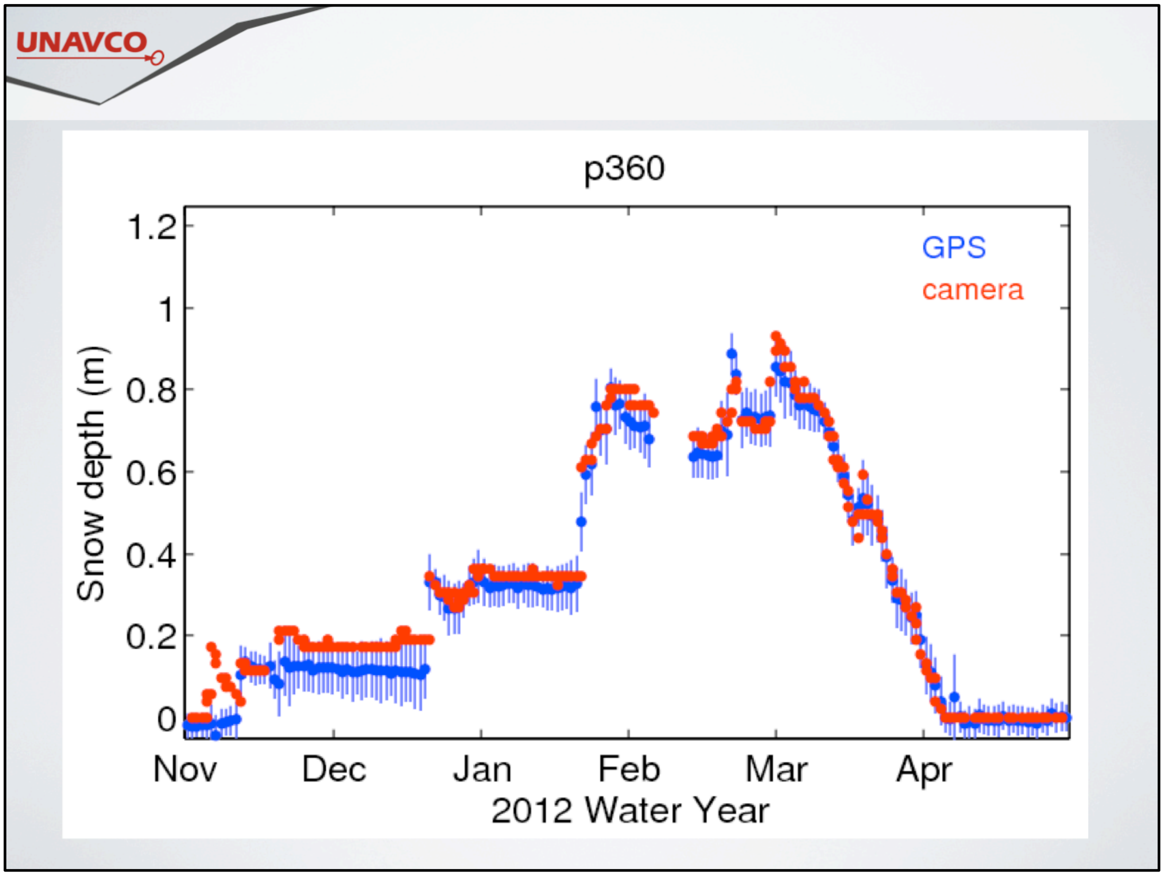

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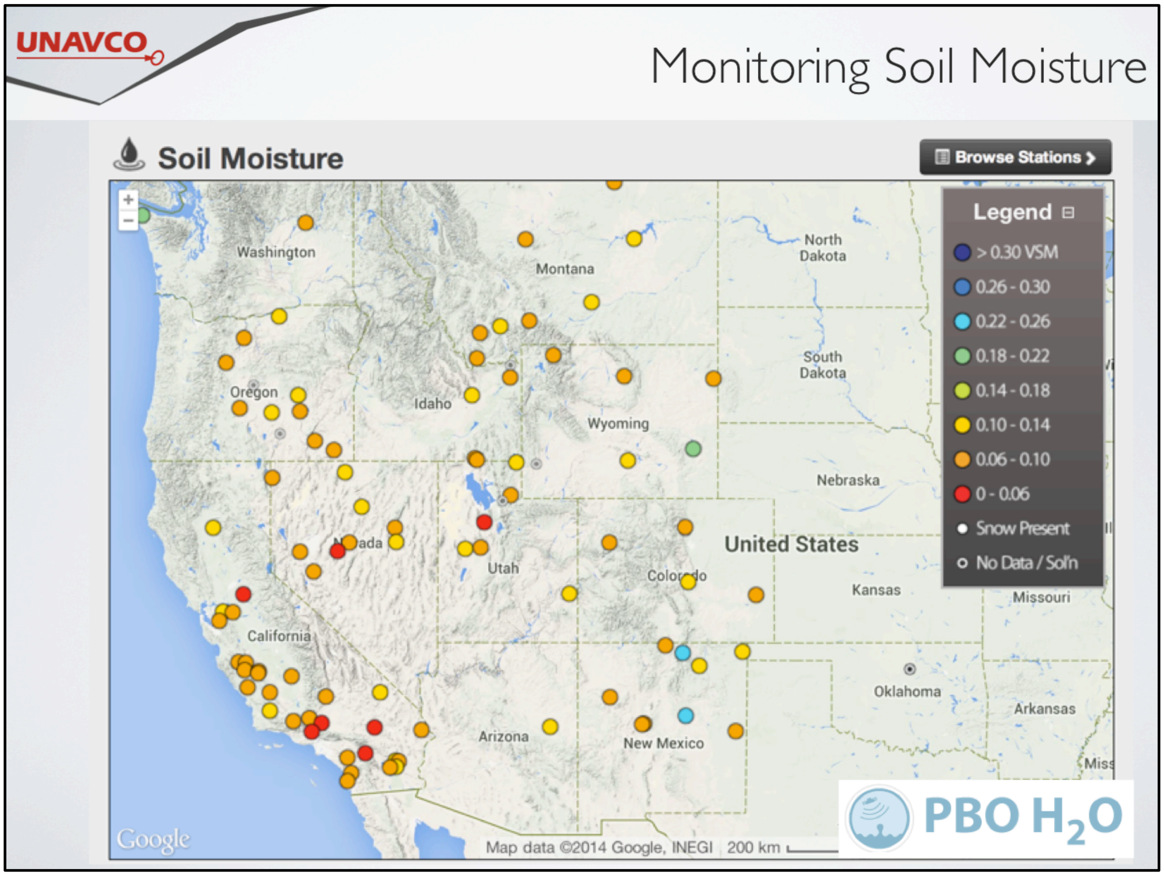


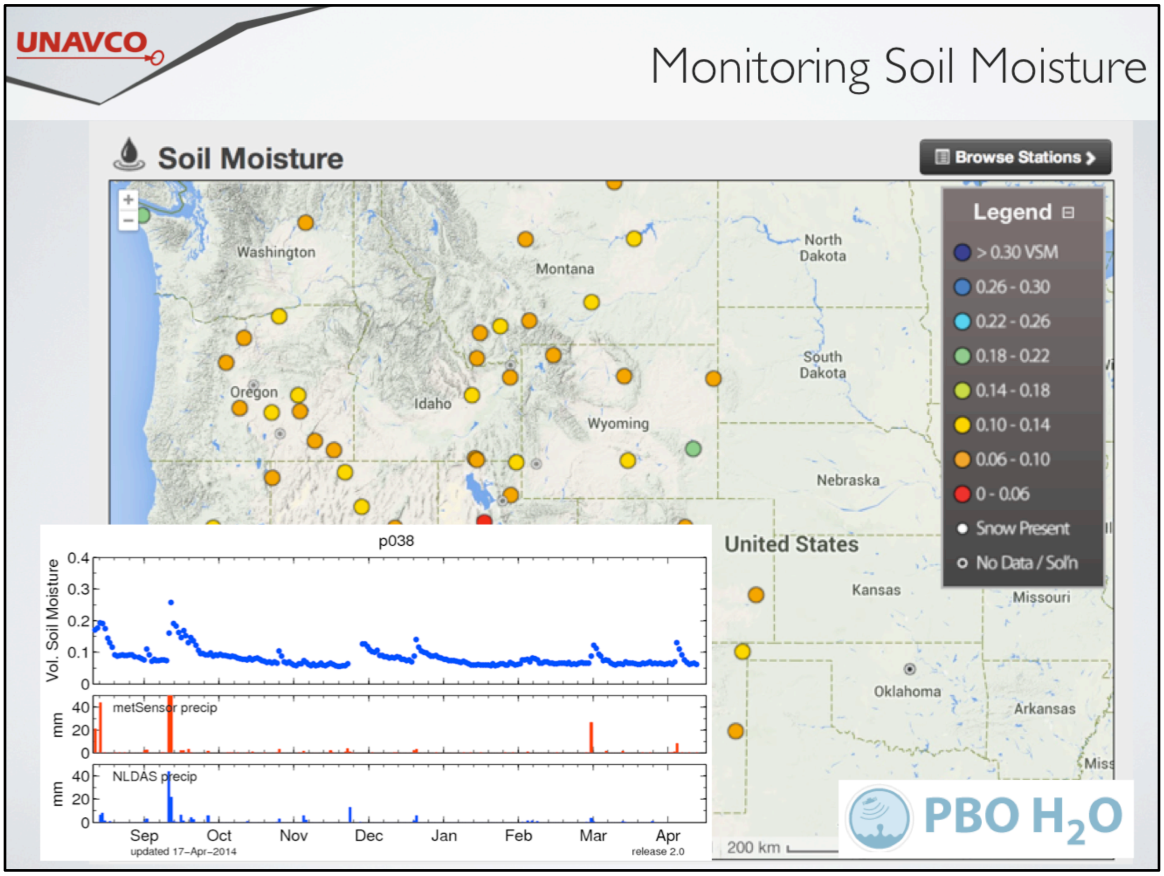
The map shows the soil moisture measured at the GPS stations in the western United States from the past summer 2014.

The stacked graphs, from April 2014, show the data from P038, location in eastern New Mexico.

The GPS measured soil moisture volume in the top graph,

The middle graph shows precipitation in millimeters from a near by met sensor

And the bottom graph shows modeled precipitation from NLDAS, also in millimeters.



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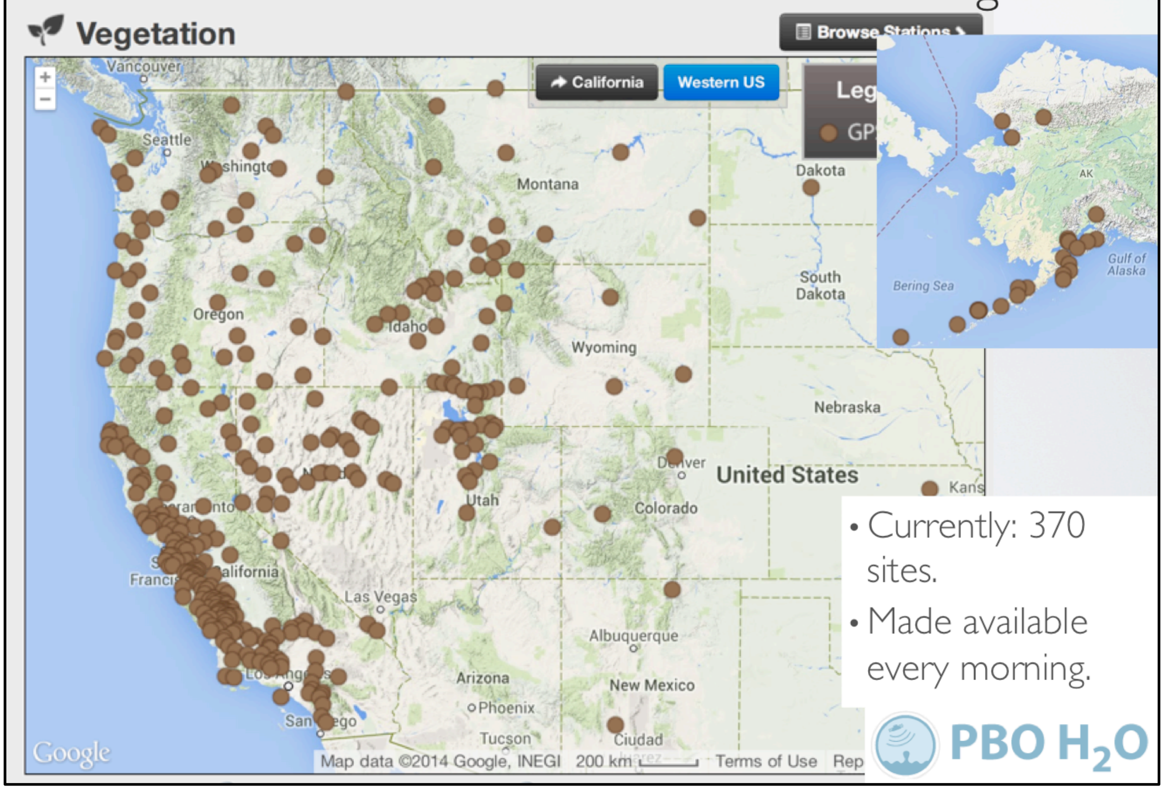
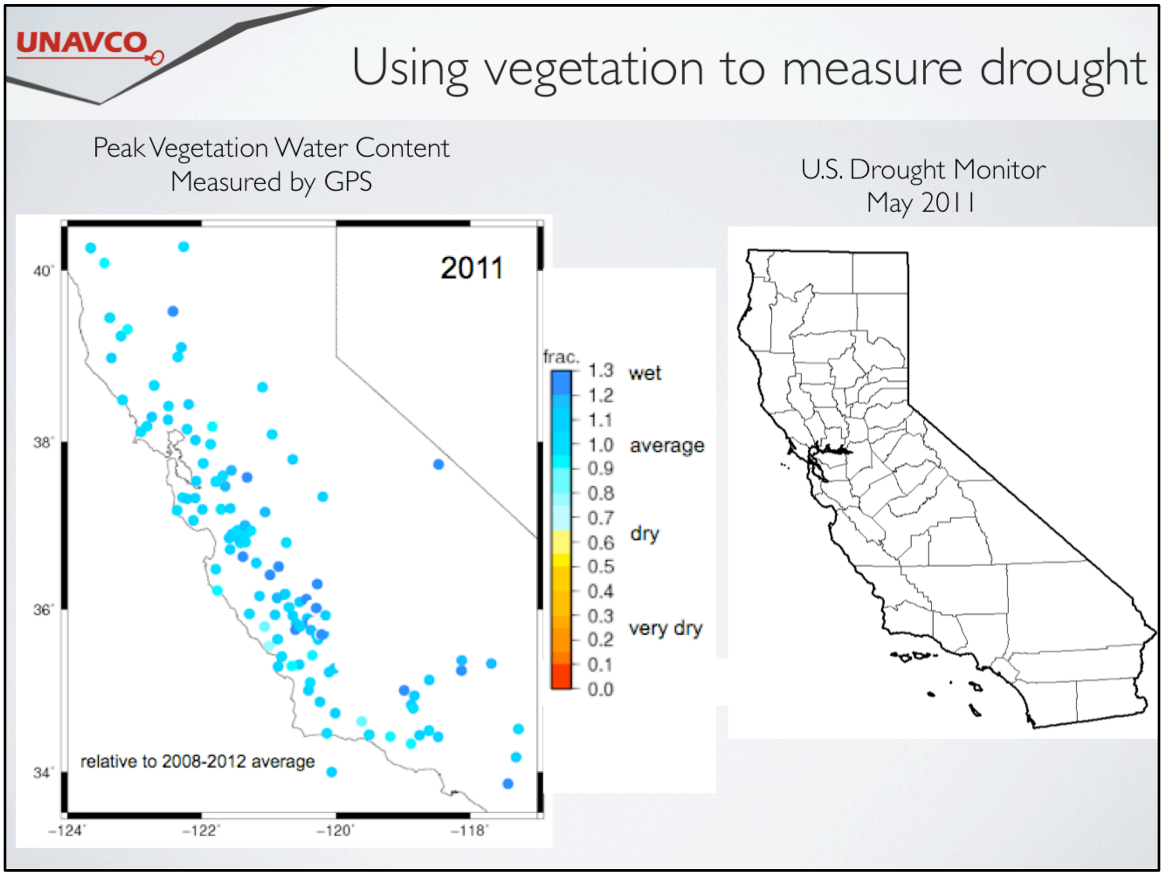
UNAVCO

Vegetation



- Currently: 370 sites.
- Made available every morning.

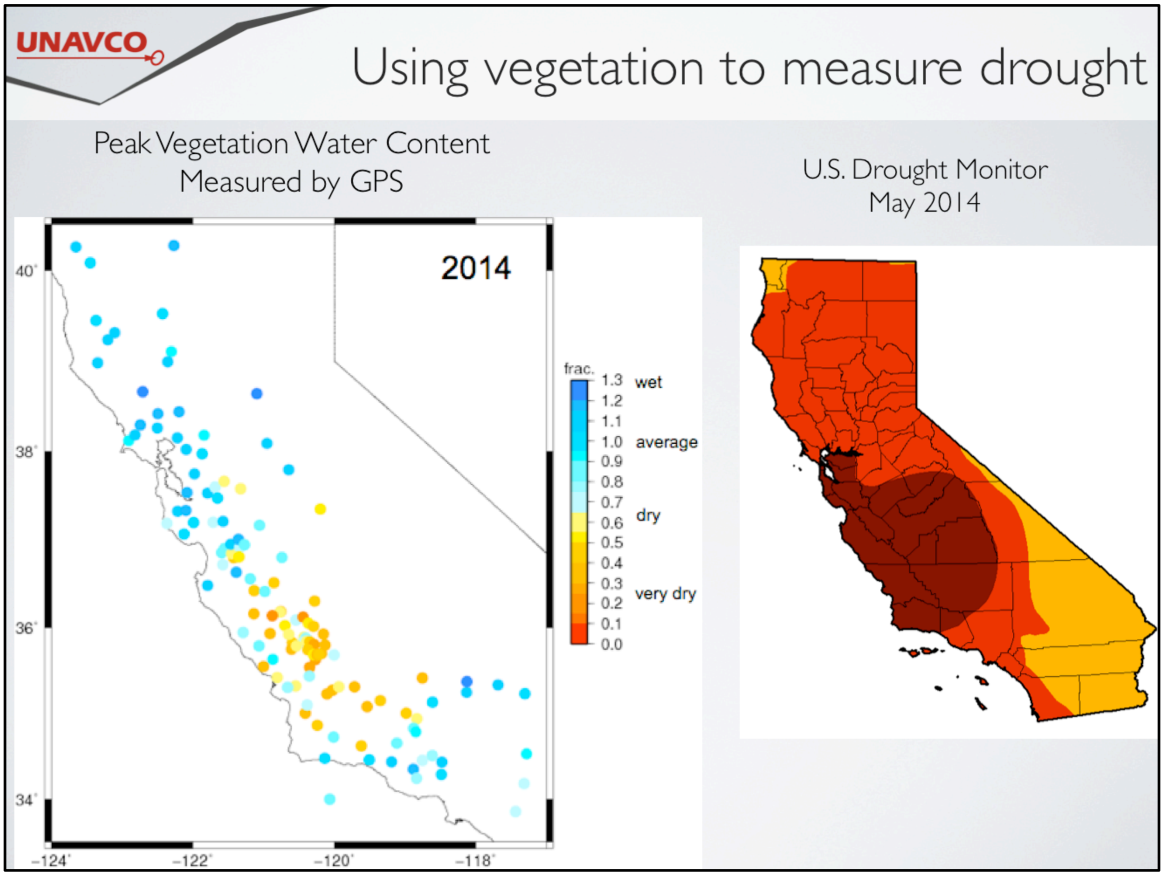
PBO H_2O



This sequence shows the Peak Vegetation Water Content for the years 2011 to 2014 compared to the four year average of 2008 – 2012.

For May 2011 most of California is average to wet based on the vegetation water content for the year and in fact the US Drought Monitor map is blank

Zoom ahead to May 2014, areas of the northern part of California still had vegetation with slightly dry to average water content. The central part of the state is moving into dry and very dry.



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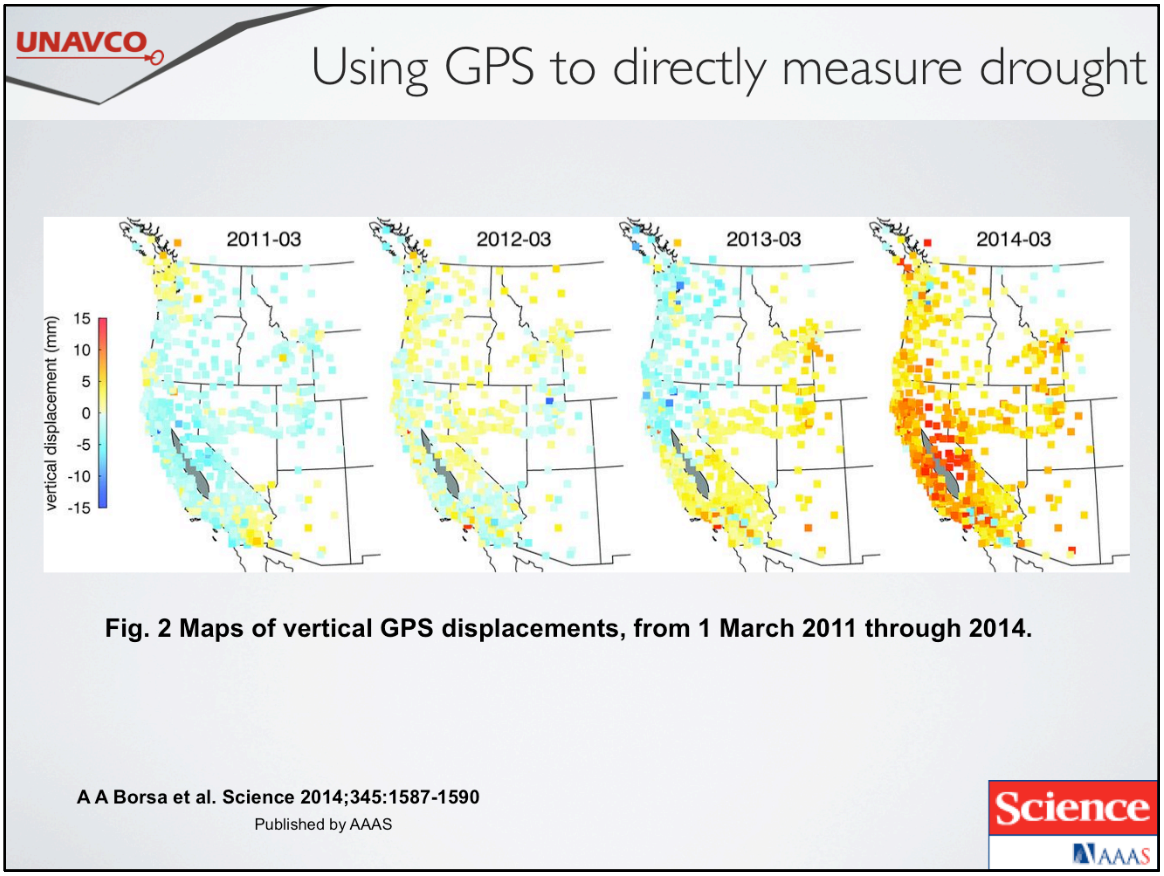


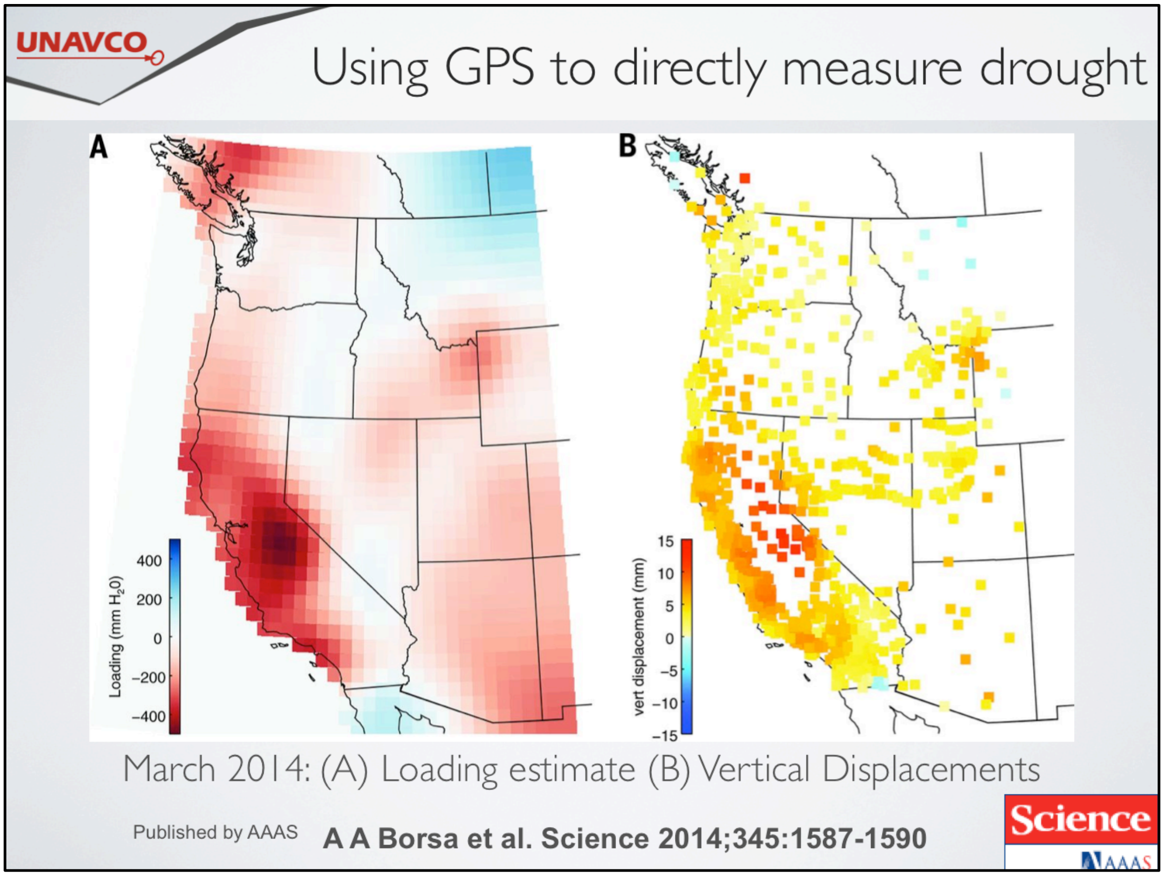
We now can see the change in the topography of the land from the loss of water and the potential implications.

Since we are on a theme of measuring water content using GPS, recent research by Borsa and colleagues used direct measurements of GPS displacements to estimate the water load (and unloading) of the Western US. This suite of maps shows the change in topography in millimeters from March 2011 through 2014.

In 2013 rainy season in the Pacific Northwest results in Oregon and Washington being elastically pushed down by 5 or so mm,

while in 2014, California's deepening drought results in the region undergoing elastic uplift. Note that the data from the Central Valley is removed (grey area).

Fig. 2 Maps of vertical GPS displacements.Spatial distribution of displacements from the time series in Fig. 1, from 1 March 2011 through 2014.



Maps of estimated loads and predicted displacements.(**A**) Loading estimate for the WUSA in March 2014. Redder areas indicate negative loading (mass deficit), bluer areas indicate positive loading (mass surplus), and white areas are unchanged. (**B**) Vertical displacements, corresponding to the loading model in (A), at the locations of the GPS stations used in this analysis (compare to actual displacements in rightmost panel of Fig. 2).

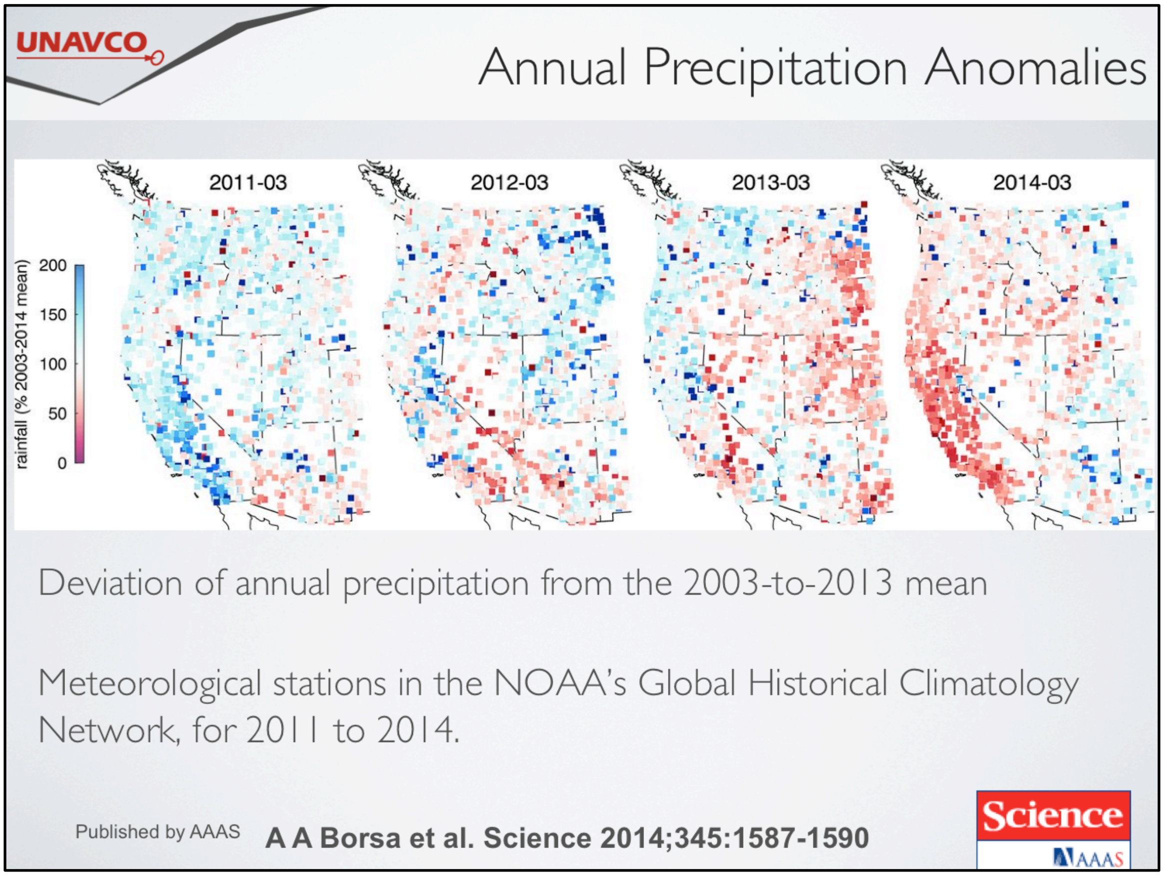
.5 degree grid

— Knowing that an area is in drought is useful for more than just water availability - how does knowing how much California has changed as a result of the drought? We can see this dramatically depicted. How quickly will severely dried soil re-absorb water? Is there a limit before soil compression won't respond? Are our aquifers being damaged long term? There are many questions that could and probably are being explored

while the modeled displacements don't have to be tied to permanent GPS stations - each station provides a known benchmark and allows for comparison with observed data collected at each site. One possible extension would be to apply this process to other GPS networks (show the UNR map), imagine having this information at every known GPS station in the world.

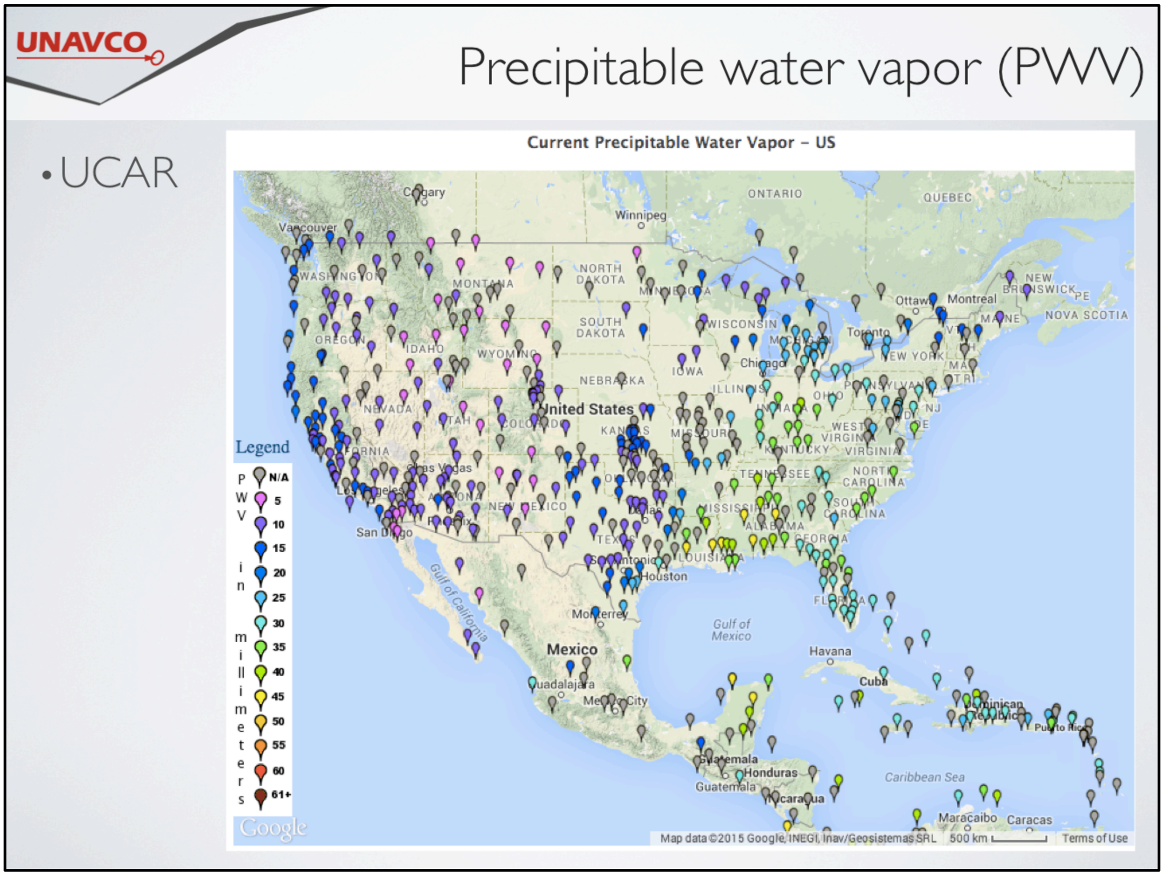
Total deficit of around 240 gigatons of water

A A Borsa et al. Science 2014;345:1587-1590



Maps of annual precipitation anomalies. Deviation of annual precipitation from the 2003-to-2013 mean at meteorological stations in the National Oceanic and Atmospheric Administration's Global Historical Climatology Network, for 2011 to 2014. The pattern of precipitation—in particular, the surplus in California in 2011 and the deficit in 2014—mirrors the pattern of uplift seen in the GPS data.

A A Borsa et al. Science 2014;345:1587-1590



- There are many techniques for measuring precipitable water vapor …
- Measuring water vapor via GPS satellites and GPS receivers on the ground has been used in research for close to 20 years and in quasi-operational settings for a number of years
- high temporal resolution (every 5 minutes), accuracy, and automation.
- Supplements the radiosondes to get vertical profiles … of the troposphere

Suominet pulls data from the PBO.. and COCONet (Continuously Operating Caribbean GPS Observational Network (COCONet)) operated by UNAVCO

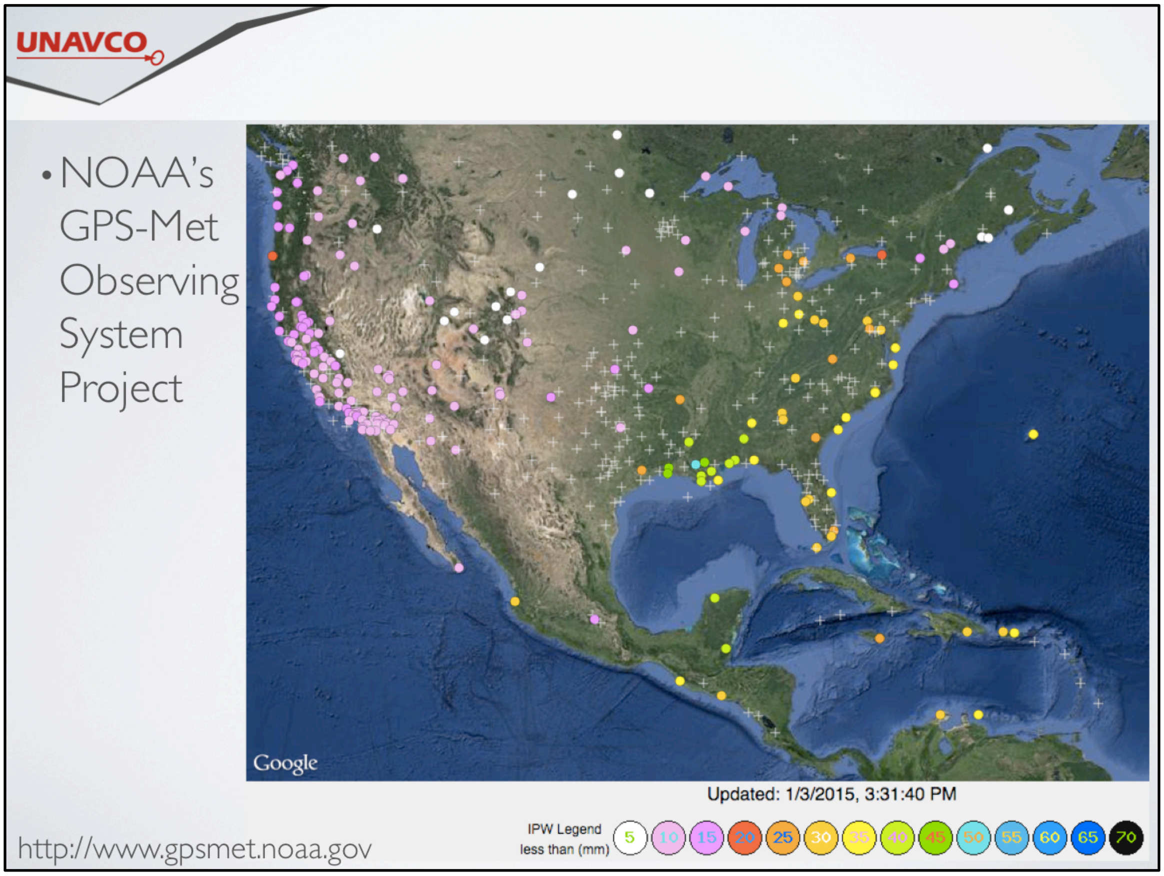
and the Amazonian Dense GNSS Meteorological Networknetworks ,

- Useful for independently validating radiosonde data
- Useful for refining weather forecasting … The changes in PWV over time helps to trace the dynamics of deep convection.
- documenting long-term trends in a changing climate
- Understanding atmospheric dynamics

Zenith total (or tropospheric) delay: ZTD

http://www.suominet.ucar.edu/

http://www.unavco.org/science/snapshots/atmosphere/2012/wang.html



GPS-Met Observing Systems project

http://www.gpsmet.noaa.gov/background.html

UNAVCO

Multiple products, multiple methods

- How can these different products be useful?
  - Real-time forecast development
  - Comparison of techniques
  - Monitoring
  - Local studies
  - Regional conditions
- How can these products be more useful?
  - Suggestions welcome for improving the products and tools to explore and display the data.
- Moving from research to quasi-operational to operational

We've seen a number of data products derived from geodetic methods that range from quasi operational (PWV), almost quasi (PBO H2O and UNAVCO Hydrologic Displacement Model), to research level (Borsa and colleagues) to measure a number of environmental parameters.

These products such as precipitable water vapor have shown their usefulness in real time situations such as hurricane and storm development.

Other products are useful as ways to verify other techniques. However, without funding resources, their lifespan is uncertain

We are soliciting input on the Hydrologic Displacement Model to improve the product and fine tune it to user needs. Right now the data is available in txt files with no visual interface. Would a map interface be useful?

Thank you for listening and I hope to have a chance to talk with you all after the session.

Thank You!

http://www.unavco.org/

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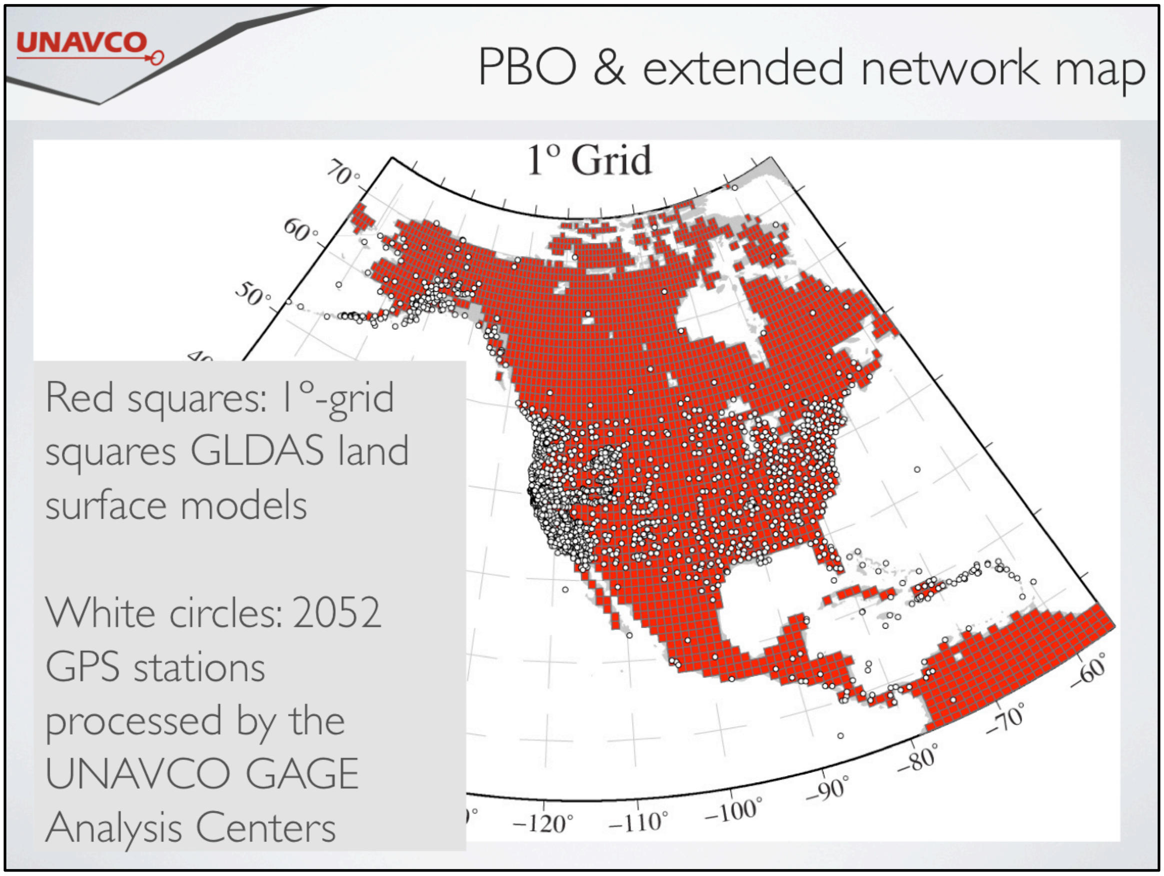
Shelley Olds
UNAVCO
Olds at unavco.org



1 degree grid.

2052 GPS stations analyzed by UNAVCO's GAGE analysis centers: PBO, COCOnet, and additional stations