The background image shows a geothermal field with large plumes of white steam rising from the ground. In the foreground, a group of people is walking across a wooden boardwalk that stretches across the water. The scene is captured in a high-contrast, almost black and white style, with the steam and water surface reflecting light.

Transient Hydrologic Effects from Surface Loading and
Pumping in the Western U. S. Observed with the
Plate Boundary Observatory

Chuck Meertens, UNAVCO

Adrian Borsa, UNAVCO

Tom Herring, MIT

Mike Jackson, UNAVCO

Tonie Van Dam, U.Lux

John Wahr, CU

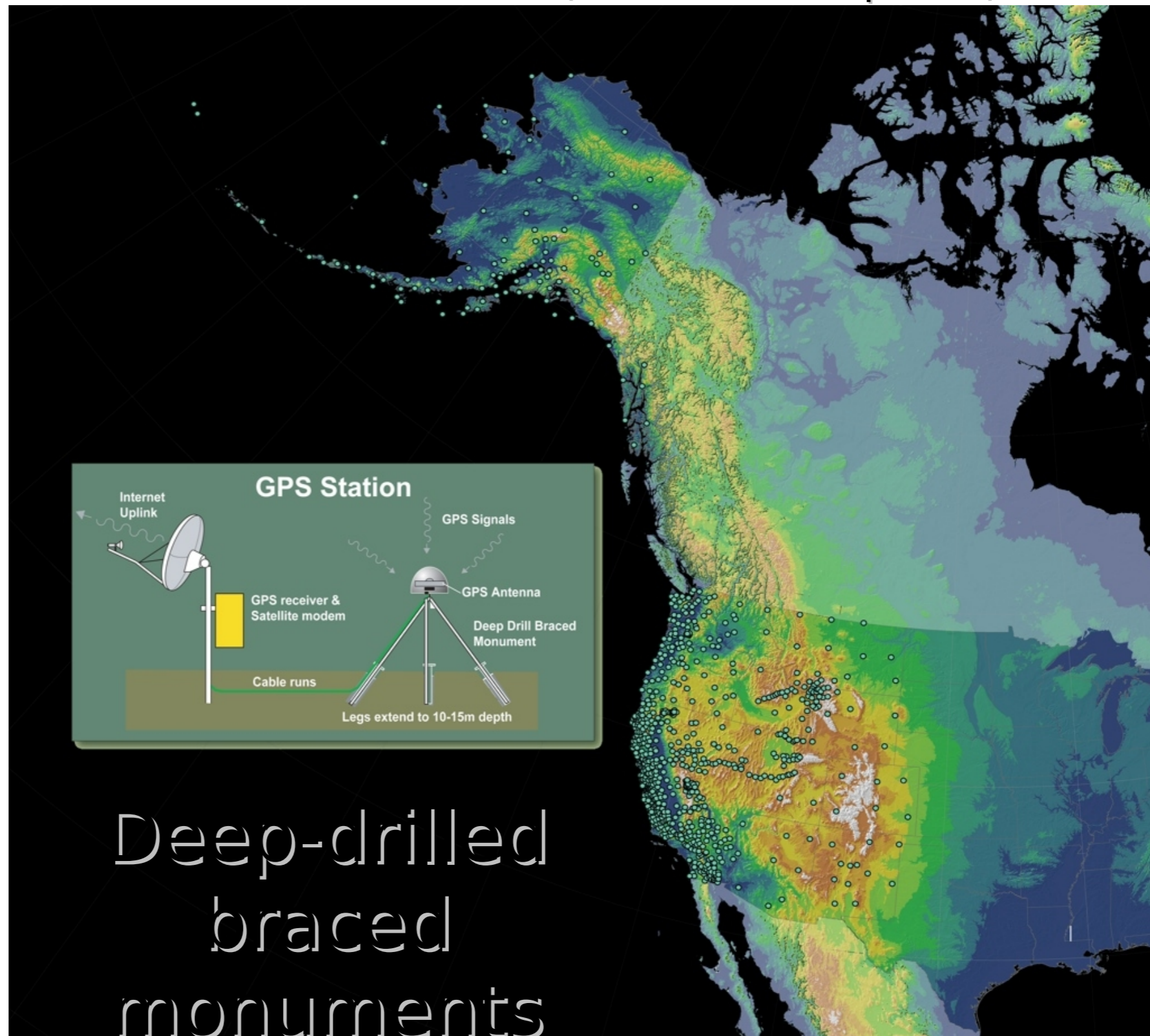
IGCP 565 Project Workshop 3, Reno, NV, Oct, 2010

UNAVCO

- Annual signals and longer term trends in GPS time series
- Hydrologic effects
 - Ground water Pumping
 - Surface loading and modeling

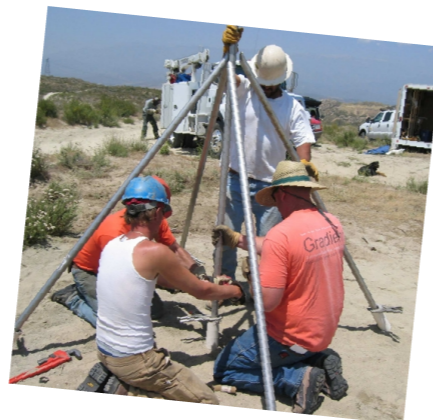


1100 continuous GPS Sites (100 with met packs)



Deep-drilled
braced
monuments

- **EarthScope** is funded by the National Science Foundation and conducted in partnership with the US Geological Survey.
- EarthScope** is operated and maintained as a collaborative effort with UNAVCO, Inc. and IRIS, with contributions from NASA and several other national and international organizations.
- **The Plate Boundary Observatory** is the geodetic component of EarthScope, installed and operated by UNAVCO and funded by the National Science Foundation.
- **The UNAVCO Facility** is supported by the National Science Foundation and NASA through a Cooperative Agreement.
- Additional thanks to students Andy Wahr, Alex Mayorga, and Elvin Mujcin who helped with the processing and analysis.



Signals of Geophysical Interest

- Earthquakes
- Volcanos
- Ocean and Atmospheric Loading
- Continental Water (surface, ground)
- Snow and Ice
- Glacial Isostatic Adjustment
- Tropospheric and Ionospheric Delays

Non-Geophysical Signals

- GPS Equipment Change, damage, or failure
- Antenna Phase Center Errors including radomes
- Survey Error (e.g. bad antenna height or metadata record)
- Multipath
- Snow and Ice on antenna
- Thermal Elastic (on ground or monument)
- Satellite Geometry (can't see through the earth)
- Human-induced pumping (out or back in)
- Very Local Monument Instability
 - actually this was the original point of our study, but to understand this you have to rule out or model all the above!

GPS Processing Service

GIPSY: Central Washington U.
 GAMIT: New Mexico Tech.
 Combination Solution: MIT
 Stable North American Reference Frame
 (SNARF2.0)

Daily Time series and periodic velocity solution products available from UNAVCO Data Center

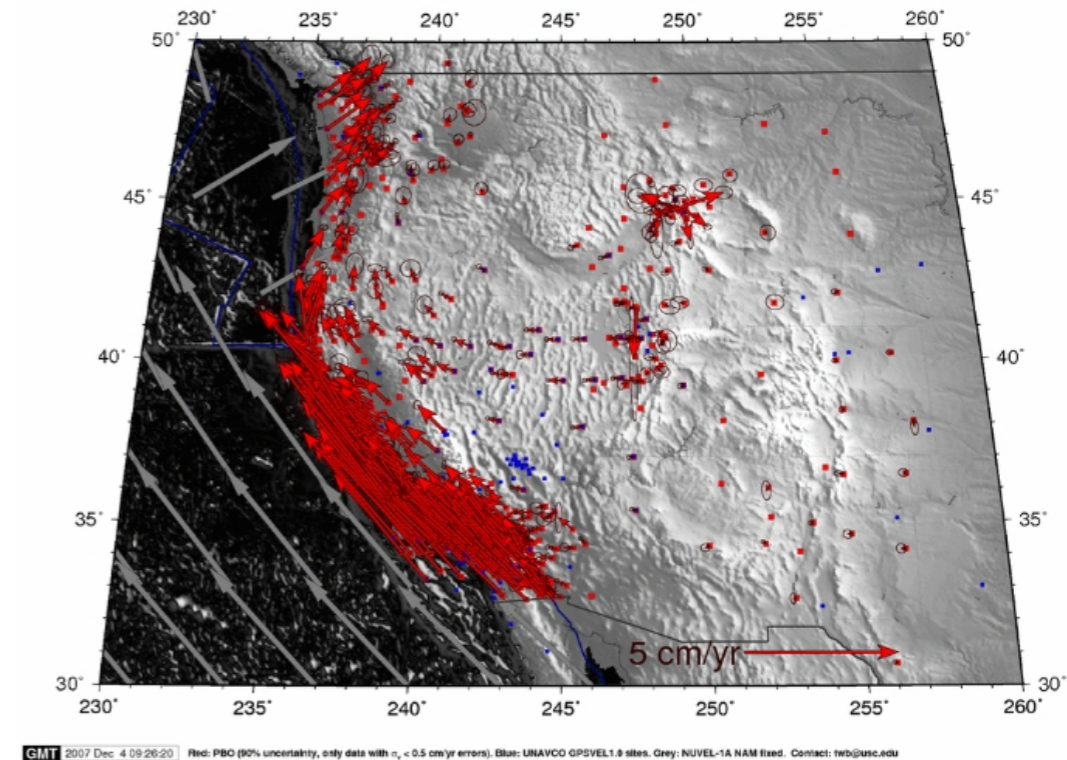
Time Series Analysis

Linear rate, annual, and semi-annual terms were fit to 450 sites that had long (>800 days of data). No Spatial Filtering was done. White and correlated noise were estimated but have not been analyzed yet. Data were screened to exclude (for now) data sets that were “contaminated” by large gaps, earthquakes, volcanoes etc.

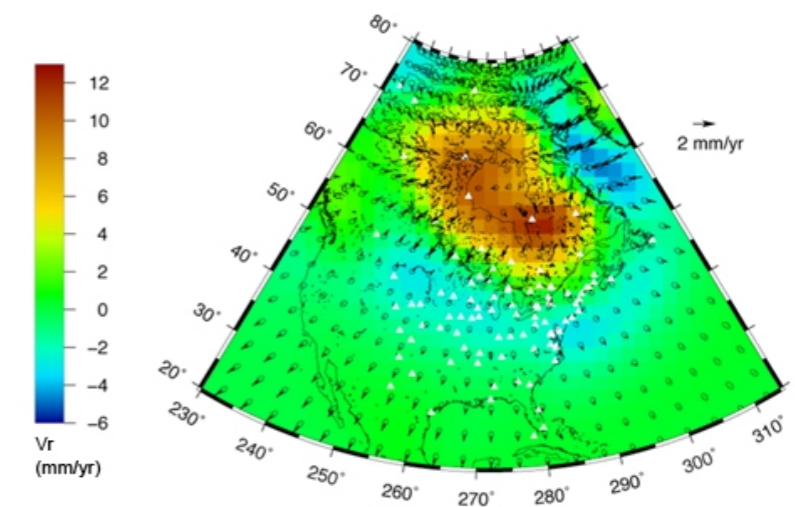
Analysis Software available on John Langbein's website

PBO MIT GPS velocities

Release date: 2006-09-21 (20060921163224)



SNARF

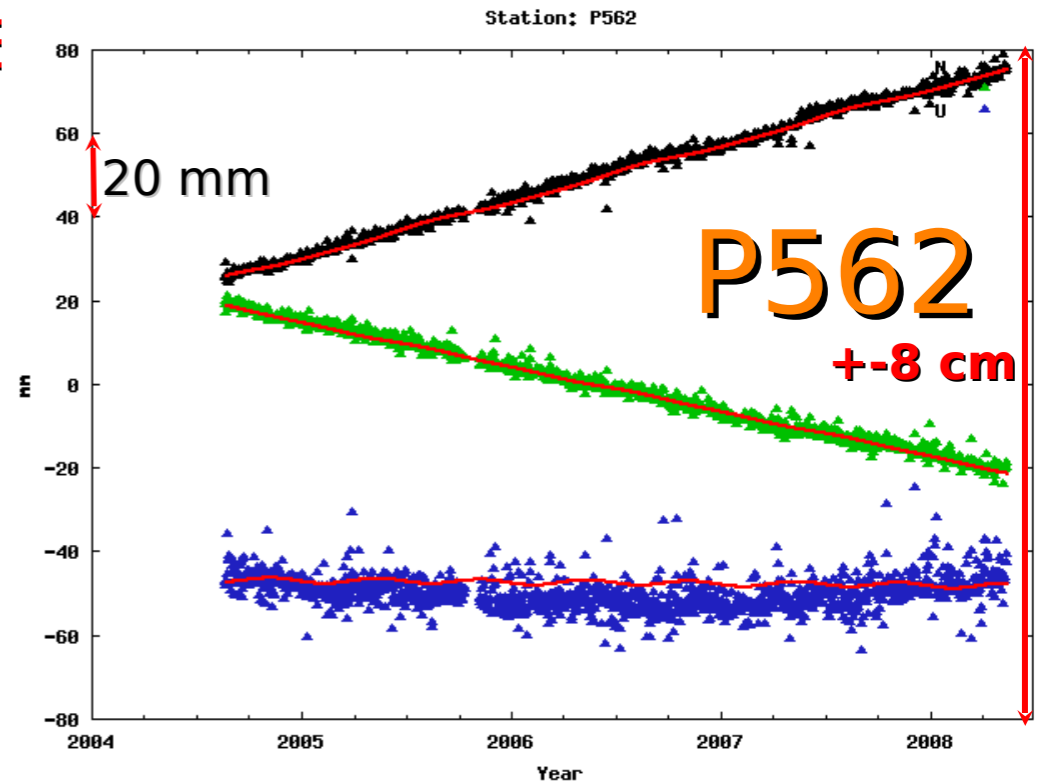


Example Small Annual Vertical Signal

P562 Short-drilled braced (Annual Vertical **0.3 mm**)

Mojave Desert, Calif

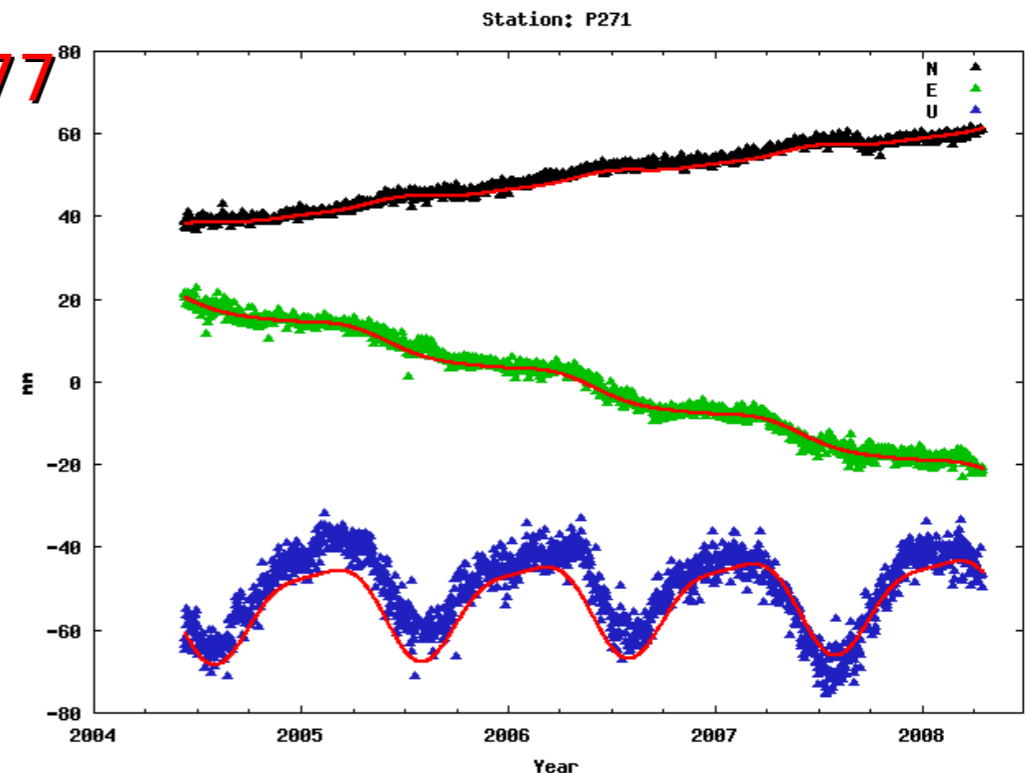
Plots show:
North, East, Vertical
components (top to
bottom)
Red lines show fit to
time series

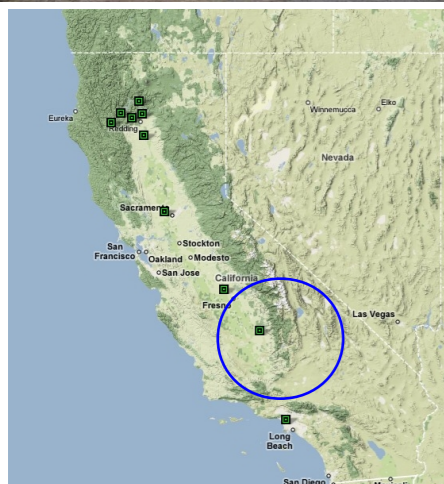
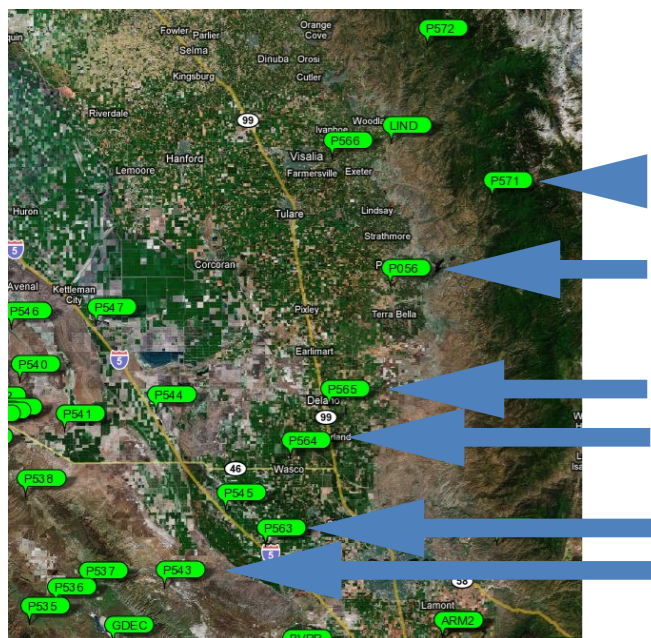


Example Large Annual Vertical Signal

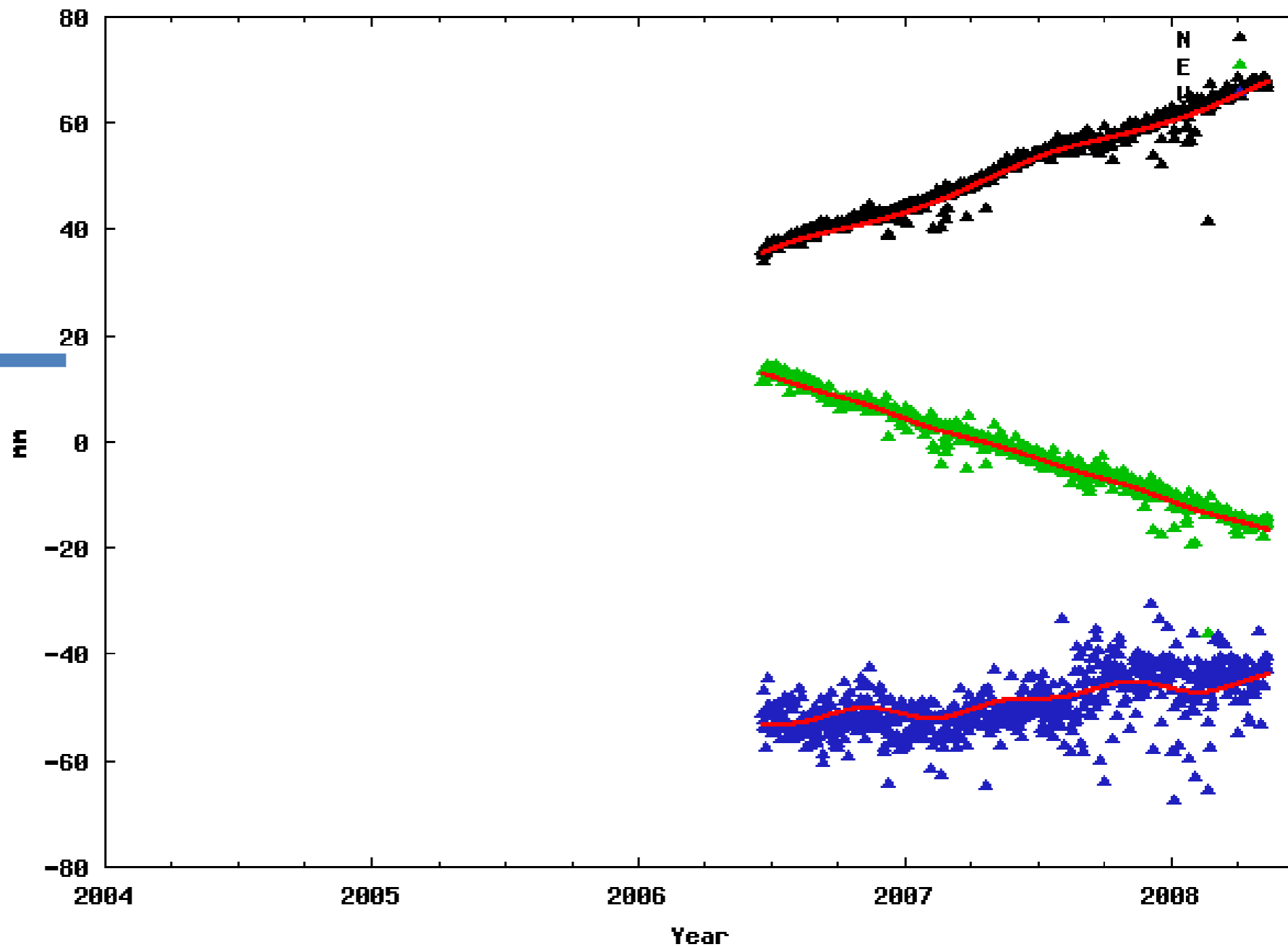
P271 Deep-drilled braced (Annual Vertical **10.77 mm**)

Sacramento, Calif.

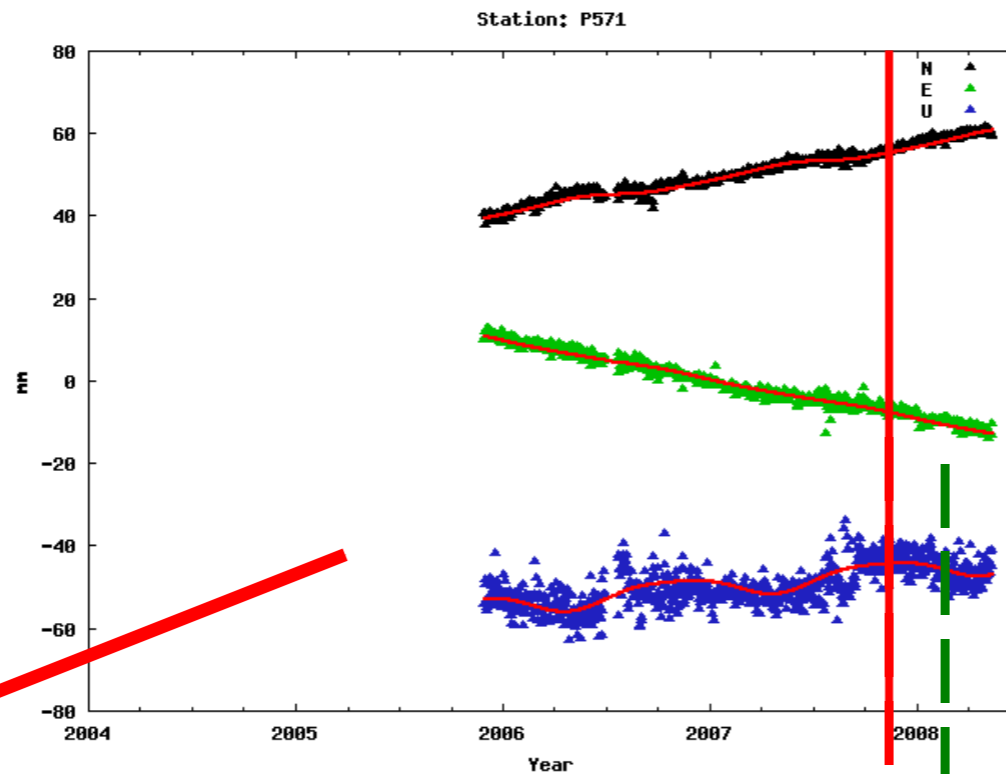




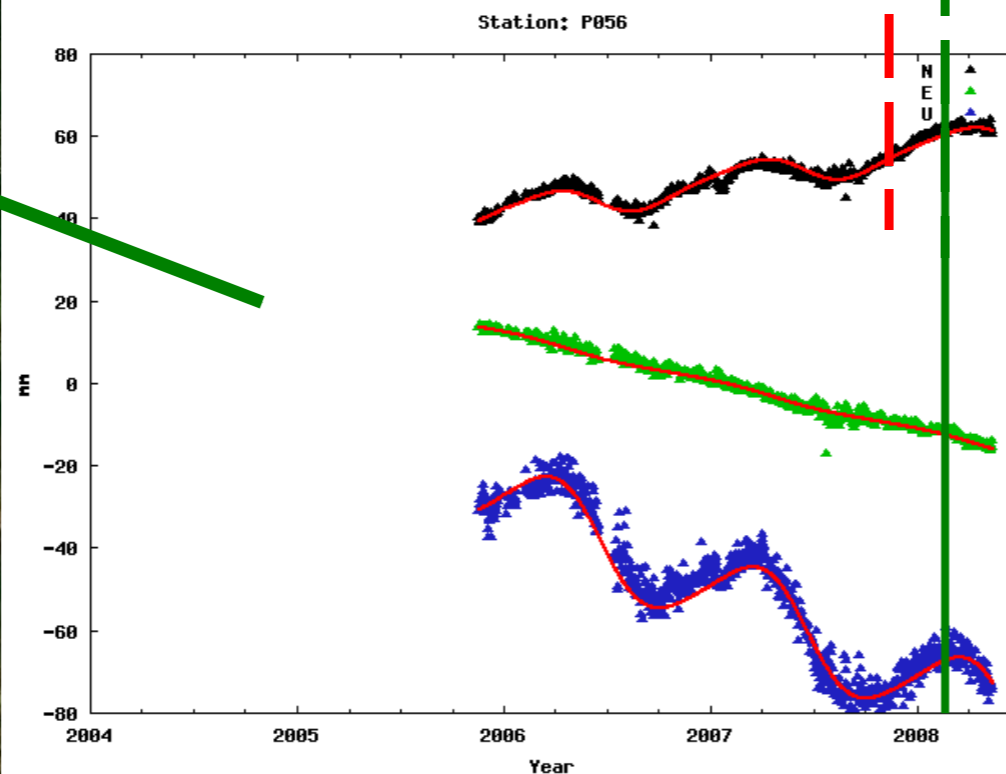
Station: P543



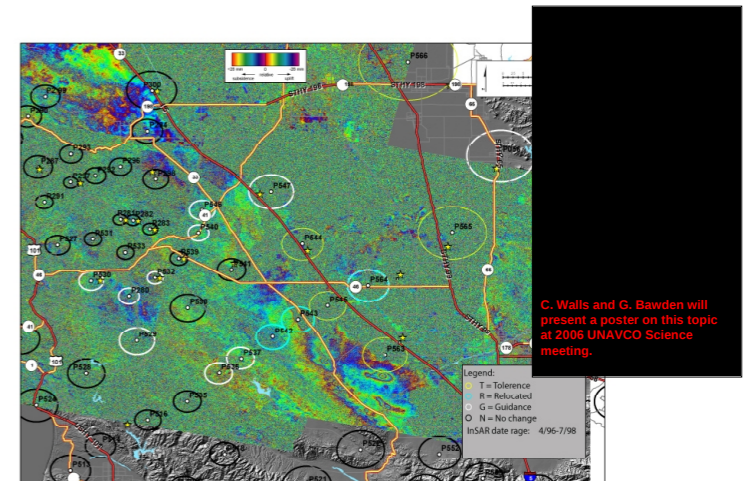
Southern San Joaquin Valley, California



- P571 Bedrock site in Sierra Nevada Foothills
- Shows secular uplift (~5 mm/yr)
- Annual Cycle peaks in October

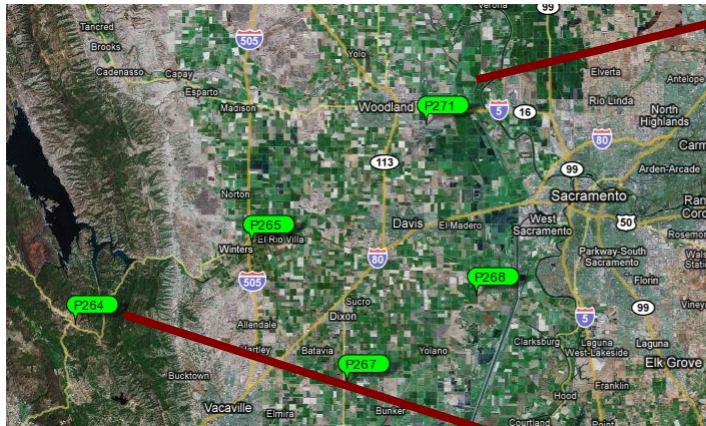


- P056 Site in Sediments in San Joaquin Valley
- Shows rapid secular subsidence rate (~30 mm/yr)
- Annual Cycle peaks in April

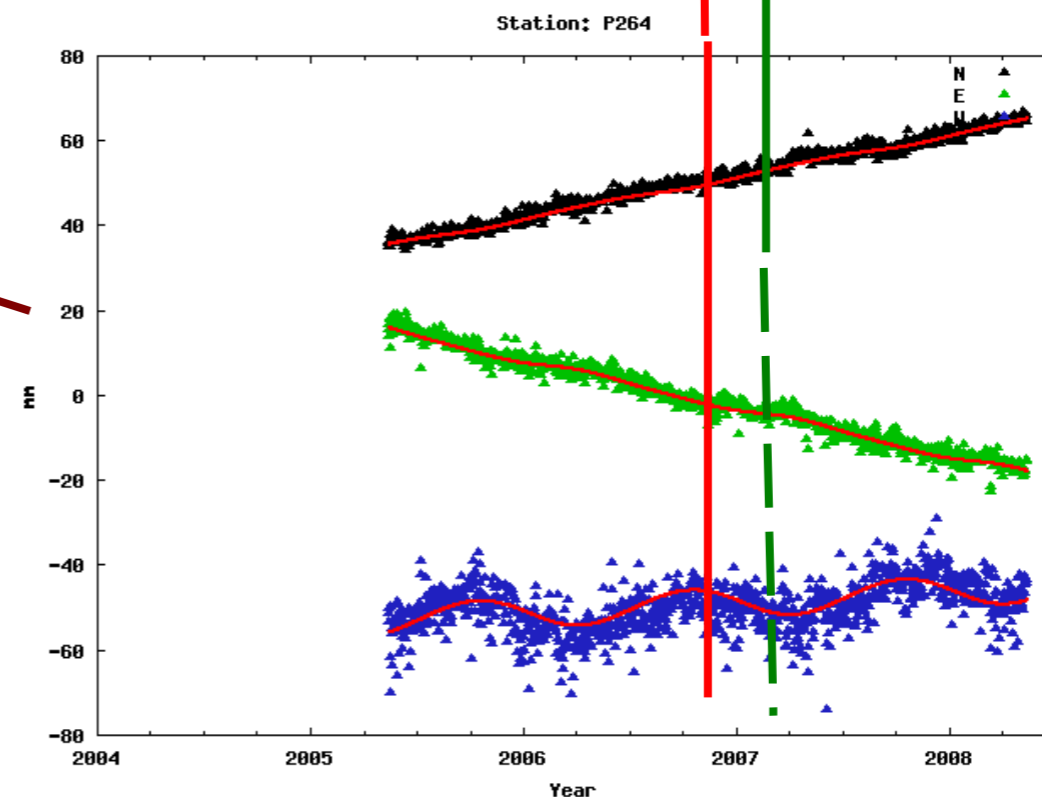
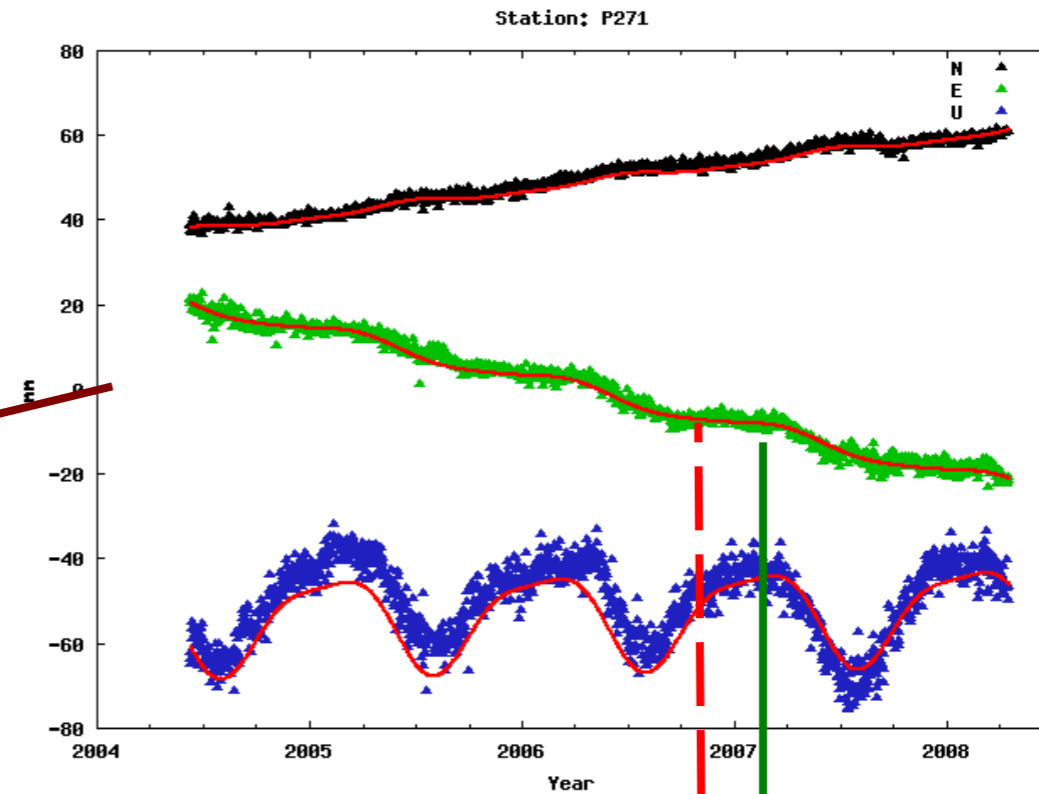


G. Walls and G. Bawden will present a poster on this topic at 2006 UNAVCO Science meeting.

Deep-drilled braced in sediments in valley show peak of annual signal in March. No overall secular trend at this site

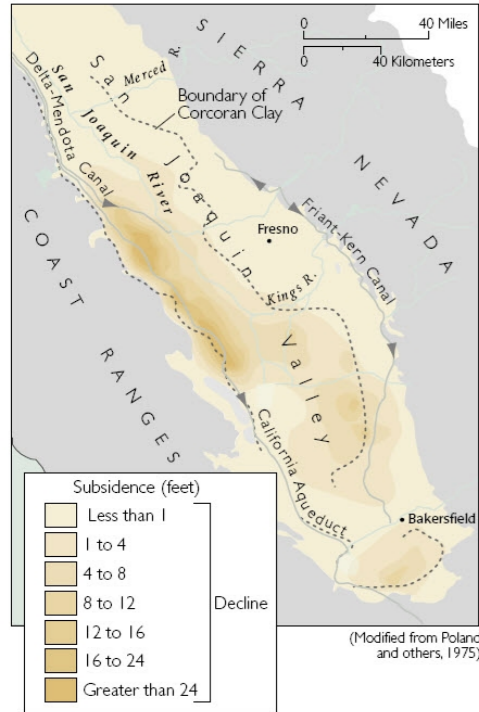


Shallow-drilled braced in bedrock in foothills. As with other foothill sites around the Central Valley peak annual signal in October. Small secular uplift trend.

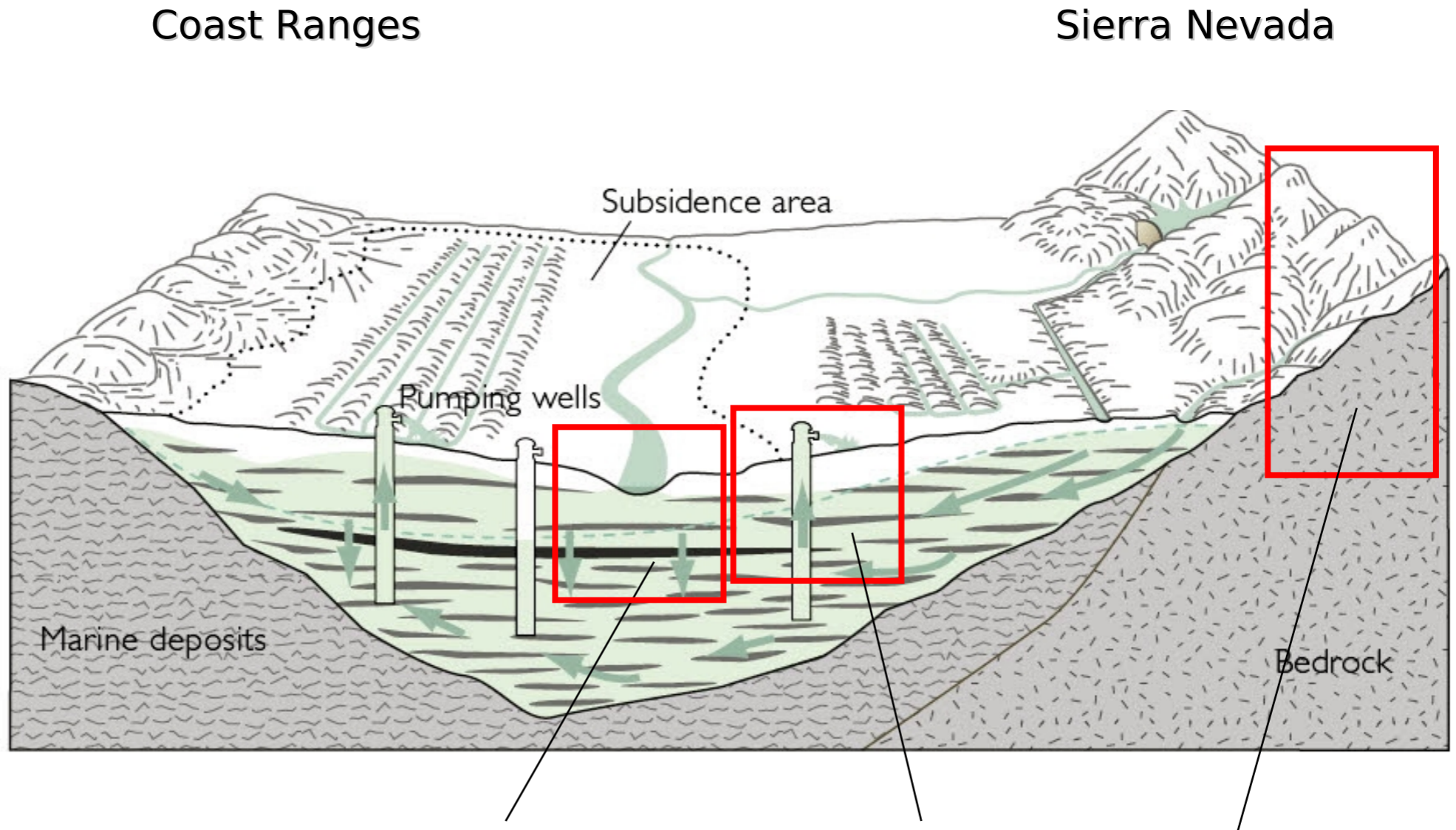


Hydrologic Effects in the San Joaquin Valley, California

Land subsidence from 1926 to 1970



(Modified from Poland and others, 1975)



Broad Subsidence

Localized Subsidence
From rapid pumping

Surface loading
from water
contained in soil
and fractures,
snow, and
reservoirs and
lakes

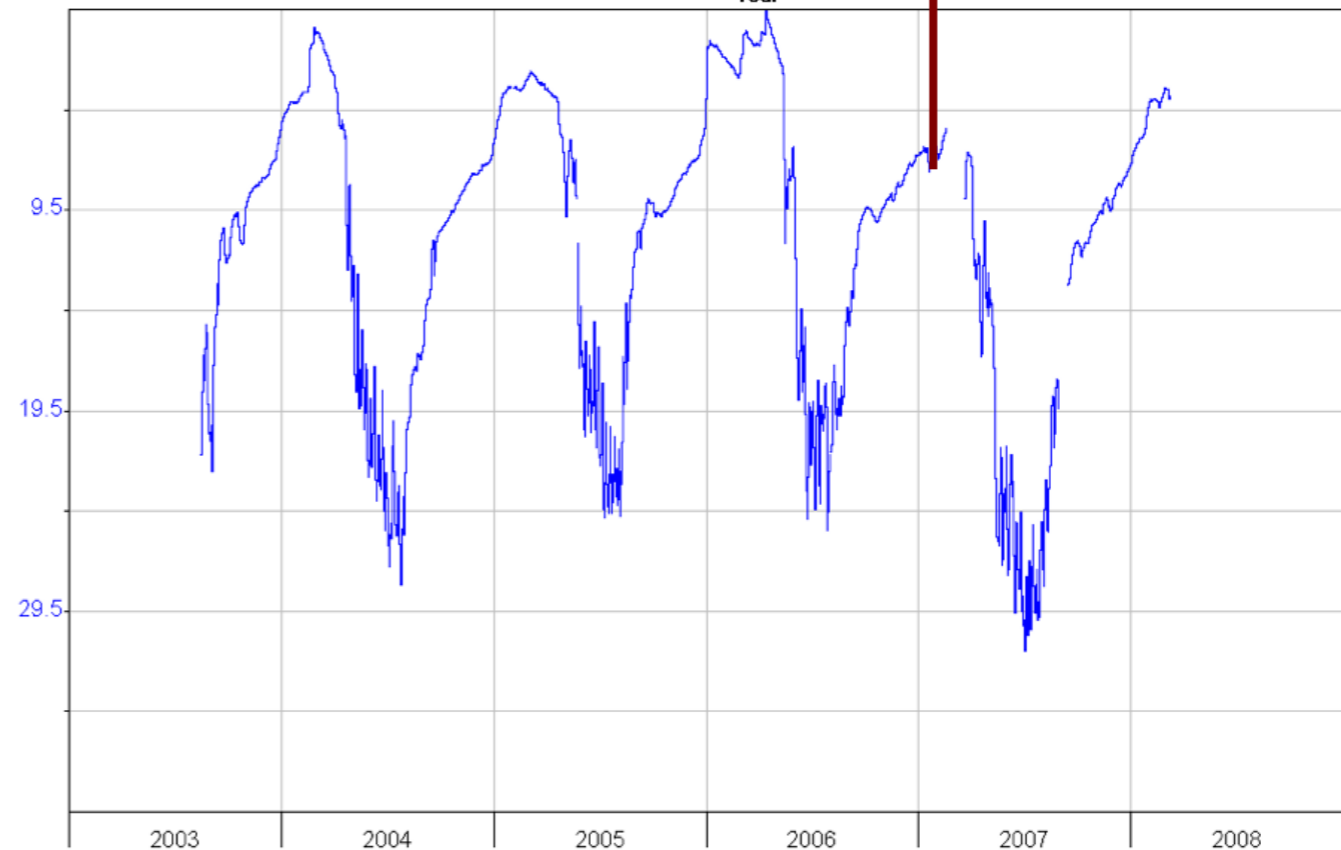
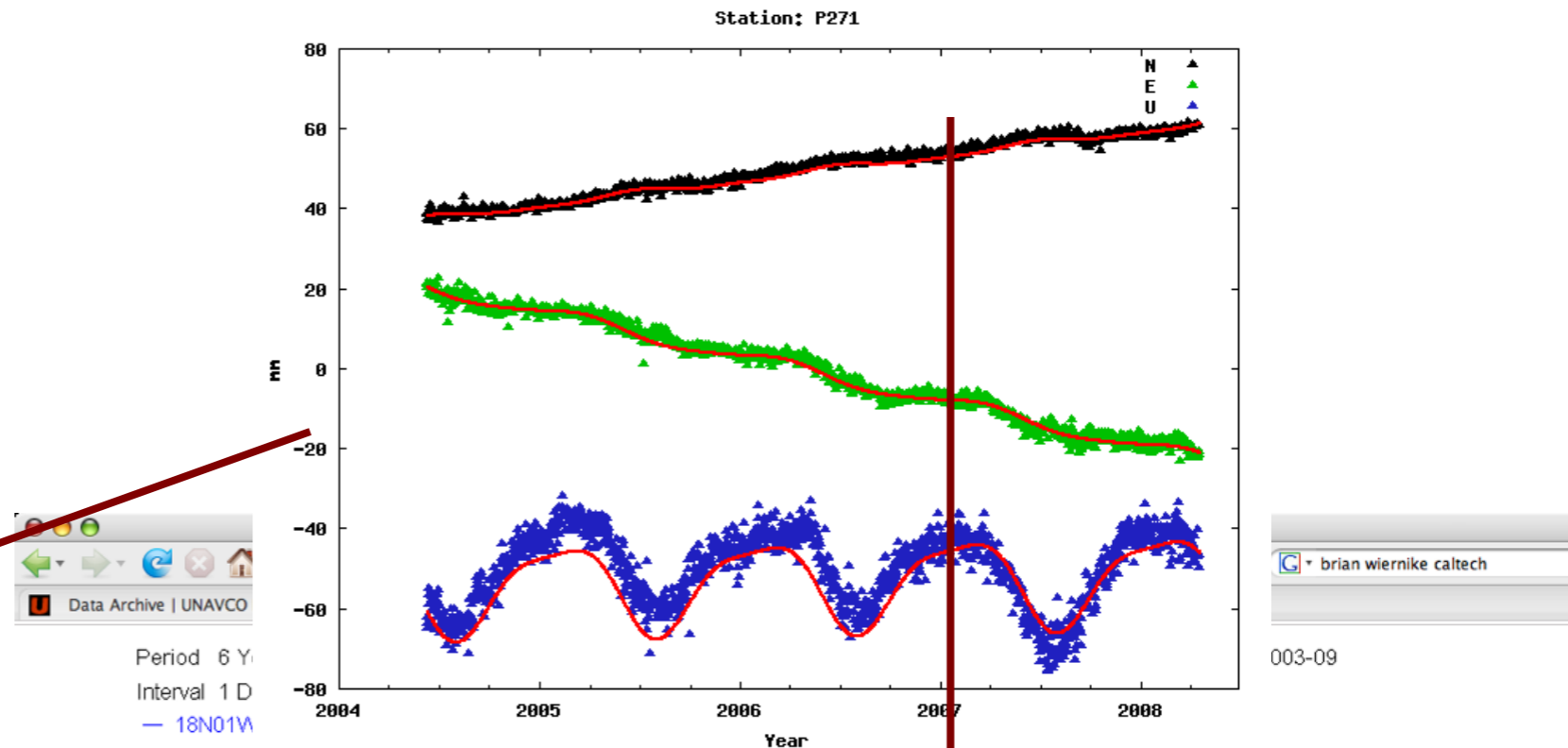
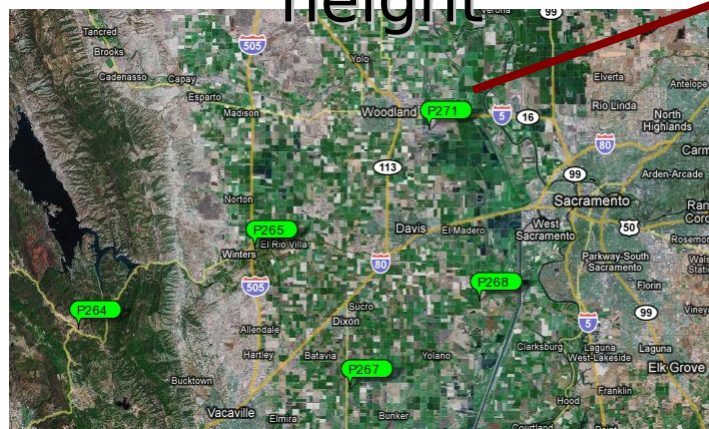


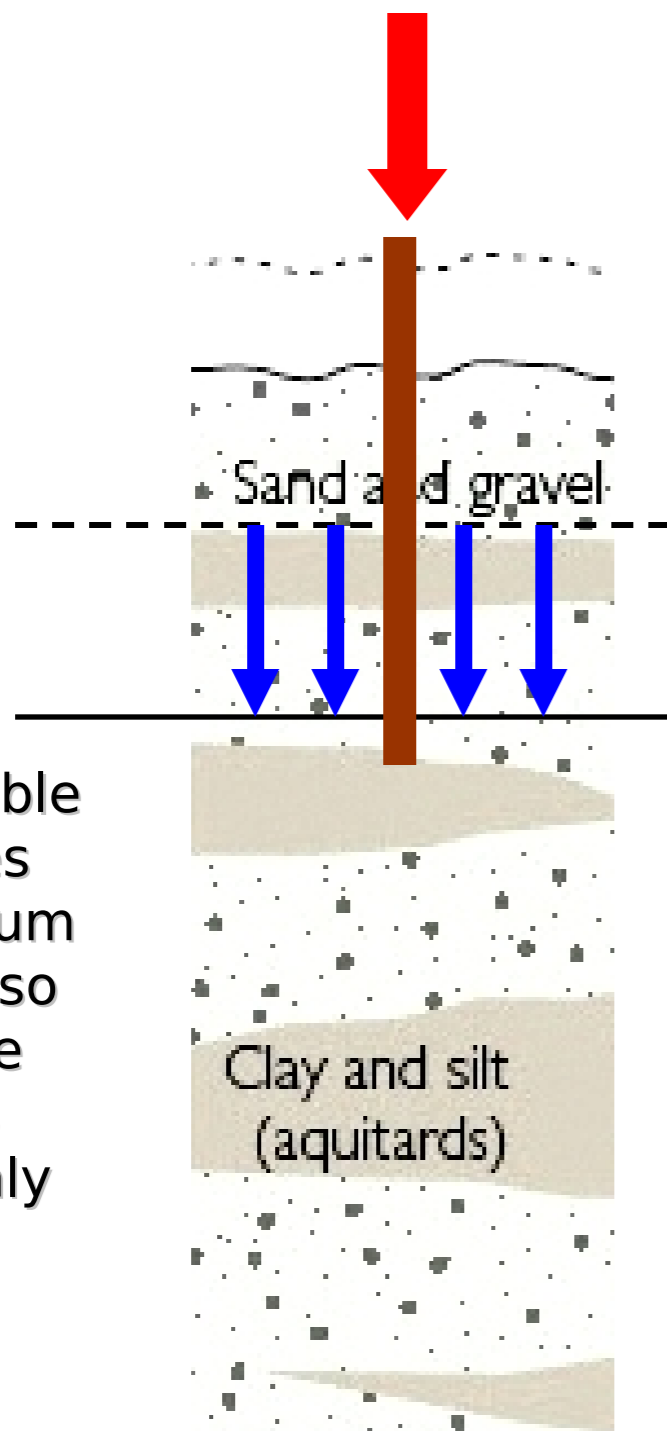
Land Subsidence in the United States by Devin Galloway, David R. Jones, and S.E. Ingebritsen

<http://pubs.usgs.gov/circ/circ1182/pdf/>

Deep-drilled braced in sediments in valley near Sacramento, Calif.

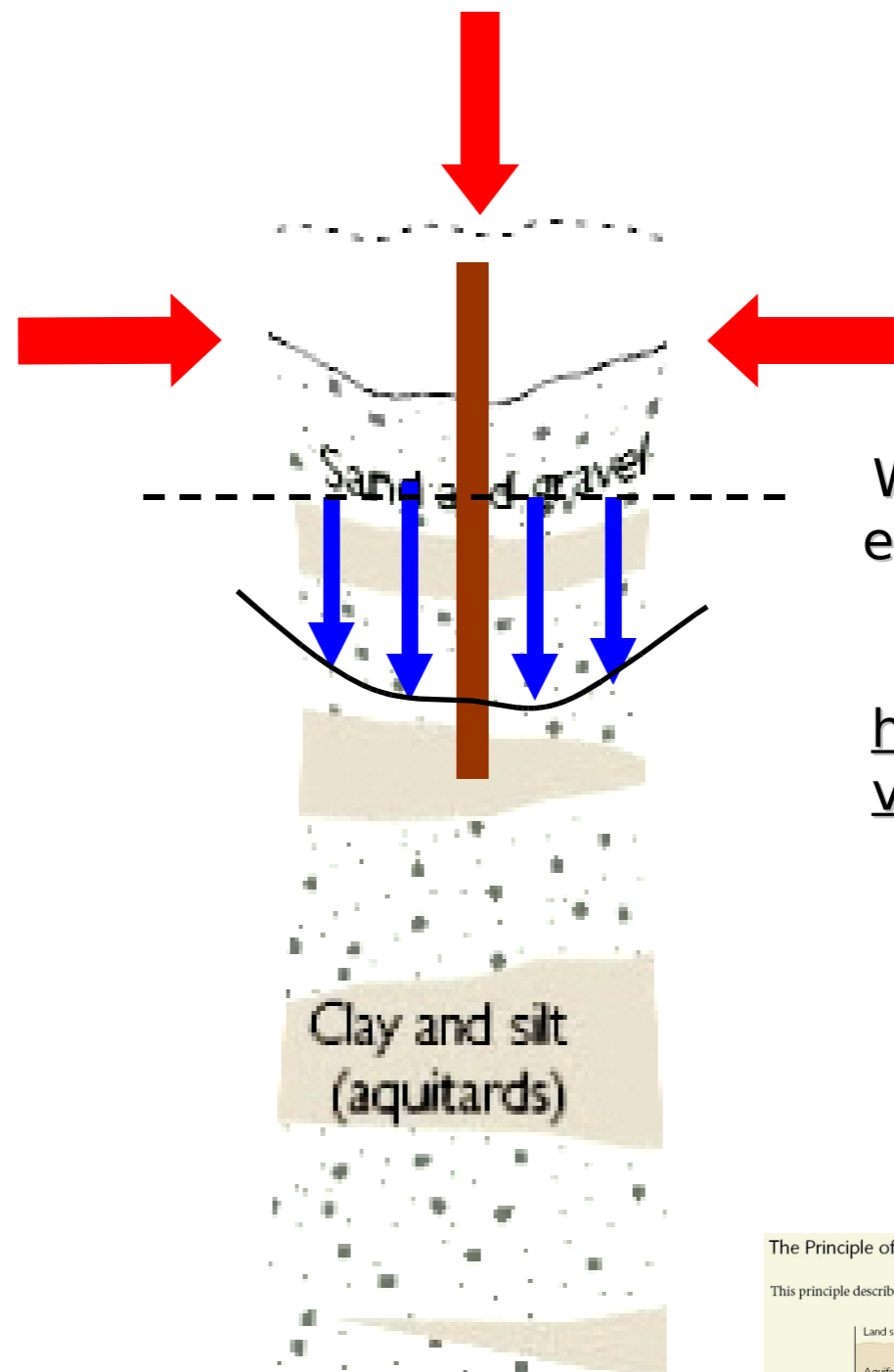
The peak of the annual signal is in March-April and is in phase with water table height





Water table reaches equilibrium quickly so surface drops uniformly

Slow pumping or natural water table fluctuations

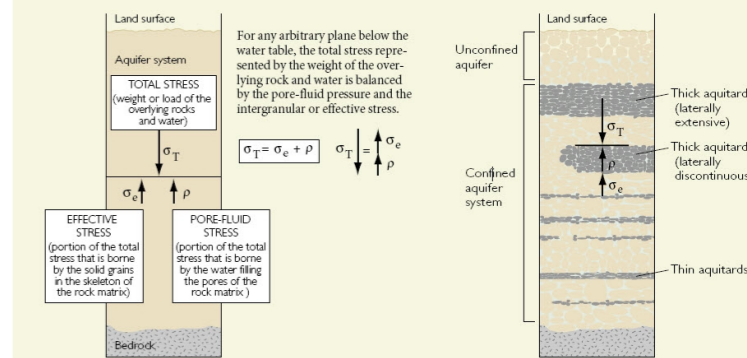


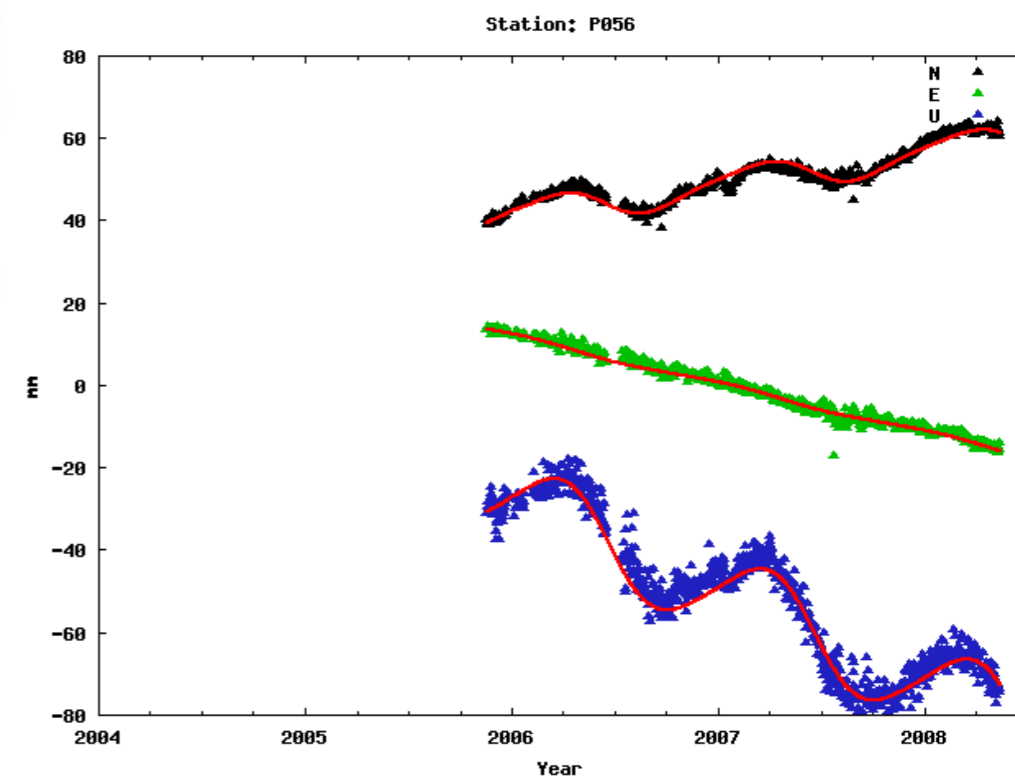
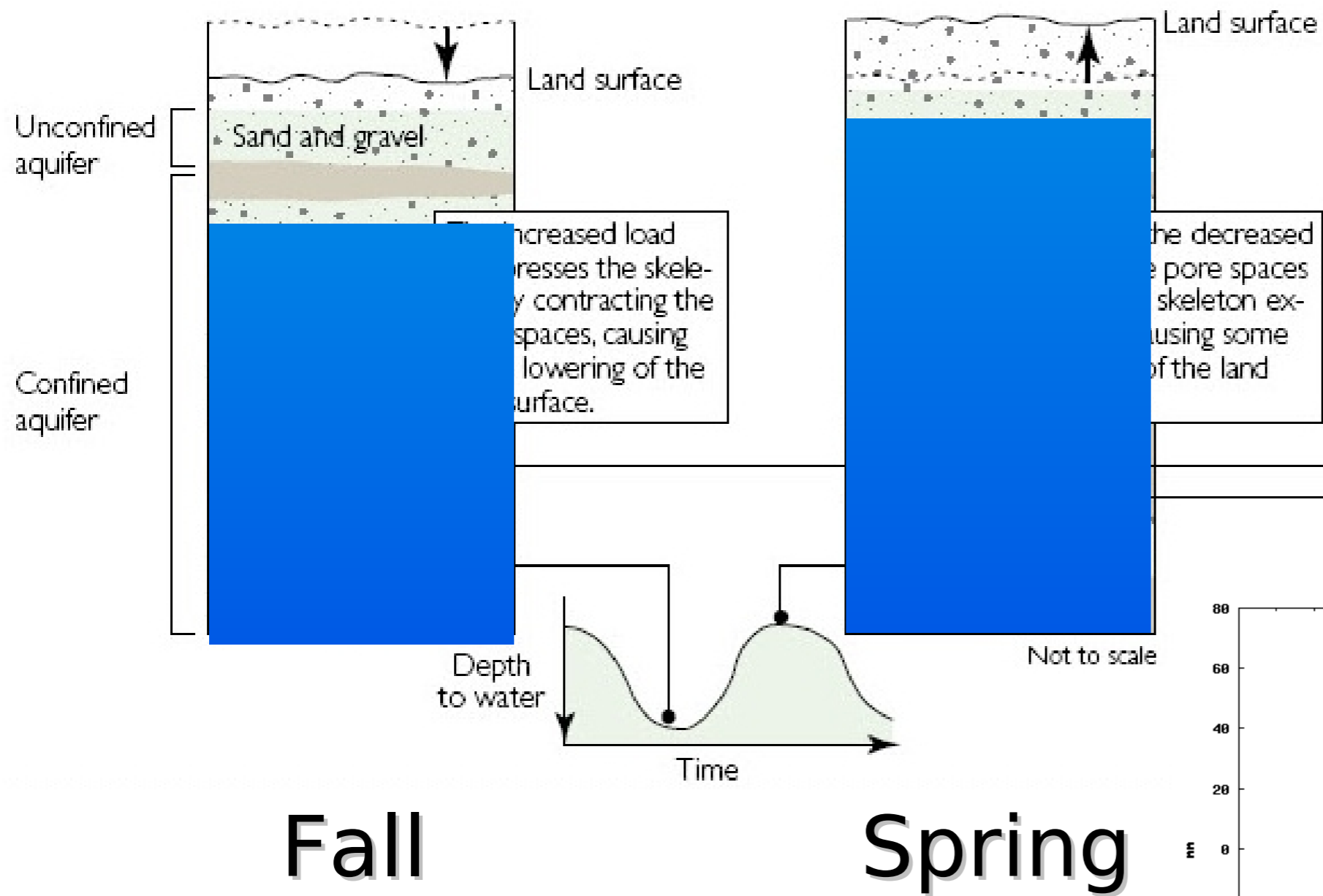
Water table reaches equilibrium slowly so surface drops non-uniformly causing horizontal as well as vertical deformation

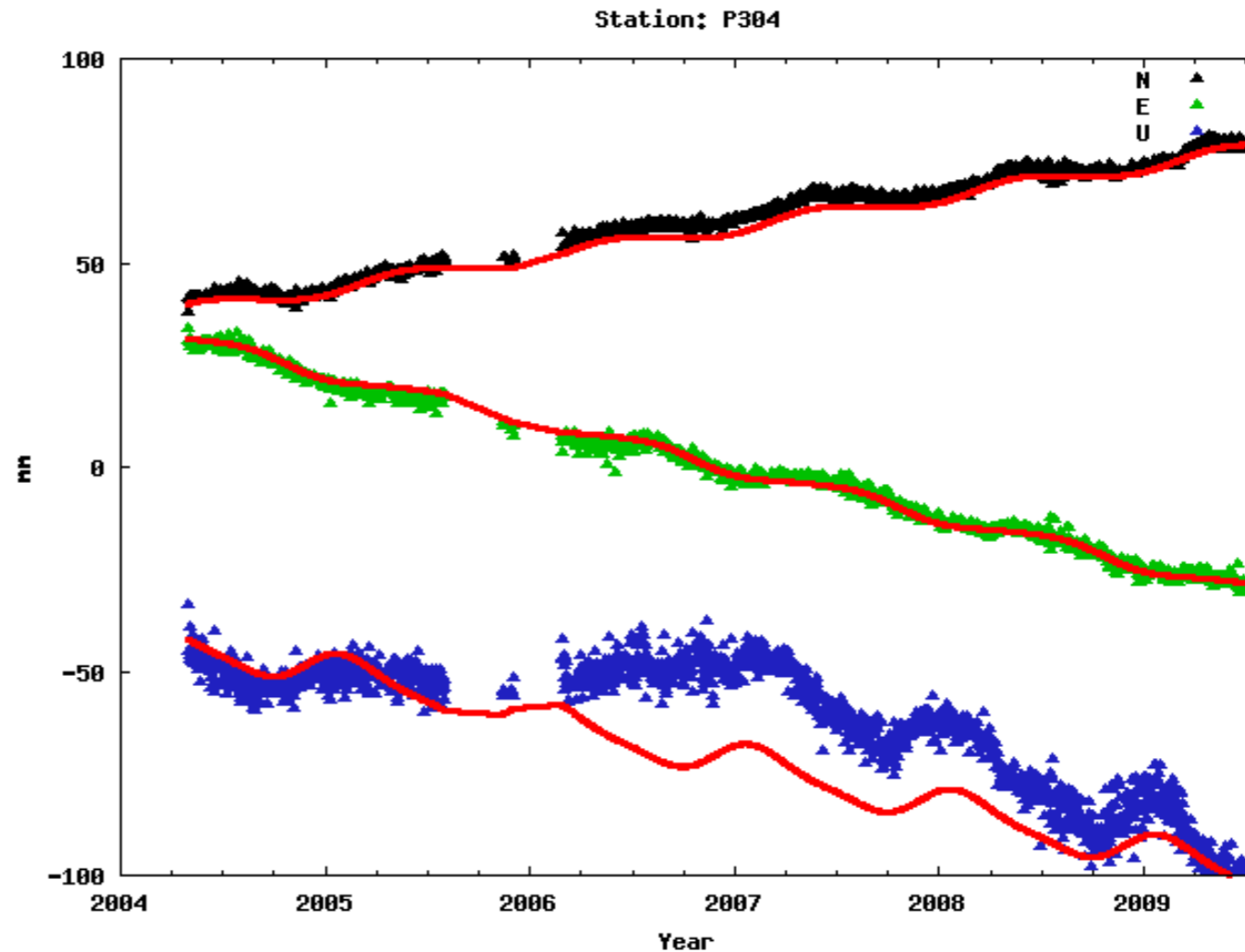
Rapid pumping

The Principle of Effective Stress

This principle describes the relation between changes in water levels and deformation of the aquifer system.

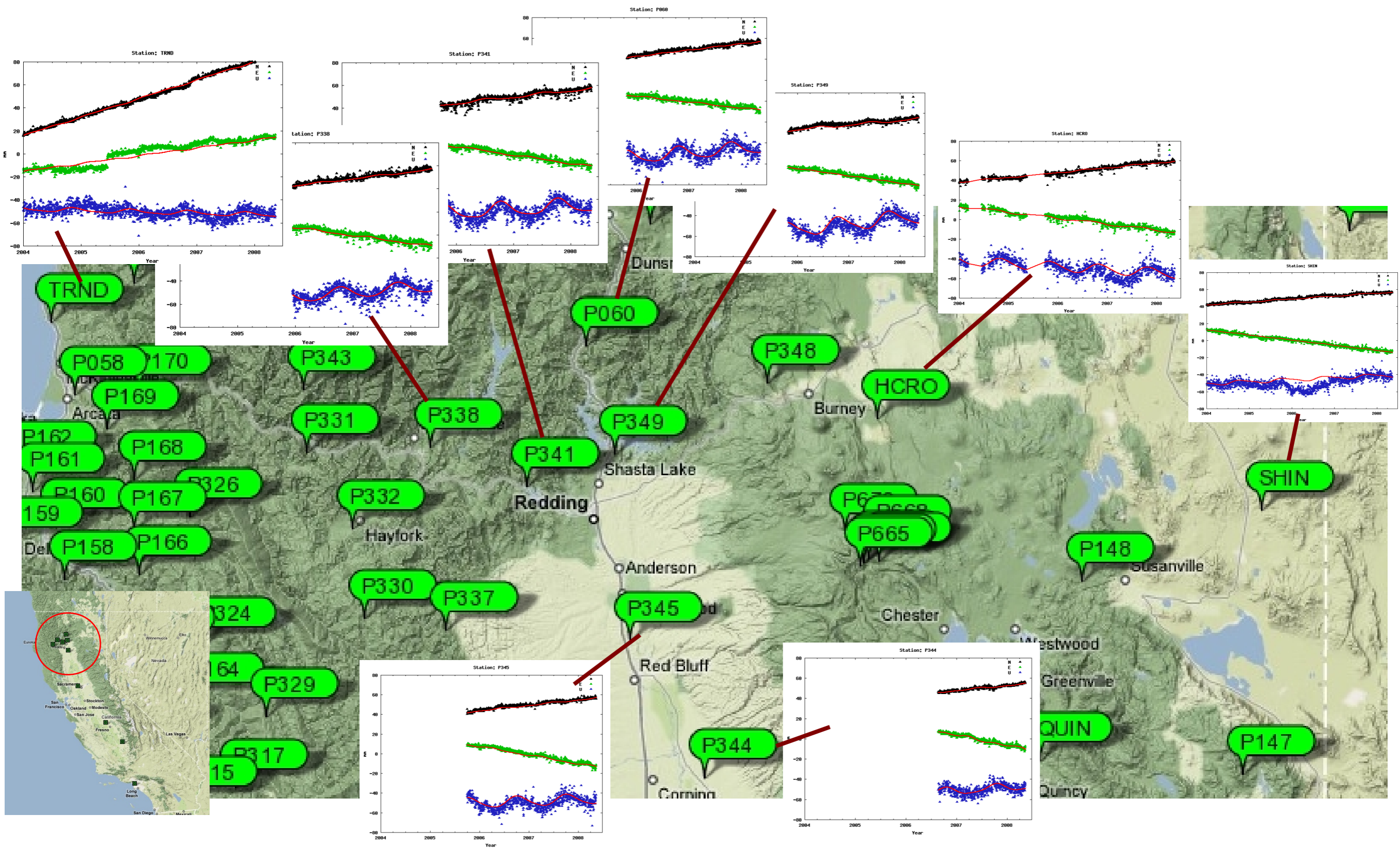


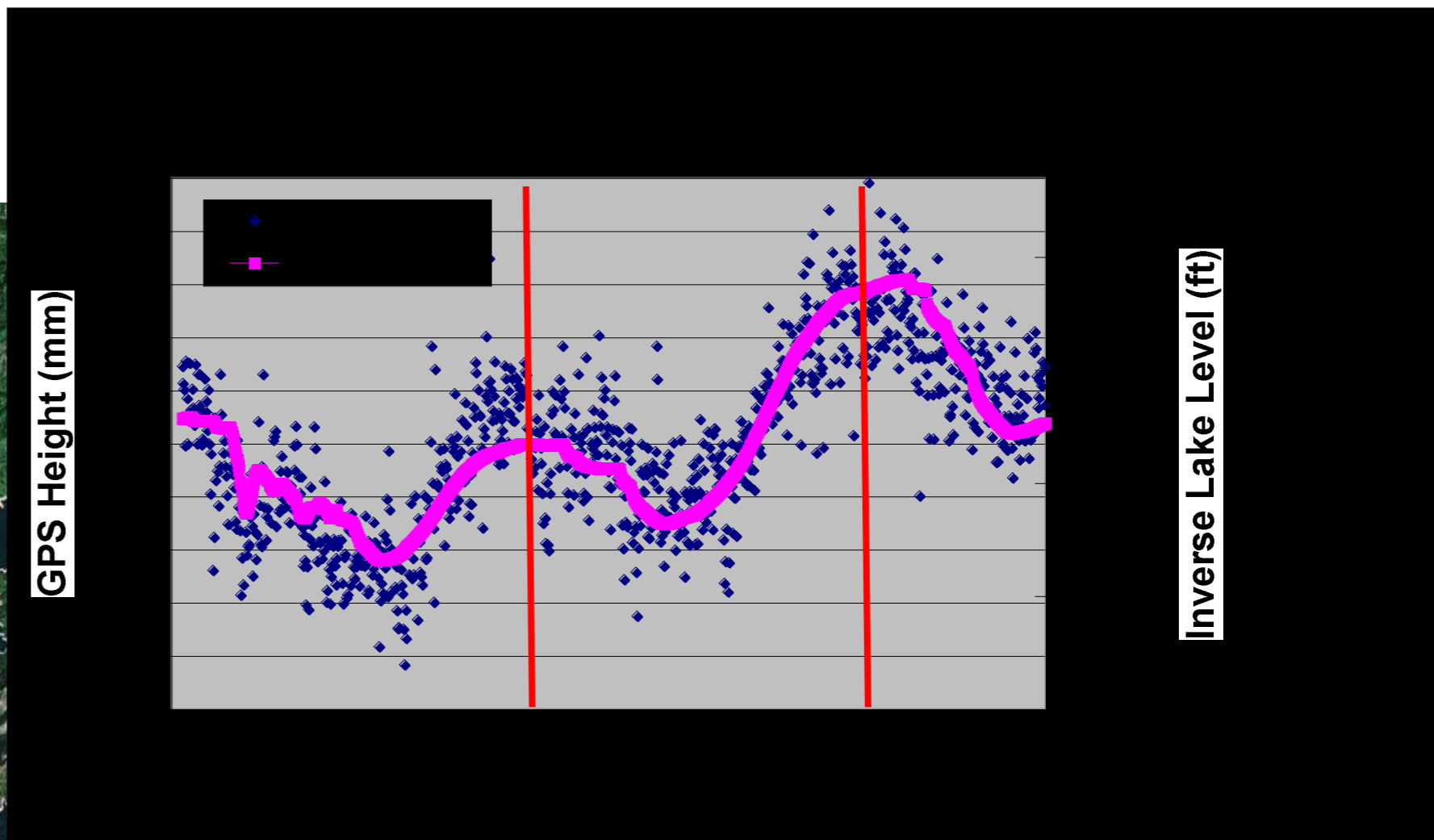




PBO GPS station P304 near Mendota. A clear annual pumping signal is evident as is the beginning of longer term subsidence in 2007 possibly due to increased need for irrigation water due to the drought. Currently demand exceeds recharge resulting in about 2 cm/yr of net subsidence. Note that historical rates exceeded 50 cm/yr of subsidence!

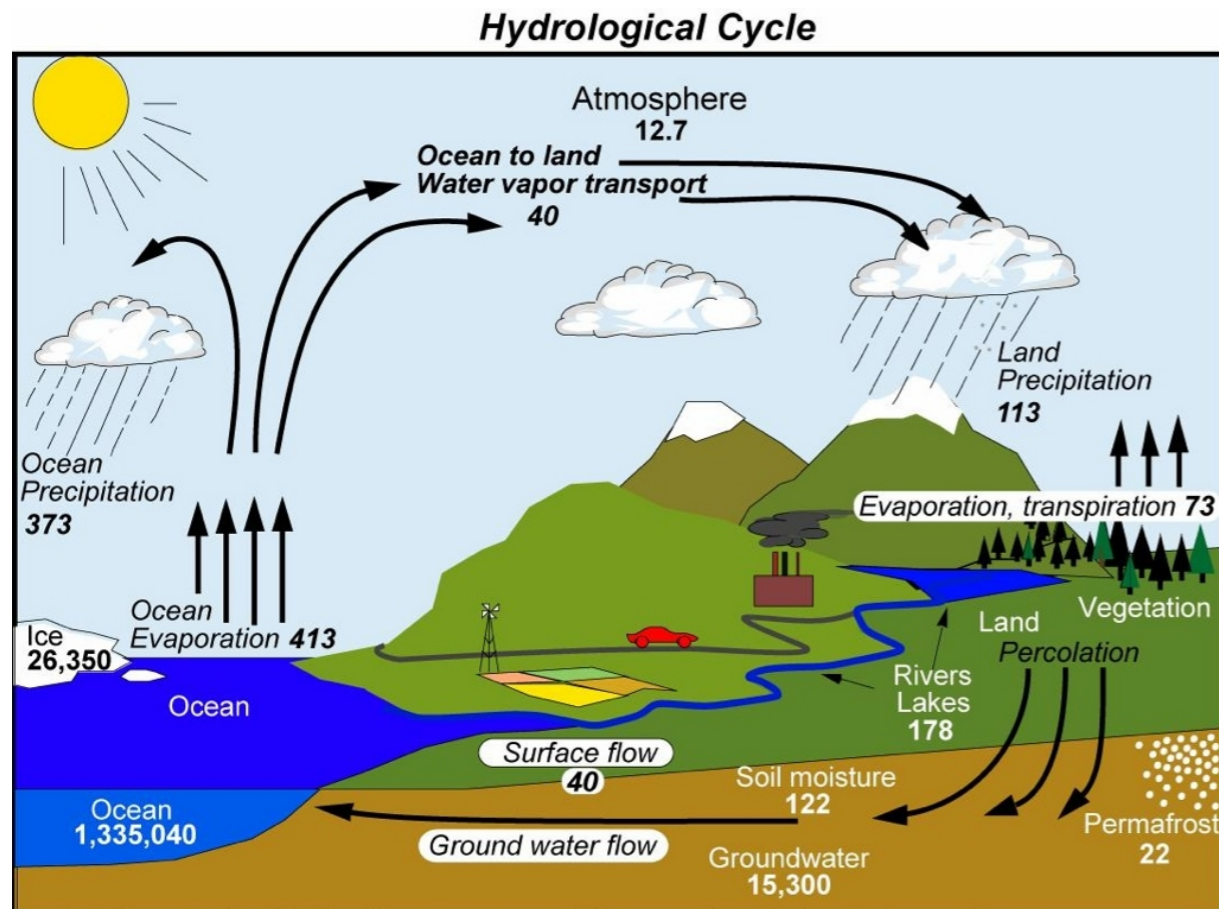






□ Peak uplift late October when lake level is lowest (opposite of when water table typically is lowest)

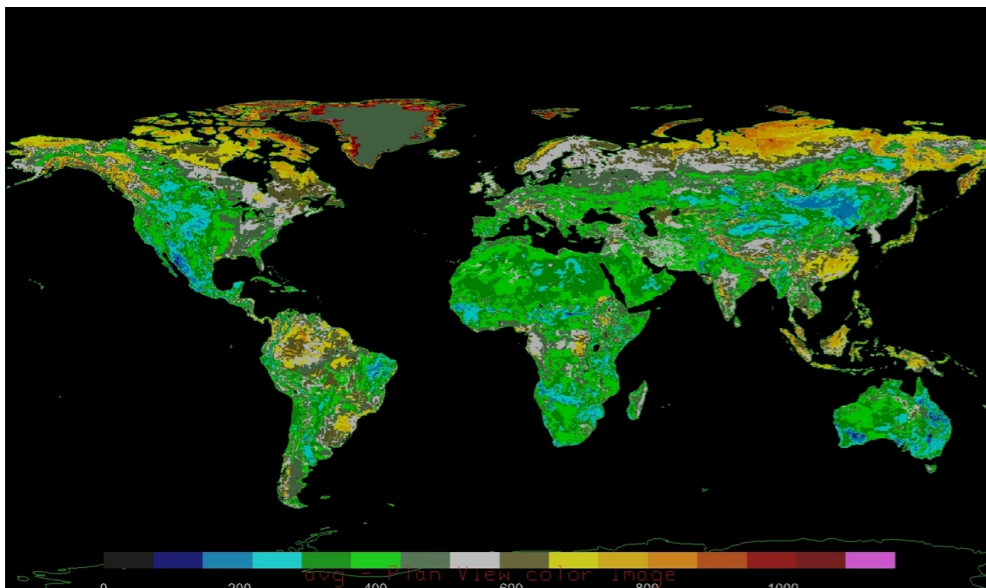
□ California Dept. of Water Resources water level data



Units: Thousand cubic km for storage, and *thousand cubic km/yr* for exchanges

<http://www.ucar.edu/news/people/Dai/hydrocycle.jpg>

- ❑ Two types of hydrologic models were used to estimate global water storage change time series - the Global Land Data Assimilation System (GLDAS) and NCEP "Leaky Bucket" models.
- ❑ The Leaky Bucket model is comparatively simpler than the GLDAS and employs a single soil layer, with surface precipitation and temperature observations as input providing evaporation, streamflow divergence, groundwater loss, and soil moisture as output

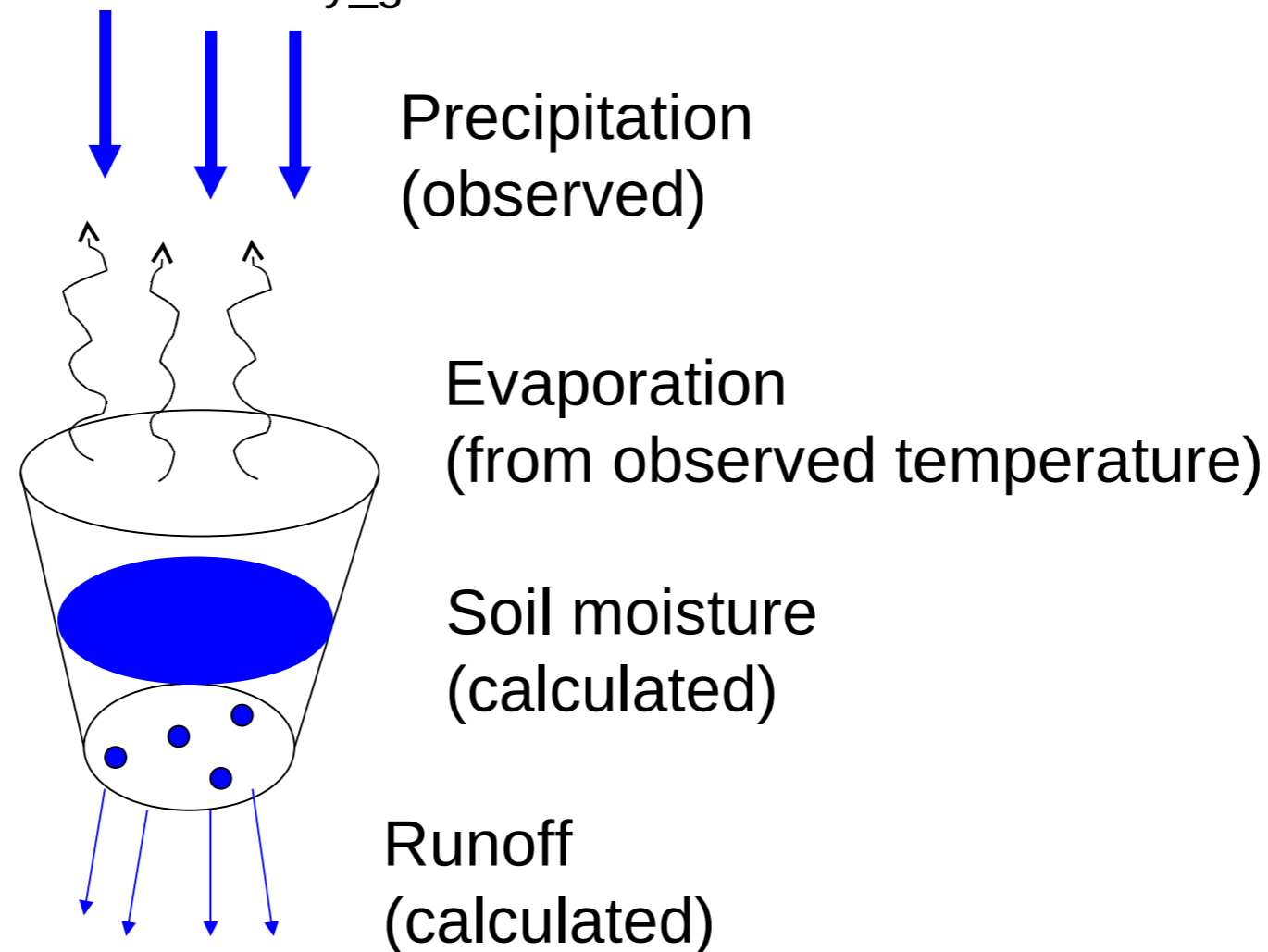


GLDAS/NOAH LAND-SURFACE MODEL (LSM) Global Hydrologic Storage (mm H₂O)

National Weather Service Climate Prediction Center Leaky Bucket Model

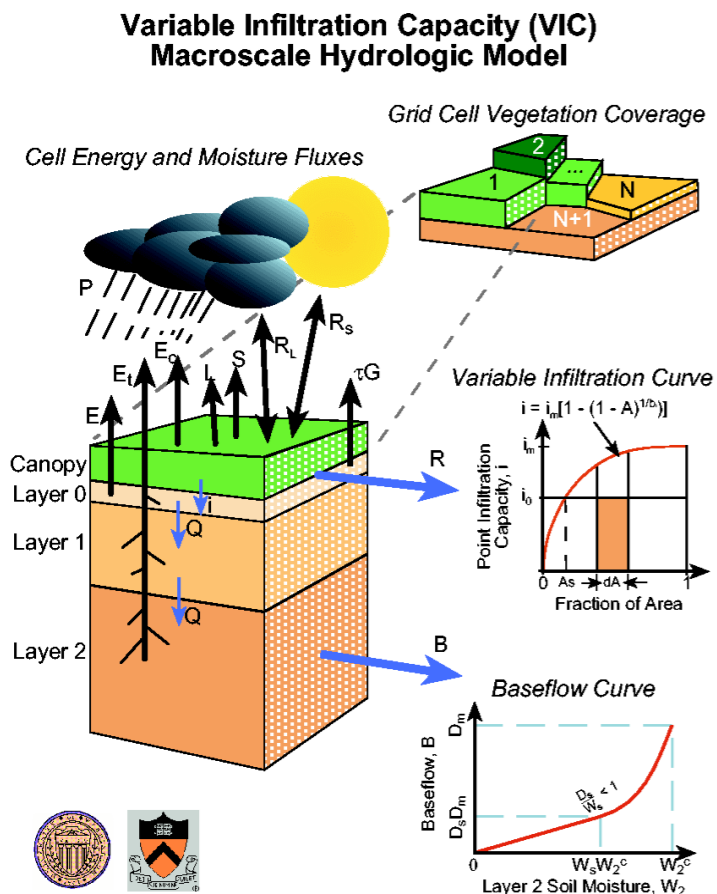
Soil moisture is estimated by a one-layer hydrological model (Huang et al., 1996; van den Dool et al, 2003) and is calculated based on the water balance in the soil. The model takes observed precipitation and temperature (from 15,000 ground stations) and calculates soil moisture, evaporation and runoff. The potential evaporation is estimated from observed temperature. The effective holding capacity for "leaky" bucket model is 760 mm water in 1.6 meter column soil (model depth) at a porosity of 0.47. Extra water will be lost to ground. The grid spacing is 0.5 degree.

http://www.cpc.noaa.gov/soilmst/leaky_glb.htm



Global Land Data Assimilation System (GLDAS)

GLDAS ingests satellite- and ground-based observational data products, using advanced land surface modeling and data assimilation techniques, in order to generate optimal fields of land surface states (e.g. soil moisture and temperature) and fluxes (e.g. evaporation, snow melt..) Rodell et al., 2004a. The grid spacing is 2.5 to 0.25 degrees depending on models. <http://ldas.gsfc.nasa.gov/GLDAS/docs/GLDASgoals.shtml>



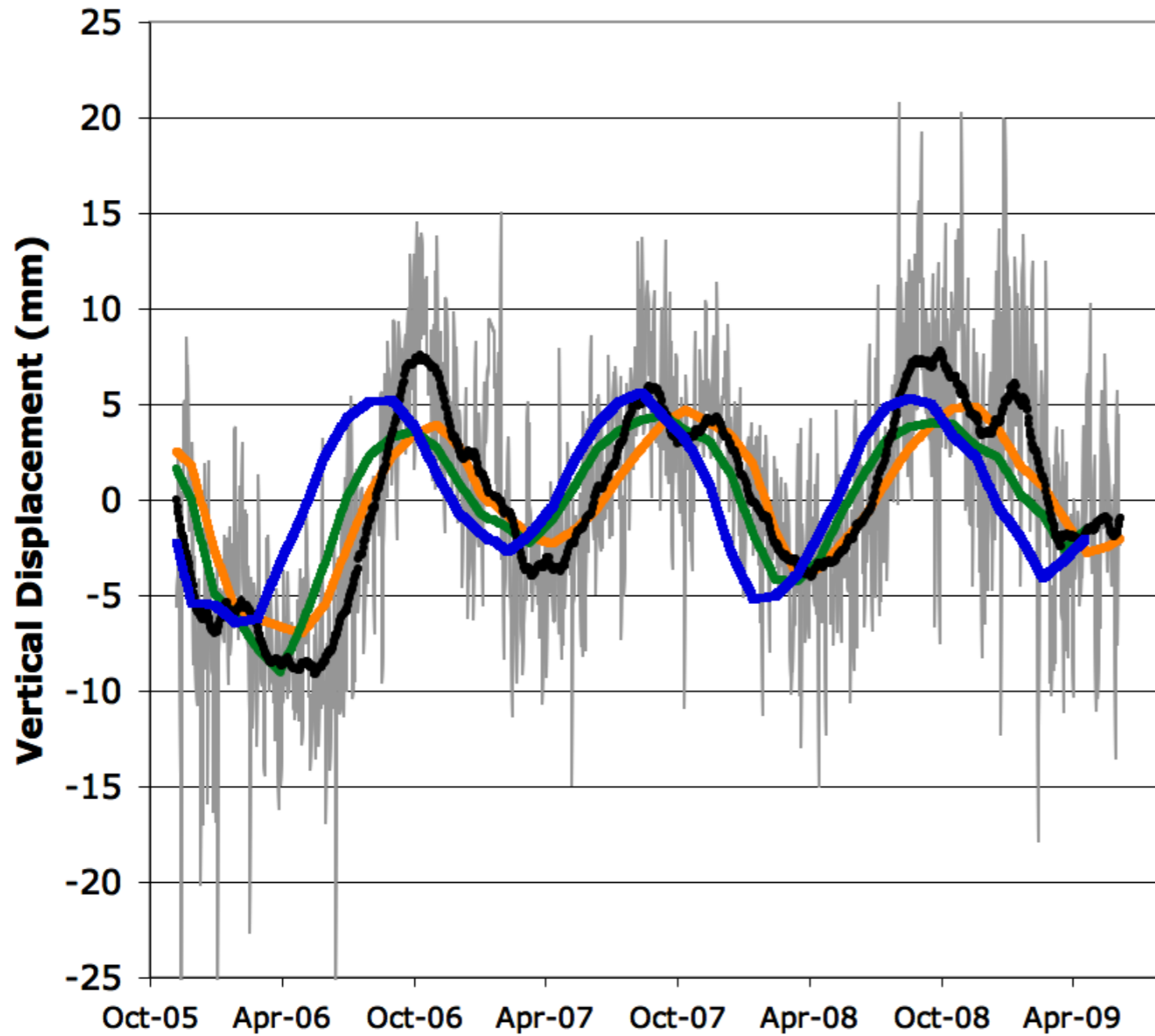
Forcing: Observation-based precipitation, humidity, temperature, wind, pressure, and downward radiation products from NCEP, GEOS, ECMWF, etc.

Global Land Surface Input Parameters: Datasets include vegetation (coverage and leaf area), soil (porosity, texture, color, fraction of clay, sand and silt) and elevation.

Land Surface Models: GLDAS currently drives 4 LSMs including NOAH, CLM, MOSAIC, VIC (shown here in figure from Andy Wood, 2007)

Outputs: soil moisture in each layer, snow depth, surface and subsurface runoff, evaporation, canopy transpiration, snowfall and snow melt, rainfall, etc.

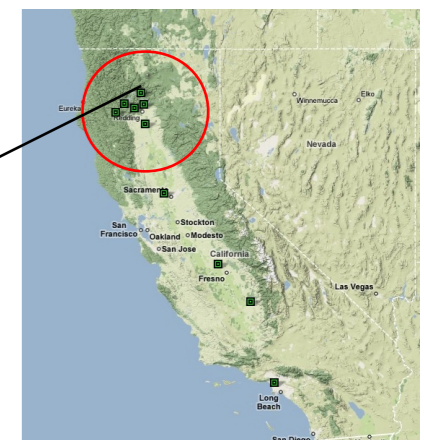
Load Model: time variable hydrologic storage load at each point on a global grid was then used to calculate the vertical deformation at each individual GPS station in the network. Soil moisture storage is the primary contributor.

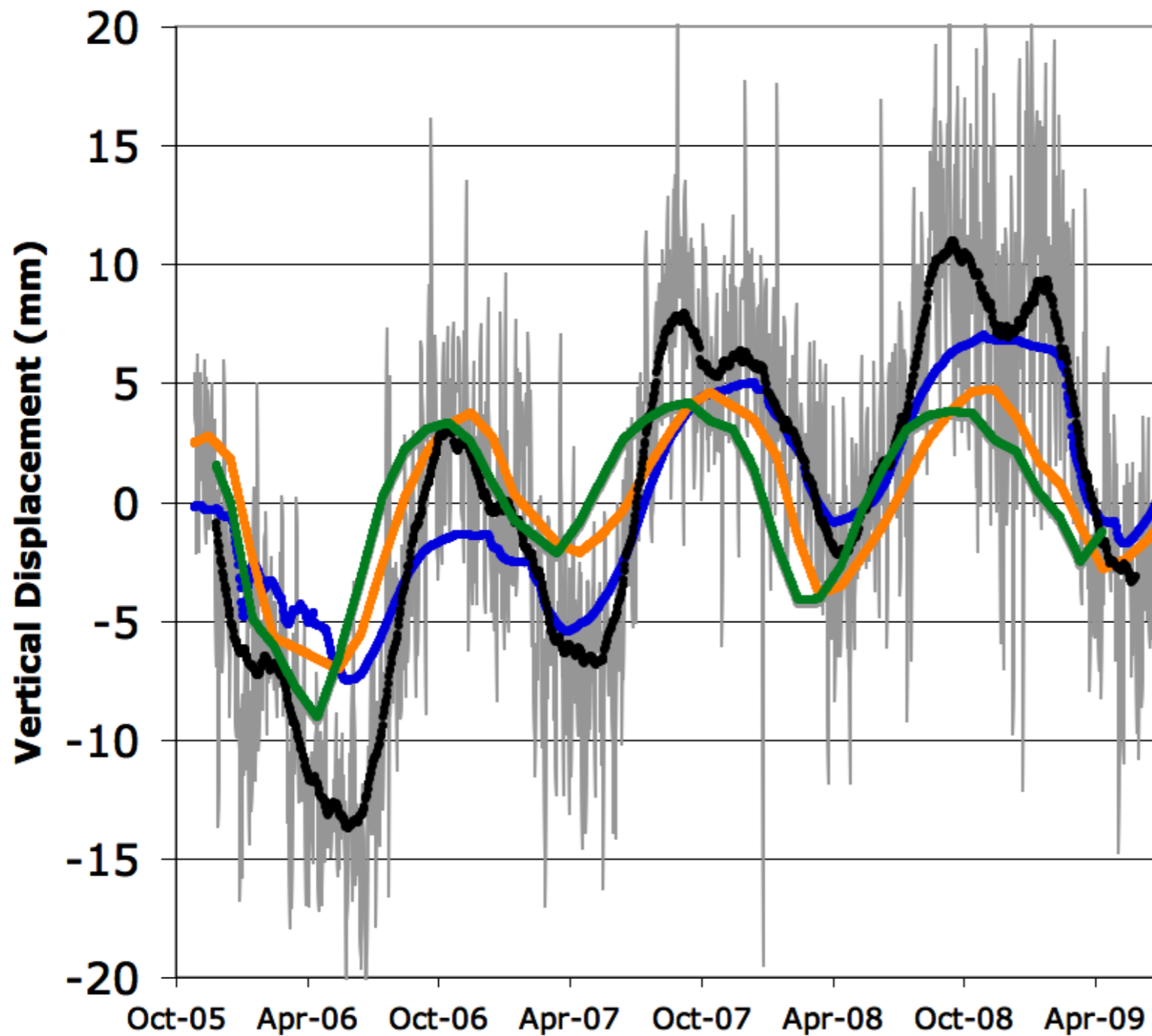


- GPS
- █ Leaky Bucket
- █ Mosaic
- █ GPS smoothed
- █ NOAH

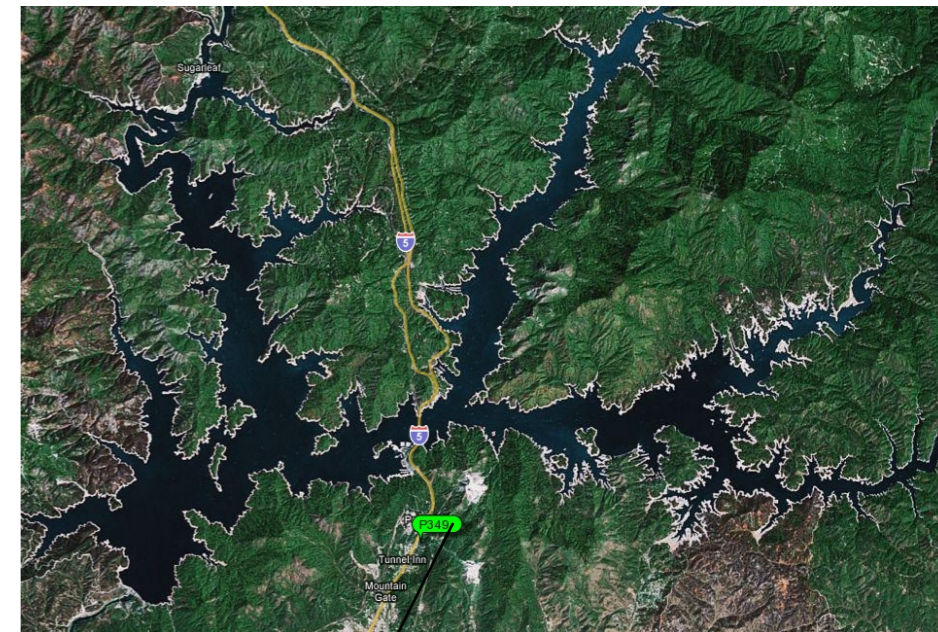
Model Statistics	Variance mm ²	Standard Dev. mm
GPS	43.2	6.6
GPS Smoothed	21.2	4.6
Leaky Bucket	4.2	2.1
NOAH/Advance 60d	16.9/3.8	4.1/2.0
Mosaic	5.9	2.4

Station P060

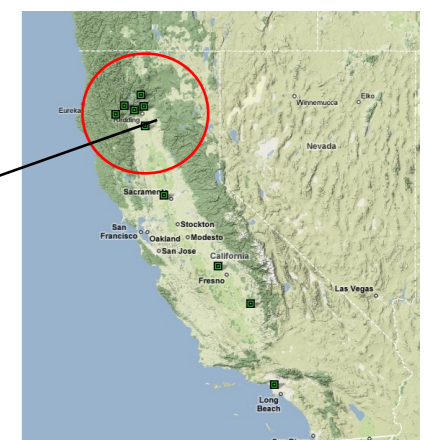




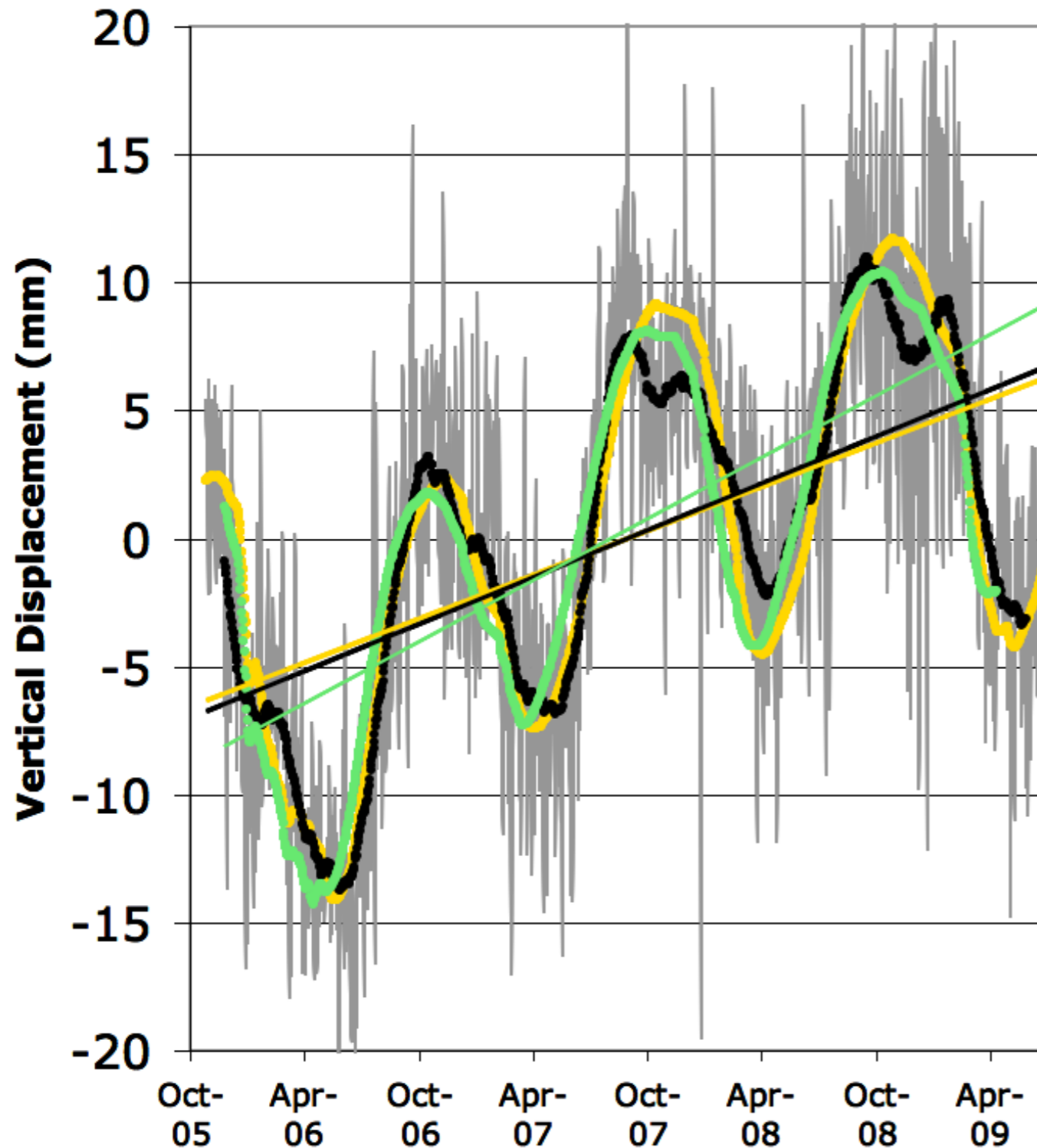
- GPS Vertical
- Lake Load
- Leaky Bucket
- GPS Smoothed
- Mosaic



Station
P349



Hydrologic surface loading insufficient to account for all of the observed vertical GPS signal at P349. Lake loading contribution is needed.

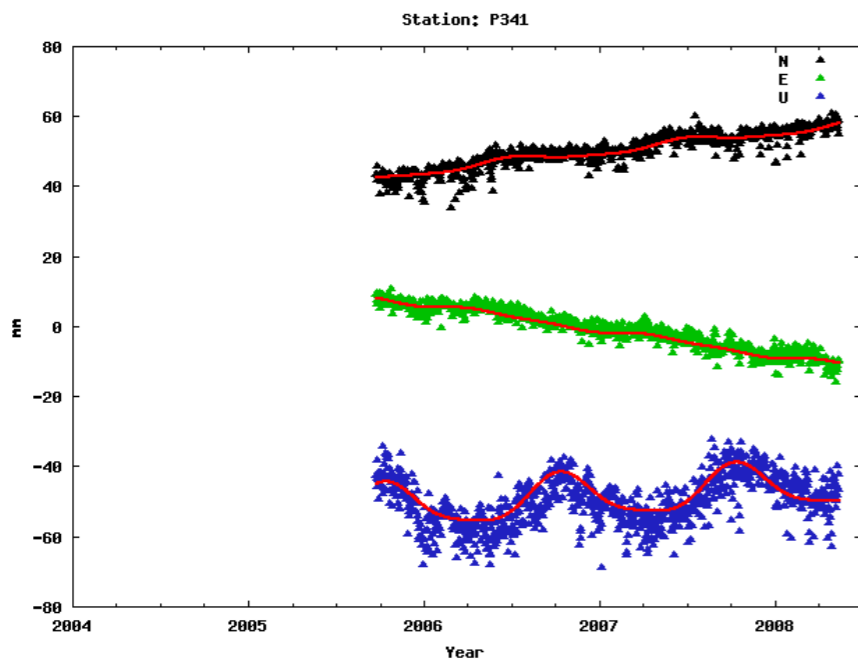
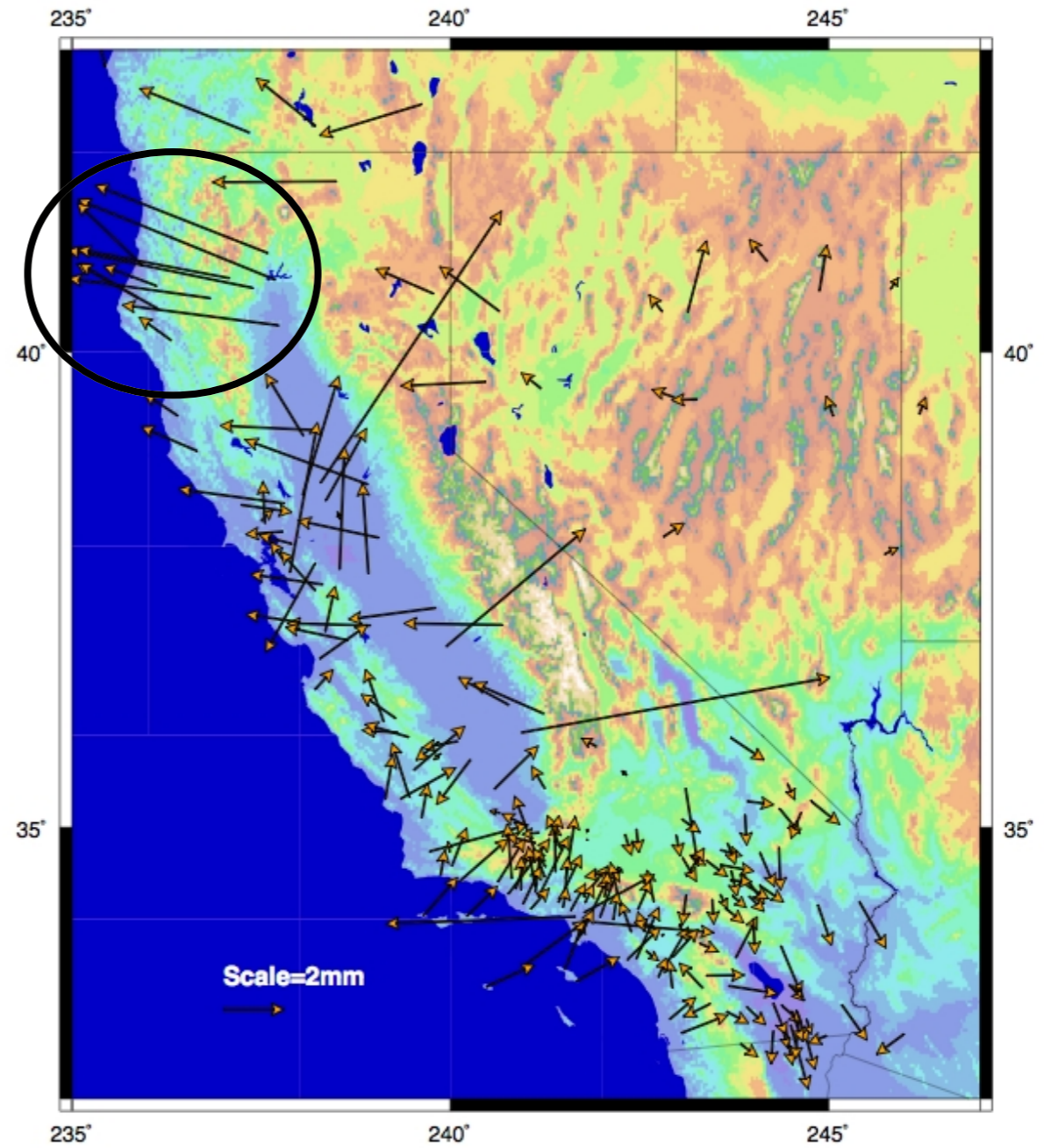
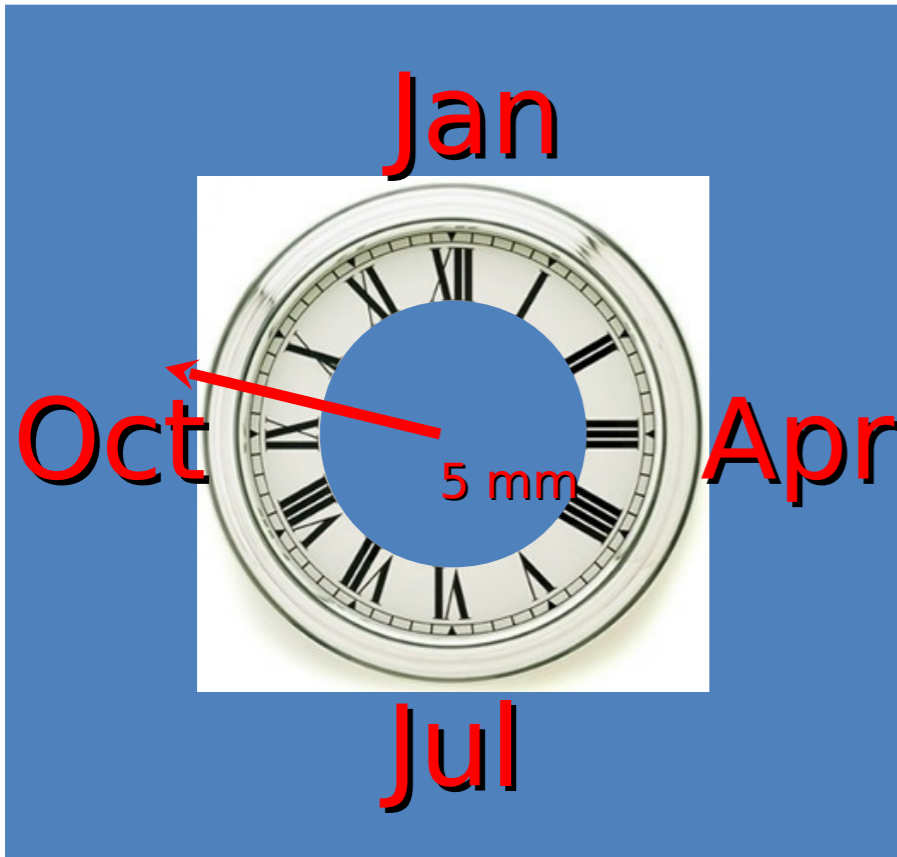


- GPS Vertical
- LB+Lake Load
- GPS Smoothed
- Mosaic+Lake Load
- Linear (LB+Lake Load)
- Linear (GPS Vertical)
- Linear (Mosaic+Lake Load)

Model Statistics	Variance mm ²	Standard Deviation mm
GPS	62.8	7.9
GPS Smoothed	41.5	6.4
Leaky Bucket LB	16.3	4.0
LB+Lake Load	3.5	1.9 mm
Mosaic	22.3	4.7
Mosaic+Lake Load	4.3	2.1 mm
Lake Load	8.33	2.9

Hydrologic surface loading *plus* lake loading fits vertical GPS signal to sigma ~2 mm.

Annual Signal Phasor Plot

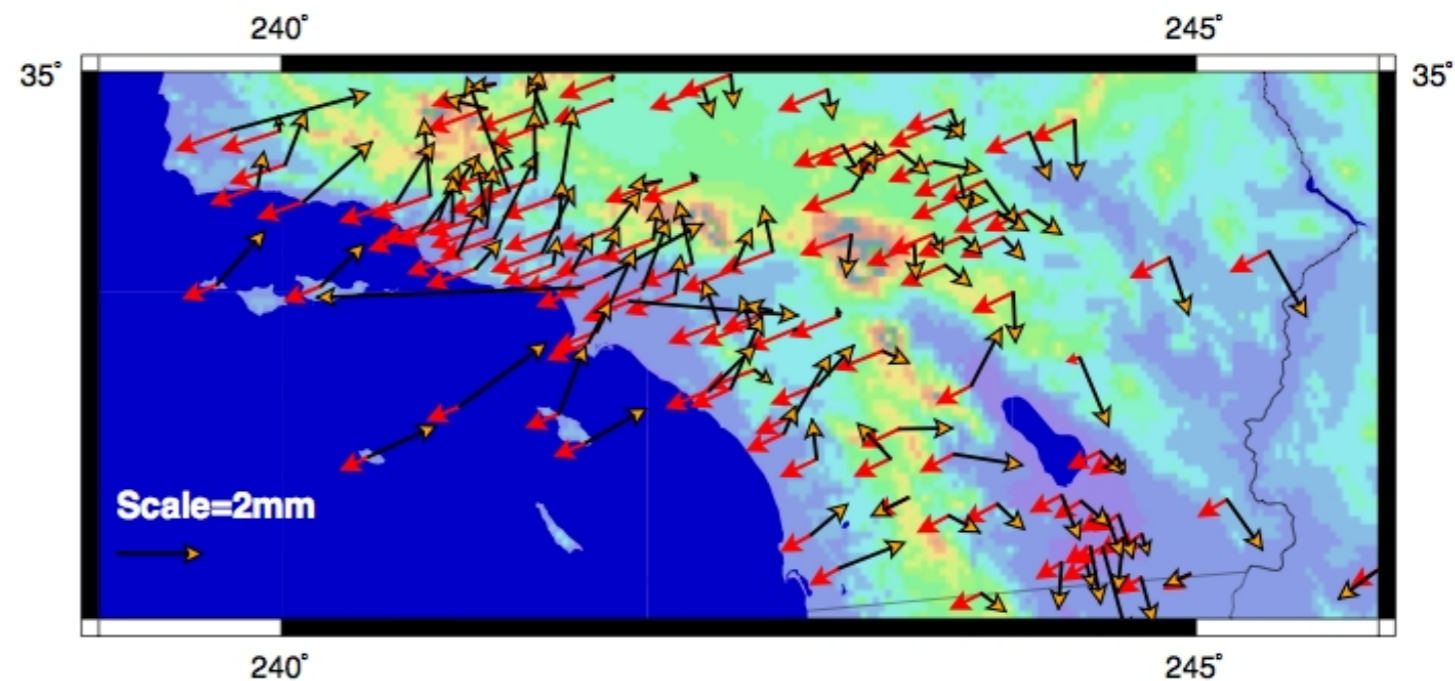
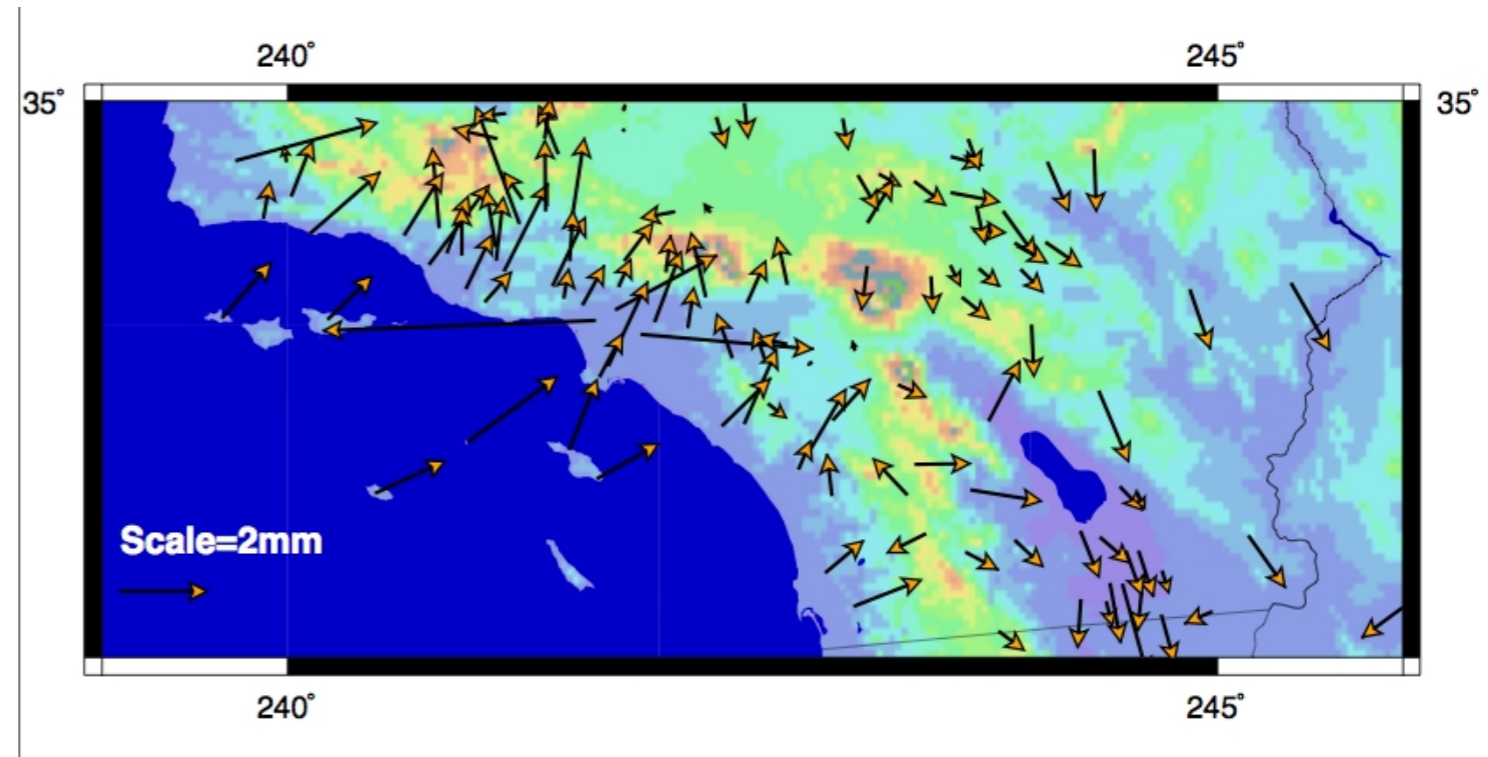


Annual Signal Phasor Plot

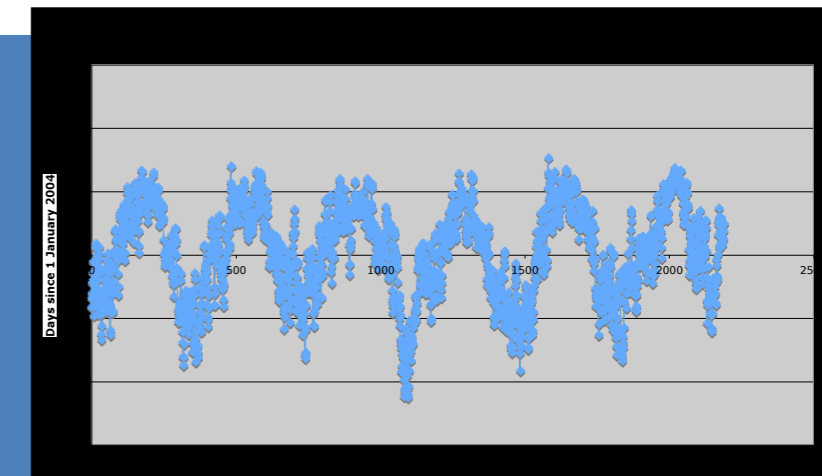
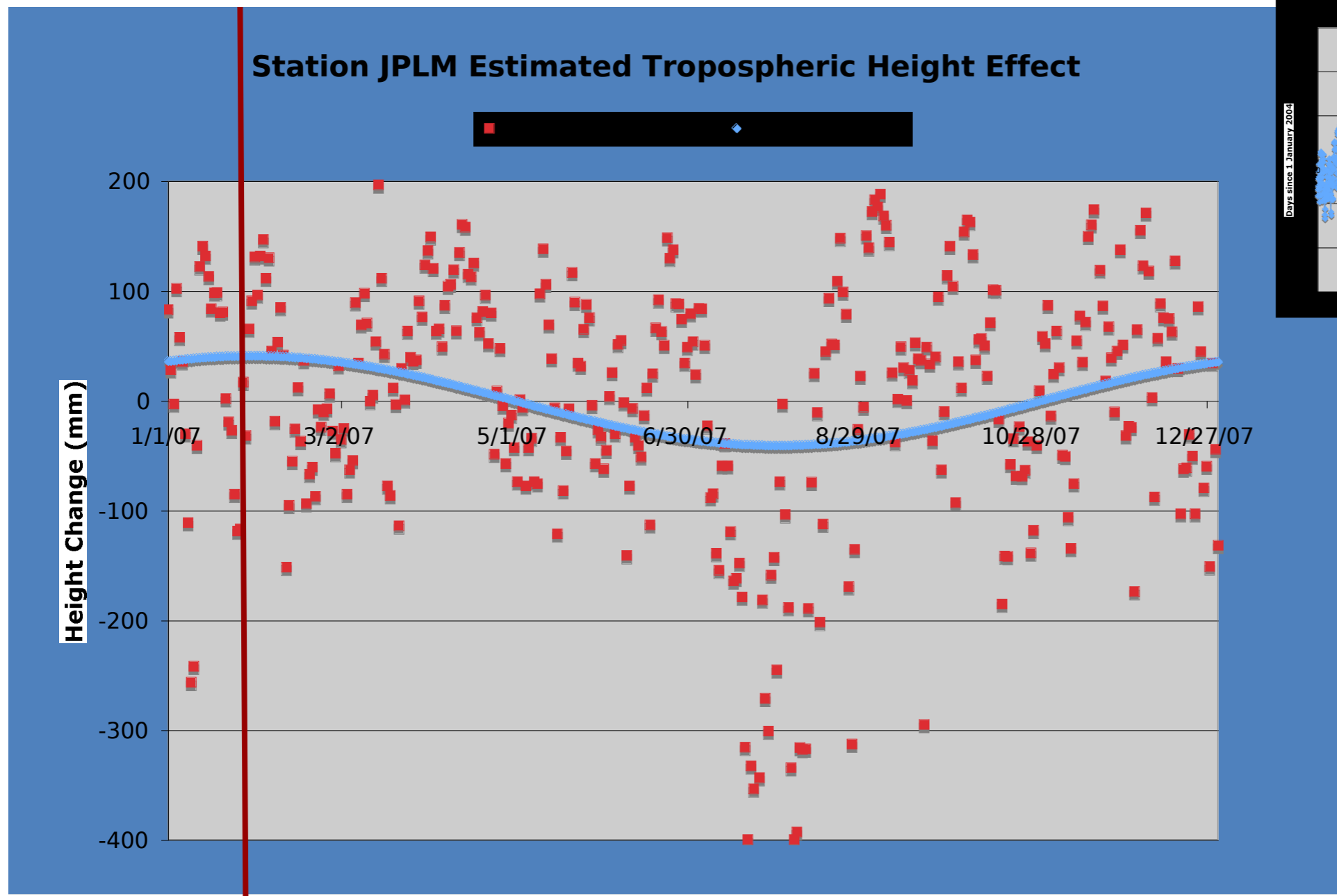


Peak vertical annual signal (max up) in winter-spring time period. Observed GPS (black vectors) do NOT correlate well with **model hydrologic loading (red vectors)**. Tropospheric effects are a possibility.

Overall pattern spatially consistent even though signals are very small (1-2 mm). Outliers are readily apparent and are due to numping

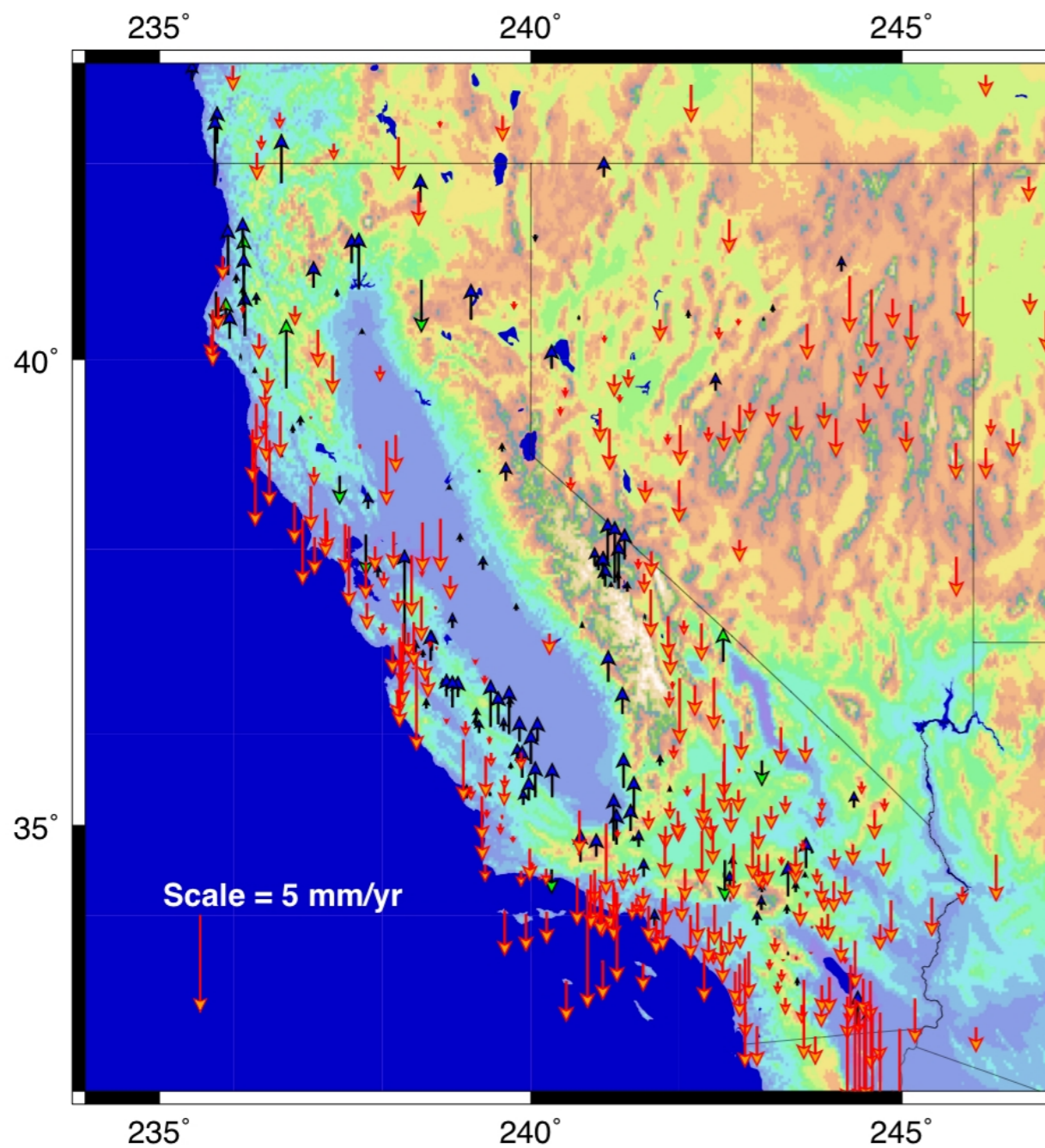


Unmodeled PWV can contribute to vertical errors in station height. To estimate the possible effect for this study, the IGS tropospheric zenith path delay product for station JPLM in S. Calif. was approximately converted to height change. The maximum annual height effect occurs in Jan-Feb. The amplitude is +/- 40 mm. Unmodeled error could contribute ~1-2 mm annual signal. Tropospheric estimates are now being made by UCAR, NOAA, PBO and others for ~100 PBO stations with meteorological packs which will allow for a better spatial picture of the PWV across the W. U.S. Another correction that needs to be made is direct atmospheric pressure loading (~1mm or less in the vertical coordinate).

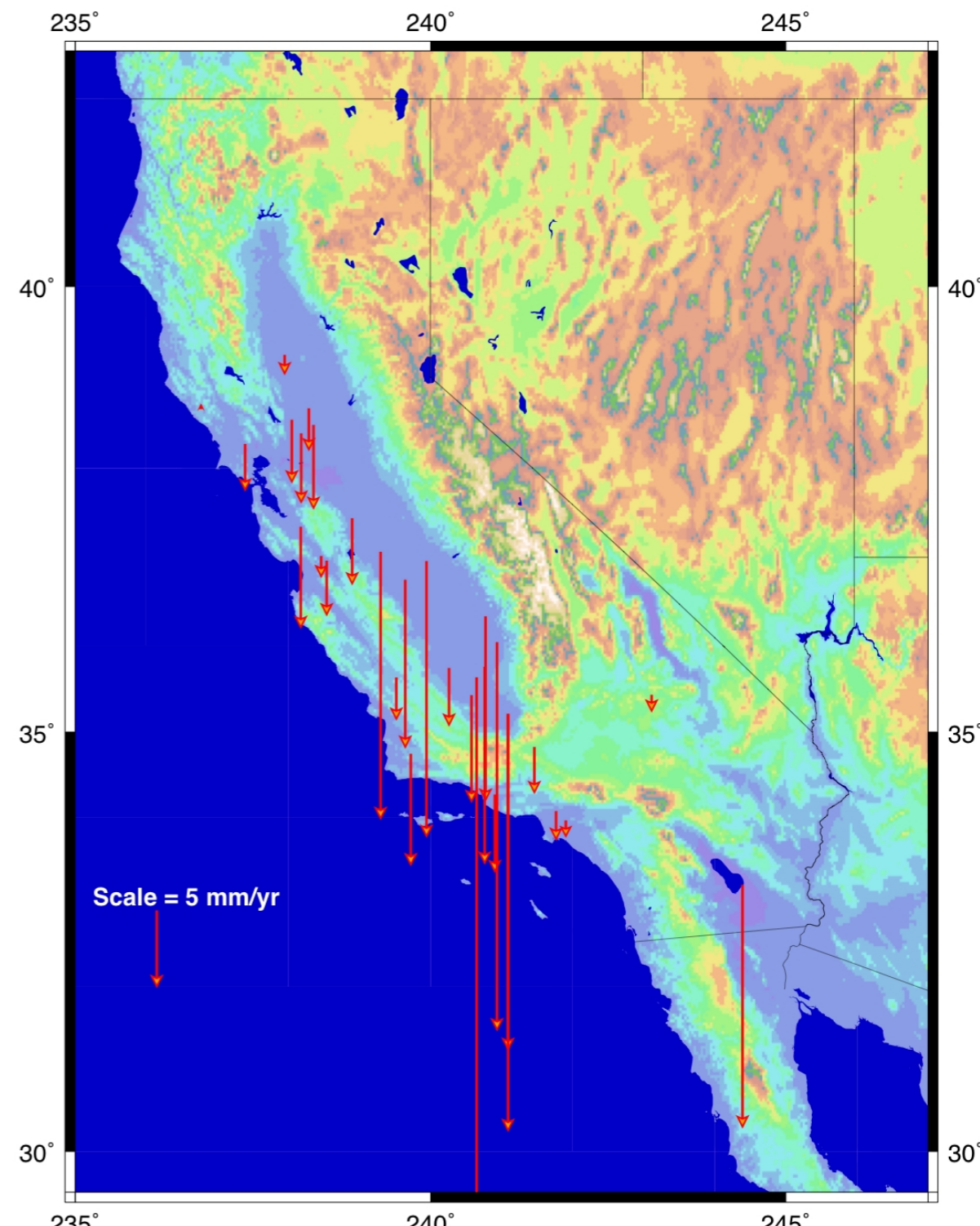


Pressure Load
~1 mm peak
to peak
vertical

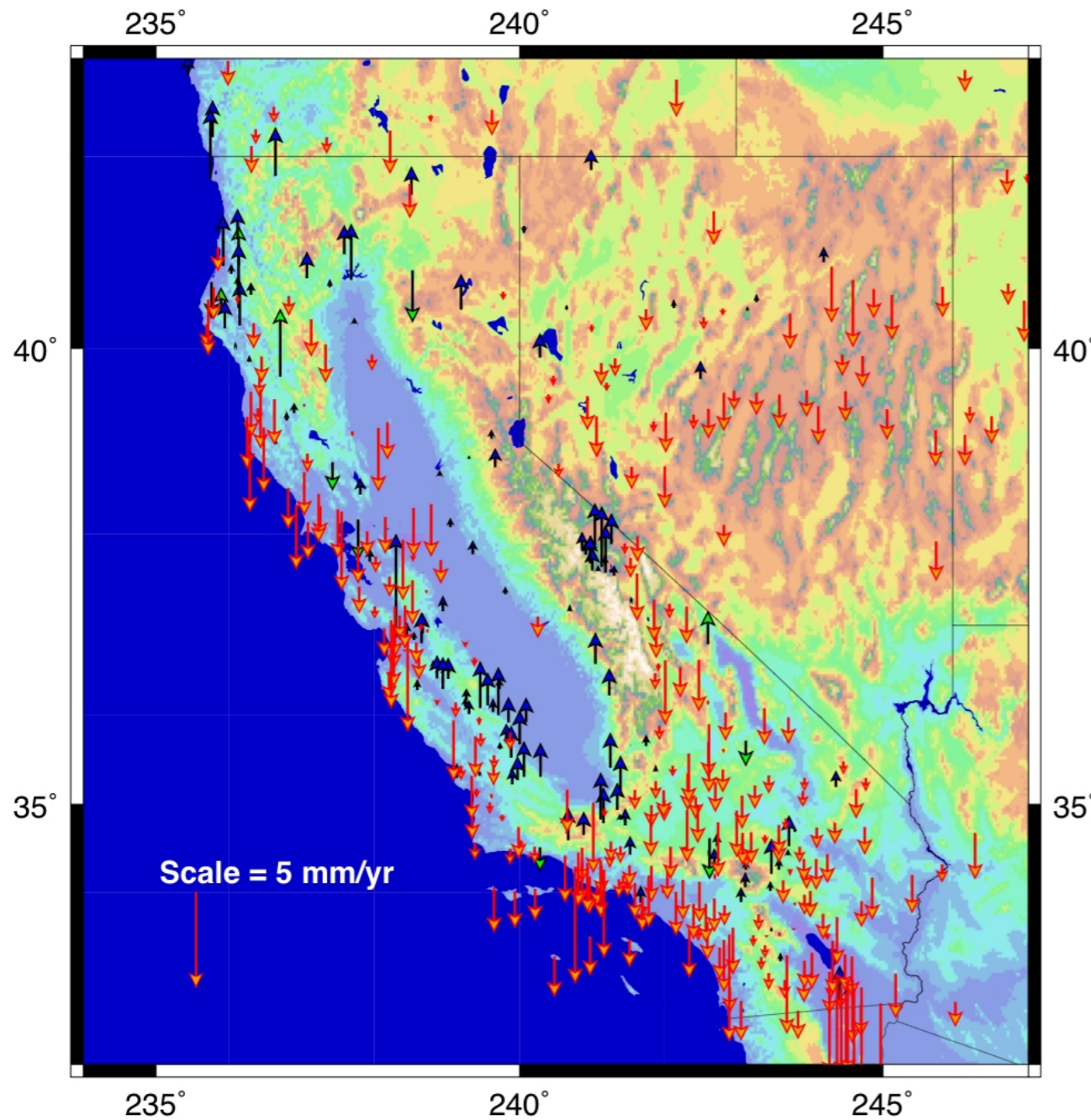
GPS Vertical Secular rates
Black vectors show uplift and red subsidence



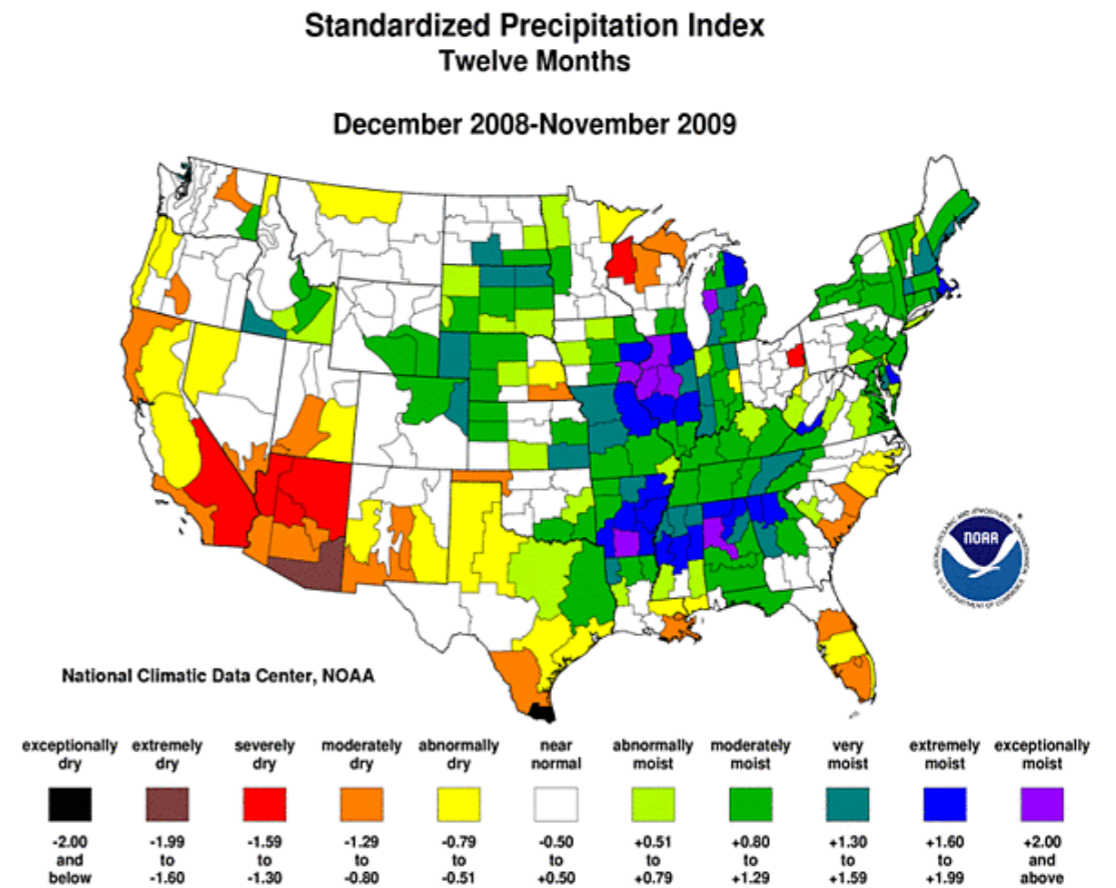
Excluded Stations with pumping signals



GPS Vertical Secular rates
 Black vectors show uplift and red subsidence



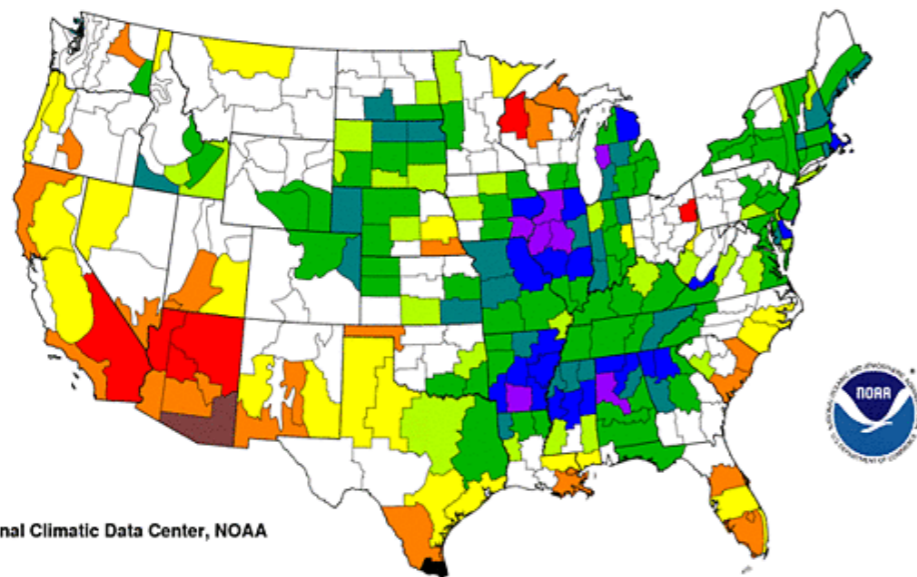
Observed GPS uplift in mountainous areas of California suggest possible cause is drought and loss of water load



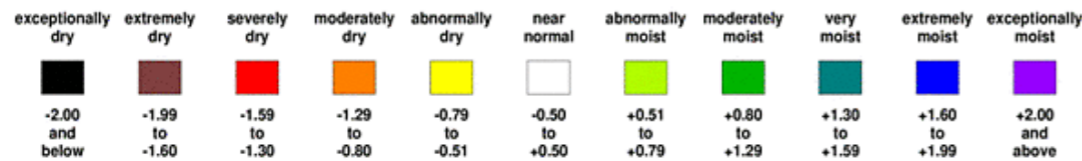
However...the drought has ended in the west coast. The vertical GPS trends may change as in the case of the Lake Shasta site (next slide)

Standardized Precipitation Index
Twelve Months

December 2008-November 2009

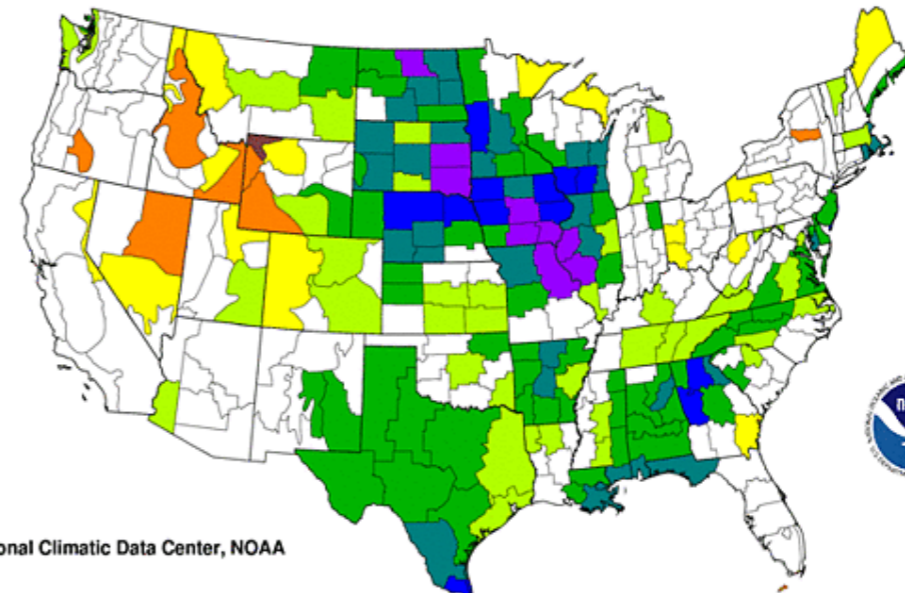


National Climatic Data Center, NOAA

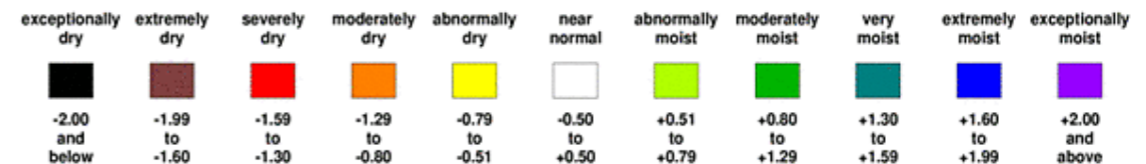


Standardized Precipitation Index
Twelve Months

September 2009-August 2010



National Climatic Data Center, NOAA



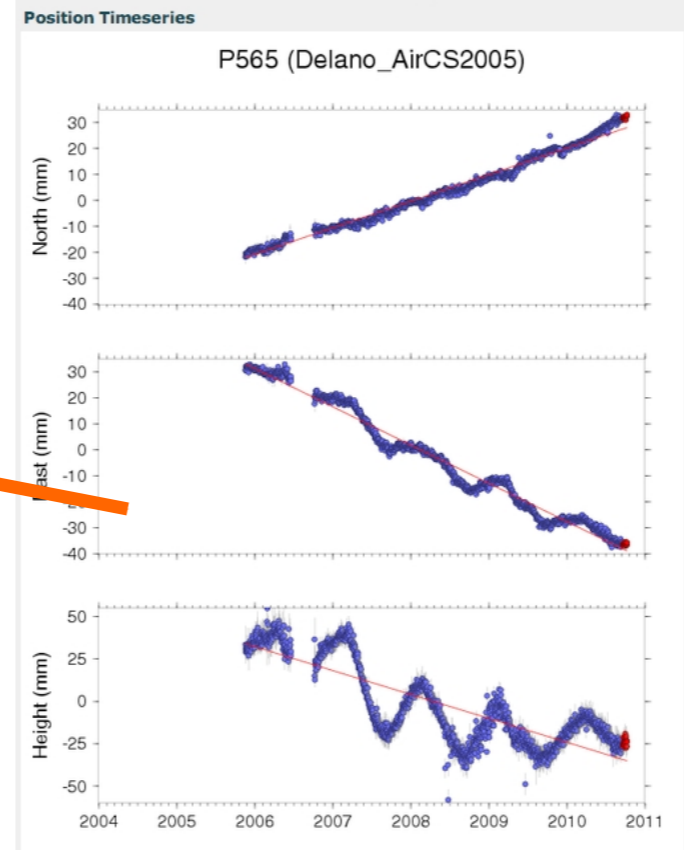
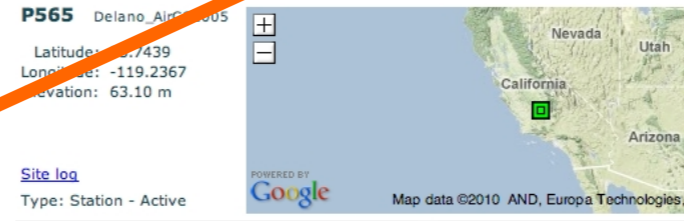
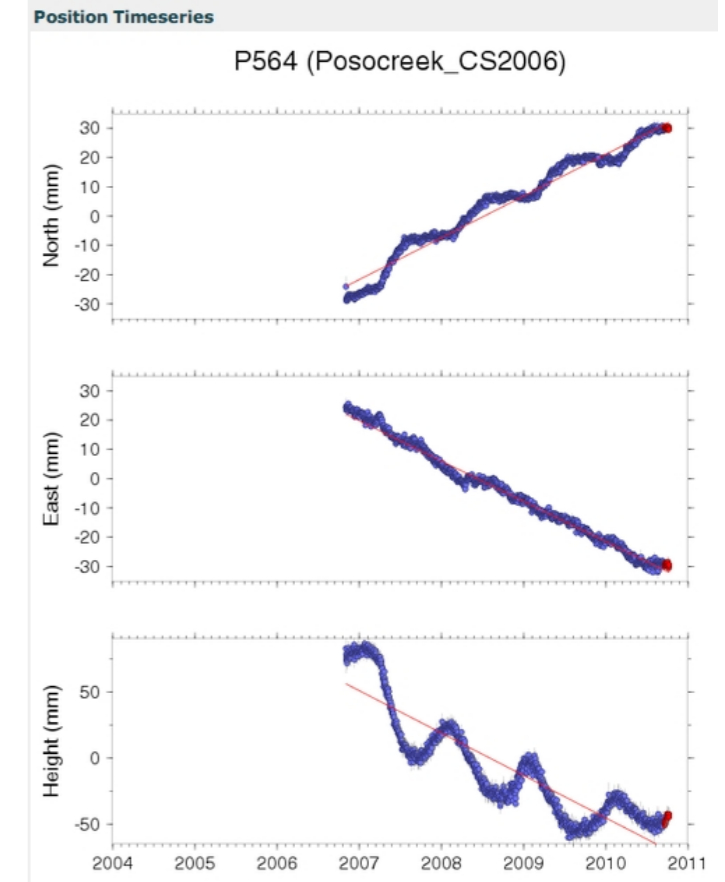
Dec 2008-Nov 2009

Sept 2009-Aug 2010

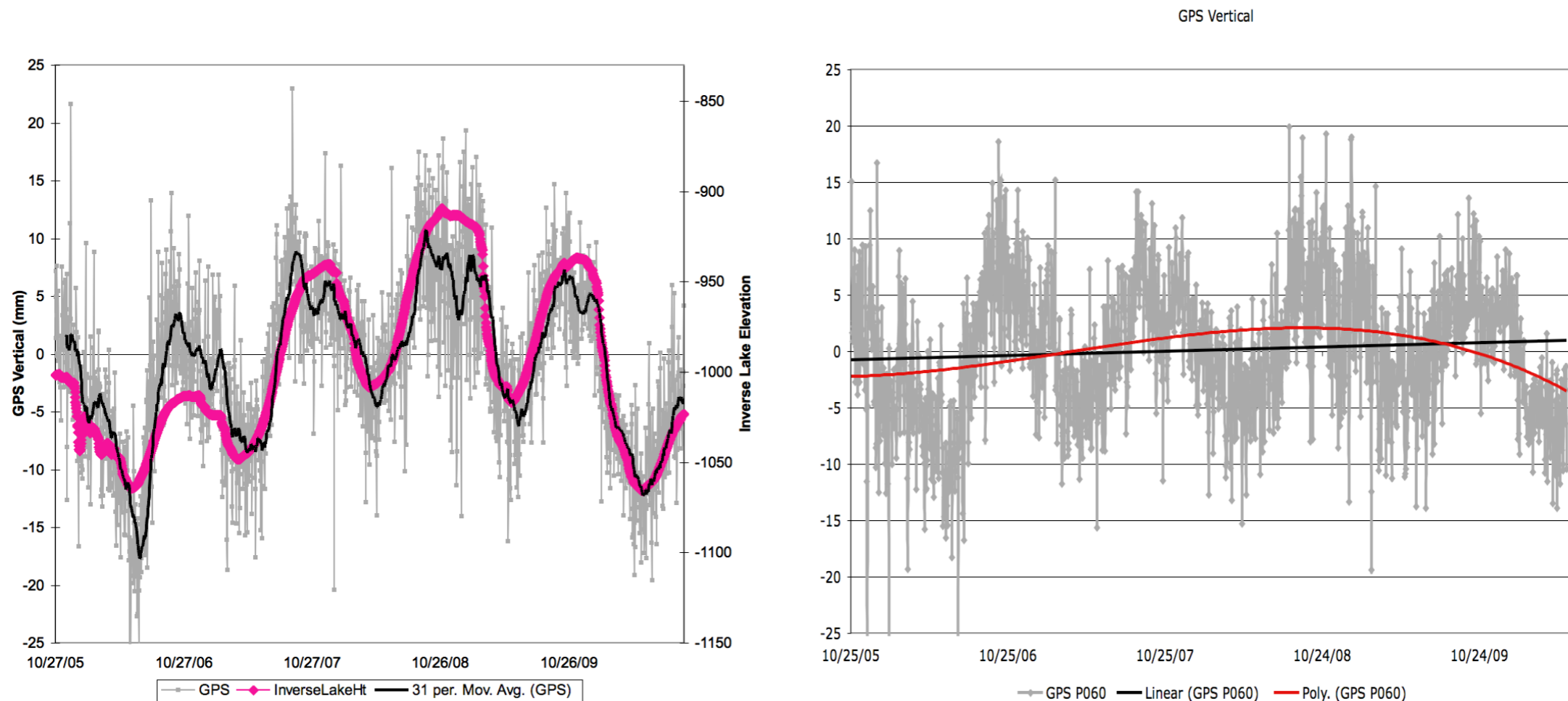
Drought Slowing Down?

P564 and P565 Site in Sediments in San Joaquin Valley

- Show recovery from prior rapid long term subsidence and show possibly decreasing annual signals. Need to separate increased natural recharge from reduced pumping rates.



The Lake Shasta GPS site P349 (Left) is heading back down in response to increased lake and soil moisture loading. P060 (Right) is not affected by lake load but recent trends also suggest increase hydrologic load (from soil moisture).



- The quality and density of PBO observations is excellent and shows coherent spatial patterns in the observed vertical annual and longer term signals
- Observed hydrological effects:
 - Anthropogenic signal from ground water pumping due to poroelastic response of sediments in valleys to water table fluctuations
 - Reservoir surface loading
 - Hydrologic surface loading in mountains from natural water cycle and variations in soil moisture and snow pack
- The annual cycle in mountains shows uplift in fall at times of minimum soil moisture and snow pack (minimum load). In valleys peak amplitude is in spring before pumping and after maximum recharge of sediments from runoff
- The recent drought conditions may be causing longer term uplift in mountains, subsidence in valleys (may be exacerbated by increased pumping). However drought is ending in western US so trends may reverse.
- GLDAS and Leaky Bucket models do a good job of fitting the observed GPS vertical signals in areas with significant hydrologic input/output e.g. mountains of California and the Pacific Northwest
- In order to measure tectonic mountain building (rates of $<1\text{mm/yr}$) we will need to be able to understand and model hydrologic loading effects

- This presentation contains unpublished results.
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