Investigation of Non-tectonic Signals at GPS Stations

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IGS Workshop, 2012

Talk Overview

Overview

- Non-tectonic signals: seasonal and longer term variations in GPS time series
- Hydrologic effects
  - Ground water Pumping
  - Surface loading and modeling
- Equipment Degradation
- Monument Stability

GNSS Signals of Interest

GNSS Signals of Geophysical Interest

- Tectonic
    - Plate tectonics, Boundary zone deformation, Earthquake cycle
- Volcanoes and other magmatic sources
- Ocean and Atmospheric Loading
- Continental Water (surface, ground)
- Snow and Ice
- Glacial Isostatic Adjustment (GIA)
- Tropospheric and Ionospheric Delays
- Multipath (for soil moisture, snow depth, vegetation index)

Non-Geophysical Signal Sources

- Human-induced pumping (but interesting to hydrologists!)
- GPS Equipment change, damage, or failure
- Antenna Phase Center Errors including radomes
- Survey Error (e.g. bad antenna height or metadata record)
- Multipath (bad type from structures etc.)
- Snow and Ice directly on antenna
- Thermal Elastic (from ground or monument)
- Satellite Geometry (can’t see through the earth)
- 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!

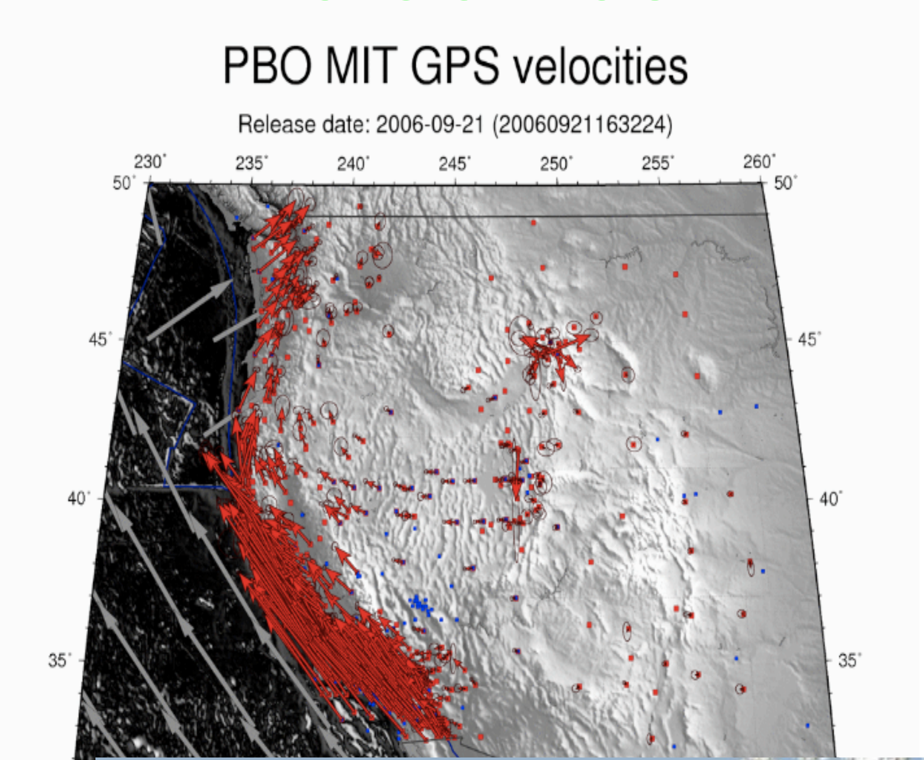
PBO “IGS-like” GPS Processing Service

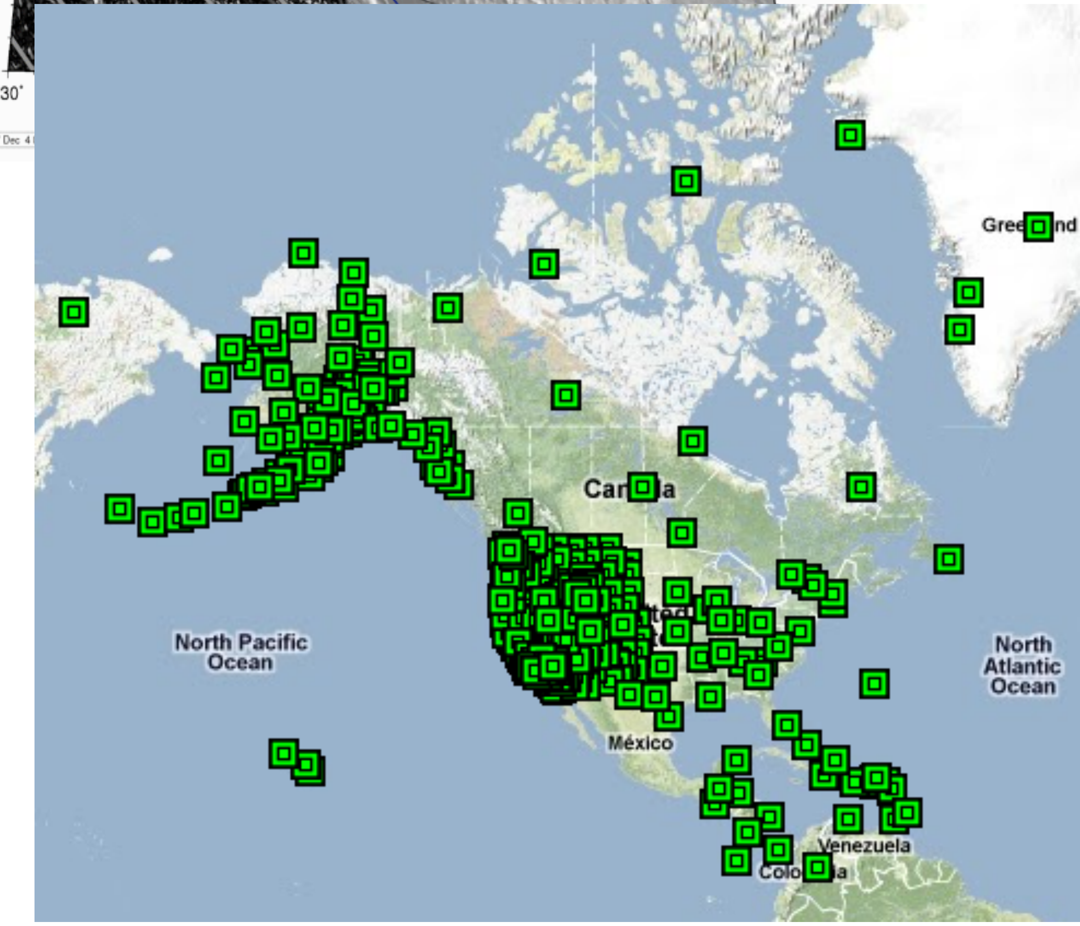
PBO GPS Processing Service

GIPSY: Central Washington U. (M. Santilan, T. Melbourne
GAMIT: New Mexico Tech. (M. Murray)
Combination Solution: MIT (T. Herring, B. King)
Stable North American Reference Frame (SNARF2.0)

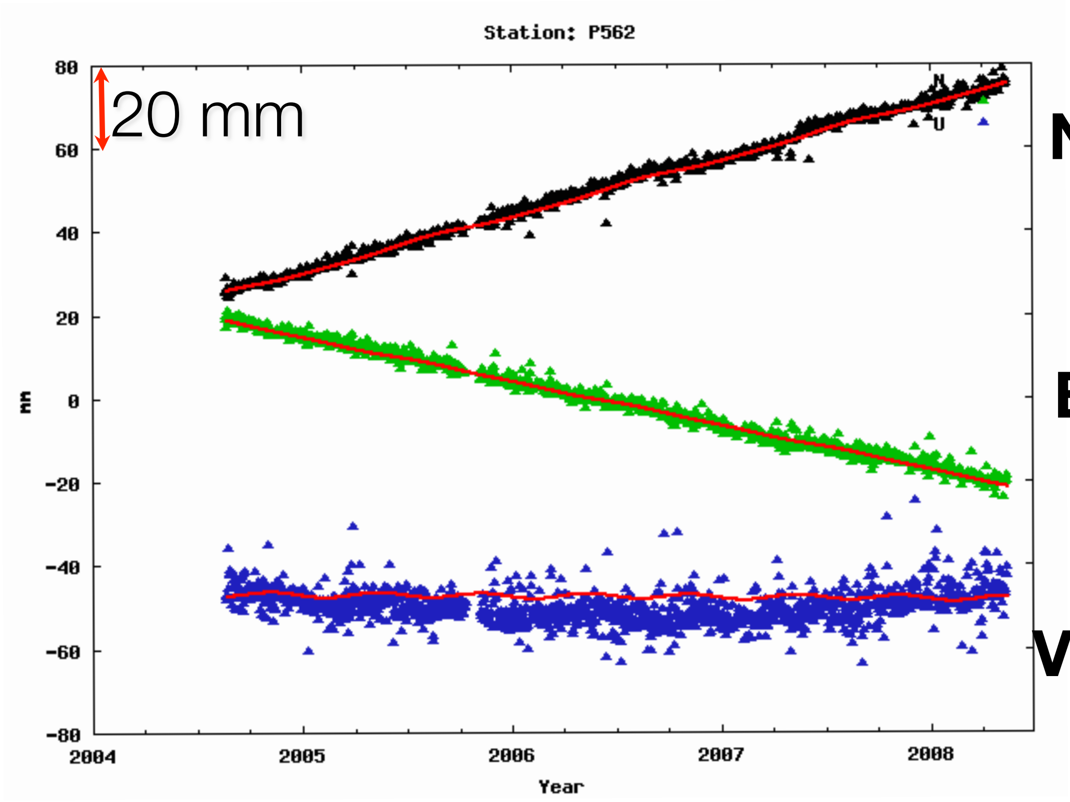
Daily Time series and periodic velocity solution products available from UNAVCO Data Center for ~1,300 stations

Velocities





Time Series



North Comp

East Comp

Vertical Comp

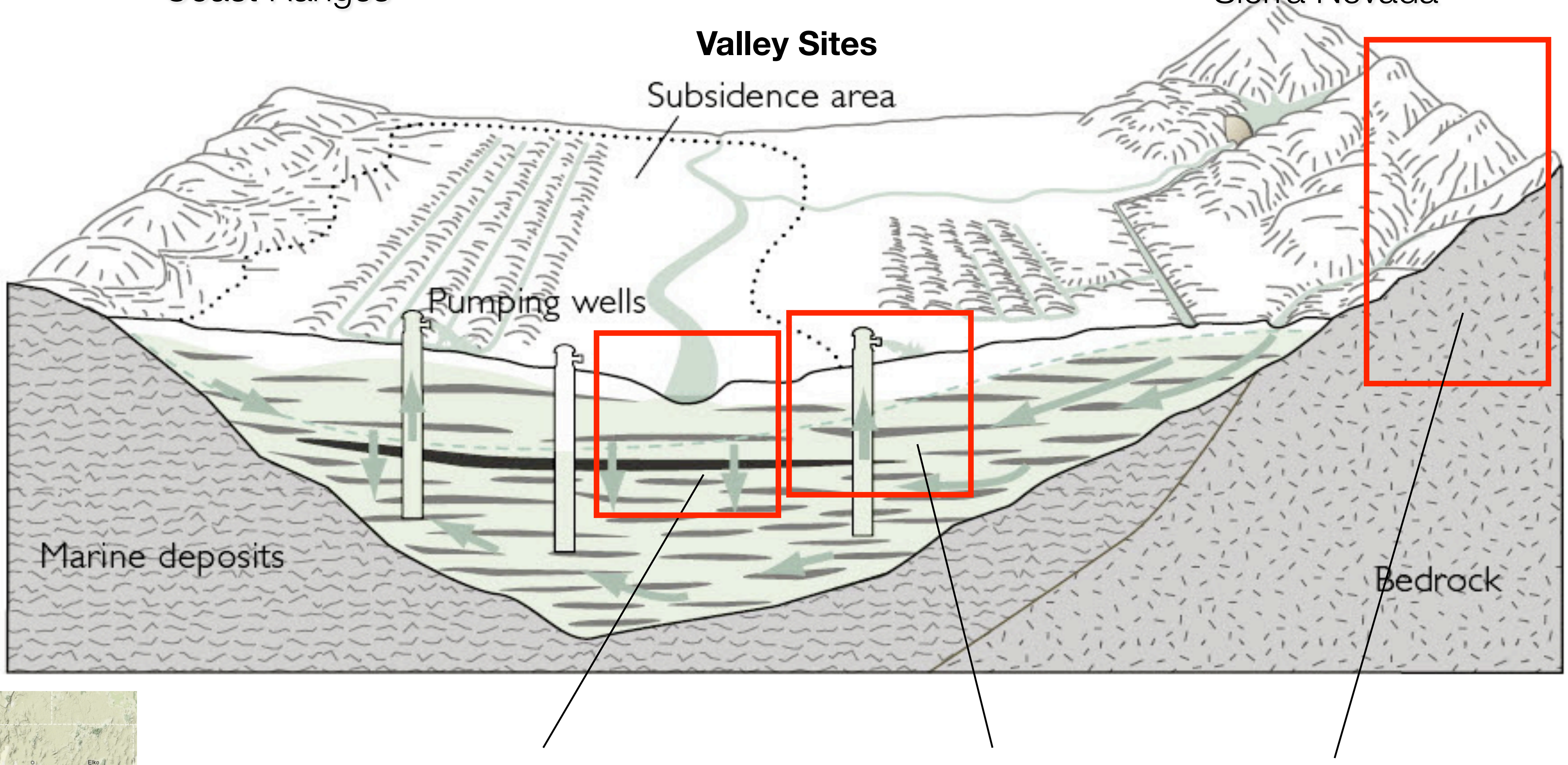
Summary of Hydrologic Effects

Hydrologic Effects in the San Joaquin Valley, California

Mountain Sites
Coast Ranges

Valley Sites

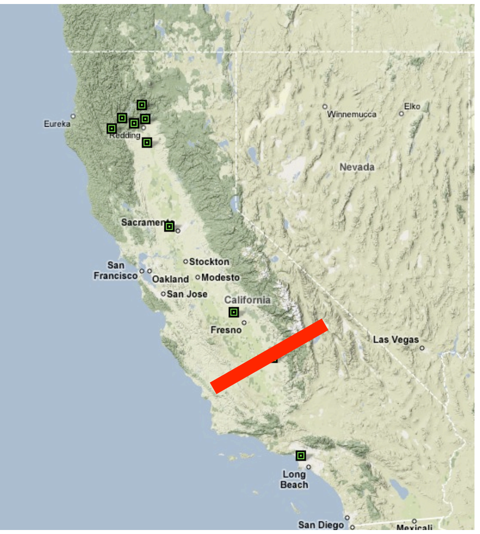
Mountain Sites
Sierra Nevada



Broad Subsidence

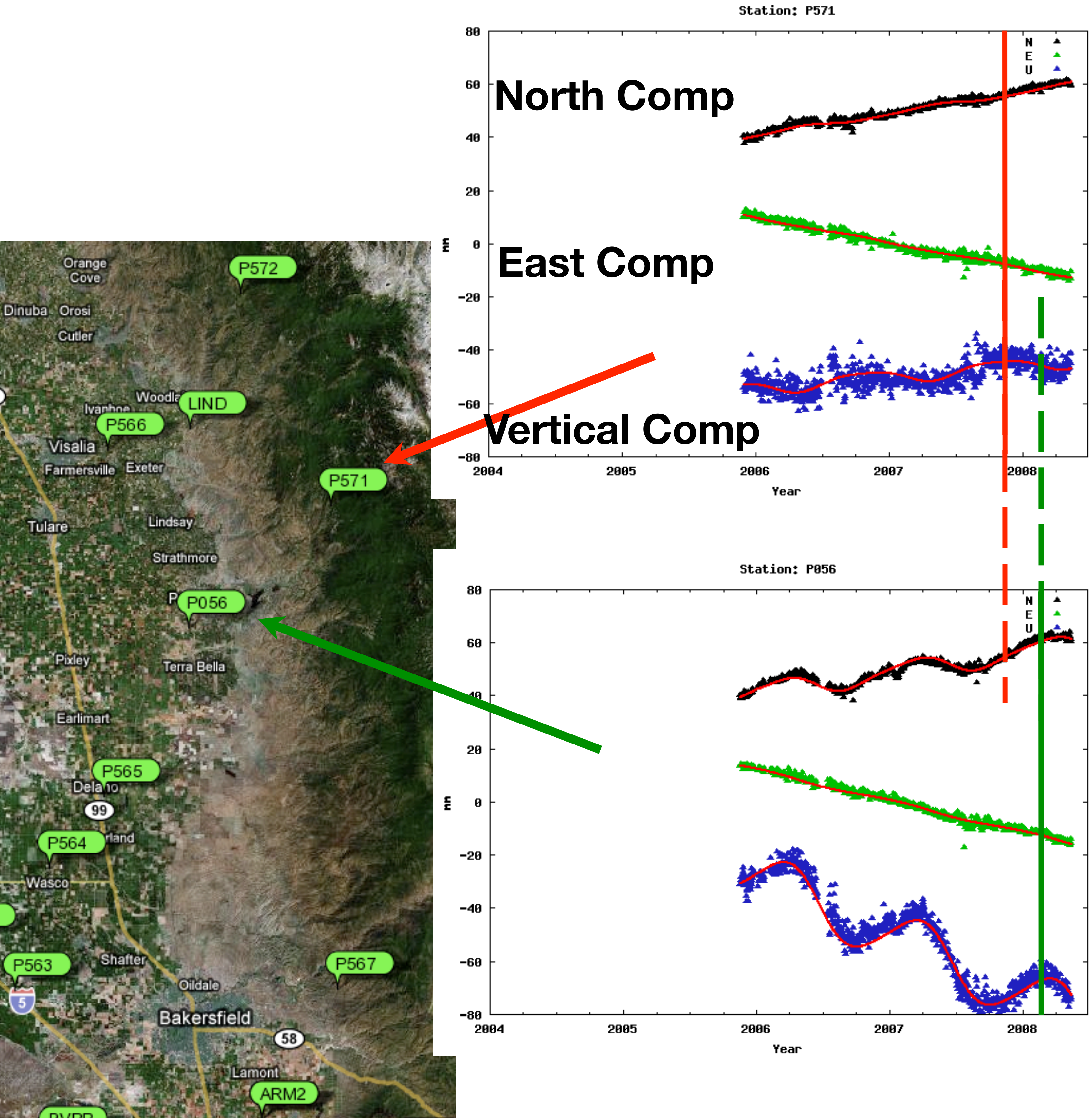
Localized Subsidence
From rapid pumping

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/

Hydrologic Effects



Mountain sites

- motions are primarily due to <u>hydrologic surface loading</u>

- Snow pack
- Soil Moisture
- Lakes

- Peak seasonal in October

Valley sites

- motions are due to water level variations from pumping for irrigation or from natural causes (coupling from <u>poroelastic effects</u>)
- Peak Seasonal in April

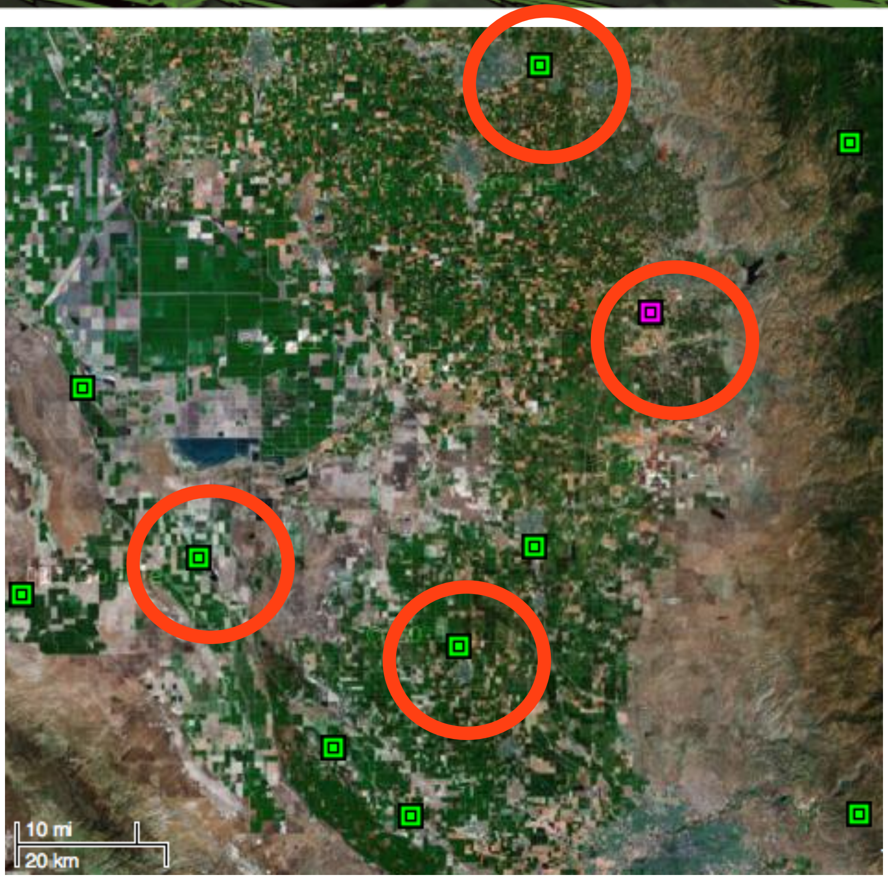
Hydrologic Signals:

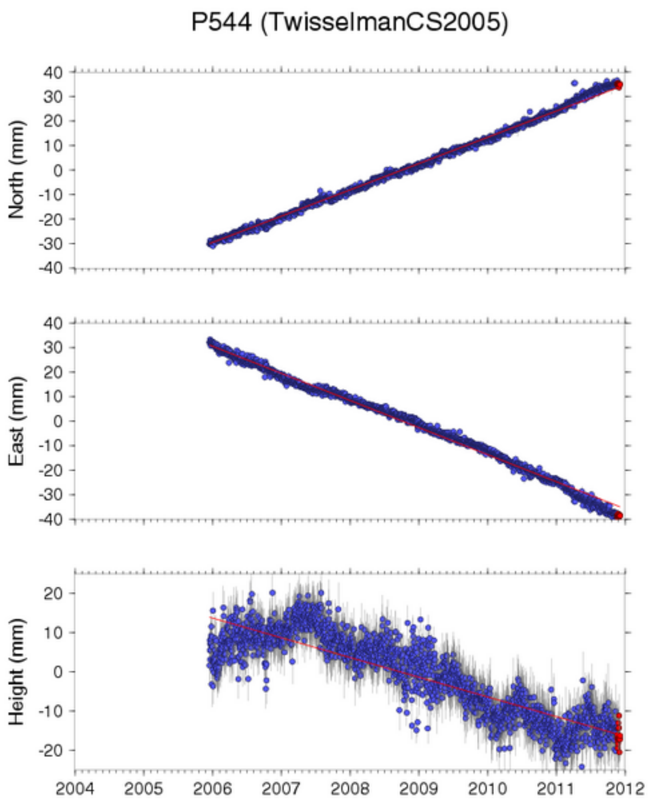
Pumping and Poroelastic Effects in sediments

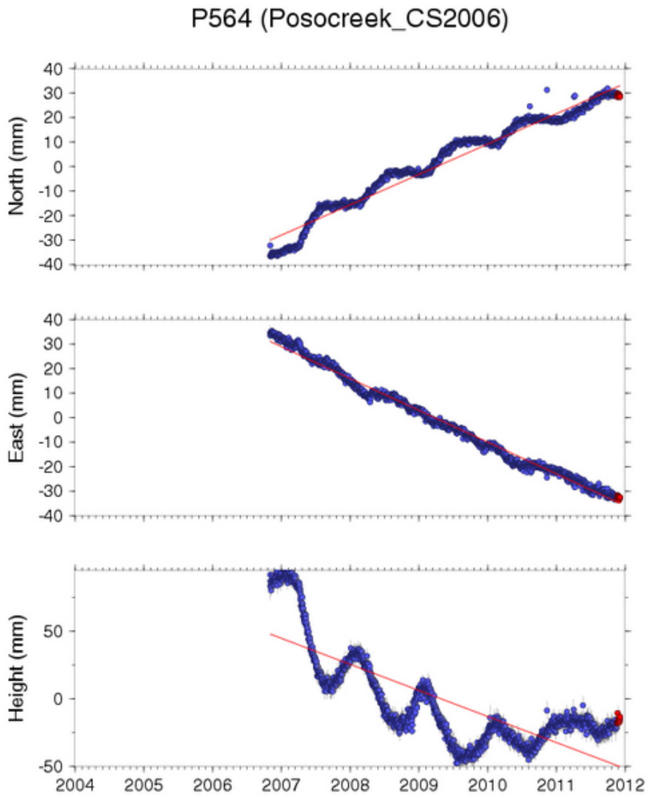
Valley Sites

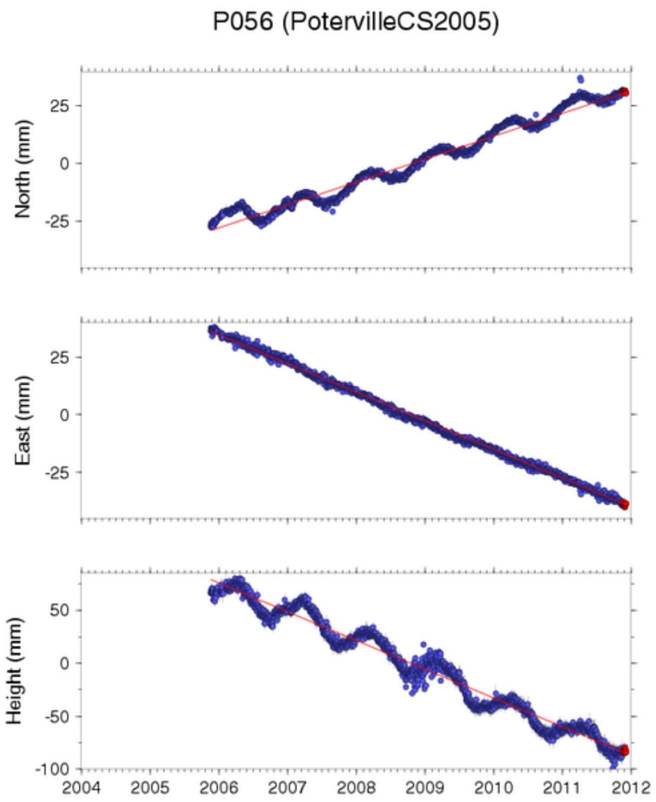
All <u>Valley Sites</u> show some indications of poroelastic effects in long term (up to 3 cm/yr) and horizontal and vertical seasonal signals that peak in April.

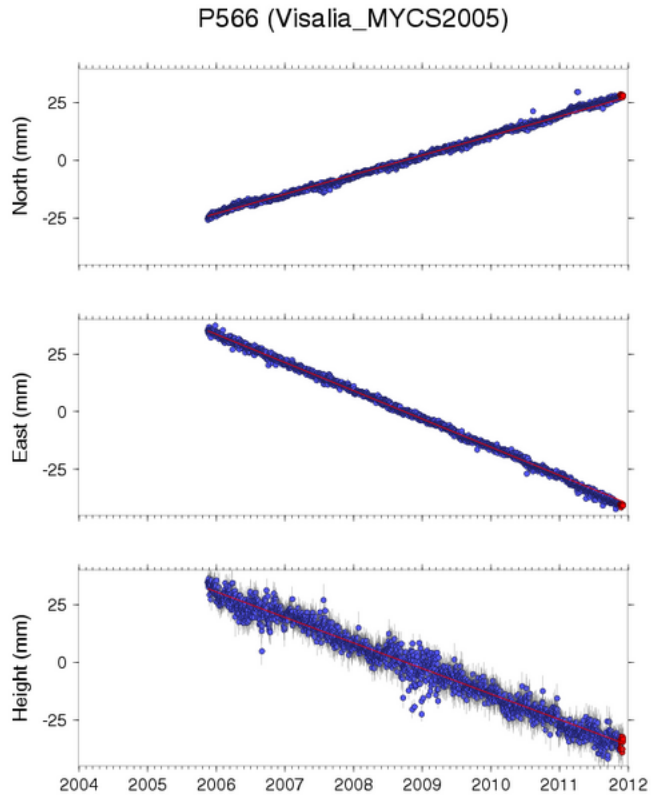
These anthropogenic signals are quite variable and depend a lot on local pumping rates.



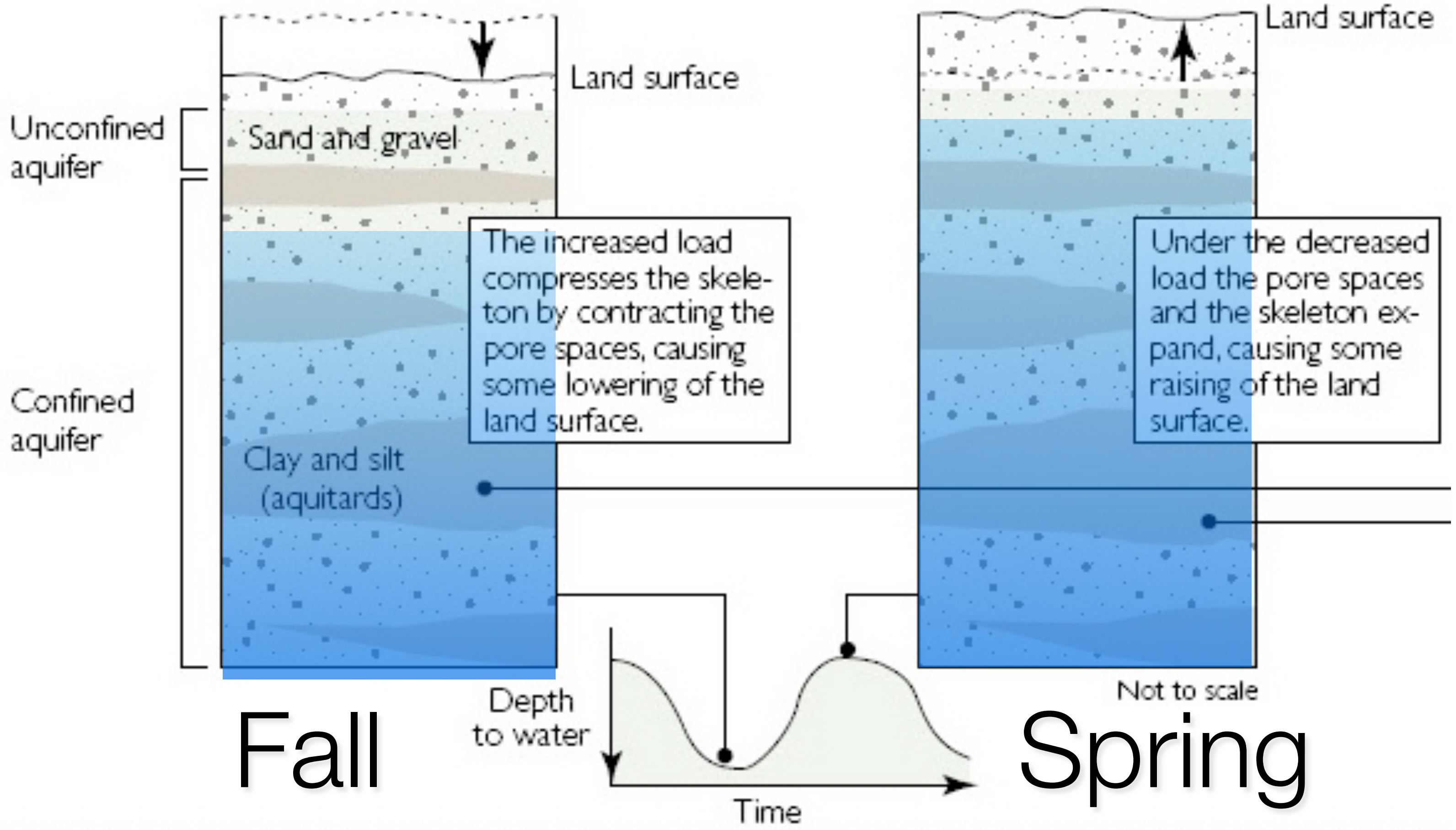

P544 (TwisselmanCS2005)


P564 (Posocreek_CS2006)


P056 (PotervilleCS2005)


P566 (Visalia_MYCS2005)

Poroelastic Effects in sediments



The increased load compresses the skeleton by contracting the pore spaces, causing some lowering of the land surface.

Under the decreased load the pore spaces and the skeleton expand, causing some raising of the land surface.

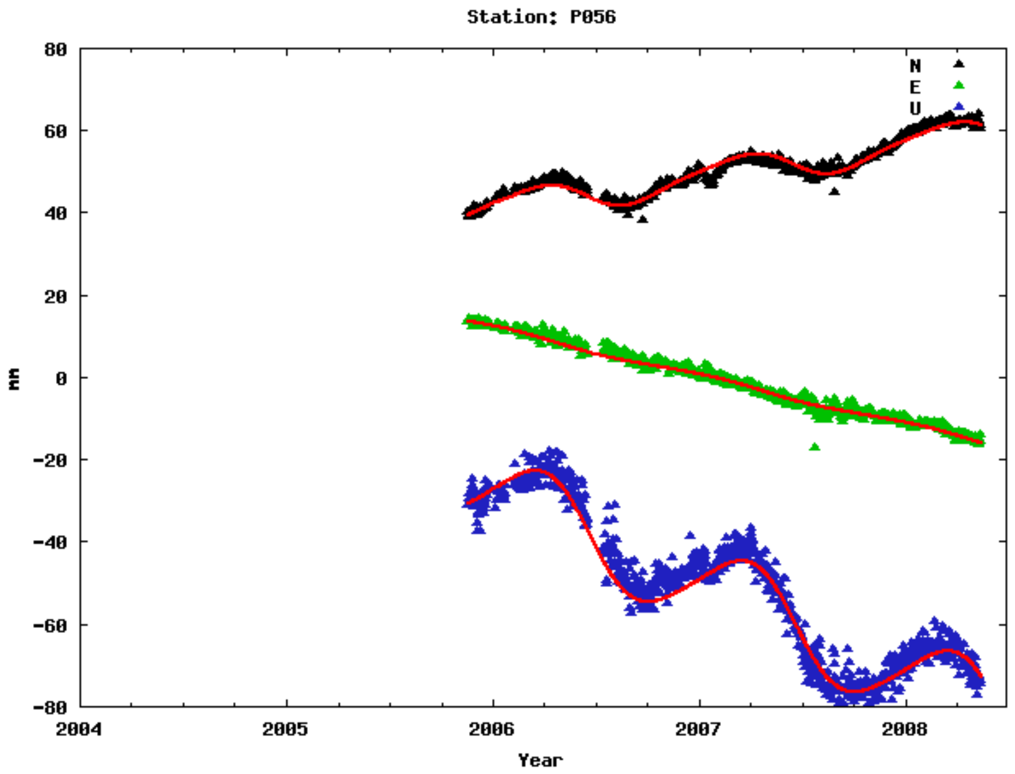
Fall

Spring

In the San Joaquin Valley the dominant signal is caused by pumping for irrigation

<u>Poroelastic effects</u> coupled with ground water level variations result in annual signals and net subsidence when recharge is less than withdrawal (as in example at right)

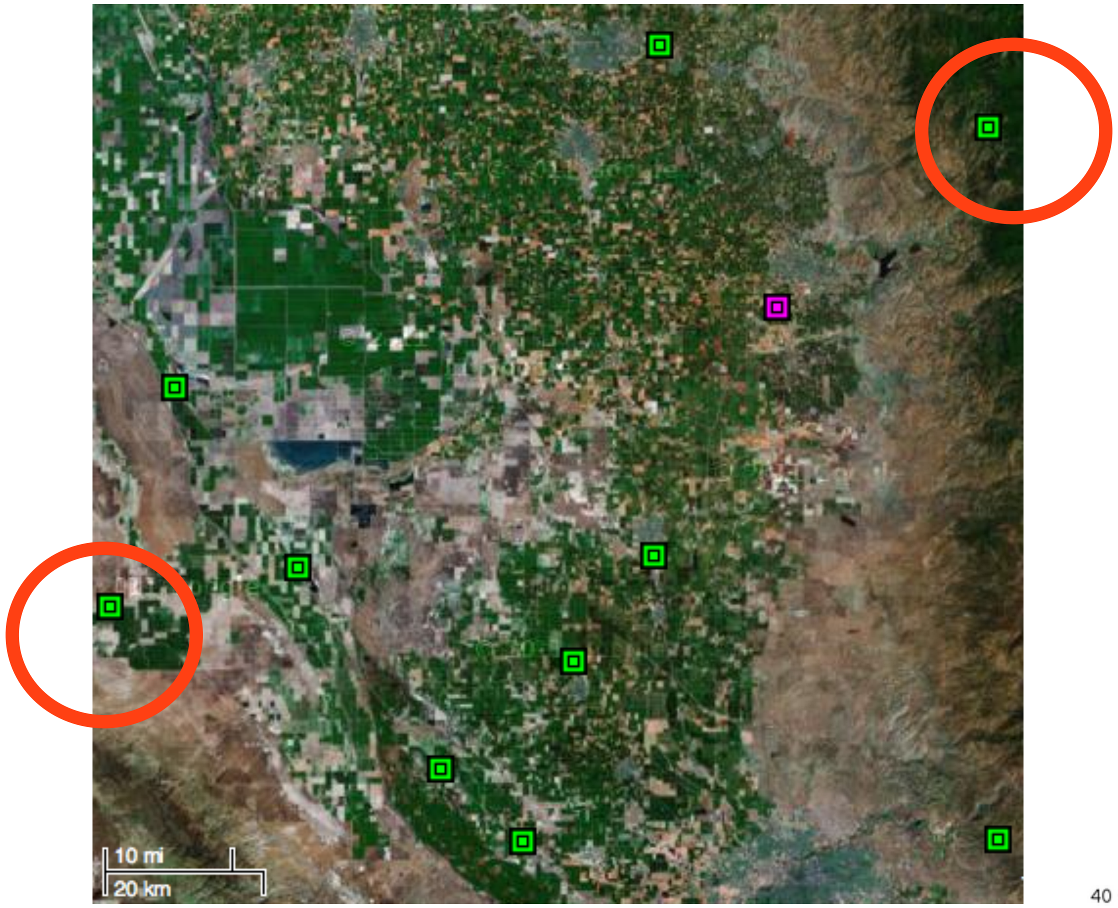
Valley site



Hydrologic Signals:

Surface Loading from soil moisture and snow pack in mountains

Mountain Sites

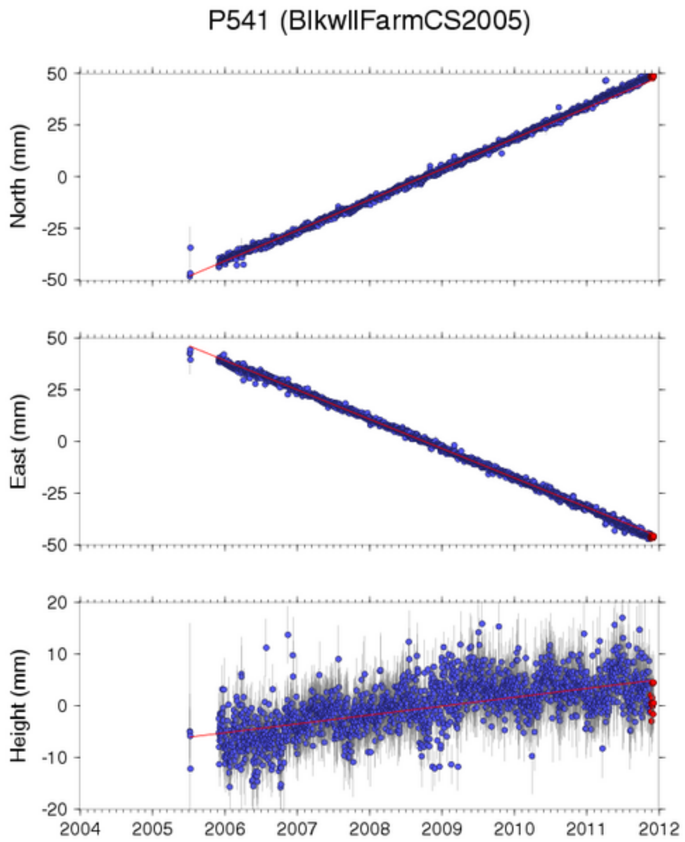


Mountain Sites

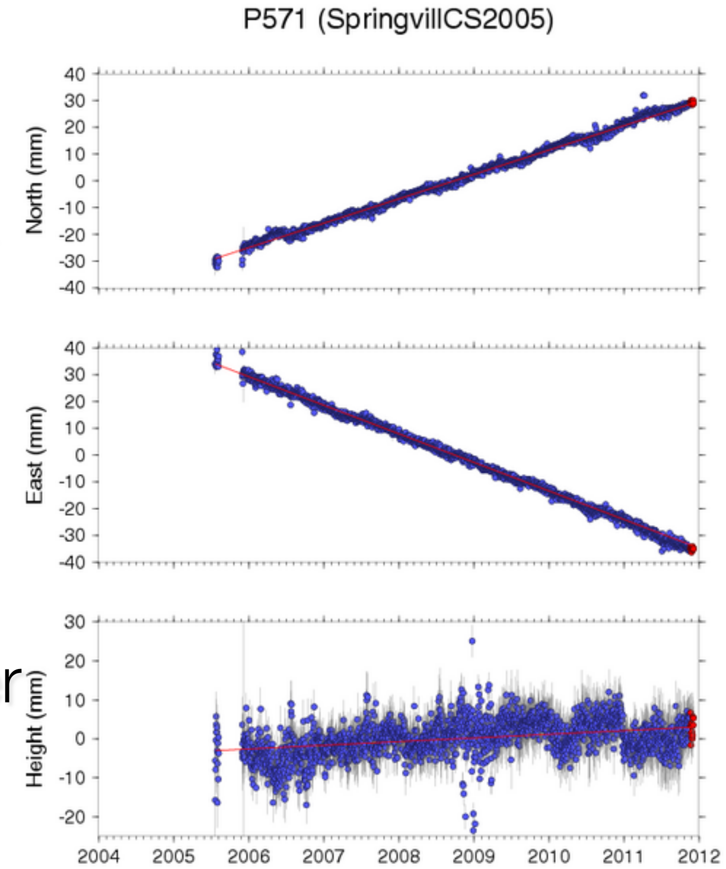
Bedrock sites in Foothills of Sierra Nevada and Coastal Ranges

- Observe slow uplift followed by slow subsidence (~1 mm/yr) from drought and recovery
- Seasonal Cycle peaks in October

Mountain Site

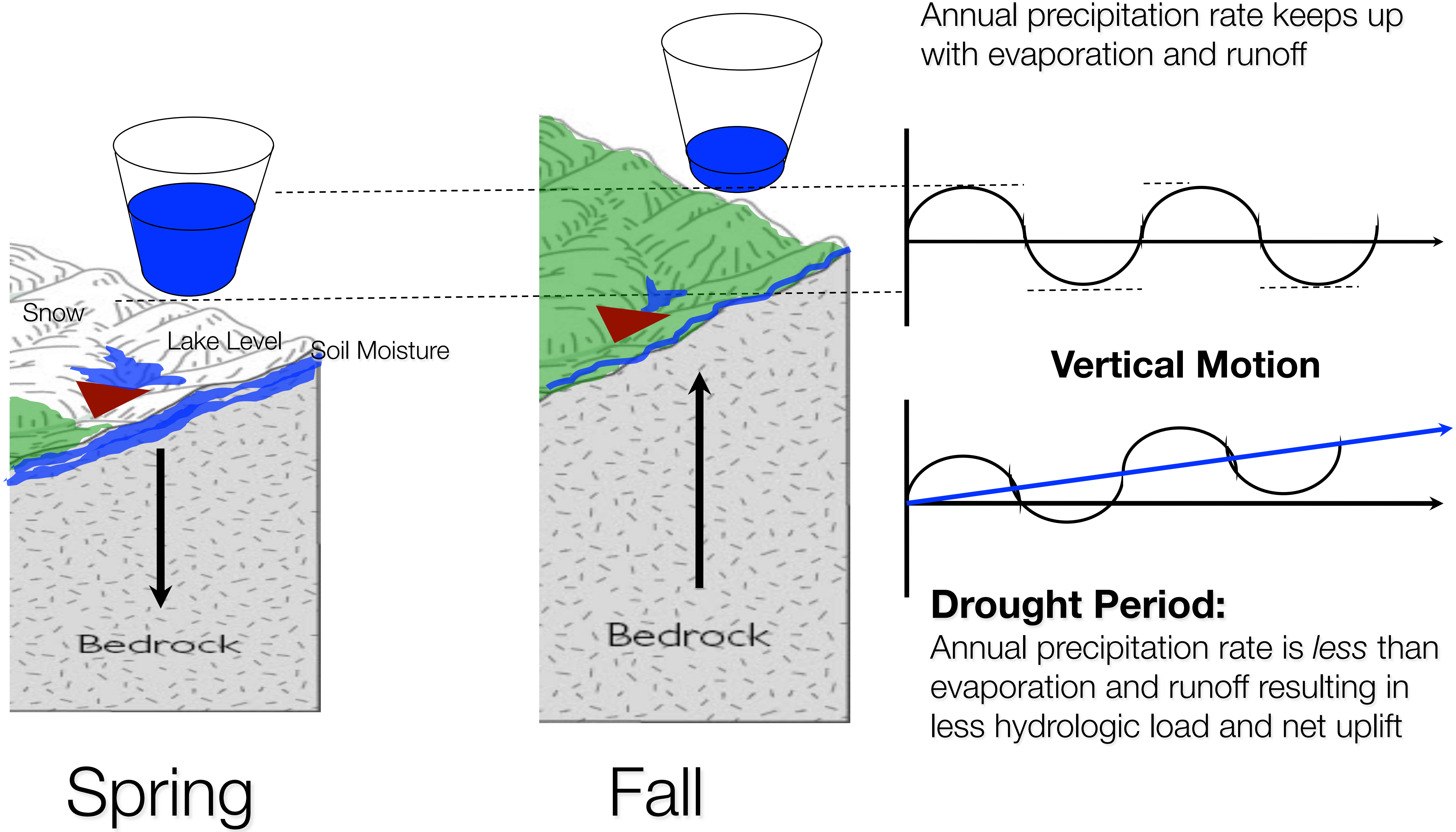


Mountain Site



Mountain Hydrologic Loading

Annual fluctuations in hydrological loads from snow, lake volumes, and moisture in thin soil layers and rock fractures maximum result in elastic uplift and fall of the mountain range observed in the GPS vertical position time series



Normal Precipitation:
Annual precipitation rate keeps up with evaporation and runoff

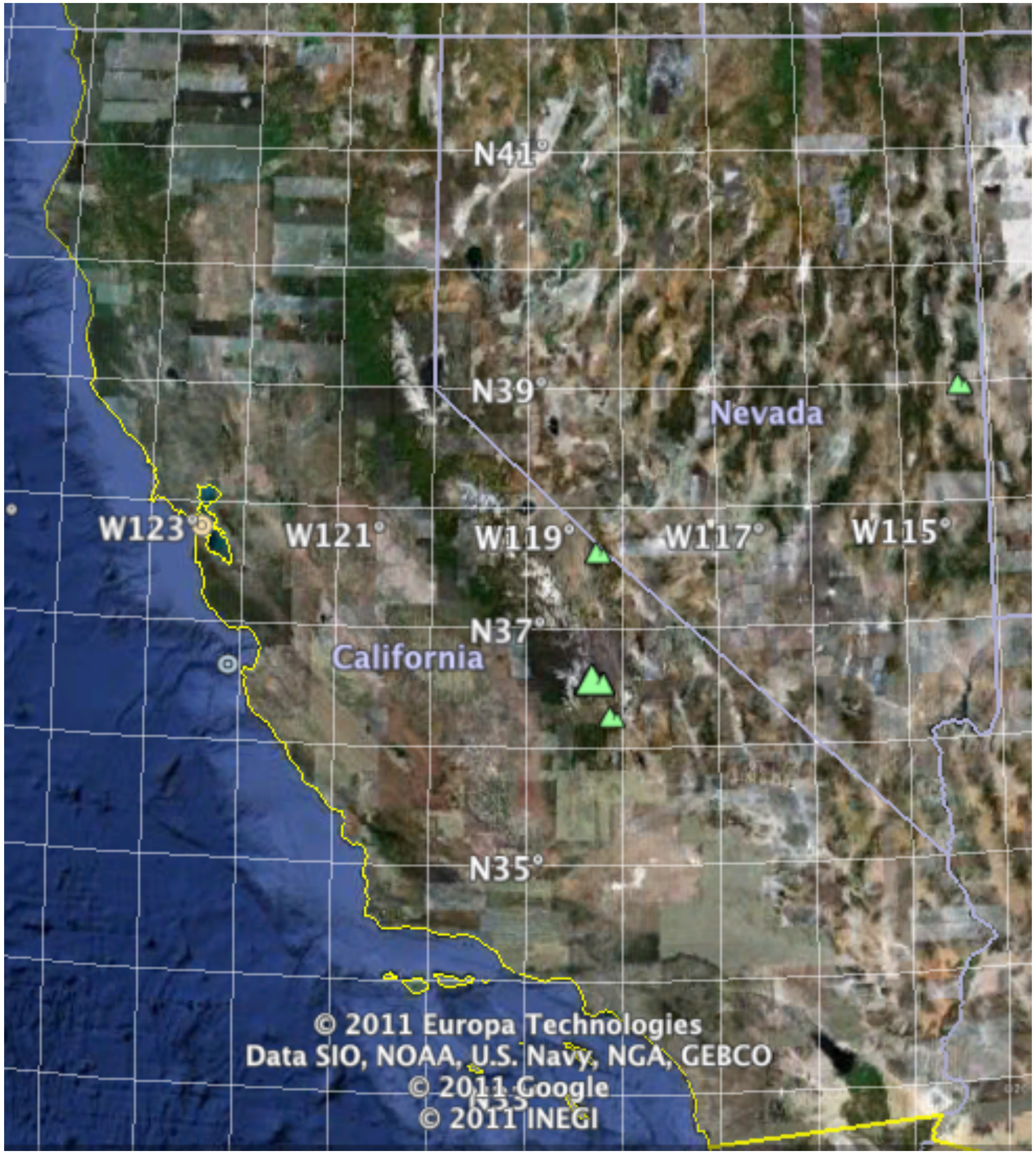
Drought Period:
Annual precipitation rate is *less* than evaporation and runoff resulting in less hydrologic load and net uplift

Green's Function Load Calculations

Hydrologic Load Model:

- Apply temporally/spatially variable hydrologic storage load from Global Land Data Assimilation System (GLDAS) at each point on a global 1 deg x 1 deg grid

- Calculate the vertical and horizontal model deformation at each individual GPS station in the network.



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Data SIO, NOAA, U.S. Navy, NGA, GEBCO
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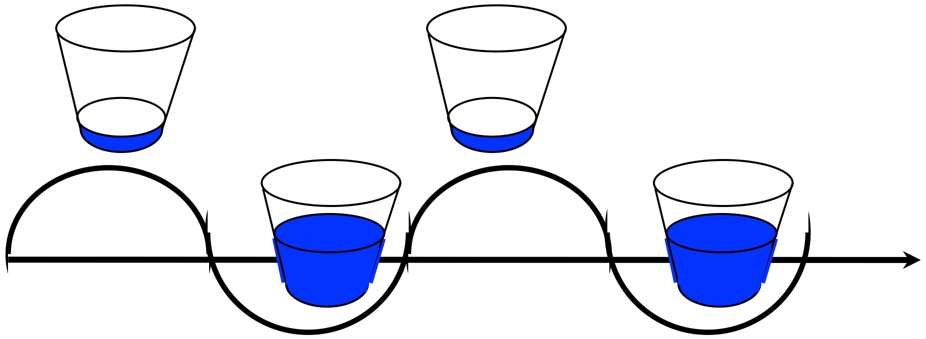
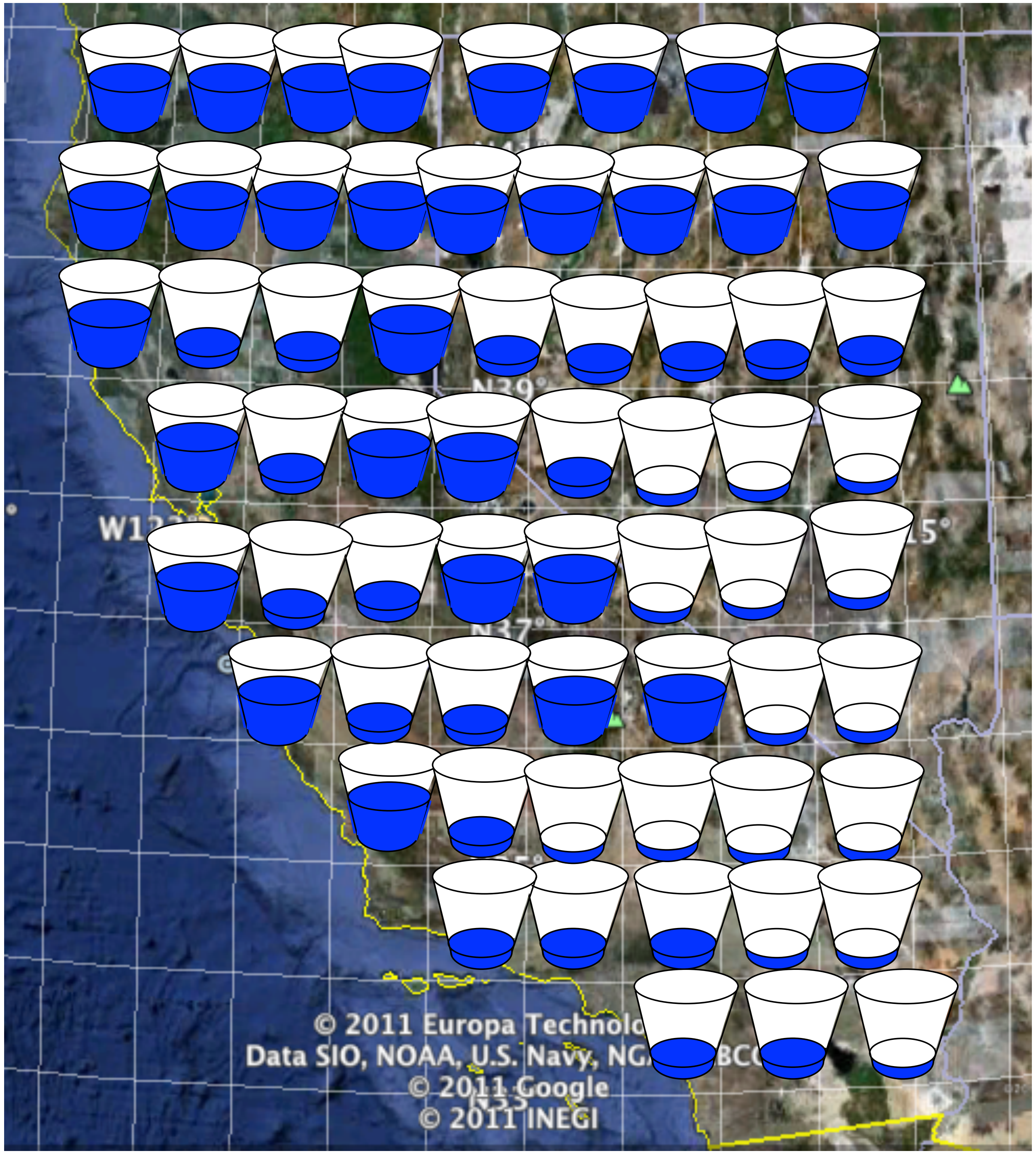
UNAVCO

Green's Function Load Calculations

Hydrologic Load Model:

The contributions from the load derived from each grid point is summed up to get the total load history for each GPS site.

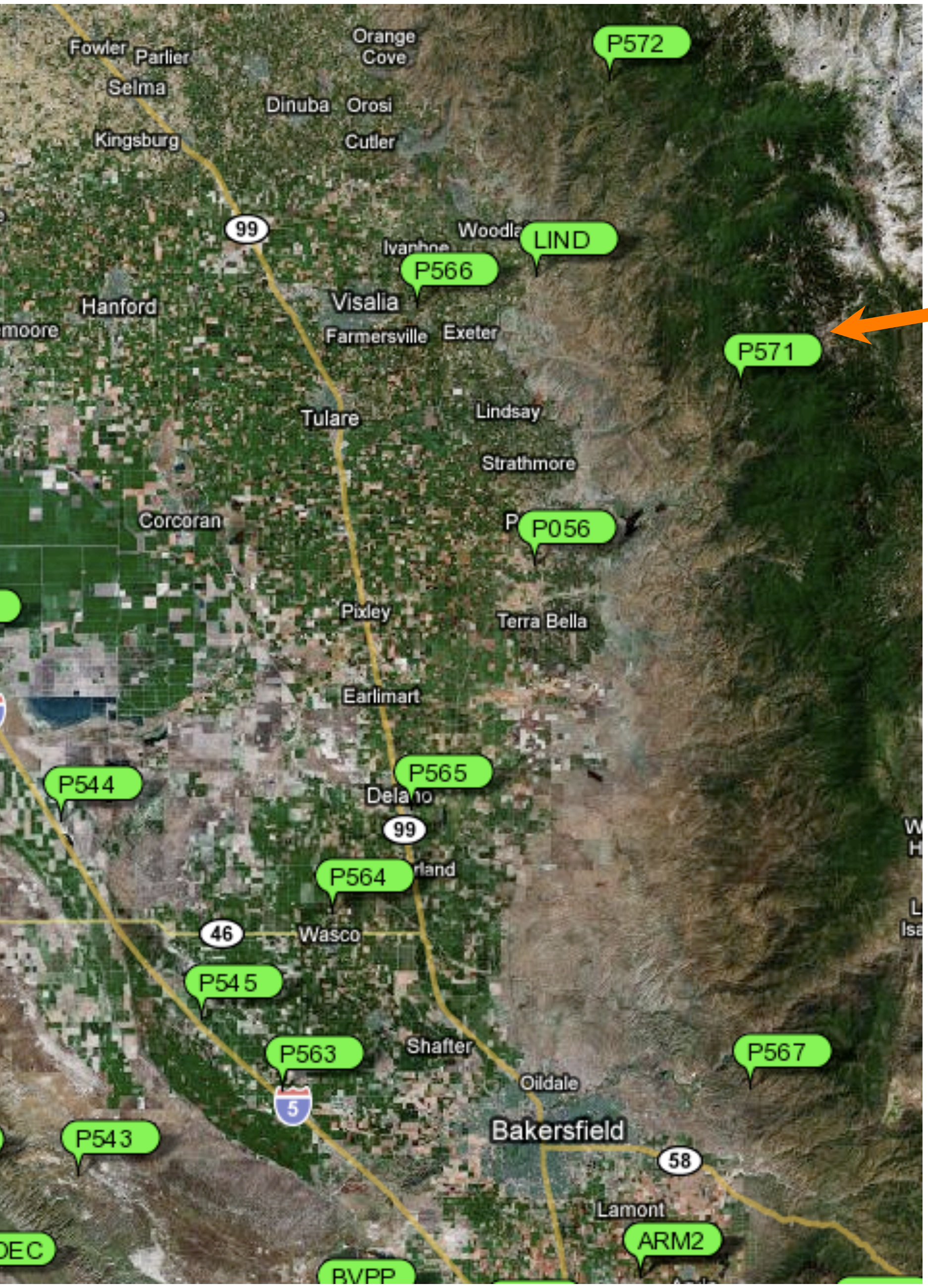


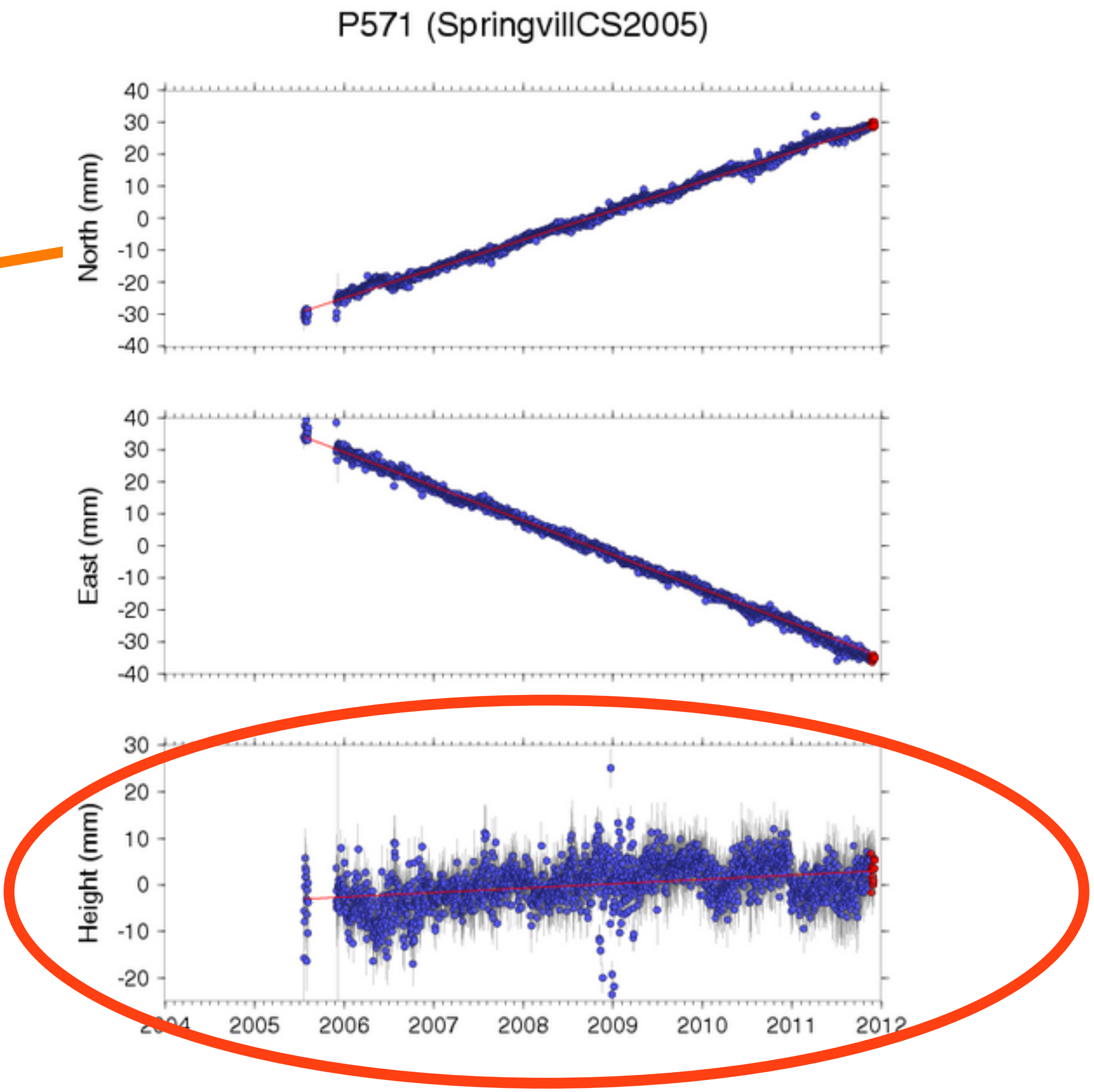


Hydrologic Loading in Sierras

Example hydrologic loading for GPS site P571 located on bedrock in the Sierra Nevada Mountains.

Model of the Vertical component of motion.

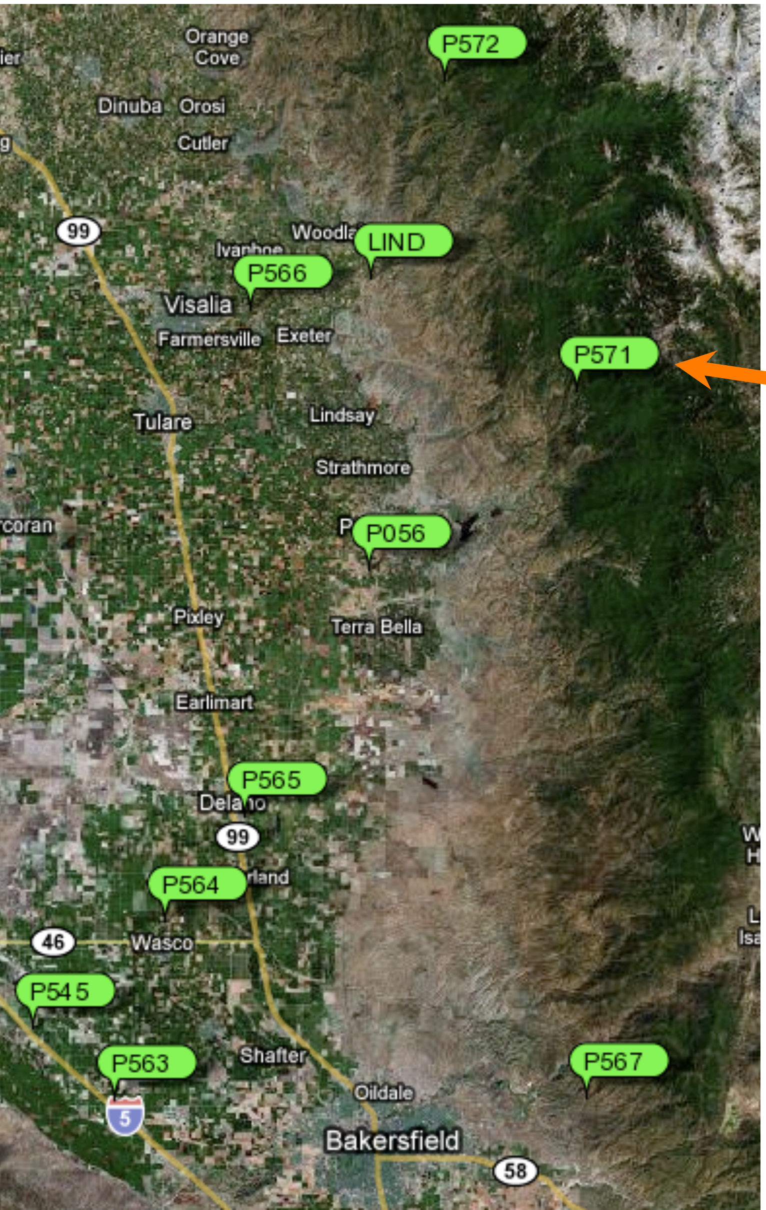


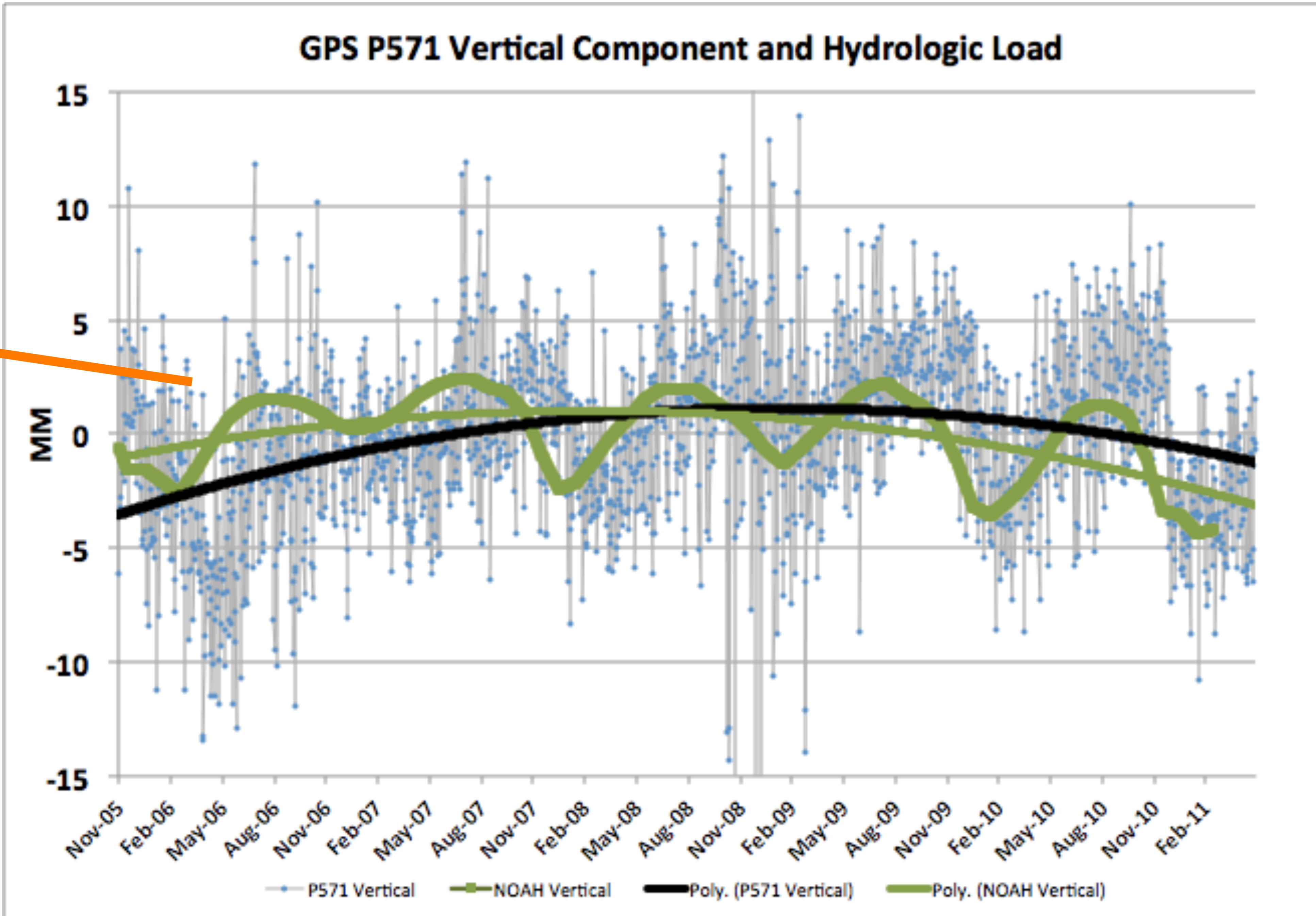

P571 (SpringvillCS2005)

Hydrologic Loading in Sierras

P571 can be modeled using the GLDAS NOAH global hydrologic land surface models. These hydrologic surface loads are entirely independent of the GPS signals.

Seasonal variation of ~4 mm peak-to-peak in vertical component.



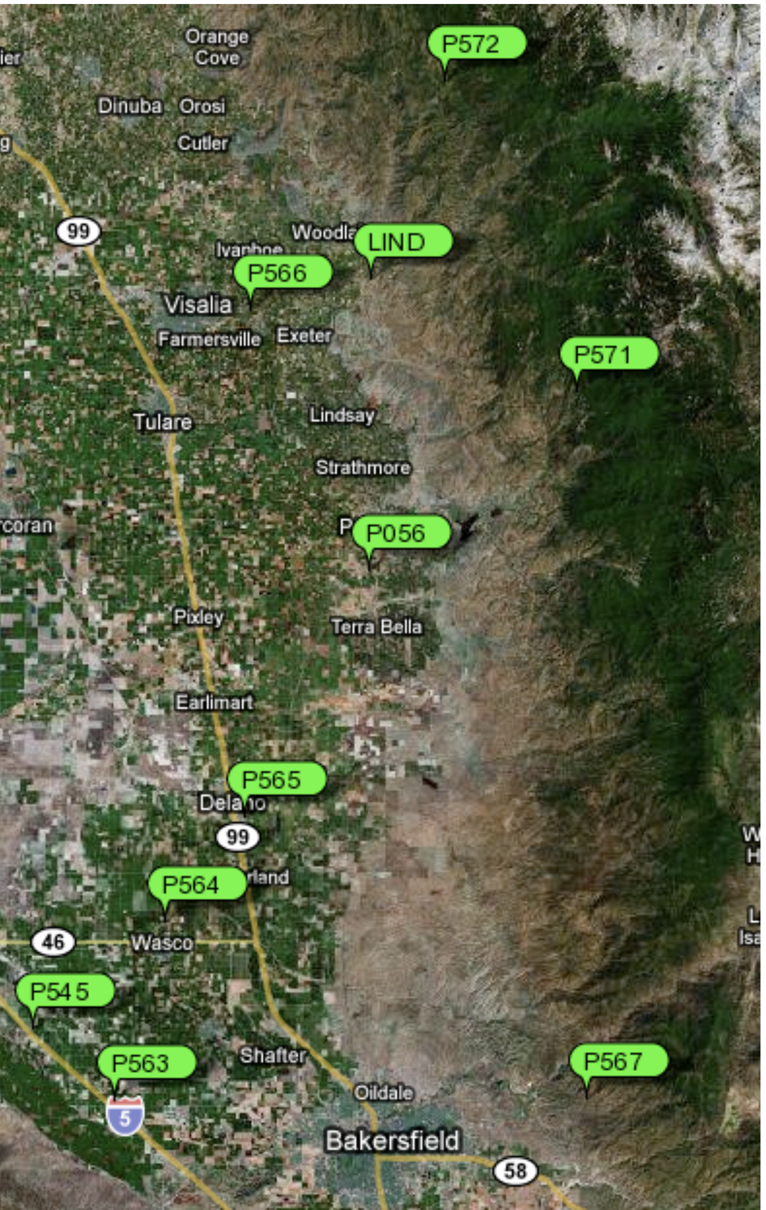


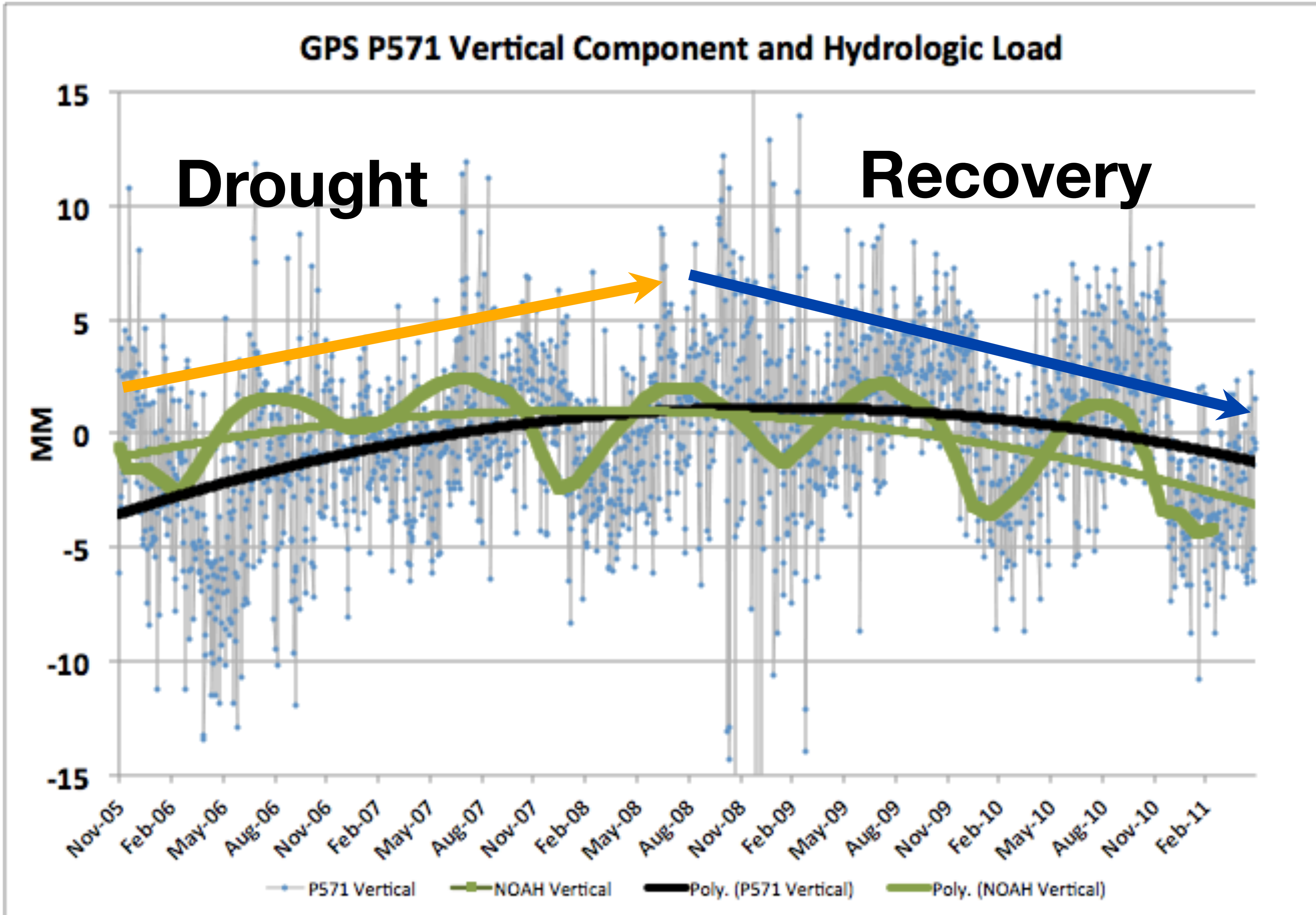
Hydrologic Loading in Sierras

Also observe very subtle changes in trend:

- Uplift at 1 mm/yr from 2005-2009 that corresponds to period of drought and reduced load

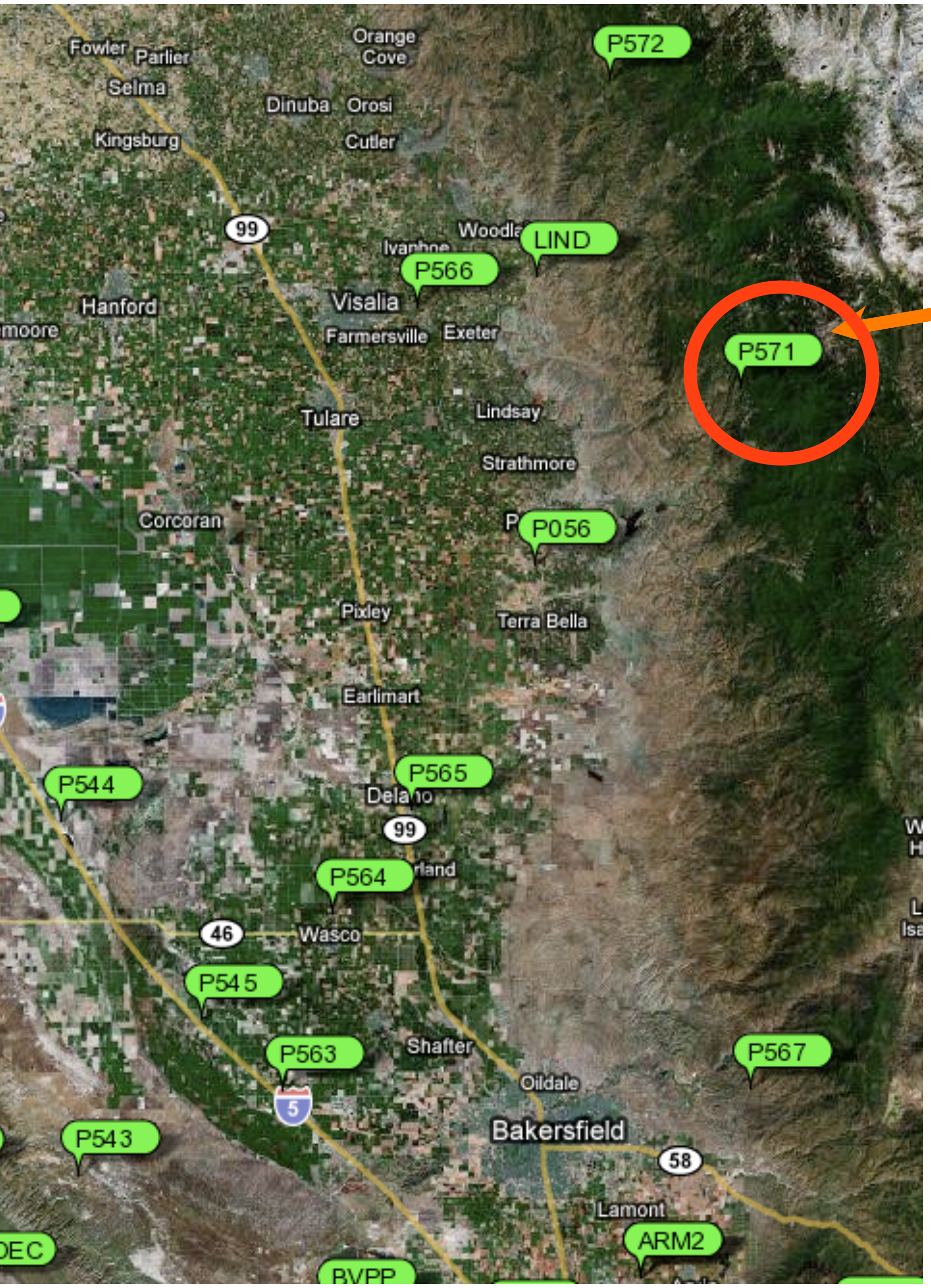
- Subsidence at 1 mm/yr from 2009-2011 that corresponds to end of drought and increased load as water mass increases during recovery phase

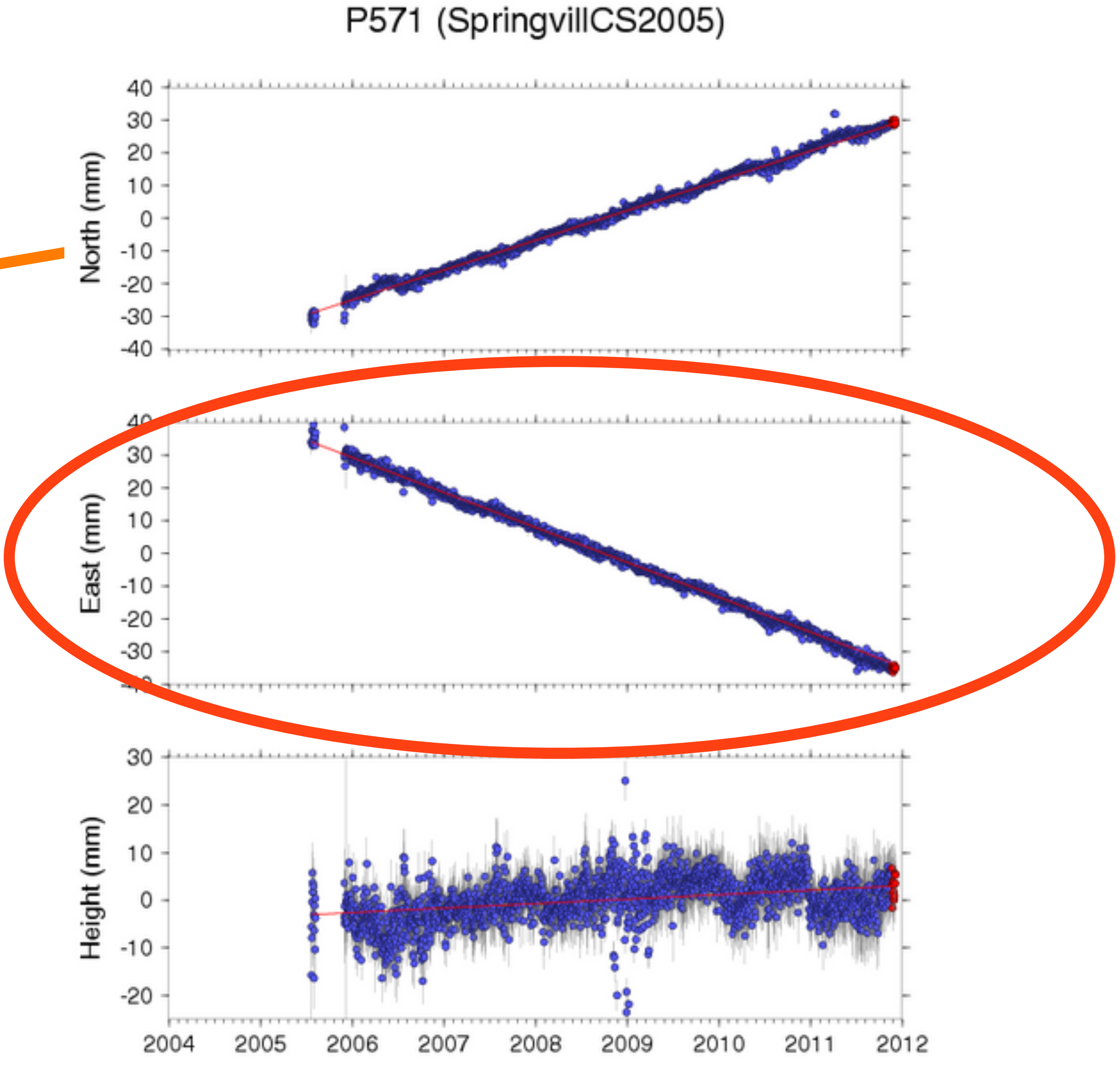



GPS P571 Vertical Component and Hydrologic Load

Hydrologic Loading in Sierras

Next model East component for mountain site after removing linear trend from plate boundary zone deformation.

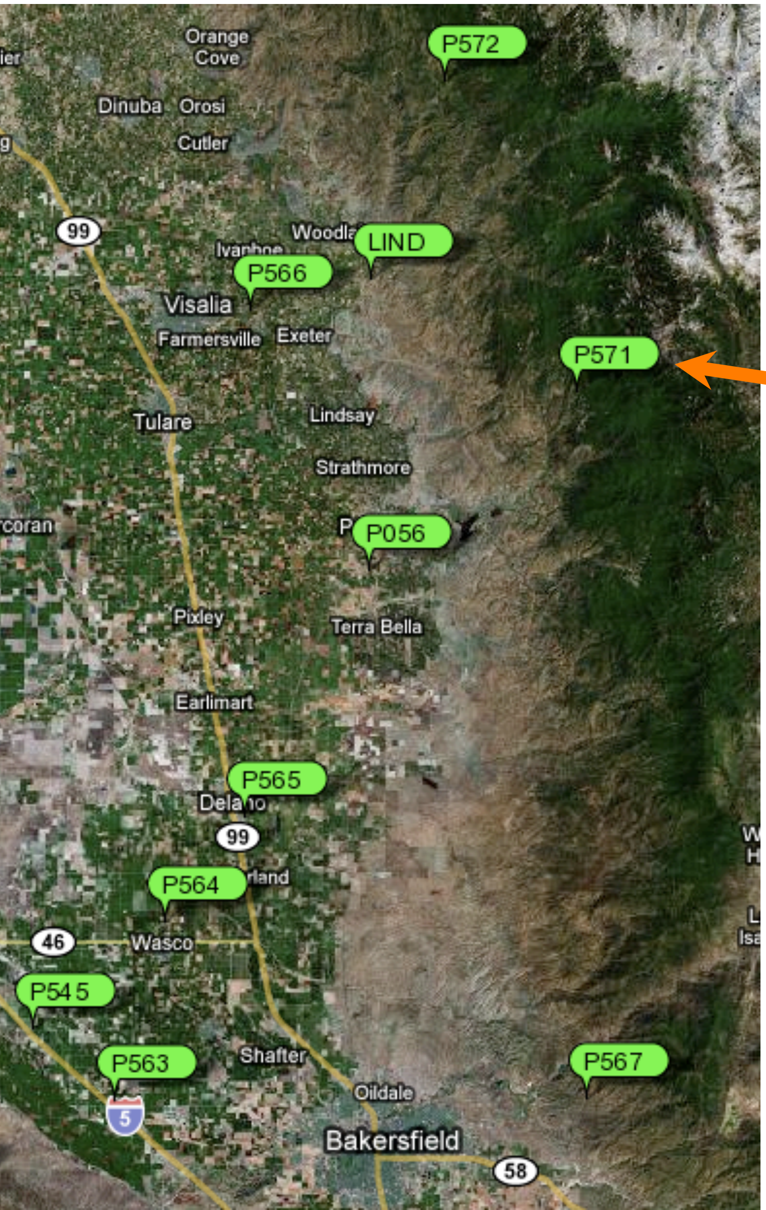


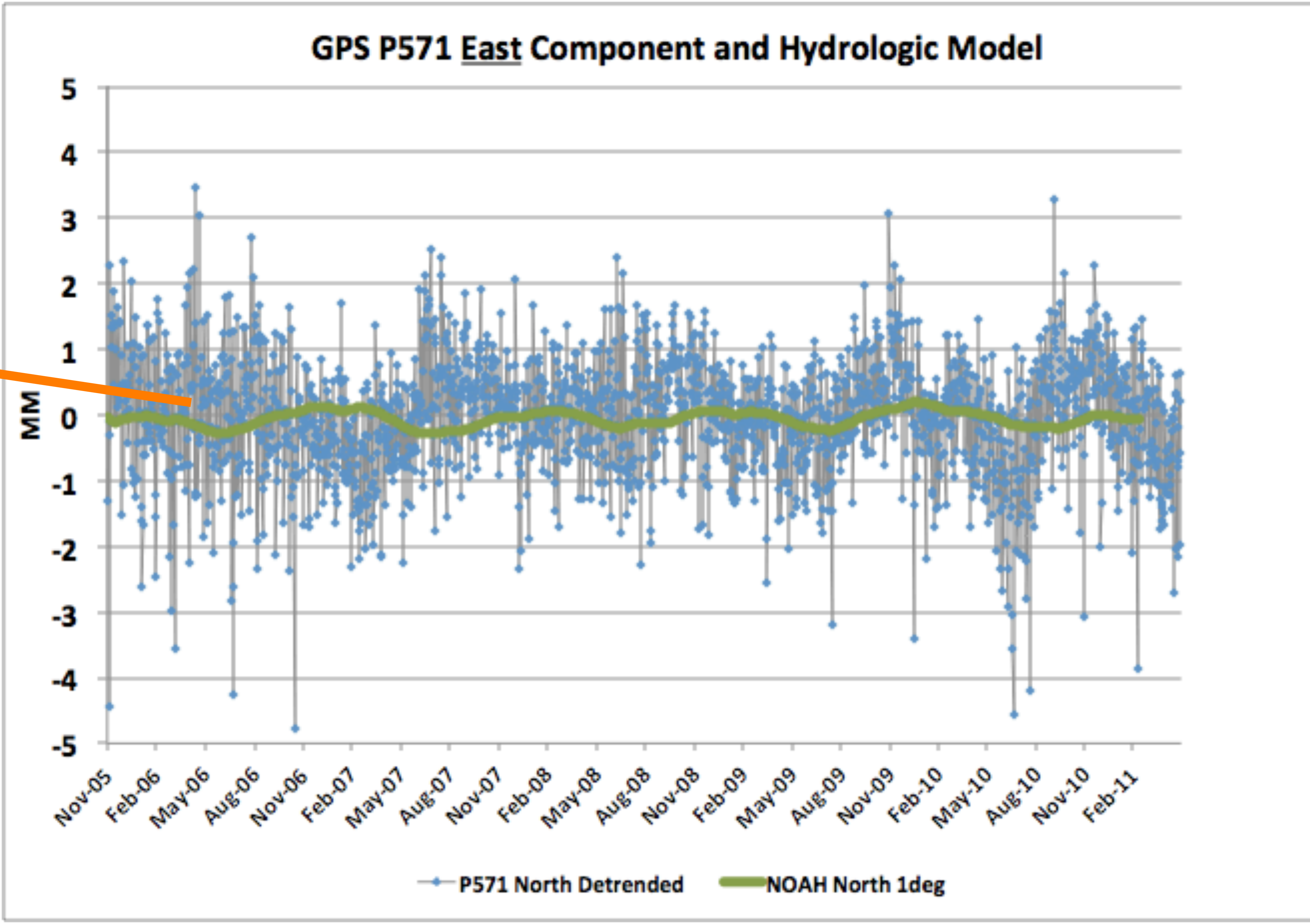


Hydrologic Loading in Sierras

East component for station P571 compared to GLDAS NOAH global hydrologic land surface models.

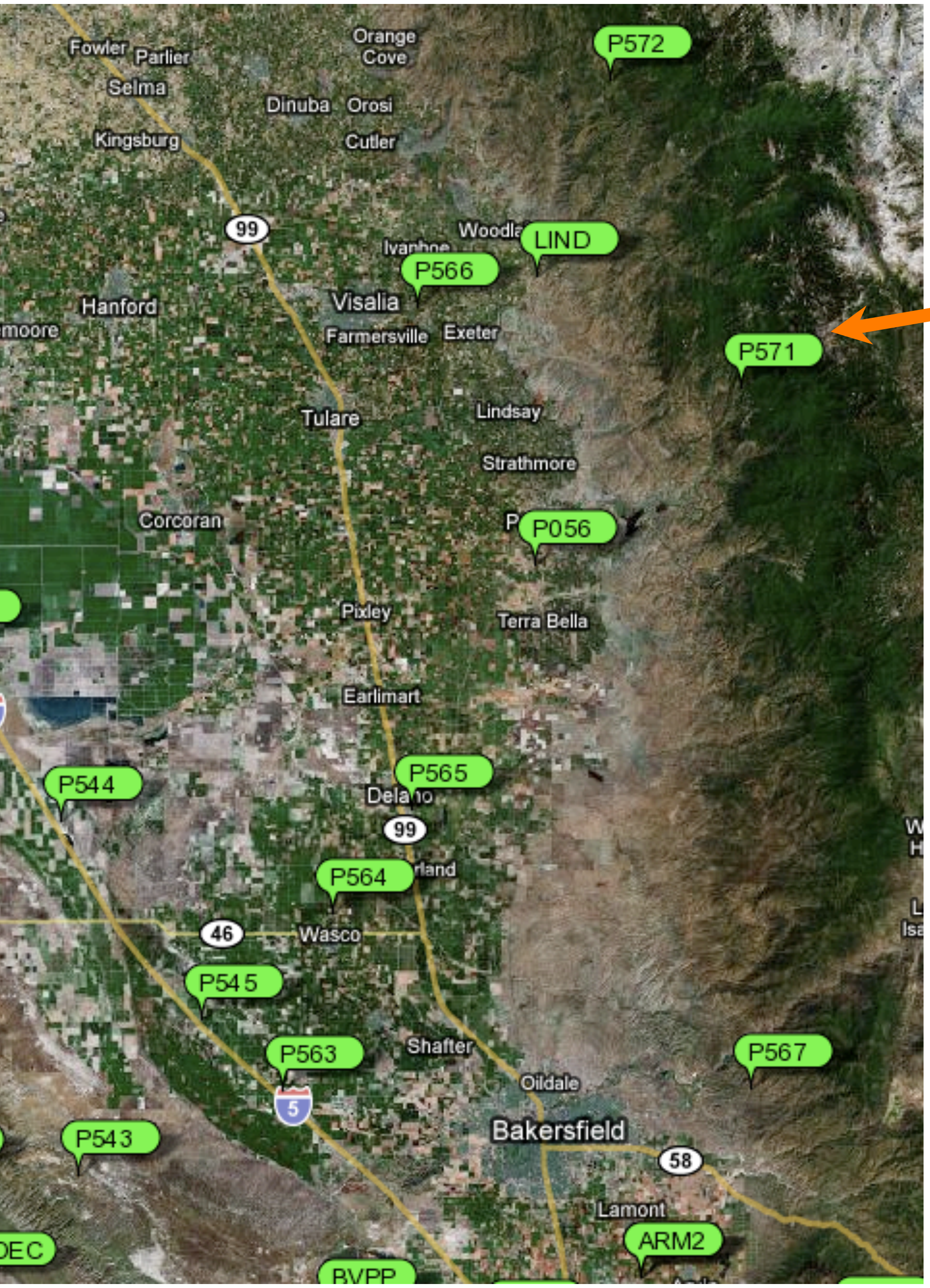
- **No significant residual longer term variation after removing linear trend**
- **Seasonal variation of <1 mm peak-to-peak in East Component**

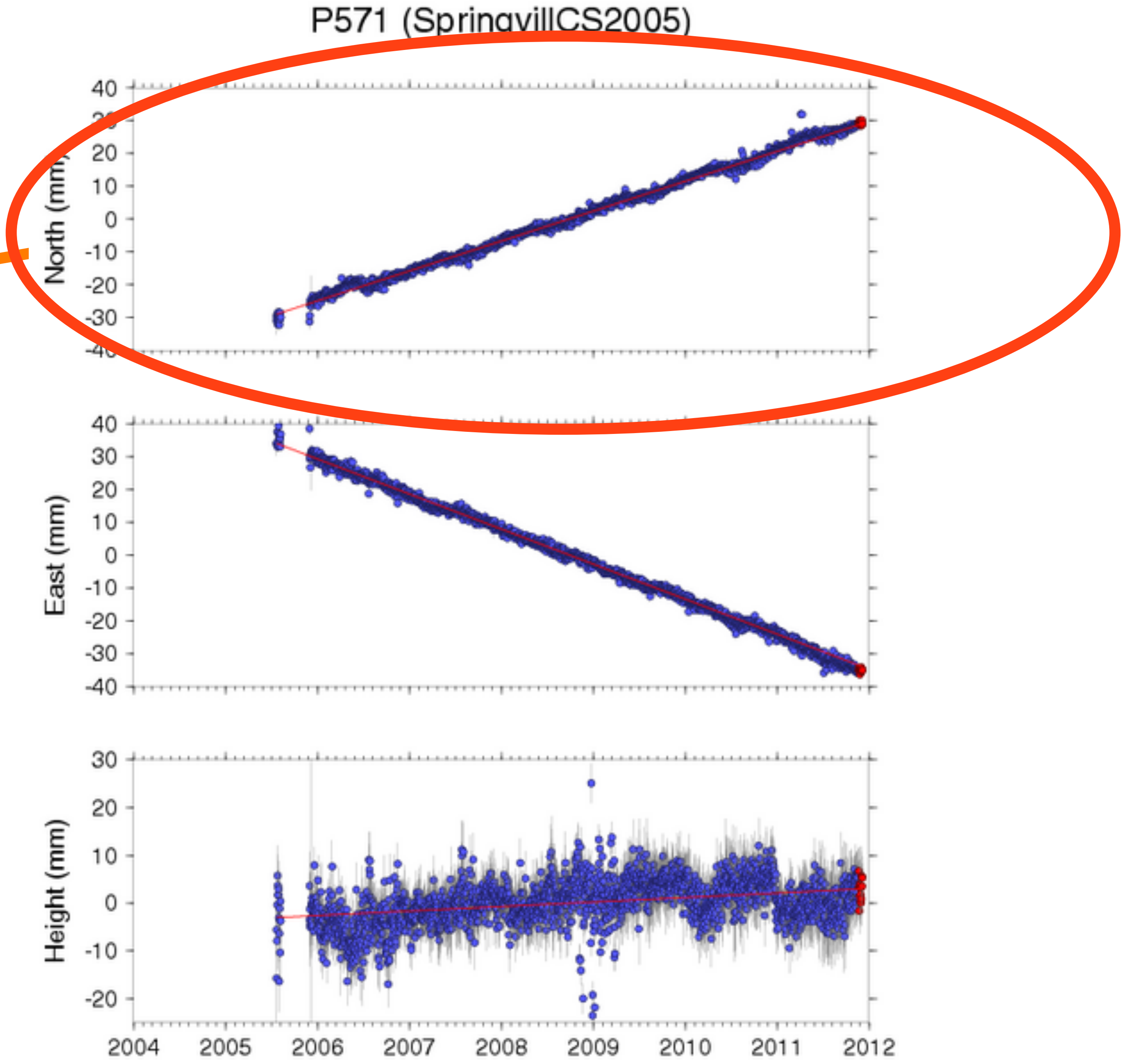



GPS P571 East Component and Hydrologic Model

Hydrologic Loading in Sierras

Next model North component after removing linear trend.

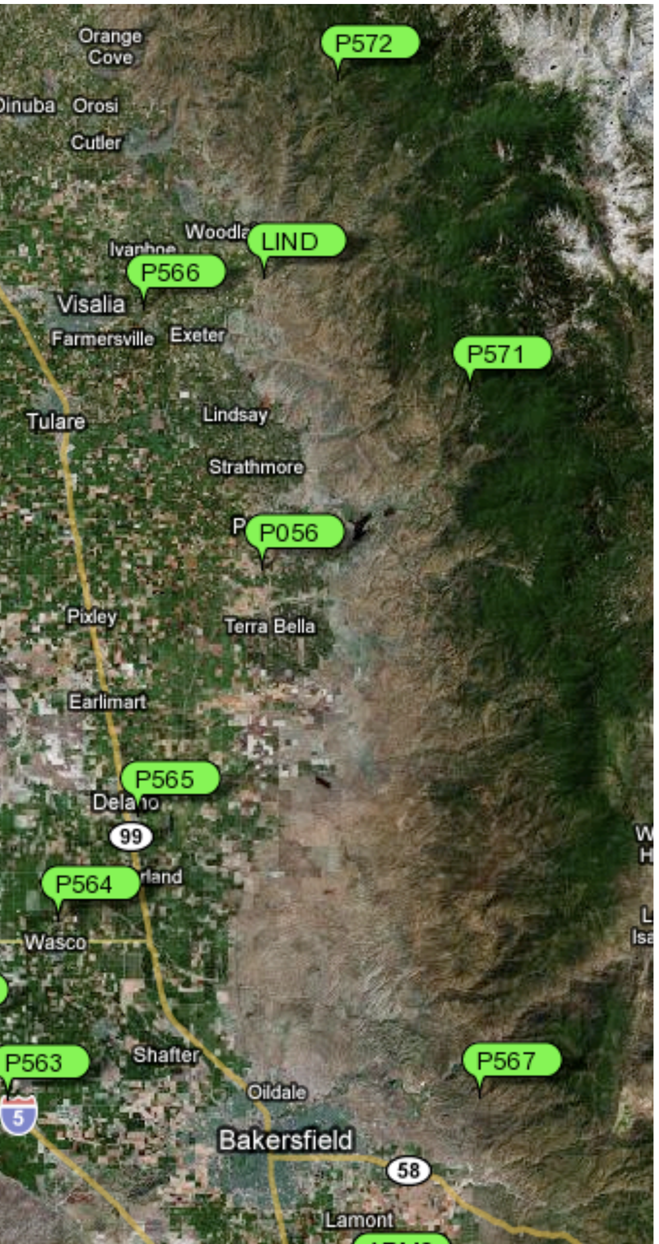


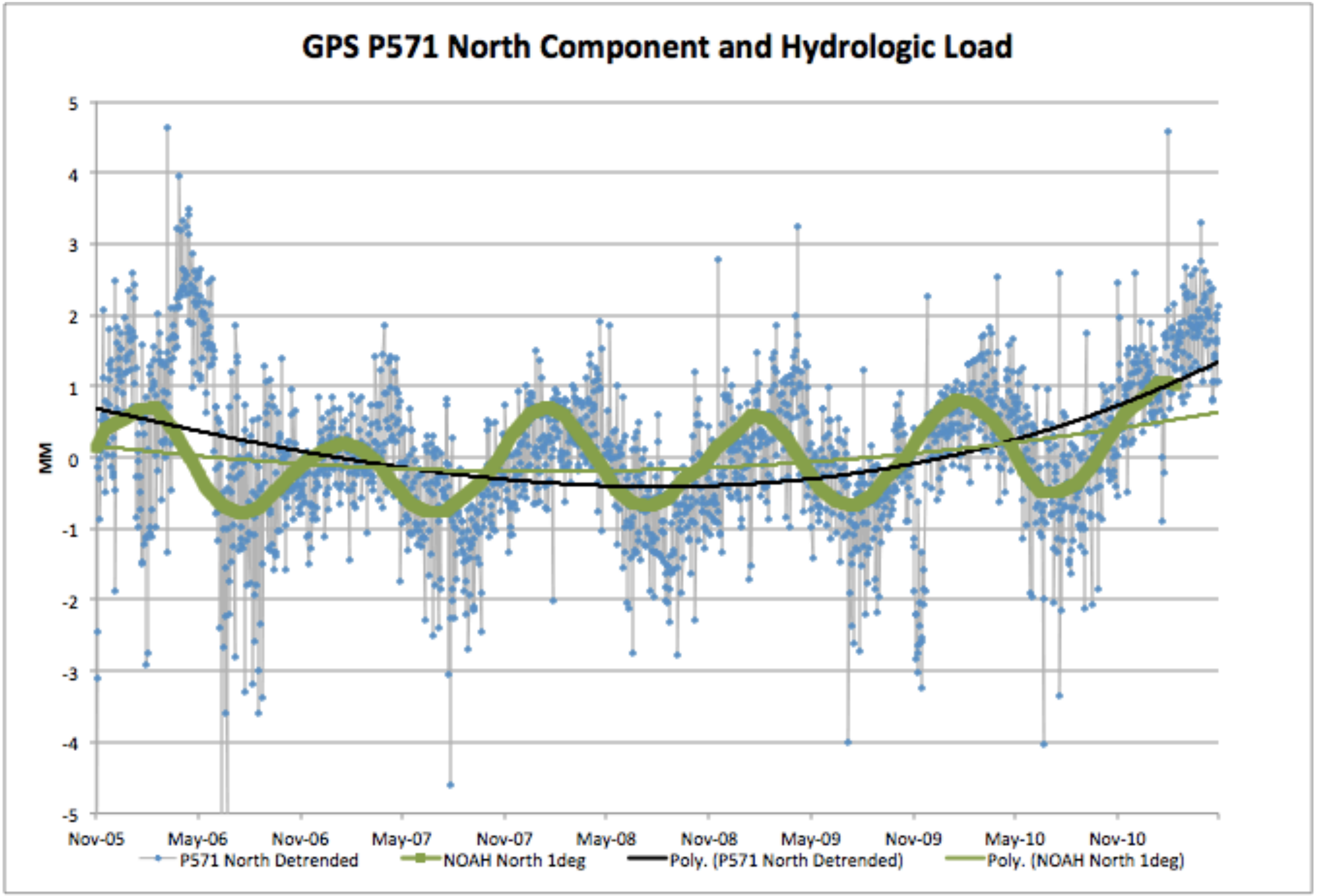


Hydrologic Loading in Sierras

<u>North component</u> for station P571 compared to GLDAS NOAH global hydrologic land surface models.

- **Observe a residual multi-year variation correlated to vertical variations**
- **Seasonal variation of ~2 mm peak-to-peak in vertical agrees with model results**




GPS P571 North Component and Hydrologic Load

GNSS Signals

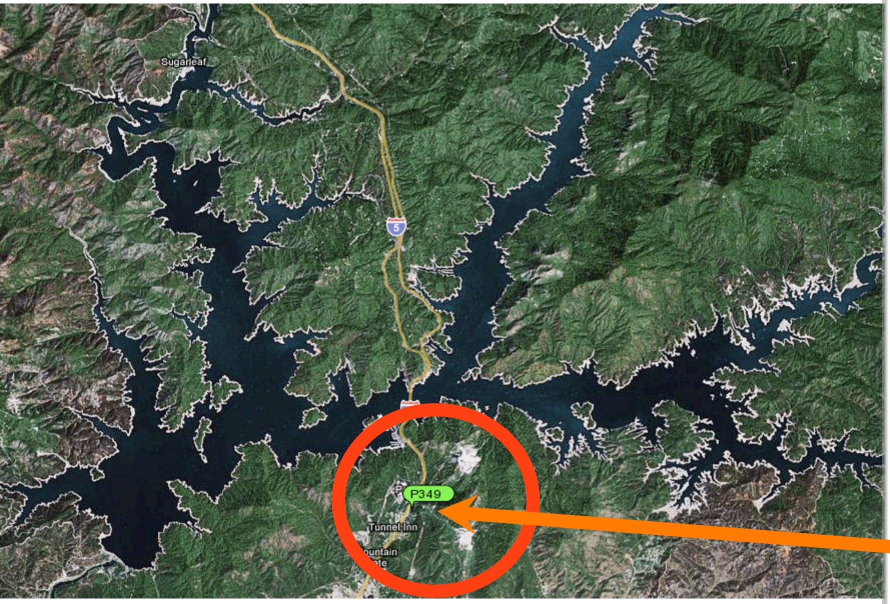
Hydrologic Signals:

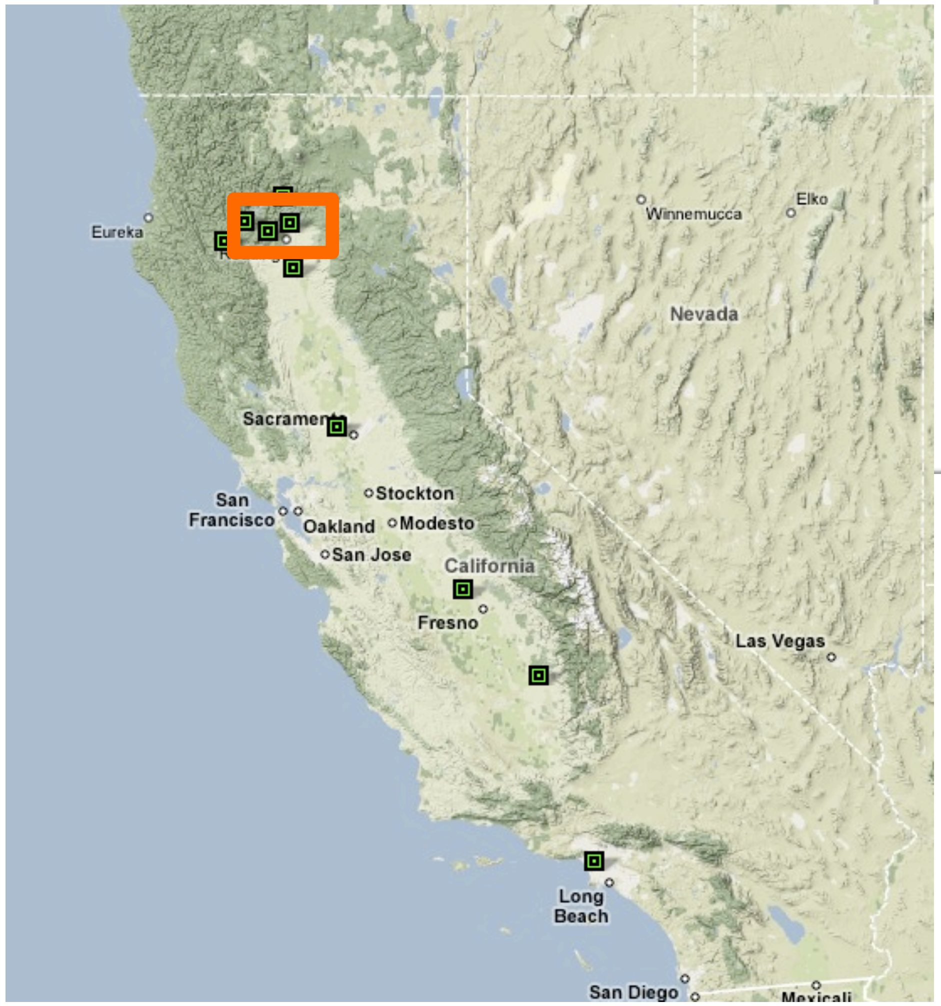
Surface loading from soil moisture and snow pack in mountains

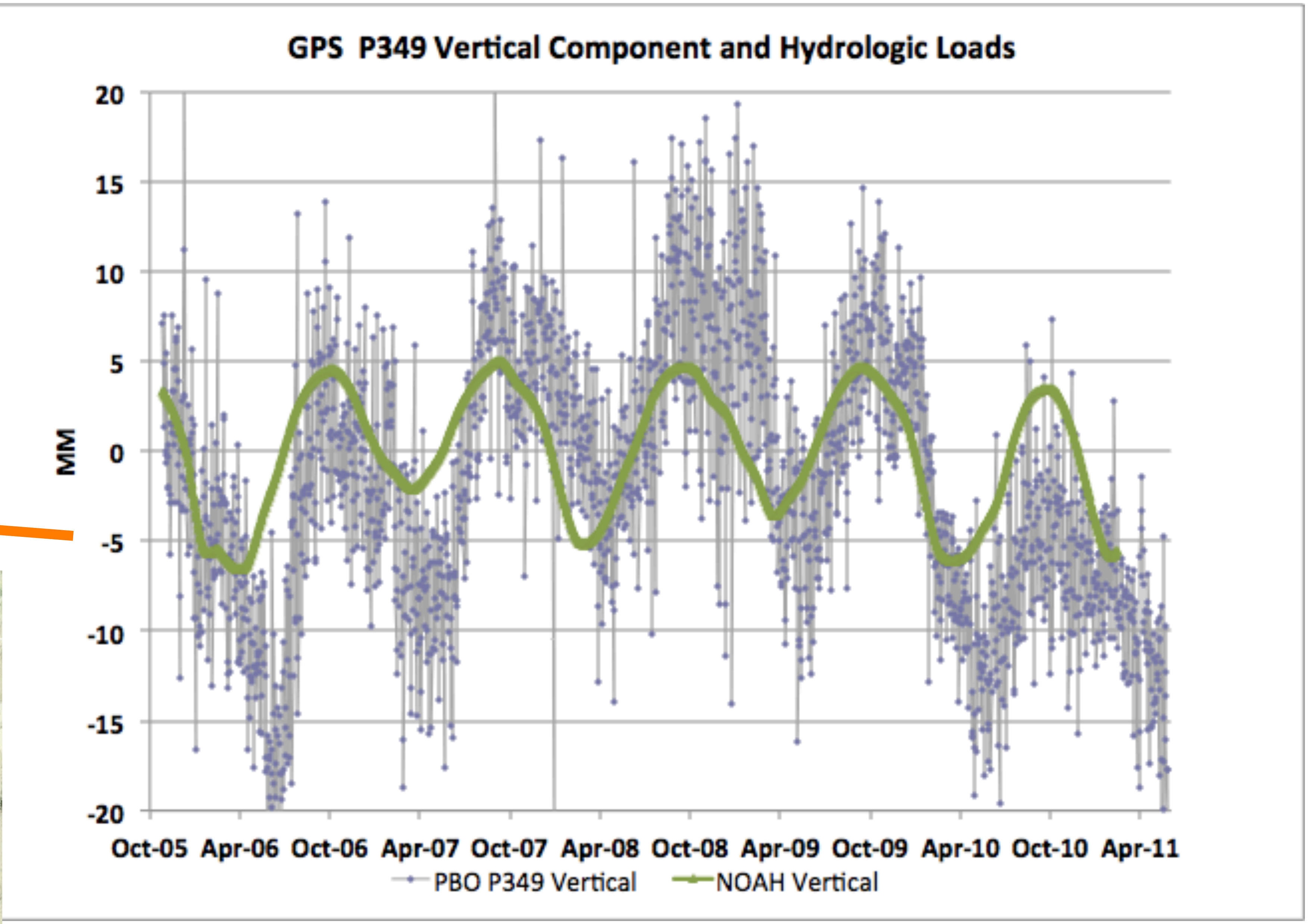
Plus

Surface loading from lakes

Hydrologic loads at Lake Shasta, California

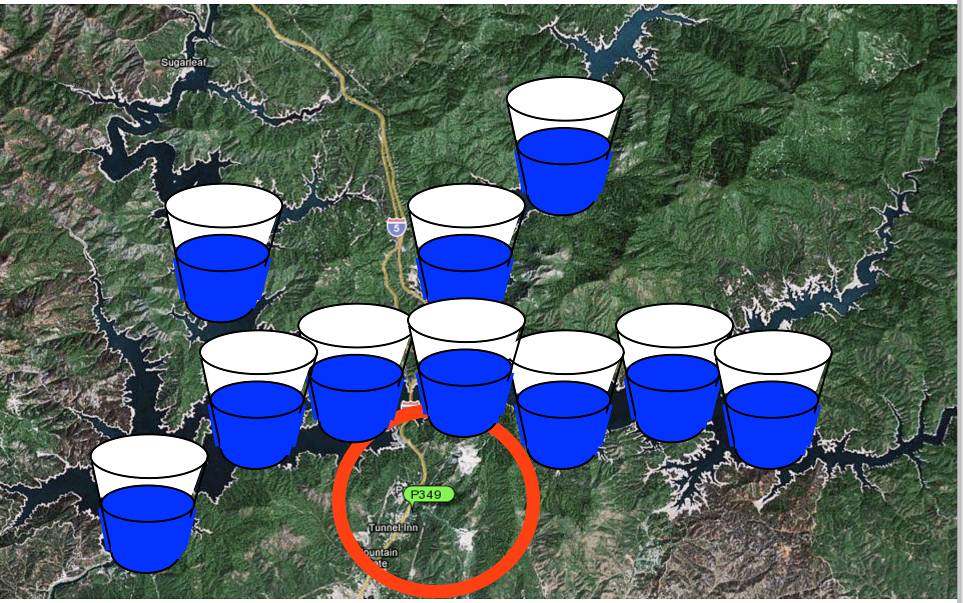


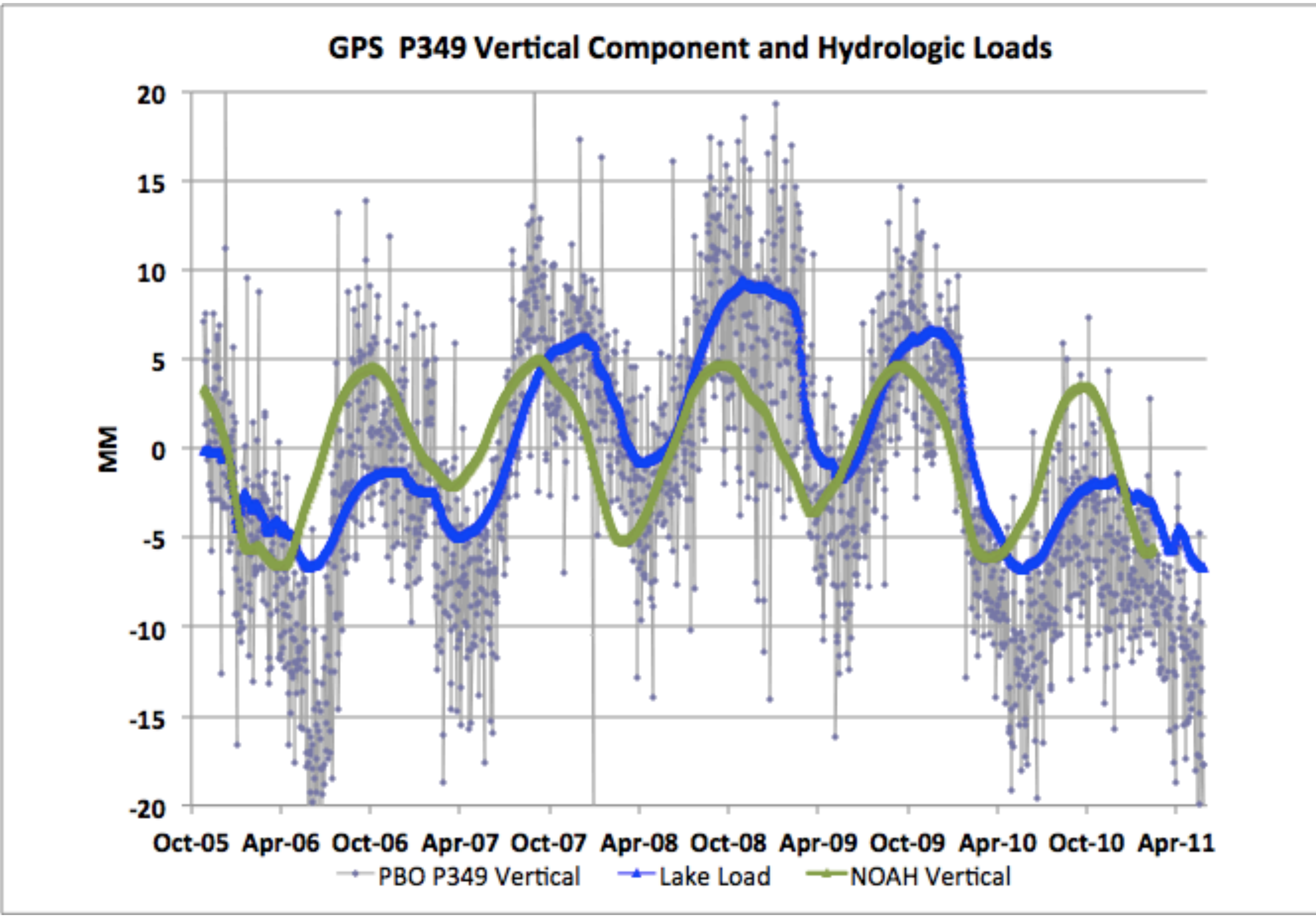




Gray = **Observed Vertical GPS Signal**
Green = Hydrologic load from GLDAS NOAH model (Snow and Soil Moisture load)

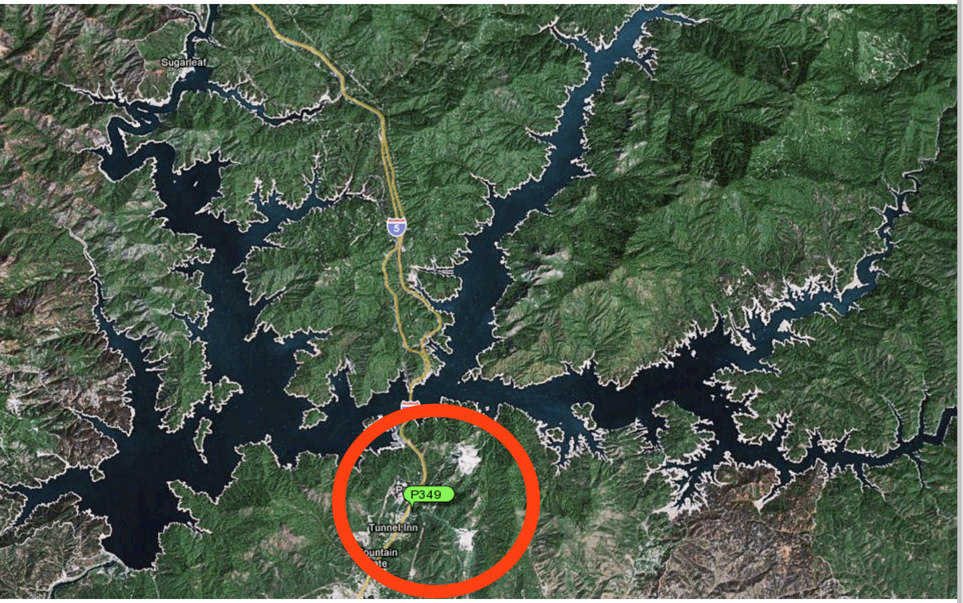
Vertical Component

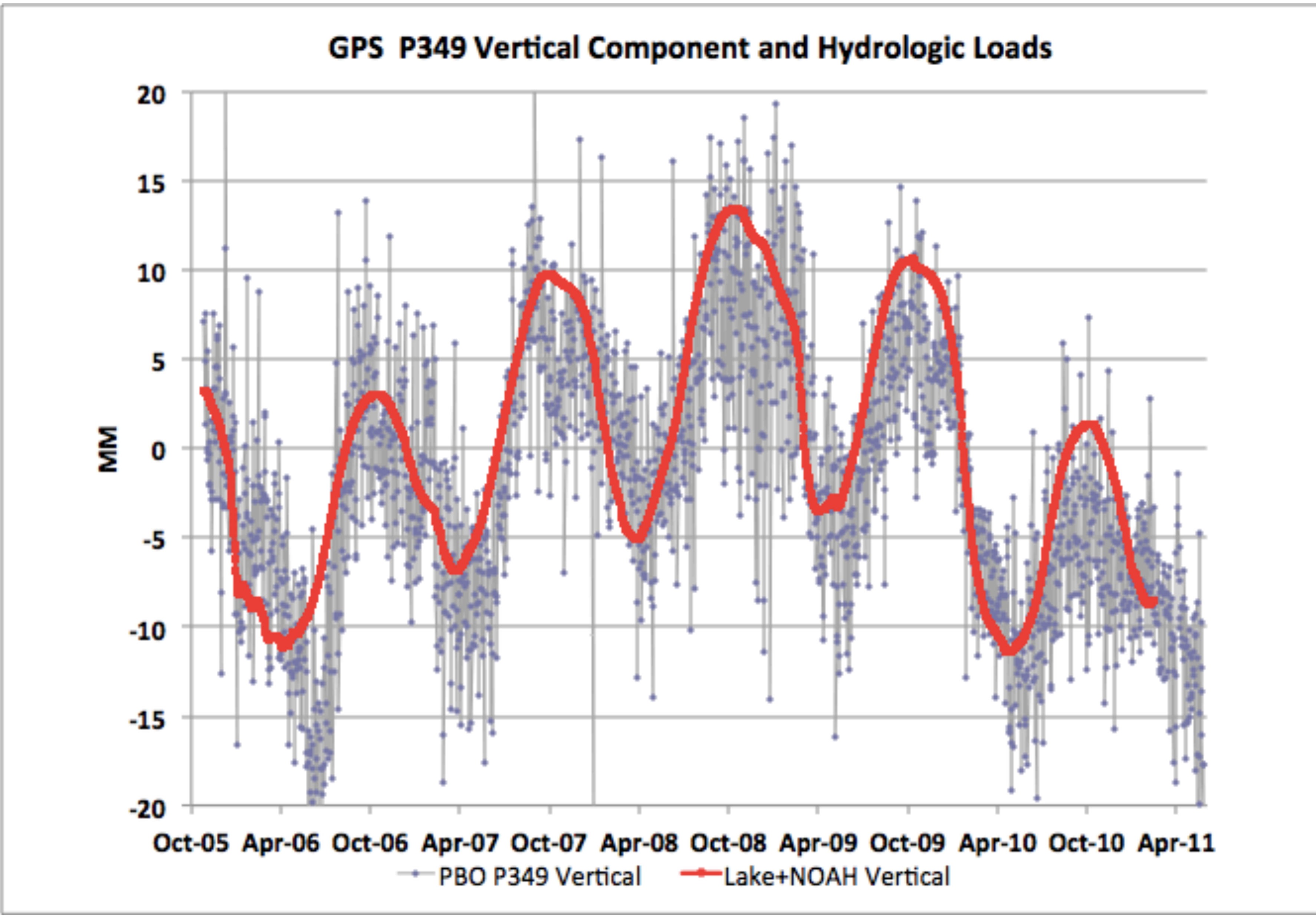




Gray = **Observed Vertical GPS Signal**
Green = Hydrologic load from GLDAS NOAH model (Snow and Soil Moisture load)
Blue = Lake Load

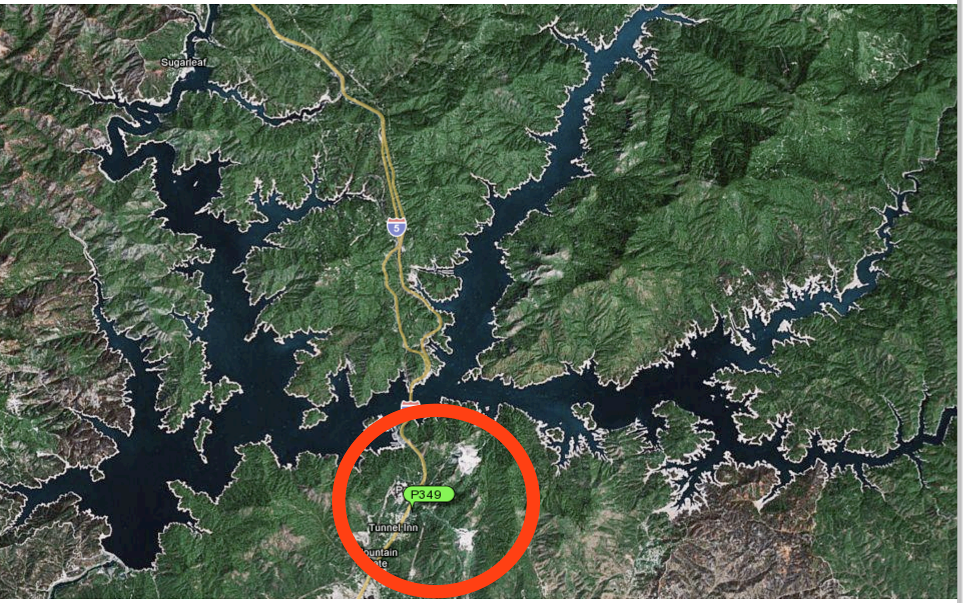
Vertical Component

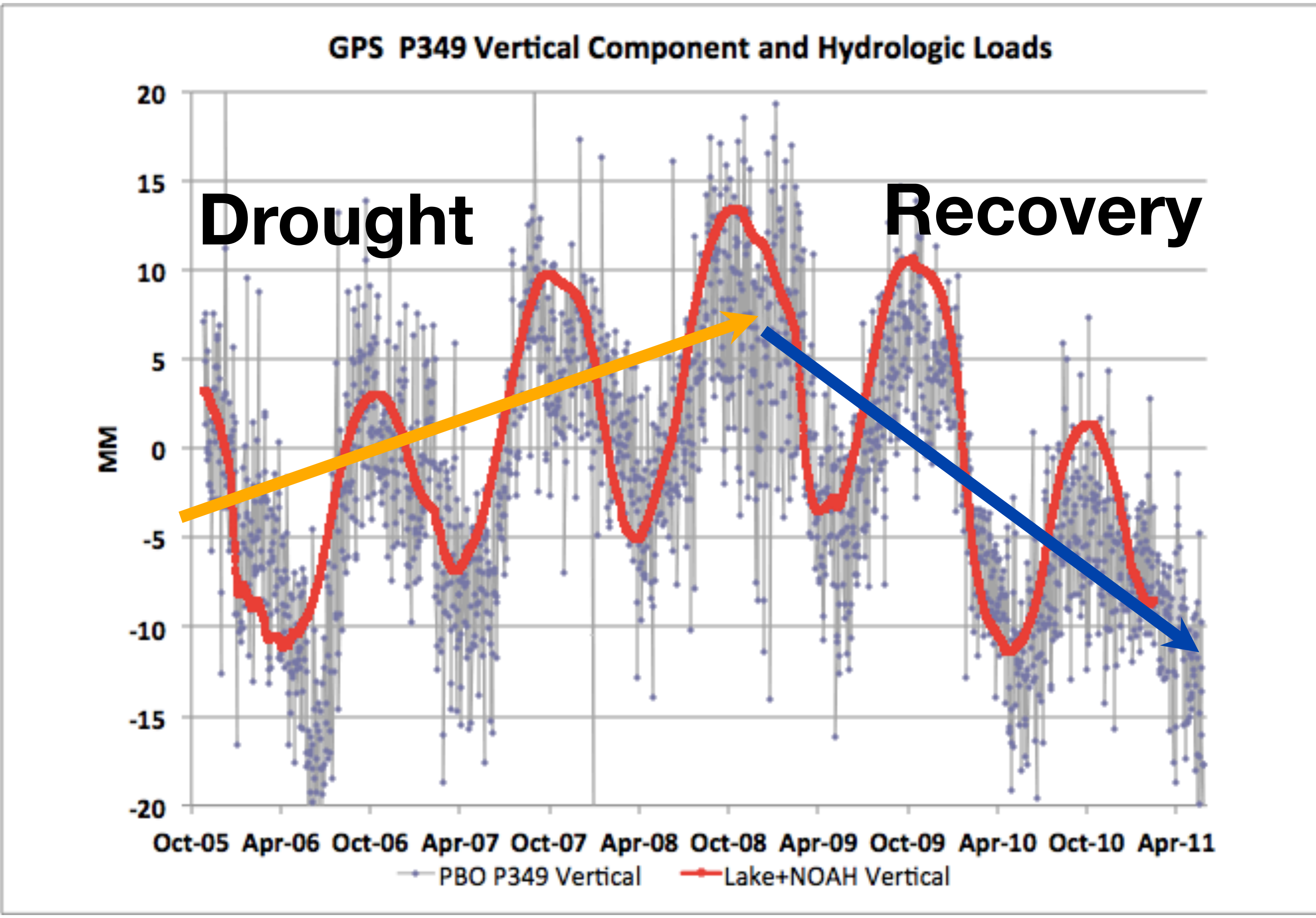




Gray = **Observed Vertical GPS Signal**
Red = **Combination of Lake and NOAH surface loads (reduces standard deviation from ~5mm to <2mm**

Vertical Component

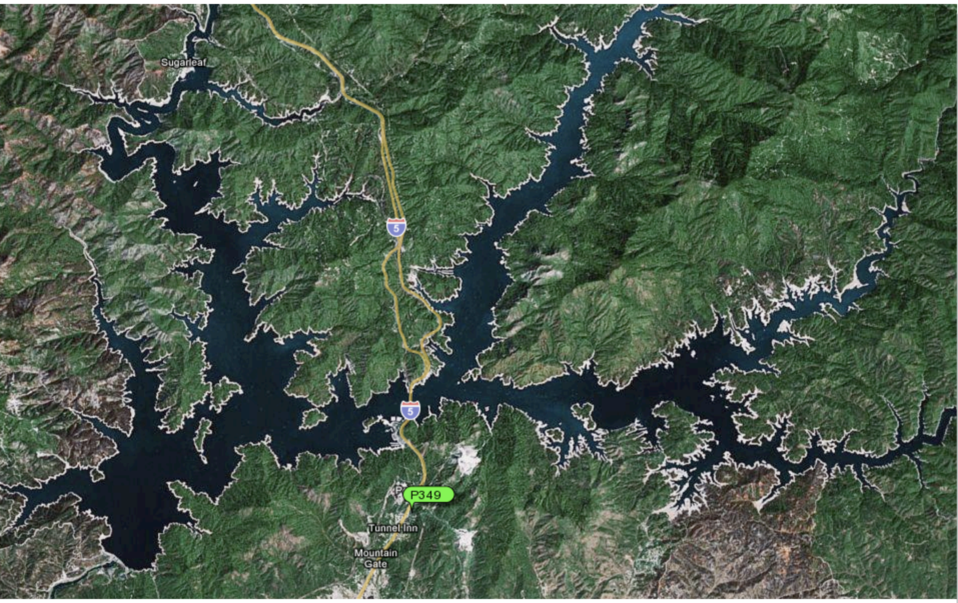


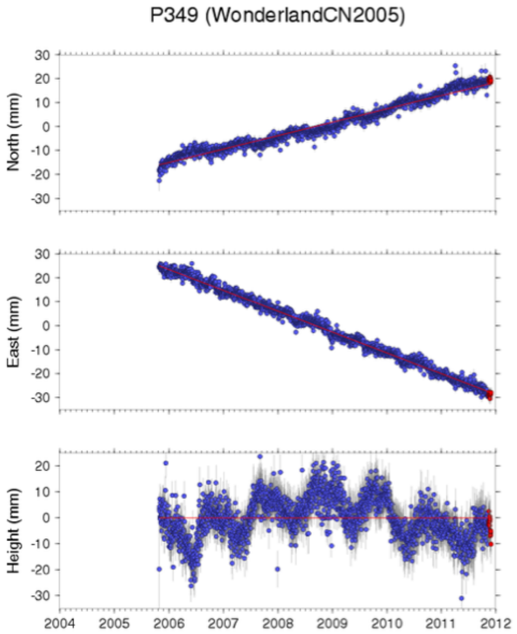


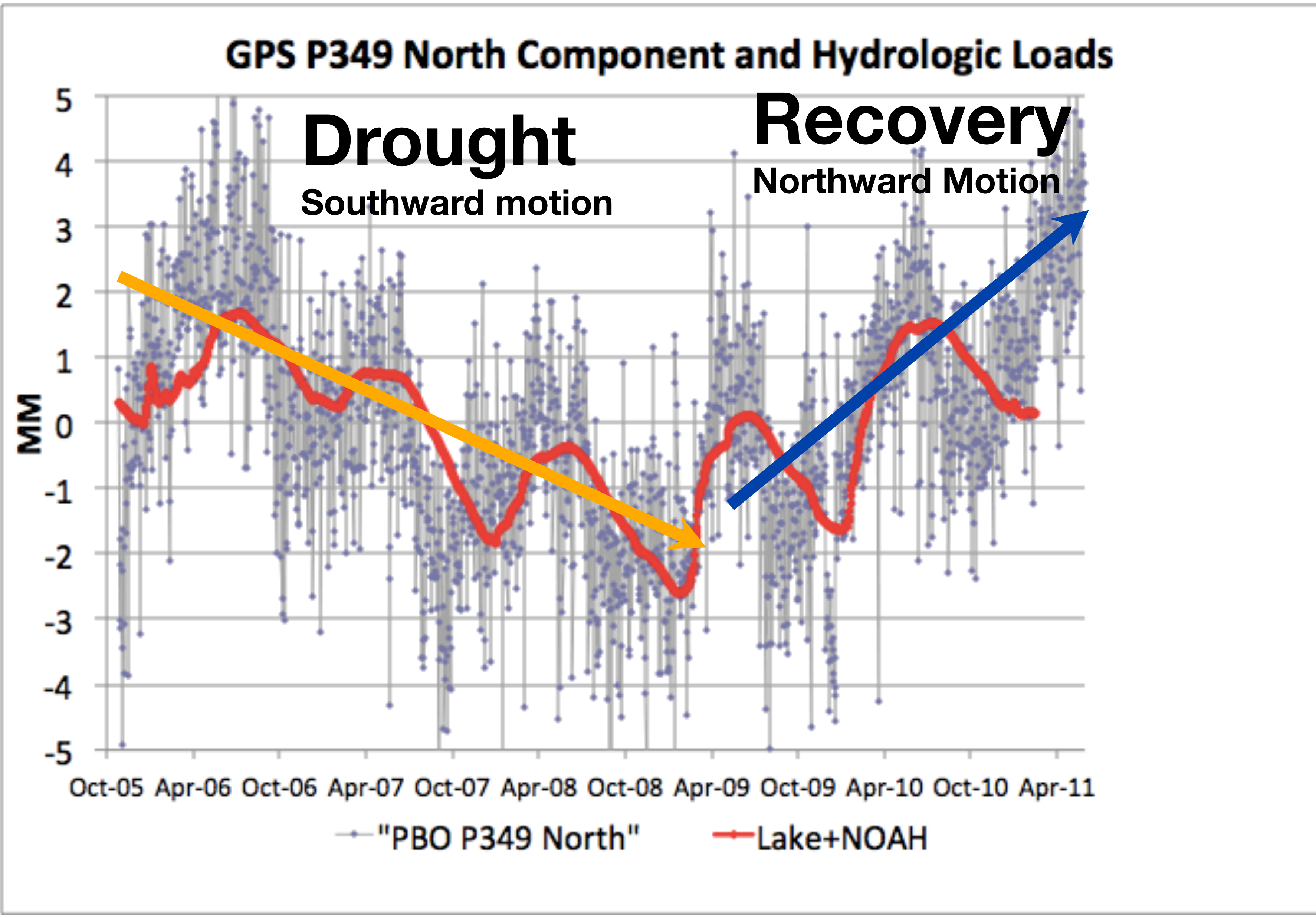
Gray = **Observed Vertical GPS Signal**
Red = **Combination of Lake and NOAH surface loads (reduces standard deviation from ~5mm to <2mm**

The trends in **vertical component** reflect uplift during an extended period of drought between 2005-2009 followed by subsidence with return to normal conditions in 2009-2011. Lake Shasta site is a good “barometer” of regional hydrology.

North Component Signal at Lake Shasta







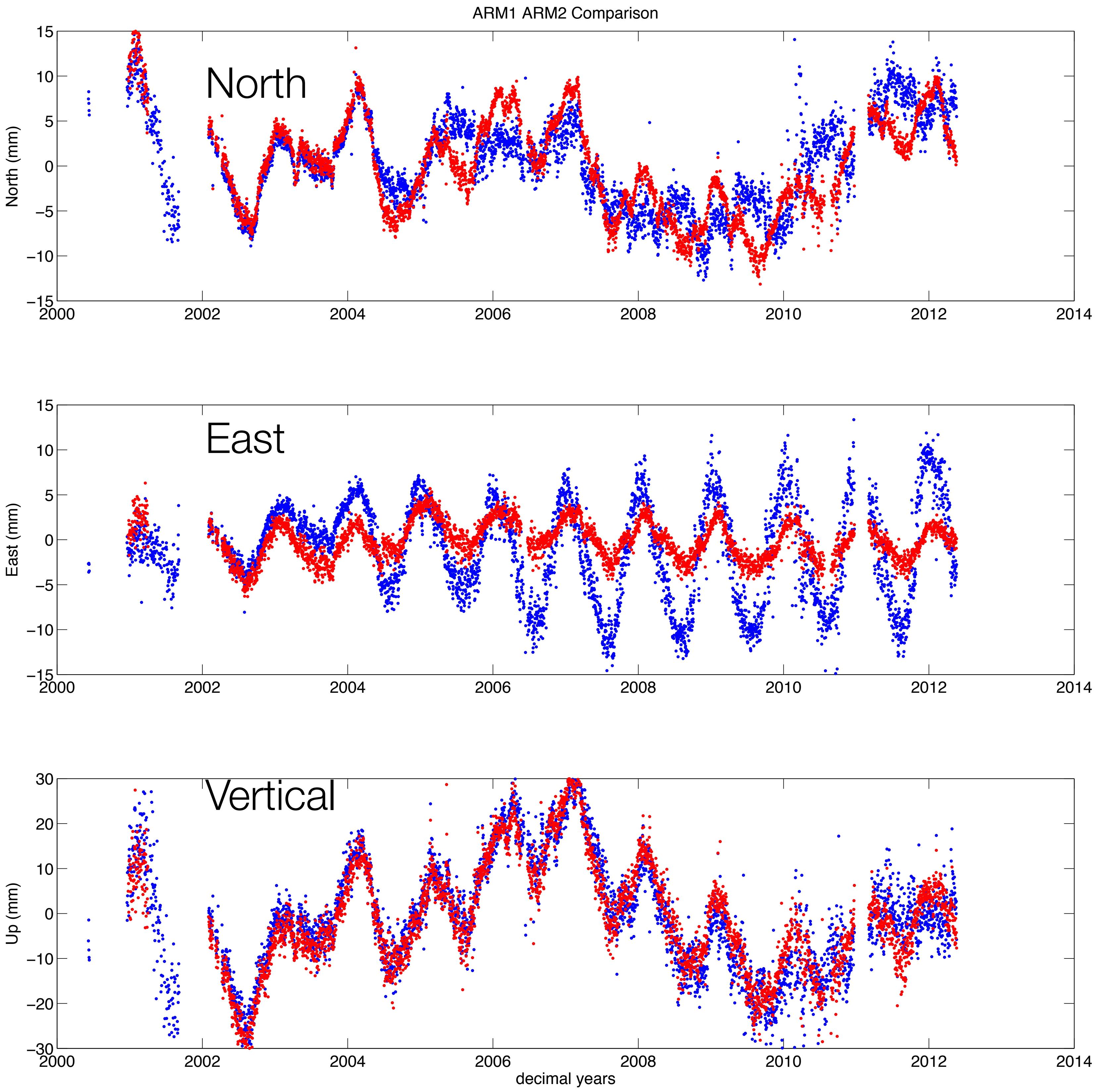
Red = **Combination of Lake and NOAH load**

North component of GPS timeseries has a linear trend (due to plate boundary deformation) removed. The residual shows an annual signal and first southward then northward trend in response the drought and then recovery in 2009. As with the vertical component, the GPS timeseries is well characterized by the combined lake load and global hydrologic GLDAS/NOAH model (snow and soil moisture load) shown in red. The motions in the east component (not shown) are negligible.

Equipment Degradation:

Slow failure of GPS antenna observed at co-located deep drilled-braced monuments in Southern California

Co-location Study



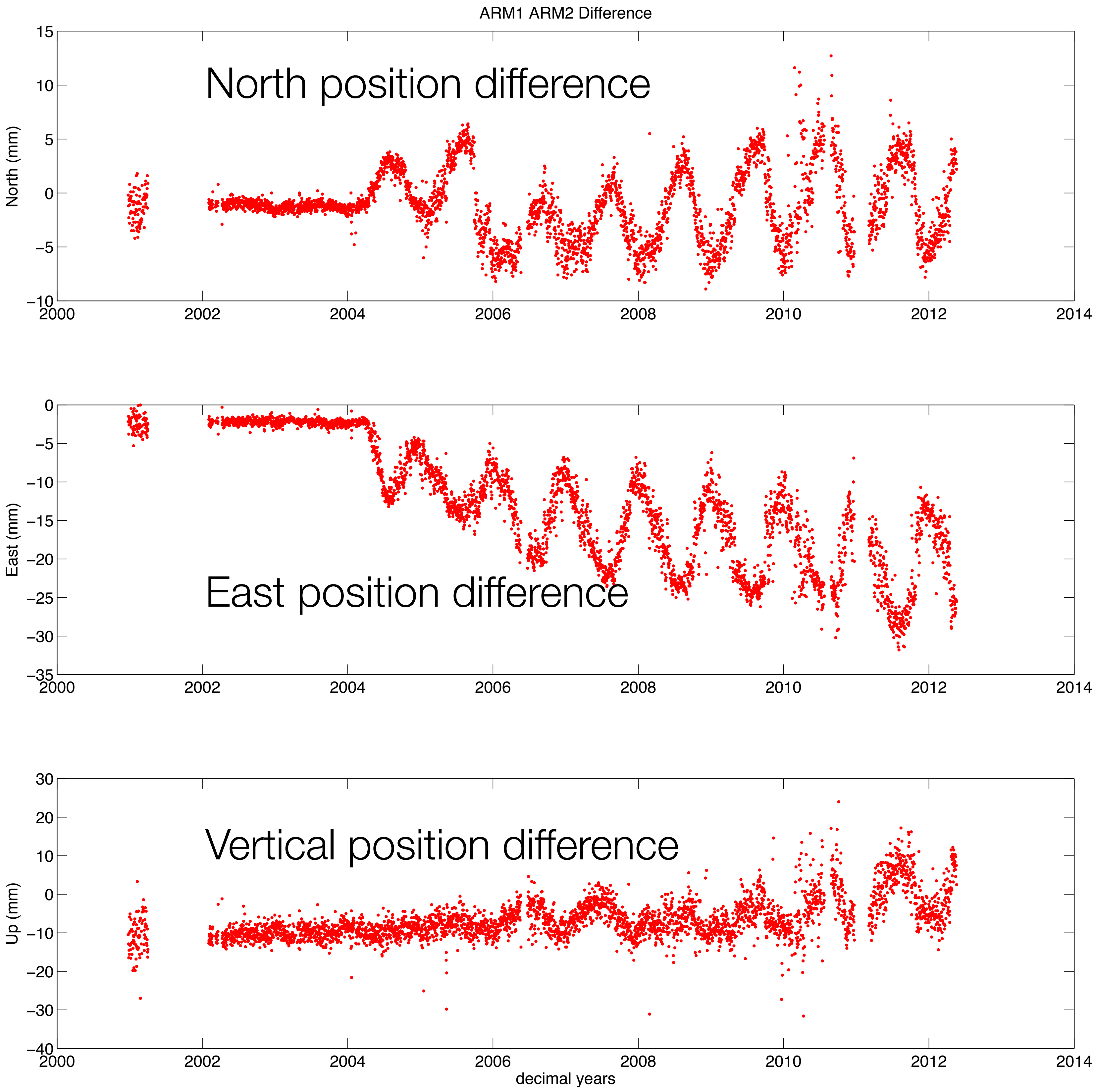
ARM1 and ARM2

-ARM1 and ARM2 are plotted together with a linear trend removed from each time series

-The east component of ARM1 has a much larger annual term than ARM2.

-These Wyatt/Agnew deep drilled-braced monuments have been collocated since ~2001. Installed and operated by SCIGN/USGS

Co-location Study



ARM1 and ARM2

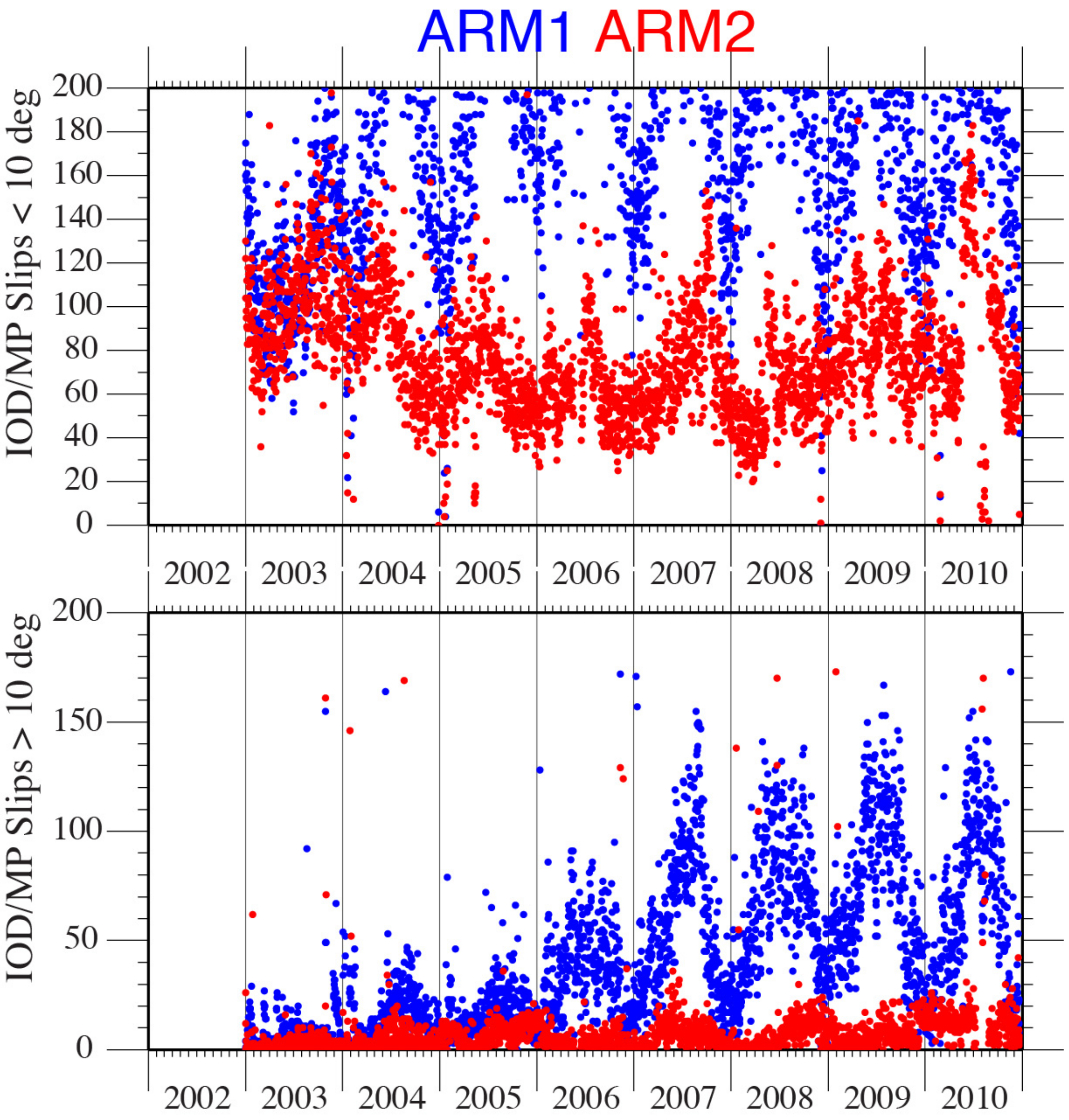
-Differencing the time series shows that the antenna likely started to fail at ARM1 in ~2004.

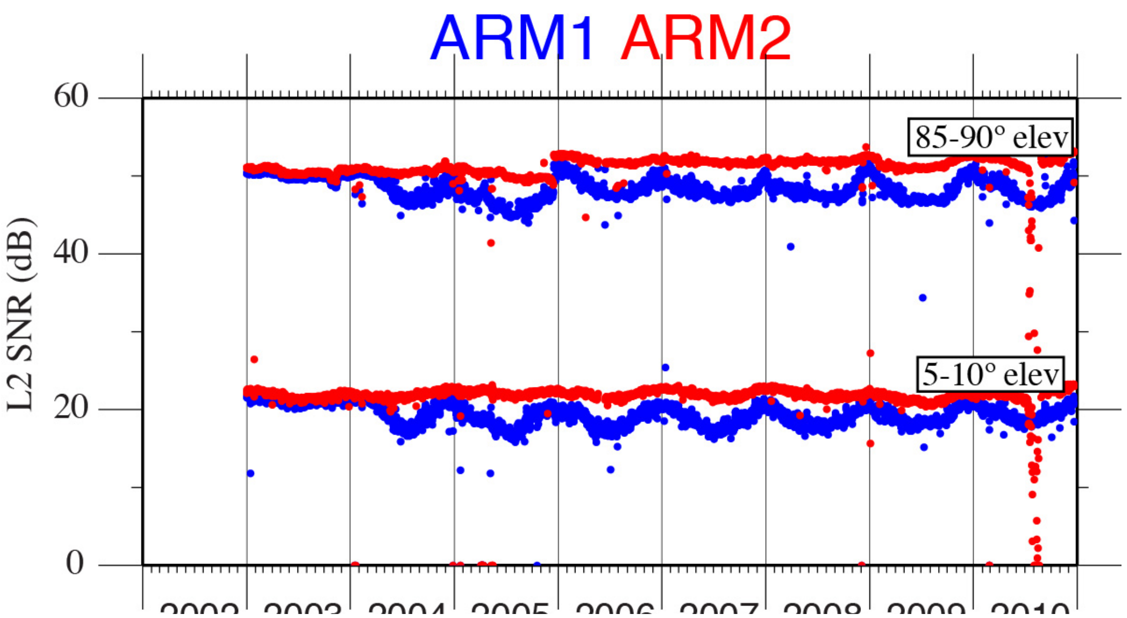
-A large annual signal becomes apparent in the horizontal components after 2004.

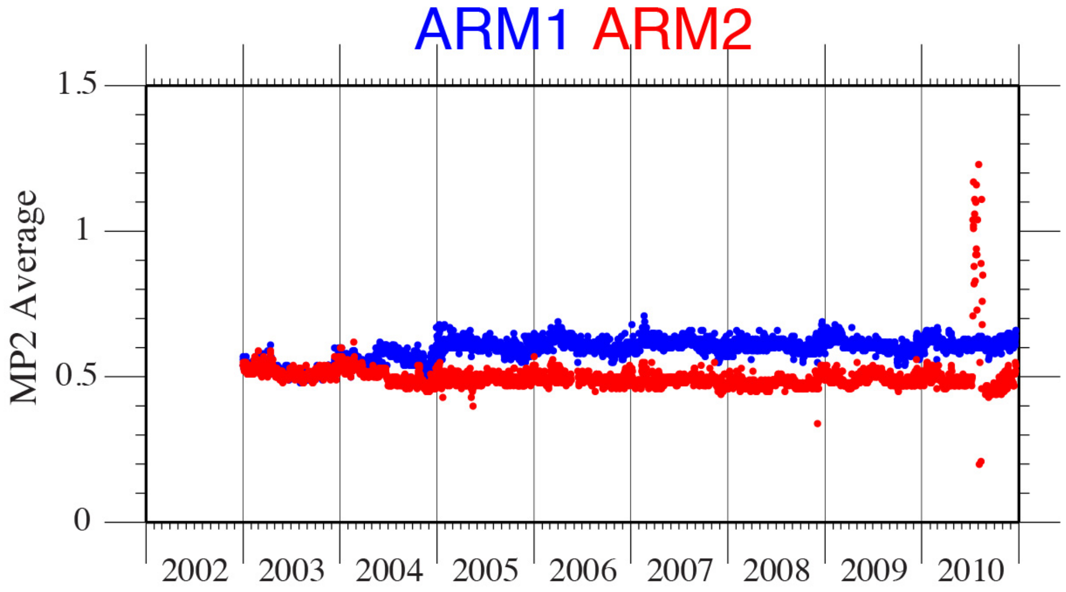
- The annual signal difference is likely a response to changing temperature.

- We also observe a significant change in the trend of the east component.

TEQC QC Analysis





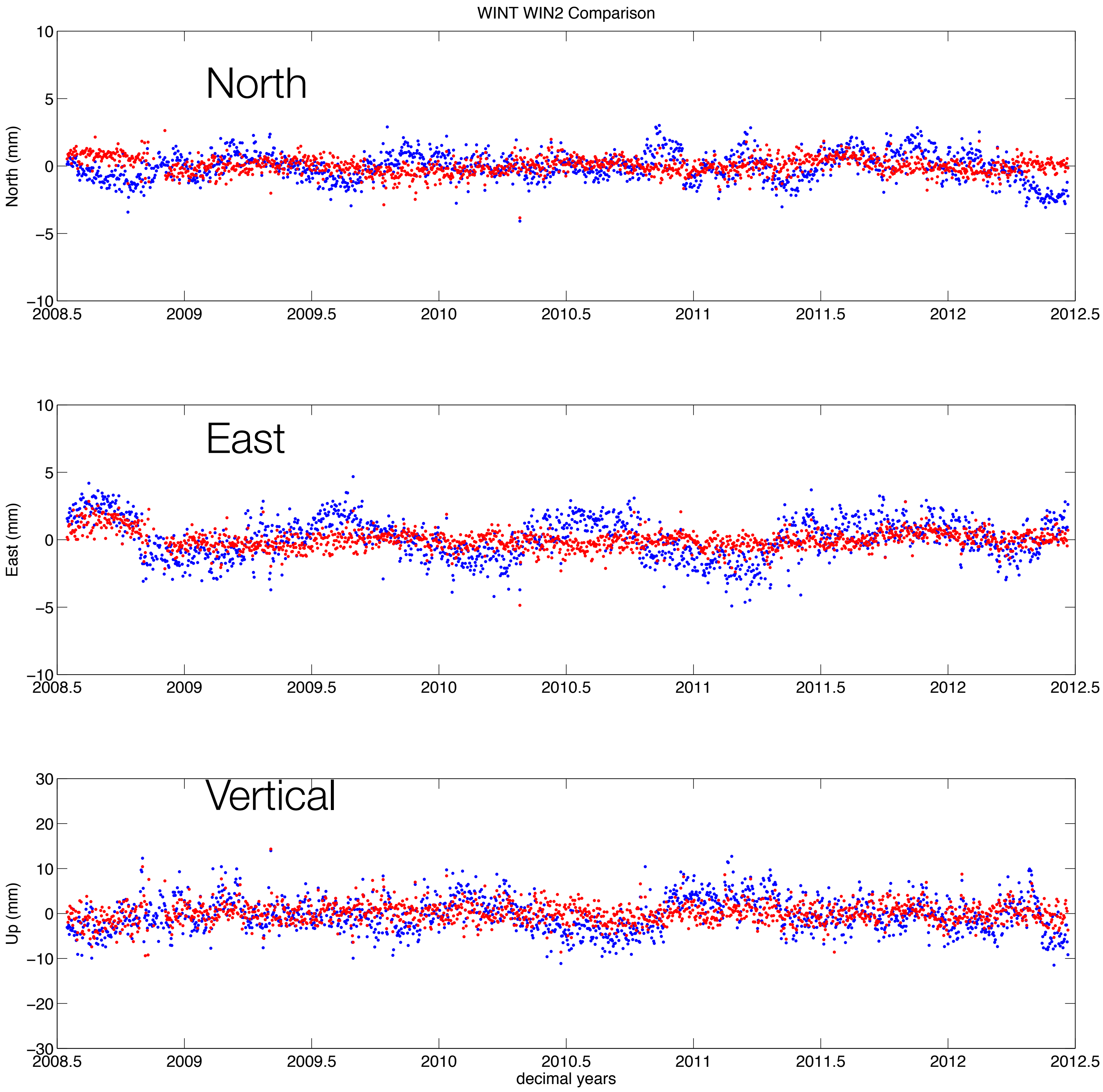


The failing antenna at ARM1 (Blue) shows an increasing number of slips, lower L2 SNR and higher MP2 average multipath

Monument Stability:

Co-located deep drilled-braced monument and concrete pillar in Nouthern California

Monument Stability Co-location Study



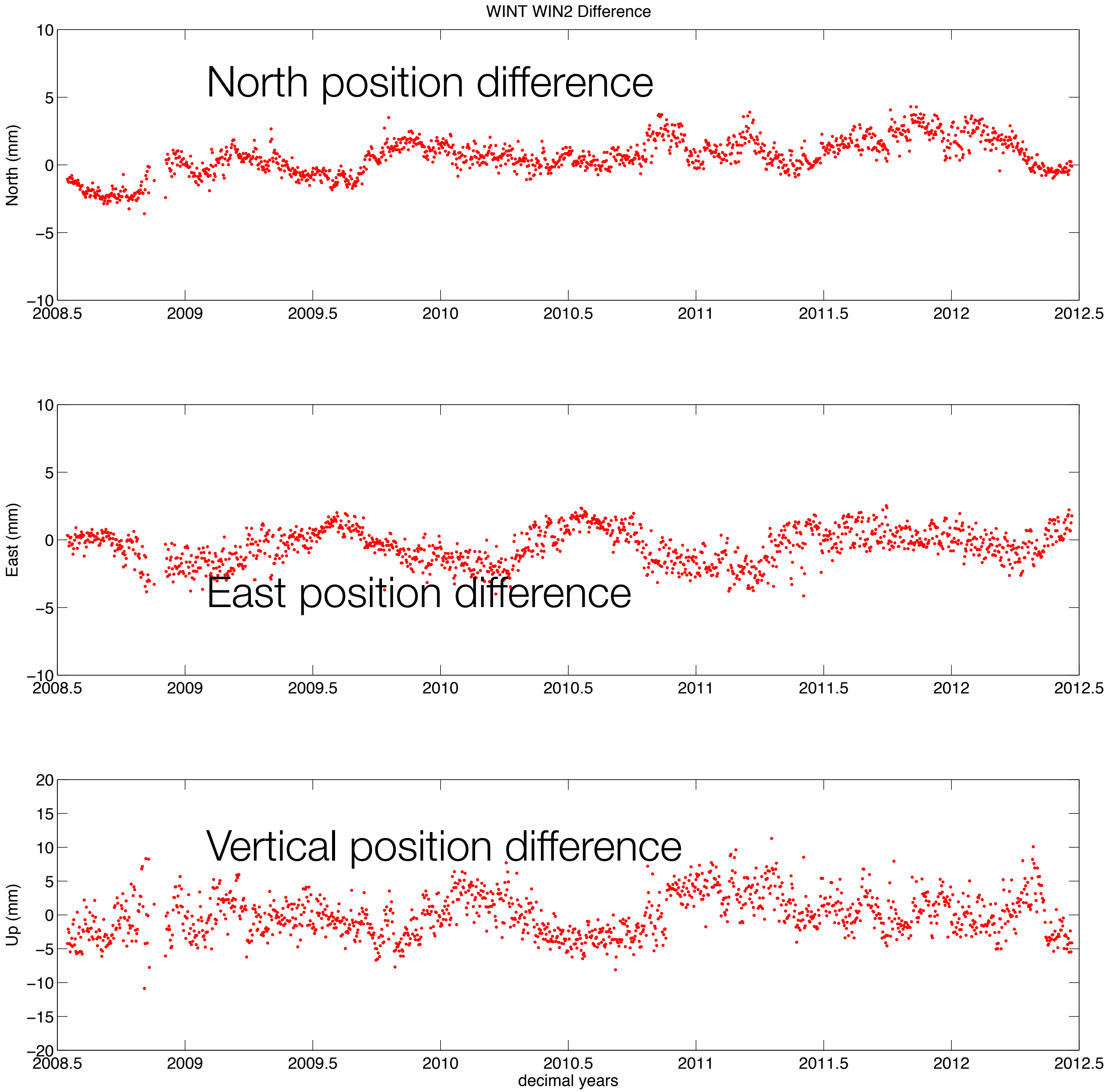
WINT and WIN2

-WINT and WIN2 are plotted together with a linear trend removed from each time series

-WIN2 was installed next to WINT in Jul of 2008.

-WIN2 was installed with a DDBM and SCIGN dome which allows for antenna phase center calibration.

Monument Stability Co-location Study



WINT and WIN2

-By differencing the time series we can see the noise in the short baseline between WINT and WIN2.

-The short baseline cancels out most error sources leaving monument noise, multipath noise and un-modeled antenna phase center variations.

-The antenna + dome combination at WINT has not been calibrated due to it's integration in the monument structure.

Upcoming Monument Stability Co-location Study

Pilar monument
- $2.5k
- 3m deep

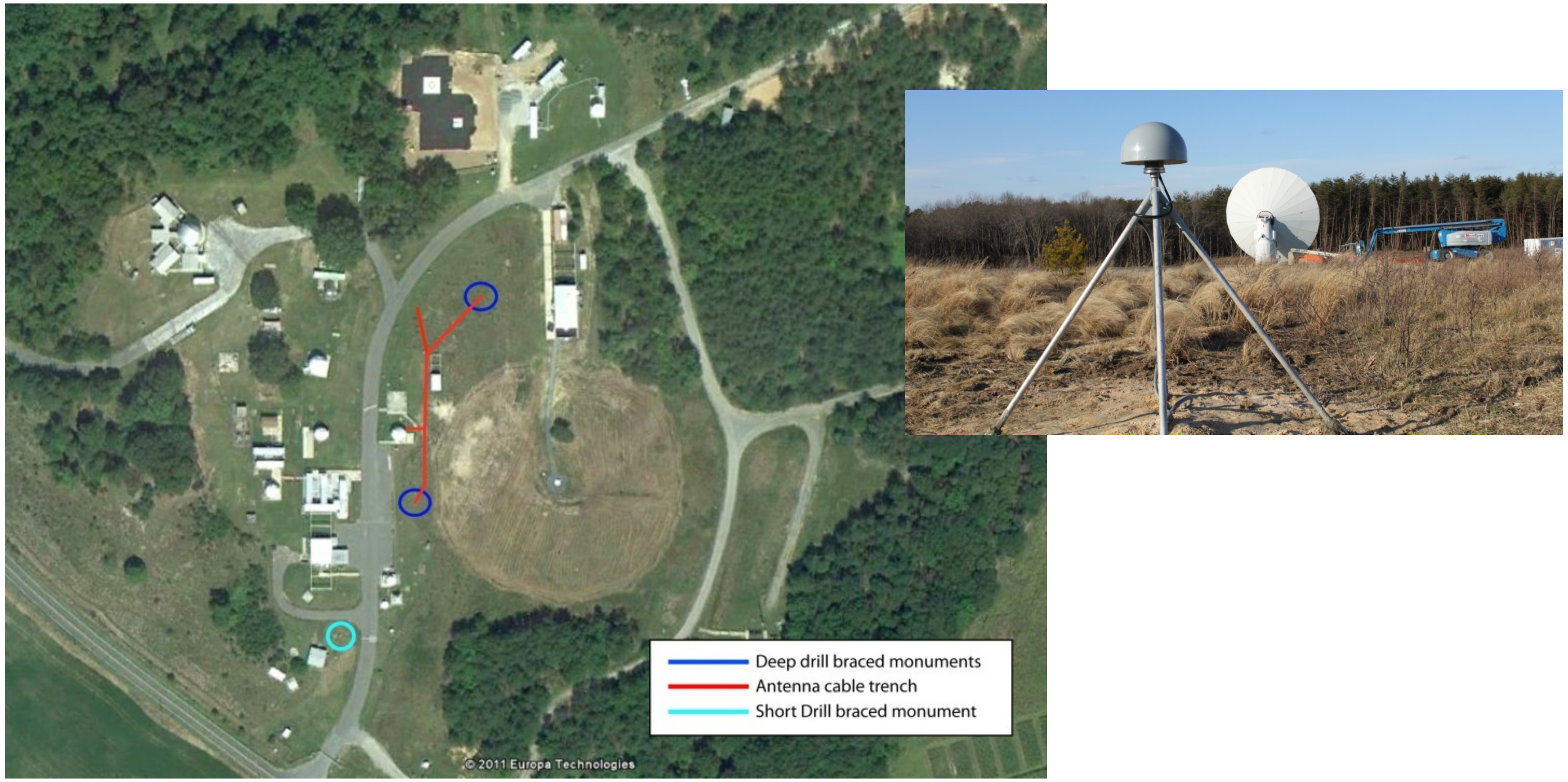
UNAVCO is commencing a new monument stability test project that will co-locate at least three different monuments operating identical instrumentation.

Short drilled-braced monument
- $1k
- 1.5m deep

Three or four locations with a variety of local geologic conditions (bedrock, soil, alluvium, etc.) will be selected from the PBO.

Deep drilled-braced monument
- $12-$20k
- 10m deep

NASA Goddard Geodetic Astronomical Observatory



(Left) GODN GNSS north site shown with NGVLBI antenna in background.

Aerial view of GGAO showing new monument locations:
GODN, GODS, and short drilled-braced monument (IGN Doris and GNSS co-lo. GODE GODZ original Flynn monuments. lso located on site are the next generation VLBI with 10m dish and moblas7 ngsSRL and other SLR telescopes.

See: NASA SGP website.

(Left) GODS GNSS south site with deep drilled-braced monument.

Summary

Hydrologic Effects:

- Several hydrological effects can be observed:
  - Anthropogenic signals (pumping)
  - Reservoir surface loading
  - Hydrologic surface loading in mountains from natural water cycle and variations in soil moisture and snow pack
- GLDAS and Leaky Bucket models do a good job of fitting the observed GPS signals in areas where hydrologic loading signals dominate e.g. mountains of California and the Pacific Northwest
- The observations and models reflect the transition from drought conditions (2005-2009) to recovery (2009-2011).
- In order to better measure tectonic mountain building (rates of <1mm/yr) and to identify transients of tectonic origin, we will need to better understand and model hydrologic loading effects. To facilitate this we plan to make the loading model timeseries available through the UNAVCO archive.

Summary

Monument Study:

- Co-located monuments facilitate the ability to detect slow equipment degradation (e.g. failing antenna at ARM1) and to identify local site effects.
- One example from co-located sites show deep drilled-braced monuments have significantly lower noise than shallow pillars.
- Regional data not helpful in making same conclusion since annual and interannual effects are ether incoherent (e.g local pumping) or generally explained by hydrologic loading models.
- With so few examples of co-located monuments available UNAVCO will be engaging in a small study to add various monuments to a handful of PBO sites using identical equipment and to operate them for 3-5 years.