Fluctuations in Subsurface Water in Oregon and Washington Inferred from Global Positioning System

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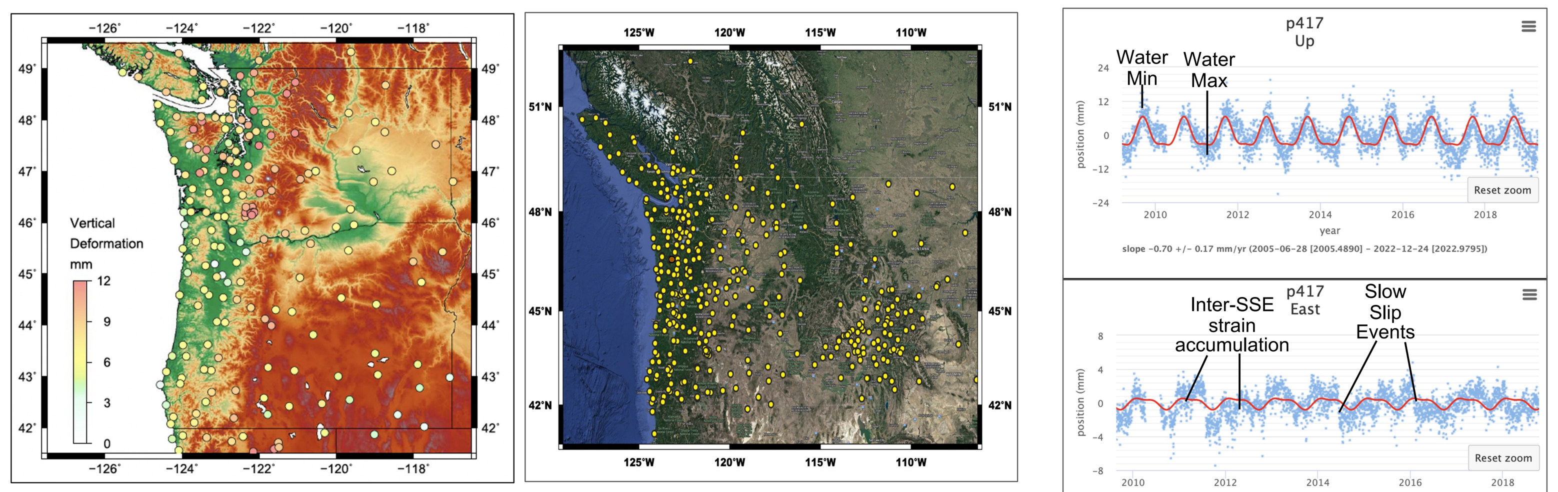
Abstract

The Global Positioning System (GPS) measures solid earth elastic response with high accuracy, providing an effective means to infer water thickness and total terrestrial water storage. The high spatial resolution of GPS allows the estimation of water storage over small-scale regions, which mitigates the limitations of geodetic satellites with coarse resolution. In this study, we quantify the anomalies in terrestrial water storage for Washington and Oregon, investigating the total, subsurface, and groundwater storages using GPS observations and hydrologic products. The GPS data from NASA Jet Propulsion Laboratory, assimilated snow water equivalent from SNODAS, and assimilated soil moisture from NLDAS-Noah are used to compute the change in total, subsurface, and groundwater storage. For our area of focus, Northern and Middle Cascades, the mean seasonal oscillation in total water from 2006-2021 is approximately 30 km^3 (0.36 m), ~22% of the 137 km^3 mean yearly cumulative precipitation. The mean seasonal oscillation in subsurface water is approximately 28 km^3, ~20% of cumulative annual precipitation. We find there to be significant fluctuations in mountain groundwater and that the time of maximum mountain groundwater lags the time of maximum snow by 2 months. Our findings can be related to the hydrologic water balance equation, where change in water storage equals precipitation minus evapotranspiration minus river discharge. The results also provide insights into identifying the moment magnitude and duration of slow slip earthquakes more accurately in Oregon and Washington.

Introduction



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GPS Network Across Columbia River Basin

NASA MEaSUREs ESESES Project
http://sopac-csrc.ucsd.edu/index.php/measures-2/

- A dense GPS network exists across Columbia River Basin (~200 stations)
- GPS vertical displacements have standard errors ranging from 2-5 mm.
- The estimated water thicknesses inferred from the vertical displacements have standard errors of about 24-60 mm.
- Since tectonic signals are mostly horizontal and water signals are mainly vertical, we can estimate the moment magnitude and duration of slow slip earthquakes more accurately by removing water loading determined in this project.

Materials and Methods

Part 1: Quantifying Water Storage Anomalies

1.1. Total water storage (TWS)

- GPS-inverted data: Jet Propulsion Laboratory - Tracking Systems and Applications
- Positioning data: Nevada Geodetic Laboratory
- GPS-inferred TWS was compared with existing hydrology model-based total water storage (soil moisture + snow water)

1.2. Subsurface water storage

- Snow water equivalent (SWE): Snow Data Assimilation System (SNODAS)
- Soil Moisture (SM): NLDAS-Noah
- Subsurface water storage was inferred by subtracting snow water equivalent from GPS-inferred TWS.

1.3. Groundwater storage

- Groundwater storage was inferred by subtracting soil moisture from GPS-inferred subsurface water storage.

Part 2: Fluctuations in Water Storage Across Time and Space

2.1. Water storage change in North and Middle Cascade Mountains

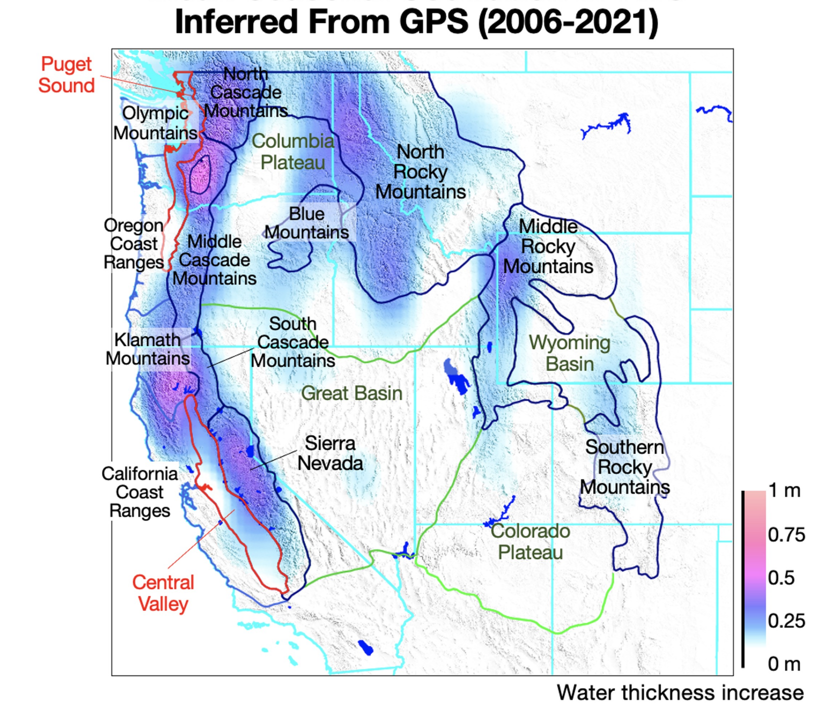
- A time-series of the sum of all pixels in the North and Middle Cascades was plotted to show the long-term change in water storage

2.1. Change in water storage in the context of the water balance equation

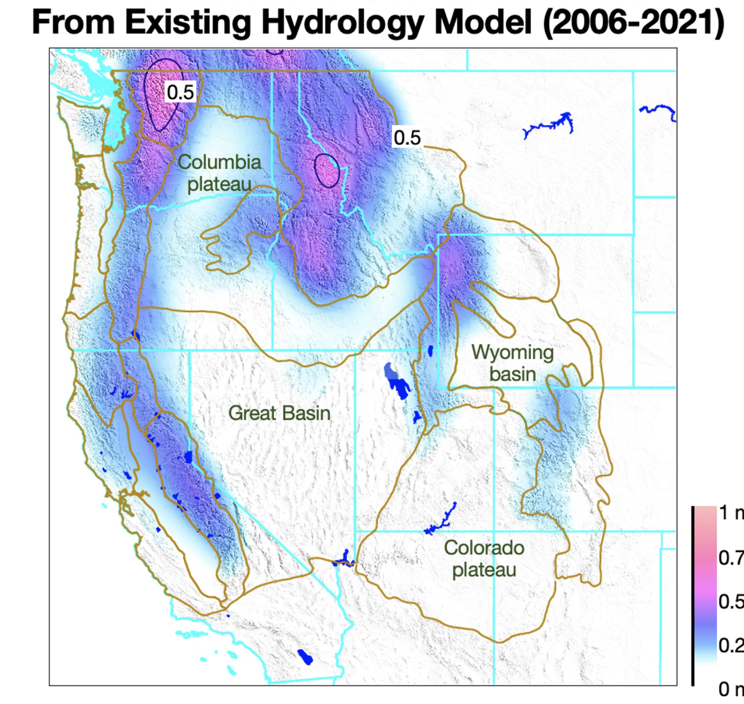
- Inferred water storages were compared with precipitation (PRISM)

Total Water Storage

Mean Seasonal Oscillation in TWS Inferred From GPS (2006-2021)



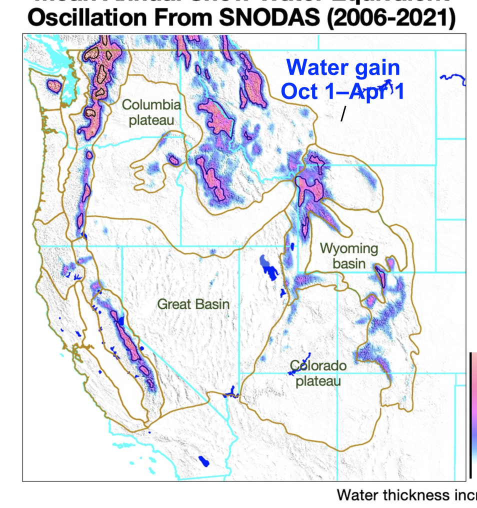
Mean Seasonal Oscillation in TWS From Existing Hydrology Model (2006-2021)



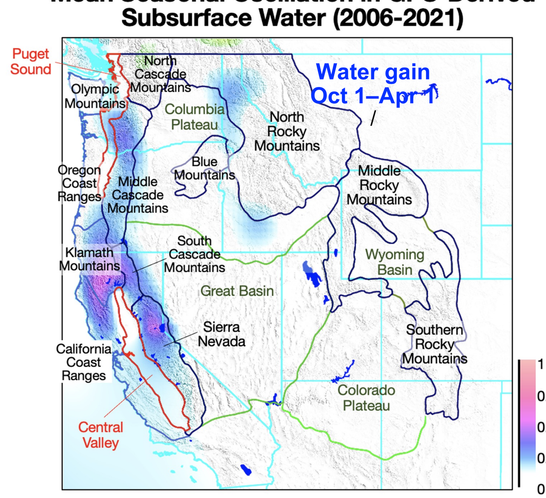
- Seasonal Oscillation = max TWS (Apr) - min TWS (Oct) of the sine fit for the time-series
- Greatest changes were found along the Cascade Mountains (WA, OR), Klamath Mountains, the Rocky Mountains (ID), and Sierra Nevada (CA).

Subsurface Water Storage

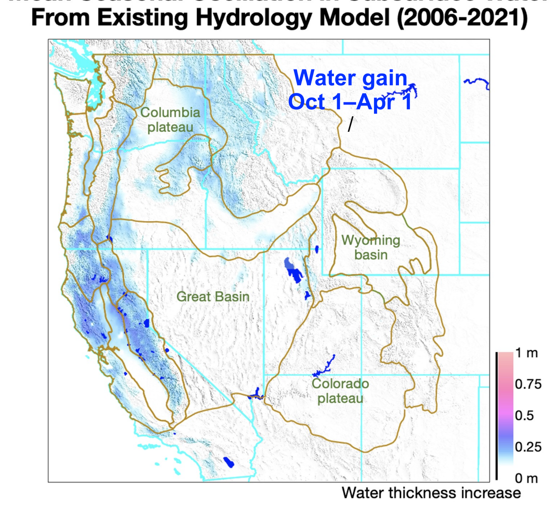
Mean Annual Snow Water Equivalent Oscillation From SNODAS (2006-2021)



Mean Seasonal Oscillation in GPS-Derived Subsurface Water (2006-2021)



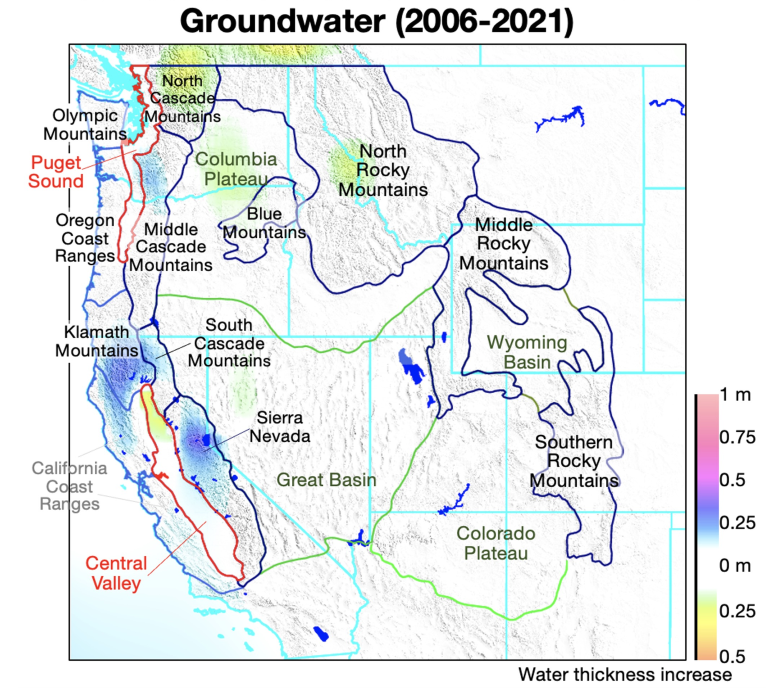
Mean Seasonal Oscillation in Subsurface Water From Existing Hydrology Model (2006-2021)



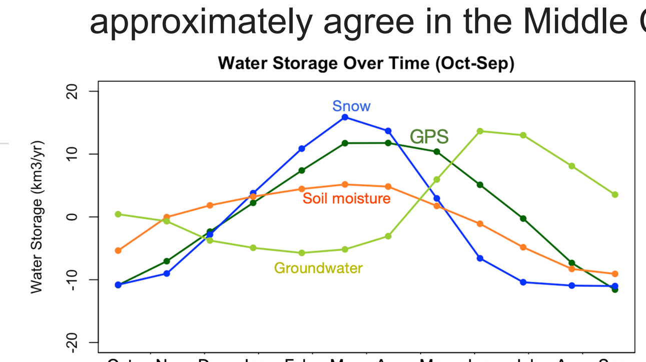
- Subsurface water
  = GPS-inferred total water storage <u>minus</u> snow water equivalent (SWE, SNODAS)
- SWE was smoothed by 110 km-Gaussian filter
- Large snowpack accumulates in the Cascades, Olympic Mountains, Rocky Mountains, and Sierra Nevada
- Subsurface water oscillations are estimated to be greatest along the Klamath Mountains, Sierra Nevada, and Mid-Cascades and small in the Rockies and North Cascades

Groundwater Storage

Mean Seasonal Oscillation in GPS-Derived Groundwater (2006-2021)



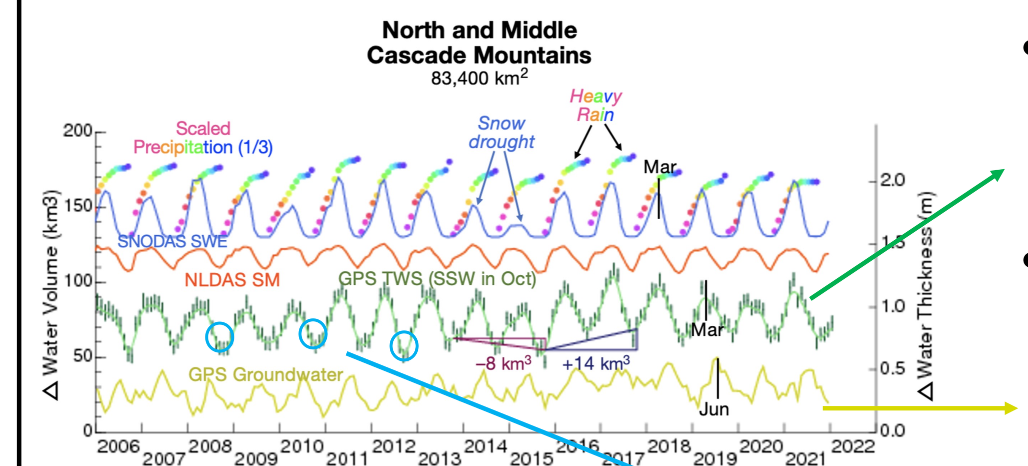
- Groundwater = GPS-inferred total water storage <u>minus</u> snow water equivalent (SNODAS) <u>minus</u> soil moisture (NLDAS-Noah).
- Snow water equivalent and soil moisture are smoothed by a Gaussian distribution with a full width of 110 km to approximate what GPS would observe if the hydrology model were correct.
- Water gain in the rainy autumn and winter is estimated with GPS to exceed that in the hydrology model in the Klamath Mountains and Northern Sierra Nevada, but the GPS estimate and hydrology model approximately agree in the Middle Cascades.



- Groundwater lags snow by 2 months.

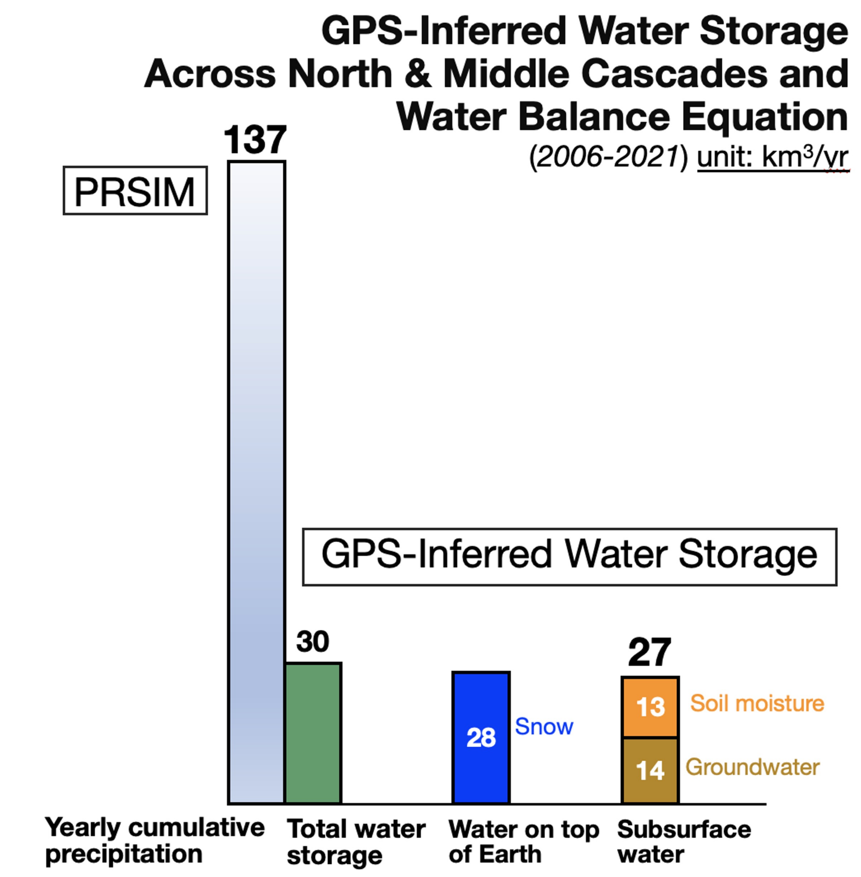
Water Storage Change in North and Middle Cascades

II. How much does water storage decrease during periods of drought and increase during years of heavy precipitation?



- The mean seasonal oscillation in total water is ~30 km^3 (0.36 m), 22 percent of the 137 km^3 mean yearly cumulative precipitation.
- The mean seasonal oscillation in groundwater is ~14 km^3 with a maximum in July, three months after snow and soil moisture are maximum in April.
- Subsurface water is lost during periods of drought and gained during years of heavy precipitation

Water Storage Change Relating to Water Balance Equation



- 4/5 of yearly cumulative precipitation runs off. The seasonal oscillation in subsurface water is 1/5 of yearly cumulative precipitation
- The seasonal oscillation in groundwater is 1/10 of yearly cumulative precipitation and 1/3 of the oscillation in total water.

$$P = dS/dt + ET + Q$$

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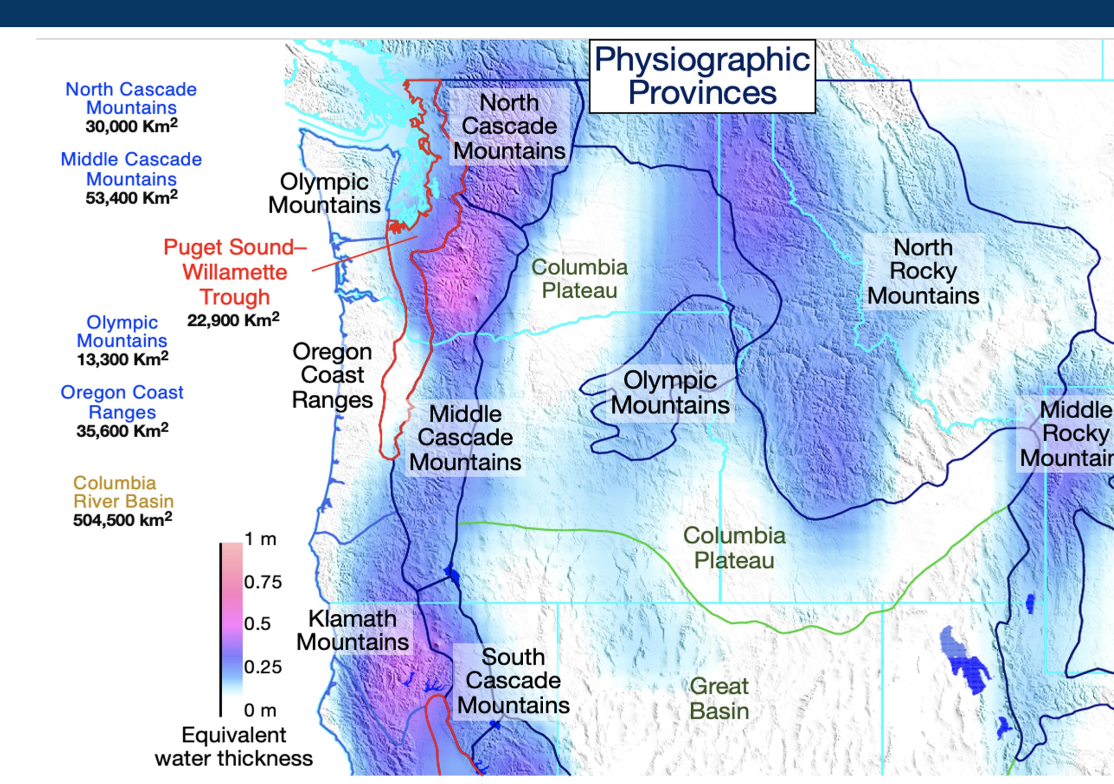
Conclusions



- GPS provides a robust means to examine water change in the narrow North Cascade Mountains, Middle Cascade Mountains, Puget Sound–Willamette Trough, Oregon Coast ranges, and Olympic Mountains.
- Geodetic satellites with coarse resolution, such as GRACE, effectively address water anomalies across larger regions like the Columbia River basin