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Using GPS to Study the Terrestrial Water Cycle

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Researchers are using GPS—usually thought of as a way to measure position—to measure water cycle properties, including surface soil moisture, snow depth, and vegetation growth, which are important for climate studies and satellite validation. Water managers need these data to predict, and possibly mitigate, hazards such as floods and droughts. While there are strong international efforts to use ground networks to measure and archive data for these quantities, the GPS-based water cycle data have the advantage that existing instrumentation can be used, significantly reducing the cost of operating this new terrestrial water cycle network.

The Plate Boundary Observatory water project (PBO H_2O) measures surface soil moisture, snow depth, and vegetation growth using a continental-scale GPS network [*Larson et al.*, 2008, 2009; *Small et al.*, 2010]. These water cycle products are derived from data collected by the EarthScope Plate Boundary Observatory (PBO), a GPS network installed in the western United States to measure deformation of the North America–Pacific plate boundary (http://www.earthscope.org). The GPS water cycle products produced by PBO H_2O represent an intermediate footprint, approximately 1000 square meters, and are currently computed and made available on a daily basis. They complement other ground sensors that sample smaller footprints and larger-scale satellite measurements, which have lower temporal resolution. Given this sensing scale and temporal sampling, the GPS data provide a unique opportunity to study the water cycle and evaluate both models and remote sensing estimates.

Measuring Water Cycle Properties

Most people are generally familiar with how GPS receivers work in cars and cell phones: We turn them on, and our location shows up on a map. Less known to the public, GPS instruments also operate in "fixed installations" around the world for either infrastructure support (transportation, farming, surveying) or geoscience experiments (fault motions, polar sciences, atmospheric water vapor sensing, precise orbit determination). These GPS networks operate continuously and typically provide their data to the public free of charge with latencies of 1 second to 24 hours.

Of the GPS networks operating in the United States, PBO is the largest, with more than 1100 sites. The original scientific goals of PBO were to measure deformations caused by faults, volcanoes, and earthquakes in the western United States. The instruments were distributed accordingly, with more than 500 located in California, about 150 in Alaska, and the remainder in the Pacific Northwest and Rocky Mountains. Of PBO sites, 90% are surrounded by natural and agricultural

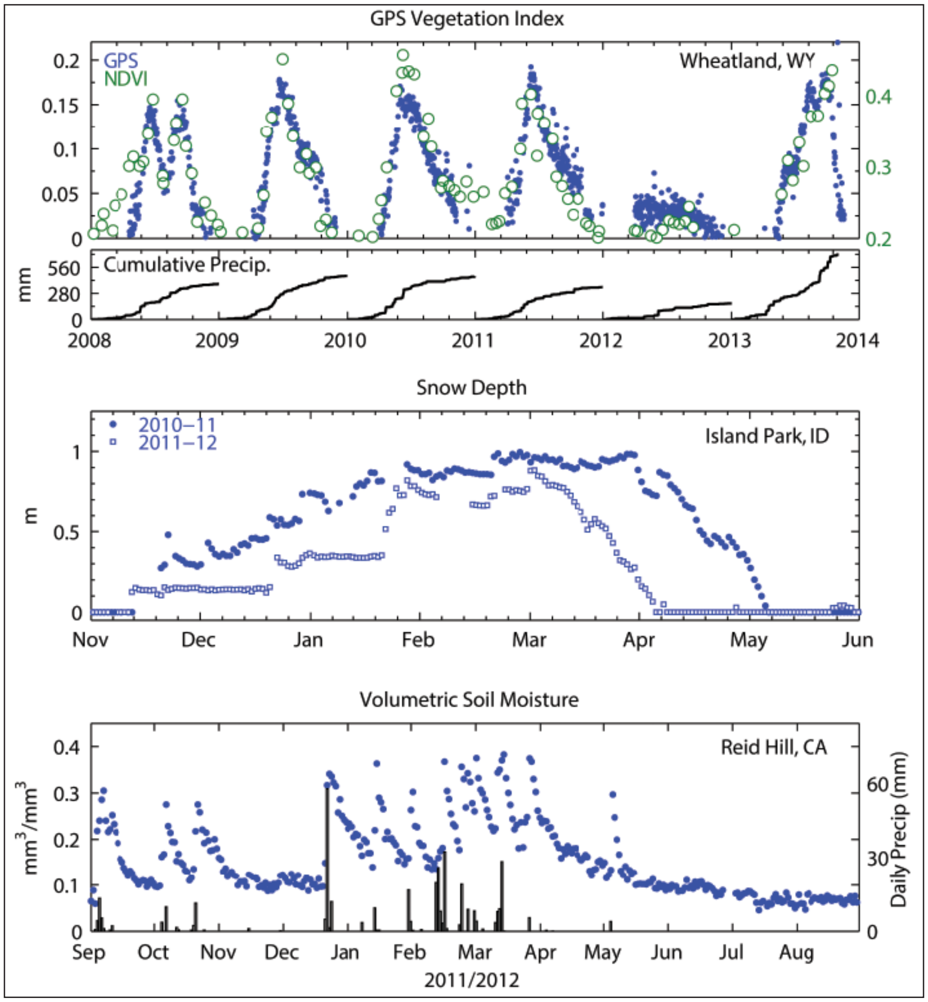

Fig. 1. (top) GPS-derived vegetation water content index compared with 16-day Moderate Resolution Imaging Spectroradiometer (MODIS) Normalized Difference Vegetation Index (NDVI) data and cumulative precipitation from the North American Land Data Assimilation System (NLDAS) for 2008–2014. (middle) Snow depth estimated using GPS data for 2 water years. (bottom) Volumetric soil moisture estimated from GPS data and NLDAS precipitation.

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landcover, which is important for terrestrial hydrology studies. Thus, many of the sites can be used to sense environmental changes to the land surface around GPS antennas. GPS instruments were installed beginning in 2004, and the network was completed in 2008.

How does a GPS instrument tell scientists anything about the terrestrial water cycle? Ironically, this information comes from an error source for GPS users. For GPS to accurately measure position, the GPS signals must travel directly from the satellite to the GPS antenna. However, some of the GPS signal also reflects off the land surface around the antenna. These reflected signals (known as multipath) travel a longer distance than the direct signal and thus cause the estimated position to be incorrect by a small amount. The PBO H_2O group uses the fact that the direct and reflected signals interfere with each other, turning the GPS unit into a de facto interferometer.

The interference effect provides two pieces of information: how wet the reflecting surface is and the distance between the GPS antenna and the reflecting surface. When it snows, the reflecting surface gets closer to the antenna, and the GPS interference pattern is sensing snow depth. Dry soil reflects the GPS signal differently than wet soil, thus linking the amplitude and phase of the interference pattern in the GPS data to surface soil moisture. Water in vegetation also influences the reflected GPS signal. PBO H_2O scientists have used electrodynamic forward models to develop retrieval algorithms that make it possible to separate the three different water cycle products: vegetation water content, snow depth, and surface soil moisture.

Water Cycle Products

The PBO H_2O project currently estimates daily water cycle products for more than 400 sites. They are available on the PBO H_2O data portal at http://xenon.colorado.edu/portal. Typical GPS vegetation water content products are shown in Figure 1 (top) for a grasslands site in eastern Wyoming [*Small et al.,* 2010]. Because GPS is an L band system (using wavelengths of ~20 centimeters), the GPS vegetation index is dominated by changes in the amount of water stored in vegetation. At this site, vegetation water content generally peaks in June. To place the GPS data in context, a cumulative record of precipitation is also shown. The data clearly show the GPS record of vegetation water content responding to extreme drought conditions in 2012 and recovering in 2013.

Two representative snow depth time series for the winters of 2010–2011 and 2011–2012 are shown in Figure 1 (middle) [*Larson et al.,* 2009]. The snow depth and duration of snow cover vary greatly between these years, with 2011 being a record snow year throughout the western United States. (Snow water equivalent data are also available.)

Finally, Figure 1 (bottom) shows surface soil moisture estimated for a PBO site in Northern California [*Larson et al.,* 2008]. Note the response in soil moisture to rainfall events. The GPS reflection technique is sensitive to shallow soil moisture, from 0 to 5 centimeters, which means it can be used to validate L band soil moisture satellite missions.

Validation of the PBO H_2O products is described on the data portal. In addition to the products described here, ancillary information (photos, landcover classification, temperature, precipitation, Google Earth™ links, Normalized Difference Vegetation Index data) about each GPS site is also available. An education portal on GPS was also developed (http://xenon.colorado.edu/spotlight).

Potential for Monitoring Hydrology Worldwide

GPS has revolutionized geodesy and geoscience research by making it possible to precisely measure the movements of the Earth's surface. The PBO H_2O project has demonstrated that GPS networks can simultaneously—and with no additional instrumentation—measure near-surface soil moisture, snow, and vegetation water content. Many countries operate GPS networks that are very similar to PBO, and many of them could be used to monitor terrestrial hydrological signals.

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