Comparison of Snow Data Assimilation System with GPS reflectometry snow depth in the Western United States

K. Boniface,1*,† J. J. Braun,2 J. L. McCreight1 and F. G. Nievinski3

1 Department of Aerospace Engineering Sciences, University of Colorado Boulder, Boulder, CO, USA
2 Constellation Observing System for Meteorology, Ionosphere, and Climate, University Corporation for Atmospheric Research, Boulder, Colorado, USA
3 Departamento de Cartografía, Faculdade de Ciências e Tecnologia, Universidade Estadual Paulista ‘Julio de Mesquita Filho’, Presidente Prudente, Brazil

Abstract:
In this study, we compare gridded snow depth estimates from the Snow Data Assimilation System (SNODAS) with snow depth observations derived from GPS interferometric reflectometry (GPS-IR) from roughly 100 Plate Boundary Observatory sites in the Western United States spanning four water-years (2010–2013). Data from these sites are not assimilated by SNODAS; thus, GPS-IR measurements provide an independent data set to evaluate SNODAS. Our results indicate that at 80% of the sites, SNODAS and GPS-IR snow depth agree to better than 15-cm root mean square error, with correlation coefficients greater than 0.6. Significant differences are found between GPS-IR and SNODAS for sites that are distant from other point measurements, are located in complex terrain or are in areas with strong vegetation heterogeneities. GPS-IR estimates of snow depth are shown to provide useful error characterization of SNODAS products across much of the Western United States and may have potential as an additional data assimilation source that could help improve SNODAS estimates. © 2014 The Authors. Hydrological Processes published by John Wiley & Sons Ltd.

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INTRODUCTION
The accurate tracking of seasonal snow accumulation is critical for monitoring the water cycle of the semi-arid Western United States. Accurate estimates of snow depth help water resource managers predict the timing and volume of peak spring runoff as well as the recharge of subsurface water storage (Regonda et al., 2005). When combined with snow density estimates, snow depth can be used to improve snow water equivalent (SWE) products that measure the liquid depth of melted snow and are critical for water resource management (Sturm et al., 2010). Long-term monitoring of snowpack is also important for understanding shifts in the seasonality of precipitation (Bradley et al., 1987; Rajagopalan and Lall, 1995) and streamflows (Roos, 1987, 1991).

The Snow Data Assimilation System (SNODAS) is a modelling and data assimilation system for the continental United States. The National Weather Service’s National Operational Hydrologic Remote Sensing Center produces SNODAS data products on a daily basis. By combining snow observations from ground stations, airborne surveys and satellites with output from Numerical Weather Prediction (NWP) models, SNODAS aims to produce the best possible snow product to support a wide range of applications. The National Oceanic and Atmospheric Administration’s National Weather Service field offices use SNODAS operationally when issuing hydrologic forecasts and warnings. A variety of federal, state, local, municipal, private sector and general public end users also rely on these real-time snowpack products (Carroll et al., 2006). Presently, it is the only daily, high-resolution snow depth and SWE product available for the entire lower 48 states with 1-km grid resolution.

It is important to understand and quantify the general error characteristics of the SNODAS data products through independent verification methods. Several studies (Hay et al., 2006; Azar et al., 2008) have suggested that SNODAS products are in need of independent validation, noting that the assimilation process utilizes most common ground-based and airborne data. Assimilating a larger variety of snow observations could benefit SNODAS, particularly in environments under-represented by the Snowpack Telemetry (SNOTEL) network (Serreze et al., 1999) and other assimilated observations. Here we focus only on the evaluation of the snow depth SNODAS product. A companion study of SWE has been conducted by McCreight et al. (2014) that also incorporates snow density from SNOTEL.
Global Positioning System (GPS) Interferometric Reflectometry (GPS-IR) is an emerging measurement technique for the monitoring of snow depth (Larson et al., 2009). Over 100 GPS-IR sites are measured in near-real-time across the Western US and Alaska. In contrast to SNOTEL, GPS sites were not originally developed to measure snow. The GPS stations of the Earthscope’s Plate Boundary Observatory (PBO; http://pbo.unavco.org, see Larson and Nievinski, 2013) were installed for tectonic applications and are primarily located in unforested locations to maximize their unobstructed tracking of orbiting GPS satellites. These stations also tend to be located at lower elevations than SNOTEL. As the GPS-IR snow depth estimates are not yet assimilated into SNODAS, they offer an opportunity to validate SNODAS snow depth estimates in an environment uncharacteristic of SNOTEL.

One strength of the GPS-IR techniques utilized here is that the snow depth is derived from a spatial footprint that is on the order of a hundred square metres. This is much larger than typical \textit{in situ} measurements, but it is still significantly smaller than the gridded products from SNODAS. Multi-scale comparisons such as this are difficult and frequently utilize downscaling methods to facilitate more accurate comparisons. We are unable to accurately utilize such methods due to sub-grid variability in snow depth caused by heterogeneous snow accumulation variability induced by wind, topography, soil and forest conditions. Nevertheless, this comparison sheds light on the representativeness of SNODAS estimates and may indicate potential systematic problems in its data products.

The objectives of this research are (1) to compare SNODAS snow depth with GPS-IR observations across the lower 48 states, (2) to illustrate and understand SNODAS snow depth sub-grid variability using both GPS-IR and other available \textit{in situ} measurements and (3) to identify areas with the greatest differences between GPS-IR and SNODAS and investigate potential causes for large disagreements.

The outline of this paper is organized as follows. We begin with a review of the GPS-IR retrieval method, explaining how snow depth can be estimated from GPS reflected signals. Then, we describe the study areas and data sets employed, both snow depth and ancillary (cameras, manual and SNOTEL automatic sensors). We follow with a presentation and discussion of the main results obtained comparing GPS-IR observations with SNODAS and the sources of uncertainties. First, a statistical comparison of seasonal GPS-IR and SNODAS is shown for four water-years (2010–2013). Differences in snow depth between GPS and SNODAS are also analysed in conjunction with vegetation and elevation variability. Then, cumulative differences in snowfall and fractional snow-covered period are analysed. In the discussion, we emphasize the utility of independent snow depth observations for validating SNODAS and help characterizing large subpixel snow depth variability. Several potential systematic errors are also identified and may be useful to help improving the current system.

**GPS INTERFEROMETRIC REFLECTOMETRY METHOD**

The GPS-IR is a bi-static radar technique, in that the transmitter and receiver are physically separate. L-band (1.5 and 1.2 GHz) signals emitted by the orbiting GPS satellites are received by omni-directional GPS antennas located ~2 m above the ground. Although most of the signal that arrives at the antenna is received directly through the line-of-sight, the surrounding terrain also reflects some of the incident GPS signal. The antenna mixes these direct and indirect signals, producing constructive and destructive interference oscillations that are observable in the signal-to-noise ratio (SNR) measurements. The SNR data exhibit a quasi-sinusoidal pattern whose dominant modulation frequency is proportional to the vertical distance between the GPS antenna and the underlying reflecting surface (Larson et al., 2009). SNR data collected during the summer are used to define the snow-free reflector height for a given satellite track (h1 in Figure 1) around a given station. The reflector height changes when snow is deposited on the ground (h2 in Figure 1). The difference between the snow-free reflector height (h1) and the snow-covered surface reflector height (h2) is then used to derive snow depth.

The antenna height defines the method sampling area (Figure 2). The snow-free footprint is ~1000 m$^2$ and becomes smaller with increasing snow accumulation as

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**Figure 1.** Schematic representation of the GPS-IR technique. Direct signal (D) and reflected signals: R1 without snow and R2 with snow have an interference pattern with a different frequency.
the reflecting surface approaches the antenna level. The method is not reliable when the snow surface is within 0.5 m of the antenna. GPS antennas used in this study are part of the PBO network and were located away from obstructions such as trees and buildings, which can block the direct signal. GPS stations are also frequently located near terrain ridges (to maximize satellite visibility and access to bedrock for improved anchoring in measuring tectonic activity), which increase their exposure to wind. Details about the GPS-IR method are provided by Larson and Nievinski (2013).

The GPS-IR snow depth has been validated in numerous studies. It was first demonstrated on a case study at a grasslands site (Marshall, CO) (Larson et al., 2009). GPS-IR estimates agreed with in situ manual transects on the 3 days sampled, with uncertainties between 2.5 and 5.0 cm. GPS-IR also followed the temporal dynamics of accumulation and ablation as recorded by more frequent measurements from a nearby ultrasonic sensor. The accuracy of the GPS-IR method was assessed by Gutmann et al. (2012) at an alpine site (Niwot Ridge) for a full water-year, using multiple techniques: manual and terrestrial laser-scanning in situ measurements as well as an airborne lidar flight. They found 13-cm root mean square error (RMSE) and a 10-cm bias at peak snow cover (up to 175 cm), with smaller errors (9-cm RMSE, 6-cm bias) during the ablation period. However, the evaluation was made difficult as GPS-IR and in situ footprints were not exactly coincident, and this site exhibits high spatial variability due to wind redistribution in the sloping terrain. Nievinski and Larson (2014) assessed the performance of GPS-IR in a forested site employing a dense sample, made of 20–150 measurements replicated around the GPS, and repeated approximately every other week for one water-year. Results show a slight negative bias (−6 cm), RMSE of 8.7 cm, and correlation of 0.96. They found that errors are substantially reduced when at least four satellites tracks are available per site in a day.

**DATA SETS AND STUDY AREAS**

**GPS-IR snow products**

The current GPS-IR methodology (Larson et al., 2009) uses the L2C GPS code (Fontana et al., 2001) that is part of a modernization of the GPS programme and was first broadcast from space in 2005. As of October 2013, 12 (out of 32) GPS satellites transmit L2C signals. This signal was not widely tracked or utilized until water-year (WY) 2010, when a few of the PBO sites were enabled with this signal-tracking capability; the remaining sites were enabled with this tracking capability by WY 2012. Approximately 125 sites on the network have been determined suitable for measuring snow depth, with 25 of these GPS sites in Alaska (Larson and Nievinski, 2013) and 100 primarily in the Western US: Idaho, Montana, Wyoming, Oregon, Washington, Colorado, Utah, California and Nevada (Figure 3).

The daily GPS-IR snow depth estimates (available for download at http://xenon.colorado.edu/portal) represent an average overall satellite tracks on a given day. GPS-IR derived snow depths of less than 5 cm are not reliable and considered snow-free. Their standard deviation is...
combined in quadrature with the bare-soil reflector height uncertainty. The full set of satellite tracks at an antenna comprises the spatial footprint of the GPS-IR method. A snow-free GPS antenna has spatial footprint of approximately 1000 m² and represents about 1/10 of 1% (1‰) of a 1-km² SNODAS grid cell.

In this study, GPS sites were categorized by individual water-years as either ‘snowpack’ or ‘ephemeral’. In an ephemeral year at a site, snow accumulation and melt occur over short time scales. In contrast, snowpack years have a distinct accumulation period followed by an ablation period (Serreze et al., 1999; Liston and Elder, 2006). We classify ephemeral (snowpack) years as those with snow cover persisting for less (more) than 20 consecutive days. Note that the snowpack/ephemeral designation is not a property of a site only. It is dependent on a particular water-year, too.

**SNODAS gridded products**

The SNODAS products were obtained from the National Operational Hydrologic Remote Sensing Center (2004) and archived at the National Snow and Ice Data Center (http://nsidc.org). SNODAS aims to provide a physically consistent framework for integrating snow observations with model estimates of snow cover. SNODAS begins with a physically based, near-real-time, energy-and-mass-balance, multi-layer and mass-balance snow model. The snow model is run daily at 30-arc-second resolution (nominally 1 km) and is driven with analysis products from the Rapid Update Cycle (RUC2) NWP model. Thermodynamic profile variables (pressure, temperature and relative humidity) from this NWP model are downscaled to 1 km using a digital elevation model (Carroll et al., 2001). In addition, some static gridded geophysical data sets such as derivatives of slope and aspect and canopy parameters (forest cover and type) are also used. The model is also updated with surface weather observations that are combined with snow observations (satellites, airborne and in situ) using data assimilation techniques.

Following Barrett (2003), SNODAS represents point estimates at the centre of each grid cell (not an areal average); at the same time, Barrett (2003) states that SNODAS estimates can be applied as representative average conditions when necessary for hydrologic applications. The latter interpretation suggests the lack of reliable spatial up-scaling and down-scaling methods for snow depth. It must be recognized that the SNODAS model has an inherent spatial resolution, dictated more by the ancillary data and observations assimilated and less by the model discretization scheme (grid posting interval and areal/point evaluation choice).

Previous studies conducted by Clow et al. (2012) revealed weak agreement of SNODAS snow depth estimates with measurements in alpine areas ($0.16 R^2$, 55-cm RMSE) but reasonable agreement in forested areas ($0.72 R^2$, 15-cm RMSE). An explanation for this is that the primary set of observations assimilated into SNODAS comes from the SNOTEL network that is located almost exclusively in sub-alpine, forested areas.

**SNOTEL and other in situ measurements**

Three additional data sets are used to help construct a more complete picture of SNODAS data products. This includes SNOTEL observations, in situ manual measurements and camera measurements. Each of these data products has their own unique characteristics that are important for this intercomparison. SNOTEL network consists of sonic sensors to make automated measurements of snow depth. In contrast to the GPS sites, SNOTEL sites are specifically located to measure snow – as opposed to its absence. Therefore, water-years at SNOTEL sites are rarely

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**Figure 3.** Location of PBO GPS sites (red circles) used for snow measurements in the Western US in this study. SNOTEL network is shown for comparison (blue dots). GPS stations used for validation in this study are represented with filled circles.
ephemeral in nature. Figure 3 depicts the location of the SNOTEL and GPS sites used for the study over the Western US. SNOTEL data are available from the National Resource Conservations Service (http://www.wcc.nrcs.usda.gov/snow/).

In situ manual measurements of snow depth were collected at a number of GPS site locations in WY 2012 for GPS-IR validation purposes (McCreight et al., 2014) and a subset is used here. Average manual measurements over the GPS footprint are taken for sites p351 (Idaho), rn86 (Utah), p101 (Utah) and p360 (Idaho). The manual measurements provide a snow depth value that is representative of the footprint around the GPS site. The disadvantage of these observations is that they were not frequently collected. They were collected on one-time visits within weeks of peak snowpack time; as an exception, station rn86 was visited nine times.

Cameras were used to take time-lapse photographs of marked poles (Parajka et al., 2012) at p101, p360 (from WY 2012) and rn86 (from WY 2013). Their readings provide single-point measurements within the GPS footprint; their advantage is the high temporal sampling rate (a few times per day).

Explanatory variables: National Elevation Dataset and National Land Cover Dataset

To explain differences between SNODAS, GPS-IR and SNOTEL estimates of snow depth, we differentiate sites using commonly available terrain elevation and land cover data available from the US Geological Survey (http://nationalmap.gov/viewer.html). Spatial variability in terrain and canopy heterogeneity can strongly influence snow depth within a single SNODAS pixel. We utilize this terrain and land cover indices to isolate SNODAS pixels where snow cover is governed by a narrower (wider) range of physical processes and is expected to be more homogeneous (heterogeneous). A more refined comparison of GPS-IR and SNOTEL for low-variability SNODAS grid cells is also performed. The National Elevation Dataset (NED, Gesch et al., 2002; Gesch, 2007) was obtained at 1-arc-second (about 30 m) spatial resolution. Data were analysed over each SNODAS grid cell that contained a GPS-IR site. The collocated National Land Cover Dataset (NLCD2001) is also gathered at a similar resolution.

We calculate the standard deviation in NED elevations and a canopy heterogeneity index from NLCD2001 (Homer et al., 2007). Each SNODAS pixel contains approximately 1000 NED and NLCD pixels. The canopy heterogeneity index \( C_{Hi} \) runs from 0 to 100, 100% being the most heterogeneous situation and has been computed as follows:

\[
C_{Hi} = \begin{cases} 
C_d > 0.5, & 200 \times |C_d - 1| \\
C_d \leq 0.5, & 200 \times C_d 
\end{cases}
\]

with \( C_d \) being tree canopy density, as taken from NLCD. Here the heterogeneity refers to the presence/absence of trees, not to the heterogeneity to the types of vegetation.

Snow depth spatial variability considerations

When treating SNODAS snow depths as point estimates at the centre of each grid cell, the locations of the SNODAS estimates do not align with the locations of the GPS site locations. It is possible for a GPS-IR observation in a SNODAS pixel to be up to 0.7 km from the centre of that pixel. We found that bilinear interpolation of SNODAS to GPS-IR locations resulted in slightly lower RMS differences than using nearest-neighbour interpolation. Thus, SNODAS outputs were bilinearly interpolated to the evaluation sites. Furthermore, we analysed differences between SNODAS grid cell elevation and the site elevation as a function of absolute snow depth difference value (not shown) and no correlation was found.

Spatial variability of snow depth is notoriously large at virtually all spatial scales (Serreze et al., 1999; Grünwald et al., 2010; McCreight et al., 2012), which inevitably complicates comparisons. As such, we perform a network-wide comparison of SNODAS. We will consider overall statistics of the SNODAS and GPS-IR discrepancies. In several locations where GPS stations are in close proximity to SNOTEL sites, we offer specific examples of SNODAS variability to illustrate potential problems with data assimilation in SNODAS.

RESULTS

Illustrative time series

Snow depth time series from four different GPS-IR validation sites are shown in Figure 4 during water-year 2012. These four sites include all data types: GPS-IR (Figure 4a–d), SNODAS (Figure 4a–d), SNOTEL (Figure 4a, b and d), manual surveys (Figure 4a–d) and camera measurements (Figure 4c and d). These four sites illustrate the general agreement between GPS-IR and SNOTEL in capturing the overall seasonal pattern of snow accumulation and melt. Individual snowfall events are also clearly seen in their data. Correlation coefficients between GPS-IR and SNODAS range from 0.64 to 0.96 over the four sites (not shown) considering all data over the water-year. As serial correlation was suspected, we applied a high-pass temporal filter (60-day window width) that resulted in slightly smaller correlation coefficients, now ranging from 0.49 to 0.82. Correlations are larger for sites that experienced one or more heavy snowfall events (p351 and m86). The camera and manual measurements at the GPS sites are shown to corroborate the measurement accuracy of the GPS-IR technique (McCreight et al., 2014, in review). Despite the general
agreement between the different data sets, differences between SNODAS and GPS-IR can be quite large (Figure 4a, b and d).

At p351 (Figure 4a), the surrounding SNODAS pixel has a $C_{HI}$ of 85 signifying that the site is located in a heterogeneous vegetative area. The SNODAS time series is similar to the SNOTEL record. The manual survey within the GPS-IR footprint in early March serves to validate the GPS-IR time series. In this instance, the observed snow depth differences (SNODAS and SNOTEL greater than GPS-IR) are consistent with vegetation controls on snow accumulation and melt, in that the lack of trees around the GPS location increases exposure of the site to both wind and solar radiation, which reduce snow depth compared with forested areas, particularly during the melt phase.

Site m86 (Figure 4b) is illustrative of the types of differences that can be found over a SNODAS pixel area. In this instance, there are GPS-IR and SNOTEL sites in close proximity to each other (400 m), but there are substantial differences between the two time series. At m86, the GPS station lies in a tree clearing area whereas the SNOTEL is sheltered in the forest. Given nearly identical elevations, vegetation likely governs their observed difference. Indeed, canopy heterogeneity is very high (0.95) at this SNODAS pixel.

Because SNODAS assimilates SNOTEL data, it is not surprising that the two time series are very similar. This is particularly true for cases when the bilinear interpolation of the SNODAS products to the GPS locations also contains SNOTEL observations that are in close proximity (e.g. p351 and m86, Figure 4a and 4b). Our analysis of daily SNODAS snow depth at 229 SNOTEL stations (those within 50 km of GPS locations) reveals a coefficient of determination of 0.94 between SNODAS and SNOTEL for the three water-years 2010–2012. However, comparison of SNODAS with GPS-IR within the same pixel suggests that the SNODAS value is representative of open areas within the pixel and may not be representative of the observed average snow depth in the entire SNODAS pixel area.

Figure 4c shows GPS-IR and SNODAS snow depths in relatively good agreement at site p101 in Utah. The uncertainty of the GPS-IR time series is indicative of variability in snow depth around the GPS antenna location. Recall that the GPS-IR product is a combination
of reflectometry measurements made in the direction of several satellite tracks that sample an area that approaches 1000 m² around the GPS antenna (see Figure 2). The camera measurements that are obtained within the GPS-IR footprint are generally consistent with the GPS-IR product, but somewhat less (~10 cm) than either the GPS or SNODAS time series. This may be indicative of a point measurement that is not able to capture the spatial variability of snow depth around the site. Two snowfall events (beginning of October and late February/early March) are apparent in the SNODAS records that are absent from both the GPS-IR and camera measurements.

At site p360 (Figure 4d), unlike the other four sites shown in the figure, SNODAS snow depth estimates are less than observed by GPS-IR. In this case, the GPS-IR SNODAS pixel is much farther from SNOTEL (12.3 km) although only 60 m lower in elevation. The camera and manual snow depth at the GPS site location support the GPS-IR accuracy. The SNODAS time series matches the GPS-IR closely until immediately after a snowfall event in late January when the SNODAS value exhibits a 40-cm spike. In contrast, both GPS-IR and camera measurements indicate a jump rather than a spike, i.e. accumulation did occur but there was no subsequent melt. The temperature record at the closest weather station (MITD23, within 200 m of the GPS station) does not support the concept of melt processes, as the temperature record did not rise above 0 °C at any point during this time period. The camera provides an additional validation of the GPS-IR retrievals for this episode. The assimilation of GPS-IR data would likely have improved the SNODAS estimates in this area.

Statistical comparison of seasonal GPS-IR and SNODAS

The mean annual bias in snow depth (GPS-IR minus SNODAS) is shown for water-years 2010–2013 in Figure 5, for each station with at least five snowfalls in a single water-year. The year-to-year increase in the number of GPS-IR sites is clearly evident in this figure. This is particularly true in 2012 and 2013 when all stations in the PBO network were configured to track the

Figure 5. Annual mean bias (GPS-SNODAS) in metres represented at each station between water-year 2010 and 2013
L2C signals that were used to derive snow depth. The majority of these sites indicate that the GPS-IR products report lower snow depths (negative values in Figure 5) than the SNODAS products. This result is consistent with other findings from this intercomparison and does not appear to have a discernable link to either geographic location or snow depth. One definite source of this difference is the placement of GPS sites in open areas that tend to record lower snow accumulations than the surrounding areas that have higher vegetation fractions.

Figure 6a shows the differences in annual mean snow depth (as in Figure 5) between the GPS sites and their associated SNODAS pixels. The differences generally skew in the direction of SNODAS (GPS-IR) time series having higher (lower) snow depths, particularly in the 2012 and 2013 water-years when there are enough stations to observe a significant difference between the two data products. More than 35% of the stations have a difference in mean annual snow depth that is within −10 cm (SNODAS high) and 5 cm (SNODAS low). More than 60% of the stations in water-years 2012 and 2013 have a mean annual difference in snow depth that is within ±20 cm.

To better understand these differences, the mean annual snow depth at these stations is shown in Figure 6b. The majority of sites locations have snow depths of less than 0.5 m. It appears the differences in annual mean snow depth may be constrained by the magnitude of annual mean depth. The figure further supports the finding that SNODAS reports more snow than does the GPS-IR products.

The absolute percent error between GPS-IR and SNODAS (Figure 6c) is the absolute annual mean difference (GPS-SNODAS) normalized by the annual mean SNODAS snow depth in a given year. Five stations have an absolute percent error greater than 80% (p360, WY 2010; p033, p457 in WY 2012 and p447, p457 in WY 2013). More than 70% of the stations with percent error greater than 75% have a denominator (annual mean SNODAS) larger than 40 cm. In general, percent errors of 80% or more were not due to small denominators. Nearly 50% of these errors had SNODAS water-year mean
depths greater than 50 cm whereas only 26% had values below 15 cm.

Figure 6d presents coefficient of determination between GPS-IR and SNODAS calculated using only days when both GPS-IR and SNODAS have at least 5 cm of snow. The distribution of coefficient of determination is nearly uniform indicating a spectrum of agreement and disagreement between the GPS-IR and SNODAS time series.

**GPS and SNODAS differences**

To help understand poor, or even negative, correlations between GPS-IR and SNODAS, we present two examples from water-year 2012 in Figure 7. In Figure 7a, GPS measurements at site p460 are shown with the associated SNODAS estimates. The correlation of these time series is $-0.49$. At this site, we see major differences (>0.75 m) between the SNODAS snow depth and that observed by GPS. The large difference in snow accumulation suggests that large elevation differences are important in this SNODAS pixel. In fact, the standard deviation of NED 30 m elevations over this SNODAS pixel is in the top 10% of all SNODAS pixels in this study. There were 14 stations with negative correlation coefficients in 2012 (not shown). More than 30% of these sites were located in regions with highly variable topography (standard deviation of elevation greater than 40 m), which most likely influences the spatial distribution of snow. About 25% of these sites were in the top 30% of NED standard deviation (standard deviation above 60 m).

Figure 7b presents site p123 in water-year 2012 with near-zero correlation between GPS-IR and SNODAS ($R^2 = 0.07$). We note the low mean snow depth at the site in this water-year and that the differences between the two time series have small magnitudes. Although some of the behaviour of the SNODAS is seen in the GPS record, some is not. About 70% of sites looking to all water-years (p085, p381, p460 and p033) with near-zero correlation were classified as ephemeral. For all these sites, there is no SNOTEL in the vicinity (less than 25 km) except for p085 that has a SNOTEL station within 19 km. Stations with a small but positive correlation ($R^2 < 0.1$), such as p123 in Figure 7b, tended to have shallow snow (typically less than 25 cm) that remained on the ground throughout the water-year. The average snow depth for all these near-zero correlation sites was not exceeding 30 cm along the water-year.

In Figure 8, we attempt to systematically explain the absolute difference in snow depth between GPS-IR and SNODAS as a function of canopy heterogeneity index for each SNODAS pixel on the y-axis and local terrain standard deviation within the SNODAS pixel on the x-axis. Points nearer the origin represent SNODAS pixels with low standard deviation in elevation and with low canopy heterogeneity index. In theory, this eliminates two of the greatest factors governing variability in snow depth across a pixel, e.g. between GPS-IR and SNODAS. Pixels contained within both 40 m (x) and 40% (y), the box drawn on the figure, show a relatively low (less than 20 cm)
absolute annual mean bias (GPS-SNODAS). For pixels where canopy heterogeneity index exceeds 40% or the standard deviation of subpixel elevation is greater than 40 m, the absolute snow depth difference between GPS-IR and SNODAS exceeds 20 cm in 70% of the cases. Although variability of these two controls does not perfectly predict the differences between GPS-IR and SNODAS, they appear to explain a majority of cases. The GPS-SNODAS correlation of determination exhibited no dependence on these ancillary variables, in contrast to the GPS-SNODAS bias, which can be partially explained by canopy heterogeneity and terrain variation.

**Cumulative differences in snowfall**

Cumulative snow depth computed along a water-year is of particular interest for water budget characterization and water resource availability. We compute the annual cumulative snowfall (ACSF) for each GPS-IR and SNODAS, based on which the ACSF difference is defined as follows:

$$\text{ACSF}_{\text{difference}} = \sum_{d=1}^{365} \left( \Delta^+ \right) \text{GPS}_d - \left( \Delta^+ \right) \text{SNODAS}_d$$

where the $d$ is the day index and $\Delta^+$ denotes positive increments in snow depth. Note that cumulative snowfall is computed indirectly and therefore is sensitive to local redistribution of snow from wind (Winston et al., 2002). Wind is recognized as one of the dominant controls of snow accumulation and redistribution especially in mountainous region.

The ACSF time series for two snowpack sites (p360, ID and p101, UT) for which validation with both camera and manual measurement were available (Figure 4) are displayed in Figure 9. SNODAS and GPS-IR agree well until March at p360. In particular, snowfall timings generally agree although the quantities differ and SNODAS exhibits more numerous smaller events than seen in the GPS-IR. By May, SNODAS exhibits an annual difference greater than 60 cm compared with GPS-IR. SNODAS and GPS-IR accumulations at p101 are similar. Although they do not agree on several snowfalls, by the end of the season, SNODAS and GPS-IR ACSF are only 10 cm apart. Assuming a snow density of 0.3 g cm\(^{-3}\) this represents 3 cm of liquid water.

Maximum cumulative snowfall differences between GPS-IR and SNODAS at all 91 sites available during the 2012 water-year are shown in Figure 10a and with a magnified area over the North Central Rockies sites in Figure 10b. For both snowpack and ephemeral sites, ACSF differences are typically negative, consistent with SNODAS snow depth estimates generally exceeding those measured by GPS-IR. Some sites with positive ACSF differences (e.g. the two sites located in New Mexico and Arizona) may be located far from SNOTEL or other operational snow depth observations. Mean and median on ACSF difference are respectively $-0.53$ and $-0.27$ m.

**Fractional snow-covered period**

There were 125 GPS stations in water-years 2012 and 2013 suitable to retrieve snow depth. Some of these stations reported depths for a large percentage of days during the water-year (classified as snowpack sites), some stations reported depths for only a few days (ephemeral sites), and some stations did not have any days with measurable snow depths. From a radiation balance perspective, it is useful to compute the fraction of time in a year that snow cover was present at a location.

Figure 11 shows the fractional number of days that snow depths greater than 5 cm were reported by either GPS-IR or SNODAS for water-years 2012 (Figure 11a) and 2013 (Figure 11b). There are clear differences in the percentage of time when the two products indicated that snow was present at a particular site location. In general, the SNODAS products reported a much larger percentage of days with snow than the GPS-IR products. This is particularly true for ephemeral sites where snow was not

![Figure 9](image_url)
present for the majority of the time during the water-year. During the 2012 drought year (Figure 11a), there were more than 48 GPS stations where snow was present for less than 5% of the year. The SNODAS products had only 19 stations where these conditions existed. Slightly different results are available during water-year 2013. For this season, there were many locations where the GPS-IR products reported snow conditions less than 10% of the time whereas the SNODAS products had a broad distribution of sites where snow was reported between 10% and 40% of the year. These differences are important; the presence of snow cover has direct consequences in the computation of radiation balance, surface temperature and evapotranspiration.

**DISCUSSION AND CONCLUSIONS**

Although our study found general agreement between GPS-IR observations and SNODAS, we also uncovered differences between the two, in term of bias as well as sometimes low correlation between their time series. Given that SNOTEL is a primary data source for SNODAS (Figure 4a and b), especially over distances of less than 10 km, differences in physiographic conditions between GPS-IR and SNOTEL observations could explain the bias of GPS-IR relative to SNODAS. Vegetation and elevation variability within a SNODAS pixel show some success in explaining such large differences in their snow depths. Large variability in either governing variable leads to an increased likelihood of a large difference in snow depth between GPS-IR and SNODAS. However, low correlations between GPS and SNODAS are not similarly explained by these variables.

Our analysis prompts two questions: (1) Do the snow depth differences between GPS-IR and SNODAS represent true, subpixel variability? (2) Do SNODAS estimates need adjustment to more properly represent pixel average conditions? Neither of these questions can be fully answered without intensive snow observations over the SNODAS pixels of interest. Our study nevertheless helps characterize large subpixel snow depth variability and offers one view.
into potential systematic errors in SNODAS which may provide useful for improving the system.

Comparison of GPS-IR retrievals with SNODAS estimates illustrates the utility of independent snow depth observations for evaluating SNODAS and characterizing its uncertainties, including spatial representativeness, a consequence of natural variability. Several comparisons of SNODAS with GPS-IR and SNOTEL observations in close proximity shed light on this important source of error. Although admittedly we have far too few observations to estimate robust error statistics, our investigation does highlight that SNODAS overestimates snow depth compared with GPS-IR retrievals. This is mainly a consequence of the GPS-IR site locations compared with SNOTEL.

We also showed that large differences between SNODAS and GPS-IR can be explained to first order by subpixel topographic or vegetation heterogeneities (Figure 8). On the other hand, correlation between the SNODAS and GPS time series spanned a range of values with no apparent link to physiographic controls, and warrants further investigation. Our analysis of annual cumulative snowfall differences between GPS-IR and SNODAS, as well as their differences in snow persistence, further indicated discrepancies between the two in terms of the water-cycle budget.

Generally, we have highlighted GPS-IR as a complementary network to the existing SNOTEL automatic sensors that observe significantly different snow dynamics, likely as a result of different location and physiographic conditions. Thus, assimilation of GPS-IR into SNODAS could improve estimates in two different situations: for regions void of SNOTEL sensors and areas with strong elevation and/or vegetation heterogeneities.

The use of point measurements at GPS sites, particularly manual surveys and camera measurements, indicates that the GPS-IR products are accurate within the 1000 m² measurement footprint around the GPS antenna (Figures 4 and 7a). For the majority of locations where the GPS-IR and SNODAS data products were compared, SNODAS snow depths were generally larger than the GPS-IR products (Figures 5 and 6). This difference produced GPS-IR snow depths that were fractionally less than the SNODAS depths (Figure 6c).

In summary, snow measurements derived using GPS-IR techniques across four water-years (2010–2013) have been compared against SNODAS data products from more than 125 stations across the Western US. Additional comparisons were made using point (collocated manual, camera and SNOTEL) measurements to help explain differences between the GPS-IR and SNOTEL products. The purpose of this study was to evaluate the differences between the two independent data sets over a broad geographic distribution so that their differences, and the sources of these differences, could be identified.

The advantage of GPS-IR snow measurements as complementary observations is twofold. First, they provide currently an independent observation system that has been validated under several conditions and locations to the SNODAS. Second, we have demonstrated that snow depth differences and annual cumulative snowfalls difference existing between SNODAS and GPS-IR could be significant (10% of the stations have an annual bias greater than 20 cm) and are not only explained by landscape heterogeneities. The integration of GPS-IR observations in the SNODAS would contribute new information for the model, however no longer remaining an independent data set. Development of a statistical GPS-IR SWE product may also provide additional information for such hydrological models (McCreight and Small, 2014).

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