The Phase 2 North America Land Data Assimilation System (NLDAS-2) Products for Modeling Water Storage Displacements for Plate Boundary Observatory GPS Stations

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Abstract

In this paper, we compare the efficiency of two models to estimate the surface displacements due to continental water storage (CWS) variations over continental North America. The first model, the monthly North America Land Data Assimilation System Phase 2 Noah (NLDAS-2 Noah) is a model of CWS restricted to North America. The second data set, the Global Land Data Assimilation System Noah (GLDAS Noah), is global. To compare the models, we use coordinate time series from GPS stations within the Plate Boundary Observatory (PBO). We find that the NLDAS-2 Noah CWS estimates of vertical surface displacements are correlated with PBO height coordinate time series with an average correlation of 0.4. Of the selected 986 PBO stations, stations with their weighted root mean square (WRMS) reduced after removing the surface displacements predicted using NLDAS-2 Noah surface mass, account for 13%, 27% and 56% for the north, east and up components respectively. The highest reductions in scatter occur on coordinate time series from stations in the mountains.

Comparing NLDAS-2 Noah to GLDAS Noah, we find that the NLDAS-2 Noah model reduces the horizontal WRMS more than GLDAS for 88% and 73% of the PBO stations in the North and East components. In addition, stations in the mountains of the northwest and southeast part of the NLDAS-2 Noah spatial coverage (25% of the total stations) have their vertical scatter reduced by more than 10%. Therefore, we conclude that the NLDAS-2 Noah model better estimates the CWS induced 3-D surface displacement for PBO GPS stations in continental North America. The reasons may due to the finer spatial resolution, the updated Noah model, together with the more accurate surface forcing data of the NLDAS-2 Noah model.

Keywords

Continental water storage • GLDAS Noah • GPS time series • NLDAS-2 Noah • PBO

1 Introduction

Strong correlations exist between the continental water storage (CWS) and height changes in global positioning system (GPS) coordinate time series (van Dam et al. 2001, 2007; Tregoning et al. 2009; Fritsche et al. 2012). This environmental surface displacement could add residual signal to GPS data that is being used for geodynamic studies, e.g. tectonics, and postglacial rebound. To remove this environmental signal, CWS mass models are needed to predict surface displacements. Currently, one of the most cited models used for estimating CWS loading effects is the monthly Global Land Data Assimilation System (GLDAS) model. The model has a spatial resolution of 1° in longitude and latitude (Rui 2011). The components of water storage in GLDAS include

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soil moisture (SM) and snow water equivalent (SWE). There is no groundwater change component in GLDAS.

The Plate Boundary Observatory (PBO), part of the EarthScope project, was installed to measure Earth deformation across the coterminous western United States and Alaska, primarily using permanent GPS receivers. PBO is the most precise spatial reference system realization available in United States history (Anderson et al. 2006). It consists of 1,100 continuously operating GPS stations[1]. CWS driven surface displacements introduce residual signal into these time series primarily at annual periods with significant inter-annual variability.

Under funding from the National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Program of the Americas (CPPA), the National Centers for Environmental Prediction (NCEP) Environmental Modeling Center (EMC) team has developed the North America Land Data Assimilation System Phase 2 Noah (NLDAS-2 Noah) that includes improved forcing data and land surface models (LSM) simulations (Xia et al. 2012; Rui 2013). This model is provided, in near real time, at 1/8th-degree grid spacing over North America for a period extending from January 1979 to the present at hourly and monthly temporal resolutions. As NLDAS is eight times more spatially dense than the GLDAS product, we want to evaluate whether the higher spatial resolution of LDAS might improve the correlation between the CWS driven displacement and the GPS coordinate time series as compared to GLDAS Noah model.

Since our previous analysis show that under the same spatial resolution, for example, the GLDAS monthly and 3-hourly products, there is only a slight difference for the loading displacement at the weekly samples (see Fig. 2 of Li et al. 2014), and the higher temporal resolution could improve the performance by almost the same magnitude for different CWS models (see Table 2 of Li et al. 2014), while the GLDAS monthly model is currently one the most cited models for estimating the CWS loading effects, in this paper, we investigate the difference between the weekly surface displacements interpolated from the monthly GLDAS Noah and NLDAS-2 Noah CWS (SWE + SM) models. Even though the PBO network extends up into Alaska, we will restrict our comparison to sites in the continental US, as this is essentially the coverage for the NLDAS-2 Noah data set.

2 Data Processing

2.1 Farrell's Green's Function Approach

The predicted 3-D surface displacement of a point on the Earth's surface driven by changes in CWS can be determined by convolving Farrell's Green's functions (Farrell 1972) with a surface mass model over the surface of the Earth (van Dam and Wahr 1987). The basic equations can be written as:

$$
\begin{aligned}
d_n(\theta,\phi) &= \sum_{i=1}^{nlon}\sum_{j=1}^{nlat} \Delta P_{i,j}\, G^n_{i,j}\, A_{i,j} \\
d_e(\theta,\phi) &= \sum_{i=1}^{nlon}\sum_{j=1}^{nlat} \Delta P_{i,j}\, G^e_{i,j}\, A_{i,j} \\
d_u(\theta,\phi) &= \sum_{i=1}^{nlon}\sum_{j=1}^{nlat} \Delta P_{i,j}\, G^u_{i,j}\, A_{i,j}
\end{aligned}
\tag{1}
$$

where the subscripts i and j denote a unique grid point in the GLDAS Noah or NLDAS-2 Noah data sets, $\Delta P_{i,j}$ is the CWS variation at the grid point, $A_{i,j}$ is the area of the grid point, *nlon* and *nlat* represent the maximum number of grid units in longitude and latitude. For GLDAS Noah grid, $nlon = 360$; $nlat = 150$, while for NLDAS-2 Noah data, $nlon = 464$; $nlat = 224$. θ and ϕ represent the co-latitude and longitude of the point on the Earth where the loading effect is being determined, $d_n(\theta,\phi)$, $d_e(\theta,\phi)$, $d_u(\theta,\phi)$ are the 3-D surface displacements of the given point, $G^n_{i,j}$, $G^e_{i,j}$, $G^u_{i,j}$ denote the Green's function for each component (Farrell 1972). The Green's functions are a function of the angular distance between the loading point and the point where the effect of the load is being calculated. We choose the Green's function derived in the center of figure (CF) frame to maintain consistency between the predicted loading and GPS coordinate time series (Dong et al. 1997; Dong et al. 2003; Blewitt 2003).

For all of the CWS data, we remove a 10-year mean that is calculated using data from 2000 to 2009 for each model. Then, the residual from this mean is convolved with the Farrell's Green's function to obtain the 3-D surface displacement. The resulting monthly surface displacements are then detrended and interpolated into weekly solutions that correspond to the GPS week.

2.2 Data Description

2.2.1 Water Storage Model

We model the CWS induced surface displacements for 986 PBO GPS stations in continental North America using both the GLDAS and NLDAS-2 Noah models. The time period for our comparison is 01/01/2000 to 31/12/2012. For the GLDAS Noah products, we use the 1-degree SM and SWE data[2]. We do not include the SWE data above the latitude of 60.5 N. This area includes Greenland and most Arctic regions. GLDAS Noah does not model snow dynamics well

[1] http://www.unavco.org/instrumentation/networks/status/pbo

[2] ftp://hydro1.sci.gsfc.nasa.gov/data/s4pa/GLDAS_V1

Table 1 Details of the CWS data in the GLDAS and NLDAS-2 Noah models

	GLDAS Noah	NLDAS-2 Noah
Data source	SM, SWE (below 60.5°N)	SM, SWE
Unit	Kg/m^2	Kg/m^2
Spatial resolution (degree)	1° × 1°	0.125° × 0.125°
Latitude extent (degree)	−59.5 to 89.5	25.063 to 52.938
Longitude extent (degree)	−179.5 to 179.5	−124.938 to −67.063
Dimension	360 (lon) × 150 (lat)	464 (lon) × 224 (lat)
Latency	1–4 months	1–2 months

in these regions (Rui 2011; Jiang et al. 2013). The summations in Eq. (1) are over the entire globe.

For NLDAS-2 Noah, we also use the SM and SWE data[3], however for this data set the spacing is at 0.125°. Table 1 shows the details of the CWS data in both models.

The top panel of Fig. 1 shows the root mean square (RMS) of the weekly vertical loading time series using NLDAS-2 Noah for each PBO (Wessel and Smith, 2013) station, while the bottom panel represents the vertical RMS of each station with respect to the elevation. We can see that the amplitude of the vertical displacement induced by NLDAS-2 Noah shows a slight increase at the higher elevations[4], among which almost all the stations above the elevation of 500 m have the scatter larger than 1 mm, and the maximum RMS reaches 4 mm. In comparison the NLDAS-2 Noah horizontal displacements for all PBO stations are small, with a maximum RMS at the coast less of than 0.7 mm (not shown).

In Fig. 2 we compare NLDAS-2 Noah surface displacements with those predicted using GLDAS Noah. Figure 2 shows the standard deviation (SD) (top) and the maximum (bottom) of the difference between the vertical loading displacement using NLDAS-2 and GLDAS Noah models. We use SD in this comparison, because we want to determine which model has the larger signal. Positive SDs indicate that the NLDAS-2 Noah predicted displacements are larger than those determined the GLDAS Noah model. Similar as Fig. 1, here we also show the relationship between SD and the elevation to better illustrate the difference between NLDAS-2 Noah and GLDAS Noah with respect to the elevation (Fig. 3). From Figs. 2 and 3, we find that large difference exists in the predicted vertical displacement, and generally the difference increases with increasing elevation. The SD and the maximum displacements reach more than 1.4 and 4 mm for the predicted verticals in the high mountains respectively. For the horizontal components, we only observe small differences between the NLDAS-2 and GLDAS Noah predictions (not shown).

2.2.2 GPS Data

The latest PBO coordinate time series in IGS08 reference frame[5] are used to evaluate the performance of the CWS models. Note that the UNAVCO announced a GPS data quality issue that the GPS coordinate time series between the dates of 01 January 2014 and 15 October 2014 contain inaccurate daily positions[6]. Here we only use the GPS data until the end of 2012, so it has no impact on our comparison results. Before comparing the GPS observations with the detrended loading results, offsets and obvious errors in the GPS coordinate time series are detected and removed. These two steps are manually done station by station. The obvious errors refer to those station coordinates deviate largely from the neighboring points, and those with uncertainty larger than 10 and 5 mm for the vertical and horizontal components respectively. After we remove the above obvious errors, we then look at the linear trend of the time series. Whenever the linear trend changes, we define the epoch as an offset, and separate the time series. Although this manually detection method is time consuming, we think that this is the most reliable way to prepare the GPS data. Finally, since the published PBO GPS time series are daily solutions, we need to first average the daily GPS data into weekly solutions. The weekly averaging is sufficient since water storage changes are primarily annual. Then a linear trend should also be removed from the weekly GPS solutions.

To evaluate the effectiveness of the two models for precisely estimating CWS in the PBO time series we compare the predicted 3-dimensional surface displacements from NLDAS-2 and GLDAS Noah models with coordinate times series from the PBO GPS sites.

3 Results

Figure 4 shows an example of the detrended weekly loading time series for station SC02 (Friday Harbor, Washington) generated from the NLDAS-2 Noah and GLDAS Noah data sets in millimeters. From the top to the bottom, the panels represent up, north, and east components respectively. The CWS monthly time series are interpolated to GPS weeks using a cubic spline interpolation. The GPS time series represented by the black curve in the figure.

In Fig. 4, we observe that the predicted peak-to-peak horizontal displacement for station SC02 from both the

[3] ftp://hydro1.sci.gsfc.nasa.gov/data/s4pa/NLDAS-2

[4] http://www.sage.wisc.edu/atlas/maps/elevation/atl_elevation_nam.jpg

[5] ftp://data-out.unavco.org/pub/products/position

[6] https://www.unavco.org/data/gps-gnss/derived-products/derived-products.html

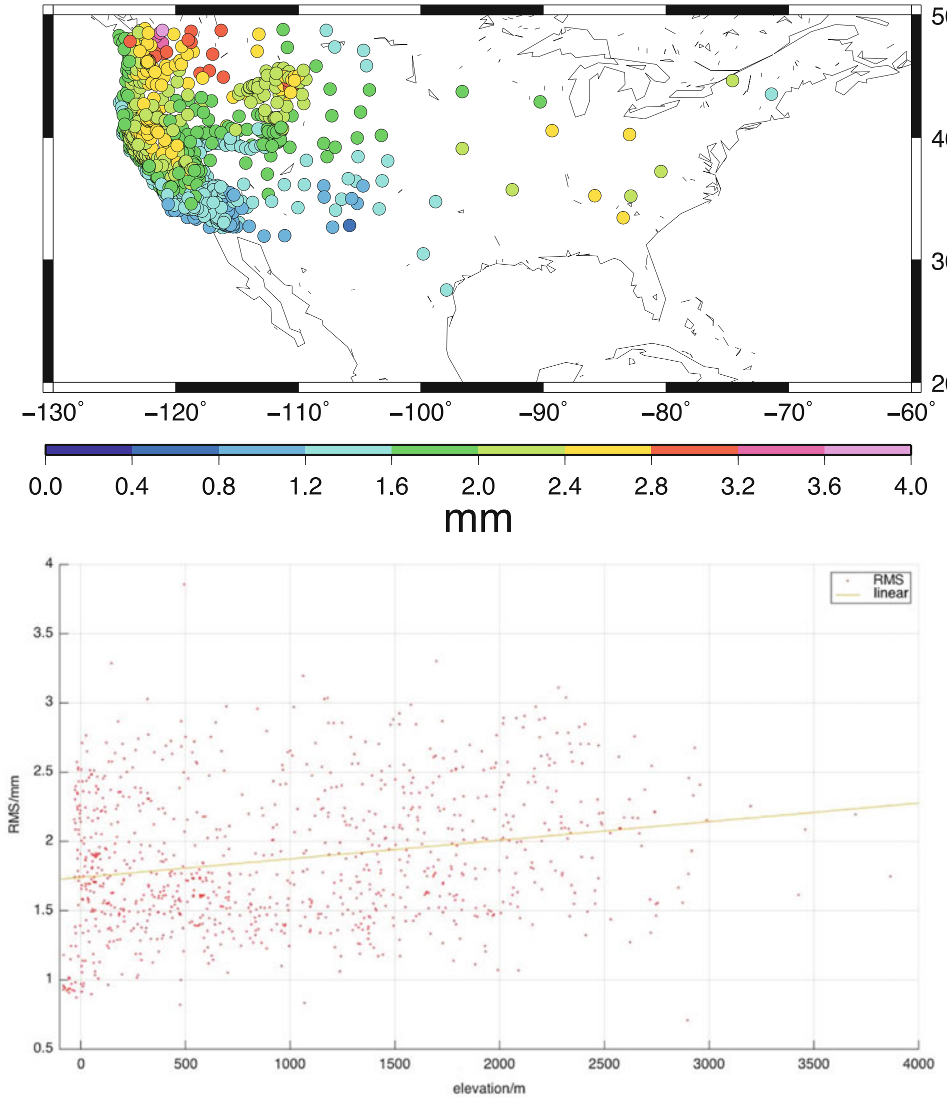

Fig. 1 (*Top*) RMS of the predicted weekly vertical displacement driven by NLDAS-2 Noah CWS. (*Bottom*) Vertical RMS of each station with respect to the elevation

NLDAS-2 and GLDAS Noah models are smaller than 2 mm. There is big discrepancy between the predicted and the horizontal GPS time series. With respect to the vertical component, both models fit the GPS height variation well, with the NLDAS-2 Noah model being slightly closer to the GPS when compared with the GLDAS Noah model.

The top panel of Fig. 5 shows the correlation between the NLDAS-2 Noah predicted vertical displacement and the GPS height time series. We find that in general the larger the RMS the higher the correlation. The average correlation between the predicted and the observed vertical component is approximately 0.4. Of all the stations, 52% have a correlation greater than 0.4. Stations located in the mountains, including the Pacific Coast Ranges, have correlations greater than 0.6.

Compared to the vertical results, poor correlations exist between NLDAS-2 Noah CWS loading and the GPS in the horizontal components. Stations with correlation coefficients larger than 0.4 account for only 5% and 12% for the North and East components respectively, most of which are located in the mountains.

The bottom panel of Fig. 5 shows the weighted root mean square (WRMS) reduction rate of the GPS coordinate time series after removing the predicted NLDAS-2 Noah CWS loading effect. The WRMS reduction rate here is a percentage, and is defined as

$$\begin{aligned}\%diff &= [WRMS(GPS) - WRMS\,(GPS - CWS)]\\ &\quad \times 100/WRMS(GPS)\end{aligned}$$

Positive values indicate that a station's WRMS is reduced.

After removing the NLDAS-2 Noah loading effects in the vertical coordinates, Fig. 5 shows that 56% of the PBO stations have their WRMS reduced. Stations with an improvement greater than 5% represent 31% of all stations. Most of these sites are located in the mountains. With respect to the

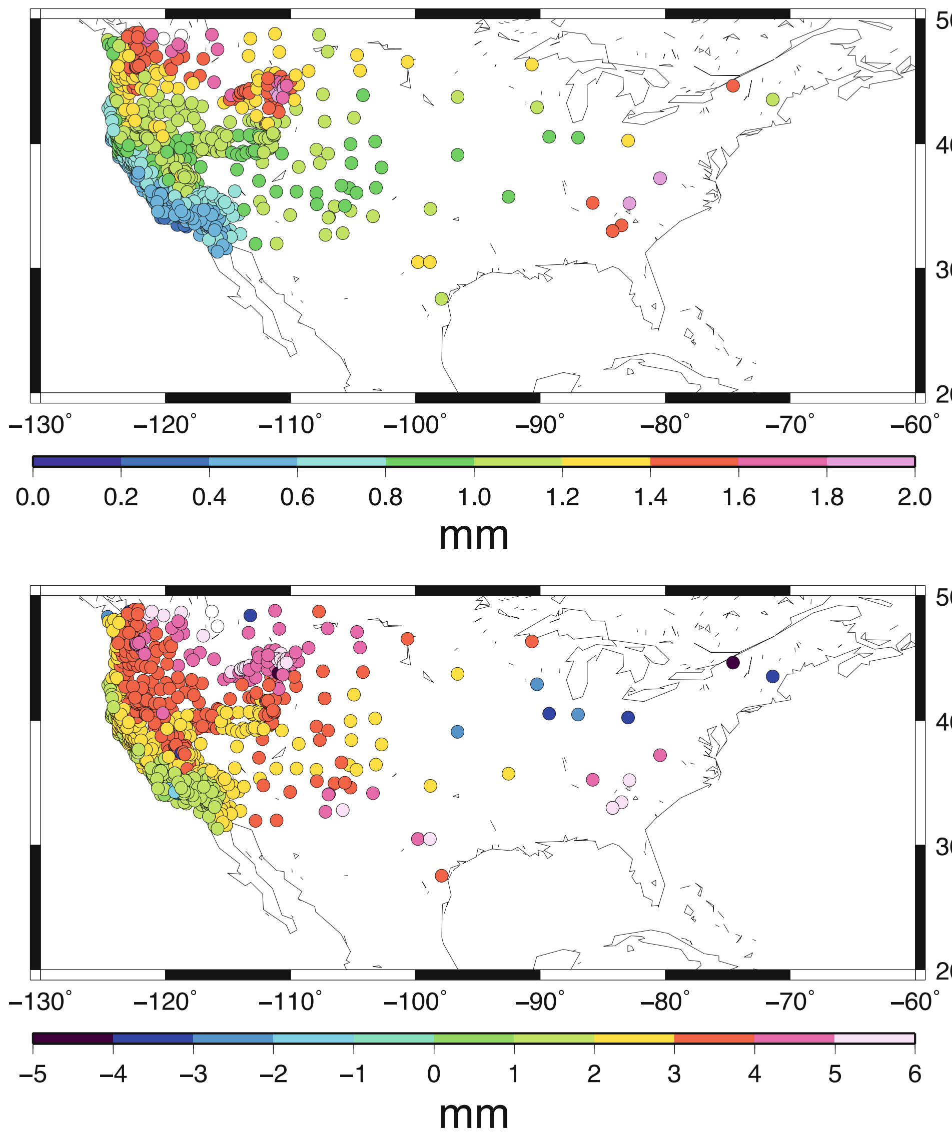

Fig. 2 Standard deviation (SD) (*top*) and the maximum differences (*bottom*) between NLDAS-2 and GLDAS Noah predicted vertical loading displacement. *White circles* indicate that the SD and the maximum difference are bigger than the maximum value on the scale. *SD* represents the scatter of the difference between NLDAS-2 and GLDAS Noah obtained displacement time series

horizontal component, only a small number of stations in the mountains have their WRMS reduced. The WRMS increases on the remaining stations when displacement from NLDAS-2 Noah are removed from the GPS horizontal coordinate time series. Specifically, 87% and 73% of the time series have their WRMS increased in the north and east respectively. This result is expected given the observed poor correlation.

4 Comparison of GLDAS and NLDAS-2 Noah Models

GLDAS Noah is one of the most common datasets used to model the CWS driven surface displacements. To determine if there are advantages to using NLDAS-2 Noah, a regional model (coterminous United States) with higher spatial resolution than GLDAS, we compare loading displacements predicted using NLDAS-2 Noah and the GLDAS Noah with observed station coordinates in GPS time series from the PBO network. From Sect. 2.2, we find only small differences between the NLDAS-2 Noah and GLDAS Noah horizontal predictions, with larger differences in the predicted vertical displacement.

Figure 6 shows the WRMS (in units of %) difference between GPS coordinate time series corrected for NLDAS-2 and GLDAS Noah CWS models. Positive values indicate that the scatter is reduced more using NLDAS-2 Noah product. From Fig. 6, we observe that 58% of the stations have their vertical WRMS improved using NLDAS-2 Noah instead of GLDAS Noah. Moreover, 25% of the improvements are more than 10%, and these stations are concentrated in the mountains of the northwest and southeast. With respect to the horizontal components, NLDAS-2 Noah could improve the WRMS reduction rate obtained

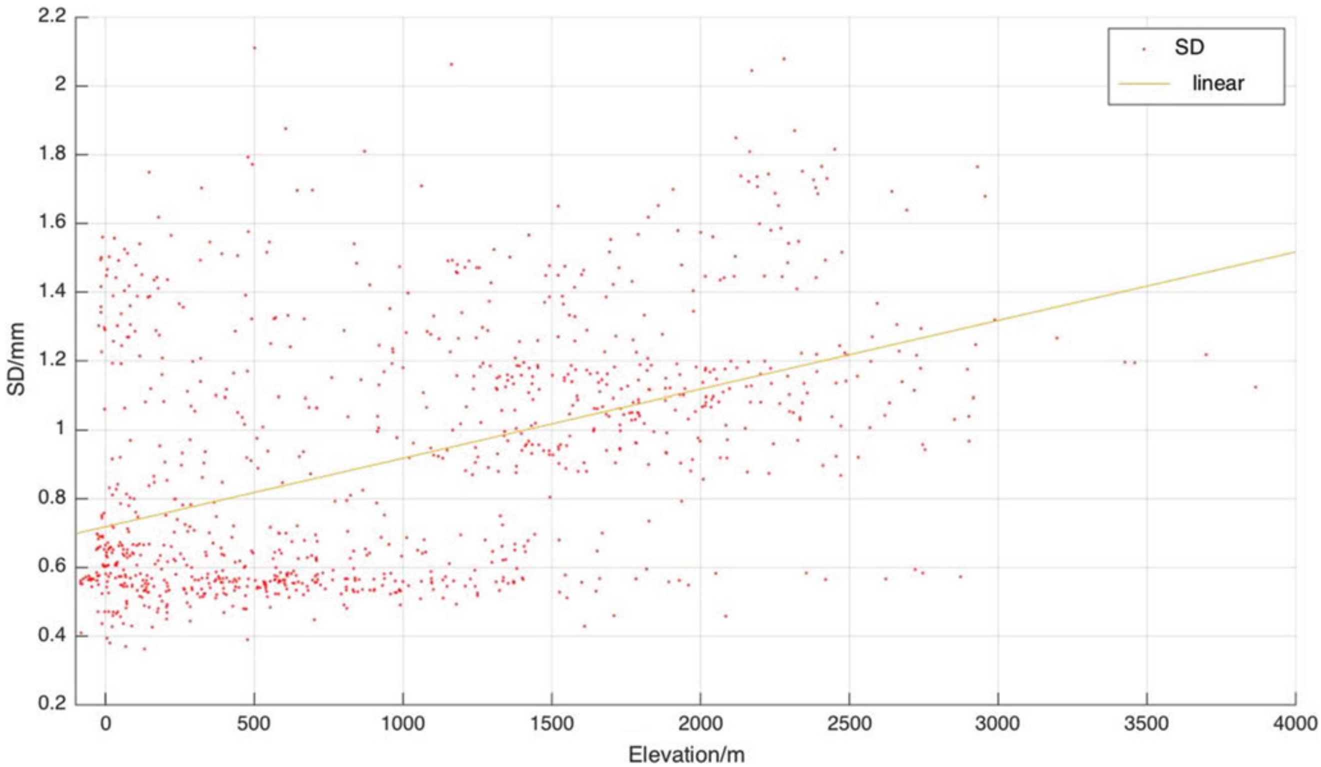

Fig. 3 Scatter of the SD for each PBO station with respect to the elevation

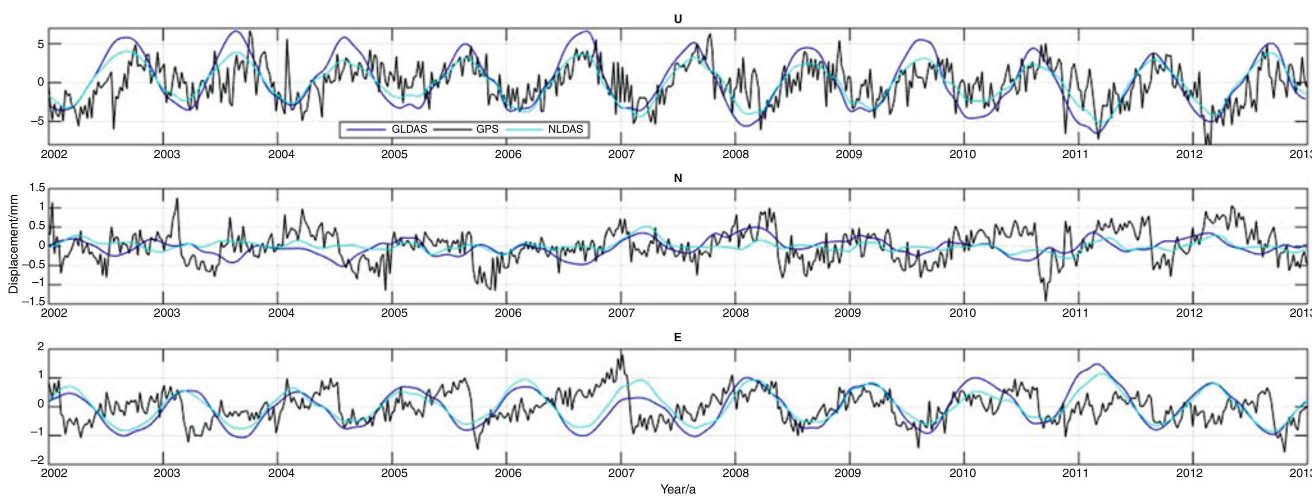

Fig. 4 3-D displacements of station SC02 generated from NLDAS-2 and GLDAS Noah models. The NLDAS-2 Noah model is shown in *cyan* (or *light blue*); GLDAS Noah is shown in *blue*

from the GLDAS Noah product to some extent for most PBO stations (88% and 73% for the North and East components respectively), although the performance is very small (see Sect. 3). The best improvement is in the North component where most stations show an improvement of more than 10%. These account for about 63% of the total stations. We partly contribute this improvement to the much higher spatial resolution of the NLDAS-2 Noah model.

Another reason is that the NLDAS-2 Noah uses an upgraded Noah version (Noah version 2.8) compared with GLDAS Noah model (Noah version 2.7.1), which includes a snow model enhancement for cold season (Livneh et al. 2010) and model parameter tuning for warm season (Wei et al. 2013). Moreover, the NLDAS-2 total column soil moisture and snow water equivalent have been comprehensively evaluated against in situ observations and

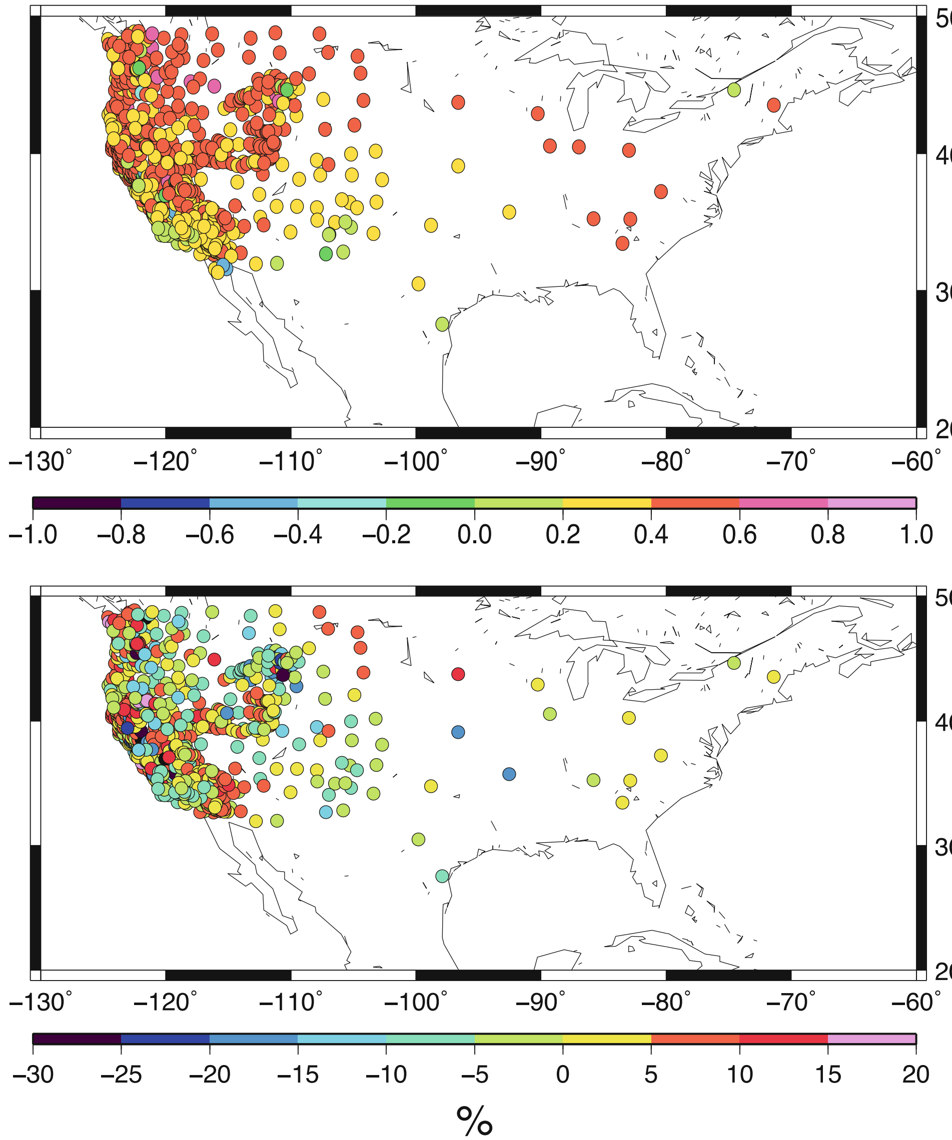

Fig. 5 *Top*: Correlation between NLDAS-2 Noah predicted loading and the GPS height time series. *Bottom*: WRMS reduction (%) after removing the NLDAS-2 Noah predictions from the GPS height

satellite retrievals (Xia et al. 2014; Livneh et al. 2010) in the continental United States. Therefore, the overall performance is that Noah version 2.8 has better performance than Noah version 2.7.1. Besides the model version differences, the surface meteorological forcing data driving the Noah model are different, with NLDAS-2 surface forcing data maybe more accurate. Due to these reasons, we demonstrate that NLDAS-2 Noah is better than GLDAS Noah in modeling the CWS driven surface displacement for PBO GPS stations over the continental North America.

Since our focus here is to compare the CWS models only, we do not evaluate the impact of atmospheric mass on our comparison result. However, in our previous studies, we did this kind of analysis. Our results show that after considering the impacts of non-tidal atmosphere and ocean loading effects, the performance of CWS model in correcting the GPS height could improve by at least 10% globally, but the characteristics of the comparison results between different CWS models would not change (Li et al. 2014). Therefore, we expect that the performance of NLDAS-2 Noah model would be better in reducing the GPS height if removing the effects of non-tidal atmospheric and oceanic mass, but our comparison result between NLDAS-2 and GLDAS would not change.

5 Conclusions

We model the 3-D surface displacement induced by CWS from the regional NLDAS-2 Noah model with high spatial resolution for the continuous PBO GPS stations over the continental North America. We find that the CWS induced displacements in the horizontal are small and have a poor correlation with the GPS coordinate time series. Correspondingly,

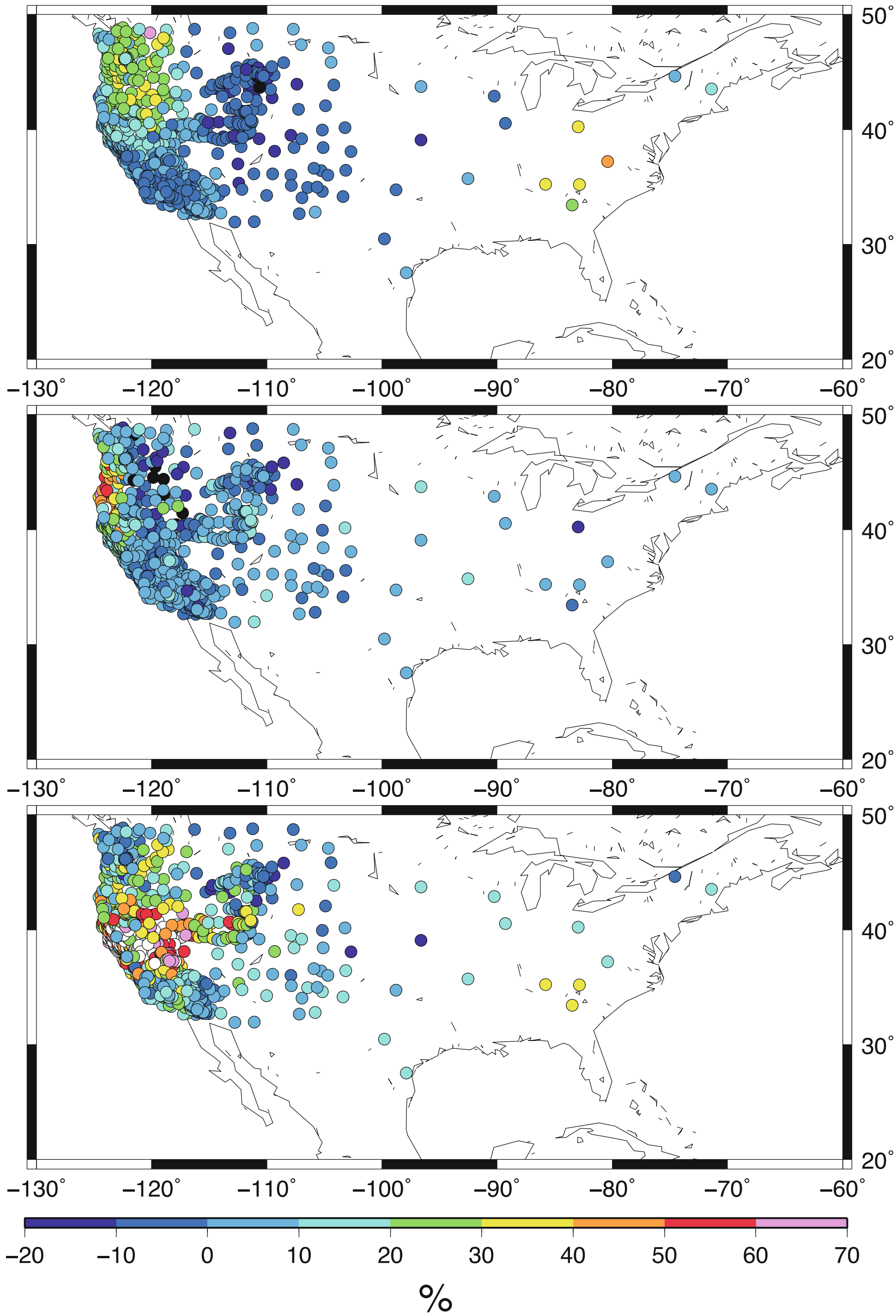

Fig. 6 WRMS difference between NLDAS-2 and GLDAS Noah models. *White* and *black dots* indicate stations' WRMS difference exceed the maximum and the minimum scale respectively. From *top* to *bottom* are the Up, East and North components

only 13% and 27% of the selected stations, mainly those located in the mountains, have their WRMS reduced in the North and East components after removing the NLDAS-2 Noah CWS loading effects from the GPS observations.

For the vertical coordinate, we find that the magnitude of the NLDAS-2 Noah predicted vertical displacement for the PBO stations increases with increasing elevation, and that the maximum RMS reaches 4 mm in the mountains. We also find that much higher correlations between the predicted vertical height changes and the GPS height coordinates. Stations with vertical WRMS reduced when the NLDAS-2 Noah CWS signal is removed represent 56% of the total; stations with the scatter reduced the greatest are concentrated in the mountains.

Compared with the GLDAS Noah product, we find that NLDAS-2 Noah could improve the WRMS reduction rate of the horizontal GPS time series obtained from the GLDAS Noah for most stations (88% and 73% of the stations in the north and east components respectively). With respect to the vertical component, 25% of the stations have their WRMS reduced by more than 10% using NLDAS-2 Noah product. Hence, we conclude that the NLDAS-2 Noah estimates of CWS are better for modeling the CWS induced 3-D surface displacement for PBO GPS stations over the continental North America. The reason may due to the finer spatial resolution, the updated Noah model, together with the more accurate surface forcing data of the NLDAS-2 Noah model.

NLDAS-2 Noah corrections for the PBO sites can be accessed from the PBO H2O data portal located at http://xenon.colorado.edu/portal/.

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