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Seasonal hydrological loading in southern Alaska observed by GPS and GRACE

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[1] We compare vertical seasonal loading deformation observed by continuous GPS stations in southern Alaska and modeled vertical displacements due to seasonal hydrological loading inferred from GRACE. Seasonal displacements are significant, and GPS-observed and GRACE-modeled seasonal displacements are highly correlated. We define a measure called the WRMS Reduction Ratio to measure the fraction of the position variations at seasonal periods removed by correcting the GPS time series using a seasonal model based on GRACE. The median WRMS Reduction Ratio is 0.82 and the mean is 0.73 ± 0.26, with a value of 1.0 indicating perfect agreement of GPS and GRACE. The effects of atmosphere and non-tidal ocean loading are important; we add the AOD1B de-aliasing model to the GRACE solutions because the displacements due to these loads are present in the GPS data, and this improves the correlations between these two geodetic measurements. We find weak correlations for some stations located in areas where the magnitude of the load changes over a short distance, due to GRACE's limited spatial resolution. GRACE models can correct seasonal displacements for campaign GPS measurements as well. **Citation:** Fu, Y., J. T. Freymueller, and T. Jensen (2012), Seasonal hydrological loading in southern Alaska observed by GPS and GRACE, *Geophys. Res. Lett.*, *39*, L15310, doi:10.1029/2012GL052453.

1. Introduction

[2] Geodetic observations have been used to study the seasonal hydrological mass cycle and its loading effects, such as the Global Positioning System (GPS) seasonal position variations in Japan [*Heki*, 2004], Amazon basin [*Bevis et al.*, 2005] and Iceland [*Grapenthin et al.*, 2006]. The NASA/DLR Gravity Recovery and Climate Experiment (GRACE) has been used to study the ground seasonal deformation together with GPS [e.g., *Davis et al.*, 2004]. Although *van Dam et al.* [2007] reported poor correlation between GPS and GRACE over Europe and attributed it to GPS processing flaws, more recent studies have shown consistent seasonal displacements between GPS and GRACE in West Africa [*Nahmani et al.*, 2012], and the Nepal Himalaya [*Fu and Freymueller*, 2012], because of strong seasonal hydrological loading and improved GPS processing.

[3] Mountainous and located at high latitude, southern Alaska has a long winter season for snow and ice accumulation and a warm summer season for melting, an ideal situation for strong seasonal hydrologic mass variation. Seasonal vertical deformation of GPS timeseries in southern Alaska was reported by *Freymueller et al.* [2008]. Previous GRACE studies indicate clear seasonal gravity changes in southeast Alaska caused by seasonal hydrologic mass variations [*Tamisiea et al.*, 2005; *Chen et al.*, 2006; *Luthcke et al.*, 2008; *Davis et al.*, 2012]. In this paper, we investigate the seasonal variation observed by GPS and GRACE across southern Alaska, and analyze the correlation between these two geodetic observations using an elastic loading model.

2. Data

2.1. GPS Data

[4] Sixty-four former and current continuous GPS stations in southern Alaska (Figure 1) are analyzed in this study. Thirty of them are Plate Boundary Observatory (PBO) GPS stations, and others are installed and maintained by a variety of other organizations (see Table S1 in the auxiliary material).[1] We used GPS data between July 2002 and December 2011. We employ the GIPSY/OASIS-II (Version 5.0) software in point positioning mode to obtain daily coordinates and covariances, and then transform the daily free network solutions into ITRF2008 [*Altamimi et al.*, 2011]. We estimate this daily frame alignment transformation ourselves, using a set of reliable ITRF stations (~30 stations each day). The complete analysis procedure is as described in *Fu and Freymueller* [2012]. We correct for solid earth tides and ocean tidal loading [*Fu et al.*, 2012] in the GPS processing, but not atmospheric pressure loading or any other loading variations with periods >1 day. We average the GPS daily solutions to weighted 10-day averages (using GIPSY's utility stamrg) to compare with the GRACE solutions.

2.2. GRACE Data

[5] We use spherical harmonic coefficients of the Earth's gravity field estimated from GRACE data [*Bruinsma et al.*, 2010] and load Love numbers [*Farrell*, 1972] to model the elastic displacements due to the changing load [*Wahr et al.*, 1998; *Kusche and Schrama*, 2005]. In order to maintain consistency with the loading effects present in the GPS solutions, we add GRACE's Atmosphere and Ocean De-aliasing Level-1B (AOD1B) solution (GAC solution) to the GRACE spherical harmonic solutions. By doing this, both atmospheric and non-tidal ocean loads are present in both GPS and GRACE solutions.

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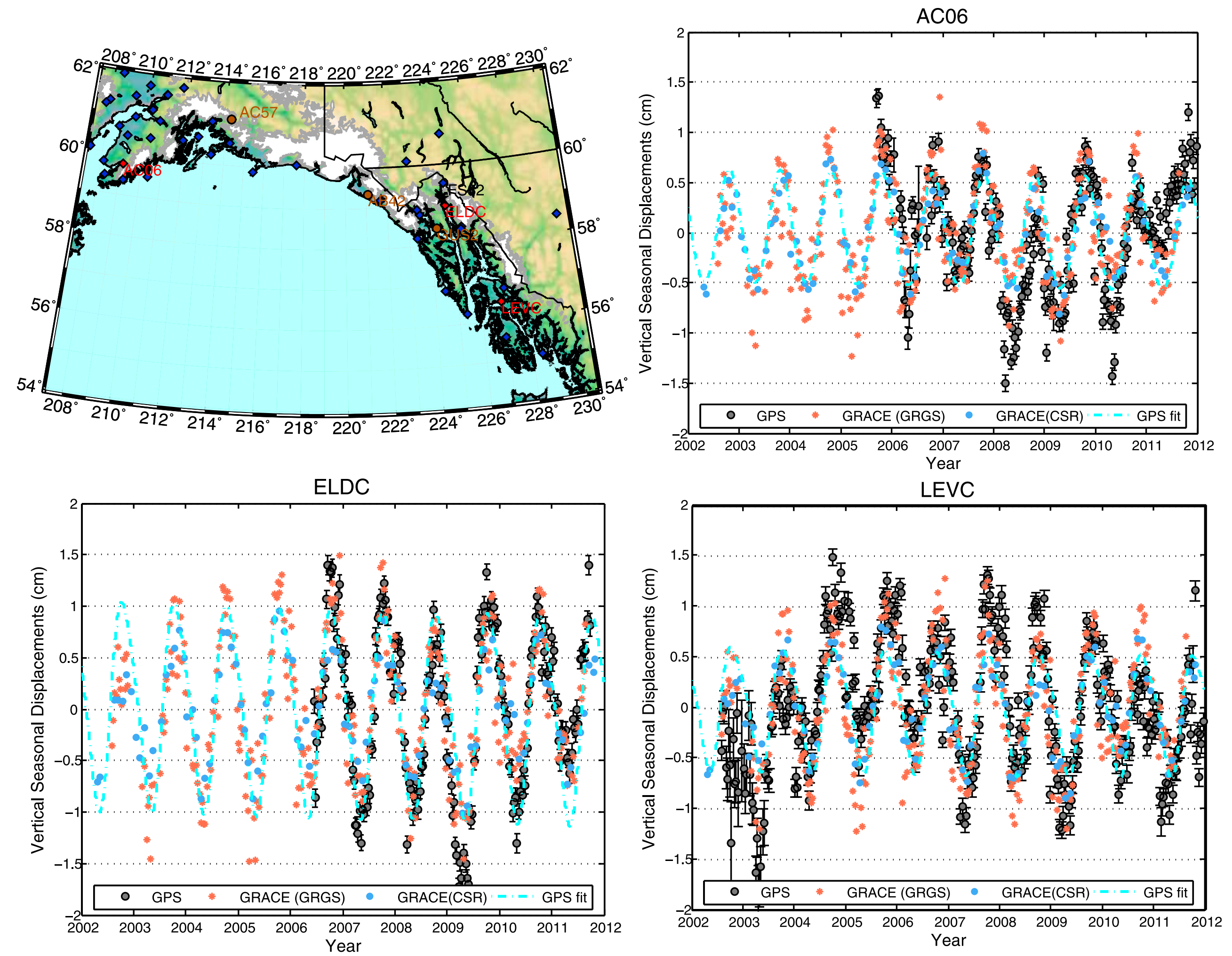

Figure 1. (top left) Distribution of continuous GPS stations (blue diamonds) in southern Alaska; white-color regions denote glaciated areas. Brown circles are sites used for the AOD1B study (Figure 4). Black star is the campaign site used for Figure 5. Three examples, (top right) AC06, (bottom left) ELDC and (bottom right) LEVC, of GPS vertical seasonal (detrended) timeseries and their GRACE-modeled seasonal vertical displacements are shown. GRACE solutions from GRGS and CSR are used.

[6] We use the second release of 10-day gravity fields models (RL02) provided by the Space Geodesy Research Group (GRGS), a scientific consortium of 10 French research teams. Spherical harmonic coefficients up to degree and order 50 for the gravity field are provided every 10 days. The North-South striping noise is reduced with an improved data editing and solution regularization, and no further smoothing is required since it has been stabilized during the data process. *Bruinsma et al.* [2010] described the GRACE data processing strategies. We replace the degree-1 components with results obtained by *Swenson et al.* [2008]. All the analyses in this paper use the GRACE solutions from GRGS for its better temporal resolution. Our previous study of the Himalaya [*Fu and Freymueller*, 2012] found that this GRACE solution showed slightly better agreement with GPS than other solutions. We also show GRACE Level-2 RL-04 solutions from CSR (Center for Space Research, Austin, USA) for comparison (Figure 1). For its monthly products, we replace C20 terms with the results from observations of Satellite Laser Ranging [*Cheng and Tapley*, 2004], and Degree-1 components using Stokes coefficients derived by *Swenson et al.* [2008]. We adopted 350 km as the averaging radius for Gaussian smoothing for the CSR solution [*Wahr et al.*, 1998].

3. Results

[7] We compare the GPS observed and GRACE modeled vertical seasonal (detrended) displacements, and find that both show significant and consistent seasonal variations (Figure 1). We fit annual and semiannual variations to the GRACE displacement predictions, and use this seasonal correction for analysis rather than the raw timeseries. In order to quantitatively evaluate the consistency between GPS-observed and GRACE-modeled seasonal height variations, we define a measure termed the "WRMS (Weighted Root-Mean-Squares) Reduction Ratio", expressed as follows:

$$Ratio_{WRMS\_reduction} = \frac{WRMS_{GPS} - WRMS_{GPS-GRACE}}{WRMS_{GPS} - WRMS_{GPS-GPS_{fit}}} \qquad (1)$$

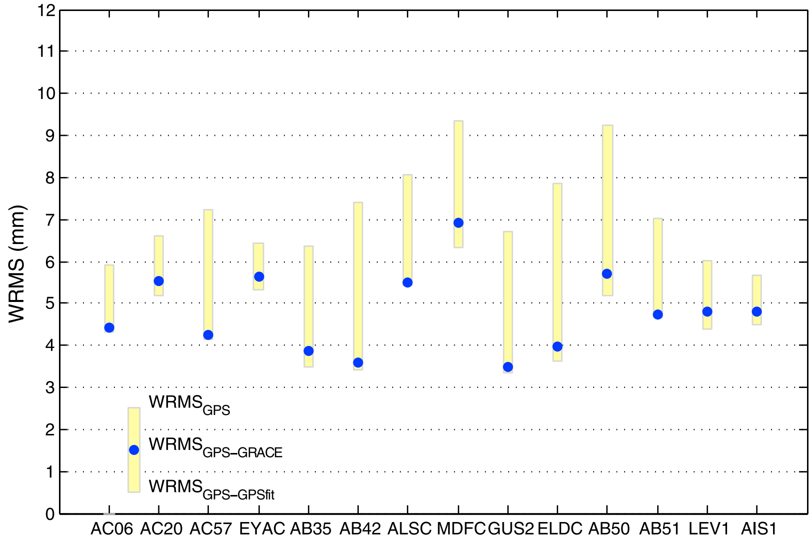

Figure 2. Selected examples of the WRMS reduction when removing GPS seasonal variation using GRACE-modeled seasonal displacements. Selected stations are distributed from west to east (southeast).

$WRMS_{GPS}$ is the WRMS of the GPS detrended timeseries, including its seasonal variations; $WRMS_{GPS-GRACE}$ is the WRMS of the GPS timeseries with seasonal effects corrected by seasonal GRACE-modeled detrended displacements; $WRMS_{GPS-GPS_{fit}}$ is the WRMS of the GPS timeseries with seasonal signals removed by fitting annual plus semiannual terms to the GPS timeseries. The WRMS Reduction Ratio reflects the agreement of the GPS and GRACE timeseries in both amplitude and phase, and scales the improvement relative to the amplitude of seasonal variations actually present. A value of 1.0 would indicate perfect agreement between GPS-observed and GRACE-modeled annual plus semiannual seasonal displacements. Theoretically, the WRMS Reduction Ratio can not exceed 1, because the fit of GPS timeseries with annual and semiannual terms can not be worse than any other model of annual and semiannual terms.

[8] Figure 2 shows examples of the WRMS reductions for 14 GPS stations. The top of each bar indicates $WRMS_{GPS}$; the dots demonstrate $WRMS_{GPS-GRACE}$; the bottom of each bar denotes $WRMS_{GPS-GPS_{fit}}$, which is not zero because of noise remaining in the GPS timeseries and also interannual variations. When the dot is close to the bottom of the bar, it indicates that the seasonal variation in the GPS and GRACE are very similar.

[9] Figure 3 depicts the WRMS Reduction Ratios for all the continuous GPS sites analyzed in this study; values are provided in the auxiliary material. The WRMS decreases for 62 out of 64 stations when corrections based on GRACE are applied, with a median WRMS Reduction Ratio of 0.82 and a mean WRMS Reduction Ratio of 0.73 ± 0.26. The only two sites with negative WRMS Reduction Ratios are AC03 and SELD (at the SW tip of the Kenai Peninsula, Figure 3), with -0.03 and -0.02, respectively. The consistency of seasonal signals between GPS and GRACE demonstrates that the seasonal position oscillations in southern Alaska are mainly caused by long-wavelength hydrological mass loading, which is due to snow and ice accumulation during the winter season and melt during the spring and summer seasons. This seasonal cycle is also accompanied by massive long-term mass losses [*Arendt et al.*, 2002; *Chen et al.*, 2006; *Larsen et al.*, 2007; *Luthcke et al.*, 2008; *Berthier et al.*, 2010].

[10] Figure 3 indicates that stations close to high mountains and heavily glaciated areas show better agreements between GPS and GRACE; and distant stations show weaker correlation. This is due to the discrepancy of spatial resolutions for two geodetic tools. Within the mountainous coastal areas, the long-wavelength seasonal hydrological loading (snow and ice) is uniform for most places, so the GRACE solutions, which are averaged over a larger spatial area, accurately represent the loads at any specific point measured by GPS. However, in areas where the magnitude of the load changes over a short distance, the spatial averaging of GRACE can result in inaccurate predicted displacements. The sites AC03 and SELD are good examples of this problem. These sites are located at low elevation along the coast, so snow accumulation is relatively low within 30–40 km of the sites. However, coastal mountains that accumulate very large snow loads extend from ~60 to 200 km to the east of these sites. Because GRACE cannot

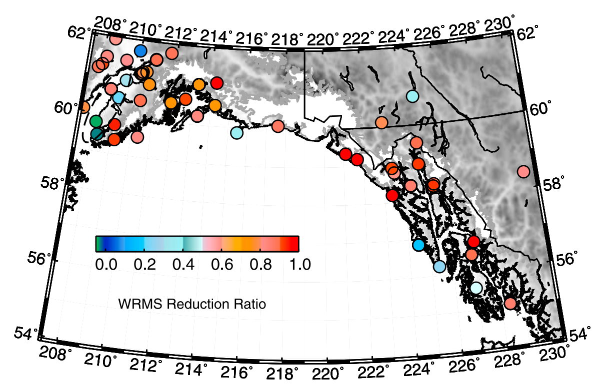

Figure 3. The WRMS Reduction Ratios for all continuous GPS stations in southern Alaska. The Ellipse (northwest) highlights low-elevation coastal stations of Cook Inlet, where GRACE consistently overestimates the amplitude of the seasonal variations.

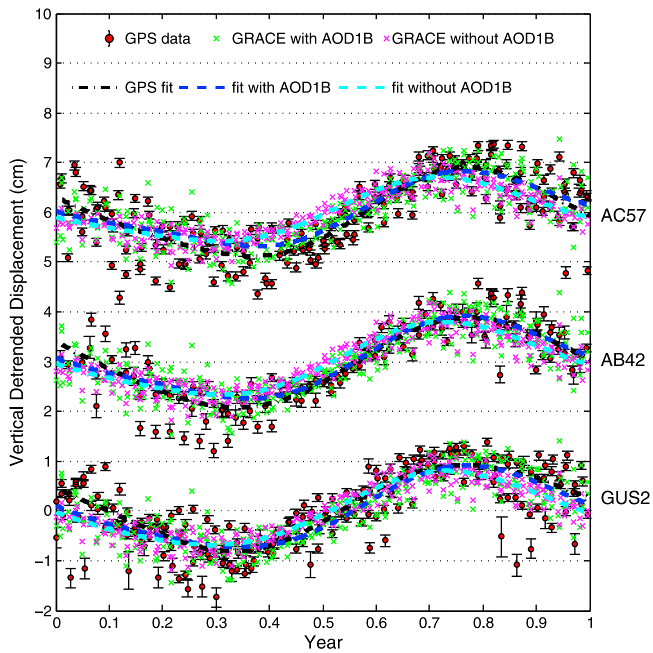

Figure 4. Seasonal variations for three example stations (AC57, AB42 and GUS2, see Figure 1 for their locations), plotted by fractional year. GRACE-modeled vertical displacements (and their best-fit lines) using solutions with AOD1B and without AOD1B are plotted together for comparison.

resolve such short-wavelength variations in the loads, the displacements predicted from GRACE overestimate the amplitude of the seasonal variations at these sites. The same is true for all other low-elevation stations in the Cook Inlet area (ellipse in Figure 3). This low-lying area is surrounded by mountains with large accumulations of snow, and GRACE over-predicts the amplitudes of seasonal displacements across the entire region by varying amounts.

[11] Interannual variations of seasonal oscillations are also apparent (Figure 1). One example is the low "peak" in 2008 for station ELDC, and the low "trough" in early 2009 (see Figure 1); it is clear that both GPS and GRACE show the same interannual variations. The summer of 2008 was wet and cold over most of southern Alaska, so there was less melting than usual in summer 2008 and a resulting heavier-than-average snow load throughout the next year. The period from 2002–2005 also showed more rapid uplift than the period since 2005 for many sites (see LEVC in Figure 1). A correction based the time series may produce even better results.

[12] In this study, we do not correct for atmospheric and non-tidal ocean loading effects during GPS data processing. Instead, we combine the GRACE and AOD1B solutions [*Flechtner*, 2007] so that atmospheric and non-tidal ocean loading effects are included in both the GPS and GRACE solutions. Figure 4 shows three example GPS sites (AC57, AB42 and GUS2) comparing the GRACE-modeled height displacements with and without the AOD1B model. It is clear that the seasonal fit of the GRACE solutions with AOD1B (blue dashed lines) agrees with the GPS seasonal variations (black dashed lines) better than the solutions without AOD1B (cyan dashed lines), for both amplitude and phase. The WRMS Reduction Ratio also improves for AC57 from 0.75 using GRACE solutions without AOD1B to 0.96 with AOD1B included; the improvements are from 0.81 to 0.95 for AB42; and from 0.73 to 0.96 for ATW2. The mean WRMS Reduction Ratio improves from 0.67 to 0.73 for all continuous stations analyzed in this paper. Consistent

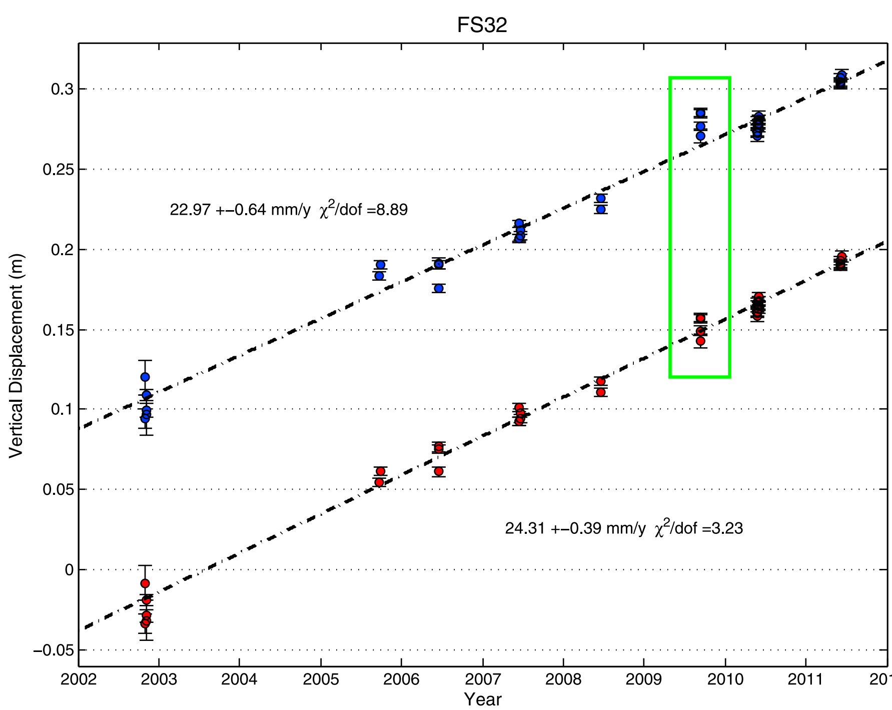

Figure 5. Timeseries of campaign GPS site FS32, see Figure 1 for its location. (top) original observed GPS timeseries (blue). (bottom) Corrected timeseries with seasonal loading deformation removed based on GRACE data (red). An obvious improvement for the measurements in 2009 is highlighted.

treatment of atmospheric and non-tidal ocean loading is essential for comparing or combining GPS and GRACE solutions.

4. Discussion

[13] GPS campaign measurements, or GPS episodic measurements, usually re-survey the bench marks once per year at most. When estimating the velocity for a campaign GPS site, seasonal effects are ignored due to limited observations. However, for the GPS campaign stations located where seasonal hydrologic loading is significant, and if the sites were surveyed at different times of year, the estimated linear velocities can be biased by neglecting the seasonal impacts.

[14] We can use GRACE continuous measurements to model the seasonal ground displacements, and use them to correct the seasonal effects for campaign GPS data. Figure 5 shows an example for GPS campaign site FS32 located near the Juneau Icefield (see Figure 1). The upper GPS timeseries (blue) show the original observed data. With seasonal impacts corrected based on GRACE measurements, the misfit (χ^2 per degree of freedom) decreases by 64% (from 8.89 to 3.23) in the seasonally corrected timeseries (red). The most evident improvement occurs in 2009 (see highlight box in Figure 5); the GPS site was measured at a different time of year in 2009, and its seasonal effect can be corrected well with GRACE data.

5. Conclusions

[15] GRACE-modeled vertical displacements due to seasonal hydrologic loading show high correlation with GPS observed seasonal position variations, which confirms that the hydrological mass cycle is the main cause of seasonal ground deformation in southern Alaska. Loading models based on GRACE data can effectively remove seasonal effects in both continuous and campaign GPS measurements in this region of very large seasonal hydrological load variations. Loading models based on GRACE perform well except in areas where the magnitude of the seasonal load changes over short spatial distances; this limitation is a consequence of the lack of spatial resolution in GRACE. Because the seasonal deformations can be so large, periodic seasonal displacements should be considered in regional reference frame realization [*Freymueller*, 2009].

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