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A comparison of annual vertical crustal displacements from GPS and Gravity Recovery and Climate Experiment (GRACE) over Europe

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[1] We compare approximately 3 years of GPS height residuals (with respect to the International Terrestrial Reference Frame) with predictions of vertical surface displacements derived from the Gravity Recovery and Climate Experiment (GRACE) gravity fields for stations in Europe. An annual signal fit to the residual monthly heights, corrected for atmospheric pressure and barotropic ocean loading effects, should primarily represent surface displacements due to long-wavelength variations in water storage. A comparison of the annual height signal from GPS and GRACE over Europe indicates that at most sites, the annual signals do not agree in amplitude or phase. We find that unlike the annual signal predicted from GRACE, the annual signal in the GPS heights is not coherent over the region, displaying significant variability from site to site. Confidence in the GRACE data and the unlikely possibility of large-amplitude small-scale features in the load field not captured by the GRACE data leads us to conclude that some of the discrepancy between the GPS and GRACE observations is due to technique errors in the GPS data processing. This is evidenced by the fact that the disagreement between GPS and GRACE is largest at coastal sites, where mismodeling of the semidiurnal ocean tidal loading signal can result in spurious annual signals.

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1. Introduction

[2] The annual surface mass-loading signal as observed in Global Positioning System (GPS) heights is both a nuisance and an opportunity. On the one hand, an accurate measurement of the loading signal offers a possibility for observing environmental change. For example, *Blewitt et al.* [2001] and *Wu et al.* [2003], have used observed variations in GPS coordinates to solve for global-scale, seasonal variations in continental water storage. Using global GPS station coordinates and covariance matrices, *Kusche and Schrama* [2005] demonstrated that by combining GPS data with estimates of the oceanic and atmospheric loading contributions, that the hydrological loading can be estimated up to degree and order 7. *Wu et al.* [2006], using a similar technique, determined the continental water storage field up to degree and order 50 (half wavelength of 400 km). These investigations indicate the utility of GPS observations of crustal displacement for constraining estimates of continental water storage.

[3] For research relying on the accurate interpretation of GPS motion in terms of surface stress, the deformation signal from surface mass loading is a source of noise. For these applications, we would like to have at our disposal reliable loading models or even surface mass observations, which can be used to reduce the environmental loading contributions to the GPS observations. For some surface loads, such as the atmosphere, the loads are currently modeled to a fairly high degree of accuracy [*Velicogna et al.*, 2001; *van Dam and Wahr*, 1987; *van Dam et al.*, 1994]. However, for other loads, especially the distribution of water mass on continents (soil moisture, groundwater, snow and ice) the load is poorly known in most regions of the globe, but the deformation it causes is large enough to contribute to the GPS signal [*van Dam et al.*, 2001; *Blewitt et al.*, 2001; *Wu et al.*, 2003].

[4] In March 2002, the Gravity Recovery and Climate Experiment (GRACE) gravity mission was launched. The primary objective of the mission is to monitor hydrological mass redistributions through their integrated gravitational effect (see *Tapley et al.* [2004] for a review of the present status of GRACE). We would like to know if GRACE observes the same annual water storage signal as GPS. *Davis et al.* [2004] found excellent agreement between GRACE predicted effects and GPS height time series for sites surrounding the Amazon River Basin in South America.

[5] In Figure 1 we plot time series of monthly GPS height residuals and predicted vertical surface displacements from GRACE for some sites in Europe. Both deformation series

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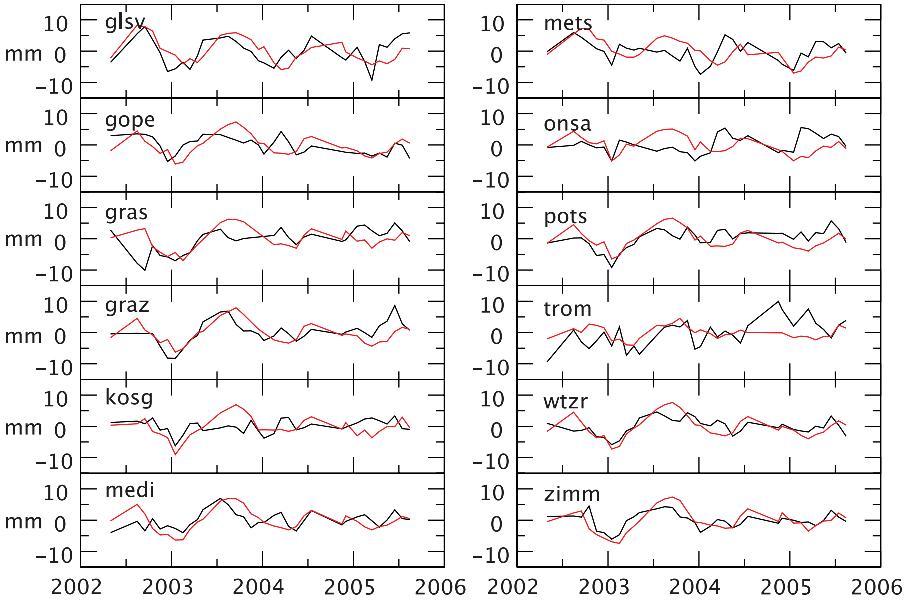

Figure 1. IGS observed height residuals (black) and predicted vertical surface displacements from GRACE (red). Locations of sites are shown in Figure 2.

should represent the variability of water storage with time. (Details on how the time series were generated are provided below.) An annual signal is clearly visible in both the observed and predicted heights. For most sites, excluding perhaps mets, onsa, and trom, the GRACE signal appears to be in phase and have the same amplitude as those from the GPS heights. However, when we remove the GRACE signal from the GPS heights, the weighted root-mean-square (WRMS) [*Dixon*, 1991] of the GPS heights is reduced on only three of the sites shown: glsv, graz, and trom. In fact, when we remove the GRACE predicted loading signal from the 51 European GPS height time series used in this paper, we find that we are able to reduce the WRMS of the heights on only 10 time series.

[6] Further, when we compare the annual signals from GPS and GRACE we find that while there is some agreement, there are also many sites where the GPS and GRACE differ significantly in amplitude and phase. We would like to understand why the annual height signals do not agree and why the WRMS of the GPS height time series from Europe is not reduced when we remove the loading signal derived from GRACE. In this paper, we compare GPS height time series with predictions of vertical surface displacements derived from the GRACE gravity fields for stations in Europe. We focus on the annual signals as these represent the largest periodic signals in the water storage field. We choose Europe for this analysis, first, because it is a tectonically stable region and any vertical tectonic noise will be minimal. Second, the water storage signal here is large enough that GRACE should be able to recover the long-wavelength component (>500 km) of the field with a reasonable degree of accuracy, i.e., the signal-to-noise ratio is about 10 as will be shown later in the paper [*Wahr et al.*, 2006]. Third, the density of long-running, high-quality GPS sites in the region will allow us to examine the results with some statistical reliability.

[7] We consider three possibilities for the disagreement between GPS and GRACE heights in this region: (1) the predicted signal from GRACE does not represent the true environmental load signal, i.e., the GRACE observations are inaccurate; (2) the annual signal in the GPS heights is driven by shorter-wavelength environmental variability than is captured by GRACE gravity fields; or (3) in addition to the environment, other sources contribute to and dominate the annual signal in the GPS measurements.

[8] We demonstrate that the GRACE results are reliable at least down to wavelengths on the order of 500 km. The possibility exists for real short-wavelength signals in the water storage/ocean bottom pressure masses that have not been captured by GRACE. Using a simple load model, we find that short-wavelength loads cannot completely explain the observed discrepancy between the annual signals from GRACE and GPS at all the stations in Europe. We conclude that most of this disagreement in the GPS and GRACE annual signals must come from site or network specific technique errors in the GPS observations. Many nongeophysical factors can contribute to an erroneous annual signal in GPS height time series including zenith tropospheric delay, bedrock thermal expansion, monument thermal expansion, phase center modeling, orbital errors, mismodeling of real periodic signals, etc. [*Dong et al.*, 2002]. The relative contribution of these factors will be site dependent. If we edit the set of sites based on the theory that spurious annual signals arise in the GPS data from the mismodeling of semidiurnal ocean tidal loading effects (i.e., we remove the coastal sites from the comparison), we find a 25% improvement in the agreement between the annual amplitude from GPS and GRACE over Europe. The difference in the average phase remains the same.

2. Data Sets

2.1. GRACE Data

[9] In this comparison we use the first 34 months of University of Texas Center for Space Research (UTCSR) GRACE level 2 gravity products (the Stokes coefficients).

We use the Release 1 unconstrained products. These products are described by *Bettadpur* [2004], which details the processing standards, models and parameters that have been used. We replace the C20 component in these data with C20 components derived from Satellite Laser Ranging data [*Cheng and Tapley*, 2004]. The raw fields have been corrected for the mean field by removing the weighted average of the 34 approximately monthly fields. The residual Stokes coefficients, then, primarily contain variations in the gravity field driven by the geographic redistribution of water mass (groundwater, soil moisture, snow and ice, and ocean mass), as well as errors due to measurement and processing errors, aliasing effects (the aliasing of any mismodeled submonthly gravity signals into the GRACE monthly solutions) and errors in the atmospheric and ocean corrections.

[10] We scale the GRACE Stokes coefficients to obtain spherical harmonic Stokes Coefficients of surface mass [*Wahr et al.*, 1998] to find the radial surface displacement at any point. The mathematical relationships between the Stokes coefficients of mass and the radial surface displacement is

$$dr(\theta,\phi) = R\sum_{l=1}^{\infty}\sum_{m=0}^{l}\tilde{P}_{l,m}(\cos\theta) \cdot (C_{lm}\cos(m\phi) + S_{lm}\sin(m\phi))\frac{h'_l}{1+k'_l} \tag{1}$$

where $dr(\theta, \phi)$ is the displacement of the Earth's surface in the radial direction, $\{h'_l\}$ and $\{k'_l\}$ are the load Love numbers of degree l, $\tilde{P}_{lm}$ are normalized Legendre functions of degree l and order m, and C_{lm} and S_{lm} represent the Stokes coefficients of mass. We use the load Love numbers of *Han and Wahr* [1995] to transform those mass coefficients into estimates of crustal deformation.

[11] The GRACE Stokes coefficients are dominated by errors at high degrees [*Wahr et al.*, 2006]. To reduce the effects of those errors on our deformation estimates, we apply a Gaussian averaging kernel with a half amplitude radius of 500 km [*Wahr et al.*, 1998] when scaling the coefficients to obtain surface displacements. Equation (1) becomes

$$dr(\theta,\phi) = R\sum_{l=1}^{\infty}\sum_{m=0}^{l}W_l\tilde{P}_{l,m}(\cos\theta) \cdot (C_{lm}\cos(m\phi) + S_{lm}\sin(m\phi))\frac{h'_l}{1+k'_l} \tag{2}$$

where W_l represents the weighting function [*Wahr et al.*, 1998]. We chose a 500 km radius as a compromise between trying to minimize the GRACE errors (by making the radius large) while trying to keep our smoothing to a minimum by making the radius small. This means, in effect, that we are estimating the deformation caused only by those components of the mass distribution that have scales in excess of 500 km. Except otherwise explicitly stated, these Gaussian smoothed estimates of the loading effects are used in this paper.

[12] GRACE cannot determine the $l = 1$ variations in the Earth's gravity field (geocenter motion). The l = 1 values needed to describe surface mass, need to be determined relative to a coordinate system fixed to points on the Earth's surface. However, that is not what is observed with satellite-to-satellite tracking. GPS receivers on each GRACE spacecraft do give some sensitivity to their position relative to the Earth's surface, since the GPS orbits are tied to the surface through surface tracking of the GPS satellites. However, that sensitivity is not yet strong enough to give good $l = 1$ solutions. Thus the $l = 1$ terms are not included in the GRACE solutions.

2.2. GPS Data

[13] In this analysis, we use three-dimensional displacements obtained from the International GNSS (Global Navigation Satellite System) Service (IGS) combined weekly solutions made available by R. Ferland (personal communication, 2006). The solutions are publicly available at ftp://macs.geod.nrcan.gc.ca/. The displacements provided are residuals with respect to a defined reference frame at any particular GPS week.

[14] A semiautomated procedure is used to generate the weekly IGS combined solution which includes the following: (1) validate the SINEX files from the IGS analysis centers (corrections for the solid Earth pole tide and the short-term effects due to the excess of Length of Day are applied when appropriate, i.e., when these corrections have not been already applied by the analysis center), (2) unconstrain of the results which have a priori station coordinate constraints applied, (3) transform the solutions to the current ITRF using a seven-parameter similarity transform, (4) Compare these results with the object of detecting and rejecting outliers, and (5) combine into a weekly solution [*Ferland et al.*, 2000]. The residuals are then determined with respect to the ITRF reference frame.

[15] The reason for using combined solutions as opposed to the solution from any single analysis center is that much of the random processing noise introduced by any one analysis scheme will average out. This is evidenced by the fact that the scatter in the vertical component for the combined solution is 5 to 15 mm smaller than the scatter in any one Analysis Center solution [*Ferland et al.*, 2000]. The combination is more robust than any individual analysis product, as it allows one to detect blunders. Finally, the combination includes more sites at any one epoch than an individual analysis alone.

[16] The GPS data must be corrected for atmospheric and barotropic ocean loading to be consistent with the GRACE data. We have determined the effects of the ocean and atmospheric loading effect in the GPS data using the GRACE AOD1B product [*Flechtner*, 2005]. This product, the Stokes coefficients up to degree and order 100, represents the daily change in the gravity field from variability in the European Centre for Medium-Range Weather Forecasts surface atmospheric pressure and ocean mass as determined from a barotropic ocean model [see *Ali and Zlotnicki*, 2003; *Ponte and Ali*, 2002]. These data are used to de-alias the GRACE gravity fields for daily atmospheric and oceanic mass variations. Using equation (1), we can convert the de-aliasing fields into daily estimates of the three-dimensional surface displacement at each GPS site in the CF reference frame [*Blewitt*, 2003] as this most closely represents the frame of the IGS residuals [*Dong et al.*, 2003]. No Gaussian

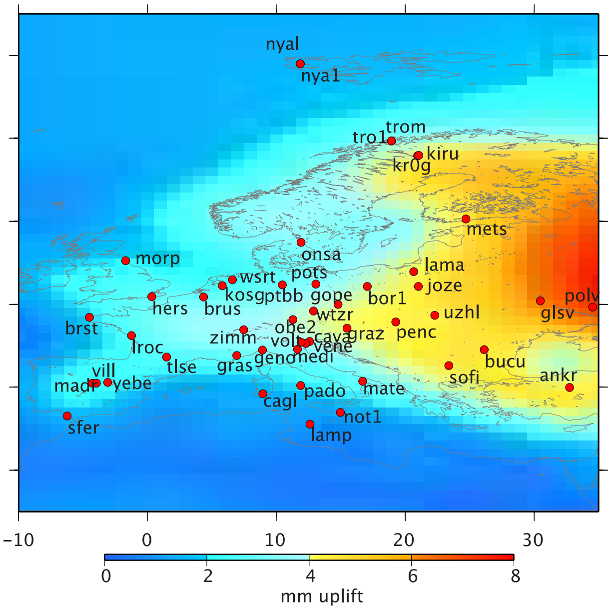

Figure 2. Location of GPS sites overlaid on a gridded estimate of the amplitude of the annual height signal predicted from 25 years of output from a model of water storage.

averaging is done as we want to correct the GPS heights for the nonhydrological effect as accurately as possible. We then average the daily loading effects due to the ocean model and atmospheric pressure into weekly corrections that are centered on the GPS week and subtract these from the GPS heights.

[17] An important consideration when comparing the GRACE and GPS data, is the consistency between the reference frame in which the GRACE data are provided and that for the GPS data. Our GRACE predictions do not include any $l = 1$ terms. *Dong et al.* [2003] found that GPS network solutions which have been transformed into the ITRF, are in fact, in a frame defined by the center of figure of the Earth (see *Blewitt* [2003] and *Dong et al.* [2003] for a thorough discussion of the GPS reference frame). However, since the ITRF at any epoch is defined by a limited number of stations, we cannot be confident that the degree 1 component of the deformation has been adequately captured. To insure that the degree 1 term is not in the GPS residuals, we fit and remove the $l = 1$ spherical harmonics, Y_1^0 and Y_1^1, from the GPS three-dimensional deformation field. The Y_1^0, Y_1^1, terms are determined in a simultaneous fit to the global data. *Lavallée et al.* [2006] showed that as long as the network is not too poorly distributed (as in the case of the IGS combined solutions used here) then simultaneously estimating degree 2 removes most of the "network geometry" aliasing in degree 1. The RMS of the fit of the degree 1 Stokes coefficients to the GPS heights is on the order of 0.5 mm indicating that it is sufficient to simply ignore this correction.

[18] Before comparing the annual signal in the GPS and GRACE heights, we verify that the annual signal in the GPS height time series from Europe is significant for the 34 months that we analyze. We calculate the power spectral density of the heights for time series from Europe using an algorithm suited to handle data unevenly sampled in time [see *Press et al.*, 1997]. We find that on 36 of the time series there is a peak in the power spectral density at 1 cycles/yr. Many of these time series also have power at the 0.5 cycles/yr and 2 cycles/yr frequencies. There are 14 time series where there is no significant power at the annual frequency (cava, geno, gras, lroc, not1, obe2, onsa, pots, sfel, tlse, vene, volt, wsrt, wtzr). When discussing the GPS and GRACE annual signal, these stations will not be considered.

[19] For these 36 sites, we are concerned that the annual signal obtained from the subset of GPS data that overlaps with the time frame of the GRACE data is significantly different than the annual signal one would obtain using the full time series (10 years in some cases). Using the IGS residuals (which have not been corrected for the GRACE alias fields, as these fields extend back only to the beginning of the GRACE mission), we compare the annual amplitude and phase obtained using the entire GPS time series and only those data which correspond to the GRACE time period. For the stations without offsets in the height time series, we find that on average the annual signal obtained using the subset of data differs by 5% in amplitude and 7 degrees in phase from the annual signal determined using the entire data time span. This means that the annual signal determined from the data coinciding with the GRACE mission are a reliable representation of the long-term annual signal in the GPS heights.

[20] Finally, we generate monthly averages of the GPS heights to correspond to the center of the approximately monthly GRACE predictions.

3. Comparison of GPS and GRACE Heights

[21] Figure 2 shows the location of the GPS sites used in the analysis. The site locations are overlaid onto a grid of the amplitude of the annual vertical load signal predicted from LaDWorld-Euphrates Land-Energy balance model. (For a complete description of the method used to generate the Euphrates data set please refer to *Milly and Shmakin* [2002] and *Shmakin et al.* [2002].) The water storage model consists of 25 years of monthly estimates of water storage due to snow, groundwater and soil moisture variability at $1^\circ \times 1^\circ$ over the land surface of the Earth. We ignore the loading due to the snow component of the model at latitudes north of 75N and south of 60S as the snow dynamics are not considered reliable in these regions. We then determine the monthly Stokes coefficients up to degree and order 180 for these monthly mass fields and convert to deformation using equation (1). The amplitude, A, and phase lag (degrees), ϕ, are defined as $A\sin[\omega(t - t_0) + \phi]$, where t_0 is 2002.0 and ω is the angular frequency equal to 1 cycle/yr. Using this water storage model we predict an annual signal with an amplitude of approximately 3–4 mm/yr over most of Europe. The amplitude increases to 6 mm/yr at the eastern edge of the region under consideration. Annual signals of this amplitude in the vertical are well within the observing capability of GPS [*Dong et al.*, 2002].

[22] We first evaluate how well the GRACE and GPS heights agree by comparing the WRMS of the GPS heights before and after removing the GRACE predicted heights on

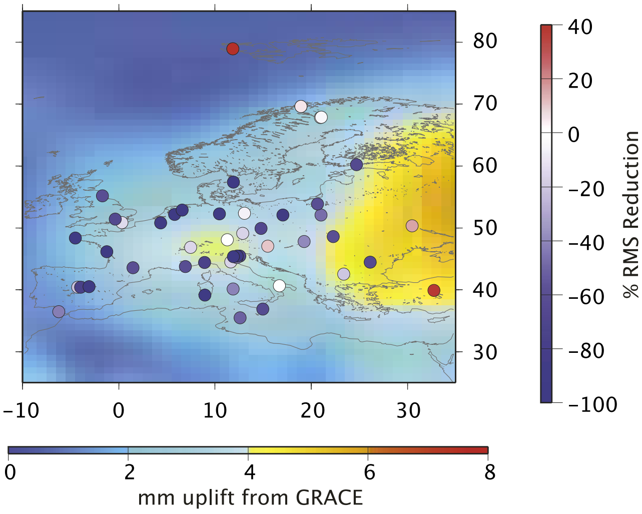

Figure 3. WRMS reduction in GPS heights when total GRACE signal is removed. Background and scale for background represent gridded estimates of the amplitude of the annual height signal predicted from GRACE. A 500 km Gaussian smoothing has been applied to the GRACE data.)

a epoch-by-epoch basis. In Figure 3, we show the percentage of the RMS reduction at the sites in Europe. The colored spots in Figure 3 represent the percentage of WRMS reduction at a particular site as a function of the original WRMS of the heights, i.e.,

$$\frac{\mathrm{WRMS}[\mathrm{GPS}_i] - \mathrm{WRMS}[\mathrm{GPS}_i - \mathrm{GRACE}_i]}{\mathrm{WRMS}[\mathrm{GPS}_i]}$$

The blue/turquoise dots indicate sites where the WRMS has increased; the pink to red, where the WRMS has decreased: ankr, glsv, graz, mate, nico, nyal, nya1, obe2, trom, and tro1. We find that using the GRACE predictions we are able to reduce the WRMS on only 10 of the 51 stations. Despite the apparent agreement between the GPS and GRACE height time series in Figure 1, we are not able to reduce the scatter on many of the GPS stations in Europe.

[23] The background of Figure 3 represents a gridded estimate of the amplitude of the predicted annual height signal determined from GRACE. Comparing Figure 3 with the annual signal estimated from the water storage model (the background to Figure 2) we observe that the annual amplitudes from the 25-year water storage model agree well with the annual signal from the 34 months of GRACE observations. However, the amplitudes predicted by the model are slightly larger. The phases from the model (not shown) also agree quite well with those observed from GRACE and indicate that the maximum load occurs in the mid to late summer.

[24] Next, we compare the annual height variations observed from GPS and predicted from GRACE. In Figure 4a we plot the amplitude and phase of the annual signal in the GPS height residuals. The annual signal was determined in a simultaneous fit for the mean, the trend, and the annual and semiannual signals, using only the data that fell within the time span covered by the GRACE observations. The short time span used to compute the annual signals results in large uncertainties on the GPS estimates of the annual components. Using the GPS formal errors, we determine that the errors on the amplitudes are on average 30% the amplitude of the annual signal; however, the error is clearly larger at some sites. The amplitude errors are shown in Figure 4a. The radius of each circle indicates the size of the error on the amplitude determination. The uncertainties are much larger at coastal stations and at all sites are much larger than those in the GRACE estimates. An inspection of Figure 4a, demonstrates that while there appears to be some similarity in the annual signal for some pairs of closely located GPS sties, there are also large disagreements in both amplitude and phase for sites located within a few hundred kilometers of one another, e.g., lama and joze, kr0g and kiru, and trom and tro1. There is also a slight tendency for the annual signal to increase on stations located near the high predicted by GRACE.

[25] The annual height signals (amplitude and phase) from GRACE are shown in Figure 4b. The annual phases and amplitudes from GRACE results are much more spatially coherent than those determined from the GPS heights. The phases of the GRACE data indicate that the annual signal peaks sometime between July and August.

[26] Comparing the GPS and GRACE annual signals, we find that there are sites where the annual signal from GRACE and GPS agree, e.g., zimm, glsv, and ankr. However, there are more sites where the signals disagree in both amplitude and phase. Sites in coastal regions stand out as locations where the two signals disagree in amplitude and phase. There are also many sites where the GPS heights show no annual signal but GRACE predicts there should be one. This result would imply that effects other than regional loading (wavelengths on the order of 500 km) tend to offset the GRACE annual loading predictions.

[27] To compare the annual amplitudes and phases from GRACE and GPS heights more precisely, we compare the in-phase (cosine) and out-of-phase (sine) component of the annual signals from both techniques. The results are plotted in Figure 5. Note that the errors on the components determined from the GPS data are much larger than the errors on the GRACE components. In fact, in some cases the errors on the GPS components are larger than the components themselves. A line fit to the sine amplitudes have a slope equal to 0.53 ± 0.19. For the cosine amplitudes the slope of the best fit line is 0.64 ± 0.52. The slope is significantly different from 1.0, and the lines do not pass through the origin, indicating that the GRACE annual signal does not fit the GPS annual signal well over Europe. The reduced χ^2 for the in-phase and out-of-phase annual components is 2.1 and 1.8, respectively. These values are much greater than 1.0, further evidencing the disagreement between the GPS and GRACE annual signals.

[28] On the basis of these results we conclude that the annual vertical surface displacement observed with GRACE does not, in general, explain the observed GPS annual for European sites. The disagreement arises either from limitations in the GRACE water storage estimates, i.e., actual errors or the inability of GRACE to capture real short-wavelength features in the water storage field, or from other, more dominant, sources of the annual signal in

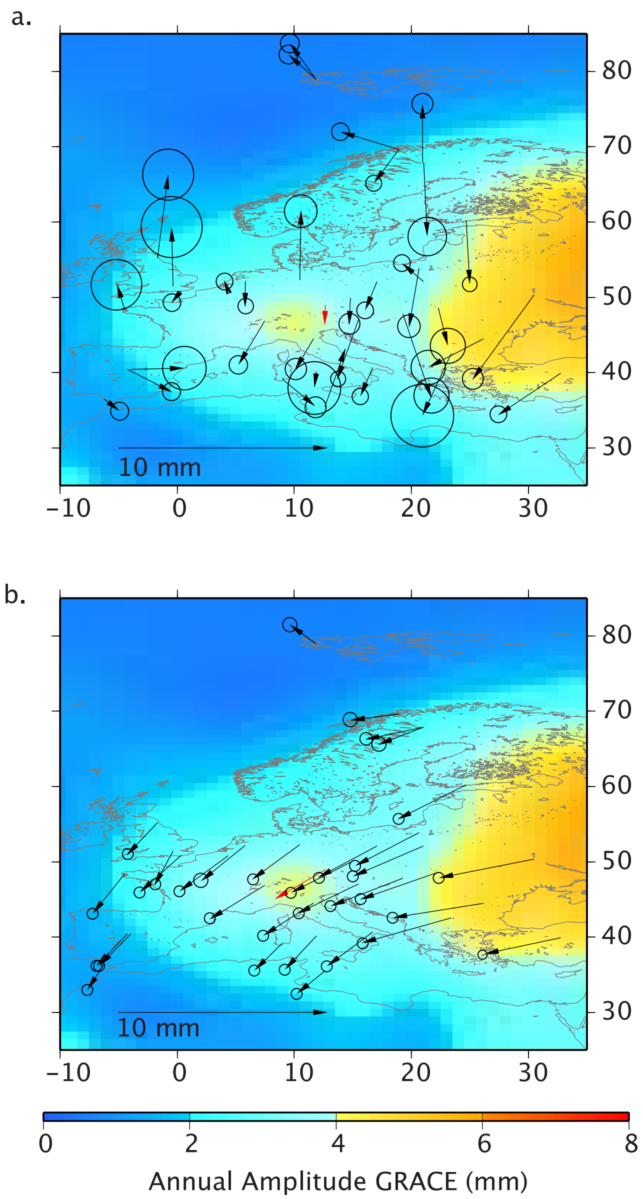

Figure 4. (a) Annual amplitudes and phases of the height component of surface displacement from GPS. The amplitude A and phase ϕ are defined as $A \sin[\omega(t - t_0) + \phi]$, where t_0 is 2002.0 and ϕ is the angular phase lag in degrees. The black vectors represent the amplitudes and phases of the individual sites. The phases are counted counterclockwise from the east. The red arrow represents the average annual amplitude and phase of the sites in Europe. The black line in the lower left is the scale for both the individual and average signal. (b) Same as Figure 4a but for the predicted vertical surface displacement from GRACE. (Background and scale for background described in Figure 3.)

the GPS heights. We consider all these possibilities in sections 4–6.

4. Errors in the GRACE Data

[29] There are two classes of errors to be considered in the GRACE surface displacement calculations. The first is true errors in the GRACE gravity fields, i.e., that the Stokes coefficients do not represent real monthly water storage changes at the wavelengths we are considering. A second type of errors are those introduced into our height estimates through the process of transforming the GRACE gravity fields into radial surface displacements.

[30] First we examine the errors in the GRACE observations. Ground truth observations cannot be used to validate the GRACE mass estimates. There is no place where monthly variations of surface mass are known well enough to compare to GRACE. Instead, we adopt the error analysis described by *Wahr et al.* [2006].

[31] In Figure 6, we show the RMS of the errors in the GRACE estimates caused by errors in the GRACE gravity fields. These errors are estimated by fitting and removing an annual signal from each Stokes coefficient, and interpreting the RMS of the residuals as a measure of the error in that coefficient [*Wahr et al.*, 2006]. These errors, which decrease with increasing latitude, represent 68.3% confidence intervals. In other words, we are 68.3% confident that the errors in the GRACE heights due to errors in the GRACE gravity fields are less than a few tenths of a millimeter as shown in Figure 6. Comparing the GRACE annual amplitudes (shown as the background in Figure 4) with Figure 6, we see that the signal-to-noise ratio is significantly greater than 1.0 over land. In fact, the errors are far smaller then the level of discrepancy between GPS and GRACE (compare Figures 4 and 5).

[32] For the second type of error in the GRACE heights, we examine how the choices we make for the Earth model and the weighting function in equation (2) might introduce an error in the predicted heights. Since we use Gaussian averages of 500 km, we essentially sampling Earth

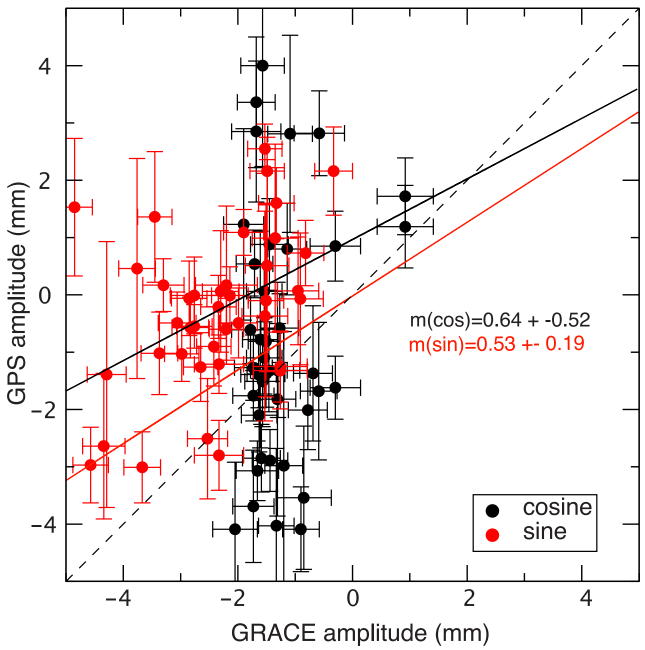

Figure 5. Comparison of in-phase and out-of-phase components of annual signals from GPS and GRACE. If the annual signal in the GPS data were due to water storage loading, the slope of the best fit line to the GPS and GRACE cosine and sine of the annual signal would be 1.

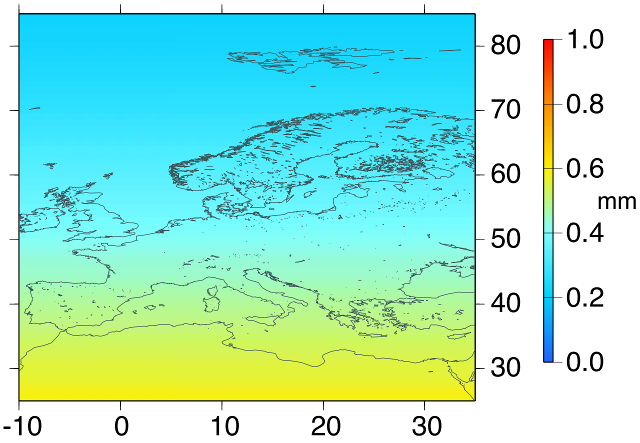

Figure 6. Best estimate of the amplitude of the errors on the annual signal from the GRACE deformations in millimeters.

properties only up to degree and order 40. Differences in the ratio, $h'(n)/(1 + k'(n))$, for the different elastic Earth models (e.g., Bullen B or Prem) at these degrees are insignificant. This means our predicted deformations would not be affected if we had chosen different Love numbers in the analysis. The largest error in our Love numbers is that we use values computed for an elastic rather than anelastic Earth. The effects of anelasticity at seasonal periods, however, are no more than a few percent [*Wahr and Bergen*, 1986].

[33] We also consider the possibility that we may also be introducing an error into the height estimates by applying a Gaussian average. We examine the amplitude of this error by comparing annual signals determined with and without the averaging function. In this example, we use the 25-year LaDWorld-Euphrates water storage model described above. Using the gridded mass estimates, we determine the Stokes coefficients up to degree and order 80. Degree 80 should have a spatial resolution of twice a Gaussian weighting radius of 500 km. We then determine the deformation at 1-degree spacing over Europe using the Stokes mass coefficients (equation (1)) and using the 500 km Gaussian weighting (equation (2)). The difference in the annual signal determined from each data set is shown in Figure 7. This is the error that we could expect on the annual amplitude if the GRACE data were reliable up to degree 80. In fact, the GRACE data are too noisy above degree 30 so this is a worst-case scenario. Nonetheless, the error is always less than or equal to 1.0 mm and on average is much smaller. As these errors are much smaller than the difference we observe between the GPS and GRACE determined annual signals, we conclude that the Gaussian weighting cannot explain the observed difference.

5. Short-Scale Water Storage Variations

5.1. Degree Amplitudes

[34] In section 4, we demonstrated the validity of the GRACE observations down to 500 km. However, what about shorter-wavelength surface mass loads? For example, are there water storage loading signals at wavelengths less than 500 km that dominate the annual loading signal at a GPS site, but are too short in wavelength to be captured by the loading model? By analyzing the degree amplitude of the annual load deformation field, we can determine how the power of the annual deformation changes with degree.

[35] We generate an environmental model (ENV) that consists of approximately 7 years of continental water storage estimates from the LaDWorld-Euphrates land energy balance model (described above) and bottom pressure from the National Ocean Partnership Program Estimating the Circulation and Climate of the Ocean (ECCO) partnership (http://www.ecco-group.org). We interpolate the monthly water storage data to weekly estimates and average the 12 hourly ocean bottom pressure data to weekly averages. Both the original water storage and ocean bottom pressure data sets are provided on a 1° × 1° grid. This allows us to determine the Stokes coefficients up to degree and order 180 or a spatial resolution of ~100 km. We determine the vertical surface displacement by convolving the mass spherical harmonics with the Love numbers of *Han and Wahr* [1995].

[36] First, we fit a mean, trend, annual, and semiannual signal to each C_{lm} and S_{lm} in the induced deformation fields for the 368 weeks of ENV data. Next we determine the degree amplitude for each degree. The degree amplitude is derived from the amplitudes of the spherical harmonics used to characterize the deformation and is defined as

$$\sigma_l = \sqrt{\sum_{m=0}^{l} \left(A_{C_{lm}}^2 + A_{S_{lm}}^2 \right)}$$

where $A_{C_{lm}}$ and $A_{S_{lm}}$ represent the annual amplitude of each C_{lm} and S_{lm} component. Thus σ_l is a measure of the contribution to the scatter in the deformation field from all terms of a given spatial scale (the scale ~20,000/l km).

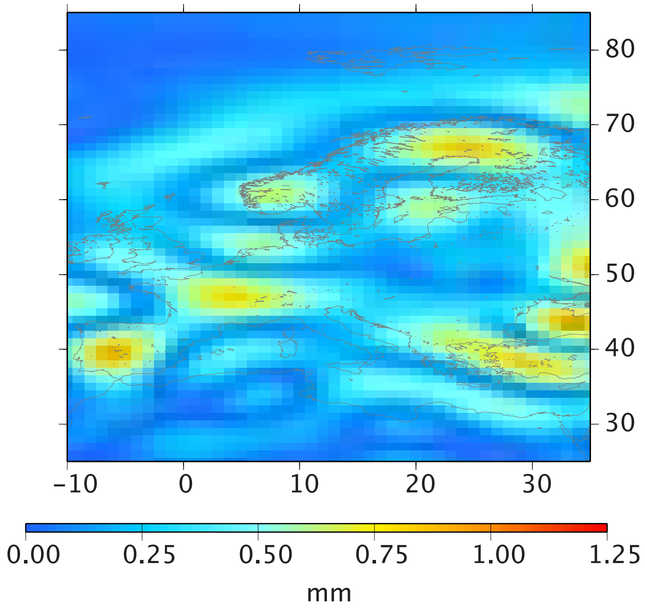

Figure 7. Estimated amplitude of the errors on the GRACE annual signal introduced by the 500 km Gaussian averaging.

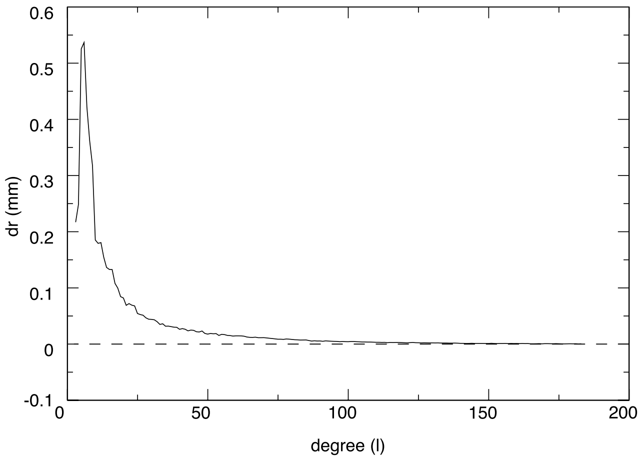

Figure 8. Degree amplitudes of the annual deformation signal determined from an environmental model. The deformation results have converged to ~0 at l = 85 or a scale of 235 km indicating that annual deformation signals at scales shorter than this do not exist in the data set.

[37] In Figure 8, we show the degree amplitudes of the annual radial surface displacement as a function of l. The degree amplitudes of the deformation have converged to ~0 at l = 85 (1/2 wavelength scale of 235 km). On the basis of these environmental models, we conclude it unlikely that there is significant annual variability in the vertical surface displacement at wavelengths shorter than about 235 km due to annual mass changes of water storage or bottom pressure variability.

[38] This result is based on environmental models which are in fact derived from spatially sparse observations. The observations have been smoothed and interpolated to provide global gridded results so that some real variability in the water storage or ocean bottom pressure field that may have been smoothed out. In section 5.2, we use an example to show that even if the models used here are in error, that it is still unlikely that significant short-scale (less than 200 km) mass anomalies exist in the true annual water storage that would cause the discrepancies observed between GPS and GRACE over Europe.

5.2. Case Study

[39] We would like to determine if it is possible to have two loads geographically limited in space and of significant magnitude that the annual surface displacement induced at two points in the center of each load could differ by more than 1 mm in amplitude. If this is possible, we might be able to use local water storage effects to explain the difference in the annual amplitude of the GPS heights for closely located station pairs. For example the station pairs lama and joze, trom and kiru, and kosg and wsrt are all separated by distances of less than 250 km. The amplitude of the best fitting annual signal to the heights differs by at least 1 mm on each pair.

[40] The largest amplitude difference is observed on the lama and joze station pair located in Jozefoslaw and Olsztyn Poland, respectively, and separated by 150 km. The amplitude of the annual signal at joze is 3.4 mm peaking in late summer and at lama is 2.0 mm peaking in early summer. There are no obvious geographical issues that can account for the observed difference in annual amplitude and phase. (For example, we might expect the annual amplitude and phase of two sites within a short distance (100–150 km) to be different, if one were at the top of a mountain and the other was located in the foothills.)

[41] We assume the large-scale hydrology signals at these sites are accurately represented by GRACE, and we remove the GRACE predictions from the GPS results. The resulting amplitudes of the annual residuals are 4.2 mm at joze and 1.7 mm at lama (with the phases now in agreement). Thus there is a 2.5 mm difference in the annual amplitudes at the two sites that cannot be explained with large-scale environmental loading.

[42] To see whether short-scale hydrological loads could cause a difference this large, we set up a simple loading model to determine the deformation at two sites, A and B, due to loads acting at both sites. The deformation induced at each site will depend on the spatial extent and amplitude of each load. In this problem we force the spatial extent of the load to be half the distance between the two points such that the loads do not overlap. The situation is pictured in Figure 9a. The sites are separated by a distance r, and each

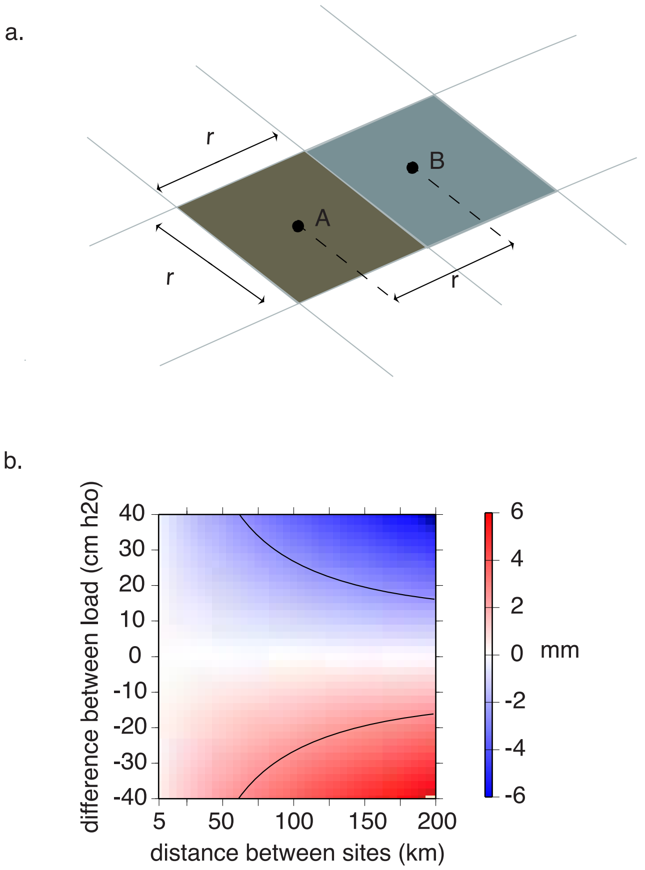

Figure 9. (a) Two sites separated varying distances and each centered on a load. (b) Difference in radial displacement at A and B as a function of the distance between the sites and the difference in the loads acting at the sites. The black lines indicate where the difference in the deformation is 2.5 mm.

load has dimensions $r \times r$. The two loads vary in amplitude between -20 and 20 cm of water thickness.

[43] In Figure 9b, we plot the difference in the annual amplitude of the vertical surface displacement at A and B as a function of the distance between the sites (x axis) and the difference in the load acting at A and B (y axis). Two sites separated by 50 km could never have a 2.5 mm difference in the annual deformation, given the geometry defined in the model. However, this difference in the amplitude of the annual deformation at A and B could be induced by a load difference of 20 cm if the stations were 150 km apart. A difference in water storage of 20 cm is large in terms of annual water storage variability and is very unlikely to occur over such short spatial wavelengths unless there is a significant difference in the geology (e.g., bedrock versus thick soils) (C. Milly, personal communication, 2006).

6. Other Annual Signals in the GPS Heights

[44] Disagreements between the GRACE and GPS annuals, as well as the observed spatial variability of the GPS annuals themselves, probably arise in part from the GPS technique. *Dong et al.* [2002] have provided an extensive list of potential contributions to the observed annual height variations in GPS time series. These include: atmospheric modeling (Zenith tropospheric delay), mapping functions, bedrock thermal expansion, monument thermal expansion, phase center modeling, common orbital errors, and effects due to estimating network transformation parameters. For a summary of the range of the annual vertical variations in site positions due to these effects, see *Dong et al.* [2002, Table 3].

[45] Spurious annual signals can also arise due to the mismodeling of semidiurnal ocean loading effects. Using simulated GPS data and orbits, *Penna and Stewart* [2003] demonstrated that unmodeled subdaily ground displacements will propagate into a GPS height time series at longer periods. A spurious annual signal can arise due to the 24-hour observation window used in GPS data processing. Also, semiannual signals can arise due to range model truncation errors [see *Stewart et al.*, 2005]. These simulated results have been subsequently substantiated using real data [*Penna et al.*, 2007]. The amplitude of an induced annual signal in newl height time series (50.0°N, 0.53°W in the United Kingdom) is about 3 mm. Referring again to Figure 4, we observe that sites with the most disagreement between the GPS and GRACE annual signals (excluding madr and pots) are coastal sites indicating that a spurious annual signal arising from mismodeling of the ocean loading tides may be a problem.

[46] In another study, *Watson et al.* [2006] found that changing the body tide model in the GAMIT GPS processing software from the *Wahr* [1981] model to the *Mathews et al.* [1997] introduced an annual signal of between 1 and 1.5 mm into GPS height time series at midlatitude to high-latitude sites. This effect will be geographically correlated over Europe and so cannot explain the observed spatial variability in the GPS annual heights.

[47] Another consideration when analyzing annual signals is the effect of combining processing results as is done to generate the IGS combined residuals used here. A combination of height time series derived from the various IGS analysis centers using different software and processing techniques, will contain errors if any single contribution has an error. For example in July 2004, a bug in the component of the Bernese GPS data processing software, which is used to determine the solid earth tide effects was discovered (http://www.bernese.unibe.ch/Bugs07-JUL-04.html). This coding error introduced annual signals into GPS heights from midlatitude sites processed with the Bernese software with amplitudes of more than 10 mm. It is not clear how this error would manifest itself in the combined time series; however, it is something to consider when discussing spurious annual signals in this particular data set. In addition, when transforming to an ITRF as is done with the combined series, the inclusion of the scale in the Helmert transformation of the data into an ITRF introduces a spurious annual signal into the time series [*Tregoning and van Dam*, 2005].

[48] In a recent presentation, *Ray et al.* [2005] demonstrated how certain data quality metrics, i.e., phase cycle slips, code multipath scatter and data dropouts, can have an annual dependence which often correlates with GPS heights.

[49] A thorough analysis of each GPS height time series from Europe in terms of these effects is beyond the scope of this comparison. We only list these potential sources of spurious annual signals in the GPS heights to point out the possibility that the discrepancy between the GPS and GRACE annuals could arise due to the GPS technique itself.

7. Conclusion

[50] We have compared the annual signal observed in GPS heights with that predicted from GRACE gravity field observations at 36 sites over Europe. We found that the annual signal in the GPS heights is not particularly coherent over the region, displaying significant variability in amplitude and phase. In addition, while the GPS annual signals from inland European stations display some agreement with the annual signal predicted by GRACE there are many stations where the difference is large. The agreement between the GPS and GRACE vertical annual signal is poor at coastal sites and some anomalous inland sites.

[51] There are three possible explanations for why the GRACE annual signal and that from GPS do not agree over Europe. These include (1) errors in the GRACE estimates, (2) small-scale features in the load field not captured by the GRACE data, and (3) technique errors in the GPS.

[52] To test for errors in the GRACE gravity fields, we compared the annual surface displacement in the GRACE results with the errors on those estimates. The errors on the GRACE annual signal over Europe is about 0.5 mm determined to 68.3% confidence. Errors introduced into the annual amplitude from using the 500 km Gaussian smoothing of the GRACE data are also on the order of about 0.5 mm. Both of these errors are far smaller than the level of discrepancy between GPS and GRACE annual signals, implying that the GPS/GRACE difference is not due to errors in the GRACE data.

[53] The degree amplitudes give us some indication of the power in the data field at all degrees. When we determine the degree amplitude values for the annual component of the Stokes coefficients of deformation derived from a model of

water storage and bottom pressure, we find that the degree amplitude has converged to ~ 0 at $l = 85$. This result indicates that there is not significant variability in the deformation field from deformations at scales less than 235 km. However, because the models are derived by interpolating sparse observations, the possibility of real short-wavelength variability in the mass field does exist. Using a simple loading model, we determined that differences in the annual amplitude of 2.5 mm at two sites separated by 150 km could only be caused by a difference in load of greater than 20 cm acting at the two sites. This load is large in terms of annual water storage effects and we conclude that it is unlikely to explain the spatial variability in the GPS annual signals over Europe.

[54] Alternatively, annual signals of the same magnitude as the predicted GRACE signal can be introduced into the GPS annual signals from effects such as the aliasing of periodic signals, seasonal monument motion, reference frame effects, etc. These errors have already been shown to affect a number of sites in Europe and most likely contribute to the cause of the disagreement between the GPS and GRACE annual height signals. Coastal sites appear to be particularly problematic in the comparison.

[55] The results presented in this paper demonstrate that the annual height signal from many GPS sites in Europe do not agree with the signal predicted by the continental water storage loading signal predicted from the GRACE data set. We originally set out to understand this result. We are confident that the GRACE data are providing reliable estimates of the annual water storage signal at regional scales. Further, the agreement between GRACE and global inversions of the GPS data combined with nontidal ocean loading estimates over the ocean with barotropic ocean models down to wavelengths of 400 km [*Wu et al.*, 2006]. We expect that the uncertainties in the GRACE data will continue to decrease as more and more data become available. The GRACE data set allows us to reliably remove the long-wavelength component of continental water storage signal from the GPS data. This in turn will help us to understand the errors in the GPS data to a better extent.

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