Choice of optimal averaging radii for temporal GRACE gravity solutions, a comparison with GPS and satellite altimetry

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Summary: One of the initial challenges of the GRACE mission is to validate the accuracy of the time-variable gravity fields. These gravity fields contain both spatially correlated (systematic) and random noise and hence spatial averaging needs to be implemented. Before the fields may be interpreted, optimum averaging radii need to be determined through comparison with independent data. We compare time series of vertical solid Earth deformations computed from 22 approximately monthly GRACE gravity fields (covering 2002.3 until 2004.6) with vertical displacements measured using a global GPS network of 63 sites, about half of which are located on small islands. The GPS data were processed using a Precise Point Positioning approach using fiducial free orbits and attempting to minimise propagated systematic errors. The optimum mean correlations were obtained at 500 km averaging radii for continental sites (R=0.55), >=2000 km for island sites (R=0.3). Subtracting the GRACE displacement time series from the GPS ones revealed a mean Variance reduction of ~14%. To supplement the GPS data at the island sites, we also computed displacements based on TOPEX/POSEIDON (T/P) sea surface height data between 2002.3 and 2003.96 corrected for steric effects. Correlations reached a maximum at 2000 km with a correlation of 0.38, increasing to 0.47 after the removal of six outlying sites. Overall, we conclude that optimum averaging radii are ~500 km for continental sites and >=2000 km over the oceans, but that the measurement precision of GPS and T/P may be inflating these values.

Keywords: Gravity, Satellite Geodesy, Global Positioning System (GPS), Hydrology, Crustal Deformation

Introduction

Following the launch of the Gravity Recovery and Climate Experiment (GRACE) twin satellites in 2002 (Tapley *et al.*, 2004), early results have demonstrated the importance of this new data set for better understanding the Earth system, most notably the hydrological cycle (Andersen & Hinderer, 2005; Chen *et al.*, 2004; Davis *et al.*, 2004; Wahr *et al.*, 2004). While these early results are impressive, the GRACE mission is yet to meet its pre-launch error budget (Wahr *et al.*, 2004) due to the presence of unmodelled systematic errors and these are evident in the time series of near-monthly GRACE fields. Figure 1 shows that the annual component of vertical deformation using a 300 km averaging radius is dominated by longitudinal bands of streaking, particularly over the oceans. One common approach to overcome these systematic errors is to spatially average the fields, such as using a Gaussian filter (Jekeli, 1981; Wahr *et al.*, 1998), although other approaches exist (e.g., Luthcke *et al.*, 2006). This raises the question about the optimum spatial averaging radii or radius that should be applied in order to avoid contamination by systematic errors whilst resolving gravity field changes at the highest possible spatial resolution.

Three complementary approaches to this problem involve i) internal assessment of sensitivity of the GRACE fields to different combination strategies; ii) external assessment by way of comparison with measured ocean bottom pressure, gravity or surface displacements (e.g., Crossley *et al.*, 2004); or iii) comparison with hydrological/atmospheric/oceanic model output (e.g., Chen *et al.*, 2004). The particular advantage of comparing external measurements is that constraints may be placed on GRACE gravity field accuracy using in situ observations without interpolation (as occurs in a model). However, the challenges of measuring quantities that may be compared with global GRACE gravity fields at sufficient spatial scale and accuracy are significant, although these may largely be overcome with care and the appropriate dataset(s).

Figure 1

One helpful approach is to compare station displacements measured by the Global Positioning System (GPS) with estimates using the GRACE fields (Davis *et al.*, 2004). This comparison is possible since changes in gravity may be related to surface displacements through the well-established theory relating to surface mass loading (Farrell, 1972). However, even after the conversion of the GRACE measurements into surface displacements, GPS and GRACE remain incompatible and several corrections must be applied before comparison (Chen *et al.*, 2004). GPS time series contain deformations due to the degree-1 component of the surface load (Blewitt *et al.*, 2001) to which GRACE is insensitive. Estimates of degree-1 gravity or displacement variations must be obtained from measurements or models (e.g., Lavallee *et al.* 2006) and added to the GRACE fields or subtracted from the GPS time series. Short period atmospheric and oceanic mass variations are removed at the GRACE processing stage and need to be added back in prior to comparison (these background fields are provided along with the GRACE fields).

In this paper, we describe a comparison of GPS and GRACE vertical deformation time series using ~monthly GRACE fields covering the period ~2002.3-2004.6 with the purpose of determining the optimum averaging radii for GRACE fields. We also supplement the GPS data with TOPEX/POSEIDON (T/P) data. The two approaches are complementary since the GPS data are from onshore sites whilst the T/P data cover the oceans. The two techniques overlap somewhat where we have GPS data at small island sites, allowing for an assessment of their relative merit for this application. As each of the measurement techniques is subject to error, our analysis will therefore provide a conservative upper bound for the optimum averaging radii. However, we also attempt to mitigate as far as possible potential errors in the various time series, as described below.

Care must be taken with GPS coordinate time series since they may be affected by systematic errors, such as due to tropospheric mapping function error (Vey *et al.*, 2006), mismodelled ocean tide loading displacements (Penna & Stewart, 2003) or mismodelled solid Earth tides. For GPS data processed in 24-hour batches, mismodelled short-period tides appear as harmonic signals with periods of between ~2 weeks and ~1 yr and with admittances of more than 100% (N.T.

Penna, personal communication, 2005). While most modern GPS processing introduces ocean tide loading displacement models, improvements in solid Earth tide and atmospheric loading models (McCarthy & Petit, 2004; Tregoning & van Dam, 2005) and recently identified software bugs (in some software) means that historic solutions are insufficient for comparing against GRACE solutions. In addition, unmodelled possibly non-tidal GPS signals with sidereal (K_1) and half-sidereal (K_2) periods have also been identified (King *et al.*, 2005; Schenewerk *et al.*, 2001) with magnitudes of 0.5-10 mm and these may also propagate into ~0.5 and ~1.0 yr periods respectively with possible amplitudes as large as the input signals. Consequently, GPS coordinate time series obtained using "standard" solutions may not be optimal.

Once these errors are all accounted for (or minimised) and other standard corrections applied (e.g., solid Earth and pole tides), GPS and GRACE time series may be compared for different GRACE averaging radii in order to assess the optimal averaging radius for GRACE. The averaging radius that produces the closest agreement would then be the optimal averaging radius. Davis *et al.* (2004) demonstrated that GPS and GRACE time series are in close agreement in the Amazon basin at annual timescales, but did not show comparisons for shorter timescales or in other regions, most notably where gravity variations are smaller and in locations where mismodelled ocean tide and atmospheric pressure signals are more likely to alias into the GRACE time series (Knudsen, 2003; Velicogna *et al.*, 2001). It is important to note that GRACE fields are of interest not only at annual timescales and hence validation of the entire time series is required. Here, we improve and expand on this analysis, producing comparisons between GPS and GRACE on a monthly basis for a global network of 63 sites, about half of which are located on small islands.

Description of data sets

GRACE data

The Center for Space Research (CSR), University of Texas, has to date released 22 "monthly" GRACE fields covering the period between day 104, 2002 and day 213, 2004, a total time-span of ~2.3 yr. Table 1 shows the details of the individual fields, three are of particular note since they contain less data than the others (fields 3, 6 and 16, Table 1) and hence these will be of lower precision than the other solutions. The CSR fields are provided in the form of Stokes coefficients representing an expansion in spherical harmonics of the Earth's gravity potential, complete to degree l=120. There are two exceptions where a maximum degree of l=70 was used (fields 3 and 16, Table 1). To each of these fields, we added the background fields provided by CSR so that the monthly GRACE fields included the effects of atmospheric and oceanic non-tidal mass variations. To allow comparison with GPS displacement estimates, vertical displacements were computed from the Stokes coefficients of each of the monthly GRACE fields by incorporating spatial averaging (Jekeli, 1981; Wahr *et al.*, 1998) within the Love number approach (Farrell, 1972). The procedure adopted was first to remove the mean field (here taken to be GGM01S (Tapley *et al.*, 2003)) from the monthly fields. The change in the Stokes coefficients was subsequently used to compute the vertical displacement ($S_v^{(R)}$), namely

$$S_v^{(R)}(\phi,\lambda) = \frac{1}{g}\sum_l S_{v,l}^{(R)}; \qquad S_{v,l}^{(R)}(\phi,\lambda) = h_l' W_l^{(R)} V_{l,m}(\phi,\lambda) \tag{1}$$

where g is mean gravity, h_l' the load Love number of degree l, $W_l^{(R)}$ the degree l weighting from Jekeli's Gaussian averaging function (Jekeli, 1981; Wahr *et al.*, 1998), and R the averaging radius. Further, $V_{l,m}$ denotes the degree l, order m component of the Earth's gravitational potential V (after the removal of GGM01S) evaluated at latitude Φ, longitude λ for points on Earth's surface.

To date, the published work using GRACE has used averaging radii exclusively in the range 750-1000 km (Davis *et al.*, 2004; Wahr *et al.*, 2004). Figure 1 shows the annual periodic vertical deformation estimates for four different averaging radii. The most notable features are the large annual signatures over the major continents, except North America. The longitudinal streaks in the 300 km solutions are not evident in the solutions smoothed using longer radii. These streaks are considered to have their origin largely in inaccurate background models, such as ocean tides (Knudsen & Andersen, 2002; Ray *et al.*, 2001), used for GRACE de-aliasing at the processing stage and should be reduced in future GRACE releases (Luthcke *et al.*, 2006).

Table 1

GPS data

Our chosen GPS network (Figure 1; Table 2) was designed to evenly sample locations where both large and small signals were evident in the GRACE data. The GPS data were obtained from the International GNSS Service network, plus several other archives (Geoscience Australia, CDDIS, Brazilian Institute of Geography and Statistics). The Amazon basin, Siberia, Antarctica and Northern Australia each show peaks in the dominant annual GRACE signal while North America and the island sites show little GRACE signal. About half of our sites are located on small islands, where the hydrological and atmospheric signals are negligible (due to their small size and the inverse barometer effect, respectively) and hence non-tidal oceanic signals will dominate. These sites therefore provide an opportunity to assess the GRACE accuracy over the oceans.

Table 2

The GPS data were processed in GIPSY/OASIS II v2.6 (Webb & Zumberge, 1995) using the precise point positioning (PPP) strategy using 24 h batches (Zumberge *et al.*, 1997). Jet Propulsion Laboratory (JPL) fiducial-free satellite orbit and clock products were used and the final site coordinates were not transformed into a terrestrial reference frame, since we only considered the radial coordinate component which is stable in a reference frame centred on the centre of mass of the whole Earth system (Blewitt, 2003). To account for possible mismodelling of the GPS signals at near sidereal and half-sidereal frequencies (King *et al.*, 2005) and subsequent propagation into the GPS time series (Penna & Stewart, 2003) we estimated harmonic parameters at K_1 and K_2 for each of the three coordinate components, constraining these to their a priori values (0.0000 m) at the 0.2 m and 0.02 m level for the local radial and horizontal components, respectively. To reduce the effects of unmodelled multipath and tropospheric mapping errors, we used an elevation cut-off angle of 15°. Apart from these, the PPP solutions effectively followed the work of e.g., Bar-Sever *et al.* (1998), carrier-phase smoothing the pseudorange measurements and then decimating both pseudorange and carrier signals to 5 min intervals. We estimated tropospheric zenith delay and horizontal gradient parameters every 5 min, with random walk standard deviations (Lichten, 1990) of 10.2 mm/√h and 0.3 mm/√h, respectively. As a second step, and where possible, ambiguities were fixed to integers using groups of sites in regional clusters.

Figure 2 shows the effect of estimating the additional harmonic parameters at K_1 and K_2 in terms of the radial component for a typical site (AREQ; Table 2) by showing solutions both with and without these parameters. Differences between the two time series reach ~5 mm, with a dramatic change in long-period noise as predicted by Penna & Stewart (2003) when a time series is affected by unmodelled signals at tidal frequencies (notably K_1 and K_2).

Figure 2

During early 2003 the JPL observation network geometry changed rapidly, most notably including additional Southern Hemisphere sites, thereby altering the sensitivity of the network to the motion of the geocenter. As a result, an offset was evident in the fiducial-free site time series, particularly those in the Southern Hemisphere. To account for this, an offset was estimated and removed from the GPS time series at ~2003.1.

To remove the aspects of surface deformation to which GRACE is insensitive, we subtracted the deformations due to degree-1 of the surface mass load from the GPS time series for all sites. Since the degree-1 component of surface deformation is frame dependent it is important to remove the same displacements as are present in the GPS time series. The original global GPS analysis which determined the satellite orbits and clocks (and hence the reference frame of the PPP solutions) was performed at JPL and hence these data were used to obtain the degree-1 deformations at each site. The global JPL GPS analyses are made available in Solution Independent Exchange (SINEX) format via the IGS, and degree-1 deformations were estimated from them using a unified model in the centre of mass frame (Lavallee *et al.*, 2006). Since the GRACE $C_{2,0}$ term has been reported to be poorly determined in early official GRACE releases (Andersen & Hinderer, 2005), we also computed and excluded this in a similar manner as well as excluding it from the GRACE time series computations during the spherical harmonic expansion.

Since the GRACE estimates are ~monthly averages, we computed averages of the GPS data, omitting the same days as were omitted from the various GRACE solutions. The GPS point measurements within distinct regions (e.g., Antarctica, Siberia, etc.; see Table 2) were also further averaged to reduce random noise and better approximate the GRACE measurements (which were also computed at each point and then averaged across several points). After this, the GRACE deformation and GPS vertical displacement time series could be compared directly.

TOPEX/POSEIDON and Climatology data

Ocean mass change and the associated vertical deformation due to loading was inferred from global TOPEX/POSEIDON (T/P) altimetry with the sea surface height data between 2002.3 and 2004.0 corrected for steric effects using monthly climatology (Levitus & Boyer, 1994) from the 1° by 1° data set with 19 depth levels. This is similar to the approach used by Chambers *et al.* (2004), although we maintain a site-by-site comparison as opposed to their near-global-average study. Standard corrections for geophysical corrections (wet and dry troposphere, ionosphere, ocean tides, sea-state bias etc) were taken directly from the merged geophysical data records (MGDRs). Since the total loading (i.e., bottom pressure) over the oceans is the sum of the mass within the vertical water and atmospheric column the inverse barometric correction was not applied. Variability in the sea-surface heights thus corresponded to changes in bottom pressure on multiplying by the density of sea-water. Any non-climatological variations in temperature or salinity will thus remain in the corrected T/P data, as will any (probably small) degree-1 deformations that are not absorbed by once-per revolution orbit parameters. Following Wahr *et al.* (1998) the ocean mass per unit area was converted to spherical harmonic geoid coefficients for each T/P cycle. To be compatible with the GRACE time series, $C_{2,0}$ was removed from the T/P time series using the values of Nerem *et al.* (2000) derived from Satellite Laser Ranging observations. In this manner the ocean mass variations were used in Eq. (1) to determine vertical displacements spatially averaged over radii of 500, 1000 and 2000 km for the island sites.

Comparisons

GRACE-GPS comparison

In Figure 3 and 4 we show comparisons of GRACE-derived and GPS height time series for two representative regional networks covering locations where GRACE-derived signals are large (Amazon) or small (Pacific Islands), respectively. Both time series have been de-trended to remove the effects of tectonic motion or post-glacial rebound. For the Amazon, the regional agreement between GPS sites is evident (Figure 3a). The mean of these sites is shown in Figure 3b, along with the GRACE time series, generated using several different averaging radii, for each site followed by a further regional average consistent with the sites used in the GPS regional averaging. As reported in Davis *et al.* (2004), the GRACE/GPS agreement is high at large averaging radii. However, using smaller averaging radii produces similar results, down to approximately 350 km at these sites.

The agreement between the Pacific Island GPS sites is also high (Figure 4a), covering a larger region than the Amazonian network, but the GRACE estimates do not contain the same ~annual signal evident from 2003.5-2004.5 in the averaged GPS data (Figure 4b). Figure 5 shows the correlations for each of the regions considered in the study (Table 2), with correlations ranging from ~0.0-0.7. Notably, the correlations in Central America and the Hawaiian Islands are not significantly different from 0.0 at the 95% confidence interval, while the Pacific Island sites are only show marginal correlations at any averaging radii shorter than 750 km. Little signal is evident in the GRACE time series for the island sites, and GPS random errors would therefore expect to dominate any correlation statistic. However, an annual signal of ~3 mm, well within the capability of measurement by GPS, is evident for Central America in the GRACE time series (Figure 1) but the GPS time series is not in close agreement. For sites which are surrounded mainly by land, the GPS and GRACE time series are more highly correlated, (e.g., Antarctica and Siberia), with correlations above 0.5 for averaging radii >=500 km.

Figure 3

Figure 4

Figure 5

The division between island and non-island sites is summarised in Figure 6, with non-island site correlations peaking close to 500 km averaging radius. Therefore, there appears no benefit in using larger than 500 km averaging radii for continental sites. For the island sites, on the other hand, GRACE/GPS correlations are still increasing with an averaging radius of 2000 km. The Central American sites were considered continental for the purpose of this comparison, although with ocean surrounding them, and given Figure 5, considering them as island sites would only further emphasise the difference between island and non-island sites in Figure 6.

Figure 6

We subtracted the GRACE vertical deformation time series from each of the sites' GPS time series. Across all sites the variance reduction averages are 13.7% (1000 km), 13.5% (750 km) and 11.7% (500 km). There is large variation from this mean, however, although only the shortest time series at island sites showed a large percentage increase in RMS. Figure 7 shows that the height RMS approaches a constant value of 5-7 mm following the subtraction of the GRACE time series, and therefore the combined GRACE/GPS height noise is within this range.

Figure 7

The usefulness of the correlation statistic between the GRACE and GPS time series is dependent on the magnitude of the signal that exists in a region, and hence this is not necessarily a useful measure where the signal is small, such as at island sites. However, if the geophysical signals are completely removed from the GPS time series, theoretically only GPS systematic and random errors should remain. Whilst the GRACE time series do not contain a perfect geophysical signal, we examined the between-site correlations before and after removing the GRACE time series to test the reduction in baseline correlations.

The results are shown in Figure 8. Overall, between-site correlations were reduced for 84% of pairs of stations in the same region using an averaging radius of 750 km. Figure 8, however, shows that even after the subtraction of the GRACE time series, correlations >0.5 exist for the majority of regions. The main exceptions are the Siberian sites where mean correlations are reduced by ~0.4 following the removal of the GRACE time series. These results suggest that non-geophysical effects play a significant role in the regional-scale correlations evident in GPS time series. Possible candidates for these are long-period second-order ionospheric effects (Fritsche *et al.*, 2005; Kedar *et al.*, 2003), unmodelled in our solutions; tropospheric mapping function errors (Vey *et al.*, 2006); and long-period satellite orbit modelling errors. We can rule out, however, propagated ocean or Earth body tides (Penna & Stewart, 2003) or other effects at near-diurnal or near-semidiurnal frequencies (short period second order ionospheric effects) since these have been removed following the daily estimates of nuisance parameters at diurnal and semidiurnal frequencies in our GPS analysis.

Figure 8

GRACE-T/P comparison

The comparison between GRACE and T/P was performed for the island sites only (27 in total), and examination of the T/P time series shows a considerably smaller scatter than that present in the GPS time series for these same sites. Figure 9 shows time series from a representative selection of sites using averaging radii (GRACE and T/P) using an averaging radii of 2000 km. At sites in the Pacific, (e.g., ckis and kouc) and Hawaii (e.g., hilo) regions the time series are in good agreement. While these make up the majority of sites, other sites, however, are in poor agreement. For example, at asc1 (Figure 9) the two time series are not similar. Even here, however, the two signals are in agreement at the 1-2 mm level.

Figure 9

Taking all sites' time series together, we found mean correlations of 0.13 (500 km), 0.23 (1000 km) and 0.38 (2000 km) which is in agreement with the trend of the GPS/GRACE comparison (Figure 1, left hand figures). However, these mean correlations are reduced by the low (<0.2) correlations at a few sites and removing them gives a correlations of 0.37, 0.42 and 0.47 (Figure 10, right hand figures), much larger than the equivalent GPS/GRACE correlations. This is despite the T/P time series overlapping the earlier, and possibly less accurate, sections of the GRACE time series only. As with the GPS data, uncertainties in the T/P displacement time series may artificially inflate these optimum averaging radii. These include errors in the sea surface height measurements from T/P and, possibly more importantly, variations from the mean climatology. The higher correlation between T/P and GRACE than GPS/GRACE, together with the smaller T/P scatter, suggests that measurements of site displacement using GPS is not as accurate as the application of the T/P data in determining optimum averaging radii for GRACE, although unlike T/P the GPS approach is valid over land.

Figure 10

Conclusions

We have shown that both GPS and T/P time series contain information that may be used to provide upper bounds for optimum averaging radii of monthly GRACE gravity fields, such as those produced by CSR. While examining the annual component only would probably increase the level of agreement between the time series (since the annual signal is typically dominant and estimating annual signals is effectively a long-period temporal filter), we chose instead to validate the entire time series at monthly intervals. Over the continents, the GPS/GRACE agreement suggests that GRACE fields are almost as accurate using a 500 km averaging radii as 2000 km and therefore a maximum averaging radii of 500 km is recommended. Over the oceans, however, where the signal is much smaller, both the GPS and T/P comparisons show optimum averaging radii >=2000 km.

For both the island and continental sites it is clear that the quality of the GPS time series is not presently sufficient to determine lower boundaries of GRACE accuracy in different regions; even taking a pessimistic view of the GRACE accuracy leads to the conclusion that non-geophysical signals play an important role in GPS time series. For example, and as shown here, the parameterisation of harmonic signals at daily and sub-daily periods can alter the amplitude of annual and semi-annual GPS signals by several mm and the need for further work in this area is evident.

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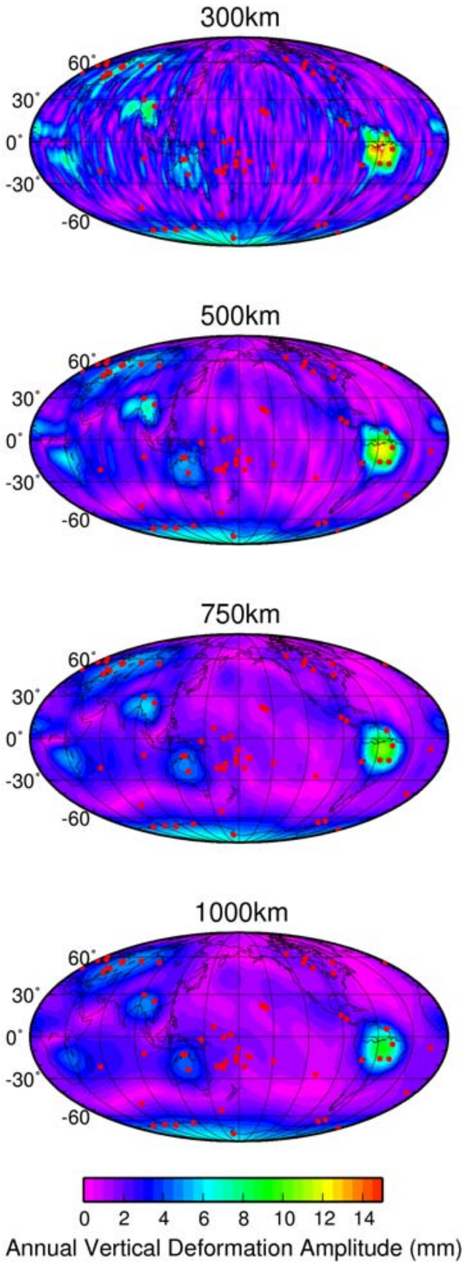

Figure 1: Annual vertical deformation signal from GRACE using four different averaging radii. The GPS site locations (see also Table 2) are shown as red dots.

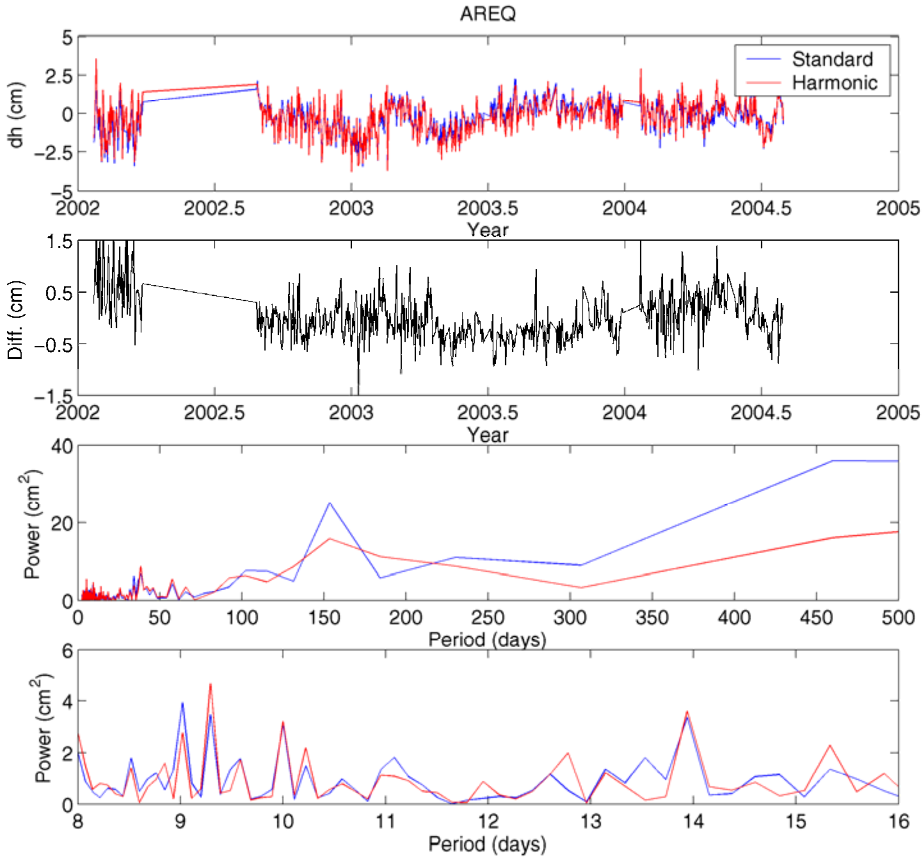

Figure 2: Impact of estimating K_1 and K_2 harmonic parameter estimates on GPS height time series for site AREQ. The upper two panels show the differences in time series using a ‘standard’ PPP strategy alongside that generated using the ‘harmonic’ strategy. The lower two panels show the periodograms at long and short periods.

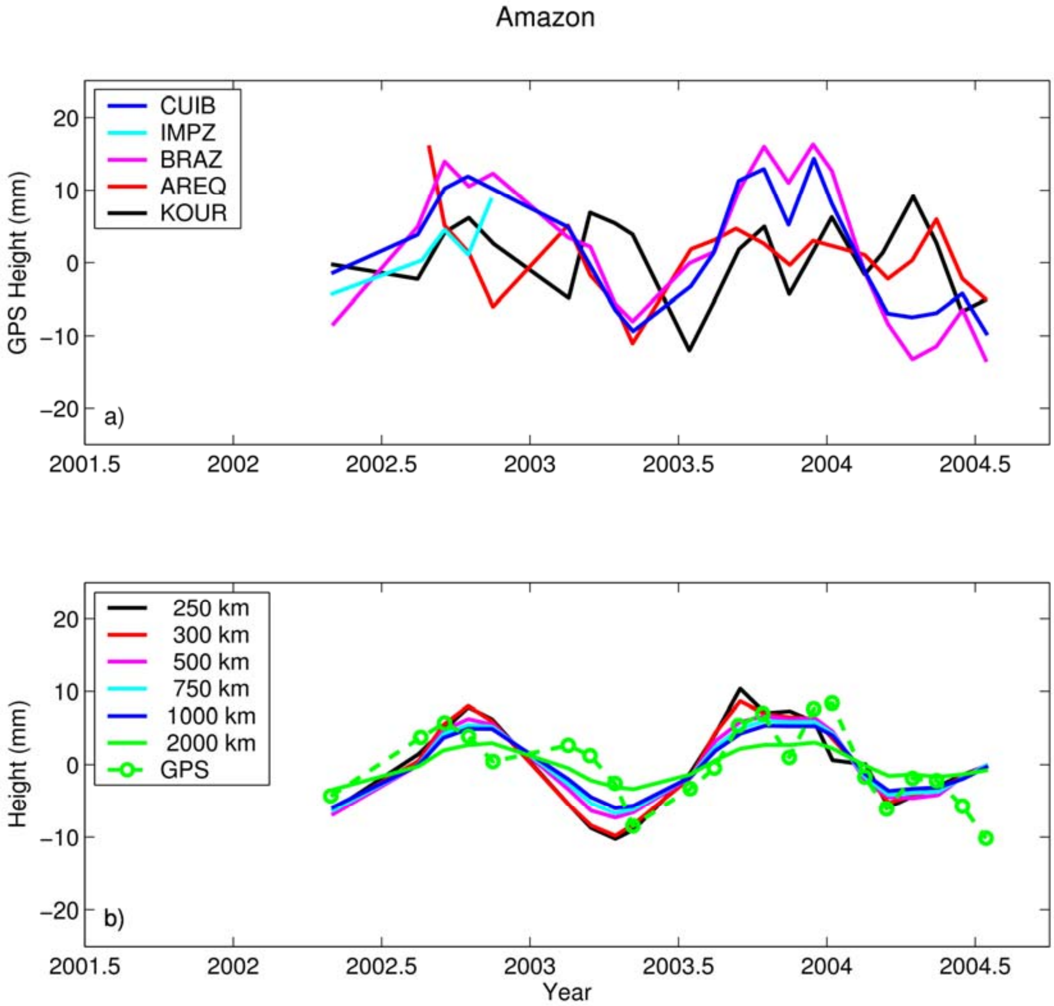

Figure 3: a) Time series of vertical coordinates at GPS sites in the Amazon basin, averaged in ~monthly bins according to the data in the various GRACE fields. b) Average of GPS time series in a) compared to GRACE solutions computed using different averaging radii for each site and then averaged. A best-fit line has been removed from each data set prior to averaging.

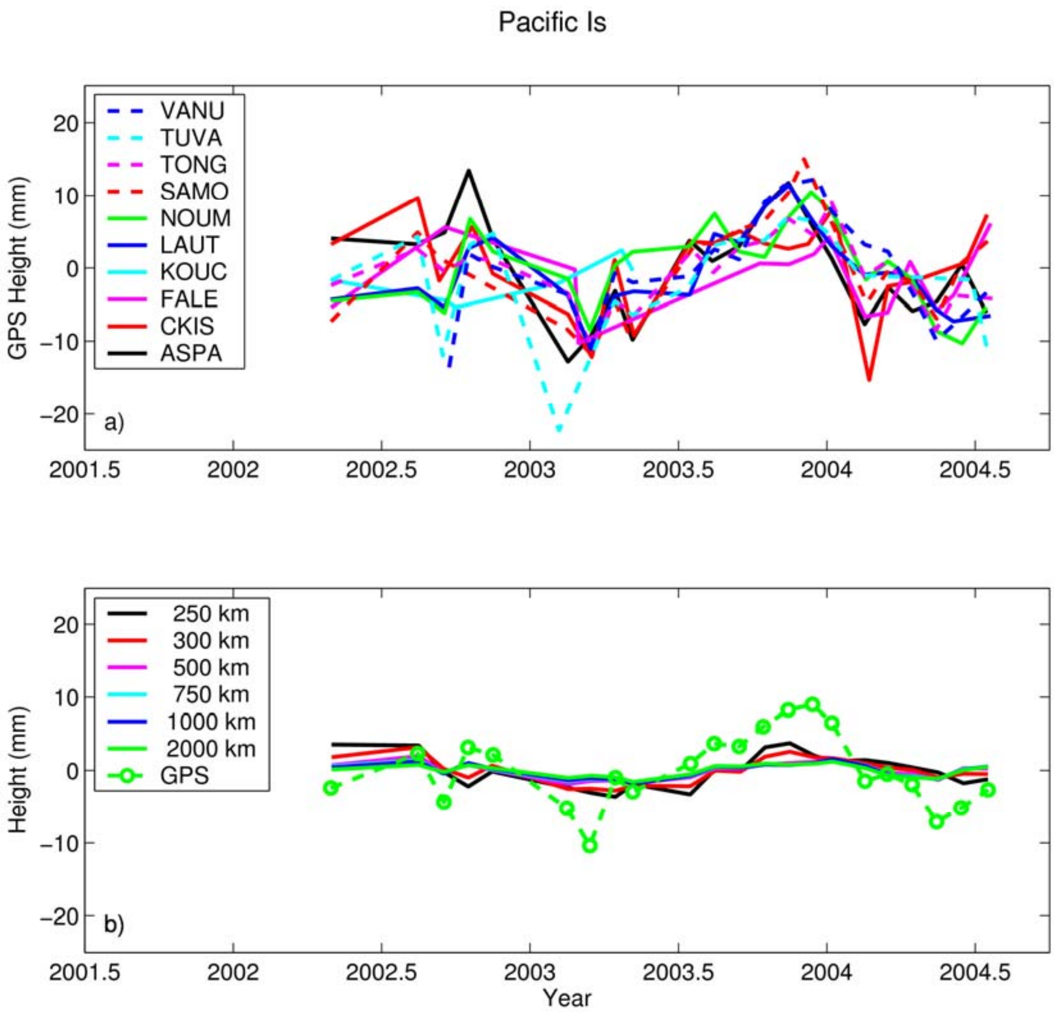

Figure 4: As for Figure 3, but for Pacific Island sites. For legibility, only a subset of the Pacific Island sites is shown.

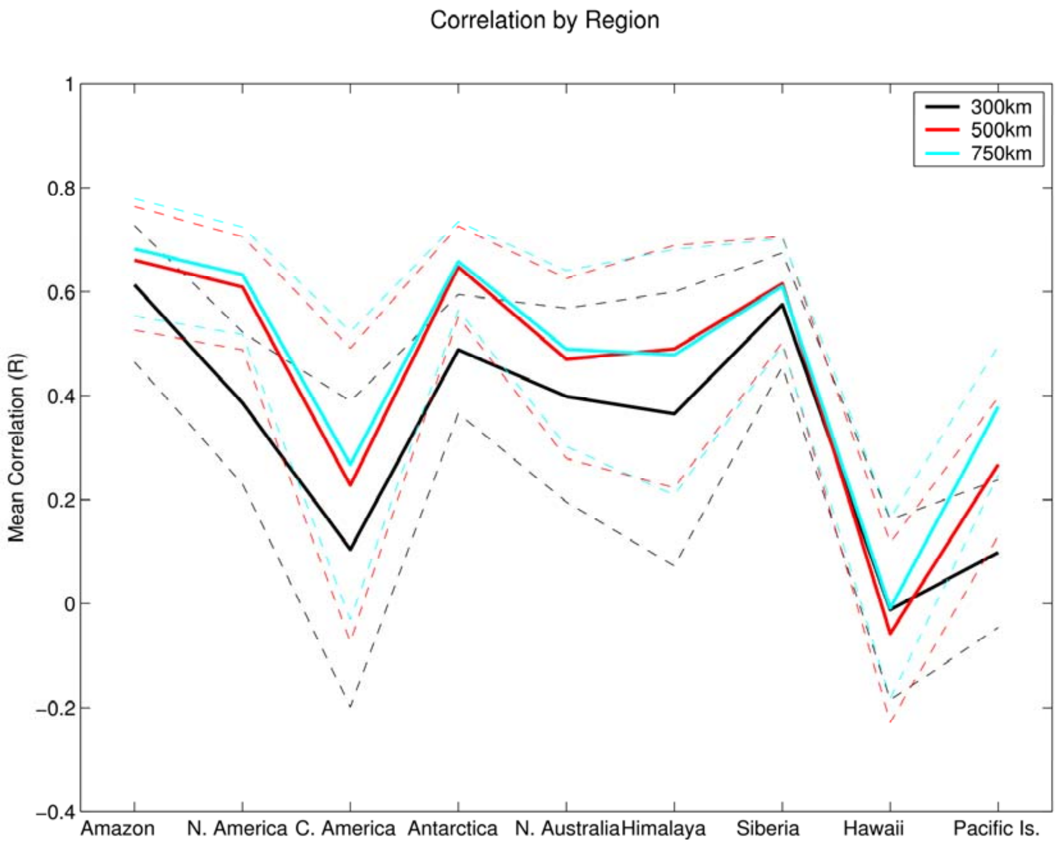

Figure 5: Correlation between GRACE and GPS time series at different averaging radii, by region. 95% confidence intervals are shown as dashed lines.

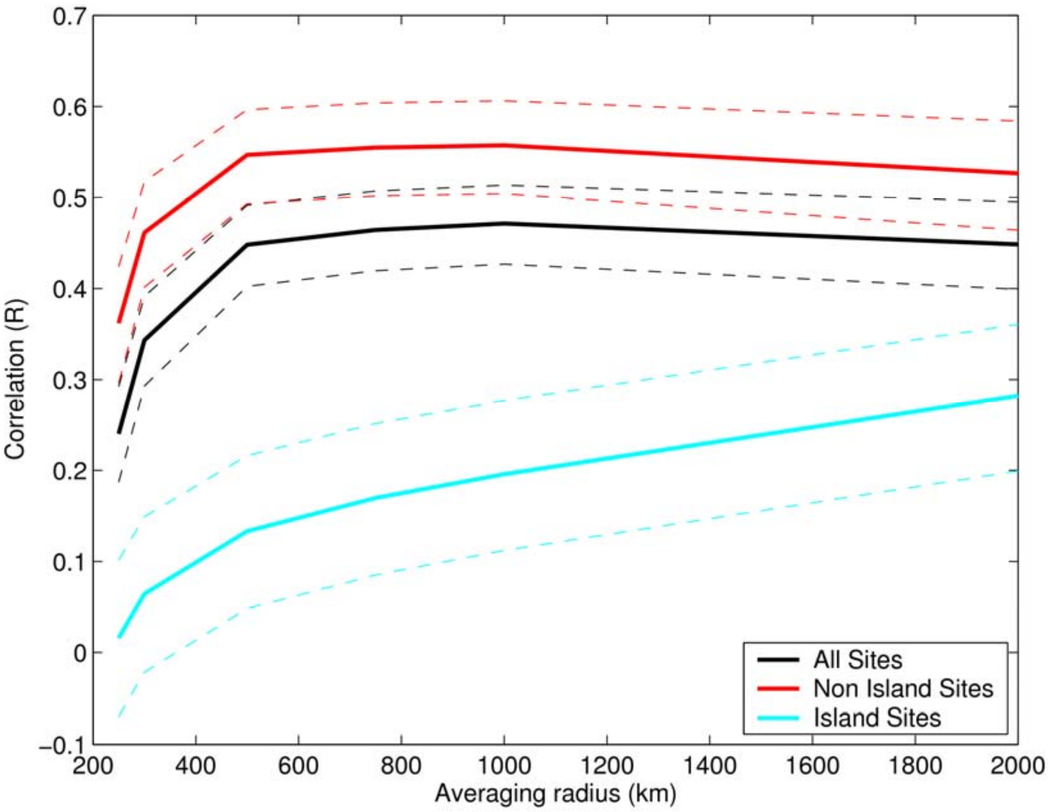

Figure 6: Correlation between GRACE and GPS time series at different averaging radii, by geographical setting. 95% confidence intervals are shown as dashed lines.

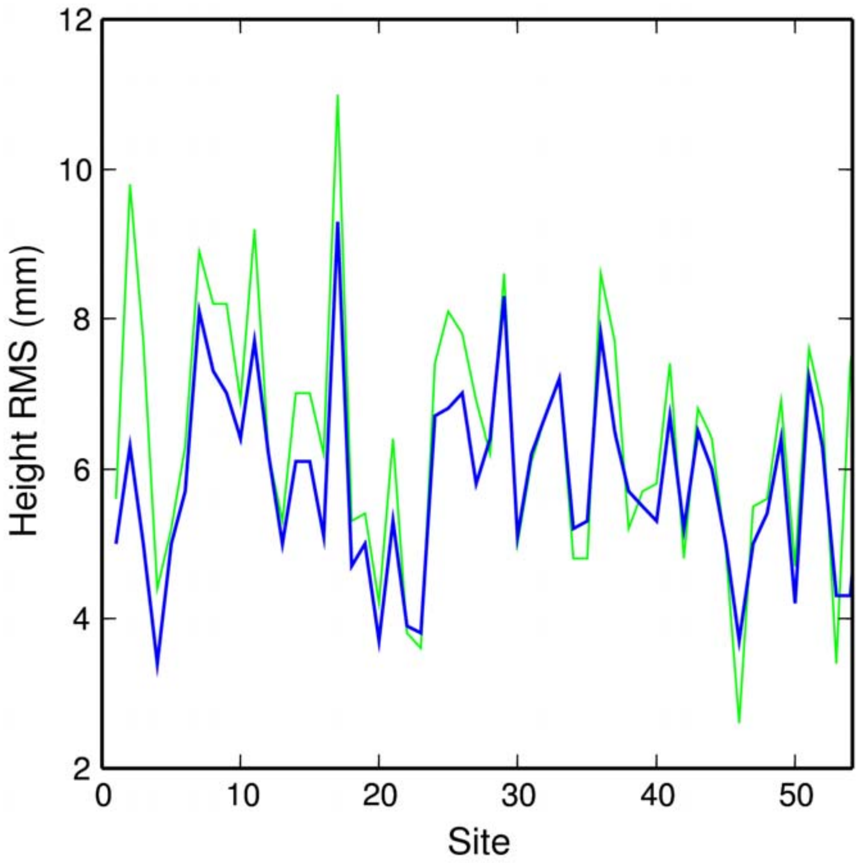

Figure 7: GPS height time series RMS before (green) and after (thick blue) the removal of the GRACE deformation time series for each site using a 750 km averaging radii.

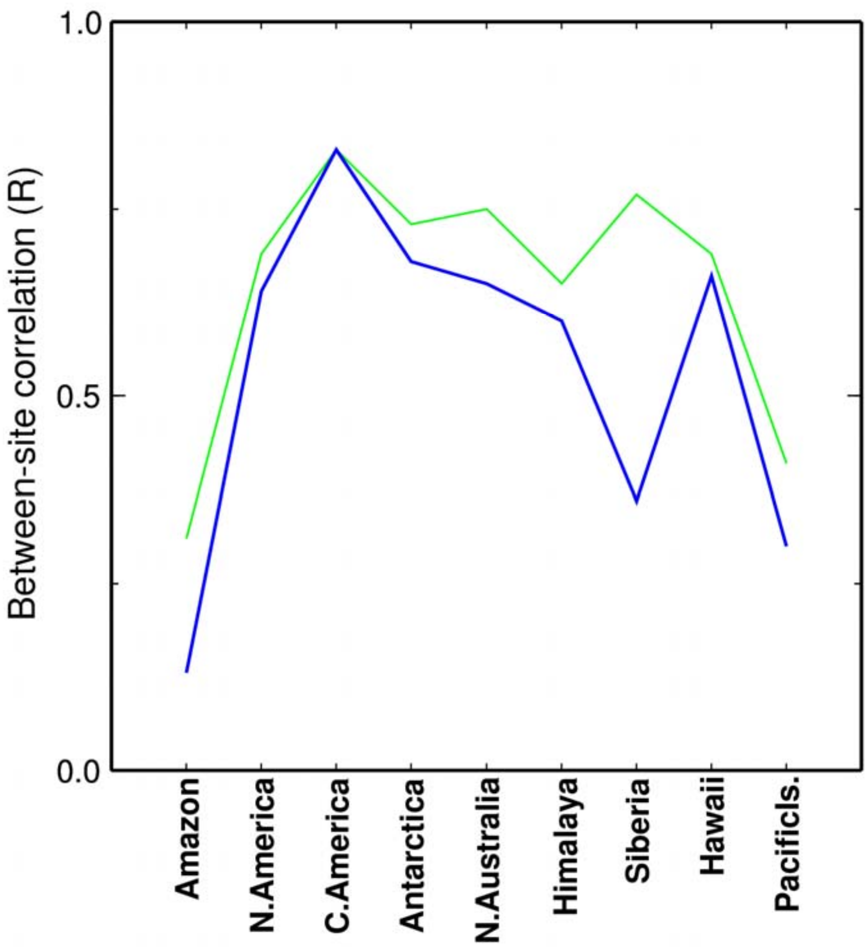

Figure 8: Average between-site correlations by region, before (green) and following (thick blue) the subtraction of the GRACE time series (750 km) from the GPS time series on a site-by-site basis.

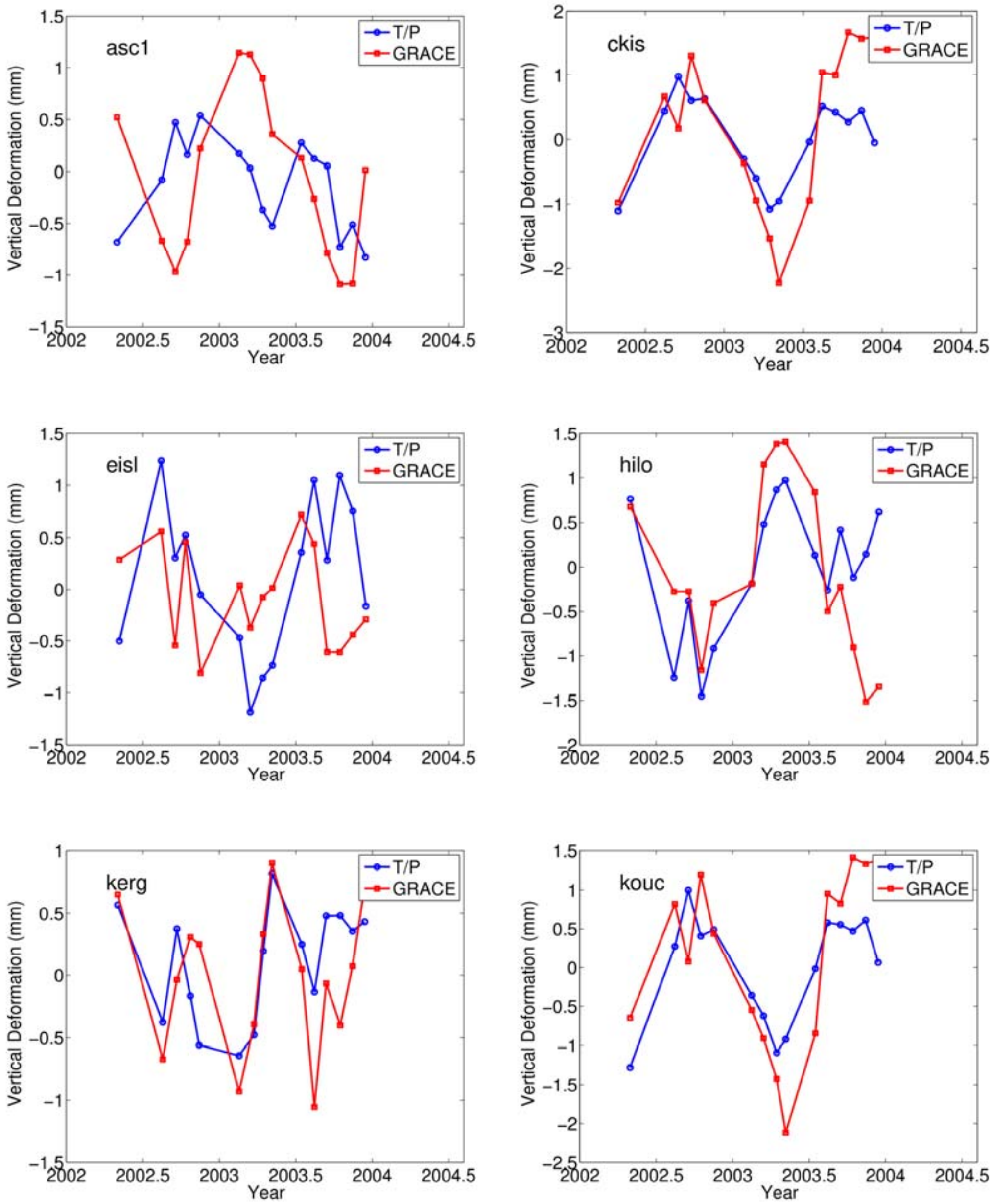

Figure 9: Representative vertical deformation time series from GRACE and T/P + climatology, using averaging radii of 2000km.

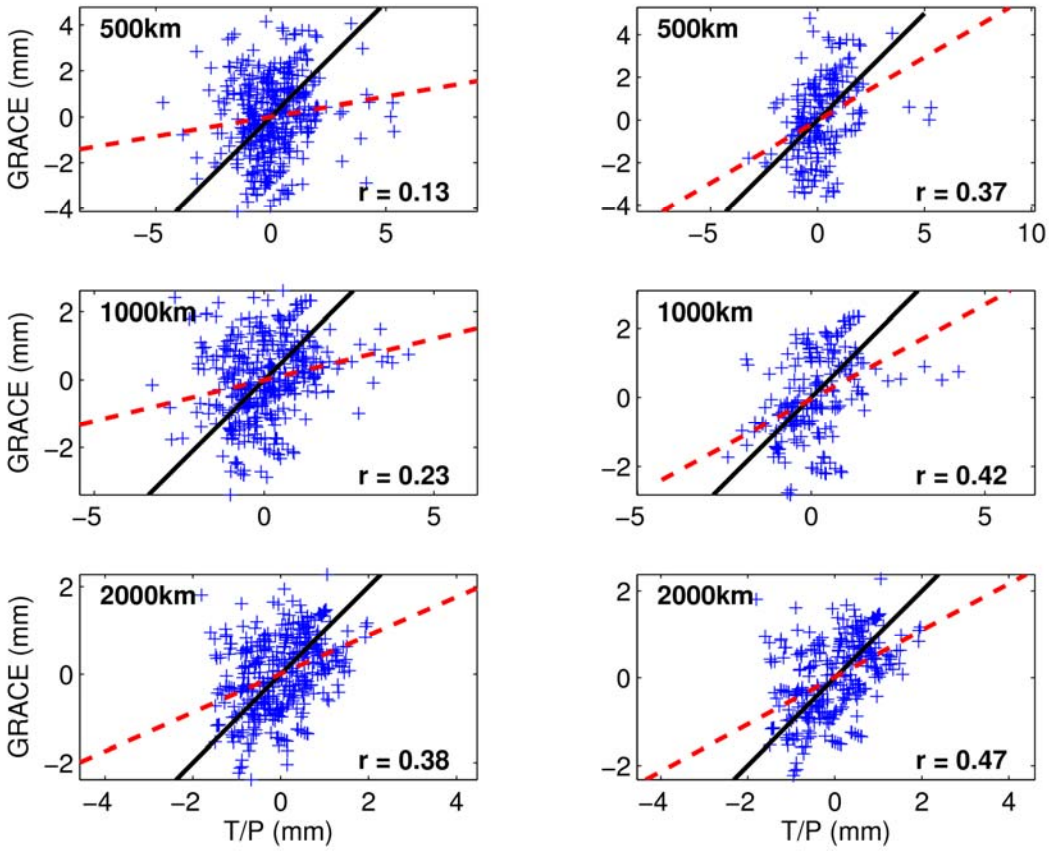

Figure 10: Correlation between GRACE and T/P time series' at different averaging radii using all sites (left) and after removing those sites that have low correlations (right).

Table 1: Details of the 22 CSR GRACE fields used in this study. Fields 3 and 16 contain Stokes coefficients to degree *l*=70, whilst the others contains coefficients to degree *l*=120.

Field No.	Year	Days	Excluded Days	# Days
1	2002	104-138	114,117,118,135	31
2	2002	213-243	222,238,240	28
3	2002	244-273	249,250,251,252,253,254,255,256,257,258,259,270	20
4	2002	274-304	280,281,282,283,284	26
5	2002	305-334	309,310,311,330	26
6	2003	035-059	039,044,051	22
7	2003	060-090	-	31
8	2003	091-119	106	28
9	2003	114-140	-	27
10	2003	182-212	203	30
11	2003	213-243	240	30
12	2003	244-273	263,264,265	27
13	2003	274-304	-	31
14	2003	305-334	327,328	28
15	2003	335-365	351	30
16	2004	001-013	-	13
17	2004	035-060	-	26
18	2004	061-091	-	31
19	2004	092-120	96,100,117	26
20	2004	122-152	140,145,146,147	27
21	2004	153-182	-	30
22	2004	183-213	-	31

Table 2: GPS site locations and regions. Small island sites are marked with a §.

Site	Lat	Lon	Region	Site	Lat	Lon	Region
algo	-78.07	45.96	N. America	laut§	177.45	-17.60	Pacific Is.
alic	133.89	-23.67	N. Australia	lhas	91.10	29.66	Himalaya
arc3	130.89	-12.42	N. Australia	lhue§	200.66	21.98	Hawaii
areq	288.18	-16.78	Amazon	mac1§	158.94	-54.50	-
artu	58.56	56.43	Siberia	mana	-86.25	12.15	C. America
asc1§	345.59	-7.95	-	maui§	203.74	20.71	Hawaii
aspa§	189.28	-14.33	Pacific Is.	maw1	62.87	-67.60	Antarctica
braz	312.12	-15.95	Amazon	mcm4	166.67	-77.84	Antarctica
cas1	110.52	-66.28	Antarctica	mdvo	37.22	56.03	Siberia
chur	-94.09	58.76	N. America	mikl	31.97	46.97	Siberia
ckis	159.80	-21.20	Pacific Is.	mkea§	204.54	19.80	Hawaii
coco§	96.83	-12.19	-	mobn	36.57	55.11	Siberia
cuib	-56.07	-15.56	Amazon	naur§	166.93	-0.55	Pacific Is.
darw	131.13	-12.84	N. Australia	noum§	166.41	-22.27	Pacific Is.
dav1	77.97	-68.58	Antarctica	nvsk	83.24	54.84	Siberia
dubo	-95.87	50.26	N. America	ohi2	302.10	-63.32	Antarctica
eisl§	250.62	-27.15	-	palm	295.95	-64.78	Antarctica
fale§	188.00	-13.83	Pacific Is.	pngm§	147.37	-2.00	Pacific Is.
flin	-101.98	54.73	N. America	pohn§	158.20	6.97	Pacific Is.
glsv	30.50	50.36	Siberia	polv	34.54	49.60	Siberia
goug§	350.13	-40.35	-	reun§	55.57	-21.21	-
guat	-90.52	14.59	C. America	samo§	177.73	-13.85	Pacific Is.
hilo§	204.95	19.72	Hawaii	sch2	-66.83	54.83	N. America
hnlc§	202.14	21.30	Hawaii	syog	39.58	-69.01	Antarctica
impz	-47.50	-5.49	Amazon	thti§	210.39	-17.58	-
jab1	132.89	-12.66	N. Australia	tong§	-175.16	-21.15	Pacific Is.
kerg§	70.26	-49.35	-	tuva§	179.20	-8.50	Pacific Is.
kiri§	172.92	1.35	Pacific Is.	vanu§	168.30	-17.75	Pacific Is.
kokb§	200.34	22.13	Hawaii	vesl	357.16	-71.67	Antarctica
kouc§	164.29	-20.56	Pacific Is.	yell	-114.48	62.48	N. America
kour	307.19	5.25	Amazon	zwen	36.76	55.70	Siberia
kunm	102.80	25.03	Himalaya				