Validation of GRACE Data Using GGP stations from Europe and Asia

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Abstract

We consider the validation of GRACE satellite data by ground gravimetry from the Global Geodynamics Project (GGP). Results are presented for central Europe, where 7 superconducting gravimeter stations have been operating through the period of GRACE (mid 2002 to present); our comparison extends previous results to the end of 2006. While the overall agreement between GGP and GRACE is consistent with the seasonal hydrology predicted by GLDAS model, many features in the gravity data differ in amplitude and phase. Using EOF decomposition, the amplitude of GLDAS is generally higher than GRACE, and much higher than the ground GGP signal. This is partly due to processing, but a major factor for the GGP data is the location of stations under the soil moisture horizon. This complicates the comparison with GRACE data. We also for the first time consider the small network of GGP stations in the Japan-Korea-China-Taiwan area, and find that the GRACE seasonal effect is complex. Good correlation between GLDAS and GGP exists for some stations, in particular Wuhan and Matsushiro, but again the phase inversion is apparent. It is clear that problems introduced by the coastlines in this part of the world will make validation even more difficult than in Europe.

Keywords: Superconducting gravimeter, GRACE, hydrology, GGP, GLDAS

Introduction

To readers of BIM, the topic of ground validation of GRACE data is no doubt familiar. Some recent papers include Crossley (2004), Crossley et al. (2004), Crossley et al. (2005), Andersen et al. (2005), Andersen and Hinderer (2005), Hinderer et al. (2006), and Crossley et al. (2007a, 2007b). GRACE satellite gravity data has been used extensively for estimating the variability of continental hydrology, especially in locations of high rainfall, but also in areas such as the US Midwest where ground hydrology is well observed (Swenson et al., 2006). The data has also been compared to the ground deformation produced by the Sumatra-Andaman earthquake of 2004 (e.g. Lambotte et al., 2006; Han et al., 2006; Panet et al., 2007). In both instances, evidence has shown that the satellite gravity field is consistent with the predicted models, based on global land assimilation models and observed ground soil moisture in the first case, and on seismic observations in the other. Yet in neither case has the same type of data been compared, i.e. surface gravity data derived from GRACE with gravity observations on the ground.

Given the size of the anticipated signal (typically a few microgal), the only instrument that is reliable at the microgal level is the superconducting gravimeter (SG), which is the main instrument of the GGP network. Unlike other studies of the two gravity data sets, we choose not to do a station-by-station comparison between GRACE and GGP data because we believe the satellite data cannot be compared directly to point measurements on the ground. Our approach has been to combine the data from several SGs that cover an area that is comparable to the highest resolution satellite projections on the ground (about 500 km). The technique is a principal component analysis, equivalent to the use of empirical orthogonal functions (EOFs) for time varying spatial data.

In this paper we summarize the result from the European array and compare the different GRACE solutions with the GLDAS hydrology and the GGP data. A more extended paper that includes data to the end of 2007 is being prepared for publication elsewhere. In addition, we here take a look at the possibilities for using the SGs in NE Asia, as they are the only group outside Europe that could be used as an array for comparison with GRACE data - all other SG stations are too isolated for such a purpose.

GGP Data

The data is the same as used previously, that is the ICET GGP database 1 minute data, uncorrected (code '00'), but extended here to the end of 2006. There are 7 SGs located in central Europe: Bad Homburg (BH) near Frankfurt in Germany, Membach (MB) east of Brussels, Medicina (MC) in Italy and south of the Alps, Moxa (MO) near Jena, Germany, Strasbourg (ST) in eastern France, Vienna (VI) which has now stopped recording, and Wettzell (WE) in eastern Germany, a major fiducial geodetic station. These are shown in Figure 1, together with the grid area used for all the comparisons. As can be seen, the GRACE footprint of 500 km is comparable to the average station spacing, but the small number of SG sites even in Europe does little to properly average the regional hydrology.

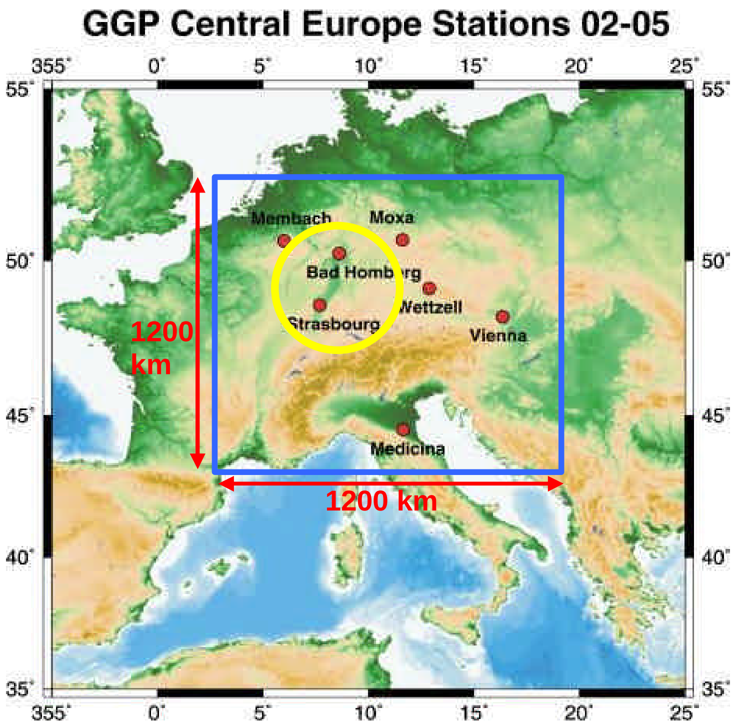

Figure 1. GGP stations recording during the GRACE satellite mission. The blue rectangle is the area for gridding and the yellow circle is about 500km, a typical ground resolution for GRACE.

The processing of the SG data is standard. We subtract a local synthetic tide, including ocean tide loading, local atmospheric pressure with a 2-D global correction for a nominal vertical temperature distribution, and remove IERS polar motion. The residual series has offsets and disturbances that must be removed; this we do with the consultation of the various station operators to ensure that the offsets are not geophysical in origin (e.g. rapid hydrology changes). The

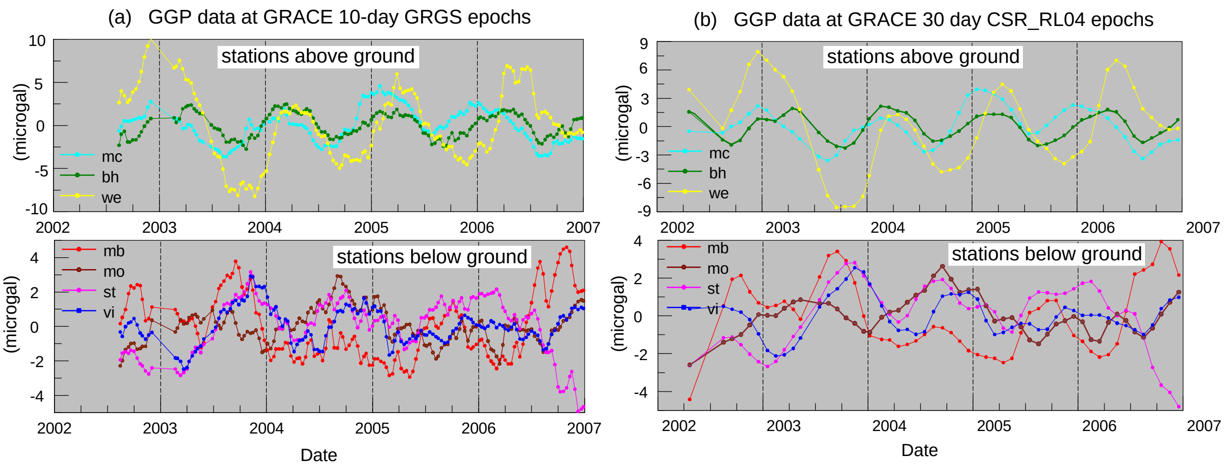

Figure 2. GGP data resampled to: (a) GRGS, and (b) CSR epochs as for the GRACE solutions. The stations are separated according to the location of the soil moisture level.

algorithm for correcting offsets includes an estimate of a linear trend to allow for data gaps during which a trend needs to be continued. After decimation to 1 day samples, the GGP data is resampled to the time periods of the GRACE data, which is about 30 days for the CSR and GFZ solutions, and 10 days for the GRGS solutions (see below). The series are then separated according to whether the SG is located at ground level (the local soil moisture), or below the surface, as shown in Fig. 2. Note that stations above ground level show simultaneous high readings in winter, but low values in summer, even though they may different somewhat in the phase (by up to a month). The 4 stations below the soil moisture level show more complex behavior, but predominantly they have a reversed phase (or sign); this is best seen in the 30-day smoothing (Fig. 2b). Station Moxa is the most complex, as is well known from many other studies. Note that the Strasbourg and Membach gravity diverge notably toward the end of 2006.

The SG series are interpolated to a grid of 65 x 49 cells, spacing 0.25°, using a robust minimum curvature algorithm. Then we perform an EOF decomposition of the spatial data on the grid at each time sample point (GRGS or CSR) and extract the top eigenvalues and their associated eigenvectors. This is a technique that allows the predominant temporal and spatial information to be quantified in the most efficient way and effectively combines the SG data over the map area for comparison with GRACE.

GRACE Data

Again we used the CSR (Texas) and GFZ (Potsdam) GRACE solutions, in Release 04 version, from mid 2002 until the end of 2006, as well as the GRGS (Toulouse) 10-day solutions. The latter are not just a 10-day coefficient solution, but to reduce noise each nominal sample is obtained from running sum of 3 raw 10-day solutions, with weights (1,2,1) indicating double weight for the central time. The mean value of the data (reference level) has been removed, and we note also the degree 2 component has been treated differently according to each data source. No temporal trend was removed from the GRACE data.

To match the effective filtering of the GRGS solutions, the ground level data from GRACE was computed with a cosine taper between degrees 20 and 40, as tapering between degrees 30 and 50 left too much noise in the data. This is designated for example as CSR24. A second solution was computed using a Gaussian weighting function of the spherical harmonic coefficients. We used 350 km as the more useful radius, whereas previously we had tried 500 km and found the surface field to be too smooth for this area. Solutions are designated for example as GFZ350. The gravity field is computed using the radial derivative of the potential at the surface, but we did not here correct for the effect of vertical station displacement which requires an additional loading factor in the computation of GRACE gravity. Recent calculations suggest that a multiplicative factor of about 1.32 should be applied to the satellite gravity to make the appropriate comparison between GRACE, GGP and hydrology, as done by Neumeyer et al. (2006) and de Linage et al. (2008).

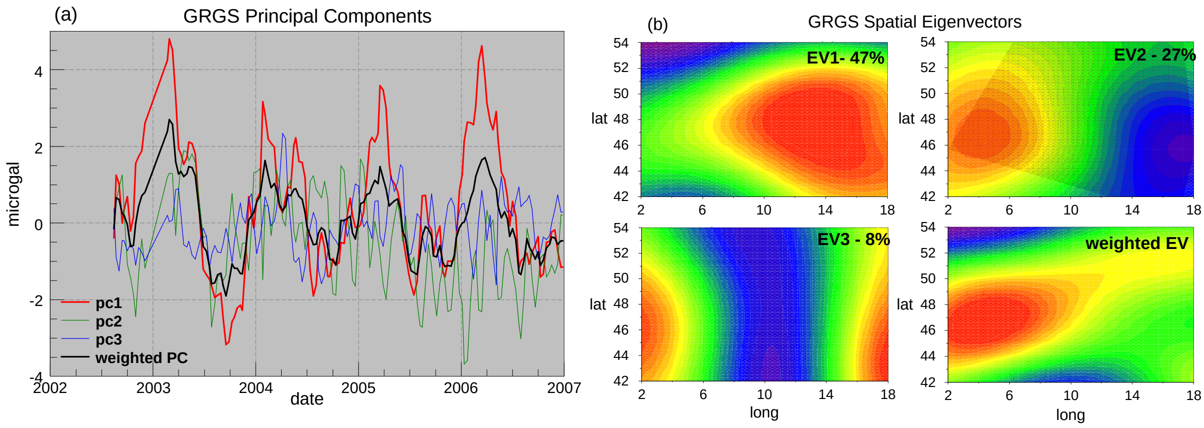

Figure 3. EOF decomposition of the GRGS GRACE field 2002-2006: (a) the first 3 principal components, and (b) the corresponding eigenvectors and variance reduction. The weighed solutions are described in the text.

Figure 3 shows the first 3 eigenmodes of the GRGS field for Europe. The first eigenvalue accounts for 47% of the variance reduction of the data, the second for 27% etc. Each principal component (PC) is a temporal eigenvector that has a corresponding spatial eigenvector (EV). Figure 3a shows that PC1 dominates the decomposition and corresponds to a large annual signal. The third PC has very little coherence and its EV is quite different to the first EV. Also shown is the weighted PC and EV, which are obtained by taking the sum of the first 7 individual PCs (and EVs) weighted by the corresponding eigenvalue (these account for > 95% of the variance reduction). The weighted solutions are an attempt to show, in a single principal component and eigenvector, the relative complexity of the time and spatial components of the data set.

GLDAS Hydrology

One of the most widely used global continental hydrology models is GLDAS/Noah (Rodell et al. 2004). The model is based on the meteorological forcing from rainfall, snowfall and energy fluxes that appear as soil moisture, evapotranspiration, canopy water and snow cover. The only missing part is the surface water (runoff, rivers, etc.). The sum of soil moisture and snow cover is used as a loading mass to compute the gravity effect. One component of gravity is mass attraction of the soil moisture layer, and we separate the local effect (at the station, effectively a delta function load) from the rest of the attraction that is considered regional. The second component is crustal loading that is not subdivided because it represents the overall deformation of the ground in response to the water load.

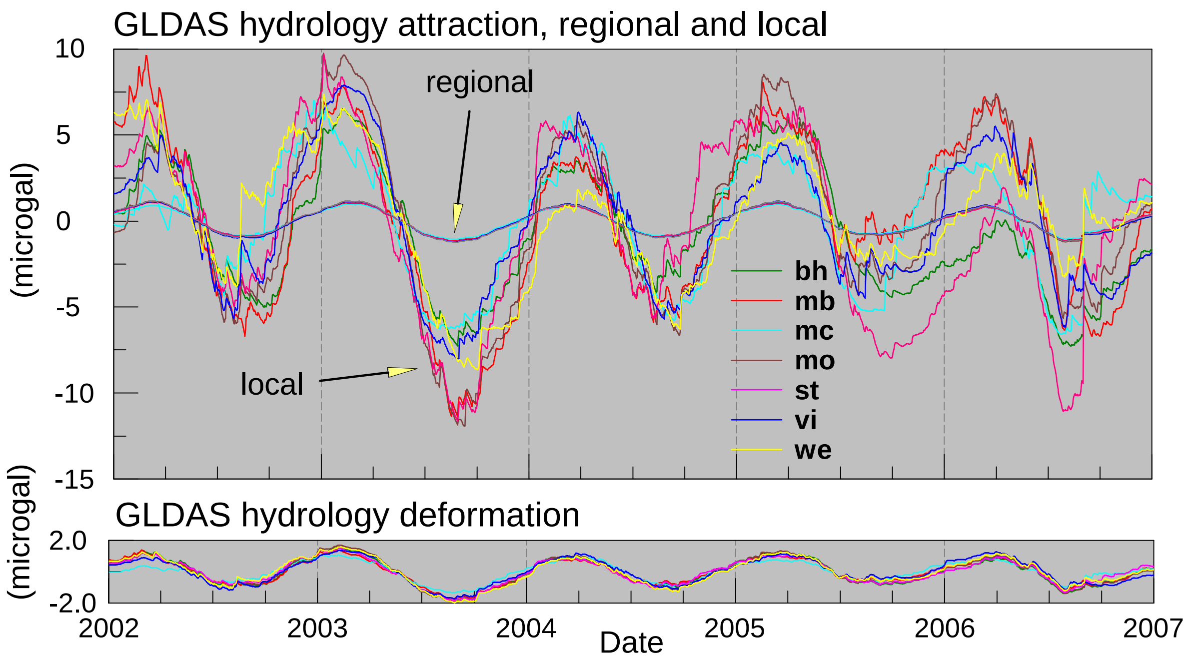

Figure 4. Components of the gravitational attraction and loading at GGP sites from the GLDAS hydrology model. The attraction is given for both the local effect (delta function at station) and for the remaining contribution (regional).

Figure 4 shows that the local attraction dominates the gravity effect at each station, and also the regional attraction and loading deformation are approximately the same; all components are in phase. This separation of the loading is a useful indicator of the extent to which hydrology needs to be accounted for if the SG is below the soil moisture level, in which case the sign of the local attraction is reversed. This assumes all the soil moisture is above the instrument, which is not always the case, especially for Moxa. The GLDAS data is also resampled to the GRACE GRGS and CSR epochs, and then the same minimum curvature grid is generated as for the GGP data.

EOF Comparisons

We now compare the 3 types of data using the EOF analysis of each data set. One feature of the decomposition is that the principal components are not affected by the relative phases of each station, so the combination of SGs being above and below ground level (Figure 2) does not reduce the amplitude of the time variation, as seen in Figure 5(a). It is also apparent that the GLDAS amplitude is significantly larger than either the GRACE or the GGP signals. In the case of GRACE, this would be compensated by the inclusion of the vertical effect mentioned earlier (factor 1.32). In the case of GGP the PC1 is reduced because only 3 of the 7 stations have a clear hydrology signal below the station, and the other 4 stations have a mixed signal that reduces the amplitude of PC1. The data for Moxa contributes little to an annual signal, either positive or negative.

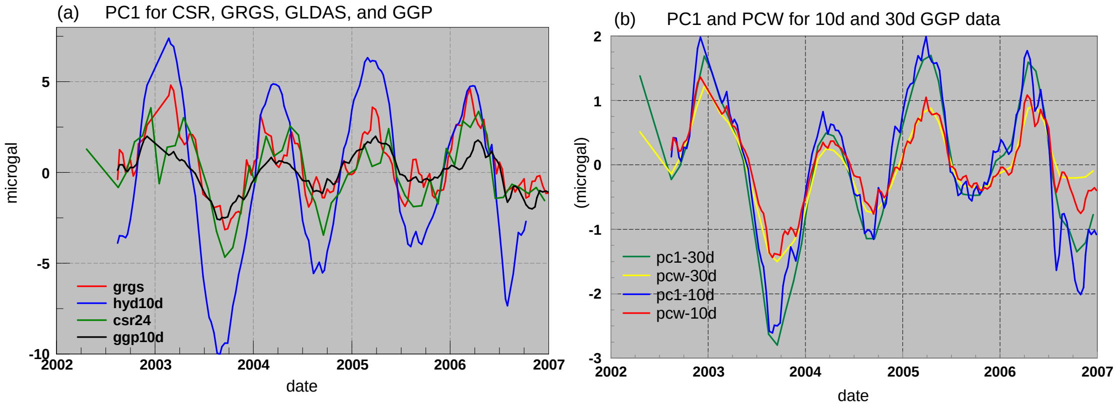

Figure 5. Comparison of the first PC for (a) representative data sets, and (b) the effect of weighting the eigensolutions for GGP data.

We show in Figure 5(b) the difference between PC1 and the weighted PC for both the GRGS and CSR solutions. The weighted PC has less amplitude because it contains components of the other eigenmodes that do not contain the annual component. The first EV and weighted EV for the 30 day GGP residuals are shown in Figure 6. It is clear that the 3 stations above ground are positive (green/red) and those below ground are negative (blue). The weighted EV is somewhat different due to the complexity of the response from other eigenmodes, as for the weighted PC.

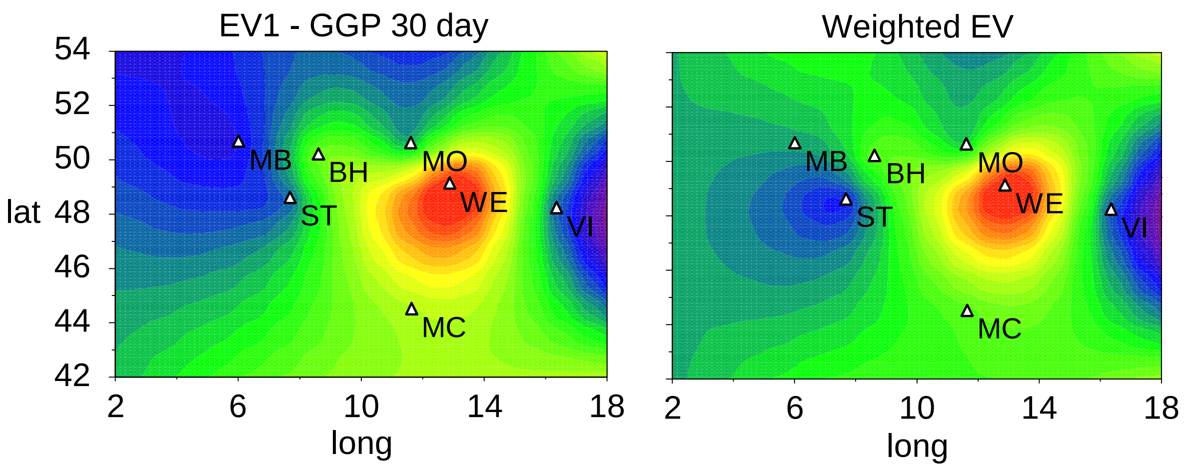

Figure 6. Comparison of the first EV and the weighted EV for the GGP data sampled at 30 days. Note that stations below ground have a negative polarity.

One of the reasons we would like to use GGP data is to verify not only GRACE data solutions, but also their comparison with GLDAS. At times when the GRACE solutions diverge from each other and from hydrology models, can GGP supply additional information? To answer this we show in Figure 7 a comparison between all solutions for two time periods, called anomaly 1 and anomaly 3. In the first case, the winter of 2003, GLDAS and GRGS solutions are both positive, whereas the CSR and GFZ solutions dip down. The corresponding GGP data has low amplitude but suggests no dip, perhaps supporting GRGS and hydrology. In late summer of 2005 the CSR solutions follow the hydrology, but the GRGS shows a positive peak. GGP solutions appear to follow better the GRGS, but are of the same sense as the CSR and hydrology, though obviously of weaker amplitude.

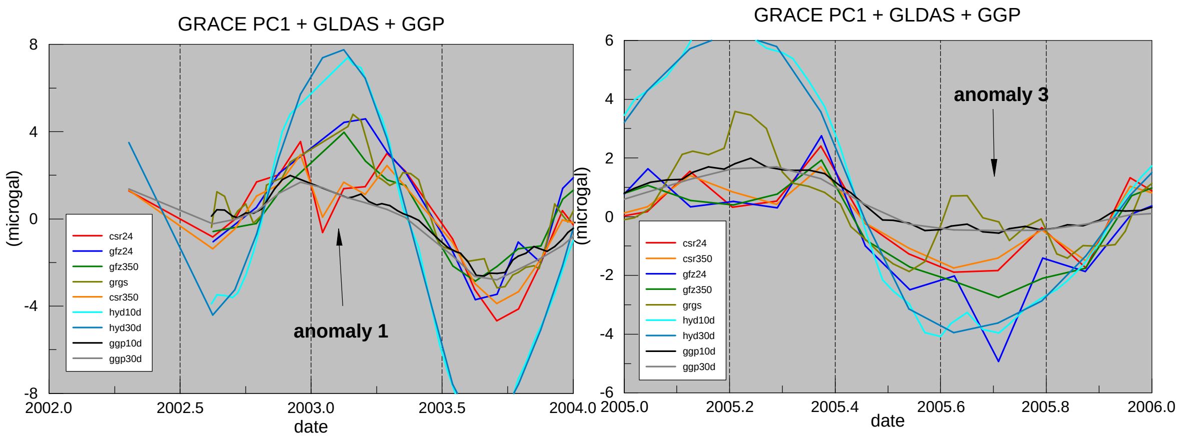

Figure 7. Details of two anomalous epochs (2003, left and 2005, right) where some of the GRACE solutions and GLDAS do not agree.

ASIA network

The only other group of GGP stations that could be used in the GRACE validation is in NE Asia (Figure 8). At the present time only 4 of the stations are supplying data to ICET: Esashi (ES), Matsushiro (MA), Kamioka (KA), and Wuhan (WU). Note that the area covered is much larger than for Europe, and the number of available stations is even smaller (especially at the present time). A further complicating factor is the relative size of GRACE averaging compared to available land areas.

Nevertheless, we processed the data for the 4 stations as for Europe, and show in Figure 9 a comparison between the GGP data and the GLDAS hydrology.

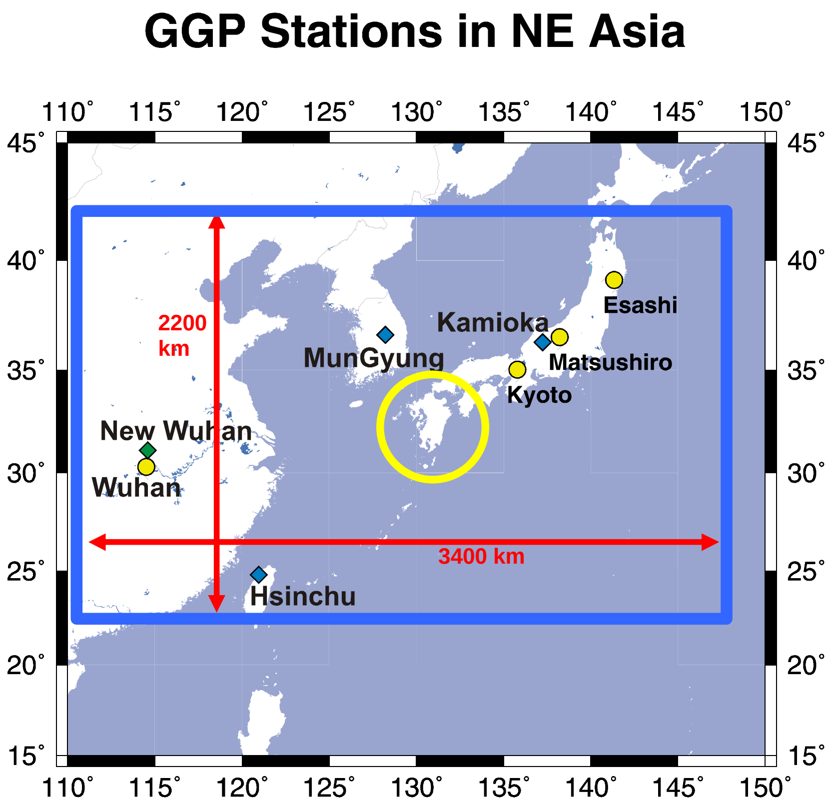

Figure 8. GGP stations in Asia for comparison with GRACE satellite data. The blue rectangle is much larger than for Europe, and the yellow GRACE target size necessarily includes ocean areas around the sites in Japan, S. Korea, and Taiwan.

There are clear annual periods at WU and MA, correlated with hydrology. WU is nominally a surface station, but partly set into a hillside according to Xu et al. (2008); they indicate there is a 1 m layer of soil on the rooftop that might serve to invert the signal for soil moisture. Station MA has been studied extensively for hydrology by Imanishi et al. (2006) who found the typical inverted response for an underground station. The situation is similar at KA, where the station is deep underground at the neutrino test facility and irregular snowfall leads to a variable seasonal signal (Imanishi, personal communication). Station ES, also underground, shows some characteristics of the inverse relationship with hydrology, but the latter part of the record in 2006 clearly needs the removal of more disturbances to reveal the hydrological signal.

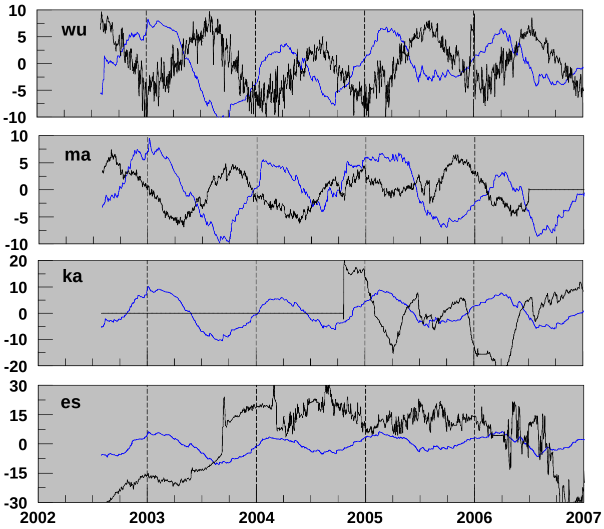

Figure 9. GGP residuals (black) and GLDAS hydrology (blue) for four stations in Japan and China. Data from Kamioka (KA) and Esashi (ES) probably require further processing for instrumental offsets.

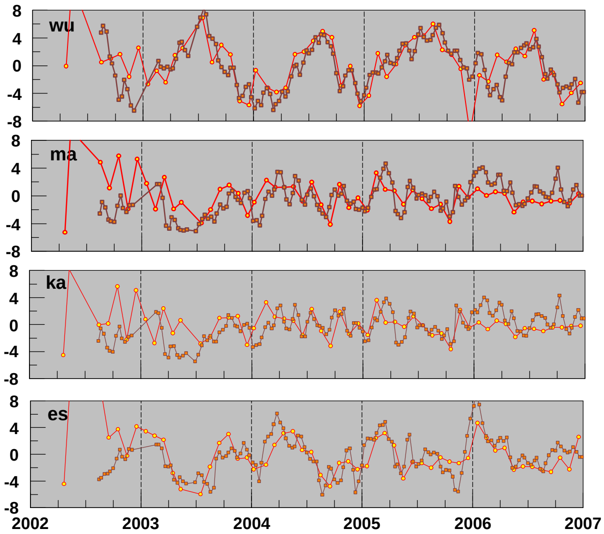

Figure 10. GRACE solutions CSR24 (red) and GRGS (brown) interpolated to GGP ground stations.

The GRACE data, interpolated directly to the four station locations, is shown in Figure 10. Only WU has a clear seasonal variability because it is well within the continental land mass, but curiously the expected phase is different from the GLDAS model – we are currently investigating the cause for this. The Japanese stations show little seasonal signal from either of the two GRACE solutions, no doubt because of the leakage of the signal due to the inclusion of the ocean (which yields no obvious hydrology signal, but there is a pressure loading).

Finally, we also show in Figure 11 the EOF decomposition of 3 of the GRACE solutions plus GLDAS hydrology. The variance reduction for the top 3 GRGS modes is only 30, 12, and 10% respectively, with similar results for the CSR and GFZ solutions. Clearly the PC1 is messy, but there is some correlation between GRGS and GLDAS. The spatial map (EV1) is also complex, caused by the mixture of land and ocean areas evident in Figure 8. We are not yet ready to say anything about the spatial coherence of the GGP data.

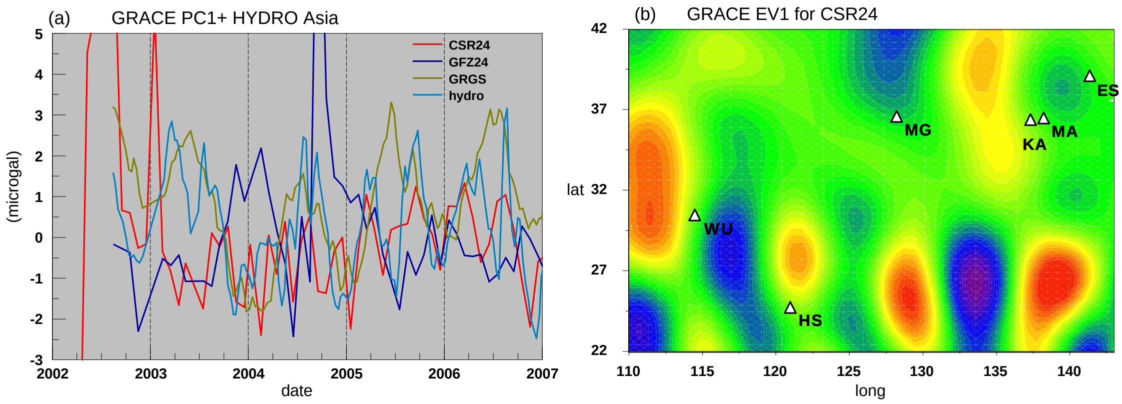

Figure 11. EOF solutions for NE Asia: (a) PC1 for 3 different GRACE solutions + GLDAS hydro, (b) EV1 for the CSR24 field.

Discussion and Conclusions

For the European data, the seasonal effect is well established up to the end of 2006, but the processing here lacks the vertical displacement that is handled by including a correction to the GRACE processing (e.g. Neumeyer et al. 2006; de Linage et al. 2008). A correction for the 3-D mass attraction of the atmosphere is also required, and we need to add data for 2007. All these deficiencies are being addressed in a more complete treatment of the European data in preparation.

As for the Asia data, there are still corrections to be added to the GGP processing, such as a 3-D atmosphere and the vertical loading effect, as well as more careful scrutiny of the station offsets, especially for Esashi. Nevertheless, we have now shown that the outlook for using the Asia stations as a network for GRACE comparisons is going to be difficult. This is, for the stations located in Japan, due to the leakage of the continental signal in the ocean and the very small land surface compared to the GRACE footprint

Acknowledgments

We thank the GGP station operators for supplying the data to ICET for this paper. Also, we appreciate discussions with C. Kroner (GFZ) and H. Wziontek (BKG) for supplying comments on offsets. Y. Imanishi provided useful comments on Matsushiro and Kamioka, but otherwise any errors in the Asian stations are a result of our own processing. This material is based upon work supported by the National Science Foundation under Grant No. 0409381, and CNRS (French Research Ministry).

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