Status of the GGP Satellite Project

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Abstract

As has been recognized for several years, attempts to validate GRACE satellite data using any kind of ground data immediately runs into the problem of horizontal scale lengths. Over Europe we have only 7 GGP stations operating since GRACE observations began and these are insufficient to give more than a simple averaging of local hydrology variations. Yet the approach from averaging ground stations is conceptually correct and would be effective if we had numerous stations all situated at the ground / atmosphere interface. Here we review how a combination of surface and underground stations (i.e. those measuring gravity below a local soil moisture horizon) can be used to validate satellite data. We show results from several GRACE models with the European GGP data since 2002.

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

Introduction

This study is a continuation of previous results from the comparison of ground and satellite gravity data over Europe that we began in 1989 (e.g. Crossley et al., 2003, 2004; Hinderer et al. 2006) and have subsequently called the GGP satellite project. The purpose of the early papers was to find a suitable method of averaging the ground gravity stations so they could be compared to the time-varying gravity fields produced monthly from the GRACE data (e.g. Wahr et al., 1998, 2004). In recent work we have also become aware of the need to modify our comparison with hydrology models (e.g. the GLDAS model of Rodell et al. 2004) according to whether the station lies above or below the local soil moisture horizon.

The question of averaging is characterized in Figure 1, which shows gravity stations located at the surface of the Earth. In the traditional view, used for example in atmospheric pressure modeling (e.g. Merriam 1992), gravity variations are divided into 3 zones of influence depending on distance from the station, Fig. 1(a). If this view is applied to the problem of hydrology variations, it suggests that to obtain a regional gravity field one should correct gravity stations for local hydrology. This is very difficult to do in practice because of the generally unknown nature of the subsurface porosity and permeability, as well as the profound effects of topography on the drainage and runoff from rainfall. In addition the storage of groundwater is a complex problem except in areas where the subsurface is geologically simple (e.g. perhaps sedimentary basins).

Fig. 1(b) is intended to suggest that a satellite averages all hydrology to arrive at a regional estimate. There is no distinction between L, R, and G, except in the averaging function implied in the sampling at an altitude of about 450 km (GRACE) and in the subsequent field reconstruction process for spherical harmonic coefficients or Gaussian averaging functions. Thus it has been our philosophy that a suitable average of ground-based stations should approximate a valid regional gravity field, without the necessity of making difficult decisions about how to subtract 'local' hydrology from ground-based, i.e. superconducting gravimeter (SG) measurements.

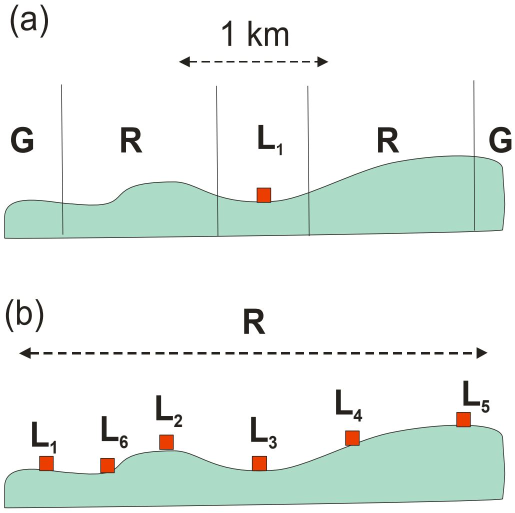


Figure 1. (a) The traditional division of a region around a gravity station into Local Regional, and Global sectors, compared to (b) the satellite averaging a sum of local gravity variations.

GGP Data

The data we use is similar to that described in previous publications (listed above). We have the 7 SG stations located within a region of approximately 1000 km in central Europe. Of these only Medicina (MC) is south of the Alps (Fig. 2). The difference is that now we are using data up to the end of October 2005, both from GGP and from GRACE. The GGP data has been stored at the ICET / GFZ database in Brussels and is freely available. It is 1 minute uncorrected data (i.e. just decimated from the original sampling). There are several approaches to processing the data for the current type of study, but the overriding factor is to correctly remove disturbances and offsets and this must be done with manual intervention, even when using a software package such as TSOFT.

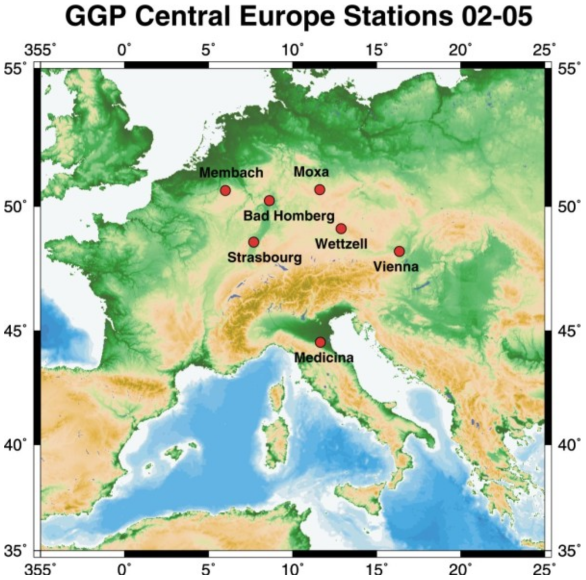


Figure 2. SG stations included in this study. Most have been in operation since 1997, and all since the beginning of GRACE (May 2002).

Here we use a traditional series of sequential processing steps: (a) fix all the problems in the local pressure data from the station, (b) construct and remove a synthetic tide based on local gravimetric factors (δ,κ) together with a nominal local pressure effect using a barometric admittance of -0.3 μGal hPa^{-1}, (c) replace obvious spikes, gaps and disturbances with a liner interpolation, decimate to 1 hr, (d) remove IERS polar motion, and (e) identify and remove offsets together with an overall linear drift function for each data set, and (f) decimate to 1 day and 1 month data sets.

Of the various processing steps, the most critical is the removal of offsets that if left uncorrected would render the time series unusable for this application. We carefully removed between 2 and 20 offsets per station (often verified with the station operators) and at the same time subtracted a linear drift between -4.1 and +3.2 μGal / year. This linear drift is mostly of instrumental origin but it does include any real tectonic gravity drift in the array. Only after the offsets and drift are corrected can we combine the data series from each of the sensors from the dual sphere instruments (BH, MO, and WE).

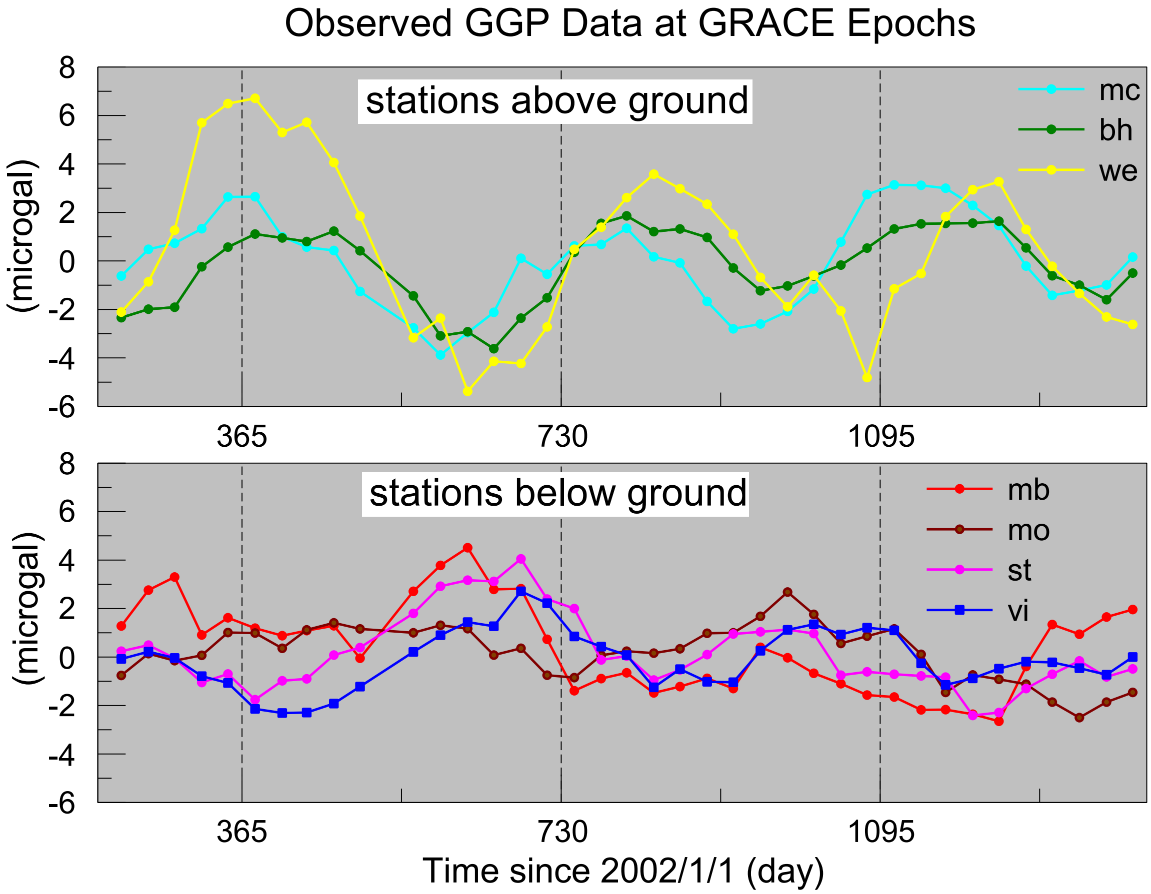


Figure 3. Residual SG data after processing described in text; stations are from Fig. 1.

The result is shown in Figure 3, in which we have grouped the stations according to whether the SGs are above or below ground level. It can be seen that a clear annual effect exists for all stations, although it is weak for station Moxa (MO) due to the complex hydrological situation (e.g. Kroner & Jahr, 2006). There are two small effects not accounted for in these residuals. The first is the 3-D atmospheric attraction, which reaches about 1 μGal amplitude (Neumeyer et al, 2004); we have most of the stations computed for this effect but not all of them for the whole time period, so elected to leave them out for the moment. The second effect is the vertical elevation effect that is sensed by the SG but is not in the GRACE data. The effect is quite small, about 1 μGal, but ideally we should use GPS data from each station to estimate this contribution. Again this data was not readily available for all stations.

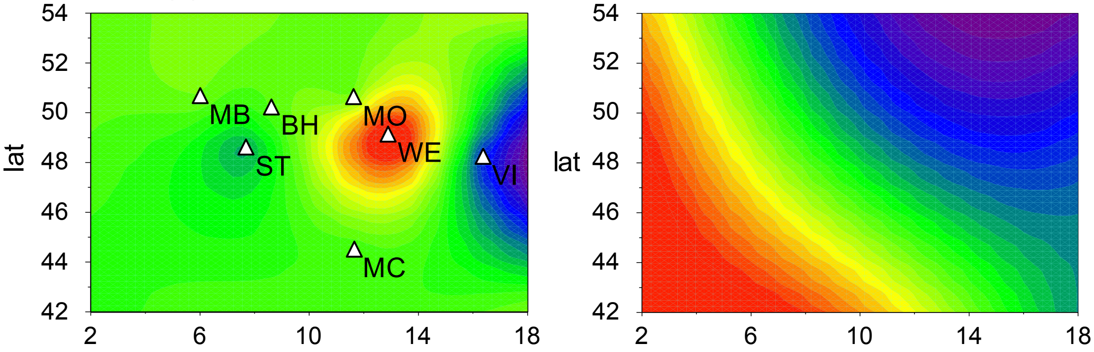
The spatial distribution of the GGP stations is so sparse that some means must be used to do appropriate space and time averaging for comparisons with the satellite data. We continue to use the minimum curvature algorithm to provide a surface at each 1 month epoch that has minimum distortion, and apart from inevitable edge effects, an appropriate average over the study area. The result for February 2003 is shown in Figure 4 (a). Note the phase difference between station WE that is above ground with VI that is below ground (the other stations are neutral for this month).

GRACE Data

We took the spherical harmonic coefficients provided by CSR Texas for the Level 2 solutions, both Release 1 and Release 2 fields (.e.g. Tapley et al., 2004). These were available from Apr/May 2002 until October 2005, and we elected to use Apr/May 02 as a reference level and took differences starting from August 2002. In all we had 38 data sets, specified at the 15th day of each month (missing June 2003). Instead of using the gravity anomaly supplied by GRACE, we computed the radial derivative of the potential field, called the gravity disturbance, on a 0.25° grid between latitudes 42-54° N and longitudes 2-18° E.

(a) GGP_min_contour

(b) GRACE_n=20_rel1



(c) GRACE_n=20_rel2

(d) GRACE_n=50_rel1

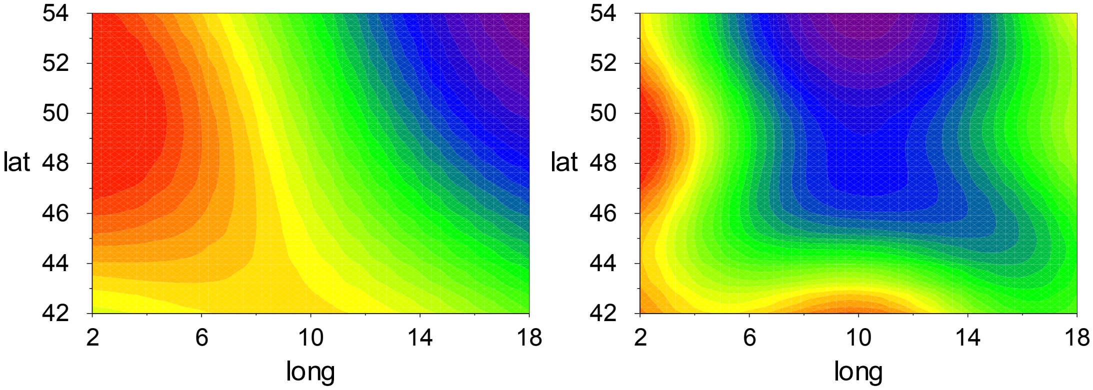


Figure 4. Gravity field over Europe for February 2003, each scaled independently (μGal) according to the ranges indicated: (a) GGP after smoothing [-4.6, 5.5], (b)-(d) GRACE Level 2 gravity disturbance (b) range [-5.4, 4.1], (c) range [-6.1, 4.8], and (d) range [-11.6, 9.4].

The Release 1 solution at a truncation of degree n=20 (about 1000 km), is shown in Figure 4 (b). Clearly the field is much more coherent that the GGP field and corresponds very little with the ground gravity. The Release 2 solutions incorporate some improvements in the processing (e.g. ocean tide models) that were added by the GRACE team retroactively, but only 22 months were available with this option. The first month available is February 2003, as in Figure 4 (c), which shows some differences from the Release 1 field but is of the same general character. Finally we experimented with a higher truncation of n=50 (about 400 km) for the Release 1 data, shown in Figure 4 (d). This field indicates more detail than n=20 and is consistent with the lower resolution data. Note, however, the scale of the n=50 solution is about twice that of the other GRACE fields and clearly much larger than the observed ground data.

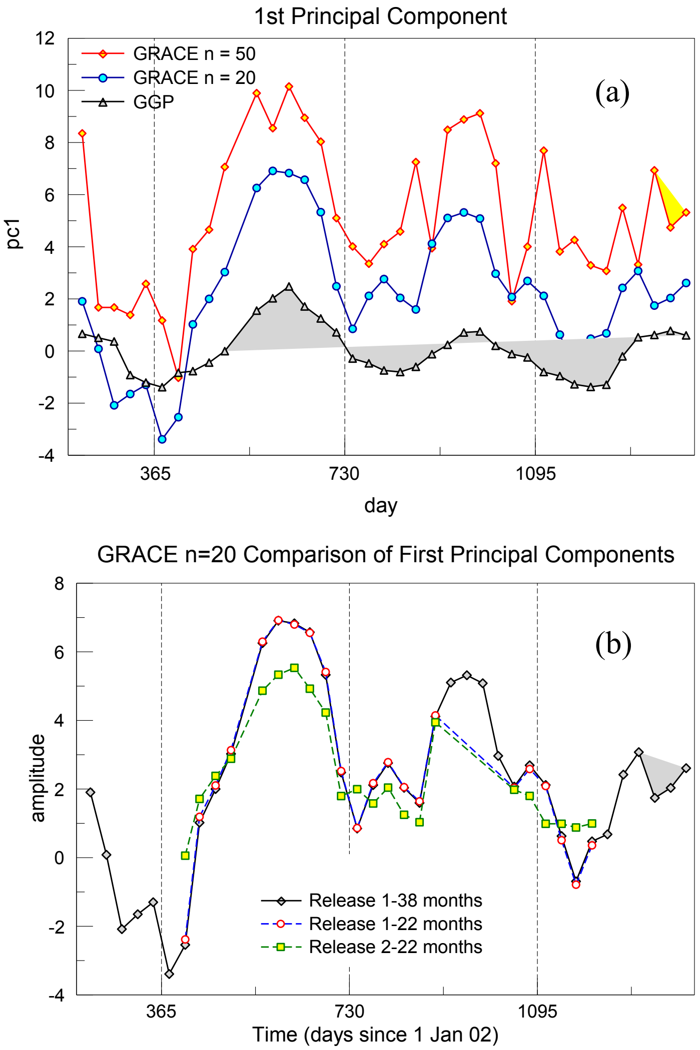


Figure 5. Principle components of the GGP and GRACE solutions showing that (a) the relative amplitudes show that GRACE tends to overestimate the ground- based values and (b) the use of only 22 months of GRACE solutions does not significantly change the EOF solution.

EOF Decomposition

A month-by-month comparison of the GGP and GRACE fields would clearly be of limited use, especially because of the different locations of the SGs with respect to ground level. We therefore turned to the EOF decomposition of the fields that characterizes them in terms of eigenfunctions (the spatial part) and principal components (the temporal part).

We show the first (largest) principle component of the EOF decomposition in Figure 5. The upper panel compares GRACE to GGP; note the good agreement on the phase of the annual variation but the differing amplitudes. Figure 5 (b) compares the EOF decomposition of the original 38 months (Release 1) with a restricted set from Release 2 (22 months) and the same months for Release 1. The latter 2 solutions are quite similar and consistent with the full data set, indicating the EOF solution is quite robust. Note the large dip in the variation at about day 365 (middle of the 2003

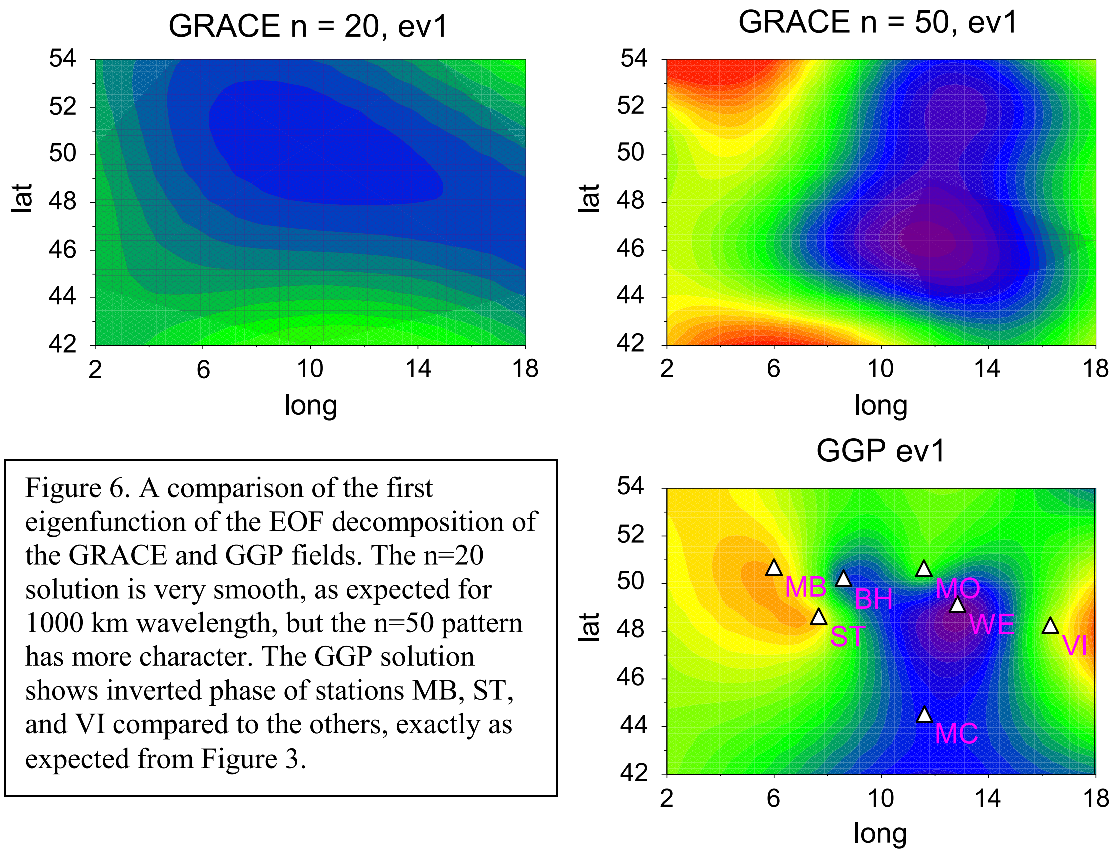


Figure 6. A comparison of the first eigenfunction of the EOF decomposition of the GRACE and GGP fields. The n=20 solution is very smooth, as expected for 1000 km wavelength, but the n=50 pattern has more character. The GGP solution shows inverted phase of stations MB, ST, and VI compared to the others, exactly as expected from Figure 3.

drought in Europe). Also we note the seasonal cycle seems to be getting weaker towards the end of the period in late 2005. This temporal behavior is better seen in the principal components than in simpler fitting of sinusoids as has been done elsewhere for the GRACE solutions.

The equivalent eigenfunctions are shown in Figure 6 for two of the GRACE solutions and for GGP. Despite the apparent similarity of the pattern for GRACE n=50 and GGP, this does not mean that the solutions support each other because the GGP pattern is clearly contaminated by the below-ground station effect. We also note that the eigenfunction of the Release 2 data is very similar to that for Release 1, n=20 (not shown)..

Each EOF decomposition can be assessed on the basis of the variance reduction when increasing numbers of eigenfunctions and principal components are included. This is shown in Figure 7 for the various solutions discussed above. Obviously the GGP solution is the most slowly convergent because of all the detail provided by the point-

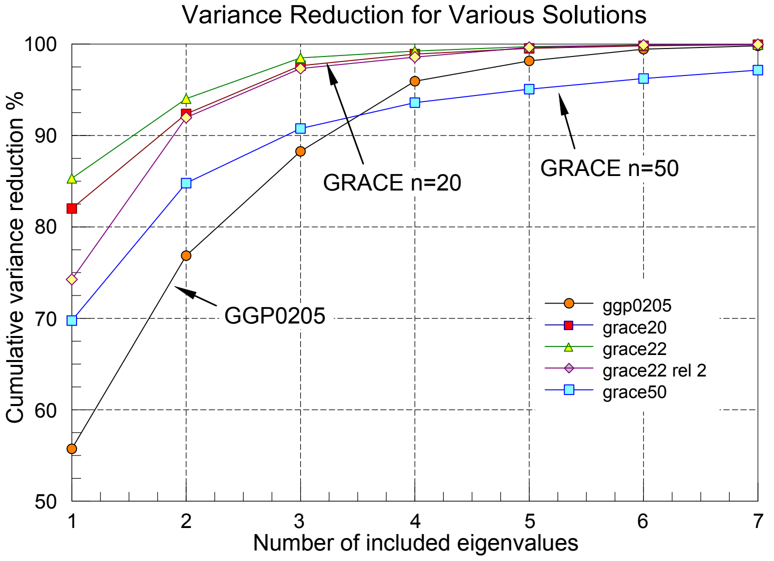


Figure 7. Variance reduction for the EOF solutions.

derived fields. It is also no surprise to see that the n=20 satellite solutions converge quickly due to the limited spatial resolution being comparable to our array size.

GLDAS Hydrology and Groundwater

Every study of the GRACE time varying solutions is compared to one or more versions of continental hydrology (e.g. LAD, Milly and Schmakin, 2002a, b; GLDAS, Rodell et al. 2004) and we do the same here. The GLDAS solutions are available at the NASA website and contain gridded solutions (0.25º) for soil moisture, snow cover, canopy water and other variables. They can be used directly for comparison with GRACE if the latter solutions are expressed in cm of water. The main difference for gravity is that the predicted water storage needs to be converted to a combination of loading (deformation) and Newtonian attraction where the location of the soil moisture with respect to the gravimeter must be correctly assessed. Our calculations show that the attraction can be further separated into a local effect, essentially a delta function right at the gravimeter, and a non-local effect (everywhere else). Of the 3 contributions to gravity, by far the largest is the local attraction (5-10 μGal for our 7 stations), and the deformation and non-local attraction are similar but smaller (1-2 μGal).

When combining these GLDAS effects we flip the sign of the local attraction for stations below the soil moisture horizon (MB, ST, and VI). The reason is that the soil moisture depth is usually only 1-2 m, and this is thin enough to place either completely above or below the SG. Station MO is partly above and partly below the soil horizon and the other stations (BH, MC, and WE) are above, or at, ground level.

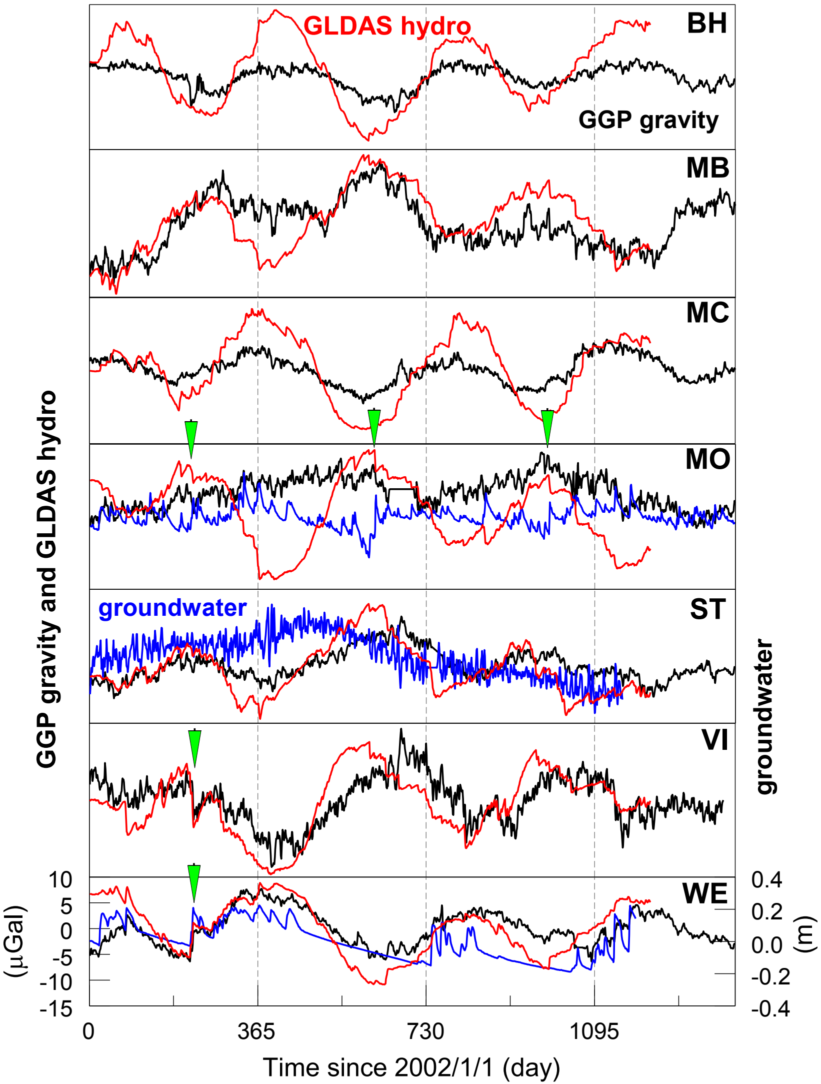


Figure 8. A comparison of GLDAS hydrology (red), SG gravity (black) and groundwater levels (blue) for each GGP station.

The resulting comparison is shown in Figure 8, together with the local groundwater data at 3 of the SG stations. Notice first that the GLDAS hydrology and SG gravity are very compatible in amplitude and phase for most stations. Second, the groundwater variations are not always a good indicator of the hydrology or gravity. The correlation coefficients for ST, MO and WE between groundwater and gravity are 0.05, 0.16, and 0.55 respectively; thus groundwater at ST has very little relation to either hydrology or gravity, whereas at WE the correlation is fairly high. This observation means that it is very difficult to 'correct' local hydrology at an SG site using groundwater data. Not only may the correlation be poor, but any admittance factor that is used will inevitably also respond to the soil moisture content that we would like to leave in the gravity residuals. Neumeyer et al. (2006) have shown some results from the point measurements and GRACE comparisons using this approach.

Finally we note that at the places marked by green arrows (Fig. 8), there is a significant offsets in all 3 signals, even at the same time at different stations. This indicates the widespread coherence of some rainfall and drainage patterns over several 100 km that is accurately captured by the SG measurements at widely separated point locations.

Hydrology Modeling

As in the past (Crossley et al. 1998) we prefer the empirical approach to modeling the hydrology at an SG station in terms of the 'leaky bucket' model with time constants. This was first used to good effect by Goodkind and Young (1991) and in later work by Harnisch and Harnisch (2006). The results shown above, however, demand an improvement over the simple approach of just rainfall and groundwater. Because the seasonal changes in gravity can be so well accounted for by placing the soil moisture level above the underground stations, this means that soil moisture must be retained in some environments for considerable time (before it leaks into the groundwater and runoff systems). We therefore need to add another stage to our previous model, to allow for the soil moisture horizon that is here represented as a thin horizontal layer, as in Figure 9

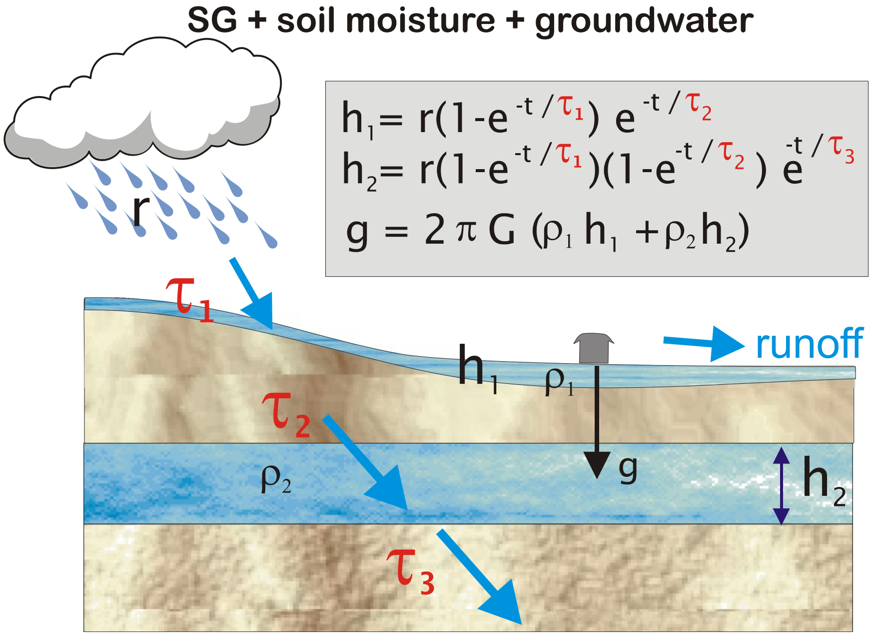


Figure 9. A 3-stage model for rainfall, soil moisture, groundwater, and gravity.

This hydrology problem can be solved empirically by modeling, using as observations the time series of rainfall, soil moisture, groundwater, and ground gravity. It is in principle possible to establish values for the thickness and porosity of the two water layers and the 3 time constants τ_1, τ_2, τ_3 as indicated in Fig. 9. If the SG is below the soil moisture horizon, the sign of $\rho_1 h_1$ in the Bouguer slab attraction formula must be reversed. We intend to pursue this approach in future studies. The more physical approach to hydrology modeling is of course more satisfying (e.g. Llubes et al., 2004; Kroner and Jahr, 2006) but a complete description of the hydrology channels in complex areas such as hills and forests is a challenge yet to be solved.

Conclusions

(1) With more than 3 years of data from GGP and GRACE, we can now say with confidence that the seasonal variation of water storage at SG sites is consistent with satellite measurements and with hydrology models.

(2) The size of the annual variations is about ± 5 μGal at most stations, with highest gravity occurring during the winter months and the lowest gravity during summer when the soil moisture and canopy water evaporates.

(3) The higher degree truncation GRACE solution (n=50) gives surface gravity that has amplitudes twice that of the more reliable n=20 fields.

(4) The spatial inconsistency of the point wise SG data and the GRACE data does not seem to pose a major problem in the intercomparison. This has been demonstrated through the EOF decomposition of both fields.

(5) The principal components of the EOF analysis of the GRACE fields are a very useful measure of the time variation in the data, and show trends in amplitude and phase that are more satisfying than fitting a simple sinusoidal variation.

(6) The problem of some SG stations being underground poses special difficulties in with the soil moisture in hydrology, but these are not insurmountable and can be solved with effective empirical modeling. The simple reversal of sign of the local soil moisture attraction appears to be a crude, but effective, first strategy in such an approach.

Acknowledgments

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