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Local and global hydrological contributions to gravity variations observed in Strasbourg

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ABSTRACT

We investigate the contribution of local and global hydrology to the superconducting gravimeter (SG) installed in the Strasbourg observatory. A deterministic approach is presented to account for the contribution of water storage variations in the soils in the vicinity of the gravimeter: both amount and distribution of water masses are determined before calculating Newtonian attraction. No adjustment is performed on gravity time series.

Two multi-depth Frequency Domain Reflectometer (FDR) probes have been installed to monitor the amount of water stored in the soil layer above the gravimeter. Since August 2005, they have been monitoring the variation of the water content of the entire soil thickness. Several investigations have been undertaken in order to estimate the distribution of water masses: a precise local DEM (Digital Elevation Model) has been determined using differential GPS. The geometry and heterogeneity of the soil layer have been evaluated thanks to geophysical and geomechanical prospections. The comparison between observed and modelled gravity variations shows that daily up to seasonal variations are in good agreement. For long-term variations, deep water storage and other processes have to be modelled to explain recorded gravity variations.

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1. Introduction

Once the Earth tides, the atmospheric and the polar motion contributions are removed, hydrology accounts for a major part of the signal recorded by gravimeters and might hide internal dynamical phenomena. Hydrology had notably been identified as a possible source of systematic errors in precise gravity surveys (see e.g. Lambert and Beaumont, 1977; Mäkinen and Tattari, 1990). Dal Moro and Zadro (1998) concluded that hydrological effects should be removed before studying signals of geodynamical interest. Moreover, in the quest to validate GRACE satellite gravity observations with ground-based observations, one should take into account the difference between kilometric-scale local hydrological contribution and continental-scale hydrological contribution (e.g. Hinderer et al., this issue).

Two methodologies have arisen to investigate hydrological effects. While both of them provide relatively good results, they are very different in terms of modelled processes and investigated spatial extent. The first methodology focuses on local effects driven by Newtonian attraction. It is generally based on correlation studies between local hydrological measurements – or models – and gravity time series (e.g. Bower and Courtier, 1998; Crossley et al., 1998; Van Camp et al., 2006). Kroner et al. (2004) and Kroner and Jahr (2006) wanted to better understand the water fluxes around the gravimeter and so focused on isolated hydrological processes thanks to controlled man-made hydrological experiments. Recently, some authors switched to a deterministic approach to evaluate Newtonian attraction (i.e. without adjusting on gravity data), leading to promising results (Hasan et al., 2005; Hokkanen et al., 2006; Meurers et al., 2007; Longuevergne, 2008).

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The second methodology, a somewhat different deterministic approach considers the physical modelling of the hydrological contribution (Boy and Hinderer, 2006). Both surface loading and Newtonian attraction effects are calculated using global hydrological models (e.g. GLDAS (Rodell et al., 2004)). No adjustment is performed on gravity data, so this process-oriented approach is likely to be more robust. However, this methodology is limited by the spatial sampling of global models (at best 0.25°) as well as their temporal resolution (3 h). Note that Virtanen et al. (2006) have set up hydrological models of several spatial extents in order to improve this approach.

This work follows Boy and Hinderer (2006). We have set up a local hydrological monitoring system to better estimate water redistribution in the unsaturated zone at the scale of several hundred of meters around the gravimeter. Two main questions need to be answered before calculating the Newtonian attraction effect: what is the amount of water and where are these water masses? The first question will be tackled using soil moisture measurements. For the second question, the sensitive test mass of the gravimeter has been precisely localized inside its environment.

2. Methodological approach

2.1. Local hydrology vs. global hydrology

Two processes forced by local and remote hydrological surface loads generate a measurable gravity effect (see Llubes et al., 2004): Newtonian attraction and surface loading, i.e. the elastic deformation of the earth crust due to the weight of water. Traditionally, the hydrological problem has been separated into a 'local' and a 'global' contribution. This separation is more pragmatic than physical since Newtonian attraction has to be modelled for both local and global water distributions.

Fig. 1 shows monthly gravity residuals (after reduction of tides, polar motion and atmospheric contribution) for 6 stations of the GGP network (Global Geodynamic Project, see Crossley et al., 1999), classified with respect to the relative position of the gravimeter with the local soil layer. In one case, storing water in the local soil layer increases gravity; in the other case, gravity decreases. For stations above ground, the residuals show a clear annual signal with large amplitude (200 nm s^{-2}). Conversely, gravity residuals of stations below ground are two times lower and no clear annual variations may be extracted from the time series. This means that local hydrology and global hydrology create constructive and destructive interferences. Both local and global hydrological effects are correlated and have the same order of magnitude, and both have to be modelled.

The real difficulty of calculating the hydrological effects to gravity observations can be stated as follows: all local and global hydrological contributions are driven by climate and thus have a correlated behaviour at seasonal time scales. These contributions mix in gravity data so estimating the gravity effect by fitting a regression coefficient between a local hydrological time series and gravity residuals should be avoided when a robust estimation of the hydrological contribution is needed. This has to be done by complementary information.

2.2. Calculating Newtonian attraction

One question remains: where is the spatial limit between local and global hydrology? This question is important to precisely calculate the local Newtonian attraction contribution but also to set up an adequate local hydrological monitoring system. In practical terms, when calculating the Newtonian attraction, all water masses should be taken into account but they should not be included in both local and global zones.

Gravity variations induced by the redistribution of surface water loads on the Earth crust was studied by Farrell (1972) among others. The gravity effect due to surface loads can be written as an infinite sum of Legendre polynomials. The effect of a unit point mass (or Green function) for a SNREI earth may also be determined by calculating this infinite sum. The Green function of Newtonian attraction GN for an instrument above the surface can be written as follows:

$$GN(\psi) = \begin{cases} \dfrac{G}{4a^2 \sin(\psi/2)} & \text{if } \psi > 0 \\ 2\pi G & \text{if } \psi = 0 \end{cases}$$

where G is the universal constant of gravitation, a the mean radius of the Earth, and ψ is the angular distance between the observation point and the point mass (see e.g. Boy et al., 1998). This way of writing the Newtonian attraction effect reflects that the Bouguer plate is $4\pi G$ for a sphere and $2\pi G$ for a flat infinite layer of unit density.

Local hydrology is described here as a Dirac function, but this expression is valid for a spherical earth only. On the real Earth, topography quickly breaks spherical symmetry when getting closer to the instrument and becomes an essential parameter to take into account when calculating Newtonian attraction. The calculation of Newtonian attraction created by a uniform layer distributed on

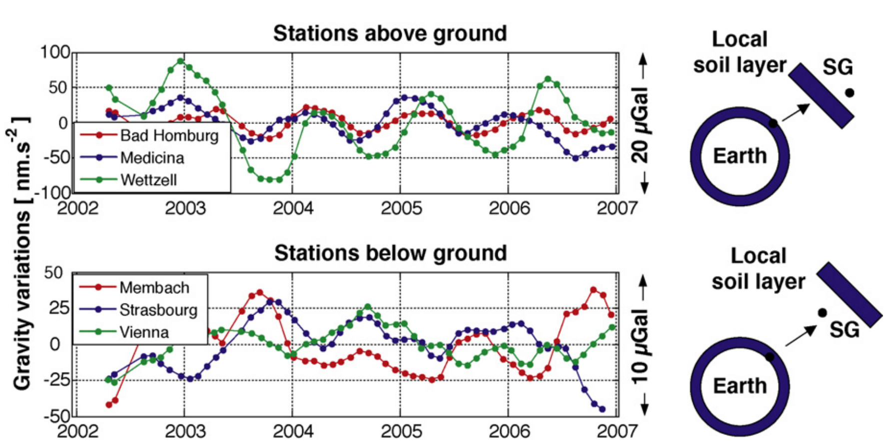

Fig. 1. Monthly gravity residuals observed at several GGP stations after reduction of tides, polar motion and atmospheric contribution. Stations are classified with respect to the relative position of the gravimeter with the local soil layer, above ground or below ground. Adapted from Crossley et al. (2006). (Colour figure can be viewed in the online issue.)

topography should be sufficient to determine the limit between local and global hydrology. This limit could be adjusted to match the extension of a local independent hydrological unit (e.g. catchment) if it exists and could be as far as several kilometers as shown by Meurers et al. (2007), depending on the observatory.

3. Local hydrology in J9 observatory

The gravimeter has been installed in an old German fort built in the 1870s, located on top of a loessic hill. A geological cut of the site may be found in Llubes et al. (2004) and Longuevergne (2008). Two hydrological units deserve to be studied:

- The small perched sand aquifer located 35 m below the gravimeter. The income of water is filtrated by the soils above, so it has little short-term and seasonal effect on gravity variations (Amalvict et al., 2004). Indeed, the income of water is first absorbed by the first meters of soil, pumped by roots and used by the vegetation for evapotranspiration. Only excess of water may infiltrate deeper down to the perched aquifer. Water level variations have thus only slow variations.
- The loessic soils around the gravimeter. On a geological point of view, loess are very special soils. They are a homogeneous, nonstratified, porous, aeolian sediment (e.g. Bittler and Elsass, 2006). They have a high water retention capacity and can store a 200-mm full water layer per meter of soil. As a consequence, they could potentially induce a non-negligible gravity contribution. In situ tests have shown a porosity greater than 50% for most of the loess soil layer above the gravimeter.

A first-order estimation of the hydrological signal induced by the top soil layer underlined its non-negligible contribution (Llubes et al., 2004). We have equipped J9 observatory with a local hydrological monitoring system. According to Wilson et al. (2004), the temporal soil moisture variability at plot scale is five times more important than the spatial variability. As a consequence, the calculation of the local hydrological contribution is split into two steps: first the estimation of the amount of water, and second the distribution of the water masses around the gravimeter.

3.1. Amount of water

We have installed two Sentek Environsmart probes to monitor volumetric soil moisture variations θ (see http://www.sentek.com.au). They are based on FDR (Frequency Domain Reflectometer) principle, i.e. the relative permittivity ε_r of a soil volume (a capacitance) is measured determining the resonance frequency of an oscillator. These probes have multiple sensors installed along a vertical profile; they therefore allow the monitoring of soil moisture changes in the entire soil thickness. These probes have been chosen because they are set up in a borehole access tube, which has several advantages: (1) it minimizes soil and root disturbance so that the natural water flow is kept unchanged; (2) it makes maintenance easier, sensors are easily replaced; (3) the vertical distribution of the sensors could be easily chosen; and (4) the resolution of the sensors keeps very good, better than 0.03% [vol]. We have installed a probe in the 1-m thick soil layer above the gravimeter at the depth of 10, 20, 30, 50 and 80 cm and a second 2-m probe in front of the fort to evaluate spatial variability and deep infiltration.

Time series of water storage variations show that most of the high-frequency contributions of water storage in the soil layer occur in the top 20 cm and are driven by rain events. The soil then behaves as a non-linear filter and the deepest probes record essentially seasonal variations.

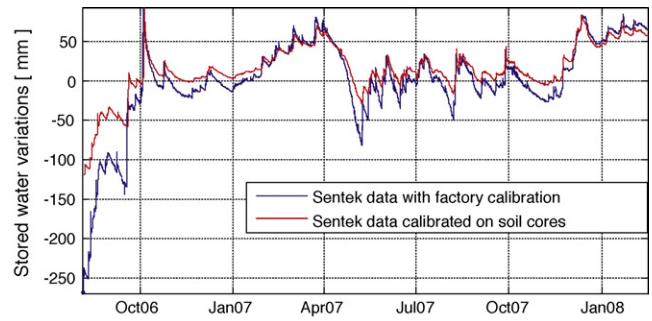

Fig. 2. Stored water variations of the entire soil thickness above the gravimeter before (blue) and after (red) calibration of the probes on soil cores. Note the highly non-linear calibration. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

The calibration factor of gravimeters is determined with an uncertainty at the 0.1% level (e.g. Francis and van Dam, 2002). As we do not want to use gravity data to calibrate the sensors, the soil moisture probes calibration has been undertaken on laboratory measurements, as follows:

- First, all the sensors are referenced with respect to a measure in air ($\theta = 0$; $\varepsilon_r = 3$ in soils) and a measure in water ($\theta = 1$; $\varepsilon_r = 81$). Sentek probes give a measurement of soil moisture N between 0 and 1, which is not calibrated yet.
- Three soil cores per depth are extracted to determine their volumetric water content θ in laboratory. These cores of known volume are weighted before and after drying during 24 h at 105 °C as recommended by Klute (1986). No clear calibration function may be extracted from the relation between the Sentek measure N and the laboratory determined soil moisture θ. A third step is needed.
- An important step lies in converting the Sentek measure N into relative permittivity ε_r following Schwank et al. (2006). This non-linear transformation is linked to the probes (i.e. the electronics and the effect of access tube) and is independent to the soil.
- Finally, a second order polynomial is used to convert the relative permittivity of the probes ε_r to the water content θ determined in laboratory. The determined calibration curve is quite different from Topp et al. (1980) polynomial generally used to transform TDR (Time Domain Reflectometer) measurements into soil moisture values. This is due to the particularities of loess soils.

Fig. 2 shows that this non-linear calibration is absolutely necessary in order to avoid an over-estimation of the largest short-term and seasonal variations in water content. For some sensors, the amplitude of the annual variation is divided by a factor 3. The error on the volumetric soil moisture estimation, determined on the calibration curves, has been reduced from 25% to 5% error thanks to this calibration process.

3.2. Distribution of water masses

The calculation of Newtonian attraction needs to localize the sensitive test mass of the gravimeter inside its environment, i.e. to determine the relative position of the water masses.

A great attention was given to the geometry of the soil layer located above the gravimeter. Applied geophysics prospections have been carried out to evaluate the geometry of this layer. We have also performed a geomechanical investigation using a dynamical penetrometer called Panda (see http://www.sol-solution.com). The soil thickness is determined by knocking a series of metal

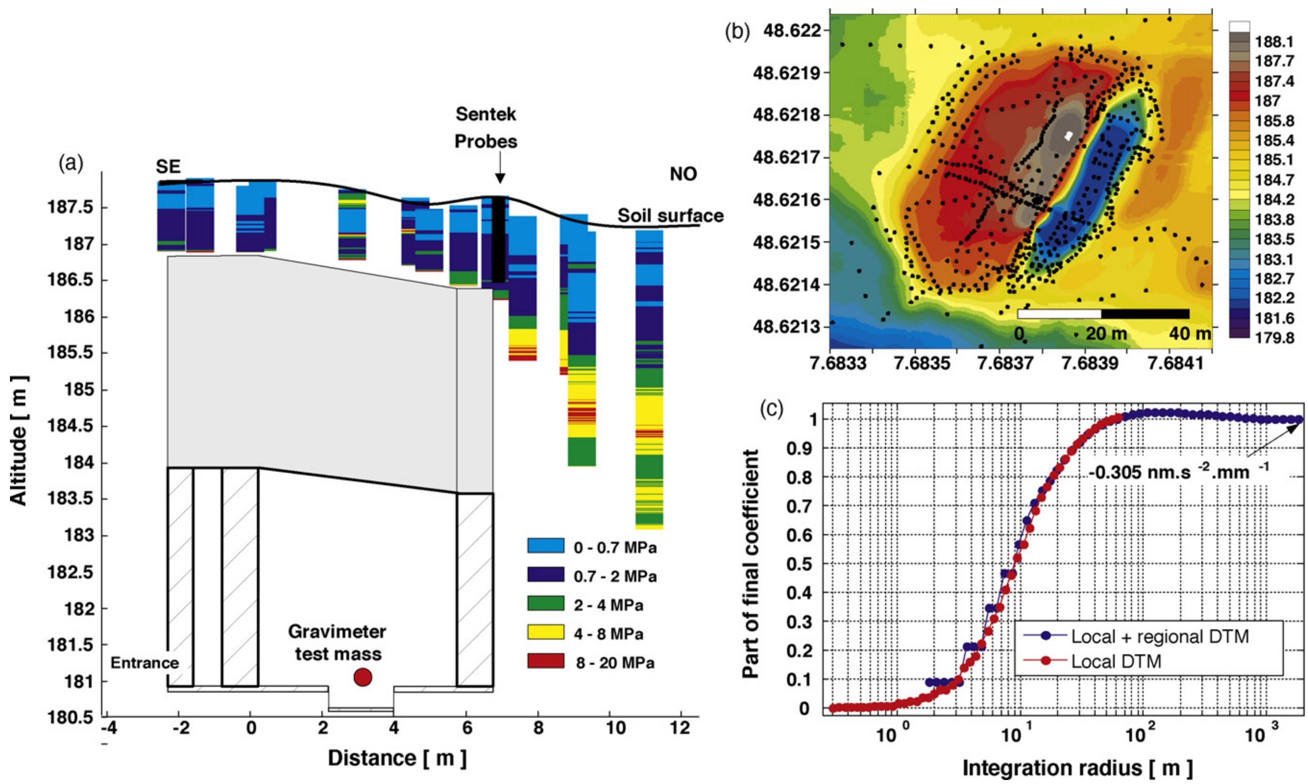

Fig. 3. (a) Fort and top soil layer geometry around the gravimeter mass test. The colours indicate the soil stiffness determined by the geomechanical prospection. In grey, the geometry of the fort. A more extended topographic and geologic map may be found in Llubes et al. (2004). (b) Local DEM determined with RTK prospection around the gravimeter. Altitudes are indicated in meters, latitudes and longitudes in degrees. (c) Determination of the gravity effect generated by a 1-mm water layer uniformly distributed on the topography. The integration radius of the gravimeter is of the order of 100 m, the final admittance is $-0.305\,\mathrm{nm\,s^{-2}\,mm^{-1}}$. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

rods. Moreover, the qualitative interpretation of the soil stiffness is used to evaluate the heterogeneities of the soil. The relative height between the gravimeter and the soil layer is finally determined using a topographic survey, evidencing the 3-m concrete roof on top of the fort (see Fig. 3a). Note that this roof is a zero flux limit condition for water that cannot be taken into account by global hydrological models.

A 25-cm vertical precision DEM (Digital Elevation Model) has also been determined thanks to a RTK (Real-Time Kinematic) survey. Note that the precision is estimated thanks to the nugget effect of the variogram (see Wackernagel, 1995). It has been connected to a regional DEM from the French Mapping Agency (IGN) to map a 2-km area around the gravimeter. The topographic map around the gravimeter is plotted in Fig. 3b.

We calculate a linear coefficient for the hydrological effect and the integration radius of the gravimeter by distributing uniformly a 1-mm water layer on the topography. Note that the integration radius and the calculated admittance are highly dependent on the topography around the gravimeter (Meurers et al., 2007). In J9 observatory, this integration radius is of the order of 100 m (see Fig. 3c). The final gravity effect of a 1-mm water layer is $-0.305\,\mathrm{nm\,s^{-2}\,mm^{-1}}$. This admittance only varies by 1.5% when the soil layer is shifted vertically by 1 m. This is due to the fact that the distribution of the soil reservoir around the gravimeter is close to a half-plane. As a consequence, a single coefficient is used for the whole soil thickness.

4. Results

The SG data processing is conducted as follows: minute raw gravity and pressure data are first corrected from major perturbations (Crossley et al., 1998) and then filtered to hourly samples. Gravity data are then corrected from polar motion and length-of-day induced effects (Wahr, 1985), using EOPC04 series from the International Earth Rotation Service (IERS), assuming an elastic Earth and an equilibrium pole tide, including self-attraction and loading terms (Agnew and Farrell, 1978). The SG instrumental drift has been determined using repeated absolute gravity measurements (AG), as explained in Rosat et al. (this issue). The observed AG drift has been removed to better focus on short-term and seasonal variations.

Atmospheric and induced non-tidal oceanic loading have been modelled using global surface pressure field provided by ECMWF (European Centre for Medium-range Weather Forecasts) and sea surface height variations from the HUGO-m (Carrère and Lyard, 2003) batropic ocean model, following Boy et al. (2002), Boy and Lyard (2008) and Boy et al. (this issue). The loading time series will also contain some atmospheric residuals since the full 3D atmospheric structure is not taken into account. This may lead to remaining effects at short-term periods (especially linked to front movements) and a potential annual effect, below $10\,\mathrm{nm\,s^{-2}}$ for gravity (Neumeyer et al., 2004). Finally, tidal analyses are performed using the ETERNA package (Wenzel, 1997).

The 5-min soil moisture measurements above the gravimeter are summed using weights representing the thickness representativeness of each sensor. These soil moisture variations, representative of the whole soil thickness are multiplied by the determined $-0.305\,\mathrm{nm\,s^{-2}\,mm^{-1}}$ coefficient. The results are finally decimated to hourly values.

The redistribution of water masses at continental scale is determined using GLDAS/Noah (Global Land Data Assimilation System) (Rodell et al., 2004), which is available on a 0.25° grid with a 3 h temporal resolution. Green's function formalism (Farrell, 1972) is

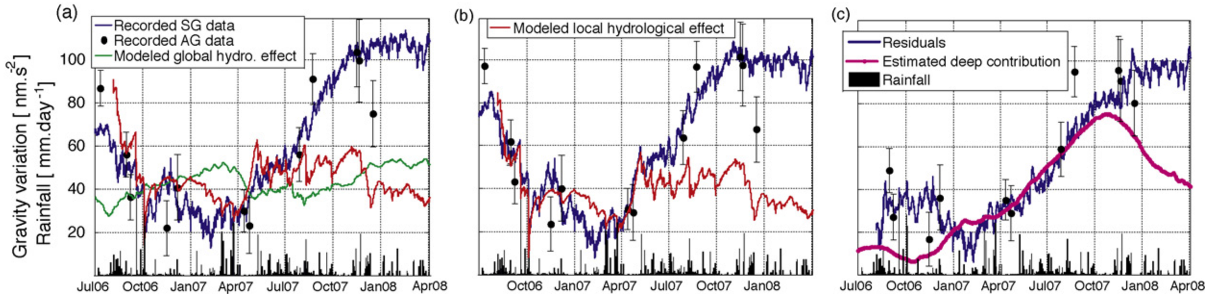

Fig. 4. 1-Year comparison between observed gravity variation and the modelled hydrological contributions. (a) Gravity residuals (blue), modelled global contribution (green), and modelled local contribution (red). (b) Gravity residuals corrected from global hydrology (blue) superimposed with modelled local soil moisture contribution (red). (c) Gravity residuals after correction of global and local hydrological signals (black) and estimated deep contribution (magenta). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

used to convolve water loads and calculate the associated gravity effect, assuming a SNREI earth.

Finally, a "deep hydrological contribution" is calculated. This effect includes both storage variations in the groundwater and in the 30-m thick unsaturated layer situated below the gravimeter. One difficulty is that a water mass located in the unsaturated zone below the gravimeter and infiltrating down to the local groundwater creates a gravity effect before reaching the aquifer 35 m below ground and being recorded as a water level variation. As a first-order estimation, we have here multiplied the observed well variations by a $0.2\,\mathrm{nm\,s^{-2}\,mm^{-1}}$ coefficient calculated by Llubes et al. (2004) using a realistic geometry and porosity of the sand aquifer. This estimation is not exact but gives the shape of the long-term variations induced by deep water storage below the gravimeter.

The comparison between the modelled hydrological contributions and gravity observations is plotted in Fig. 4a. It should be noted that the global and local hydrological contributions are anti-correlated, as determined previously. As a consequence, reducing gravity variations from the global hydrological contribution increases the variability of the residuals. The amplitude of the local hydrological signal is twice as important as the amplitude of the global hydrological effect in Strasbourg.

In Fig. 4b, gravity residuals are corrected from global hydrology to better evaluate the quality of the local soil contribution. One interesting event happened in April 2007. This period was warm and dry is Strasbourg, which enabled a quick development of the vegetation and thus, the root pumping of a non-negligible amount of water. The agreement for this 1-month event is very encouraging and allows us to validate our approach. Note that this period was warm and dry for the Europe as a whole. As a consequence, the global and local hydrological contributions are anti-correlated, even at a monthly time scale.

The gravity time series reduced from both global and local hydrological signals are plotted in Fig. 4c, the estimated "deep" contribution is also superimposed. We confirm here that the water mass variations below the gravimeter only generate long-term variations. The estimated deep contribution partly explains the residuals; however, as stated previously, more work is needed to better constrain the vertical fluxes before water can reach the sand aquifer and better evaluate this "deep" contribution. Short period variations are especially due to remaining imprecision in the hydrological corrections and to unmodelled 3D atmospheric effects.

Several uncertainties must be underlined. Every rainfall event generates a gravity effect; their amplitude is unfortunately not always correctly predicted by the Sentek probes (see Fig. 4c). The non-linear calibration of the probes maybe not perfect and more soil cores should be used to adjust the calibration curve. The main uncertainty is surely related to the spatial sensitivity of the probes (5 cm) compared to the spatial sensitivity of the gravimeter (100 m).

Fig. 5 summarizes the three investigated hydrological contributions on a 6-year time period and underlines the complex interactions and compensations between the identified units. Estimated "deep" and global contributions could be calculated since 2002, whereas the local soil moisture contribution, relying on installed probes, is only available for the last 1.5-year time period. Global hydrology contains especially seasonal variations; continental-scale dry period (April 2007) or wet period (January 2004) could however induce non-negligible short-term gravity variations. The "deep" contribution is not as regular. If the seasonal amplitude is reduced to $10\,\mathrm{nm\,s^{-2}}$, exceptional years such

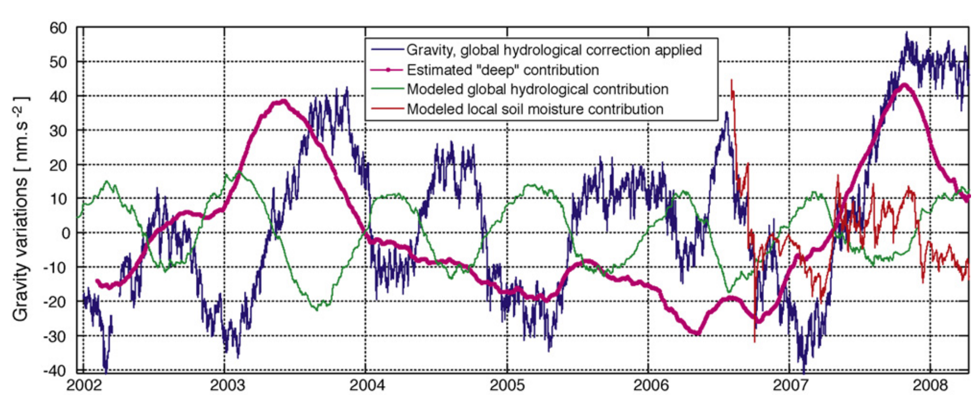

Fig. 5. 6-Year comparison between the global hydrological contribution, the estimated "deep" contribution and 1-year and a half measured local soil moisture contribution. Gravity residuals are reduced from global hydrological contribution to better show the contribution of the local soil moisture and deep hydrological contributions. (Colour figure can be viewed in the online issue.)

as 2002 and 2007 wet summers have induced a $50\,\mathrm{nm\,s^{-2}}$ gravity contribution. This is due to the non-linear behaviour of the soils which become very permeable when their water contents get closer to saturation. Finally, the local hydrological unit, at the soil moisture interface, generates most of the high-frequency events.

The deterministic approach is necessary to identify and first quantify the main hydrological units to model, as all these contributions are correlated. Deterministic approach does not mean "without a-priori", actually a priori is needed to evaluate the contribution of the less-known hydrological units (the deepest in our case). However, when independent information is available, it should be used to validate the approach or calibrate the models/measurements. Adjustment on gravity data could be seen as a final step to reduce the variance of the gravity time series, when all hydrological contributions are determined.

5. Conclusion

In this work, we have modelled the different hydrological contributions in J9 observatory using a deterministic approach, i.e. without adjustment on gravity data. Both water redistribution at the scale of several hundreds of meters around the gravimeter and water redistribution at continental scale induce a non-negligible gravity effect of several microgals. Moreover, both are driven by climate and so are anti-correlated and partly compensate each other at seasonal time scales in J9 observatory. This last remark is an a posteriori justification of the necessity to model the hydrological effect with a deterministic approach. Future improvement will focus on the estimation of stored water variations below the gravimeter. This deep contribution induces especially long-term variations and cannot be simply constrained using piezometric head time series alone.

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References

Agnew, D.C., Farrell, W.E., 1978. Self-consistent equilibrium ocean tides. Geophys. J. R. Astron. Soc. 55, 171–181.

Amalvict, M., Hinderer, J., Mäkinen, J., Rosat, S., Rogister, Y., 2004. Long-term and seasonal gravity changes at the Strasbourg station and their relation to crustal deformation and hydrology. J. Geodyn. 38, 343–353.

Bittler, C., Elsass, P., 2006. Banque régionale de l'aquifère rhénan - programme 2003–2006, rapport brgm/rp-5876-fr. Technical report.

Bower, D, Courtier, N., 1998. Precipitation effects on gravity measurements at the Canadian absolute gravity site. Phys. Earth Planet. Inter. 106 (3–4), 353–369.

Boy, J.-P., Hinderer, J., Gegout, P., 1998. Global atmospheric loading and gravity. Phys. Earth Planet. Inter., 161–177.

Boy, J.-P., Gégout, P., Hinderer, J., 2002. Reduction of surface gravity data from global atmospheric pressure loading. Geophys. J. Int. 149, 534–545.

Boy, J., Hinderer, J., 2006. Study of the seasonal gravity signal in superconducting gravimeter data. J. Geodyn. 41, 227–233.

Boy, J.-P., Lyard, F., 2008. High-frequency non-tidal ocean loading effects on surface gravity measurements. Geophys. J. Int. 175, 35–45.

Boy, J.P., Longuevergne, L., Boudin, F., Jacob, T., Lyard, F., Llubes, M., Florsch, N., this issue. Modelling atmospheric and induced non-tidal oceanic loading contributions to surface gravity and tilt measurements. J. Geodyn.

Carrère, C., Lyard, F., 2003. Modeling the barotropic response of the global ocean to atmospheric wind and pressure forcing—comparisons with observations. Geophys. Res. Lett. 30 (6), 1275, doi:10.1029/2002GL016473.

Crossley, D.J., Hinderer, J., Jensen, O., Xu, H., 1998. A slewrate detection criterion applied to SG data processing. Bulletin d'Information des Marées Terrestres 117, 8675–8704.

Crossley, D., Hinderer, J., Casula, G., Francis, O., Hsu, H.-T., Imanishi, Y., Jentzsch, G., Kaarianen, J., Merriam, J., Meurers, B., Neumeyer, J., Richter, B., Shibuya, K., Sato, T., van Dam, T., 1999. Network of superconducting gravimeters benefits a number of disciplines. EOS Trans. 80 (11), 125–126.

Crossley, D., Hinderer, J., Boy, J.-P., De Linage, C., 2006. Status of the GGP satellite project. Bulletin d'Information des Marées Terrestres 142, 11423–11432.

Dal Moro, G., Zadro, M., 1998. Subsurface deformations induced by rainfall atmospheric pressure: tilt/strain measurements in the NE Italy seismic area. Earth Planet. Sci. Lett. 164, 193–203.

Farrell, W., 1972. Deformation of the Earth by surface load. Rev. Geophys. Space Phys. 10 (3), 761–797.

Francis, O., van Dam, T., 2002. Evaluation of the precision of using absolute gravimeters to calibrate superconducting gravimeters. Metrologia 39, 485–488.

Hasan, S., Troch, P., Boll, J., Kroner, C., 2005. Modeling the hydrological effect on local gravity at Moxa, Germany. J. Hydrometeorol. 7, 346–354.

Hokkanen, T., Korhonen, K., Virtanen, H., 2006. Hydrogeological effects on superconducting gravimeter measurements at Metsähovi in Finland. J. Environ. Eng. Geophys. 11, 261–267.

Klute, A., 1986. Methods of Soil Analysis. Part 1. Physical and Mineralogical Methods. American Society of Agronomy, Soil Science Society of America, Madison, WI, USA, 1772 pp.

Kroner, C., Jahr, T., Jentzsch, G., 2004. Result from 44 months of observations with a superconducting gravimeter at Moxa/Germany. J. Geodyn. 38, 263–280.

Kroner, C., Jahr, T., 2006. Hydrological experiments around the superconducting gravimeter at Moxa observatory. J. Geodyn. 41 (1–3), 242–252, doi:10.1016/j.jog.2005.08.012.

Lambert, A., Beaumont, C., 1977. Nano variations in gravity due to seasonal groundwater movements: implications for the gravitational detection of tectonic movements. J. Geophys. Res. 82, 297–306.

Llubes, M., Florsch, N., Hinderer, J., Longuevergne, L., Amalvict, M., 2004. Local hydrology, the global geodynamics project CHAMP/GRACE perspective: some case studies. J. Geodyn. 38, 355–374.

Mäkinen, Tattari, 1990. The influence of variation in subsurface water storage on observed gravity. In: Kakkuri, J. (Ed.), Proceedings of the 11th International Symposium: Earth Tides. Schweitzerbart, Stuttgart, Germany, pp. 457–471.

Longuevergne, L., 2008. Contribution a l'Hydrogéodésie, Ph.D. thesis, 300 pp., Université Pierre et Marie Curie. Can be downloaded at: http://tel.archives-ouvertes.fr/docs/00/31/92/05/PDF/these_longuevergne.pdf.

Meurers, B., Van Camp, M., Petermans, T., 2007. Correcting superconducting gravity time-series using rainfall modelling at the Vienna and Membach station and application to earth tide analysis. J. Geodesy 81 (11), 703–712.

Neumeyer, J., Hagedoorn, J., Leitloff, J., Schmidt, T., 2004. Gravity reduction with three-dimensional atmospheric pressure data for precise ground gravity measurements. J. Geodyn. 38 (3–5), 437–450.

Rosat, S., Boy, J.-P., Ferhat, G., Hinderer, J., Amalvict, M., Gegout, M., Luck, B., this issue. Analysis of a ten-year (1997–2007) record of time-varying gravity in Strasbourg using absolute and superconducting gravimeters: new results on the calibration and comparison with GPS height changes and hydrology.

Rodell, M., Houser, P.R., Jambor, U., Gottschalck, J., Mitchell, K., Meng, C.-J., Arsenault, K., Cosgrove, B., Radakovich, J., Bosilovich, M., Entin, J.K., Walker, J.P., Lohmann, D., Toll, D., 2004. The global land data assimilation system. Bull. Am. Meteor. Soc. 85, 381–394.

Schwank, M., Green, T., Mätzlerc, C., Benedickterd, H., Flühlere, H., 2006. Laboratory characterization of a commercial capacitance sensor for estimating permittivity and inferring soil water content. Vadose Zone J. 5, 1048–1064.

Topp, G., Davis, J.L., Annan, A.P., 1980. Electromagnetic determination of soil water content: measurements in coaxial transmission lines. Water Resour. Res. 16, 574–582.

Van Camp, M., Vanclooster, M., Crommen, O., Petermans, T., Verbeeck, K., Meurers, B., Van Dam, T., Dassargues, A., 2006. Hydrogeological investigation at the Membach station, Belgium, application to correct long periodic gravity variations. J. Geophys. Res. 111, B10403.

Virtanen, H., Tervo, M., Bilker-Koivula, M., 2006. Comparison of superconducting gravimeter observations with hydrological models of various spatial extents. Bulletin d'Information des Marées Terrestres 142, 11361–11368.

Wackernagel, H., 1995. Multivariate Geostatistics. Springer, New York, 256 pp.

Wahr, J.M., 1985. Deformation induced by polar motion. J. Geophys. Res. 90 (B11), 9363–9368.

Wenzel, H.G., 1997. The nanogal software: Earth tide data processing package ETERNA 3.30. Bulletin d'Information des Marées Terrestres 124, 9425–9439.

Wilson, D., Western, A., Grayson, R., 2004. Identifying and quantifying sources of variability in temporal and spatial soil moisture observations. Water Resour. Res. 40, W02507.