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Indication of the uplift of the Ardenne in long-term gravity variations in Membach (Belgium)

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SUMMARY

We report on the results of 7 yr of collocated gravity observations made with an FG5 absolute (AG) gravimeter and a GWR C-Series superconducting gravimeter (SG) located at the Membach Geophysical Station in eastern Belgium. The SG gravity residuals track changes in gravity periodically observed by the AG, at the microgal level. Further, in the SG residual signal we distinguish a quasi-seasonal term that can be mostly explained by variations in local water storage effects. In the AG time-series we observe a small trend in the gravity of -0.6 ± 0.1 μGal yr^{-1} perhaps indicating that the Membach Station is being displaced upwards by about 3.0 mm yr^{-1}. An uplift of the region is confirmed by Global Positioning System (GPS) measurements performed 3 km away. We are able to explain the features in the gravity time-series in terms of water storage variability, post-glacial rebound and tectonic activity.

Key words: absolute and relative gravity, crustal motion, geodynamics, GPS, hydrology.

GJI Tectonics and geodynamics

INTRODUCTION

Advances in instrumental hardware, electronics and data analysis techniques have been such that absolute gravimeters (AG) and superconducting gravimeters (SG) can measure changes in the gravitational acceleration at the microgal level over a wide range of frequencies. This level of precision allows us to reliably measure vertical crustal motions of the order of a few millimetres (van Dam *et al.* 2000; Zerbini *et al.* 2001; Lambert *et al.* 2001; Williams *et al.* 2001) and changes in mass equivalent to 1 cm of water.

The fundamental component of a SG (Warburton & Brinton 1995) consists of a hollow superconducting sphere that levitates in a persistent magnetic field. An incremental change in gravity induces a vertical displacement of the sphere. A feedback voltage is induced to keep the sphere at a ‘zero’ position. This feedback voltage is proportional to the gravity change. The GWR SG provides relative gravity measurements, and the most common mode of operation is continuously at a fixed location. Being a relative meter, the SG needs to be calibrated in order to convert variations in voltage into actual gravity changes. This is achieved by operating an AG side-by-side with the SG. This method of calibration allows for a precision in the calibration factor better than 0.1 per cent (Hinderer *et al.* 1991; Francis 1997; Francis *et al.* 1998).

The most accurate, and in fact the only commercially available absolute gravimeter, is the FG5 from Micro-g Solutions (Niebauer *et al.* 1995). With this instrument, the gravitational acceleration is observed directly. A test mass is repeatedly dropped and its position is measured as a function of time. The position and time measurements are directly linked to fundamental standards of length and time using lasers and atomic clocks. Unlike the SG, the FG5 is portable and has been used to measure absolute gravity all over the world. On the other hand, the instrument is not well suited for continuous measurements lasting longer than a few days. The noise of a FG5 at a quiet site is around 22 μGal Hz$^{-1/2}$, however, noise levels as low as 5 μGal Hz$^{-1/2}$ have been observed (Francis *et al.* 1998). The instrumental accuracy of the FG5 is about 1–2 μGal as reported by the manufacturer (Niebauer *et al.* 1995). However, because we cannot model the environmental effects perfectly, the precision in practice is on the order of a few microgal.

While the AG and the SG both measure changes in the gravitational acceleration, they are actually very different in instrumental design. This means that the observations of gravity by the two instruments are subject to very different systematic effects or instrumental errors. Collocated observations by a SG and an AG can therefore be used to eliminate uncertainties in the observed gravity variations due to instrumental effects. Further, most SGs have been observed to drift (instrumental causes) by the order of a few μGal yr^{-1} (Warburton & Brinton 1995). This would appear to make the instruments useless in terms of observing long-term geodynamic effects. However, if regular observations are also made at the site with an AG, the AG can be used to determine the long-term trend and the SG can be used to monitor the temporal variability in the gravity field between

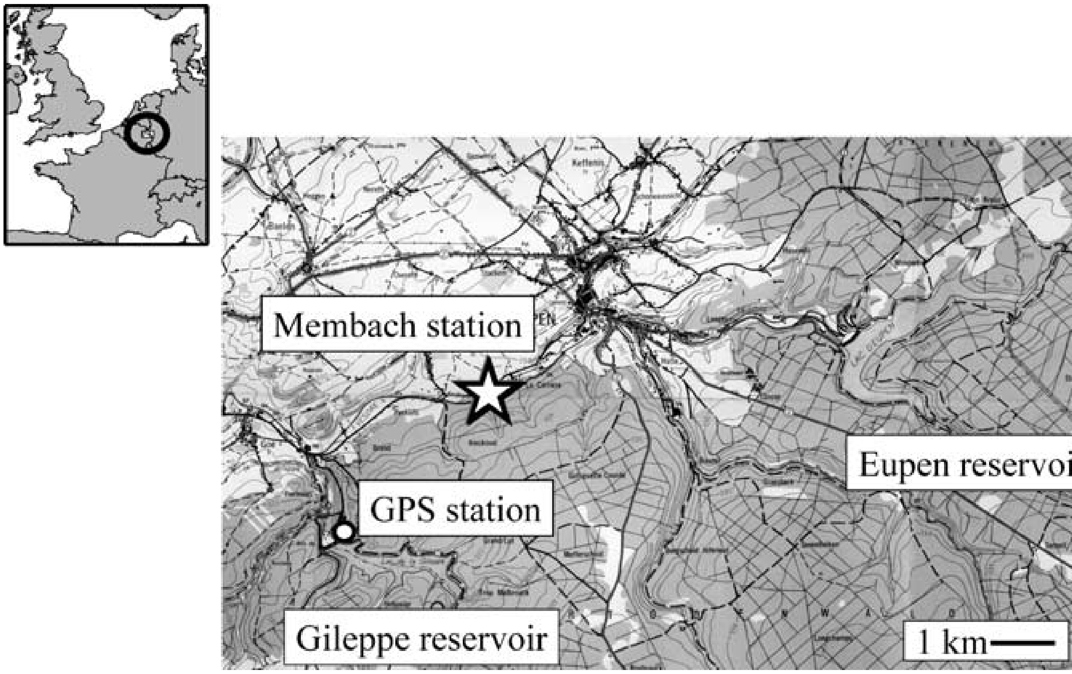

Figure 1. The Membach Geophysical Station (50.61°N, 6.60°E, elevation 250 m) and the two water reservoirs, respectively 3 km and 6 km away. The station is at the end of a 140 m long tunnel cut horizontally into the side of a hill. The GPS Membach Station MEMB is located 3 km away from the Membach Station housing the absolute and superconducting gravimeters.

AG observations. There is an additional advantage to collocation. Regular calibrations of an SG against an AG allow us to determine that any observed offsets in the AG are due to instrumental problems or are due to actual changes in gravity.

In this paper we compare 7 yr of continuous SG observations taken at the Membach Geophysical Station (Fig. 1) with periodic observations taken there with an AG. By comparing the collocated gravity observations, we were able to estimate the instrumental drift of the SG. We were further able to detect a trend in gravity of -0.6 ± 0.1 μGal yr^{-1}. Assuming that the observed gravity change is only due to a vertical motion of the station, we interpret that the Membach Station is rising by about 3.0 ± 0.5 mm yr^{-1}. This uplift is confirmed by continuous GPS measurements taken since 1997 at a site 3 km from the Membach Geophysical Station.

GRAVITY VARIATIONS IN MEMBACH

The C-021 superconducting gravimeter

In 1995 August the Royal Observatory of Belgium installed a superconducting gravimeter, GWRC-021, at the Membach Geophysical Station. The amplitude calibration factor has been determined several times using the FG5-202. A comparison of two calibration determinations, one in 1998 the other in 2001, demonstrated that the calibration factor remained stable at the level of precision of the calibration factor itself (i.e. 0.1 per cent). We additionally use the amplitude of a synthetic tide to check that the calibration is stable. For example, if the amplitude of the M2 tide in every epoch is 42 ± 0.01 μGal, then the calibration is invariant to $0.1/42 \approx 0.02$ per cent (J. Merriam, personal communication, 2004). The C-021 has also been calibrated in phase with a precision of better than 0.01 s (Van Camp *et al.* 2000).

Basic processing of the SG data includes editing and correcting for steps, spikes and other instrumental disturbances (e.g. helium fills). The gravity residuals were obtained by removing a tidal signal using a synthetic tide. Atmospheric effects (loading and mass attraction) are accounted for by using a linear admittance factor of -3.3 μGal hPa^{-1}. This value is determined by simultaneously fitting the tidal parameters and the local air pressure in a least-squares adjustment (Wenzel 1996). Polar motion effects are removed using the formulation of Wahr (1985) based on the International Earth Rotation Service daily estimates of the pole position.

The FG5-202 absolute gravimeter

Absolute gravimeters are regularly deployed in the field to monitor changes in the gravity driven by geodynamical processes. Even though the FG5 is an absolute instrument, occasional offsets due to miscalibration of the clock, the barometer, etc. have been observed. Thus the calibration of the FG5 used in this study was checked before and after every field deployment by measuring gravity at Membach where gravity changes are monitored regularly using a superconducting instrument.

The individual components of the FG5-202, including the rubidium clock, the barometer and the He–Ne laser wavelength, were also regularly checked by comparison with standards in metrology institutes. The Membach absolute gravity observations are shown in Fig. 2. Each AG point represents an average of 24 to 150 hr of observations. The raw AG data are corrected for the same effects as in the case of the SG data.

C-021 instrumental drift and geophysical trend

The instrumental drift of the SG C-021 has been estimated by comparing the SG with the AG observations. The AG observations being

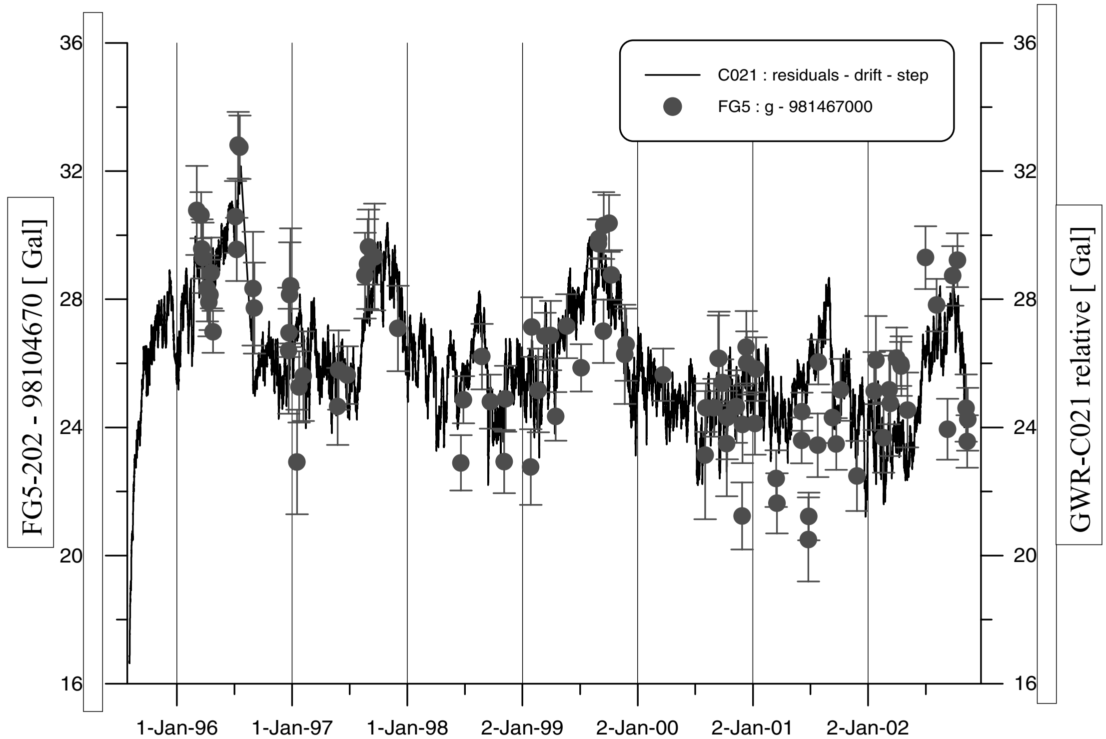

Figure 2. Comparison between gravity measurements of the SG C-021 and the AG FG5-202. The Earth tides, ocean loading and atmospheric effects, and polar motion have been removed. The SG C-021 instrumental drift of 4.3 μGal yr^{-1} was evaluated by taking the difference between the residuals of the SG C-021 and of the AG FG5-202. The initial exponential decrease from 1995 August to December is due to the SG C-021 set-up. What remains in these corrected SG residuals, from 1996 March to 2002 November, is a geophysical trend, mainly linear, and we estimate its slope at -0.6 ± 0.1 μGal yr^{-1}.

absolute are, in principle, drift-free. Thus the difference between AG and SG data should only represent the instrumental drift of the SG.

The instrumental drift has been modelled by a first-order polynomial. The two coefficients (a constant and the slope) are estimated by fitting the SG data on the AG data. The estimated trend is 4.267 ± 0.003 μGal yr^{-1}. This value is within the specifications of the manufacturer for this type of superconducting gravimeter (Warburton & Brinton 1995). A higher polynomial or more sophisticated function do not improve the fit or the statistic of the estimated parameters.

Removing this instrumental drift from the SG gravity residuals, one obtains the actual gravity changes (Fig. 2). In the SG residuals we observe near-annual variations. The AG data indicate that gravity is decreasing at a rate of 0.6 ± 0.1 μGal yr^{-1}. Hereafter, we refer to this trend as the geophysical trend.

DEFORMATION OBSERVATIONS

Repeated levellings and geology

Repeated levellings suggest a current uplift of the Ardenne reaching 1.5 mm yr^{-1} (Mälzer *et al.* 1983). Other repeated levellings provide a similar relative vertical motion across the border fault of the Roer Graben (van den Berg *et al.* 1994). However, the uncertainties are of the same order as the deformation rate (Camelbeeck *et al.* 2002). Geological observations indicate a strong sinking (0.1 mm yr^{-1} since 700 000 yr ago) of the Roer river in the Ardenne-Eifel, which results from the fast uplift of the region during the Quaternary (Cornet 1995). However, Quinif (1998) and Vandijcke & Quinif (2001) showed that the Lomme, another river in the Belgian Ardenne, has been flowing in its present alluvial plain for the last 400 000 yr. This indicates that the uplift is not uniform within the Ardenne Massif, or could be less than observed. Palaeoseismic investigations indicate that the normal faults bordering the Roer Graben are active and able to produce large earthquakes (Camelbeeck & Meghraoui 1996, 1998). Those tectonic deformations have been inducing a relative crustal vertical motion of about 0.1 mm yr^{-1} during the last 400 000 yr, which combines a subsidence in the graben with an uplift of its western border, which partly covers the Ardenne Massif. The spatial extension of this uplift should reach 10 to 20 km. The Eifel volcanism seems to be caused by a deep-reaching mantle plume, i.e. a hot, buoyant mass of mantle rock (Ritter *et al.* 2001; Keyser *et al.* 2002). This mantle plume could explain an uplift of the Ardenne with a spatial extent of about 100 km.

Thus the rates of vertical uplift in the region deduced from geological data and repeated levellings differ by an order of magnitude. In addition, the uplift might vary over the extent of the Ardenne. To obtain a reliable estimate of the rate of uplift of the region, GPS and absolute gravity experiments have been undertaken.

GPS experiments

In 1997 October The Royal Observatory of Belgium installed a continuously operating Global Positioning System (GPS) receiver 3 km from the Membach Geophysical Station, MEMB. This GPS station is equipped with a Turbo-Rogue GPS receiver with choke ring antenna.

The data are processed using the Bernese GPS Analysis Software version 4.2 (Beutler *et al.* 2001). We use GPS satellite orbits, Earth orientation and satellite clock products produced by the IGS

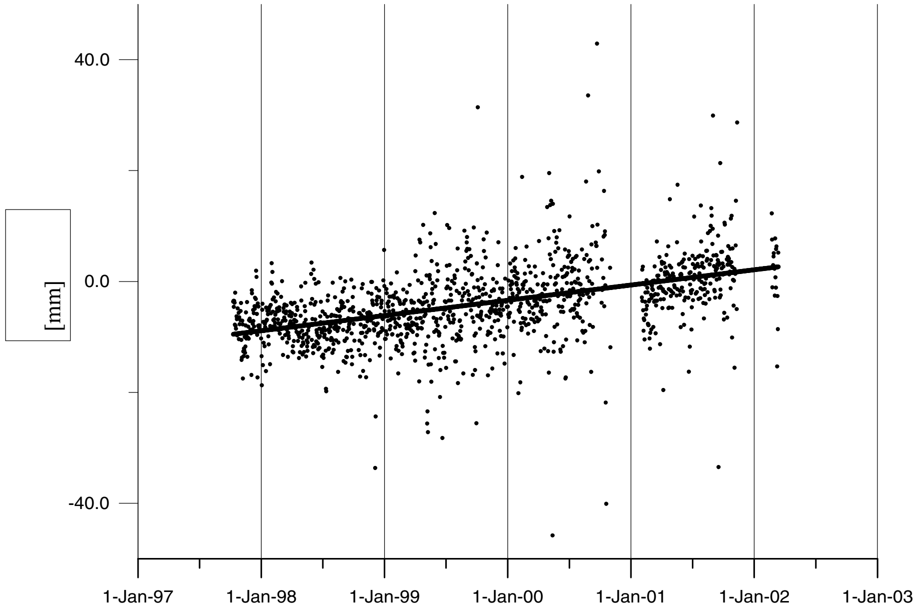

Figure 3. Vertical component of the GPS measurements made 3 km away from the Membach Geophysical Station housing the gravimeters. The data were processed using the BERNESE 4.2 software; the reference (ITRF97) was given by four EUREF fiducial sites (Waremme, Dentergem, Potsdam, Wettzell).

independent analysis of ∼40 globally distributed, continuously operating GPS receivers. After data editing, the carrier phase observations from both GPS frequencies are processed using the quasi-ionospheric-free (QIF) technique (Beutler *et al.* 2001) in order to solve the phase ambiguities. Then, the remaining parameters (station position, tropospheric refraction) are estimated using the so-called ionospheric-free combination of carrier phase measurements.

Finally, the reference frame (ITRF97) is given by four EUREF fiducial sites (Waremme and Dentergem in Belgium, Potsdam and Wettzell in Germany). Fig. 3 shows daily values of vertical positions at MEMB, where a trend of $+2.7 \pm 0.2$ mm yr^{-1} is observed.

DISCUSSION

Seasonal gravity effects

Inspection of Fig. 2 indicates that there is a very large quasi-annual signal in the continuous SG gravity observations. However, the amplitude varies significantly from year to year. A least-squares fit of a purely seasonal term to the residuals indicates that a pure annual signal has an amplitude of approximately 3 μGal. There are many environmental factors that might contribute to a seasonal trend in the gravity observations, including variations in continental water storage (Peter *et al.* 1994; van Dam *et al.* 2001), surface atmospheric mass variations (Goodkind 1986; Merriam 1992; van Dam & Francis 1998; Boy *et al.* 1998) and non-tidal ocean loading, among other things. We estimated the effect of the long-wavelength component of annual continental water storage variations using a regional water storage model (Milly & Shmakin 2002) and found that the amplitude of the predicted annual signal in gravity would be of the order of 3 μGal, an amplitude very comparable to that observed in the SG time-series.

Errors are probably present in the Milly–Shmakin model-derived water storage estimates. However, we expect that the model will tend to reproduce the long-wavelength temporal storage reasonably well. On the other hand, significant short-wavelength spatial variations in water storage are commonplace. These local variations in the water storage are very likely significantly larger than the regional effects. To estimate the gravity effect of the local variations in seasonal water storage we have obtained a record of the water level from two reservoirs in the vicinity of Membach. The records from the Gileppe and Vesdre reservoirs, a distance of 3 and 6 km respectively from the Membach Geophysical Station, are shown in Fig. 4. An inverse relationship clearly exists between the volume of water in the reservoirs and the observed gravity change at Membach. This inverse relationship may at first seem surprising as one would expect gravity to increase with an increase in water mass in the ground beneath the instrument. However, the Membach Geophysical Laboratory is in fact located within a 140 m long tunnel cut into the side of a hill. The SG is located 49 m below the surface. This means that the water mass is above, not below, the instrument, thus making gravity decrease. Further, given that the instrument is buried at such a distance, the water evaporates before it has time to percolate down beneath the instrument.

Using the Green's functions of Farrell (1972), and assuming that the mass change of the water held in the Gileppe dam (approximately 10^7 m^3) is concentrated at a single point, we determine that the change in gravity due to the elastic deformation of the Earth's surface is of the order of 0.02 μGal. The expected change in the vertical component of gravity due to the excess mass is approximately -0.2 μGal. Thus, the gravity change due to the change in water level of the reservoirs is still a factor of 10 smaller than what is actually observed. In conclusion, loading and the excess mass of the water in the Gileppe dam are most likely not responsible for the seasonal change in gravity observed at the Membach Station.

A least-squares fit of the observed long-period gravity changes to the changes in the water level of the Gileppe reservoir results in a regression coefficient of approximately -0.22 μGal m^{-1}. In other words, a change in the level of the reservoir of 1 m results in a change in gravity equal to that expected from an infinite plane of water above the gravimeter approximately 0.5 cm thick. The significantly smaller estimate of water stored in the soil with that

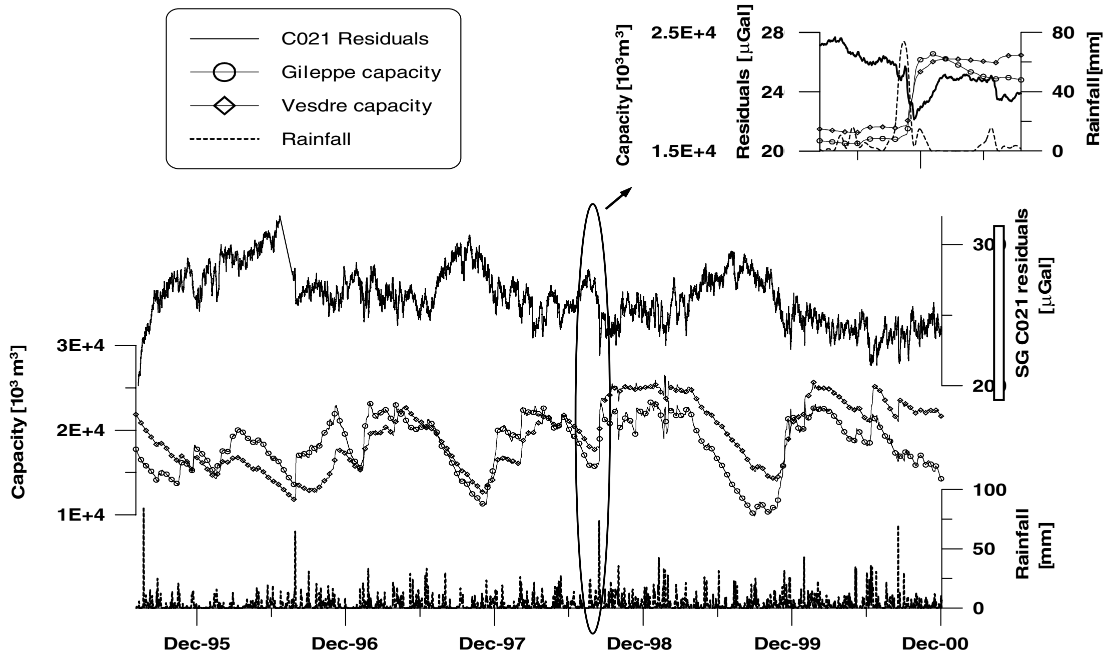

Figure 4. Environmental effects at the Membach Geophysical Station from 1995 August 4 to 2000 December 31. Top: SG C-021 drift-corrected gravity residuals. Middle: capacities of the two Gileppe and Vesdre water reservoirs, respectively 3 and 6 km away from Membach (the capacities of both dams are similar). Bottom: rainfall. Top right: enlarged view during the 1998 September heavy rainfalls. The gravity recovers its previous level a few days later, while the reservoir levels remain nearly constant.

in the reservoir (0.5 cm in the soil for every 1 m change in the reservoir level) is not surprising given that the reservoir level is fed by precipitation as well as surface run-off and stream flow. Thus the observed correlation between the reservoir levels and the gravity (Fig. 4) could be explained by the long-period temporal variations of ground water and/or soil moisture.

On the other hand, we cannot put too much confidence in the observed relationship between the water level in the reservoirs and the observed change in gravity. Reservoir levels are often artificial, the level being controlled somewhat by public consumption. Thus we are still to some extent uncertain about the physical mechanism relating the level in the reservoirs to the gravity change. Installation of a shallow monitoring well above the gravimeter would help us better constrain the relationship between water storage and gravity change.

Rainfall data are also presented in Fig. 4. The rainfall around Membach is about 1150 mm yr^{-1}, uniformly spread over the entire year. As with the change in volume of the reservoirs, the gravity is anticorrelated with the rainfall events. Hours after a significant rainfall, the gravity is observed to decrease. The largest decrease, 4 μGal, was observed in 1998 September after a significant rainfall (150 mm in 3 days). The gravity record returned to its previous level a few days later (enlarged view in Fig. 4).

We attempt to model the effect of rainfall on the gravity by following the methodology of Peter *et al.* (1994):

$$h_i = r_j\left(1 - e^{-(i-j)/\tau_1}\right)\left(e^{-(i-j)/\tau_2}\right)$$

$$g_i = 2\pi G\rho h_i$$

where r_j is the amount of rain at time j, h_i is the thickness of a layer of water at time i, g_i is the gravity observation at hour i and ρ is the density of water (1 g cm^{-3}). Using an optimum search using the last 3 yr of gravity and rain data where the anticorrelation is the strongest, we find that $t_1 = 0.25$ days, the recharge time constant, and $t_2 = 30$ days, the discharge time constant. The correlation between the observed gravity and the modelled rain-driven gravity effects is -0.46.

We are currently conducting research to better constrain the recharge and discharge time constants.

Post-glacial rebound

In a recent paper, Milne *et al.* (2001) attempted to determine the post-glacial rebound (PGR) model that best fits the GPS data in Fennoscandia. The models predict that Belgium is on the peripheral bulge of the PGR deformation. The peripheral bulge region of the crust is located at the edge of an ice load and goes up as the ice mass grows due to the transfer of mantle material from beneath the load to the edges. When the ice mass melts, mantle material moves in from the peripheral bulge structure to fill in the 'hole' left by the melting ice. The crust in the vicinity of the peripheral bulge subsides. The crust around Membach/Belgium is predicted to be subsiding at a rate of about -0.9 mm yr^{-1} (J. Mitrovica, personal communication, 2002). Wahr *et al.* (1995) empirically determined that for a wide range of viscosity profiles, a proportionality constant of -6.5 mm μGal^{-1} is the approximate relationship between vertical crustal motion and gravity changes associated with PGR (see also James & Ivins 1998). The PGR model would predict an increase in gravity of no more than 0.1 to 0.2 μGal yr^{-1}. There are still significant uncertainties about the ice load, the timing of the ice history and the earth model which result in large uncertainties in the estimated rates of PGR. Still it is unlikely that the observed trend in gravity -0.6 ± 0.1 μGal yr^{-1} and in GPS vertical position $+2.7 \pm 0.2$ mm yr^{-1} are due to PGR. We must wait a while longer to determine this conclusion definitively.

Uplift of the Ardenne

The conflicting vertical trends determined from all observations (gravity, GPS, geology, levelling) raise the questions: (1) To what extent are vertical movements reliable, whether they are inferred from geology or measured by repeated levellings? and (2) Are the possible deformations linked to active faults in the Ardenne and/or bordering the Roer Graben, or perhaps linked to the Eifel plume? Absolute and relative gravity measurements performed at the Membach Station should help in resolving these issues. Uplift or subsidence would modify the gravity at a rate of 0.2 μGal mm^{-1}. If the observed trend of -0.6 ± 0.1 μGal yr^{-1} persists into the future, it would mean that gravity observations confirm an uplift rate of about 3.0 ± 0.5 mm yr^{-1}, neglecting the post-glacial rebound.

In order to confirm this uplift and to estimate its wavelength, we are performing semi-annual AG measurements along an eight-station profile across the Ardenne and the Roer Graben (Van Camp *et al.* 2002). This campaign, which began in 1999 September, will contribute to our understanding the mechanism of the uplift. These results combined with the long-term continuous measurements currently performed in Membach should also confirm the downward gravity trend (i.e. the uplift of the Ardenne). After 3 yr of measurements, there is no gravity variation higher than what is physically detectable, i.e. $\sim$2 μGal yr^{-1} at the 95 per cent confidence level. After 10 yr of observations, we should be able to detect or to constrain any possible long-term gravity rate of change with an accuracy of 0.5 μGal yr^{-1} or better if we are able to correct for hydrological effects.

CONCLUSION

More than 5 yr of GPS and 7 yr of AG and SG data from Membach have been analysed. After removing the instrumental drift of the C-021 superconducting gravimeter, we demonstrated that the SG observations agree with those from the FG5-202 absolute gravimeter at the microgal level. The remaining signal in the SG residuals is, most likely, related to unmodelled environmental effects. The trend that has been identified in the AG data indicate a possible uplift of the Belgian Ardenne of about 3.0 ± 0.5mm yr^{-1}. This inferred uplift is confirmed by the 2.7 ± 0.2 mm yr^{-1} uplift observed by continuous GPS performed 3 km away from the Membach Geophysical Station. This uplift is the most likely explanation for the observed gravity variations in light of currently available data.

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REFERENCES

Beutler, G. *et al.,* 2001. *Bernese GPS Software Version 4.2,* eds Hugentobler, U., Schaer, S. & Fridez, P., Astronomical Institute University of Berne.

Boy, J.P., Hinderer, J. & Gégout, P., 1998. The effect of atmospheric surface loading on gravity, in: *Proc. 13th Int. Symp. on Earth Tides, Brussels*, pp. 5439–5446, eds Ducarme, B. & Pâquet, P., Observatoire Royal de Belgique, Brussels.

Camelbeeck, T. & Meghraoui, M., 1996. Large earthquakes in northern Europe more likely than once thought, *EOS, Trans. Am. geophys. Un.,* **77,** 405–409.

Camelbeeck, T. & Meghraoui, M., 1998. Geological and geophysical evidence for large paleoearthquake with surface faulting in the Roer Graben (northwest Europe), *Geophys. J. Int.,* **132,** 347–362.

Camelbeeck, T., Van Camp, M., Jongmans, D., Francis, O. & van Dam, T., 2002. Comment on 'Nature of the vertical ground movements inferred from high-precision leveling data in an intra-plate setting: NE Ardenne, Belgium' by Demoulin, A. & Collignon, A., *J. geophys. Res.,* **107**(B11), doi:1029/2001JB000397.

Cornet, Y., 1995. L'encaissement des rivières ardennaises au cours du Quaternaire, L'Ardenne, *Essai de Géographie Physique, Hommage au Professeur A. Pissart,* pp. 155–177, ed. Demoulin, A., University of Liège.

Farrell, W.E., 1972. Deformation of the Earth by surface loads, *Rev. Geophys.,* **10,** 761–797.

Francis, O., 1997. Calibration of the C021 superconducting gravimeter in Membach (Belgium) using 47 days of absolute gravity measurements. *IAG Symposia: Gravity, Geoid and Marine Geodesy,* Vol. 117, pp. 212–218, Springer, Berlin.

Francis, O., Niebauer, T.M., Sasagawa, G., Klopping, F. & Gschwind, J., 1998. Calibration of a superconducting gravimeter by comparison with an absolute gravimeter FG5 in Boulder, *Geophys. Res. Lett.,* **25**(7), 1075–1078.

Goodkind, J., 1986. Continuous measurements of non-tidal variations of gravity, in: Chapman conference on vertical crustal motions; measurement and modelling, *J. Geophys. Res.,* **91,** 9125–9134.

Hinderer, J., Florsch, N., Mäkinen, J., Legros, H. & Faller, J.E., 1991. On the calibration of a superconducting gravimeter using absolute gravity measurements, *Geophys. J. Int.,* **106,** 491–497.

James, T. & Ivins, E., 1998. Predictions of Antarctic crustal motions driven by present-day ice sheet evolution and by isostatic memory of the Last Glacial Maximum, *J. geophys. Res.,* **103,** 4993–5017.

Keyser, M., Ritter, J.R.R. & Jordan, M., 2002. 3D shear-wave velocity structure of the Eifel plume, Germany, *Earth planet. Sci. Lett.,* **203,** 59–82.

Lambert, A., Courtier, N., Sasagawa, G.S., Klopping, F., Winester, D., James, T.S. & Liard, J.O., 2001. New constraints on Laurentide postglacial rebound from absolute gravity measurements, *Geophys. Res. Lett.,* **28,** 2109–2112.

Mälzer, H., Hein, G. & Zippelt, K., 1983. Height changes in the Rhenish Massif: determination and analysis, in *Plateau Uplift,* pp. 164–176, eds K. Fuchs, *et al.,* Springer, Berlin.

Merriam, J.B., 1992. Atmospheric pressure and gravity, *Geophys. J. Int.,* **109,** 488–500.

Milly, P.C.D. & Shmakin, A.B., 2002. Global modelling of land water and energy balances, Part1: the land dynamics (LaD) model, *J. Hydrometeorol.,* **3,** 283–299.

Milne, G.A., Davis, J.L., Mitrovica, J.X., Scherneck, H.-G., Johansson, J.M., Vermeer, M. & Koivula, H., 2001. Space-geodetic constraints on glacial isostatic adjustment in Fennoscandia, *Science,* **291,** 2381–2385.

Niebauer, T., Sasagawa, G., Faller, G., Hilt, R. & Klopping, F., 1995. A new generation of absolute gravimeters, *Metrologia,* **32,** 159–180.

Peter, G., Klopping, F.J. & Berstis, K.A., 1994. Observing and modeling gravity changes caused by soil moisture and groundwater table variations with superconducting gravimeters in Richmond, Florida, U.S.A., in *Proc. 2nd Workshop on Non-tidal Gravity Changes: Intercomparison Between Absolute and Superconducting Gravimeters,* Cahiers du Centre Européen de Géodynamique et de Séismologie, Luxembourg, ed. Poitevin, C., 11, pp. 147–159.

Quinif, Y., 1998. Karst et évolution des Rivières: le Cas de l'Ardenne, *Spéléochronos Hors Série Karst and Tectonics,* pp. 145–148.

Ritter, J.R., Jordan, M., Christensen, U.R. & Achauer, U., 2001. A mantle plume below the Eifel volcanic fields, Germany, *Earth planet. Sci. Lett.,* **186,** 7–14.

Van Camp, M., Vauterin, P., Wenzel, H.-G., Schott, P. & Francis, O., 2000. Accurate transfer function determination for superconducting gravimeters, *Geophys. Res. Lett.,* **27**(1), 37–40.

Van Camp, M., Camelbeeck, T. & Francis, O., 2002. Crustal motions across the Ardenne and the Roer Graben (north-western Europe) using absolute gravity measurements, *Metrologia,* **39,** 503–508.

van Dam, T. & Francis, O., 1998. Two years of continuous measurements of tidal and nontidal variations in gravity in Boulder, Colorado, *Geophys. Res. Lett.,* **25**(3), 393–396.

van Dam, T., Larson, K., Wahr, J., Francis, O. & Gross, S., 2000. Using GPS and absolute gravity to observe ice mass changes in Greenland, *EOS, Trans. Am. geophys Un.,* **81,** 426–427.

van Dam, T., Wahr, J., Milly, P.C.D., Shmakin, A.B., Blewitt, G., Lavalee, D. & Larson, K.M., 2001. Crustal displacements due to continental water loading, *Geophys. Res. Lett.,* **28,** 651–654.

van den Berg, M.W., Groenewoud, W., Lorenz, G.K., Lubbers, P.J., Brus, D.J. & Kroonenberg, S.B., 1994. Patterns and velocities of recent crustal movements in the Dutch part of the Roer Valley rift system, *Geol. Mijnbouw,* **73,** 157–168.

Vandijcke, S. & Quinif, Y., 2001. Recent active faults in Belgian Ardenne revealed in Rochefort Karstic network (Namur Province, Belgium), *Geol. Mijnbouw,* **80,** (3–4), 297–304.

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

Wahr, J., Han, D. & Trupin, A., 1995. Predictions of vertical uplift caused by changing polar ice volumes on a viscoelastic earth, *Geophys. Res. Lett.,* **22,** 977–980.

Warburton, R.J. & Brinton, E.W., 1995. Recent developments in GWR Instrument's superconducting gravimeters, *Proc. 2nd Workshop on Non-tidal Gravity Changes: Intercomparison Between Absolute and Superconducting Gravimeters,* Cahiers du Centre Européen de Géodynamique et de Séismologie, Luxembourg, ed. Poitevin, C., 11, pp. 23–56.

Wenzel, H.-G., 1996. The nanogal software: Earth tide data processing package, ETERNA 3.30, *Bull. Inf. Marées Terrestres,* **124,** 9425–9439.

Williams, S.D.P., Baker, T.F. & Jeffries, G., 2001. Absolute gravity measurements at UK tide gauges, *Geophys. Res. Lett.,* **28**(12), 2317–2320.

Zerbini, S., Richter, B., Negusini, M., Romagnioli, C., Simon, D., Domenichini, F. & Schwahn, W., 2001. Height and gravity variations by continuous GPS, gravity and environmental parameter observations in the southern Po Plain, near Bologna, Italy, *Earth planet. Sci. Lett.,* **192,** 267–297.