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# Seasonal height change influence in GPS and gravimetric campaign data

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**Abstract**

Low motion rates, typical of intraplate settings, make it particularly difficult to isolate a tectonic signal in vertical displacements of the ground dominated by near-surface influences. Since the spring 2003, we have performed half-yearly GPS and gravimetric campaigns in NE Ardenne in order to evaluate the seasonal changes imposed to the ground height by groundwater variations. The GPS height data show an excellent negative correlation with a proxy for groundwater variations, based on rainfall in the 6 months before the survey, that allows a reliable correction of the measured height changes. During the 2003–2005 time span, the seasonal groundwater-dependent height changes have amounted to a maximum 7.5 mm. The gravimetric campaigns were able to detect reliably only gravity changes larger than 10 μgal, which corresponds to the upper limit of the gravity changes associated with the proposed groundwater-GPS model. No conclusive result may therefore be derived from the gravity observations.


*Keywords:* GPS; Gravimetry; Seasonal height change; Loading by groundwater; Ardennes; Belgium

## 1. Introduction

Vertical displacements of the ground are monitored since 1992 in NE Ardenne in order to detect possible tectonic motion either of regional extent or located on particular active faults (Demoulin, 2004; Demoulin et al., 2005). Indeed, this information may significantly contribute to define the regional seismic hazard, provided a clear separation can be made between the reported tectonic displacements and other recorded ground movements caused by near-surface influences. The tectonic signal extraction is particularly difficult in the intraplate setting of NE Ardenne, where vertical ground displacements are frequently observed to reach a few mm/year while the expected long-term tectonic motions are at best in the order of 0.1 mm/year. In this respect, groundwater level variations have been demonstrated to play a major role, causing millimetre-scale local differential vertical displacements even when the compared surveys are carried out in the same time of the year (Demoulin, 2004). Groundwater-dependent absolute movements at a particular site are thus expected to be still larger. Removing the seasonal and longer-term effects of groundwater variations

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from ground height change data obtained by campaign-mode, either levelling or GPS measurements is therefore the main challenge in such studies. In order to get an insight into the seasonal height changes and their impact on rate estimates obtained from discontinuous monitoring, we performed joint GPS and gravimetric campaigns twice a year, in March–April and September–October, from 2003 to 2005 over a part of a local GPS network established in 1999 in NE Ardenne. Gravity measurements were performed in an attempt to constrain, or at least to confirm the modelled relation between groundwater and GPS height behaviours.

The study area is located in the NE part of the Ardenne, a Paleozoic massif situated in the foreland of the Alpine orogen close to the Lower Rhine segment of the European Cenozoic rift system (Fig. 1). It is centred on the Hautes Fagnes massif, ∼20 km southwards of the major faults bounding the Roer Valley Graben to the SW. Quaternary river incision suggests that the NE Ardenne could have uplifted by up to 200 m during the last 800 kyear (van Balen et al., 2000). However, river downcutting strongly decreased since 400 ka, indicating that uplift rates up to ∼0.5 mm/year between 800 and 400 ka gave way to tectonic quiescence in recent times.

## 2. GPS network, data acquisition and processing

The GPS network, monitored since 1999, was designed to cover the three main subunits of the study area, i.e. the Hautes Fagnes massif, its northern foreland between the Vesdre valley and the Variscan front, and the Malmédy graben to the south (Figs. 1 and 2). This design also yields three transects across the active Hockai fault zone, one in each tectonic subunit. The maximum difference in height between the sites is 438 m. Purpose-built GPS antenna supports were anchored in the roof's concrete cornice of flat-topped buildings more than 20-years-old, in order to minimize problems of monument instability and to ensure that all antenna setups be strictly identical in all campaigns. Six sites were surveyed twice a year from 2003 to 2005.

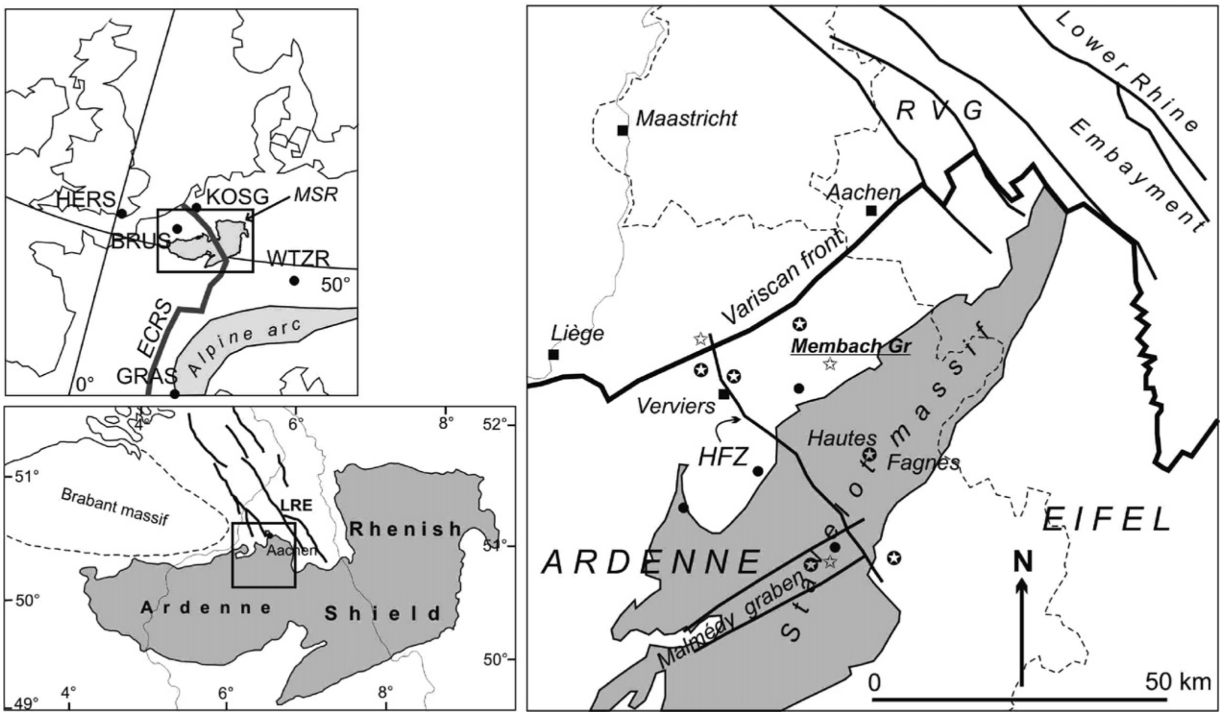


Fig. 1. Geological sketch map of the study area. In the large-scale map, solid circles denote the sites measured yearly by GPS since 1999. Circled stars locate the sites used in this study, with two GPS and gravity measurements per year. Open stars are additional sites with two gravity measurements per year. The Variscan front marks the northern border of the Paleozoic Ardennes massif and the Cambrian Stavelot massif appears in grey. HFZ, Hockai fault zone; RVG, Roer Valley Graben; LRE, Lower Rhine Embayment; ECRS, European Cenozoic rift system; MSR, Rhenish shield. The upper left inset locates the five IGS sites used in this study.

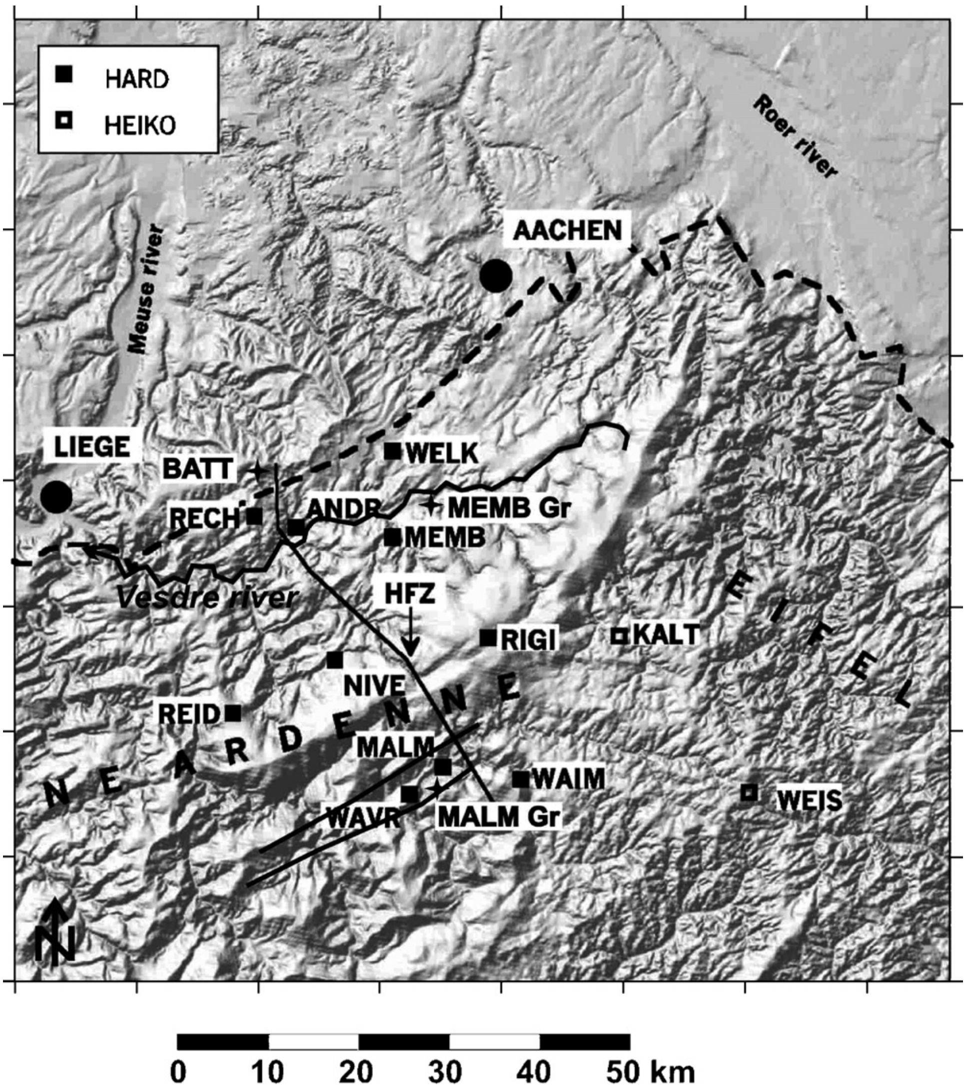


Fig. 2. Location of the measured sites on a DEM of NE Ardennes and Eifel (type and frequency of measurement, see Fig. 1). The dashed line marks the contact between the Rhenish shield to the south and, respectively, the Mesozoic Pays de Herve to the NW and the Cenozoic Lower Rhine Embayment, part of the ECRS, to the NE. HFZ, Hockai fault zone.

The measurement campaigns were carried out in March–April and September–October. At each campaign, all sites were occupied simultaneously during at least 72 h, yielding three or more 24-h-sessions. Although we were not able to use GPS equipment of the same manufacturer and type over the whole network, the same antenna/receiver pairs always reoccupied the same sites so that the network's instrumental configuration was identical from one survey to the other.

We processed the data with the Gamit/Globk 10.07 software (King and Bock, 1998; Herring, 1999), using double differences of the phase and code data on the ionosphere-free $L_c$ combination to compute firstly daily solutions. We used the IGS precise orbit sp3 files, from which orbital initial conditions were estimated. The satellite orbits were fixed on the positions integrated from these initial conditions. Badly behaving satellites, i.e. satellites with at least one orbit parameter rms > 0.5 m were removed from the computations. We also included in the calculated network five IGS permanent GPS stations (BRUS, GRAS, HERS, KOSG, WTZR) which encircle and enlarge the local network and whose well-constrained coordinates and velocities allowed the stabilization of the global solution in the ITRF00 reference frame. The antenna phase centre offsets and elevation-dependent variations were taken from the absolute calibration models of Geo++ (Wübbena et al., 2003), whose azimuth-dependent variations were averaged. Cutoff angle was set at 10°. Tropospheric zenith delays were estimated for each site and every 3-h interval. The Gamit treatment provided two daily solutions with loose constraints on all estimated parameters, respectively, with floating and fixed (integer) ambiguities. Owing to its higher quality, the fixed ambiguity solution was used in the Globk combinations.

The Globk processing step allowed the combination of individual session solutions. In a first stage, the three or more daily solutions of a campaign were used as quasi-observations in a Kalman filter and combined to yield a campaign solution for which we still applied loose constraints on the IGS site coordinates but tight ones on the earth orientation parameters. Then, the campaign solutions were in turn combined as quasi-observations to get an insight into their repeatability and to obtain estimates of the site velocities. In this last stage, we strongly constrained the IGS site coordinates and velocities (10 and 3 mm/year, respectively, on the up component of coordinate and velocity). None of them was totally fixed on their ITRF values in order to let space for their own seasonal height changes.

In the processing of the daily sessions, the statistics of the one-way phase residuals after a first adjustment and postfit data cleaning displayed rms values in the range of 6–8 mm, bearing witness to very good daily solutions. An additional information derived from one-way phase postfit residuals was the standard deviation and the elevation-dependent parameter for 'a priori' (in terms of a later run) receiver measurement error models in the form $e = \sqrt{(a^2 + b^2/\sin^2[\mathrm{elev}])}$, used for data weighting in a second adjustment (King and Bock, 1998). Depending on the propagation of these a priori assigned errors and on tight constraints imposed on the IGS station coordinates in the repeatability analysis (1.5 cm on the up component of GRAS, HERS, KOSG and WTZR, 2 cm for BRUS), the $1\sigma$ uncertainties on the up component of the daily positions of the HARD sites lay in the range 7–10 mm, yielding $\sigma$ values of 3.0–4.7 mm at the campaign level. As for the intra-campaign wrms of the up component of the sites, they were in the ranges of, respectively, 1.4–5.9 mm (2003/spring), 0.9–2.9 mm (2003/autumn), 1.0–3.0 mm (2004/spring), 1.5–8.1 mm (2004/autumn) and 1.1–4.1 mm (2005/spring). Then, we loosened again the constraints on the IGS site coordinates to compute the campaign values before we retightened them in the global solution computation (this time at 1 cm on the up component of all involved IGS stations). At this final level and with these new frame constraints, the $1\sigma$ uncertainty was 4.6–5.3 mm on the campaign values of the up coordinates and 2.1–2.9 mm on their final values (with the exception of RECH: 4.7 mm). As mentioned above, these formal errors result from the propagation of the a priori errors assigned to the phase observations on the basis of postfit one-way residuals of a first run of the daily sessions and, in this sense, they may appear realistic. In comparison, based on the five available epochs, the wrms of the campaign values of up components, which reflect the investigated seasonal forcing, lie within 2.0–10.6 mm.

## 3. Gravimetric network, data acquisition and processing

The gravimetric campaigns were performed quasi-simultaneously with the GPS measurements since the autumn 2003.

The gravimetric network is based on the three GPS transects across the Hockai fault zone but additional stations were included, one in each profile (stars in Fig. 2). The profiles were linked together by two transverse lines: Malmédy Gr–Mont Rigi–Membach Gr/ext–Battice and Wavreumont–Nivezé–Petit Rechain. The maximum gravity difference is close to −100 mgal between Petit Rechain and Mont Rigi. Each campaign was referred to the gravity value measured in Membach Gr, where absolute measurements are regularly performed (Membach Gr/abs in Table 1) and where a superconducting gravimeter is recording permanently the gravity changes.

We generally used two SCINTREX CG3M (Ducarme and Somerhausen, 1997) or CG5 gravimeters working side by side. The CG3M S265 belonging to the Royal Observatory of Belgium took part to all campaigns and was used to normalize the scale of the other instruments. An additional survey was performed in March 2005 with two LaCoste & Romberg (LCR) gravimeters.

Each profile or transverse line was observed twice on the same working day. As a first step, the gravity differences were determined separately for each day and each gravimeter (Everaerts et al., 2002). Later on, a general adjustment of the gravity differences obtained during each campaign was performed to determine the gravity values at each station, with respect to the observed value at Membach Gr/abs given in the last line of Table 1. After adjustment, the standard deviation on one gravity difference is comprised between 5 and 7 μgal ($1\ \mu\text{gal} = 10\ \text{nm s}^{-2}$). The standard deviation $\sigma$ on one gravity value for one campaign is comprised between 3 and 5 μgal for the SCINTREX gravimeters and 5–15 μgal for the LCR one.

Table 1
Variations of $g$ with respect to the Membach absolute gravity point (Membach Gr/abs) and determination of the mean seasonal effect

| Station | 04/2003 $g'$ (μgal), $\sigma$ (μgal) | 09/2003 $g'$ (μgal), $\sigma$ (μgal) | 04/2004 $g'$ (μgal) $\sigma$ (μgal) | 09/2004 $g'$ (μgal) $\sigma$ (μgal) | 03/2005 $g'$ (μgal) $\sigma$ (μgal) | Spring $g'$ (μgal) | Autumn $g'$ (μgal) | Diff. A-S (μgal) |
|---|---|---|---|---|---|---|---|---|
| *N* | 31 | 68 | 76 | 44 | 43 | | | |
| Rechain | 15,338, 5.1 | 15,537, 3.9 | 15,538, 4.4 | 15,527, 4.3 | 15,541, 11.2 | 15339.0 | 15532.0 | **−7.0** |
| Battice | 14,468, 3.6 | 14,475, 3.3 | 14,473, 4.2 | 14,468, 4.3 | 14,476, 8.5 | 14472.3 | 14471.5 | −0.9 |
| Andrimont | 12,261, 5.2 | 12,260, 4.3 | 12,257, 5.1 | 12,257, 5.7 | 12,259, 15.4 | 12259.0 | 12258.5 | −0.5 |
| Welkenraedt | 11,028, 5.9 | 11,032, 3.9 | 11,023, 5.0 | 11,025, 5.6 | 11,022, 12.3 | 11024.3 | 11028.5 | +4.2 |
| Membach Gr/ext. | 2933, 2.5 | 2942, 1.8 | 2935, 2.9 | 2940, 2.7 | 2938, 6.1 | 2935.3 | 2941.0 | +5.7 |
| Nivezé | −9488, 3.9 | −9488, 3.0 | −9492, 4.1 | −9487, 4.4 | −9488, 10.6 | −9489.3 | −9487.5 | +1.8 |
| Malmédy | −18,791, 5.4 | −18,791, 3.6 | −18,795, 5.0 | −18,792, 5.8 | −18,796, 13.0 | −18794.0 | −18791.5 | +2.5 |
| La Reid | −27,252, 3.6 | −27,253, 2.9 | −27,261, 4.1 | −27,260, 4.5 | −27,248, 10.1 | −27253.7 | −27256.5 | −2.8 |
| Malmédy Gr | −37,462, 3.9 | −37,459, 2.8 | −37,454, 4.4 | −37,454, 4.6 | −37,455, 10.6 | −37457.0 | −37456.5 | +0.5 |
| Wavreumont | −41,502, 5.4 | −41,509, 3.5 | −41,504, 4.5 | −41,500, 4.8 | −41,511, 11.1 | −41505.7 | −41504.5 | +1.2 |
| Waimes | −54,295, 5.8 | −54,291, 3.6 | −54,293, 5.0 | −54,288, 5.8 | −54,280, 15.4 | −54289.0 | −54289.5 | −0.5 |
| Mt. Rigi | −77,700, 2.6 | −77,696, 2.4 | −77,707, 3.8 | −77,686, 4.1 | −77,694, 8.7 | −77700.3 | −77690.0 | **+9.7** |
| Membach Gr/abs[a] | 3.9 | 9.2 | 5.6 | 8.0 | 7.9 | 5.8 | 8.6 | +2.8 |

Stations are ordered according to decreasing $g$ values.
[a] $g' = g - 981{,}046{,}720$ μgal; $\sigma$ (μgal), standard deviation on gravity value; $N$, number of ties.

## 4. Influence of groundwater variation on height and gravity change

### 4.1. Relation between rainfall, groundwater, atmospheric pressure and GPS height change

The time-dependent heights of the GPS sites are presented in Fig. 3. Two main near-surface influences on ground height changes $\Delta H$ are known to be atmospheric and groundwater loading (van Dam et al., 1994, 2001; Dong et al., 2002). Indeed, since we were not dealing with local-scale relative heights, we assumed that, among the effects of groundwater variations on $\Delta H$, the loading effect predominated over the pore pressure effect (Demoulin, 2006). Rather than modelling these various effects, we searched for statistical correlation between height changes and variations in atmospheric pressure and groundwater level.

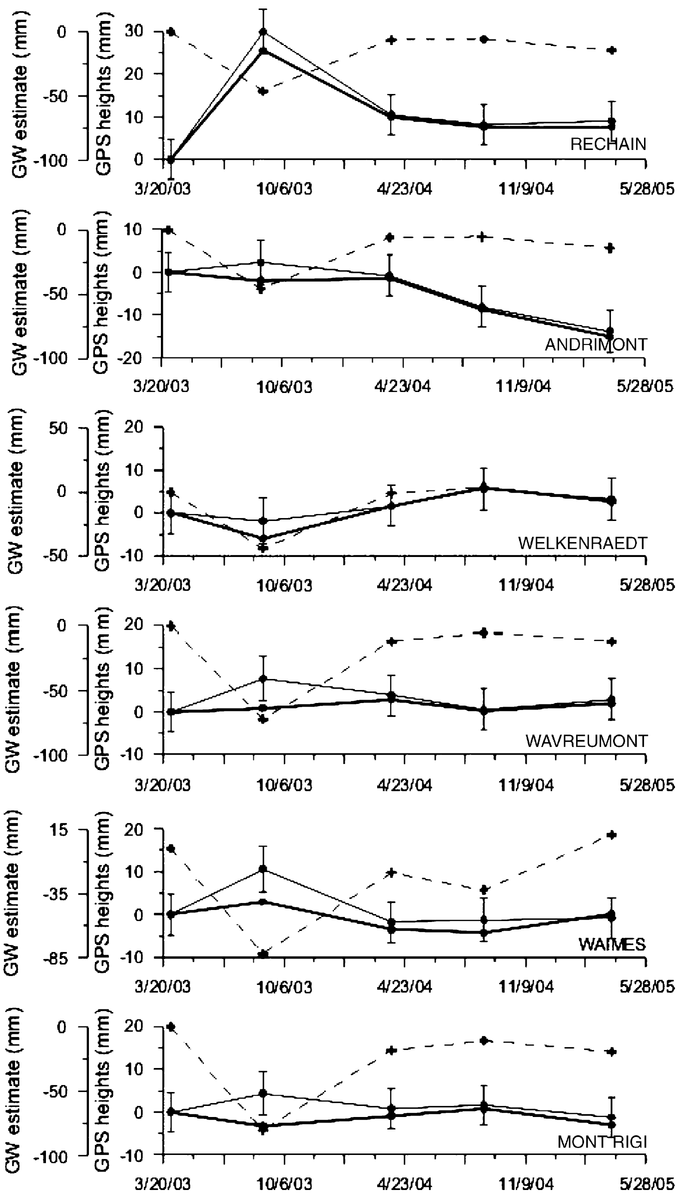


Fig. 3. Compared time series of the GPS height (thin line), $GW_{est}$ (dashed line) and corrected height (bold line) at all sites measured by GPS. Vertical bars denote the $\pm1\sigma$ uncertainty on the GPS heights. The GPS height behaviour mirrors that of the GW (groundwater level) estimate almost everywhere. The corrected heights are obtained by removal of the seasonal influence deduced from the $\Delta H$–$\Delta GW_{est}$ relation and with spring 2003 as reference epoch.

Unfortunately, no direct groundwater data were available at, or near the GPS sites, so that in a first approach we used as a proxy the rainfall amount of the last 6 months before each survey. Rainfall data were taken from stations of the Belgian meteorological network located close to our GPS sites. The efficiency of this proxy, given by the rainfall function

$$f = \sum_{m=-3}^{-1} P_m + 0.5 \sum_{m=-6}^{-4} P_m \tag{1}$$

with $P_m$ = monthly rainfall, is of course conditioned by the absence of groundwater exploitation in the area, and was demonstrated for levelling data in NE Ardenne (Demoulin, 2004).

With a predominant loading effect, a decrease in $f$, supposed to reflect a groundwater lowering, should induce a positive vertical displacement of the ground and vice versa. Considering the whole set of $\Delta H$–$\Delta f$ pairs ($n = 24$, i.e. 4 inter-survey changes at 6 sites), such a negative correlation was hardly verified. However, after removal of 5 outliers related to anomalous GPS height values at RECH and WELK in the autumn 2003 and ANDR in the spring 2005, we obtained a significant correlation between both variables ($r = -0.74$, $n = 19$) (Fig. 4A). Encouraged by this result, we tested whether a refinement of this very simple proxy definition would improve the correlation. Indeed, approximating the groundwater level by the rainfall amount of the last half-year had proved realistic as long as only one season, e.g. the winter period, was considered. However, summer rainfall is for a much greater part counteracted by evaporation and evapotranspiration, which could bias the link to groundwater (although seasonally variable runoff should also be considered). Therefore, the proxy values might be overestimated in this season, especially during wet summers like in 2004.

Thus, we tentatively weighted the $f$ values by a factor accounting for the seasonally varying, temperature-dependent loss of water in the way between rainfall and groundwater reservoir. Petit (1995) reported that in S Ardenne, an average 25% of the rainfall finally would feed the groundwater reservoir. Starting from this value, we empirically defined another groundwater proxy as

$$\mathrm{GW_{est}} = 0.25 f \times \left(1 - \frac{T_{m\,6m} - T_{m\,\mathrm{ann}}}{4\Delta_{\max}(T_{m\,m})}\right) \tag{2}$$

with $T_{m\,6m}$ = temperature averaged over the 6-month-period used to define $f$, $T_{m\,\mathrm{ann}}$ = mean annual temperature and $\Delta_{\max}(T_{m\,m})$ = maximum range between mean monthly temperatures. Estimating very roughly the bedrock porosity to $\phi = 0.2$, the observed changes in $\mathrm{GW_{est}}$ would reflect realistic seasonal variations of the groundwater level in the order of ~0.4 m.

This new proxy proved more efficient than $f$. Searching for a relation with the observed GPS height changes and still excluding the same few outliers related to anomalous GPS data, we obtained a very good negative correlation ($r = -0.78$, $n = 19$). Based on the three least noisy stations (WAIM, WAVR and RIGI), all located within the Paleozoic massif, an even stronger relation ($r = -0.86$, $n = 12$) was found. The best linear fit indicates that a +50 mm seasonal variation in $\mathrm{GW_{est}}$ would cause a $-4.7 \pm 0.9$ mm height change of the ground surface (Fig. 4B). The calculated seasonal changes of ~0–80 mm in $\mathrm{GW_{est}}$ correspond then to ~0–7.5 mm vertical displacements of the ground, consistent with what is recorded in many GPS permanent stations in temperate areas (van Dam et al., 2001).

As for the atmospheric loading, its variations revealed an unrealistic positive correlation with the observed $\Delta H$, a +1 hPa change in pressure apparently inducing a ground upheaval of +0.62 mm ($n = 19$ same data as above, $r = 0.60$) to +0.83 mm ($n = 12$, i.e. WAIM, WAVR and RIGI, $r = 0.75$). This only stresses the fact that correlation does not necessarily mean cause-to-effect relationship, the present one rather resulting from the strong anti-correlation existing between $\Delta P_{\mathrm{atm}}$ and $\Delta \mathrm{GW_{est}}$ (at least for the compared epochs) and suggesting that the atmospheric loading effect was largely overprinted by the groundwater loading effect. This was confirmed by a multiple regression analysis which showed that only $\Delta \mathrm{GW_{est}}$ explains a significant part (62%) of the variance of $\Delta H$. However, this imbalance between both effects is surprising as their causes are of the same order of magnitude (2–9 hPa $\Delta P_{\mathrm{atm}}$ against 0–8 cm $\Delta \mathrm{GW_{est}}$, i.e. ~0–8 hPa) and we cannot explain it (a possible cause could be that the estimation of tropospheric zenith delays in the GPS data processing would take up much of the atmospheric loading effect).

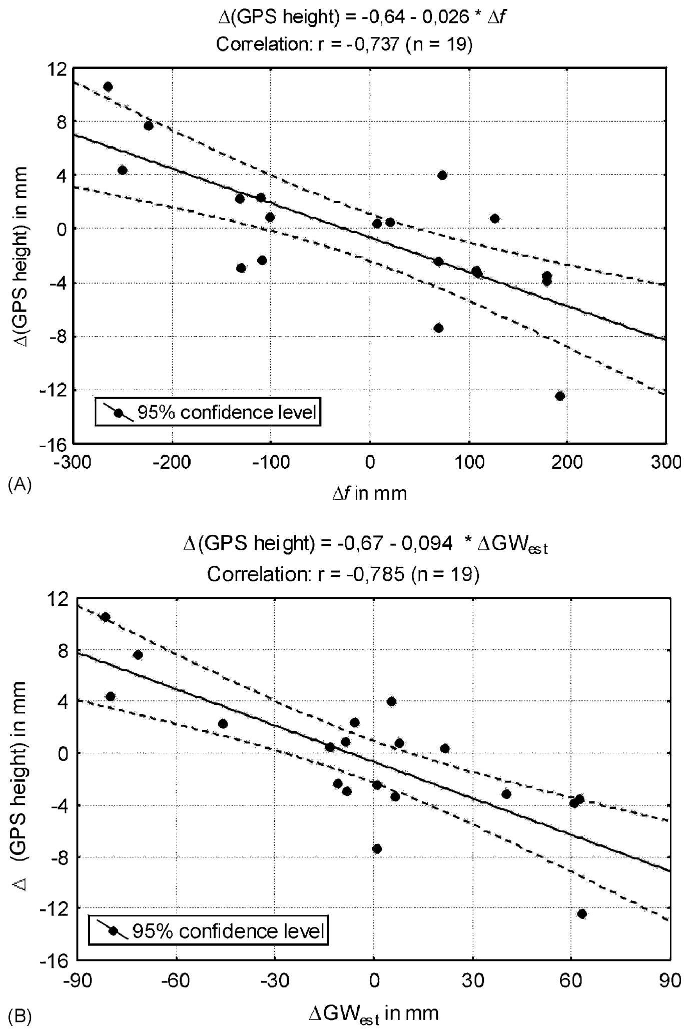


Fig. 4. Correlation between the seasonal changes in GPS heights and various expressions of the groundwater level seasonal changes, based on monthly rainfall data: (A) *f*, direct function of semester rainfall; (B) $GW_{est}$, derived from *f* and accounting for temperature-dependent evaporation and evapotranspiration. The latter proxy, probably better reflecting the true aquifer behaviour, shows particularly well the prevailing influence of groundwater level variations on GPS heights. Outliers (residuals > 1$\sigma$), related to anomalous GPS height values at RECH and WELK in the autumn 2003 and ANDR in the spring 2005, are excluded from the regressions.

### *4.2. Relation between rainfall, groundwater and gravity changes*

Table 1 displays the gravity values as referred to the absolute gravity of Membach Gr/abs, and their seasonal means. The rms error on the absolute gravity value at Membach Gr/abs is below 2 μgal. The results are extremely stable in most stations.

Fig. 5 illustrates the gravity changes recorded for stations along the north and south profiles, together with the corresponding GW function. Note that the error bars are figured at the 1$\sigma$ level. It should be pointed out that gravity changes at the level of 10 μgal correspond to the limit of detection of our observations.

The Membach Gr sites (Membach Gr/abs and Membach Gr/ext in Table 1) are particular, due to the presence, at a distance of 3 km, of a water reservoir located higher than the stations. Therefore, gravity at Membach Gr is generally larger in autumn than in spring, in opposition to the water level in the reservoir (Van Camp et al., 2003). However, this yearly cycle is strongly irregular. A similar behaviour is observed in the underground station (Membach Gr/abs) and on the exterior point. The gravity difference between the exterior and the absolute gravity points is slightly larger in autumn (2932.4 μgal) than in spring (2929.5 μgal).

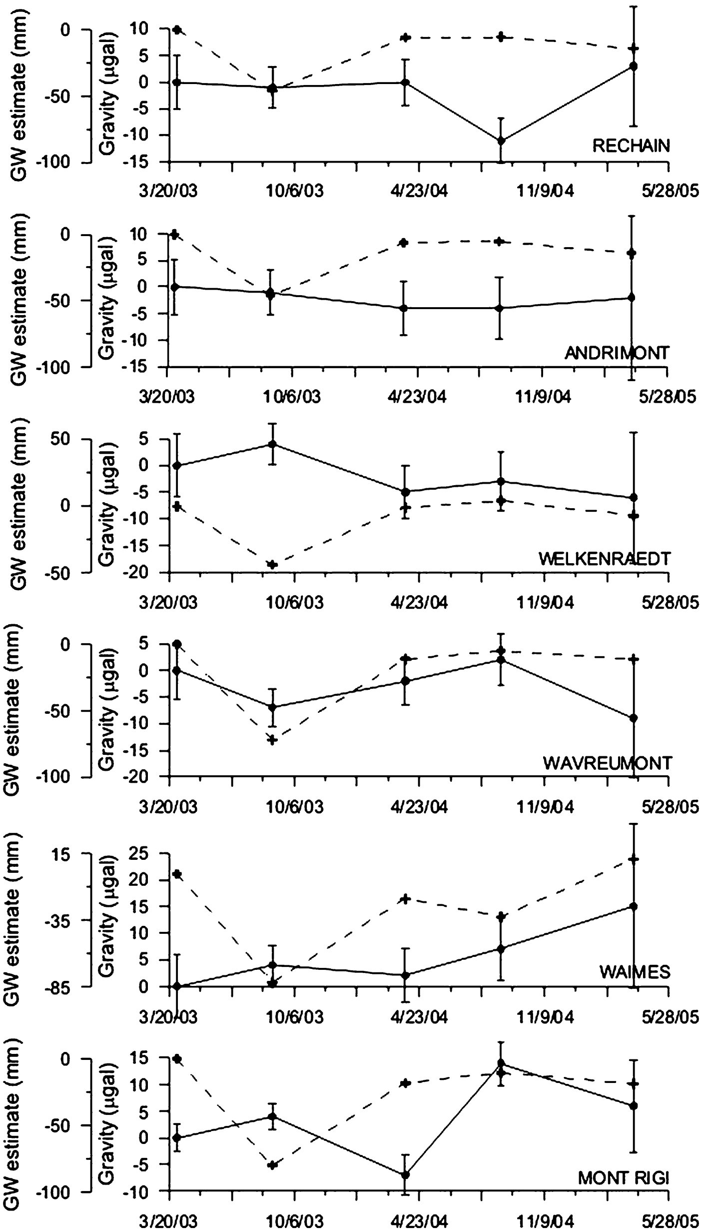


Fig. 5. Observed gravity (solid line) and $GW_{est}$ function (dashed line) variations for the stations with available seasonal GPS data. The uncertainty on gravity is shown at the 1$\sigma$ level. Significant gravity variations may exist at least in Petit Rechain and especially Mont Rigi.

As a matter of fact, significant seasonal gravity changes appear only before and after the autumn 2004 in Mont Rigi and perhaps at Petit Rechain, but with opposite signs. A question arises thus concerning a possible change of the scale factor of the S265 gravimeter between April and September 2004, as Mont Rigi ($g' = -77.7$ mgal) and Petit Rechain ($g' = +15.5$ mgal) correspond to the extreme gravity values of the network. However, the observed variations (+21 and −11 µgal) are not proportional to the corresponding gravity values. Given the large difference of elevation between stations in some loops (central transect and transverse lines) an instrumental effect due to pressure and temperature differences was suspected. This is why an additional spring campaign was performed in 2005 using a LaCoste & Romberg gravimeter in place of SCINTREX ones, but the instrumental error of this campaign is much larger, so that no firm conclusion can be derived concerning instrumental effects.

The expected gravity changes should be positively correlated with groundwater variations. As stated above, we estimate the groundwater storage through the $f$ (rainfall) and GW (corrected rainfall) functions. No correlation can be seen in Fig. 5 between gravity variations and GW function. The behaviour of the Rechain site, characterized by lower gravity values in autumn 2004, is not supported by the GW function variations. We hypothesize that the large gravity increase at Mont Rigi in autumn 2004 could have responded to the exceptional summer downpours, the peat-moss area surrounding the station reacting like a sponge. As a matter of fact, gravity is always larger in autumn than in spring at Mont Rigi.

## 5. Discussion

### *5.1. Groundwater influence and GPS height variation*

The negative correlation obtained between height change and $GW_{est}$ variation confirms our initial hypothesis, which stated that the influence of groundwater variations on vertical displacements of the ground is dominated by the loading effect. Considering exclusively the spring measurements, the $\Delta GW_{est}$–$\Delta f$ relation is approximately linear ($\Delta GW_{est} \approx 0.266\,\Delta f$) and the computed relation

$$\Delta H = (-0.094 \pm 0.018)\,\Delta GW_{est} + \varepsilon \quad (3)$$

may be interestingly compared with

$$|\Delta H_r| = (+0.014 \pm 0.001)|\Delta GW_{est}| + \varepsilon' \quad (4)$$

equivalent to

$$|\Delta H_r| = (+0.0037 \pm 0.0003)|\Delta f| + \varepsilon' \quad (5)$$

The latter relation was obtained from yearly levelling comparison for local differential ground movements in the same area (Demoulin, 2004). In this figure, the positive correlation records the increase in average relative height change between stations ~1 km apart resulting from a larger variation in $f$ or GW. This differential effect appears to be smaller than the absolute effect of loading by a factor of ~7 but, since it is given in absolute value, it contains no sense (up/down) information and is unable to reveal which groundwater effect predominates at the local scale. This may be known only when individual GW data are available at each levelled station, showing then that the pore pressure effect prevails in the differential mode (Demoulin, 2006). The reason for the predominance of either groundwater effect in the measurements lies chiefly in the nature and the spatial scale of the displacements measured. Due to the flexural rigidity of the crust, a local gradient in loading cannot be manifested by a local differential movement at the ground surface, as measured by levelling. On the contrary, a similar gradient in pore pressure will be almost entirely translated into differential ground motion as its effect concerns primarily shallow host rocks. Conversely, the loading effect generally prevails, as soon as absolute vertical motion or differential motion at the regional scale are considered.

Another interesting indication of this study is that the rate estimates of the up component of ground motion are only marginally biased when obtained from yearly surveys uncorrected for groundwater effects, provided all surveys are performed in the same time of the year. This is illustrated by the nearly identical uncorrected and corrected positions computed for the spring surveys in Fig. 3, with spring 2003 as reference time. Obviously, this holds true only as far as no too high a difference in winter rainfall occurs between the compared surveys. For instance, the highest recorded difference in spring $GW_{est}$ value over the period 1993–2005 in NE Ardenne was 90 mm between 1996 and 2002, implying an 8.5 mm correction on measured 1996–2002 $\Delta H$. But more generally, such yearly surveys appear to be a valuable substitute for continuous measurements as long as there is no long-term trend in groundwater level. In this respect, based on the spring $GW_{est}$ values, the groundwater-induced correction on $\Delta H$ between a survey in 1993 and another one in 2005 would amount to 2.6 mm in NE Ardenne (equivalent to a rate correction of 0.2 mm/year).

### *5.2. Modelling gravity changes from GPS model*

As stated in Section 5.1, the interpretation of GPS height changes with respect to groundwater variations is based on the assumption that the loading effect predominates over the pore pressure effect. Accordingly, the height variations are anti-correlated with the GW estimate (−9.4 mm for a 10 cm water sheet in Fig. 4B). Conversely, the gravity variations should be positively correlated with GW (around 4 μgal for a 10 cm water sheet) and anti-correlated with the height variations, all the more since the free air gradient is $-3$ μgal $cm^{-1}$.

We can thus derive an approximate efficiency relationship between gravity and GW estimate of +7.0 μgal/10 cm, including the direct gravitational effect (4.2 μgal/10 cm) and the associated height variation effect (2.8 μgal/10 cm). For the observed 8 cm peak-to-peak seasonal variation of GW estimate (Fig. 3), the expected gravity changes should be in the order of 6 μgal, with lower values in the autumn 2003. No obvious gravity change is seen in most stations. Moreover, in Mont Rigi, gravity is always larger in autumn. Since these facts contradict the relation between GPS heights and GW values, well supported by GPS data, it appears improbable to ascribe them to varying hydrological conditions, and it is more reasonable to acknowledge that the expected gravity variations remain within the uncertainty of the observations.

## 6. Conclusions

GPS and gravimetric campaigns have very different capabilities in highlighting the total effect of groundwater variations on seasonal changes in ground height.

In NE Ardenne, half-yearly GPS measurements showed an excellent negative correlation with $GW_{est}$, our proxy for groundwater level based on rainfall, highlighting the predominance of the loading effect over the pore pressure effect on absolute height variations. They also allowed a reliable correction of the height data for this influence. No atmospheric loading effect was detected.

The gravity variations derived from the model linking GPS height and groundwater appear acceptable. Taking into account that the observed gravity changes are generally below 10 μgal, which corresponds to the measurement uncertainty at the 90% confidence level, gravimetric observations are clearly not able to confirm or seriously contradict the GPS model.

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