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Repeated absolute gravity measurements for monitoring slow intraplate vertical deformation in western Europe

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[1] In continental plate interiors, ground surface movements are at the limit of the noise level and close to or below the accuracy of current geodetic techniques. Absolute gravity measurements are valuable to quantify slow vertical movements, as this instrument is drift free and, unlike GPS, independent of the terrestrial reference frame. Repeated absolute gravity (AG) measurements have been performed in Oostende (Belgian coastline) and at eight stations along a southwest-northeast profile across the Belgian Ardennes and the Roer Valley Graben (Germany), in order to estimate the tectonic deformation in the area. The AG measurements, repeated once or twice a year, can resolve elusive gravity changes with a precision better than 3.7 nm/s^2/yr (95% confidence interval) after 11 years, even in difficult conditions. After 8–15 years (depending on the station), we find that the gravity rates of change lie in the [−3.1, 8.1] nm/s^2/yr interval and result from a combination of anthropogenic, climatic, tectonic, and glacial isostatic adjustment (GIA) effects. After correcting for the GIA, the inferred gravity rates and consequently, the vertical land movements, reduce to zero within the uncertainty level at all stations except Jülich (because of man-induced subsidence) and Sohier (possibly, an artifact because of the shortness of the time series at that station).

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1. Introduction

[2] This study aims at assessing long-term slow vertical deformation in northwestern Europe, an intraplate zone where the vertical deformation rate is difficult to determine with Continuous Global Positioning System (CGPS) alone. In northwestern Europe and northeastern America, apart from GIA and anthropogenic signals, geodetic observations have not yet been able to resolve any surface deformation associated with possible long-term intraplate tectonic stresses [*Camelbeeck et al.*, 2002; *Calais et al.*, 2006]. CGPS studies indicate the absence of coherent horizontal intraplate deformation at long wavelengths and rates exceeding several tenths of a millimeter per year [*Nocquet et al.*, 2005; *Calais et al.*, 2006; *Sella et al.*, 2007]. However, the absolute accuracy of the vertical land movements inferred from GPS is currently still limited by the accuracy of the International Terrestrial Reference Frame (ITRF), namely ITRF 2000 [*Altamimi et al.*, 2002] and its update ITRF2005 [*Altamimi et al.*, 2007; *Bennett and Hreinsdottir*, 2007; *Teferle et al.*, 2009]. The resulting uncertainty in absolute vertical velocity is possibly at the 1 mm/yr level because of the reference frame realization [*Argus*, 2007; *Lidberg et al.*, 2008, 2010]. In addition to these systematic errors, the resolution of vertical velocities derived from CGPS is also typically about 3–5 times lower than that of the horizontal velocities [*Bennett et al.*, 2007; *Mazzotti et al.*, 2007]. These uncertainties prevent one from measuring long wavelength vertical land movements like GIA at the mm/yr level, as well as regional tectonic deformations at the sub-mm/yr level. Nevertheless, assessing these vertical displacements is very important not only to better model the GIA effects but also to determine the relative mean sea level variations, which is paramount for coastal hazard assessment, and to better understand ongoing intraplate tectonic phenomena.

[3] This paper aims to demonstrate that the monitoring of time variable gravity is a useful alternative for studying deformations in areas undergoing slow vertical motion. An absolute gravimeter is especially valuable as no instrumental drift needs to be corrected and the measurements, based on length and time standards, do not depend on any terrestrial

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reference frame. Gravity varies locally when either the mass varies or the ground undergoes vertical motion, or both. If the gravity rate of change is very small, it shows that neither vertical movement nor any kind of mass change occurs, unless mass changes are exactly compensated for by vertical motion, which is quite unlikely. Thus, AGs are the most appropriate tools to ensure a valid determination of long-term slow vertical deformations. In addition, metrologically speaking, it is advisable to rely on measurements from different techniques, especially for the vertical component, which is the most difficult to assess.

[4] Within this scope, we undertook repeated absolute gravity measurements along a profile across the Belgian Ardennes and the Roer Valley Graben (Belgium and German northern Rhine area; see Figure 1) in 1999. This project was undertaken to evaluate present-day movement related to the Quaternary activity evidenced in the Lower Rhine Graben (LRG) system and the Rhenish Shield (Figure 1). This paper reports on this experiment and shows that vertical displacements possibly due to tectonics could not be detected, but Glacial Isostatic Adjustment (GIA) and long-term climatic effects, as well as, at some places, anthropogenic effects were demonstrated. First, we describe the absolute gravity measurements and see how to correct them for the GIA effect. We then discuss the long-term climatic and anthropogenic effects, which affect the AG time series. Finally, we show that no significant trend related to tectonics can be observed presently.

2. Observations

2.1. The Absolute Gravimeter

[5] All AG measurements used in our study were performed with a FG5 ballistic gravimeter, manufactured by Micro-g Solutions [*Niebauer et al.*, 1995]. In this instrument, a test mass is repeatedly dropped and its position is measured as a function of time, using a laser and an atomic clock. In routine operation, the drops are repeated every 5 or 10 s, 200 or 100 times per hour. This sampling rate depends on the drop-to-drop noise level at the stations [*Van Camp et al.*, 2005]. The average of 100–200 drops is a set and measurements usually consist of one set per hour. Recording a set takes 17 min; in other words, there is a gap of 43 min in the set time series. The average of several sets provides a gravity value.

[6] Intercomparison campaigns have shown systematic errors (offsets) between the different absolute gravimeters that are larger than the declared uncertainties [*Vitushkin et al.*, 2002, 2010; *Francis et al.*, 2005, 2010]. Although the offsets can be determined by comparing the instruments, this is always within uncertainties and not always logistically feasible. The easiest way to avoid uncertainties due to these offsets consists in using the same instrument, in our case the FG5#202 belonging to the Royal Observatory of Belgium. The laser, rubidium clock and barometer were checked regularly against standards. This allowed monitoring of any linear drift of the aging rubidium clock, which may bias the timing of the position of the falling mass; correcting for this effect removed an apparent trend of -1 nm/s^2/yr in our case. Other malfunctioning components may also bias the AG [*Wziontek et al.*, 2008]; this is why, before and after each campaign, the instrument measured at the Membach reference station, where it was compared with the continuously measuring superconducting gravimeter [*Van Camp et al.*, 2005; *Van Camp and Francis*, 2006]. Finally, the FG5#202 was regularly compared to other AG meters [*Robertsson et al.*, 2001; *Vitushkin et al.*, 2002, 2010; *Van Camp et al.*, 2003; *Francis et al.*, 2005, 2010; *Baumann et al.*, 2010]. The FG5#202 also benefited from maintenances by the manufacturer in 1998, 2000, 2003, 2005, 2007 and 2010, where it was also compared to other FG5s.

[7] The data were processed using the g v4 software [*Micro-g LaCoste*, 2004], which consists of a least squares fit of the trajectory data (time-position) to the equation of motion [*Niebauer et al.*, 1995]. Following the standard AG data processing, tidal, atmospheric and polar motion effects were removed.

2.2. The Profile

[8] The reference for our AG data is a series of repeated measurements since 1996 at the geodynamic station of Membach [*Francis et al.*, 2004]. These are complemented by absolute gravity measurements taken by the Royal Observatory of Belgium on a profile across the Belgian Ardennes and the Roer Valley Graben since 1999. This profile is 140 km long and consists of eight stations, including Membach. Six stations are in the Ardennes, west of the Roer Graben. The two other sites are respectively inside the graben and east of it on the Rhenish Massif (Figure 1 and Table 1). We also include the data recorded at Oostende since 1997, in the framework of the GIA effect.

[9] Three noteworthy stations are Jülich, in the graben; Membach, on the western border and Oostende, on the Belgian coastline.

[10] 1. In Membach, 185 AG measurements have been completed since 1996. In addition, hydrogeological investigations are being performed to study the influence on gravity of secular, seasonal and short-period environmental effects [*Van Camp et al.*, 2006]. Membach also houses a superconducting gravimeter which continuously monitors the variations of the gravity between AG measurements.

[11] 2. Jülich is affected by continuous water pumping during the last 50 years, to prevent flooding at opencast brown coal mines, causing a subsidence of 13.6 mm/yr. As this phenomenon is studied in detail for its economic consequences, numerous data exist on these rates. Thus, this station is a test case for evaluating the resolution of repeated AG measurements for measuring gravity changes. This anthropogenic rate of change is similar to that expected because of GIA in Fennoscandia and northern Canada [*Timmen et al.*, 2006; *Lambert et al.*, 2006], in river deltas like the Mississippi [*González and Törnqvist*, 2006], or at plate boundaries [*Hayes et al.*, 2006].

[12] 3. In Oostende, along the Belgian coastline, measurements started in 1997 to provide a reference site for the study of mean sea level changes. This station is 950 m away from the tide gauge.

[13] Jülich and Oostende are located in industrialized areas and suffer from high noise, mainly due to the vibrations imparted to the unconsolidated sediments. In Oostende the vibrations are caused by the urban activity (the railway station is 350 m away) and sea-induced microseismic noise. In Jülich the noise is mainly caused by huge bucket wheel excavators and the conveyors used in the opencast mines. These effects make the single-drop noise 5 to 15 times larger than usual at the other stations. To improve the measurement

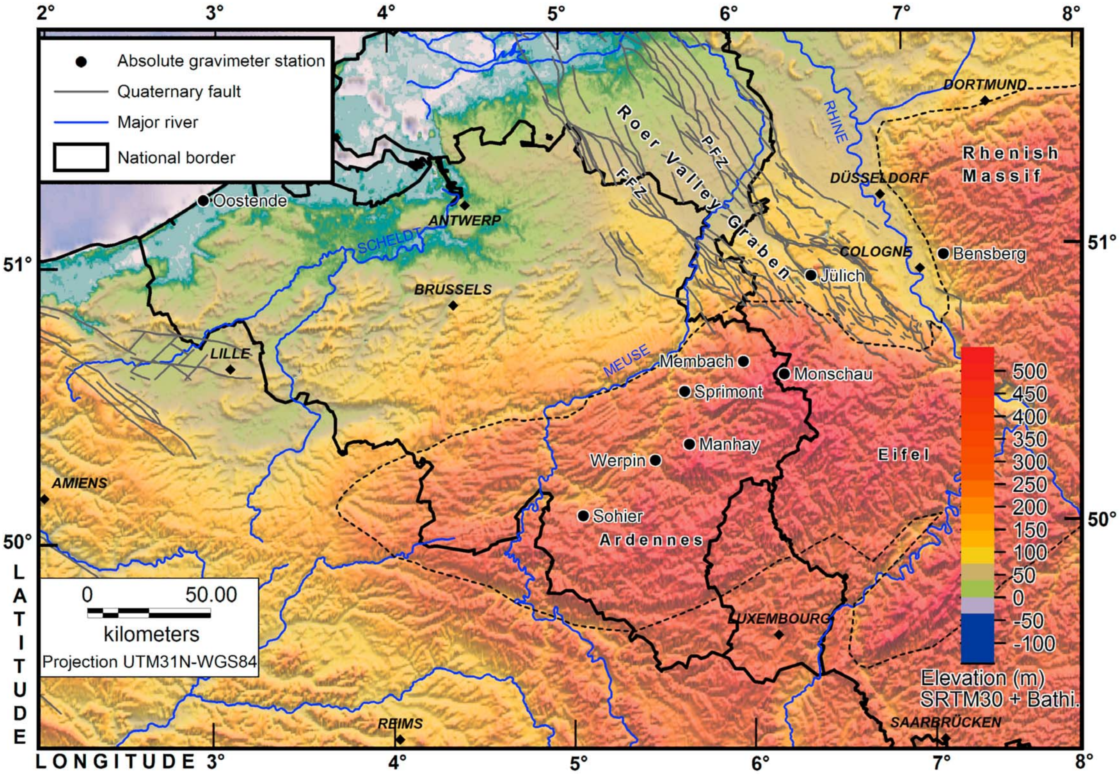

Figure 1. Absolute gravity measurement points in Oostende, across the Ardennes and the Roer Valley Graben. The Roer Valley Graben is the central graben of the Lower Rhine Graben system. Membach is the reference station and Jülich undergoes an anthropogenic subsidence of 1.4 cm/yr. The Rhenish Massif, the Ardennes, and the Eifel are indicated in the area delimitated by the dashed line; these three areas form the Rhenish Shield. The gray lines indicate the Quaternary faults, with FFZ and PFZ as the Feldbiss and Peelrand Fault Zones.

precision, longer time series were first recorded during weekends and holidays but, from our experience, reliable results could be obtained in less than 24 h during the week, by simply increasing the drop frequency from 0.1 to 0.2 Hz [*Van Camp et al.*, 2005].

[14] In the early years, campaigns were mostly performed twice a year to investigate seasonal effects and to study the stability of the stations. Except at Jülich and Bensberg, the campaigns are performed annually since 2009. In Membach, our reference station, about one measurement per month is available. To reduce seasonal influences, annual or semi-annual visits were repeated during the same season, except at Oostende where the 1996 and 1997 yearly measurements were taken in June and August, respectively. Because of an instrument malfunction, it was not possible to measure in Oostende during the winter of 2009 and in Bensberg and Jülich during the spring of 2010.

2.3. Data Analysis

[15] The AG results are shown in Figure 2. To determine the trends and to test their significance, we used a bootstrapping method allowing for a non Gaussian error distribution (see, for instance, the work of *Simon* [1997]). For each station, where N data were available, we assume that they obey the model:

$$g(t_i) = g_0 + \dot{g} \cdot (t_i - t_0) + \varepsilon_i + A \sin(\omega t_i + \varphi)$$

where $g(t_i)$ is the measurement at time t_i, g_0 is the gravity at time t_0, $\dot{g}$ is the trend true value, ε_i is the measurement error

Table 1. Coordinates and Main Characteristics of the AG Stations

AG Station	First Measurement	Latitude (°N)	Longitude (°E)	Soil Condition	Location	Sampling Rate
Oostende	winter 1997	51.222	2.920	sediment	basement	annual
Bensberg	fall 1999	50.964	7.176	bedrock	basement	2/yr
Jülich	fall 2000	50.909	6.412	sediment	garage	2/yr
Membach	Jan 1996 (173 data)	50.609	6.010	bedrock	underground	~monthly
Monschau	fall 2000	50.557	6.236	bedrock	basement	2/yr, annual after 2008
Sprimont	fall 1999	50.508	5.667	bedrock	church	2/yr, annual after 2006
Manhay	fall 1999	50.317	5.683	bedrock	observatory	2/yr, annual after 2002
Werpin	fall 1999	50.263	5.484	bedrock	church	2/yr, annual after 2006
Sohier	spring 2002	50.069	5.071	bedrock	church	2/yr, annual in 2007 and after 2008

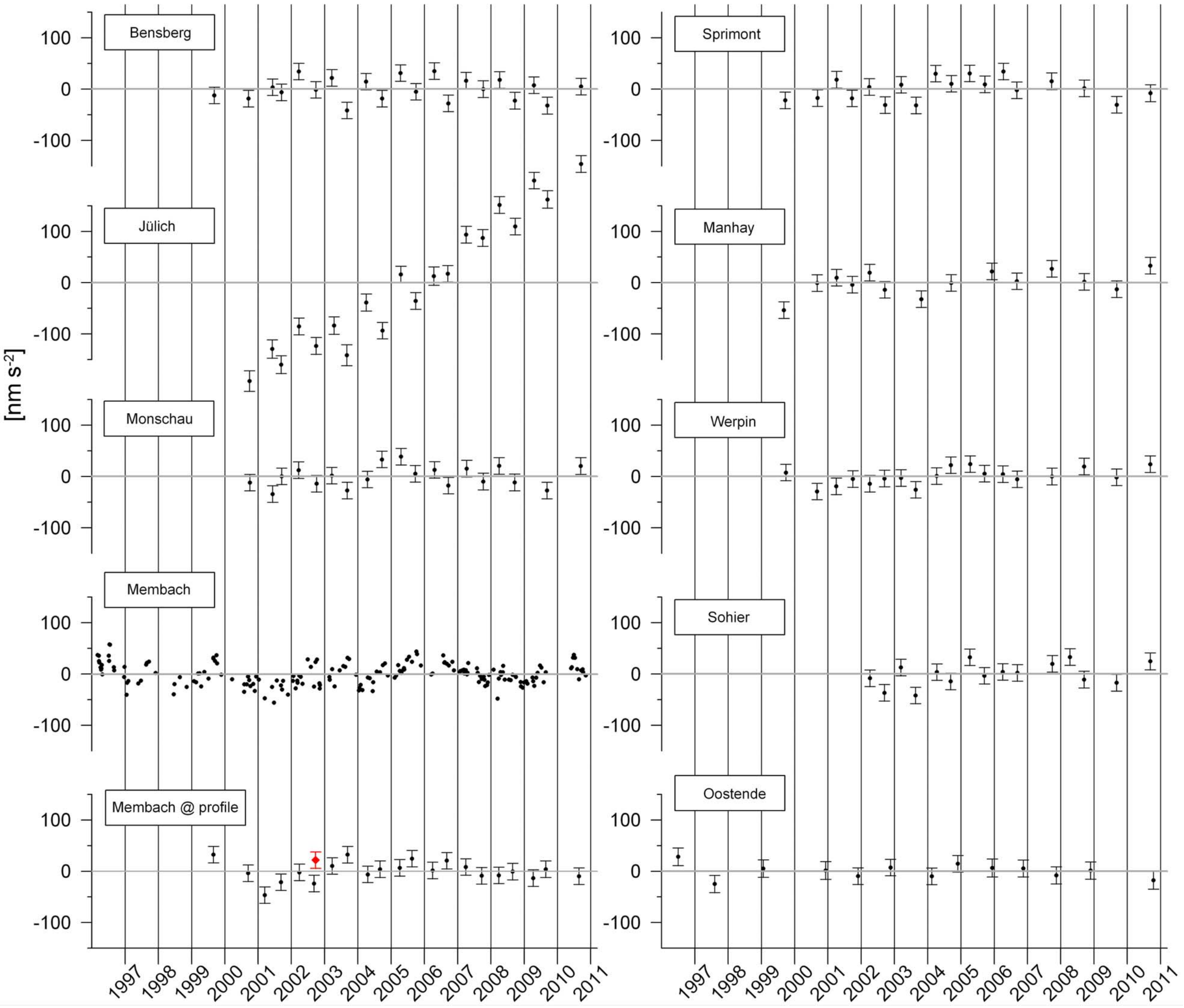

Figure 2. Absolute gravity (AG) values at all stations. Each AG gravity value usually represents the average of 1200 to 4800 drops, equivalent to 12 to 48 h of measurement. In Jülich each AG gravity value usually represents the average of 2400 to 20,000 drops, equivalent to 1 to 4 d of measurements. All the available AG values are shown for Membach as well as when starting the profile only. The red diamond indicates the AG data at the end of the fall 2002 profile (see text for details). Figures 2 and 4 show the variations with respect to the averaged gravity value, and the error bars include the experimental standard deviation of the mean and the instrumental set-up noise [*Van Camp et al.*, 2005]. For legibility the error bars are not shown for the Membach station (whole time series) but are similar to the Membach ones at the time of the profile.

of unknown statistics, and $A \sin(\omega t_i + \varphi)$ an annual term to account for possible seasonal effects. If we can consider that all the measurement errors ε_i result from a unique random variable, and are independent, we can assess the robustness of the trend estimate by Monte-Carlo resampling of the observed data set (and of equal size to the observed data set). For each data set, we performed 10,000 random resamples, i.e., we randomly ordered the N available data, with replacement, so that any data point can be sampled several times or not sampled at all. For each new sample, we estimate the parameters $\dot{g}$, A and φ from the time series. When the 10,000 trend values are sorted in ascending order, the 95% confidence interval is obtained by the values corresponding to the 250th and the 9750th values, the median being the mean of the 5000th and the 5001th values. The results are given in Table 2 and shown in Figure 3a, with confidence intervals at the 95% level, and median values. We found significant positive trends in Jülich, Manhay, Werpin and Sohier, where the confidence intervals at the 95% level do not cross zero. At the other sites, where no significant trend was detected, our study provides intervals for possible gravity rates of change.

[16] The annual term reaches a maximum during the winter or the spring at Bensberg, Jülich, Monschau, Sprimont and Sohier. At Membach (all data), this is observed during the summer, because the water mass is above this underground station. At Oostende, Manhay, Membach (at the time of the profile) and Werpin, as shown by the large confidence intervals of the phase, no significant annual signal could be identified. For Oostende and Manhay, this is because there is

Table 2. Observed Gravity Rate of Change $\dot{g}_{observed}$, Amplitude of the Annual Term, Residual Gravity Rate of Change $\dot{g}_{res}$ Corrected for the GIA Effect According to Equation (2), and Equivalent Residual Vertical Velocity $\dot{z}_{res}$ Using the Bouguer Gradient $(\dot{g}/\dot{z})_{Bouguer} = -2$ nm/s^2/mm[a]

Station	Duration (yr)	$\dot{g}_{observed}$ (Lower) (nm/s^2/yr)	$\dot{g}_{observed}$ (Median) (nm/s^2/yr)	$\dot{g}_{observed}$ (Higher) (nm/s^2/yr)	Annual	
					Amplitude (nm/s^2)	Phase (days)
Oostende	14	−3.1	−0.6	1.8	3 ≤ 18 ≤ 73	−166 ≤ 3 ≤ 154
Bensberg	11	−2.3	−0.6	1.2	18 ≤ 29 ≤ 55	24 ≤ 48 ≤ 93
Jülich	10	**29.0**	**39.9**	**48.9**	16 ≤ 40 ≤ 132	9 ≤ 73 ≤ 174
Membach (all since 1996)	15	−1.0	−0.3	0.5	6 ≤ 10 ≤ 14	−177 ≤ −157 ≤ −129
Membach @ profile	11	−2.9	−0.6	2.3	6 ≤ 49 ≤ 114	−182 ≤ 175 ≤ 182
Monschau	10	−1.8	1.4	4.1	8 ≤ 25 ≤ 52	6 ≤ 31 ≤ 174
Sprimont	11	−0.4	1.9	3.8	15 ≤ 31 ≤ 83	7 ≤ 37 ≤ 155
Manhay	11	**0.2**	**3.8**	**7.5**	12 ≤ 24 ≤ 226	−86 ≤ 71 ≤ 166
Werpin	11	**0.4**	**2.4**	**4.8**	3 ≤ 25 ≤ 73	−175 ≤ −1 ≤ 176
Sohier	8	**1.1**	**5.0**	**8.1**	18 ≤ 45 ≤ 88	6 ≤ 20 ≤ 110

Station	$\dot{g}_{res}$ (GIA Corrected) (Lower) (nm/s^2/yr)	$\dot{g}_{res}$ (GIA Corrected) (Median) (nm/s^2/yr)	$\dot{g}_{res}$ (GIA Corrected) (Higher) (nm/s^2/yr)	$\dot{z}_{res}$ Equivalent Vertical Velocity (Lower) (mm/yr)	$\dot{z}_{res}$ Equivalent Vertical Velocity (Median) (mm/yr)	$\dot{z}_{res}$ Equivalent Vertical Velocity (Higher) (mm/yr)
Oostende	−4.2	−1.3	1.4	−0.7	0.7	2.1
Bensberg	−3.5	−1.4	0.9	−0.4	0.7	1.8
Jülich	**28.2**	**39.2**	**48.3**	**−24.1**	**−19.6**	**−14.1**
Membach (all since 1996)	−2.6	−1.0	0.5	−0.3	0.5	1.3
Membach @ profile	−4.0	−1.3	1.8	−0.9	0.7	2.0
Monschau	−2.8	0.6	3.7	−1.8	−0.3	1.4
Sprimont	−1.5	1.1	3.5	−1.7	−0.6	0.8
Manhay	−0.8	3.0	7.0	−3.5	−1.5	0.4
Werpin	−0.8	1.7	4.4	−2.2	−0.8	0.4
Sohier	**0.1**	**4.2**	**7.6**	**−3.8**	**−2.1**	**−0.1**

[a] For Membach, the results using all the available data since 1996 are also shown. The slopes, amplitudes, and phases of the annual term and confidence intervals at the 95% level result from bootstrapping applied to the AG time series; for the values reduced for GIA, the error on the GIA model is included. Bold characters indicate trends which are significantly different than 0.

essentially only one data per year. For Membach (at the time of the profile) and Werpin, the amplitudes are probably too small to be evidenced by measuring twice a year only.

[17] At Monschau, the increase in gravity observed during the summers 2001 and 2004 may be due to local effects, but the changes lie within the error bars and thus may be simply statistical fluctuations; as may be also the case at other stations. For example, comparing the results from Membach with data from the superconducting gravimeter (SG) shows that the 11 September 2002 value is much lower than expected (Figure 4). This is one of the very few gravity measurements at Membach that present a set up noise at the 3σ level [*Van Camp et al.*, 2005; *Van Camp and Francis*, 2006]. This is not the case for the next measurement ending the profile on 28 September 2002 (red diamond on Figure 2). All other AG data taken at Membach station at the time of the profile agree with the SG at the 2σ level.

3. Modeling the GIA Effect and Vertical Velocities

[18] The observed gravity rates of change, resulting from the combination of GIA, tectonic, nonseasonal climatic and anthropogenic effects, can read as follow:

$$\dot{g}_{observed} = \dot{g}_{GIA} + \dot{g}_{tecto} + \dot{g}_{climate} + \dot{g}_{anthro} \qquad (1)$$

To demonstrate possible tectonic effects, the AG observations must be corrected for anthropogenic and climatic effects, discussed in sections 4 and 5, and the GIA effect. The GIA is the viscoelastic response of the solid Earth to past changes in ice sheets position, distribution and thickness, as well as sea level. GIA causes maximal uplift (~10 mm/yr) in the center of Fennoscandia, and subsidence in zones surrounding the uplifting area. South of Fennoscandia, GIA models predict subsidence extending from 55°N to 43°N at rates up to 2 mm/yr [*Peltier*, 1995; *Lambeck et al.*, 1998; *Milne et al.*, 2001]. However, the gravity rate of change $\dot{g}_{GIA}$ is not routinely calculated and included in GIA models; we therefore employ an indirect inference: first, we discuss the possible vertical velocities $\dot{z}_{GIA}$ at the AG sites and the way to convert them into gravity rates of change $\dot{g}_{GIA}$ using the ratio $(\dot{g}/\dot{z})_{GIA}$.

3.1. Vertical Velocities

[19] Using CGPS data sets spanning 2.5 to 8 years, *Nocquet et al.* [2005] discussed the GIA effects in western and central Europe, and found a maximum subsidence rate of 1.2 ± 0.6 mm/yr (error is 2σ) at latitudes 50.5–53°N, in good agreement with the surface displacements predicted by *Milne et al.* [2001]. *Teferle et al.* [2009] reported on crustal motions in Great Britain evidenced by CGPS, AG and Holocene sea level data. Aligning the GPS estimates of

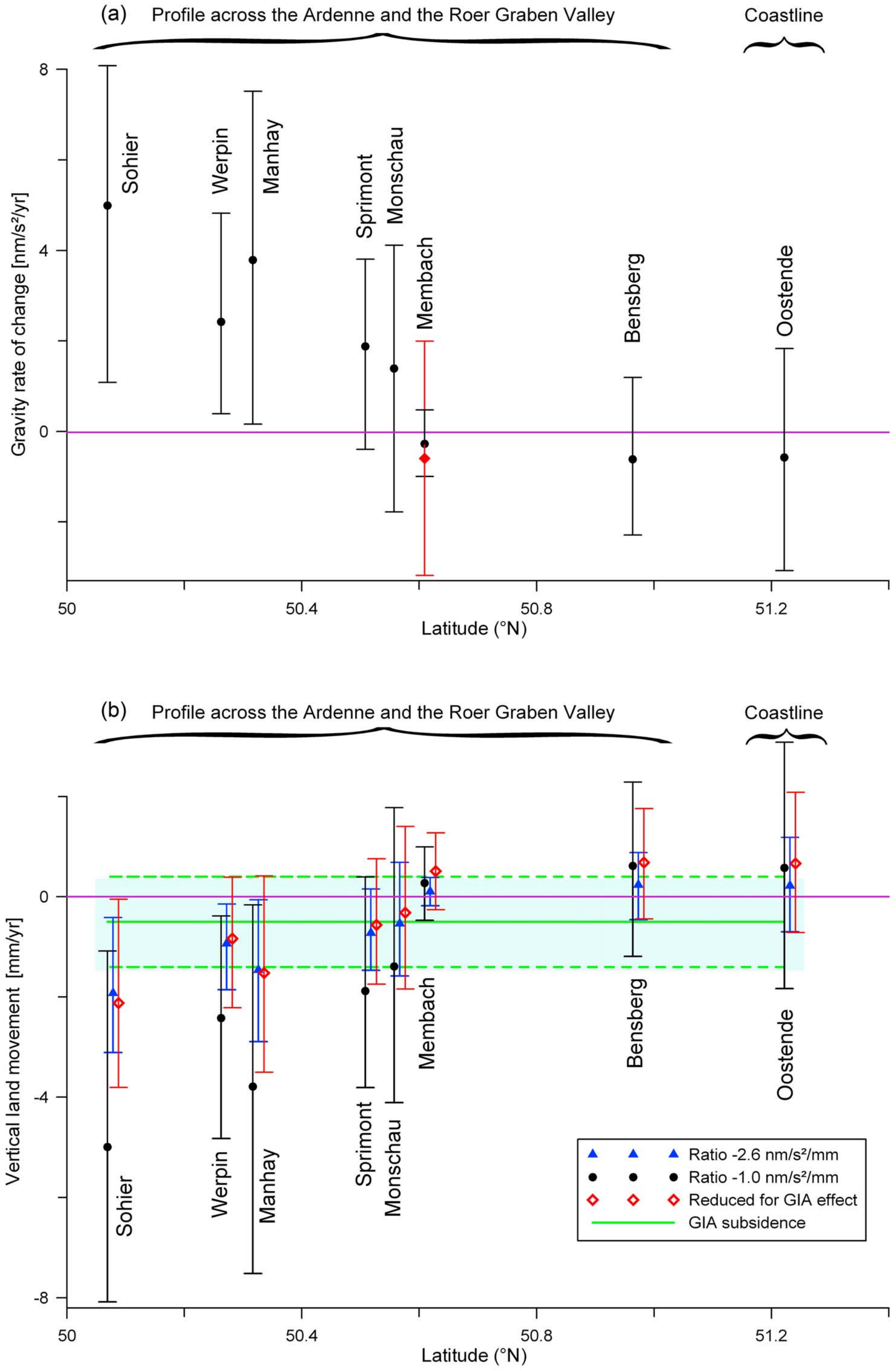

Figure 3. (a) Observed gravity rates of change $\dot{g}_{observed}$ as a function of latitude, deduced from the repeated AG measurements at all stations but Jülich. For Membach, the rates are based on all the measurements since 1996 (black) and on the 2 AG measurements per year performed since 1999 (red diamond). (b) Observed velocities $\dot{z}_{observed}$ after applying the ratio of −1.0 nm/s^2/mm (black) and −2.6 nm/s^2/mm (blue) on the gravity values shown in Figure 3a. The glacial isostatic adjustment (GIA) subsidence rate of −0.5 mm/yr comes from the model used by *Lidberg et al.* [2010] (green line), with the errors bars given by the green zone. The red diamonds show the residual vertical velocities $\dot{z}_{res}$ deduced from $\dot{g}_{res}$ using the ratio $(\dot{g}/\dot{z})_{Bouguer}$ of −2.0 nm/s^2/mm; the reduced gravity rates of change $\dot{g}_{res}$ being obtained after applying equation (2) to correct for the GIA effect. All the error bars represent the 95% confidence interval.

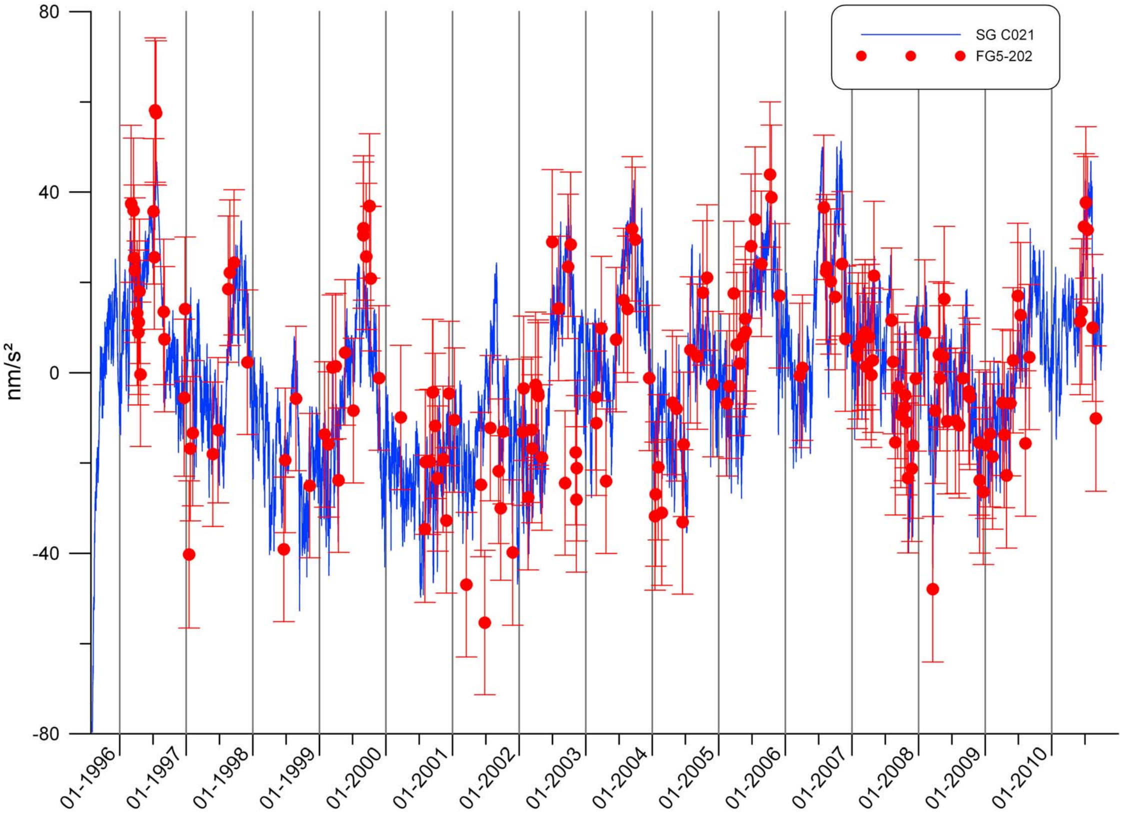

Figure 4. Gravity time series from the GWR C021 superconducting gravimeter (SG) (continuous line) and the FG5#202 absolute gravimeter (AG) at the Membach station. The SG instrumental drift was removed by comparing the SG data to the AG measurements. For details see the work of *Francis et al.* [2004].

vertical station velocity with the AG measurements, the southeast of England should be subsiding at rates ranging 1 to 2 mm/yr, depending on the CGPS processing strategies. Most recently, *Lidberg et al.* [2010] report a new 3-D velocity field of the Fennoscandian GIA, where all the 17 stations located at latitudes ranging 50.5–53°N are uplifting. Averaging the velocities at these stations yields +0.9 ± 1.4 mm/yr (2σ).

[20] According to *Lidberg et al.* [2010], these differences in vertical velocities indicate an uncertainty in absolute vertical velocity, possibly at the 1 mm/yr level because of reference frame realization. The alternative to a global alignment to a reference frame would be to apply regional constrains, based on stable CGPS time series. In northwestern Europe, this is almost impossible, as the GIA process extends to the sea or to zones affected by Alpine tectonics or sediment covers. Therefore, the observed velocities have been translated and rotated to best fit the GIA prediction model at the CGPS sites in Finland and Sweden, where the GIA effect is maximal. We took 3-D velocities at 58 of the 64 stations of the BIFROST network (Baseline Inference of Fennoscandian Rebound), dismissing six stations that had short histories or paralleled a station nearby, and used a six-parameter Helmert transformation (keeping the scale fixed), to adjust the BIFROST rates to the GIA model. The CGPS analysis and the specific GIA model (120 km lithosphere thickness, 0.5×10^{21} Pa s upper mantle and 5×10^{21} Pa s lower mantle viscosity) are described in detail by *Lidberg et al.* [2010].

[21] The value of this regional adjustment is discussed here for the site Kootwijk (KOSG, 52.178°N, 5.810°E) [see *Lidberg et al.*, 2010, Figure 1]. KOSG is located close to our profile and has an uninterrupted history in the analysis of *Lidberg et al.* [2010]. The originally estimated vertical rate of KOSG, $\dot{z}_{GIA}$ = 0.21 ± 0.43 mm/yr (uplift) became −0.75 mm/yr (subsidence) after the Helmert adjustment while the WRMS of the difference observations minus model decreased by a factor of two. The model predicts −0.63 mm/yr at KOSG, which is compatible with the CGPS rate estimate given its uncertainty. Therefore, as we adopt the GIA model predictions in this paper, we obtain a practically constant GIA subsidence $\dot{z}_{GIA}$ = −0.5 ± 0.9 mm/yr (2σ) at the gravity stations (50–51°N).

3.2. Gravity Rates of Change Versus Vertical Velocities

[22] To convert the gravity rates of change into vertical velocities, different values for ($\dot{g}/\dot{z}$) ranging from −1.0 to −2.6 nm/s^2/mm, have been published [*Wahr et al.*, 1995; *de Linage et al.*, 2007; *Teferle et al.*, 2009]. This ratio is a function of the wavelength, the rheology and the history of the deformed layers and depends on the position of the load and on geodynamic process, so it depends on whether specific sites are located inside formerly glaciated areas, or peripheral, or in between; on how wide the respective ice sheet was, and whether there is elastic response due to contemporary ice changes, earthquakes or tectonic processes [*Rundle*, 1978; *Wahr et al.*, 1995; *de Linage et al.*, 2007].

[23] The ratio ($\dot{g}/\dot{z}$) has not yet been experimentally determined with the required accuracy to allow discrimination between the modeled values [*Ekman and Mäkinen*, 1996; *Lambert et al.*, 2001; *Mazzotti et al.*, 2007]. For comparison, the observed gravity rates of change, converted into vertical velocities using the published plausible ratios are also shown in Figure 3b by the black ($\dot{z}_{observed} = -\dot{g}_{observed}/1.0$) and blue ($\dot{z}_{observed} = -\dot{g}_{observed}/2.6$) symbols, providing upper and lower values for the possible vertical velocities inferred from our AG measurements. In the region of the subsiding forebulge, our experimentation with the GIA models of Mitrovica [*Tromp and Mitrovica*, 1999] suggests that the ratio $(\dot{g}/\dot{z})_{GIA}$ only weakly depends on the viscosity structure. So, even if the viscosity is different around the subsiding forebulge from what is inferred in the zone of maximum uplift, our calculations indicate that the GIA ratio should not be smaller than −1.5 nm/s^2/mm. So, we provide an upper limit to reduce for GIA effects using the a priori estimates $(\dot{g}/\dot{z})_{GIA} = -1.5$ nm/s^2/mm and $\dot{z}_{GIA} = -0.5$ mm/yr. The residual gravity rate of change $\dot{g}_{res}$, reduced for the GIA effect, is thus given by:

$$\begin{aligned}\dot{g}_{res} &= \dot{g}_{tecto} + \dot{g}_{climate} + \dot{g}_{anthro} = \dot{g}_{observed} - (\dot{g}/\dot{z})_{GIA}\dot{z}_{GIA} \\ &= \dot{g}_{observed} + 0.75 \end{aligned} \qquad (2)$$

This rate may now be converted into vertical velocity $\dot{z}_{res}$. As no large earthquake ($M_W \geq 6.0$) was recorded since 1692 in the Rhenish Shield or in the graben area since 1756 [*Camelbeeck et al.*, 2007; *Hinzen and Reamer*, 2007] and, since evidence of extensional horizontal stress has so far been elusive [*Nocquet and Calais*, 2004], we can rule out significant mass redistribution due to postseismic relaxation or tectonic effects. So, the most reasonable choice consists of using the ratio $(\dot{g}/\dot{z})_{Bouguer} = -2$ nm/s^2/mm, which is equivalent to the classical Bouguer corrected gradient [*de Linage et al.*, 2007]. The GIA corrected vertical velocities $\dot{z}_{res} = -2.0 \times \dot{g}_{res}$, given in Table 2, are shown by the red diamonds in Figure 3b.

4. Long-Term Climatic Effects

[24] *Lambert et al.* [2006] reported on a slow oscillation of about 7 years for Canadian AG time series; they could not provide any satisfactory explanation. *Van Camp et al.* [2006] also noted a long-period oscillation, possibly due to hydrological effects, in the Membach time series. We performed a Singular Spectrum Analysis (SSA) and found a period of 15 years for both the SG and AG time series shown on Figure 4. This oscillation has the potential to have biased the analysis of *Francis et al.* [2004], who discussed a possible decrease in gravity of −6 ± 2 nm/s^2/yr, based on data spanning 1996–2002. To investigate this possibility, we investigated the stability of our estimates of gravity rates of change as a function of the length of the AG time series, both using all the available data and limiting the series to 2 measurements per year (spring and fall), in order to be consistent with the profile. The results are shown in Figure 5a, where the error bars at the 95% level are determined by bootstrapping. After 10 years, the uncertainty is at the 1 nm/s^2/yr level when all the available AG data from Membach are used. This uncertainty increases to about 3 nm/s^2/yr when limiting the series to 2 measurements per year; this is similar to the uncertainty obtained on the data from the profile. The epoch of the *Francis et al.* [2004] study, which corresponded to the decreasing part of the 15 yr quasiperiodic signal, is indicated by a vertical line. The value published in 2004 (−6 nm/s^2/yr) is slightly different from what can be seen on Figure 5a (~−4.5 nm/s^2/yr), as the annual term and the drift of the rubidium clock were not taken into account at that time.

[25] As a model to correct for local hydrological effects is available since August 2004 [*Van Camp et al.*, 2006], the same results are shown on Figure 5b before and after applying the model. Because of the shortness of the time series, it was not possible to limit the series to 2 measurements per year. Applying the hydrological model reduces the error bars by about 20%, but the gravity rate of change is not significantly affected.

[26] Figure 2 suggests an interannual behavior at the other AG stations, but this may be an artifact caused by data from the summers of 2003 and 2010. The values measured during the fall 2003 were the lowest at all stations except at the Membach underground station, where the gravity was relatively high. This effect was also observed in Fennoscandia [*Steffen et al.*, 2009] and northern Germany [*Timmen et al.*, 2008] and is probably a hydrological effect caused by an unusually dry and warm summer. In 2010, exceptional (return period of 30 years) amounts of rain were recorded in the second part of August, which caused the gravity values to be among the highest recorded at all stations but Oostende. At Oostende the measurement was made at the end of October, whereas for the other stations they were performed in the second half of September. The sparse data do not allow a reliable spectral analysis. Longer time series are necessary to confirm the interannual term and to investigate whether spatially coherent patterns can be detected, which would enable comparisons with the space-based observations like the Gravity Recovery and Climate Experiment (GRACE) [*Tapley et al.*, 2004]. If confirmed from GRACE measurements, climate indexes and other terrestrial absolute gravity time series, this effect would mean that high-precision land-based gravity measurements are helpful in monitoring slow environmental changes.

[27] To test whether long periodic phenomena may bias the results, *Van Camp et al.* [2010] examined the power spectrum of the gravity signal of hydrologic origin, to determine how, and to what precision, the hydrology can be separated from tectonic motion. Data from 18 SGs in different hydrological contexts showed that the hydrological effects have a negligible effect on the long-term trend. The time required for the environmental signal to average out to a level sufficient to separate a tectonic trend at the 1.0 mm/yr level (95% confidence level) ranges from 3.5 years to 17 years, depending on the magnitude of the hydrological signal. This is not contradicted by the results presented here, where, at all stations but Jülich, the errors range 0.7–3.9 nm/s^2/yr (95% confidence interval) for AG measurements spanning 8–15 years (Table 2). This is also confirmed by the stabilization of the trend shown on Figure 5: simulating 2 measurements per year the precision reaches 0.7 nm/s^2/yr (95% confidence interval) after 15 years. Within the next 10 years, if the rates and error bars decrease at the AG stations as

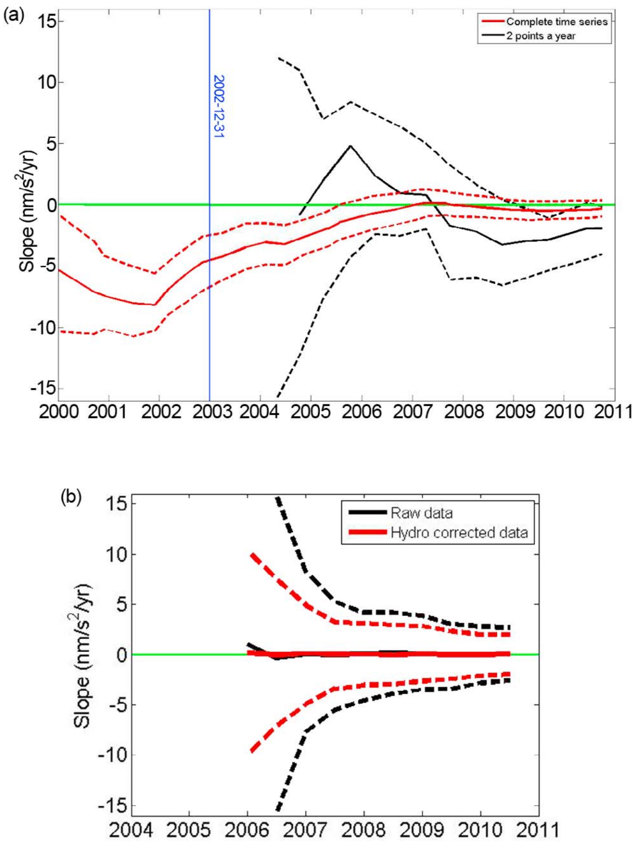

Figure 5. (a) Gravity rates of change in Membach as a function of the length of the available AG time series: in red, taking all the available data since 1996; in black, taking two data per year at spring and fall times. The time is the last date of the time series used to calculate the corresponding rate estimate. The decrease in rates as a function of time reflects more precise estimates because of the longer time span of observations. Dashed lines indicate the 95% error in gravity rates of change. The vertical line indicates the time of the *Francis et al.* [2004] analysis. (b) Same as Figure 5a but for the complete time series since August 2004, before (black) and after (red) correcting for the local hydrological effects, as described by *Van Camp et al.* [2006].

shown here for Membach, uncertainties on absolute vertical velocities across the Ardennes and in Oostende at better than the 1 nm/s^2/yr level can be expected.

[28] If, in the future, slow climate changes affect the gravity measurements, then, since these climatic signals tend to have a large spatial extent, they should be observed on the continental scale. If so, a common mode should appear in the different time series, as well as in hydrological models or climatic indexes.

5. Anthropogenic Effects in the LRG: Jülich and Bensberg

[29] This section investigates the uplift and subsidence caused by brown coal and anthracite mining activity in the LRG. On the basis of eight survey-mode GPS campaigns spanning 1993–2000, *Campbell et al.* [2002] report a vertical velocity of 2.2 cm/yr near Jülich, but they do not provide coordinates of the surveyed stations. This prevent us from making a comparison with the AG measurements as, even within 1 km of the AG station, repeated leveling shows that subsidence ranges from 0 to 22 mm/yr [*Stollenwerk and Kuckuck*, 2004]. At the AG station, repeated levelling (−558 mm between 1963 and 2004; −12.0 mm between 2003 and 2004 [*Stollenwerk and Kuckuck*, 2004]) indicate a mean subsidence of 13.6 mm/yr. Using the Bouguer ratio $(\dot{g}/\dot{z})_{Bouguer} = -2$ nm/s^2/mm implies a gravity rate of change of 27.2 nm/s^2/yr, which differs by 12 nm/s^2/yr from the observed trend. This lies outside the 95% confidence interval of the GIA-corrected value. The difference can be caused by the compaction causing the subsidence [*Bear and Corapcioglu*, 1981]. In the future, the gravity rate of changes and vertical velocities could be used to investigate this process.

[30] As the station is 6 km away from the Hambach and Inden brown coal mines, we evaluated the gravitational effects of the transported masses (Figure 6). Each year, a 46 m thick layer of lignite is removed in Hambach (45 Mt) and a 43 m thick one in Inden (25 Mt). Moreover, in Hambach, 25% of the overburden disposals (110 Mt) are moved 18 km away from Jülich. Considering prisms (3300 × 300 × 346 m and 3000 × 200 × 243 m in Hambach and Inden, respectively (RWE Power AG, personal communication, 2006)) moving southeastward, and a density of 1.15×10^3 kg/m^3 for the lignite and 1.85×10^3 kg/m^3 for the overburden, the gravitational effect is, at maximum, a few nms-2/yr level since 2000. The unloading should induce an uplift of about 2 mm/yr [*Klein et al.*, 1997], one order of magnitude smaller than the subsidence.

[31] Figure 2 suggests a slight increase in the gravity rate of change after 2006, which may explain why the confidence interval is three to four times the values at the other stations. However, this is equivalent to only one fourth of the slope and there is not enough data to confirm a change in the trend or a non linear effect.

[32] The unloading of the crust caused by the brown coal and anthracite mining areas west of Cologne and in the Ruhr region should induce an uplift of about 2 mm/yr around Bensberg [*Klein et al.*, 1997]. The residual velocity $\dot{z}_{res}$ at Bensberg is included in the 95% confidence interval [−0.4, 1.8] mm/yr, which nearly agrees with the velocity of +2 mm/yr provided by *Klein et al.* [1997]. Conversely, removing the expected anthropogenic signal, the interval becomes [−2.4, −0.2] mm/yr. This residual motion would not be detectable in CGPS data unless the observations extend beyond about 15 years (assuming a noise power spectrum and resulting uncertainty like that at KOSG). Installing a CGPS station at the Bensberg observatory and processing radar interferometric measurements in the whole LRG area should help to confirm this observation and allow a better understanding of the anthropogenic effect.

[33] The Jülich and Bensberg experiments illustrate the difficulty of monitoring small gravity rates of change and slow tectonic deformation in areas of anthropogenic motions.

6. Oostende

[34] At Oostende, reliable tide gauge measurements are available since 1927 [*Van Cauwenberghe*, 1999], and

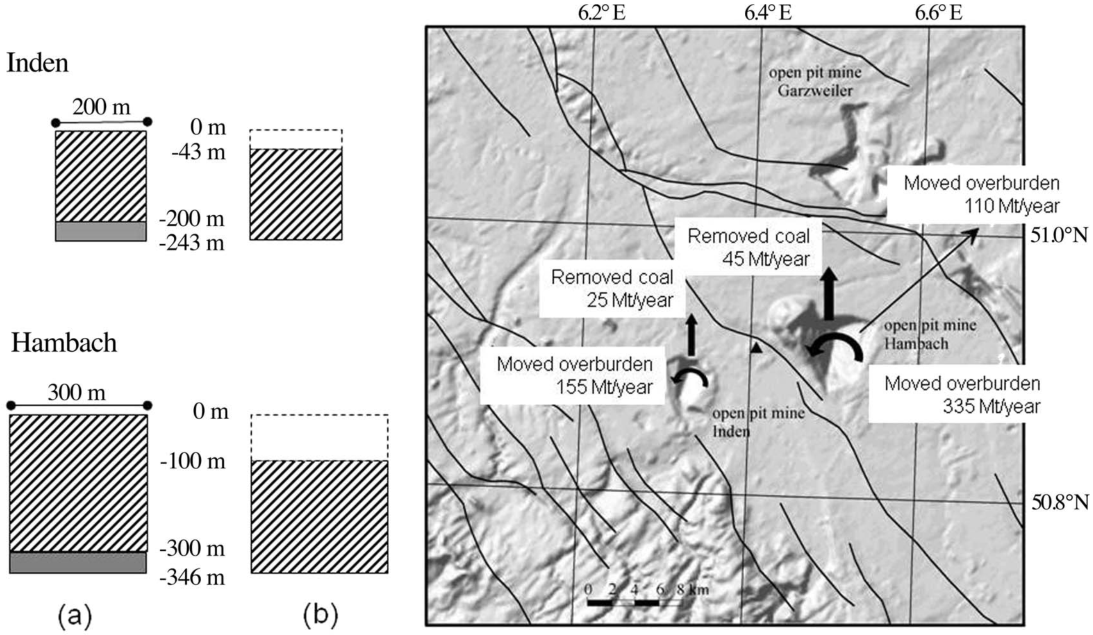

Figure 6. Relief map of the surroundings of the measuring point in Jülich (triangle) and size of the prisms used in the gravity model. The mass of annually transported materials is given in millions of tons per year (rates based on data for 2000–2005 provided by RWE Power Company). The gray and hatched bars represent the brown coal layers ($\rho = 1.15$ g.cm^{-3}) and the overburden ($\rho = 1.85$ g.cm^{-3}), respectively. The situations (a) before and (b) after the withdrawal of the brown coal.

indicate a rise of the local seal level of 1.2 mm/yr, similar to the global sea level rise of 1–2 mm/yr [*Church et al.*, 2001]. This rate implies no vertical land movement, consistent with $\dot{g}_{observed}$, which does not differ significantly from 0, ranging from −3.1 to 1.8 nm/s^2/yr (95% confidence interval). Beyond this direct effect, increasing sea level may bias the AG measurements by raising the groundwater level: with a porosity of 20%, an increase of 2 mm/yr in the water table should increase gravity by 1.6 nm/s^2/yr, causing an apparent subsidence of 0.08 mm/yr.

[35] The Oostende value agrees with the tide gauge data and the CGPS results [*Lidberg et al.*, 2010] but disagrees with the AG-aligned CGPS estimates of *Teferle et al.* [2009]. However, comparison is difficult because: (1) the CGPS measurements are aligned by 2 AG stations only, based in Newlyn (southwest Cornwall) and Lerwick (Shetlands), 600 and 1000 km respectively away from Oostende; (2) the vertical velocities are not statistically different from zero at the one sigma level; (3) for one of the AG-aligned CGPS processing strategies the subsidence decreases in the southeast toward Oostende; (4) the velocities deduced from the Holocene sea level are at the 0.5 mm/yr level; (5) the measurements were not systematically performed during the same season, which may bias the results. This is also the case for the two first Oostende measurements in 1996 and 1997, performed during summer, whereas the others were made during the winter. After removing the two first data, the trend ranges [−1.7, 2.0] nm/s^2/yr (95% confidence interval).

[36] Oostende may also suffer from a local effect like local sediment compaction. In the future, including the absolute gravity measurements performed since October 2006 at the Space Geodesy Facility at Herstmonceux in Sussex, UK [*Appleby et al.*, 2008], and processing the CGPS data on a broader scale will test this possibility.

7. Discussion

[37] At all stations but Jülich, the observed gravity rates of change $\dot{g}_{observed}$ lie in the [−3.1, 8.1] nm/s^2/yr interval, and were determined with an uncertainty ranging from 1.7 nm/s^2/yr at Bensberg to 3.9 nm/s^2/yr at Sohier (95% confidence interval). As shown on Table 2, at 4 stations in the profile (Bensberg, Monschau, Sprimont and Membach) and in Oostende, the observed gravity rates of change do not significantly differ from zero. Significant increases lying in the 0.2–8.1 nm/s^2/yr interval are found in the three southernmost stations Manhay, Werpin and Sohier. When converting the observed gravity rates of change to vertical velocities, at Oostende, Bensberg and especially, Membach, the gravity rates of changes are so small that the value of the ratio $\dot{g}/\dot{z}$ is unimportant (Figure 3b).

[38] Using the ratios of −2.6 and −1.0 nm/s^2/mm provides the smallest and largest intervals for the possible equivalent vertical velocities $\dot{z}_{observed}$, ranging [−3.1, 1.2] and [−8.1, 3.1] mm/yr, respectively. The smallest values (−3.1 or −8.1 mm/yr) are at Sohier and the largest ones (1.2 or 3.1 mm/yr), at Oostende. At all stations but Jülich, using the ratio −2.6 nm/s^2/mm, the results agree with the GIA model presented by *Milne et al.* [2001, 2004] and used by *Lidberg et al.* [2010], within the error bars. This is also the case using the ratio of −1.0 nm/s^2/mm. When more data become available and if, at all stations, the gravity rates of changes approach zero, as observed in Membach (Figure 5), it will become impossible to determine the ratio using measurements at our locations. In this case only measurements in

Fennoscandia or Canada with a much stronger GIA signal might be successful.

[39] At Sohier and Manhay, the uncertainties are larger because fewer data are available. However, if the uncertainties diminish over time as it has been observed at the other stations, a level of 2.5 nm/s^2/yr (equivalent to 2.5 or 1.3 mm/yr considering ratios of −1.0 or −2.6 nm/s^2/mm), similar to the observed one at the other stations, should be reached within a couple of years.

[40] When correcting for the GIA effect, the residual gravity rates of change $\dot{g}_{res}$ are not significantly different from zero at all the stations but Jülich and Sohier. For Sohier, the relative shortness of the time series (starting 2002) may bias the result, as was the case in Membach some years ago. Concerning the expected tectonic effects, in northwestern Europe, Quaternary activity in the Lower Rhine Graben system and the Rhenish Shield (Figure 1) has been demonstrated, where vertical relative movements reached 0.05–0.1 mm/yr [*Camelbeeck et al.*, 2007; *Hinzen and Reamer*, 2007]. During the Late Pleistocene, vertical slip rates within this range of values along the border faults of the Roer Valley Graben were shown by paleoseismic investigations on the Peelrand and the Feldbiss fault zones [*Camelbeeck and Meghraoui*, 1998; *Vanneste et al.*, 1999; *Vanneste and Verbeeck*, 2001; *van den Berg et al.*, 2002; *Camelbeeck et al.*, 2007]. The pronounced river incision in the Rhenish shield and its present-day elevation also suggest a significant uplift during the Quaternary [*Demoulin and Hallot*, 2009]. Our question is whether it is possible to detect such an elevation of the Rhenish shield, possibly related to rift shoulder uplift in response to rifting in the Roer Graben System. This is presently impossible, but the AG profile shows already that the possible gravity rates of change $\dot{g}_{res}$ lie in the 95% confidence interval [−3.5, 7.6] nm/s^2/yr, these lower and upper bounds being given by Bensberg and Sohier, respectively. In terms of vertical velocities $\dot{z}_{res}$, this is equivalent to [−3.8, 1.8] mm/yr, considering the Bouguer ratio of −2.0 nm/s^2/mm.

[41] This rift shoulder uplift may explain the latitude dependence suggested on Figures 3a and 3b, but this may also be due to anthropogenic influence. The Membach and Monschau stations are over 20 km away from the zones undergoing anthropogenic uplift due to the abandonment and unloading effects of mining activities [*Klein et al.*, 1997; *Bense et al.*, 2003; *Caro Cuenca and Hanssen*, 2008], such that uplift may mask the GIA and tectonic effects. GPS, InSAR and PSInSAR investigations covering the whole Roer Valley Graben should provide insights on the wavelength of this anthropogenic phenomenon. For completeness the possible influence of the Eifel volcanism, 30–40 km southeast from Membach and Monschau [*Regenauer-Lieb*, 1998; *Ritter et al.*, 2001] has to be considered, although no measurable deformation or gravity changes are expected [*Ritter et al.*, 2007]. Campaign GPS measurements undertaken in 2003 [*Spata and Koesters*, 2006] should provide further information in the future.

8. Conclusions and Perspectives

[42] We present the results of repeated absolute gravity measurements performed at Oostende on the Belgian coastline and across the Belgian Ardennes and the Roer Valley Graben. After 8–15 years (depending on the station), all stations but Jülich show that the observed gravity rates of change belong to the [−3.1, 8.1] nm/s^2/yr 95% confidence interval.

[43] At all stations but Jülich, the results agree, within the error bars, with the subsidence predicted by the GIA model presented by *Milne et al.* [2001, 2004] and used by *Lidberg et al.* [2010]. At four stations in the profile (Bensberg, Monschau, Membach and Sprimont) and in Oostende, the gravity rate of change does not significantly differ from zero. Significant increases lying in the 0.2–8.1 nm/s^2/yr interval are found in the three southernmost stations Manhay, Werpin and Sohier. In the northern part of the profile, the Jülich station, in the Roer Graben, is influenced by anthropogenic effects: water withdrawal for mining purposes induces subsidence, causing, together with the GIA effect, an increase in gravity belonging to the [29.0, 48.9] nm/s^2/yr 95% confidence interval. This interval becomes [28.2, 48.3] after reducing for the GIA effect. In the future, combining the gravity measurements with other geodetic and hydrogeologic data should provide information on the compaction processes causing the subsidence.

[44] After correcting for the GIA effect using a ratio $(\dot{g}/\dot{z})_{GIA}$ of −1.5 nm/s^2/mm and a subsidence $\dot{z}_{GIA}$ of −0.5 ± 0.9 mm/yr, the inferred gravity rates and consequently the vertical land movements, reduce to zero within the uncertainty level at all stations except Jülich and Sohier.

[45] The velocities as a function of longitude and latitude may indicate a possible shoulder uplift in response to rifting in the Roer Graben, but the determination of the possible gravity rates of change, ranging [−3.5, 7.6] nm/s^2/yr (95% confidence interval), is still not precise enough to support this hypothesis. Anthropogenic uplift or volcanism may also bias the results in Monschau, Membach and Bensberg, masking the GIA effect, but this cannot be resolved at this time. By measuring for one more decade we should be able to separate contributions from these different sources and to resolve the GIA effect.

[46] This study demonstrates the importance of precisely measuring and modeling the GIA effects in order to investigate intraplate vertical tectonic movements at the submillimeter level. We also show that AG measurements, repeated once or twice a year with the same, well-calibrated and well-maintained instrument, can resolve gravity rates of changes at the 1.7–3.9 nm/s^2/yr level (95% confidence interval) after 11 years, even under difficult conditions, confirming the predictions of *Van Camp et al.* [2010]. Seasonal variations do not influence the trend significantly if campaigns are repeated during the same season, and can provide insights into ongoing hydrological processes. Finally, a 15 year gravity oscillation at the Membach station indicates that slow environmental changes can be investigated by repeated land-based gravity measurements.

[47] Intraplate deformations linked to active tectonic structures such as the Roer Valley Graben or to the GIA around the peripheral bulge remain close to or below the accuracy of current geodetic techniques. Identifying them is further complicated by anthropogenic effects in the vicinity of the Roer Valley Graben and possibly, from the Eifel volcanism [*Ritter et al.*, 2001]. Provided the instruments are carefully maintained, absolute gravimetry is an appropriate tool to monitor low gravity rates of change and slow vertical land movements. In the future, other investigations such that

InSAR, PSInSAR and densifying CGPS stations, aligned with the ongoing AG measurements, should provide a clearer picture of the anthropogenic influences, and further allow the investigation of latitude dependence of GIA and/or the influence of the rifting in the Roer Graben.

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