Hydrological Influences on the Gravity Variations Recorded at Bad Homburg

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Summary

The gravimetric observatory in the cellar of the Bad Homburg castle was established more than 25 years ago. In 1999 the double-sphere superconducting gravimeter GWR CD030 was installed and has been recording up to the present. Three ground water gauges at distances of between 200 m and 3.5 km show a clear correlation between the variations in the ground water level and the recorded gravity data in the long-term (annual) range. The comparison with the observed gravity variations was based on the "corrected minute data" (repair code 02), stored in the GGP data-bank. A regression coefficient of about 50 nm s^{-2}/m results from the amplitudes of the annual wave in the residual gravity (about 19 nm s^{-2}) and that of the ground water variations at the Meiereiberg gauge (about 37 cm). - In the daily and weekly range the correlation is less clear. It seems that during late winter and spring strong precipitation events are clearly reflected in the ground water level while in autumn no precipitational influences are to be recognized.

1. Introduction

With increasing accuracy of the gravimetric measuring techniques the correct consideration of hydrological influences has become increasingly important. At first the gravity effect of the varying soil moisture was assumed to be a limiting threshold of the accuracy achievable in gravimetric measurements (Bonatz, 1967). Later in special studies aimed at the detection of the small gravity variations resulting from weak tectonic processes the attempt was made to consider the disturbing hydrological influences by corrections derived directly from the measured soil moisture and the ground water level in the neighborhood of the measuring site (e.g. Elstner, 1987; Elstner et al., 1993). The interest in the consideration of hydrological influences again increased when the first superconducting gravimeters came into practical use (e.g. Peter et al., 1995; Harnisch and Harnisch, 1995). Meantime the estimation of corrections for the influence of precipitation and ground water variations is an essential part of detailed studies of different gravity effects, especially. in the long-term range (e.g. Lambert and Beaumont, 1977; Harnisch and Harnisch, 2002; Harnisch and Harnisch, 2006; Kroner, 2002; Llubes et al., 2004).

In contrast to the consideration of the local air pressure variations no standard procedure is available for the correction of the different hydrological influences. The reason is that generally the hydrologic conditions are very complicated and differ from site to site. To model the particular situation in detail and to estimate the varying density distribution beneath the surface a multitude of parameters and continuously measured data series would be needed (precipitation, topography of the ground water level and its variation with time, soil moisture, temperature, evolution of the plant cover, topography of the different soil layers, density and porosity within the layers, position of faults and clefts in the bedrock, etc.), which in practice cannot be provided completely and in time. Therefore statistical regression techniques are preferred, which relate the gravity effect to be eliminated with hydrological data (precipitation, ground water level, soil moisture) measured near the site of the gravity observations.

At Bad Homburg ground water data became available in the beginning of 2004. The surprisingly strong variations of the ground water level near the gravimetric laboratory (Schlosskirche gauge) and their correlation with the recorded gravity variations showed that in future, even at this very stable station hydrological influences on the gravity measurements have to be taken into account.

2. The gravimetric laboratory in the Bad Homburg castle

Bad Homburg is a town on the south eastern slope of the Taunus Mountains in the vicinity of Frankfurt a.M. The official addendum "v.d.Höhe" (= "before the heights") hints at the near Taunus Mountains. In the centre of the town on a local elevation is the castle with the White Tower, the oldest part of the castle from the 14th century. The other parts of the castle date from the 17th century, among them the Archive Wing (1679 – 1686), the southwestern part of the castle buildings.

The gravimetric laboratory in the basement of the Bad Homburg castle was built in 1978 in an old apple cellar in the Archive Wing. It was developed as a testing site for the BKG (formerly Institute for Applied Geodesy, IfAG). Nowadays there are two isolated huts with pillars for absolute gravimeters and for permanently recording superconducting gravimeters. Beginning with the TT40, one of the first superconducting gravimeters in practical operation, several other superconducting gravimeters, manufactured by GWR Instruments, San Diego, USA, have been operated or have been tested before continuous operation elsewhere (TT60, SG103, RG038, CD030). Also many calibration experiments have been carried out in the Bad Homburg castle with the moving platform as well (Richter, B. et al., 1995) as with comparison of superconducting and absolute gravimeters (Harnisch, G. et al., 2002). This laboratory has been used for more than 15 years as a reference site for the absolute gravity measurements within Germany and Europe (Wilmes and Falk, 2006).

3. The Gravity Data

At the end of 1999, the dual sphere superconducting gravimeter GWR CD030 was installed in the gravimetric laboratory. During the first year of operation the data series is distorted by several calibration activities of various kinds. Since that time the gravimeter has produced reliable data available in the GGP-ISDC (minute data; corrected minute data, rep. code 02; corrected minute data, rep. code 22; station log file). All data series begin with the February 9, 2001. In the present study the residual gravity has been derived from the corrected minute data, repair code 02 (i.e. corrected by P. Wolf, BKG).
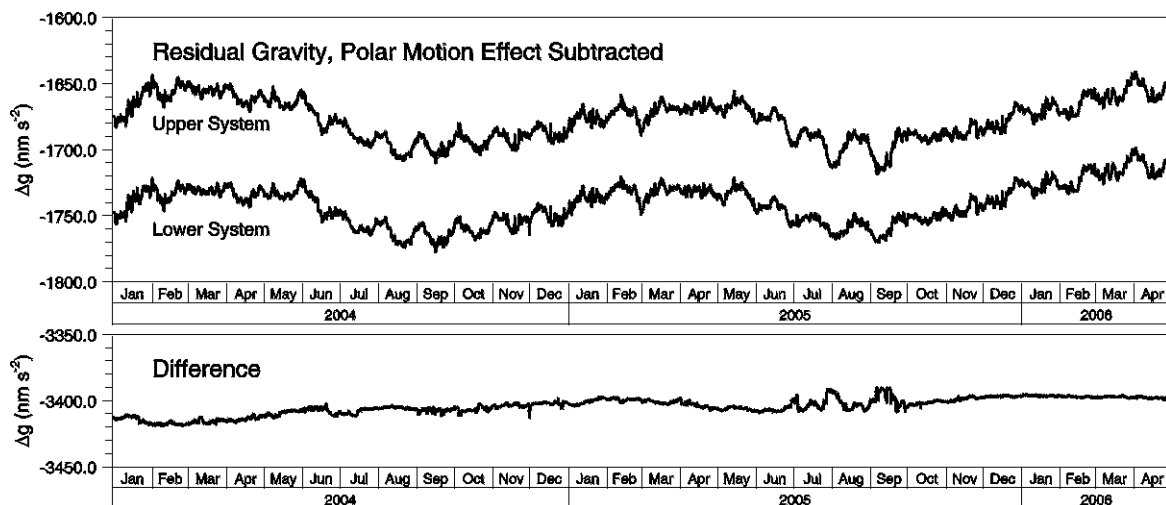
Fig. 1: GWR CD030, Bad Homburg, January 1, 2004 – April 30, 2006: **Upper frame:** Residual gravity of both systems of the gravimeter. Tidal model, gravity effect of the local air pressure and theoretical gravity effect of the polar motion subtracted. **Lower frame:** Difference of the residuals of both systems of the gravimeter.

The general problem of the use of gravity residuals is the preservation of the influences to be studied as completely as possible while all other known disturbing influences have to be eliminated. To this aim the tidal model was derived by a usual tidal analysis (ETERNA 3.30) including several long-term waves up to the annual wave Sa and the local air pressure. A second additional channel was used for the consideration of the theoretical gravity effect of the polar motion (IERS data, δ = 1.16). This way the parameters of the long-term tidal waves (e.g. Sa and Ssa) should be minimally influenced by the local air pressure and the polar motion. Nevertheless the parameters of Sa resulting from this tidal analysis are unrealistic. Obviously the annual tidal wave is affected by non-tidal influences with amplitudes und phases significantly different from those of Sa. Therefore the parameters of Sa are replaced by the "theoretical" values δ = 1.16 and the κ = 0.0. If this modified tidal model, the influence of the local air pressure (on the basis of the air pressure regression coefficient resulting from the actual tidal

analysis) and the theoretical gravity effect of the polar motion are subtracted from the observed gravity variations, an annual wave results with an amplitude of the order of 20 nm s^{-2} and with a maximum late in the winter. Generally this wave has to be interpreted as some non-tidal gravity effect in the annual range. In our special case it should be caused by the hydrological influences in question.

The data recorded by the two measuring systems of the double sphere gravimeter GWR CD030 are treated as the data of two independent gravimeters. In the upper frame, Fig. 1 shows the residual gravity of both systems of the gravimeter CD030, derived in the described way. The remaining gravity residuals look very similar in both systems. The instrumental drift is very small and therefore has not been eliminated. The difference between the residuals of both systems shows no systematic tendencies (Fig. 1, lower frame). Only noise and some disturbances due to icing problems in the year 2005 are visible.

4. Influence of the Castle Pond

The pond in the nearby landscape garden has a surface area of 11000 m^2 and a maximum depth of 1 m. The horizontal distance between the middle of the pond and the gravimetric laboratory is about 110 m. In the vertical direction the bottom of the pond is 15.3 m beneath the surface of the pillars in the gravimetric laboratory. Every two or three years the pond is emptied for repair or cleaning purposes. A rough estimation (approximation of the water volume in the pond by rectangular prisms) results in a maximum influence of about 8 nm s^{-2} if the pond has been totally emptied (Falk, 1995).

Concerning the absolute gravity measurements in the Bad Homburg castle the individual disturbing events resulting from the variations of the water level in the castle pond may be neglected. On the other hand gravity variations of the order of 8 nm s^{-2} should be detectable in the recordings of the superconducting gravimeter, at least from the theoretical point of view. However, in practice there is no chance because the weak "pond signal" changes very slowly. It extends over several months with a steep beginning (when the pond is emptied) and a moderate decrease (refilling of the pond). Moreover no exact notes are available which could enable a stacking of different events to separate them from the surrounding noise.

5. The hydrological situation around the Bad Homburg castle

The local hydrological influences are essentially determined by the grouping of the different buildings of the castle. Above the gravimetric laboratory there is the solidly built Archive Wing. Its large roof and the gutters let the precipitation immediately run off and this way the infiltration of water into the ground near the gravimeter is hindered. Similarly the strong sealing of the soil surface acts in the castle area. For all these reasons the precipitation near the gravimetric laboratory cannot contribute to the formation of ground water and therefore clear precipitation signals are to be expected neither in the ground water residuals nor in the gravity.

In order to understand the occurrence of ground water around Bad Homburg the catchment area has to be taken into account. In this context the hillside position of Bad Homburg also plays an important role. The ground water is formed in higher regions of the Taunus Mountains and flows down towards the plain of the Main River. On its way the water is dammed by the castle hill. There it can pass neither upward (due to impermeable layers above the aquifer) nor laterally; and therefore the pressure in the aquifer grows. This is the typical behavior of a confined aquifer. In consequence, at the Schlosskirche gauge (about 110 m northeast of the gravimetric laboratory) variations of the pressure in the borehole are to be observed which have no influence on the observed gravity variations. In this way the position of the mean ground-water level at the Schlosskirche gauge about 8 m above the level of the Meiereiberg gauge may also be explained. Heavy rainfall in the catchment area causes frequent and strong variations of the pressure in the Schlosskirche gauge. During the vegetation period evapotranspiration reduces the formation of ground water.

In the nearby valley of the Heuchelbach covering layers are nearly totally missing above the aquifer. Therefore the Meiereiberg gauge which was drilled there (about 200 m south of the gravimetric laboratory) should react to local precipitation more clearly than the Schlosskirche gauge. Nevertheless the local formation of ground water is minimal and therefore it causes only a moderate rise of the ground water level.

6. Influence of precipitation

Since 1998, daily weather data (precipitation, maximum and minimum temperature) have been noted in the castle gardener's house (distance to the gravimetric laboratory about 130 m). The precipitation is measured with a simple glass gauge, read every day in the early morning (about 6:30 a.m.).

A second measuring site at a distance of 1.35 km to the southwest of the gravimetric laboratory was installed by the municipality of Bad Homburg. It is equipped with an automatically recording precipitation gauge. The precipitation data recorded at the municipal station should be very reliable. Unfortunately the data series begins only on May 10, 2005.
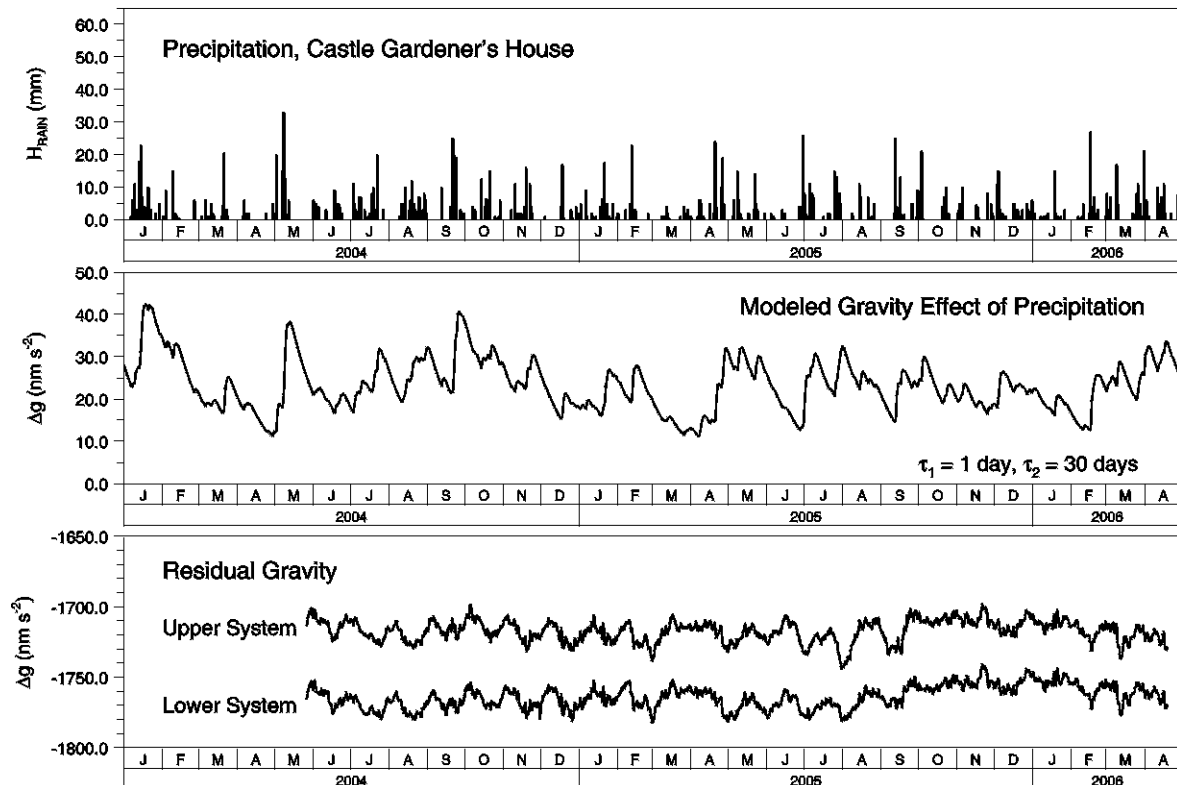

Fig. 2: Bad Homburg, precipitation at the castle gardener's house. **Upper frame:** Daily sums of precipitation. **Middle frame:** Modeled gravity effect, resulting from the exponential model (Crossley et al., 1998) with τ_1 = 1 day and τ_2 = 30 days. **Lower frame:** Residual gravity of both systems of the gravimeter GWR CD030, corrected for the influence of ground water (Meiereiberg gauge, conversion factors 51.7 nm s^{-2}/m and 49.8 nm s^{-2}/m for upper and lower system, respectively.).

In a first step the discrete rain volumes recorded by the rain gauges are transformed to a continuous data series. For this purpose the exponential model proposed by Crossley et al. (1998) was used. Two time constants describe the infiltration of water into the ground ("recharge time constant" τ_1) and the following gradual dry out ("discharge time constant" τ_2). In the present study of hydrological influences at Bad Homburg τ_1 = 1 day and τ_2 = 30 days were chosen, keeping in mind, that the basic assumptions for the exponential model are not fulfilled (homogeneous half-space, unsealed flat surface) and therefore the use of this model can be only a very formal step. However, the "modeled gravity effect of precipitation" has the great advantage that in computations it can be better handled than the discrete data coming directly from the rain gauges. If the precipitation (daily sums or modeled gravity effect) is compared with the recorded gravity variations no significant influence of the precipitation can be recognized (Fig. 2).

7. Ground water

Ground water data are available from the three gauges Schlosskirche, Meiereiberg and Seulberg. Some information on these gauges is summarized in Tab.1. The variation in the ground water level at these gauges is plotted in Fig. 3. The very similar behavior of the ground water variations at the three gauges is surprising. However, the amplitudes are different. The strongest variations occur at the Schlosskirche gauge. But these are first of all variations of the pressure in the confined aquifer as it has been discussed already in section 5.

From the Seulberg gauge (about 3.5 km northeast to the Bad Homburg castle) only weekly values are available. Nevertheless the general tendency in the ground water variations is very similar to that at the other two gauges. An advantage of the Seulberg gauge is the length of the data series, which goes back to 1951 and among other things it covers the TT40 data series recorded 1981 – 1984 at Bad Homburg.
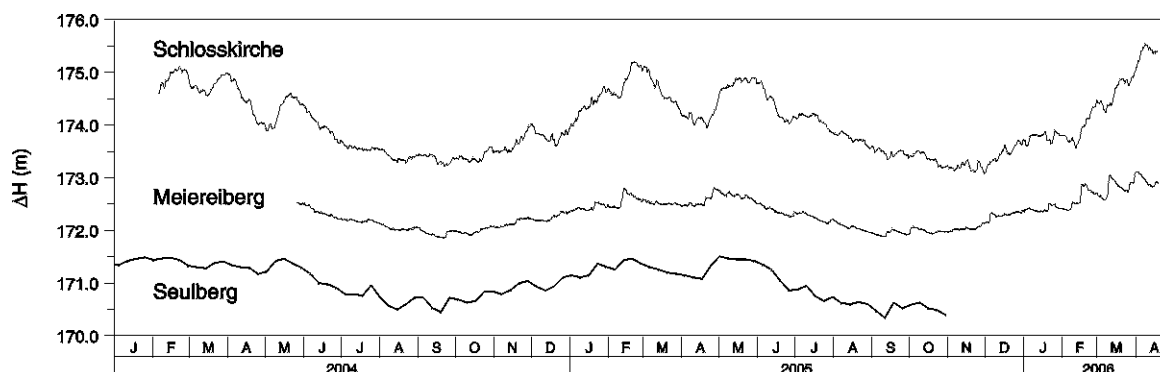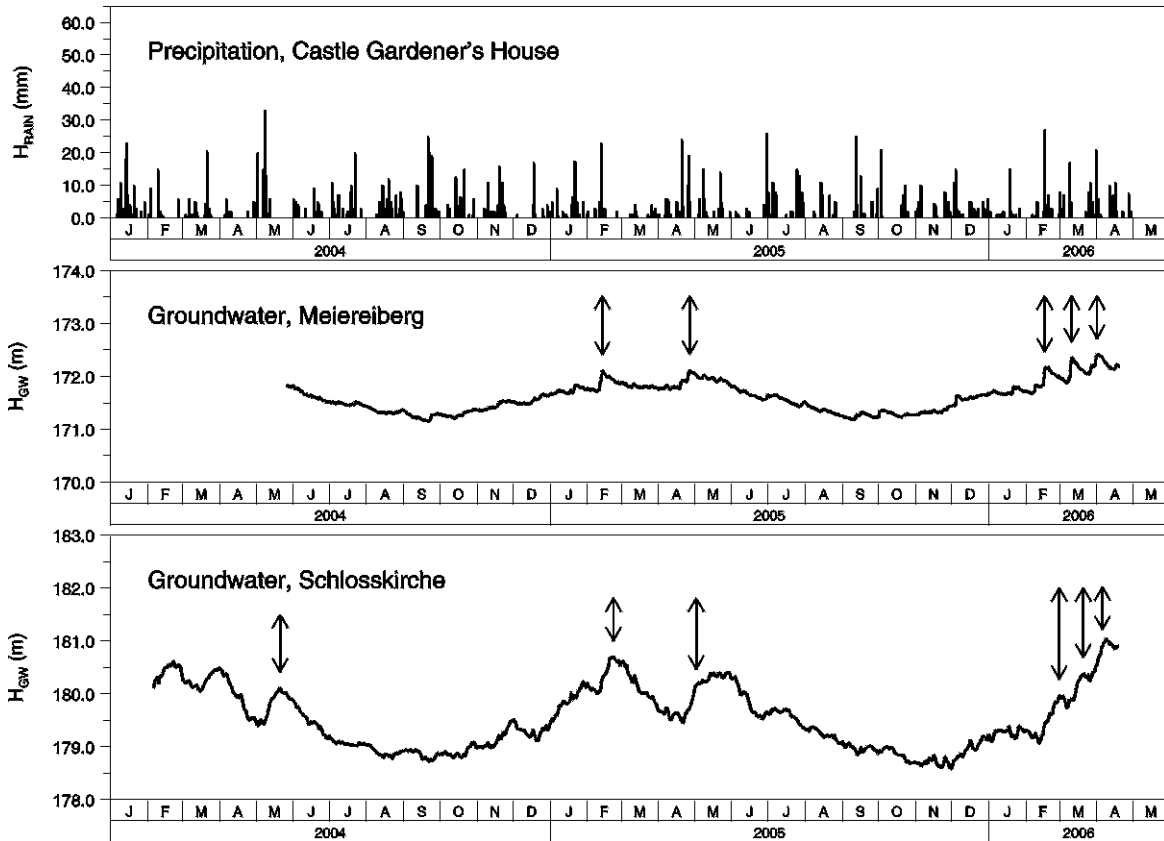

Fig. 3: Groundwater variations at the gauges Schlosskirche (Offset -5.5 m), Meiereiberg (Offset +0.7 m) and Seulberg (Offset -0.5 m)

**Tab.1:** The ground water gauges Schlosskirche, Meiereiberg, Seulberg

	Schlosskirche	Meiereiberg	Seulberg
Height of the terrain	191.94 m	174.1 m	174.31 m
Mean ground water level	179.49 m	171.57 m	171.80 m
Distance to the gravimetric laboratory	110 m	200 m	3.5 km
Range of the ground water variations (peak-to-peak amplitude of an annual wave)	(1.38 ± 0.64) m	(0.75 ± 0.21) m	(0.66 ± 0.41) m
Sensor	SEBA Dipper II	SEBA Dipper II	Manual sounding
Sampling rate	1 hour	1 hour	1 week
Begin of the dataset	February 5, 2004	May 26, 2004	April 9, 1951

At first glance the influence of precipitation on the ground water gauges Schlosskirche and Meiereiberg seems to be inconsistent (Fig. 4). Some significant anomalies in the ground water which obviously are caused by strong precipitation are marked by double arrows. All these events occur in the first half of the year. This may be explained by the growth of vegetation in summer and the early autumn. From section 5 we know that vegetation reduces the infiltration of precipitation into the ground. However, the two gauges have to be considered differently. While the anomalies at the Schlosskirche gauge are caused mainly by precipitation in the extended catchment area and increased by the pressure in the confined aquifer, the anomalies at the Meiereiberg gauge also include local influences.

The gravity residuals remaining after the tidal model, the influence of the local air pressure and the influence of the polar motion have been eliminated show long-term undulations like annual waves (Fig. 1, upper frame, Fig. 5, uppermost curves in both frames). The amplitudes are (19.33 ± 0.08) nm s^{-2} (upper system) and (18.59 ± 0.06) nm s^{-2} (lower system). A brief visual comparison with the similar behavior of the ground water makes it seem probable that the variations in the gravity residuals are caused by the influences of the ground water. The amplitudes of the annual wave in the ground water level are (0.69 ± 0.32) m (Schlosskirche gauge) and (0.37 ± 0.11) m (Meiereiberg gauge). If ratios of the correspondent amplitudes are formed, conversion factors ("regression coefficients") result of the order of 28 nm s^{-2}/m (Schlosskirche gauge) and 50 nm s^{-2}/m (Meiereiberg gauge). Detailed values are given in Tab. 2. Corrections based on these conversion factors clearly diminish the undulations in the gravity residuals (Fig. 5, middle and lower curves in both frames). Especially if the data of the Meiereiberg gauge are used, the influence of ground water variations seems to be totally eliminated.

Fig. 4: Influence of precipitation on the ground water gauges Schlosskirche and Meiereiberg. **Upper frame:** Daily total precipitation. **Middle frame:** Ground water variations at the Meiereiberg gauge. **Lower frame:** Ground water variations at the Schlosskirche gauge. The double arrows mark times at which clear influences of precipitation on the ground water gauges may be recognized.
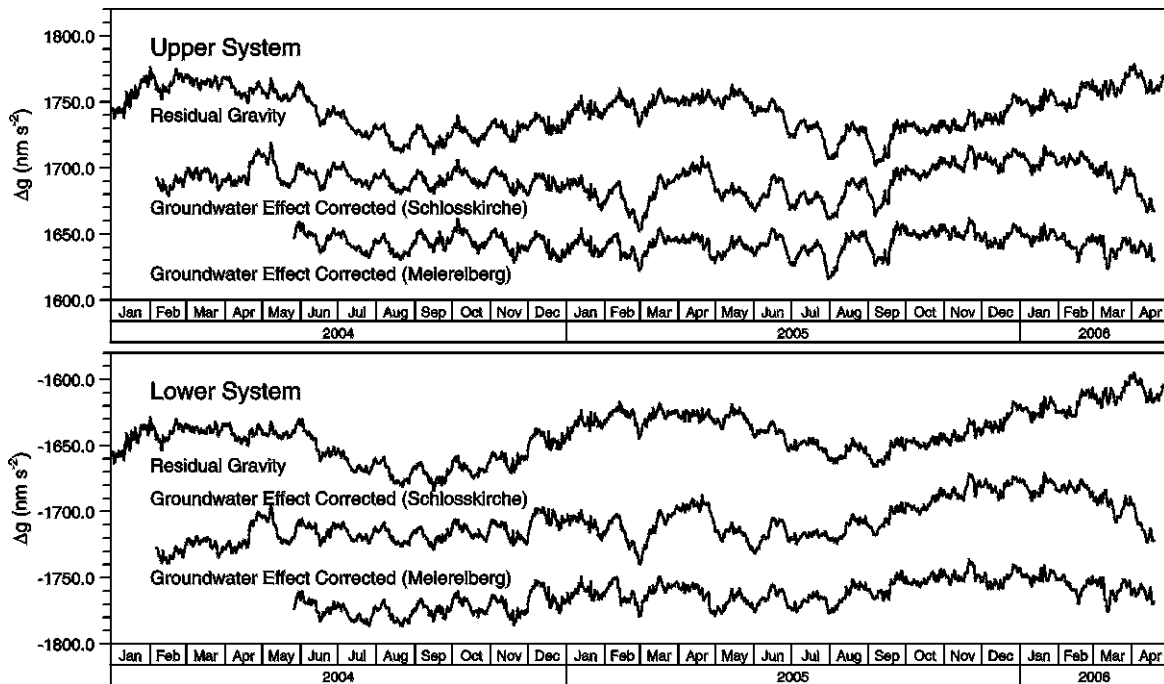
Fig. 5: GWR CD030, January 1, 2004 – April 30, 2006. Residual gravity. Air pressure influence and gravity effect of the polar motion subtracted. Ground water corrections based on the Schlosskirche gauge as well as the Meiereiberg gauge. **Upper frame:** Upper system. **Lower frame:** Lower system.

Tab. 2: Influence of ground water variations on gravity measurements at the Bad Homburg castle. Conversion factors ("Regression coefficients").

GWR CD030	Ground water gauges	
	Schlosskirche	Meiereiberg
Upper system	28.0 nm s^{-2}/m	51.7 nm s^{-2}/m
Lower system	26.9 nm s^{-2}/m	49.8 nm s^{-2}/m

8. Possible other explanations for the observed gravity variations

Generally the interpretation of gravity variations in the annual range is problematic. Many processes in nature recur at nearly annual periods but not necessarily with the same or a similar phase (e.g. variations of the temperature throughout the year, rainfall and snow, seasonal development of the plant cover, foliation and defoliation of the trees). In the rating of the tidal model resulting from the tidal analysis of the recorded gravity data the strongly deviating δ- and κ-values of the annual wave were rejected and replaced by the theoretical values $\delta = 1.16$ and $\kappa = 0$. Therefore it may be asked whether the annual wave in the gravity residuals is a real one and whether it is possible to explain this wave by hydrological influences. We consider two alternative explanations: Gravity variations induced by the three-dimensional redistribution of air masses and seasonal motions of the earth's surface, detected by GPS observations.

8.1. Three-dimensional anomalies of the air density

Usually the distribution of the air density in the atmosphere is assumed to be in agreement with the model of the standard atmosphere. On this basis the gravity variations caused by variations of the air density may be derived from the local air pressure alone. Simon (2003) studied the influence of discrepancies between the standard atmosphere and the real density distribution in the atmosphere derived from data of radiosondes. As a very important result he found out that after the air pressure corrections based on the local air pressure have been applied there remains a seasonal gravity variation with an amplitude (peak to peak) of the order of 10 nm s^{-2}, slightly different from station to station (about 6 nm s^{-2} at Miami and 16 nm s^{-2} at Ny Ålesund).
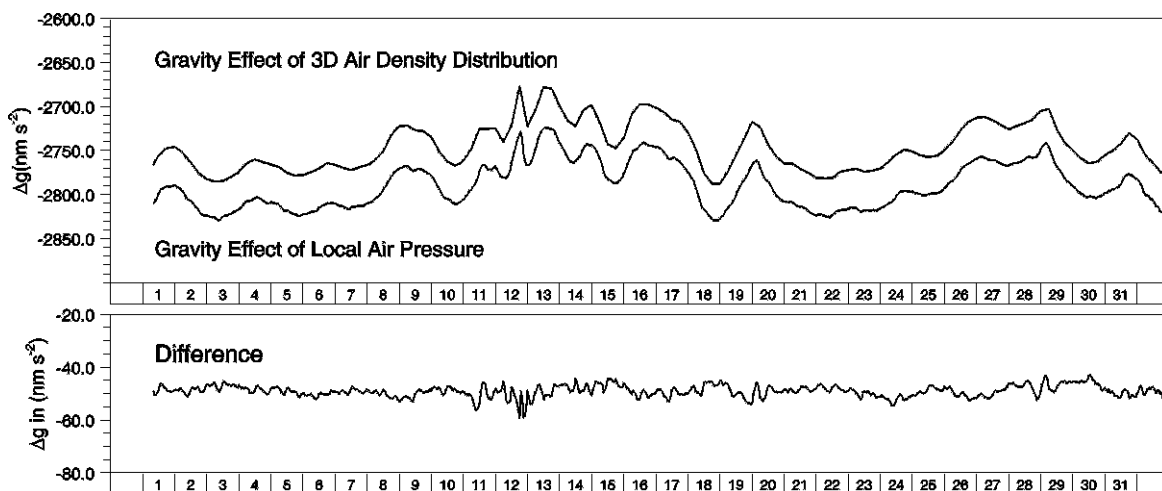

Fig. 6: Gravity effect of density anomalies in the atmosphere, January 1 – 31, 2005. **Upper frame:** Comparison of the estimates based on the local air pressure and on the 3D-model. **Lower frame:** Difference of the two models.

On the basis of three-dimensional air density data from the European Centre for Medium-Range Weather Forecasts (ECMWF) Neumeyer (2004) calculated the total gravity effect of the atmosphere (attraction term as well as elastic deformation of the earth's surface due to the atmospheric loading) at selected stations. The ECMWF data are referred on a grid with meshes of $\Delta\varphi$ and $\Delta\lambda = 0.5°$ and in vertical direction on 60 pressure levels up to a height of 60 km; the spacing in time is 6 hours. The 3D-model includes the model developed by Simon completely, based on vertical anomalies of the air density alone; the different origin of the air pressure data used by both the authors is unimportant.

The 3D-model also includes the gravity effect of the local air pressure. Therefore the correction of air density anomalies has to be based on the 3D-model alone. In practice that means that the 3D-model has to be subtracted from the measured gravity data before they are analyzed and no air pressure channel has to be introduced into the tidal analysis as it is done usually.

For a monthly period the estimates based on the local air pressure and the 3D-model are compared in Fig. 6. As may be seen from the lower frame the difference between both estimates varies more or less randomly and remains below about 10 nm s^{-2}.
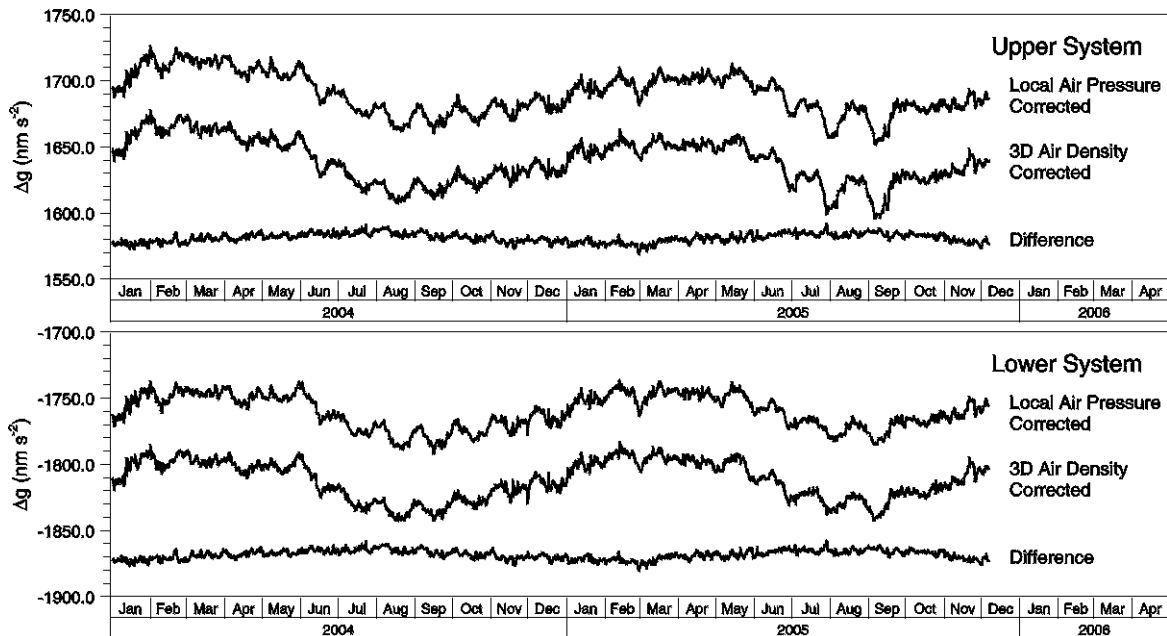
Fig. 7: GWR CD030, January 1, 2004 – December 7, 2005. Residual gravity. Air pressure influence and gravity effect of the polar motion subtracted. Consideration of air density variations based as well on the local air pressure (upper curve) as also the 3D-model (middle curve). Difference of he two estimates (lower curve). **Upper frame:** Upper system. **Lower frame:** Lower system.
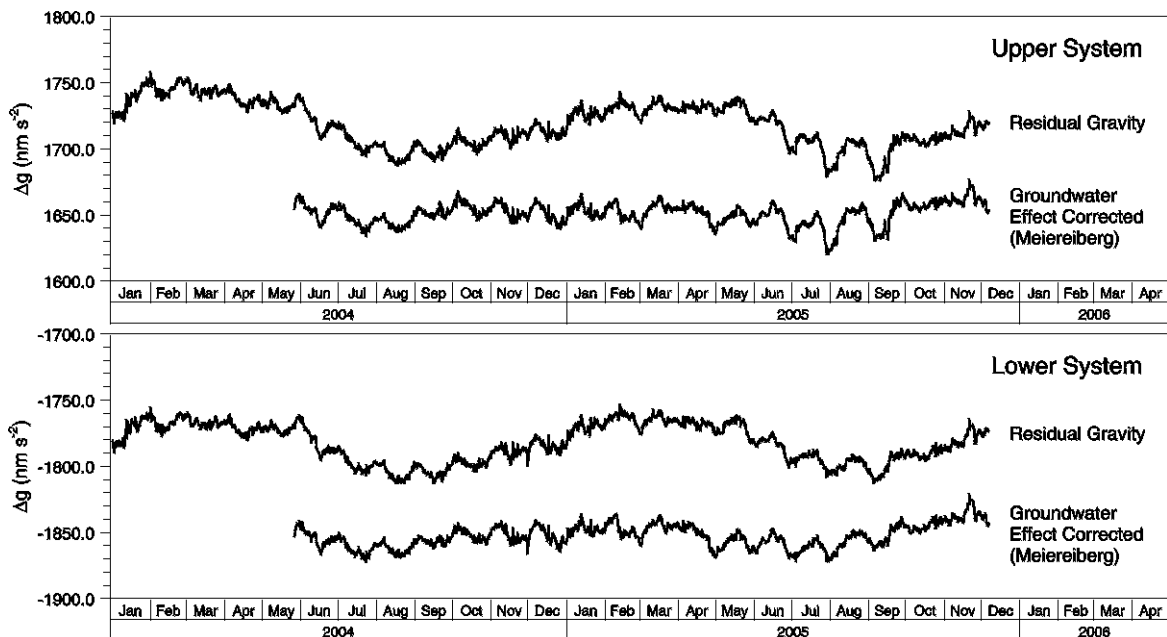
Fig. 8: GWR CD030, January 1, 2004 – December 7, 2005. Residual gravity. Air pressure influence and gravity effect of the polar motion subtracted. Air density correction based on the 3D-model. Ground water correction based on the Meiereiberg gauge. **Upper frame:** Upper system. **Lower frame:** Lower system.

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If the gravity residuals are compared resulting from both estimates of the air pressure influence the slight seasonal variation of the order of 10 nm s^{-2} becomes visible (Fig. 7), also described by Simon (2003). Moreover it is very important that the plots of the gravity residuals (Fig. 8) are very similar to the correspondent plots based on the local air pressure correction (Fig. 5), i.e. also the consideration of the spatial distribution of the air density (3D-model), cannot explain the annual wave remaining after the polar motion influence has been subtracted from the standard residuals.

If the gravity residuals based on the 3D-model are compared with the variations of the ground water level in the Meiereiberg gauge regression coefficients of 44.6 nm s^{-2}/m (lower system) and 63.6 nm s^{-2}/m (upper system) result which are very similar to those derived in section 7 from the gravity residuals based on the local air pressure correction (49.8 nm s^{-2}/m respectively 52.9 nm s^{-2}/m).

8.2. GPS Observations at the Bad Homburg castle

At the beginning of 2005, a GPS antenna was installed on the Bad Homburg castle. It is mounted on a brick wall at a height of about 20 m. The distance to the gravimetric laboratory is about 70 m. The first year of observations shows a slight undulation in the daily values of the vertical component (Fig. 9, upper frame). For comparison, in the middle frame the daily means of the air temperature at the Frankfurt a.M. airport have been recorded and in the lower frame the gravity residuals of both systems of the gravimeter GWR CD030 are plotted. Obviously the motion of the earth's surface derived from the GPS data is in opposite phase to the variations of the gravity residuals of both systems of the gravimeter. This would mean that the gravity changes could be totally or partly explained by the local uplift and subsidence of the earth's surface.
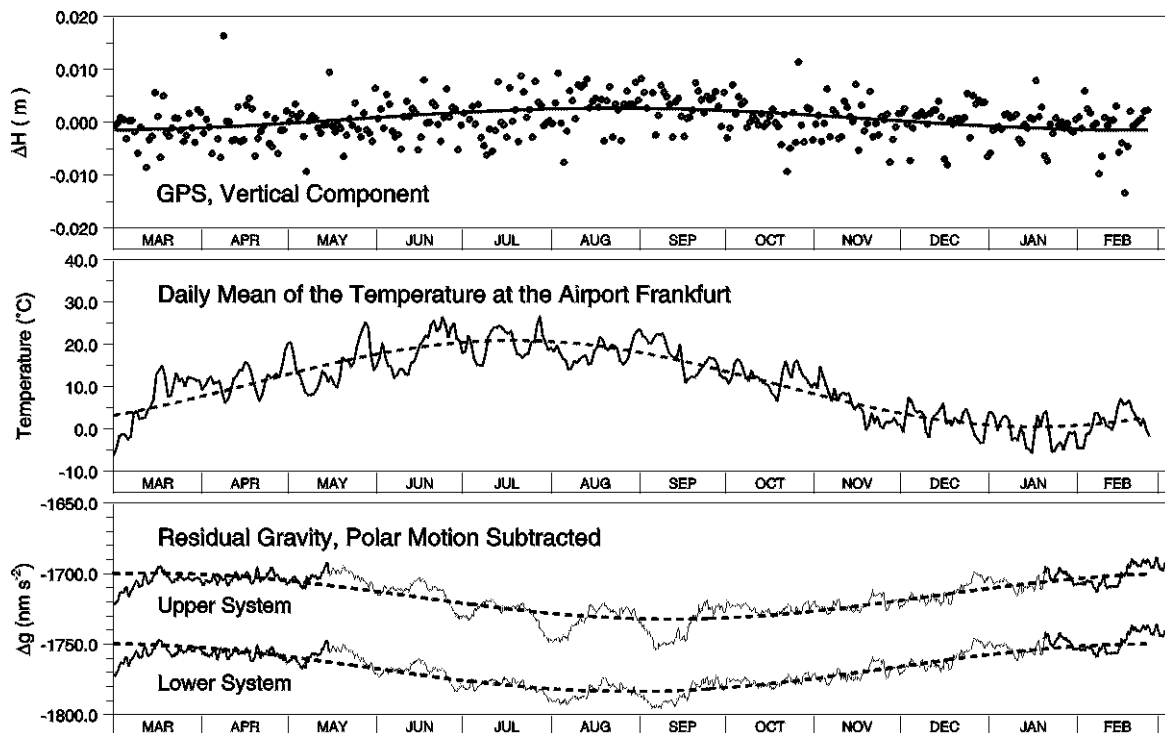
Fig. 9: GPS, Bad Homburg castle, March 1, 2005 – February 23, 2006. **Upper frame:** Vertical displacement of the GPS antenna. **Middle frame:** Daily mean temperature at the airport Frankfurt a.M. **Lower frame:** Gravity residuals of both systems of the gravimeter GWR CD030. Solid and dotted lines: annual waves with the amplitudes 2.1 mm (GPS, vertical component), 10.2 K (Mean daily temperature), 16.3 nm s^{-2} (Residual gravity, upper system) and 16.8 nm s^{-2} (Residual gravity, lower system).

For a more detailed examination of the mutual dependences, sinusoidal functions with annual period were fitted to the data series. The resulting amplitudes are (2.1 ± 0.4) mm for the vertical component of the GPS data and (16.8 ± 0.1) nm s^{-2} respectively and (16.3 ± 0.1) nm s^{-2} for the lower and the upper system of the gravimeter GWR CD030. If the free air gravity gradient of 3 nm s^{-2}/mm is used, the annual wave in the GPS data could explain annual gravity variations with amplitudes of 6.2 nm s^{-2}. That is only about 37 % of the observed annual variation of the gravity residuals. Due to a smaller vertical gradient the true effect of the vertical motions should be less than this value.

Up to now in the present discussion the GPS data have been assumed to describe real motions of the earth's surface around the GPS antenna. However, the variations can also be explained otherwise, e.g. by thermal expansion of the masonry. To this aim in the middle frame of Fig. 9 the mean daily temperatures at the airport Frankfurt a.M. (about 20 km to the south of Bad Homburg) are shown together with a sinusoidal function fitted to these data. The amplitude of this annual wave is (10.2 ± 0.3) K. If a coefficient of $5 \cdot 10^{-6}$/K is assumed, the thermal expansion of the masonry could explain annual variations of the GPS antenna with amplitudes of 1.0 mm, i.e. about 50 % of the observed motion. In view of the phase shift obviously existing between the temperature variations and the vertical motion of the GPS antenna (see Fig. 9) it is very questionable whether a significant influence of the temperature really exists.

In summary, it can be stated that the vertical motions detected by the GPS observations may influence the gravity measurement, but they cannot explain the main part of the annual wave in the gravity residuals.

9. The TT40-Series, recorded 1981 – 1984 at the Bad Homburg castle.

In the well known TT40-series recorded 1981 – 1984 at the Bad Homburg castle the gravity effect of the polar motion clearly could be detected (Richter, 1987). Now it is possible to correct retrospectively also this data series for hydrological influences. In the upper frame of Fig. 10 the variations in the ground water level at the Seulberg gauge are shown and in the lower frame from top to bottom the results of three main steps of the data processing:

- Gravity residuals, corrected for the instrumental drift (by subtraction of a polynomial of second degree)

- Polar motion influence eliminated (IERS data, $\delta = 1.16$)

- Ground water influence eliminated (regression coefficient 31.2 nm s^{-2}/m)
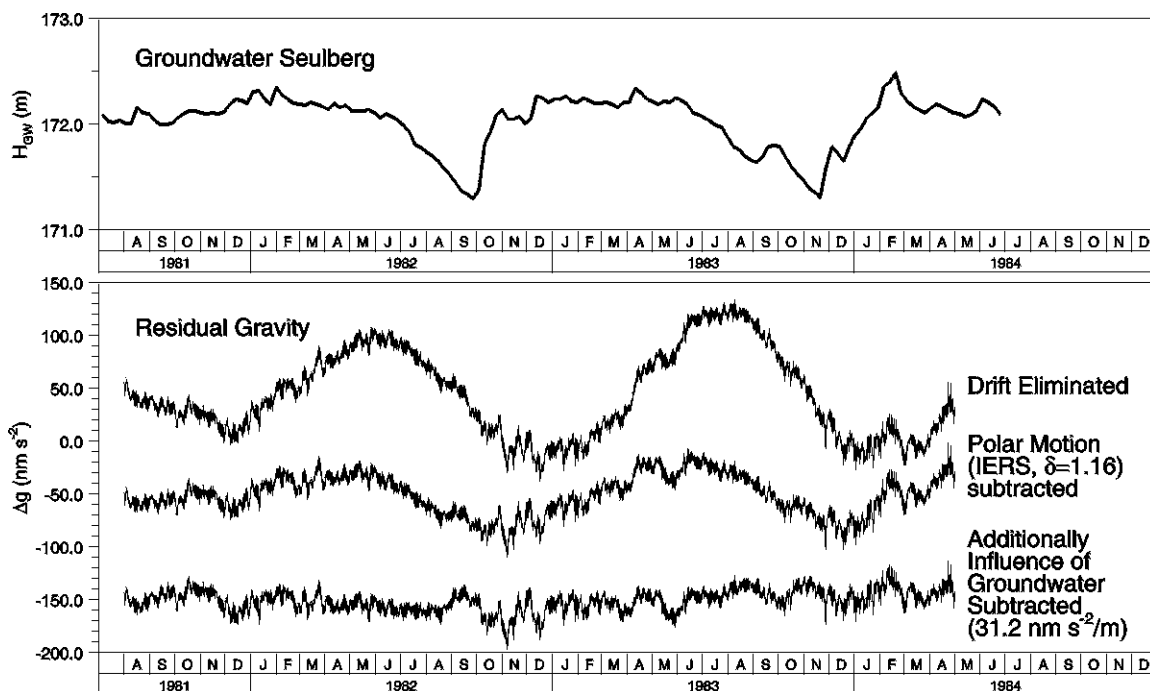
Fig. 10: Influence of ground water corrections on the TT40 data series, recorded 1981 – 1984 at the Bad Homburg castle. **Upper frame:** Ground water level at the Seulberg gauge. **Lower frame:** Effect of the ground water correction on the gravity residuals.

The ground water regression coefficient was derived from the comparison of the ground water variations in the Seulberg gauge with the gravity residuals of the TT40 during the period 1981 - 1984. The shape of the middle curve in the lower frame of Fig. 10 is caused mainly by the ground water influence. After this influence has also been eliminated the gravity residuals take the expected straightened shape (lower curve in the lower frame).

Results, Conclusions

- The study presented here is the first such attempt with the gravity data recorded by the gravimeter GWR CD030 at Bad Homburg.

- The recorded gravity data are significantly disturbed by hydrological influences.

- The gravity residuals remaining after the tidal model, the influence of the local air pressure and the gravity effect of the polar motion have been subtracted may be approximated by an annual wave with an amplitude of about 20 nm s^{-2}. Obviously this wave is caused by hydrological influences.

- From comparisons with the ground water gauges conversion factors ("regression coefficients") of the order of 50 nm s^{-2}/m (Meiereiberg gauge) and 28 nm s^{-2}/m (Schlosskirche gauge) result. Most effective are corrections derived from data of the Meiereiberg gauge.

- Other influences or effects (consideration of the 3D air density distribution; displacements of the earth's surface detected by GPS) cannot explain the annual wave in the gravity residuals alternatively, at least not completely.

- The studies concerned with hydrological influences on gravity measurements at Bad Homburg should be continued.

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