Seasonal Variations of Hydrological Influences on Gravity Measurements at Wettzell

Martina Harnisch, Günter Harnisch
formerly Bundesamt für Kartographie und Geodäsie (BKG)
Richard-Strauss-Allee 11, D-60598 Frankfurt am Main

1. Introduction

During the first years of gravimeter recordings at Wettzell hydrological influences were assumed to be unimportant. Arguments were: station on a mountain top, rocky underground, water circulation only in clefts etc. However, at least since R. FALK [7] found a clear correlation between absolute gravity measurements and groundwater, there is no doubt about the presence of hydrological influences on the gravity at Wettzell (fig. 1). If the influence of groundwater variations is corrected, the scattering range of the measured absolute values decreases from more than 100 nm s^{-2} to about 50 nm s^{-2}, which much better corresponds to the expected accuracy of the FG5.

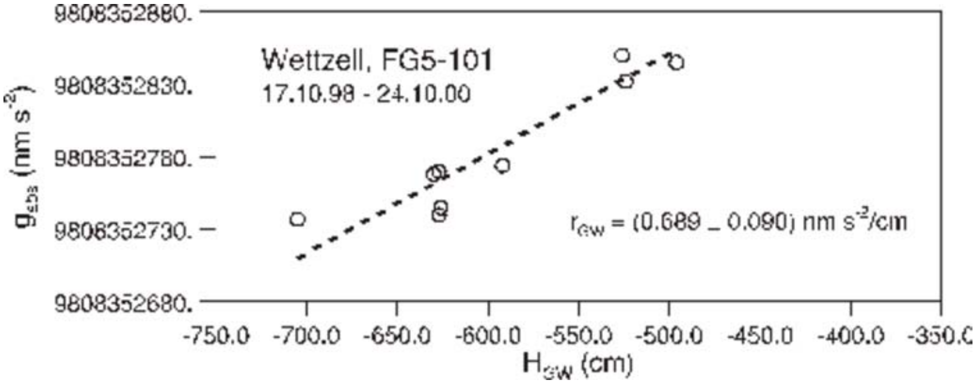

Fig. 1: Correlation between changes of the groundwater level and gravity variations, measured with the absolute gravimeter FG5-101 at Wettzell.

The changes of the groundwater level at Wettzell may reach about 4 m (fig. 2). The formal fit of a sinusoidal wave with a period of 365.25 days to the groundwater data results in an amplitude of 57.02 cm. Using a groundwater regression coefficient of 0.689 nm s^{-2}/cm (the value which was derived from the comparisons with absolute gravity measurements), the corresponding gravity variations would be near ±40 nm s^{-2}. It is clear that variations of such an amount are very dangerous for investigations of long-term gravity phenomena and that they must be taken into account and eliminated very carefully.

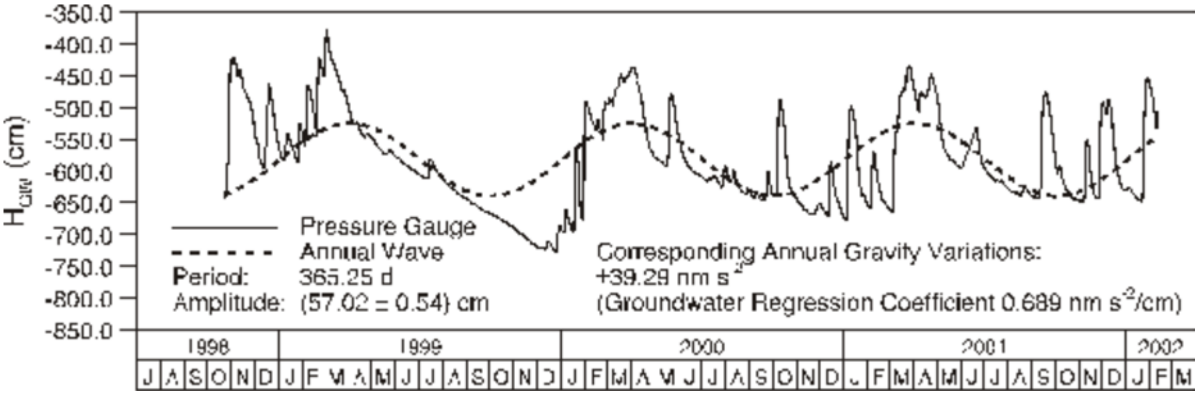

Fig. 2: Long-term changes of the groundwater level at Wettzell and the corresponding annual gravity variations.

2. Some problems of hydrological modeling in gravimetry

The infiltration of water into the underground and its redistribution are very complex processes. Because of the great economical importance there are many attempts of hydrological modeling, which aim at the estimation of water resources. Generally the fundamental equation of hydrology (equation of the water balance) is valid

$$P = R_0 + E + (A - C) \tag{1}$$

where P = precipitation, R_0 = run-off at the earth's surface, E = evaporation, A = accumulation (= increase of water in a certain area during a certain time) and C = consumption (= decrease of water in a certain area during a certain time). Each of the constituents of this equation may be influenced by different factors in different ways.

First of all the accumulation of water depends on the rocks in the underground, their state of weathering and tectonic influences (formation of clefts and cavities of different size). The run-off depends on the properties of the superficial material, the evaporation on meteorological parameters (air temperature, humidity of the air, wind) and on the plant cover, etc. In hydrologic modeling generalized input data and parameters are commonly used, which are representative for a certain area or a certain period of time.

In contrast, models for gravimetric purposes should describe with high accuracy the actual hydrologic situation in the area under consideration and its variation with time.

In view of the multitude of factors influencing the hydrologic modeling, which themselves stand for different complex processes, the following conclusions may be drawn:

- It seems to be nearly impossible to develop physically based models, which describe very accurate the actual distribution of water and soil moisture in the underground and which moreover may be realized in practice (especially with regard to the input data to be measured). Therefore for gravimetric purposes statistic models are preferred. However, such models may also be improved if basic principles of the deterministic hydrologic modeling are incorporated.

- Many of the factors mentioned above, which influence the infiltration of water and its distribution in the underground, change seasonally (e.g. precipitation, air temperature, plant cover). Therefore not only seasonal changes of the groundwater level and of the soil moisture measured at single points are to expect. Varying influences on the resulting gravimetric signal, i.e. seasonal variations of the corresponding regression coefficients are also possible.

3. Meteorological and Hydrological Data at Wettzell

Meteorological data are gathered at Wettzell since 1986. A small meteorological station continuously records air temperature, air pressure, humidity of the air, precipitation (since 1.4.1998), direction and velocity of the wind. In August 2000 a second rain sensor was added, and since December 2000 soil moisture is also recorded continuously. The soil moisture sensor (Type TRIME-EZ, accuracy ±1%) was placed in a depth of about 50 cm beneath the earth's surface. The position of the measuring points as well as that of the gravimeter building is shown in fig. 3.

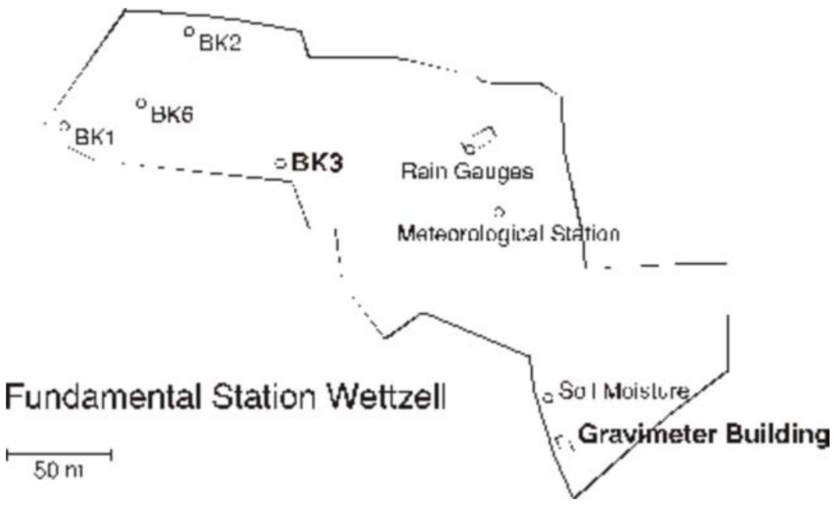

Fig. 3: Schematic map of the Fundamental Station Wettzell (Bavarian Forest, Germany).

As a part of the site investigation for the installation of the 4 × 4 m ring laser at Wettzell, several bore-holes were drilled within the station area in 1998. The first groundwater data were measured “by hand” with a light gauge. In October 1998 an automatically recording pressure gauge was installed in the bore-hole BK3. The variations of the groundwater level in the bore-holes BK1, BK2, BK3 and BK6 between August 1998 and November 1999 are shown in fig. 4. From the data of BK3 (lowermost frame) it may be seen, that there is no significant difference between the measurements by hand (small circles) and the data from the pressure gauge (solid line).

The variations of the water level in all the bore-holes are similar but not identical. The water level has its deepest position in BK1 (between -12.5 and -8.5 m) and the highest in BK6 (between -5.0 and -2.0 m). The maximum amplitudes of the level changes are also different (about 4.0 m at BK1 and 2.0 m at BK2). Finally it has to be mentioned that the most detailed variations of the groundwater level occur in BK3, while the changes in BK1 are very smooth. From these more or less general facts alone it may be concluded, that the distribution of soil moisture and groundwater in the area of the station Wettzell is very inhomogeneous and that it should be very problematic to describe the corresponding gravity effect and its variation in time by a simple deterministic (physical) model.

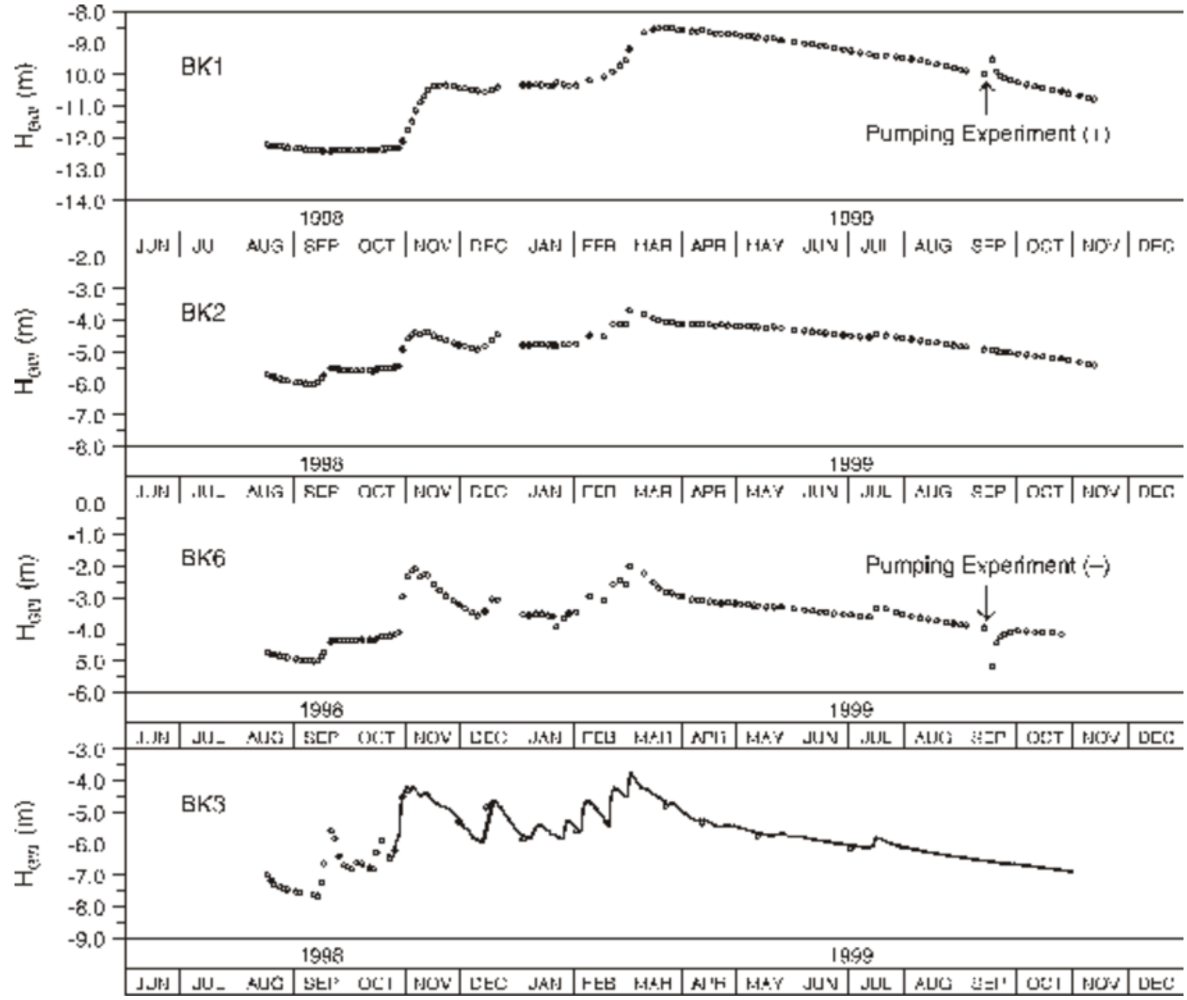

Fig. 4: Groundwater variations in the bore-holes BK1, BK2, BK3 and BK6, measured between August 1998 and November 1999 with the light gauge.

A pumping experiment gives also an idea of the complicated hydrologic situation at Wettzell. Between 15.9.1999, 13:00 CEST and 16.9.1999, 14:00 CEST about 100 m^3 water were pumped out from BK6 and injected into BK1. The pumping rate decreased from 1.2 l/s in the beginning to 1.0 l/s at the end of the experiment. After one day the water level in BK6 returned again to its original position. The gravity variations recorded by the CD029 show a clear influence of the pumping experiment. The distance from BK6 is 250 m. With a delay of 12 hours the residual gravity decreased by about 10 nm s^{-2}. On the other hand, in a distance of only 70 m from BK6 and nearly in the same direction as to the gravimeter, no clear changes of the water level occurred in BK3. If a groundwater regression coefficient $r_{GW} = 0.689$ nm s^{-2}/cm is assumed (derived from the absolute measurements, see above) about 15 cm had to be expected. The downward directed bulge in the air pressure is not related to the pumping experiment.

A summary of all the precipitation, groundwater and soil moisture data available at Wettzell from the beginning of the recordings up to the end of January 2002 is given in fig. 6. The groundwater data measured with the light gauge (see fig. 4) as well as the data from rain gauge RE2 were not included in the figure. The series of the rain data starts in April 1998, the groundwater data followed in October of the same year (BK3, pressure gauge). The measurements of the soil moisture started more than two years later in the end of December 2000.

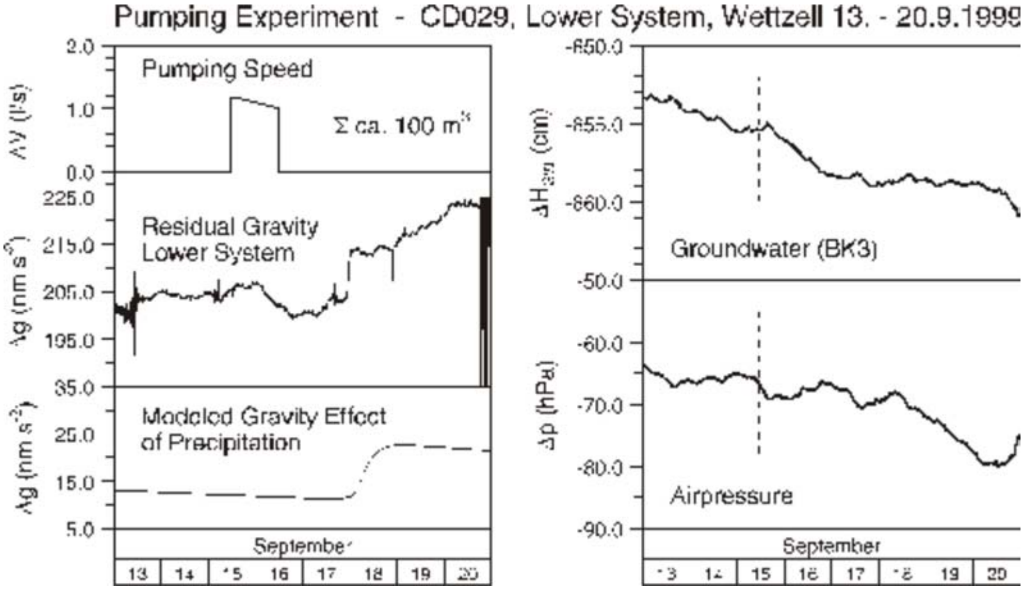

Fig. 5: Pumping experiment. In the two frames at the right the vertical broken lines mark the time of the pumping experiment.

Within the precipitation data two small sections are marked by rectangles. In both cases gaps in the precipitation data occurred which are filled up with data from the nearby power station at the Hoellenstein reservoir (in a valley about 2 km to the south-west from Wettzell, elevation difference about 200 m). Such manipulations are problematic from different points of view, but better than data gaps.

4. Preparation of the SG-Data

The investigations concerned with the influence of groundwater variations on the gravity are based on the residual gravity, derived from the recordings of the superconducting gravimeter CD029 at Wettzell. “Residual gravity” means that from the observed gravity data several “disturbing” influences are eliminated. It is of great importance, that the “right” influences are eliminated. In our case these are

- **Tides**. In the period range greater than one month the amplitude factor 1.16 has to be used, regardless of the results of the tidal analysis of local gravity data. Otherwise there is a risk, that the groundwater effect under study is partly eliminated together with the tides.
- **Air pressure**. The influence of varying air density in the atmosphere is eliminated by a linear regression model, using the local air pressure variations at the gravimeter site and an regression coefficient derived by the standard tidal analysis. More details of the air pressure model (e.g. regional air pressure distribution, deviations from the standard atmosphere) are not included.
- **Polar motion**. The gravity effect of polar motion has to be eliminated before any estimates of the instrumental drift are made. To this end IERS pole co-ordinates and the amplitude factor of 1.16 have to been used.
- **Instrumental drift**. Different constituents of the instrumental drift have to be taken into account. The exponential drift, occurring in the initial phase after the initialization of the gravimeter, has to be eliminated by fitting an exponential model. After the exponential constituents have been eliminated, the remaining long-term drift in most cases may be described by a linear model. If a sufficient number of absolute measurements is available, they may be used to

check the drift model derived alone from the data of the superconducting gravimeter. Commonly there is a good agreement. In the case of discrepancies the residual gravity of the SG may be fitted linearly to the AG data and in this way a corrected value of the drift rate may be found.

The data series of the CD029 is interrupted by a gap of about 6 weeks (May 5 – June 12, 1999), caused by total loss of the Helium. In the first section before the gap a strong linear drift of -136.15 nm s^{-2}/month occurred in the lower system. After a careful re-initialization the drift-rate reduced to a very low value in the section after the gap. Altogether 9 absolute measurements were available, which could be used to correct the instrumental drift. The result is shown in the uppermost frame of figure 7. Especially in the second section of the data series a clear correlation between gravity variations and changes of the groundwater level at BK3 can be recognized. Anomalies in the residual gravity can now be explained simply by strong groundwater variations, e.g. the large peak of the residual gravity in the first half of 2000.

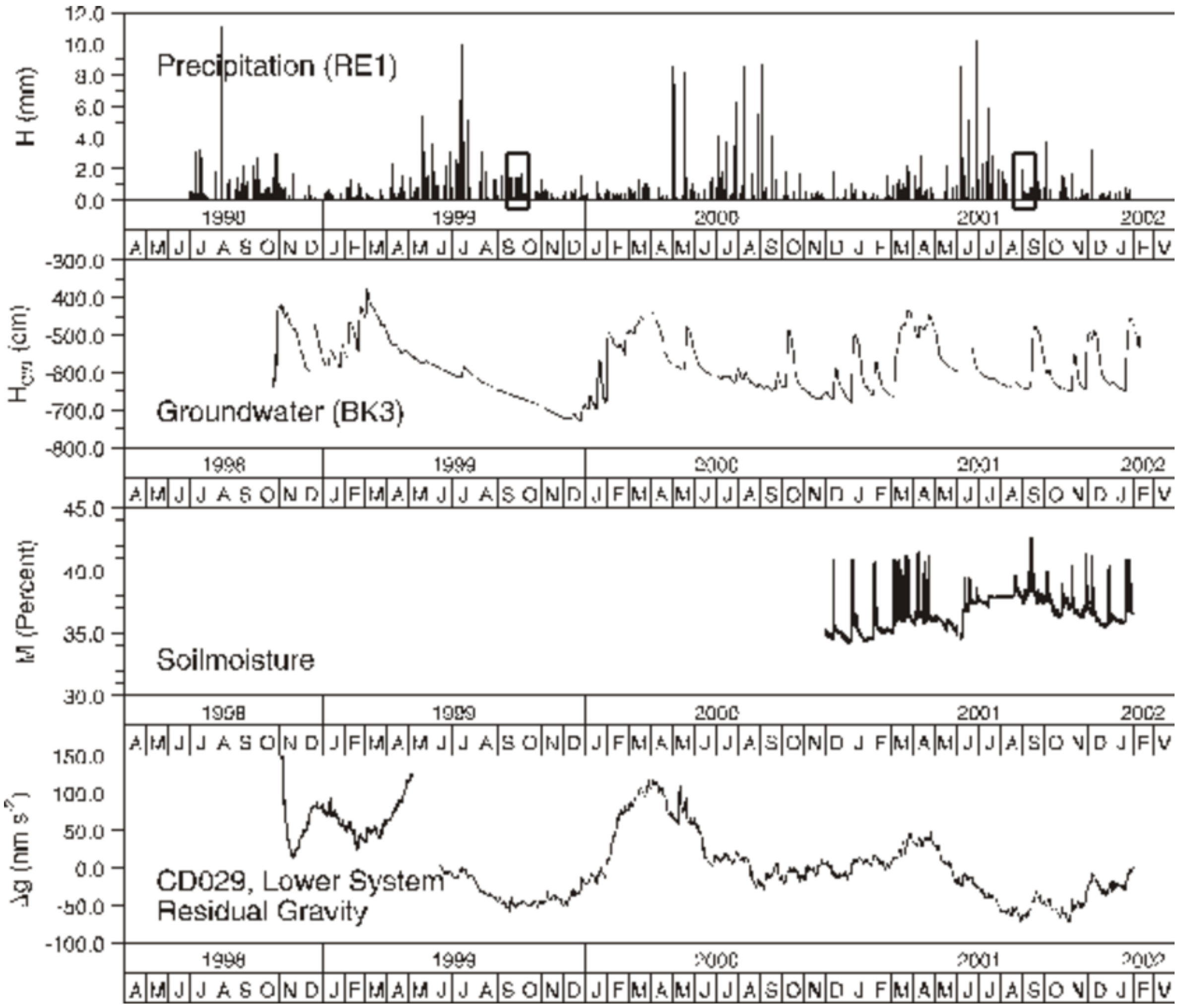

Fig. 6: Precipitation, groundwater and soil moisture at Wettzell from the beginning of the recordings up to the end of January 2002. The rectangles mark gaps in the precipitation data, which have been filled up with data from the nearby power station at the Hoellenstein reservoir.

Unfortunately the first section of the data series recorded by the CD029 is supported only by two absolute measurements. Considering moreover the very strong linear drift and the remaining residuals of the exponential constituents, it may be concluded that the gravity data before the gap are very unreliable and therefore unsuited for further investigations.

5. Correlation between precipitation and gravity

From equation (1) follows that in a closed hydrological system precipitation is the only input of water. The precipitation infiltrates and distributes in the ground. In this way changes of the groundwater level and of the soil moisture arise. Inflow and run-off of water in the underground may change the situation in detail. However, precipitation measurements in principle provide the most important input data of hydrological modeling.

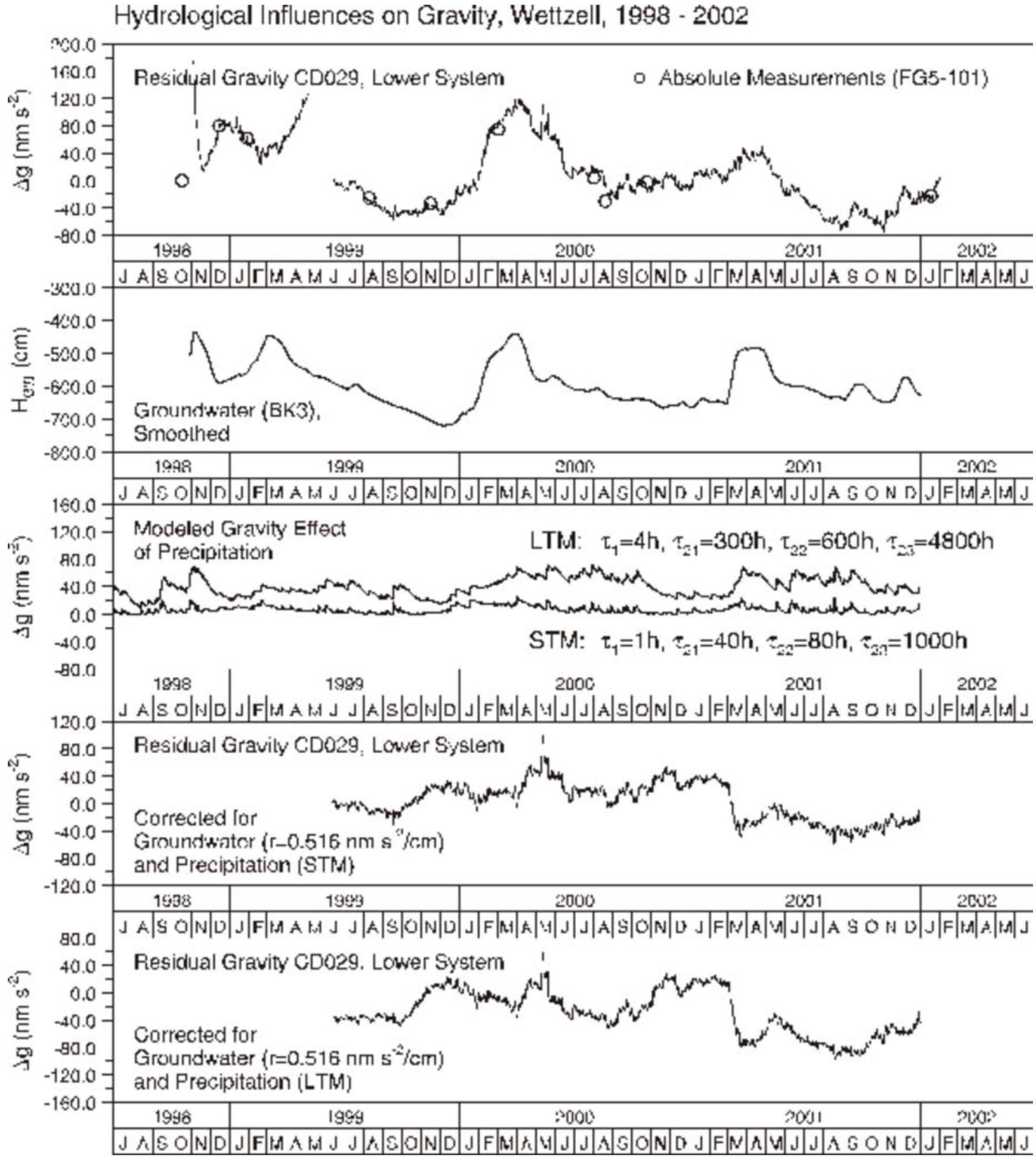

Fig. 7: Corrections for the influences of precipitation and groundwater, applied to the residual gravity of the gravimeter CD029 at Wettzell.

The rain-meter used at Wettzell counts ticks of a rocker arm. However, there is always the problem to discern from the distance between “no rain” and “no data due to a malfunction of the instrument”. In every case precipitation sensors must be maintained very carefully.

Generally precipitation data may not be correlated directly with gravity changes. At first the precipitation (measured in height or volume per unit of time) has to be converted into the corresponding gravity effect. For that purpose the simple formula

$$\delta g_i = 2\pi G\rho\, r_j \left(1 - e^{-(i-j)/\tau_1}\right) e^{-(i-j)/\tau_2}$$

(2)

was used, which was proposed and very successfully applied by D. CROSSLEY et al. [2] to correct a data series recorded at Boulder. δg_i is the contribution of the precipitation r_j at the time j to the gravity change at the time i ($i \geq j$). To get the total time dependent gravity effect the single δg_i have to be summed up over i and j. The time constants τ_1 and τ_2 stand for a multitude of different influences. According to the balance equation (1) τ_1 describes the accumulation, i.e. the infiltration of the precipitation into the underground, and τ_2 the consumption, i.e. the disappearance of the moisture due to evapotranspiration and downward migration. Numerical values of τ_1 and τ_2 representative for a certain station are derived by fitting the mathematical model to the observed gravity data. In [2] the values τ_1 = 4 hours and τ_2 = 91 days are given, which are valid for the local hydrological situation at Boulder. First attempts of hydrological modeling at Wettzell were done using the modified values τ_1 = 4 hours and τ_2 = 30 days [5,6 [1]].

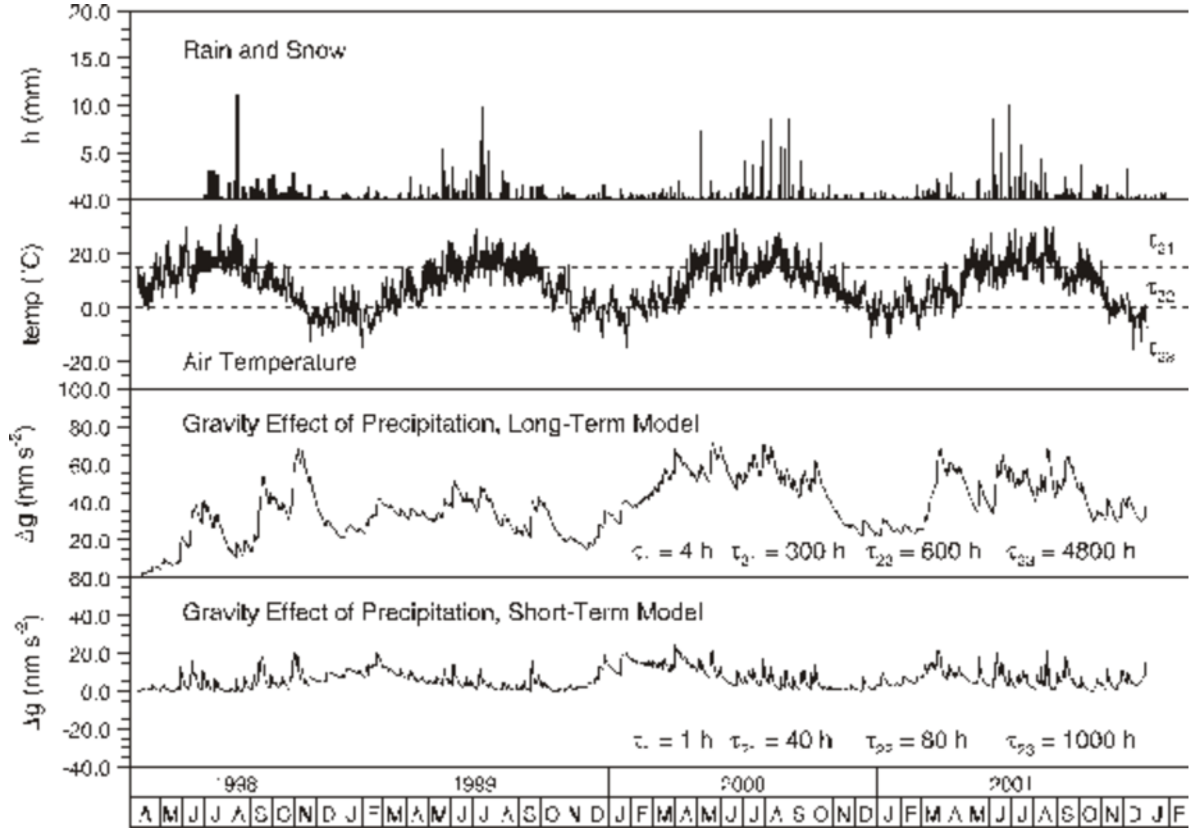

Fig. 8: Precipitation and air temperature at Wettzell, 1.4.1998 – 30.6.2001. Modeled gravity effect of precipitation according to equation (2). First frame: precipitation. Second frame: air temperature. Three different values of the time constant τ_2 were used in dependence of the air temperature. Third frame: long-term model (LTM). Fourth frame: short-term model (STM).

Many of the influences themselves vary during the year and as a consequence seasonal variations of the time constants are to be expected too. A very expressive example are the variations of temperature which not only influence the direct evaporation and the evapotranspiration (which additionally includes the contribution of the vegetation), but are also responsible for the kind of precipitation (rain or snow) and for the state of the underground (frozen or not). Therefore the attempt was made to introduce time constants τ_{21}, τ_{22} and τ_{23}, being valid for the temperature ranges above 15°C, between 0 and 15°C, and below 0°C respectively. Examples of the gravity effect of precipitation modeled in this way are given in the third and the fourth frame of fig. 8. As may be seen from a comparison of both examples, the time constants influence the amplitude of the modeled gravity effect. However, it has to be considered that no irreversible long-term accumulation occurs. The greater values used in the long-term model (fig. 8, third frame), result in more pronounced gravity anomalies as compared with the short-term model (fig. 8, fourth frame). Another example is given in fig. 12. There it could be shown, that the short-term model is equivalent to corrections derived from the directly measured changes of the groundwater level and variations of the soil moisture.

The relation between precipitation and gravity variations changes during the year. The correlogram is similarly muddled like that of the groundwater influence (fig. 10, upper left frame), however it looks even less clear. At first for the relation between precipitation and groundwater as well as for the relation between precipitation and gravity changes regression coefficients were estimated over fortnightly periods. Similarly to the considerations with concern to the groundwater influence (as described in the next paragraph) these fortnightly values were stacked with an annual period and averaged over the years (fig. 9). In a last step moving averages over every three neighboring values were derived. In this way the thick solid lines result, which more or less clearly show the seasonal variations of the regression behavior.

Due to the fact that precipitation cannot be directly correlated with changes of groundwater or gravity, the interpretation of the resulting regression coefficients differs slightly from that of the corresponding groundwater regression coefficients. With regard to the influence of precipitation on gravity the regression coefficients describe the deviations from the respective model and its parameters.

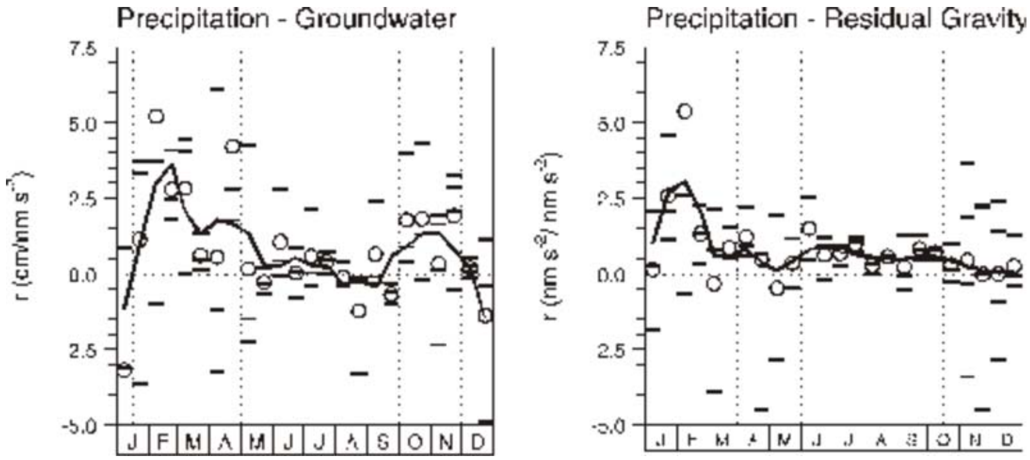

Fig. 9: Correlation between the modeled gravity effect of precipitation, groundwater and residual gravity. Stacked representation of the regression coefficients. Horizontal bars: regression coefficients estimated over fortnightly periods in the different years. Circles: mean values of the fortnightly regression coefficients over the years. Solid line: moving average of the fortnightly mean values. The vertical dotted lines separate the periods of high and low correlation.

As may be seen from the left frame of fig. 9 during the cold first months of the year as well as in the rainy autumn a strong correlation between precipitation and changes of the groundwater level occurs (upward curved sections of the solid line), while in the remaining time of the year the influence nearly vanishes. The right frame shows, that the influence of precipitation on the gravity has also a maximum in the cold season (snow cover, persistent frost), i.e. the modeled gravity effect during this time is too low. Due to increased run-off and evaporation the influence of precipitation is less in the remaining time of the year. While in summer the observed values nearly correspond to the modeled effect (regression coefficient near 1.0), for two short periods in spring and in the early winter the influence is very low (regression coefficient near zero).

6. Correlation between groundwater and gravity

At the end of 2000 a first attempt was made to estimate the dependency of groundwater variations and gravity. This investigation was spread over the period 13.6.1999 – 31.12.2000. The result was the clear proof of a varying regression behavior during the year. From February to August groundwater variations have a strong influence on the gravity, while from September to January the influence is weak.

At the end of 2001 a similar investigation was started on the basis of an enlarged data set. All data of the second part of the CD029 series having been available up to that time were included (i.e. all data after the large gap in May 1999). At first sight the result was disappointing. The correlogram looks like a chaotic muddle of lines, obviously caused by residuals of incompletely eliminated systematic influences (fig.10, upper left frame). However, if the correlogram is studied more in detail (especially during the period when its visualization develops step by step on the screen of the computer), the visual impression alone suggests to distinguish between sections with weak slope and steeper ones. A separation of these sections results in the graphic representations shown in the upper right and the lower left frame of fig. 10. The different slopes being characteristic for both subsets of the correlogram are clearly seen. However, like in the total data set, the data of both subsets are not homogeneous. Therefore regression lines were separately derived for each uninterrupted section of the correlograms. The results are given in the lower right frame of fig. 10. The solid lines relate to the weak sloped sections, the broken lines to the steep sections. The averaged regression coefficients are (0.248 ± 0.028) and (0.933 ± 0.048) nm s^{-2}/cm respectively. These numbers very clearly confirm the visual impression of different slopes being characteristic for both subsets of the correlogram. If the fact of different slopes is neglected, the adjustment of the total data set (upper left frame) would result in a regression coefficient of (0.516 ± 0.003) nm s^{-2}/cm. This value is near to the weighted mean of 0.476 nm s^{-2}/cm derived from the both seasonal values. The weights were set proportional to the respective range of validity. The directly estimated total value as well as the weighted mean correspond to the value of (0.689 ± 0.090) nm s^{-2}/cm, derived from absolute measurements (fig. 1). However, due to the use of only 9 separate absolute gravity values this first estimation of the groundwater regression coefficient is less reliable than the later values on the basis of the continuous CD029 data series.

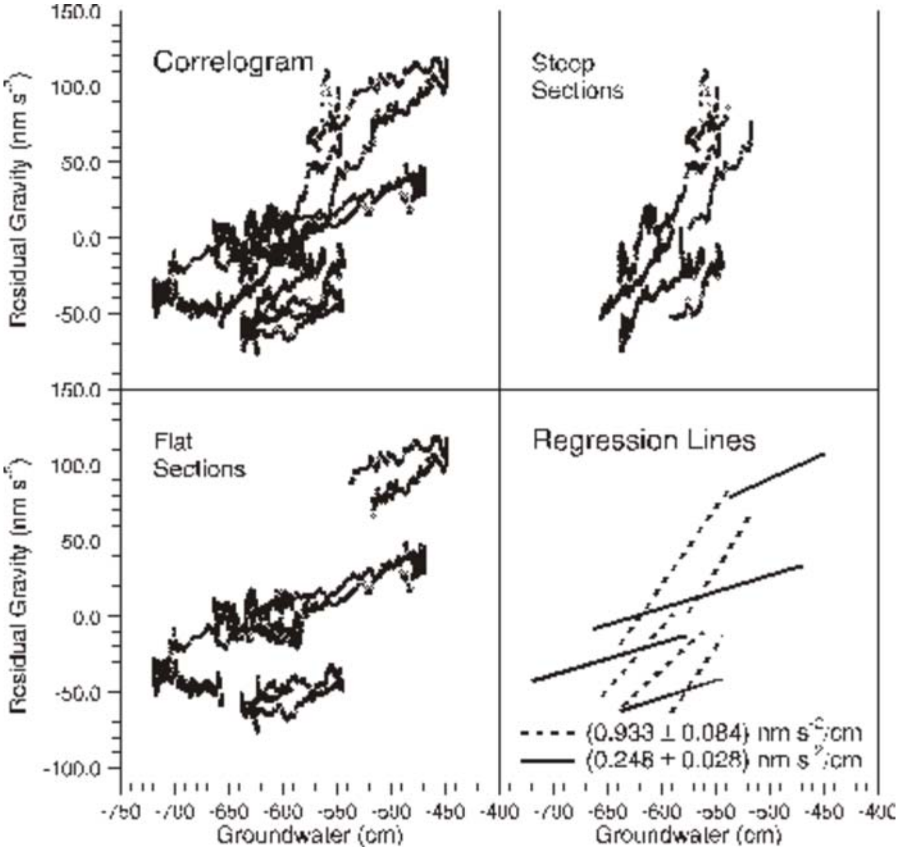

Fig.10: Correlation between groundwater and residual gravity. Seasonal variations of the groundwater regression coefficient

Generally correlograms have no relation to time. However, if the data are transferred to the time scale, the sections with different regression behavior (described by the different regression coefficients) may be related to different times of the year. From this kind of representation it becomes clear, that the periods with similar regression line slope repeat very regularly from year to year. Therefore in a last step the data were stacked over a yearly period. The result is given in fig.11, which very clearly shows the strong influence of groundwater changes from mid-May to mid-September (high regression coefficients, broken lines) and the weak influence from mid-September to mid-May (low regression coefficients, solid lines). The short sections of broken lines in February and November/December are related to the marginal sections of the data set and therefore may be ignored.

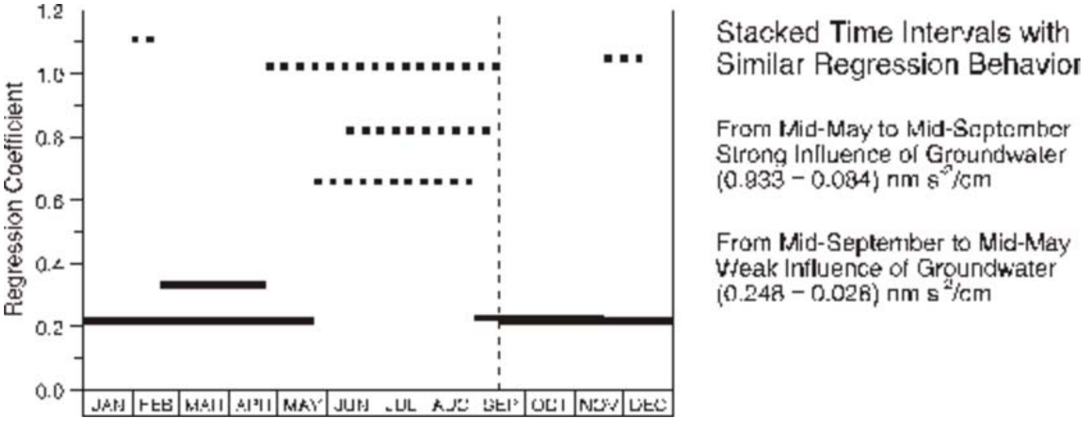

Fig. 11: Wettzell, 13.6.1999 – 31.12.2002. Stacked time intervals with similar regression behavior. The vertical dotted lines separate the period of strong groundwater influence (from mid-May to mid-September) from that of weak groundwater influence (from mid-September to mid-May).

7. Examples of corrected gravity data

The change of soil moisture and groundwater after rainfall and the response of the gravimeter are clearly to be recognized, if short sections of the data series are studied. An example is given in fig. 12, covering the two monthly period from October 1 to November 30, 2001. Between November 6 and 9 numerous rainfalls occurred (the plot is based on the precipitation sums over 15 minutes each), which are followed by clear signals of the soil moisture as well as the groundwater level. The vertical dotted line at November 7, 2001, 15:00 UT marks a steep rise of the soil moisture immediately after the beginning of the rainfall. The groundwater level changes with a time delay of about two days. After the rainfall both signals go down, the soil moisture more rapidly than the groundwater.

The residual gravity (fifth frame from above) is also influenced by the rainfall. A clear peak is to be seen similar to the change of the soil moisture. At last it has to be pointed out, that the modeled gravity effect of the precipitation corresponds very well to the change of the residual gravity, especially to its amplitude. However, it decreases more slowly than the residual gravity. - In the lowermost frame two attempts of corrections are shown.

In the first variant the modeled gravity effect of precipitation is subtracted from the residual gravity (short-term model, second frame from above). However, for better approximation additionally a factor c_{rain} = 1.5 was used. Due to the fact, that the modeled gravity represents the total effect of precipitation, in this way changes of the soil moisture as well as those of the groundwater level are corrected (assuming that the parameters of the model are chosen correctly). As may be seen from the lowermost frame, the result of this correction is a clear diminution of the roughness of the curve. However, a total elimination of the precipitation influence could not be achieved.

In the second variant instead of the modeled gravity effect of precipitation the directly measured changes of soil moisture and of the groundwater level are used. The corrections are based on the groundwater regression coefficient 0.150 nm s^{-2}/cm, valid for the time between mid-September and mid-May, while for the soil moisture a value of 2.5 nm s^{-2}/percent is assumed (roughly estimated from the graphical representations).

If the results of both correction procedures are compared, no significant differences are to be recognized, i.e. both variants are equivalent. Strictly this is valid only for the example under consideration (1.10. – 30.11.2001, fig. 12). From other examples a similar visual impression results. However, details and the numerical values may differ.

The residual gravity during the total recording period of the CD029 at Wettzell is shown in fig. 13 (lowermost frame). The two curves beneath are corrected for the influence of groundwater changes and additionally for the influence of precipitation (short-term model, instead of a soil moisture correction). As already mentioned, caused by certain reasons the first section of the record (before the gap in May, 1999) is unfavorably affected, and therefore it cannot be included in the detailed studies. The second section is dominated by the large anomaly in the first half of 2000, clearly caused by an anomaly of the groundwater (uppermost frame). A similar behavior repeats in the first half of 2001. After the groundwater correction was applied, the large anomaly in 2000 reduces considerably. Only a part of the second half of the anomaly remains. In contrast to that, the correspondent anomaly in 2001 seems to be overcompensated. As may be seen from the third curve below, the correction for precipitation has only a small influence. There are two exceptions. At first the overcompensated groundwater anomaly in 2001 seems to be increased. The second exception concerns the sharp double anomaly in May 2000. While the second spike unambiguously is caused by a heavy rainfall, the first spike has no correspondence to rainfall, soil moisture or groundwater. Therefore only the second spike vanishes after the data have been corrected for the influence of precipitation. The first spike remains unchanged. To sum up it can be said that the greatest part of the hydrological influences is eliminated by the groundwater correction on the basis of smoothed data, while details are covered by corrections for the influence of precipitation (modeled gravity effect of precipitation, STM). Residuals of the anomalies may remain or overcompensation may arise if the seasonal changes of the regression behavior are neglected.

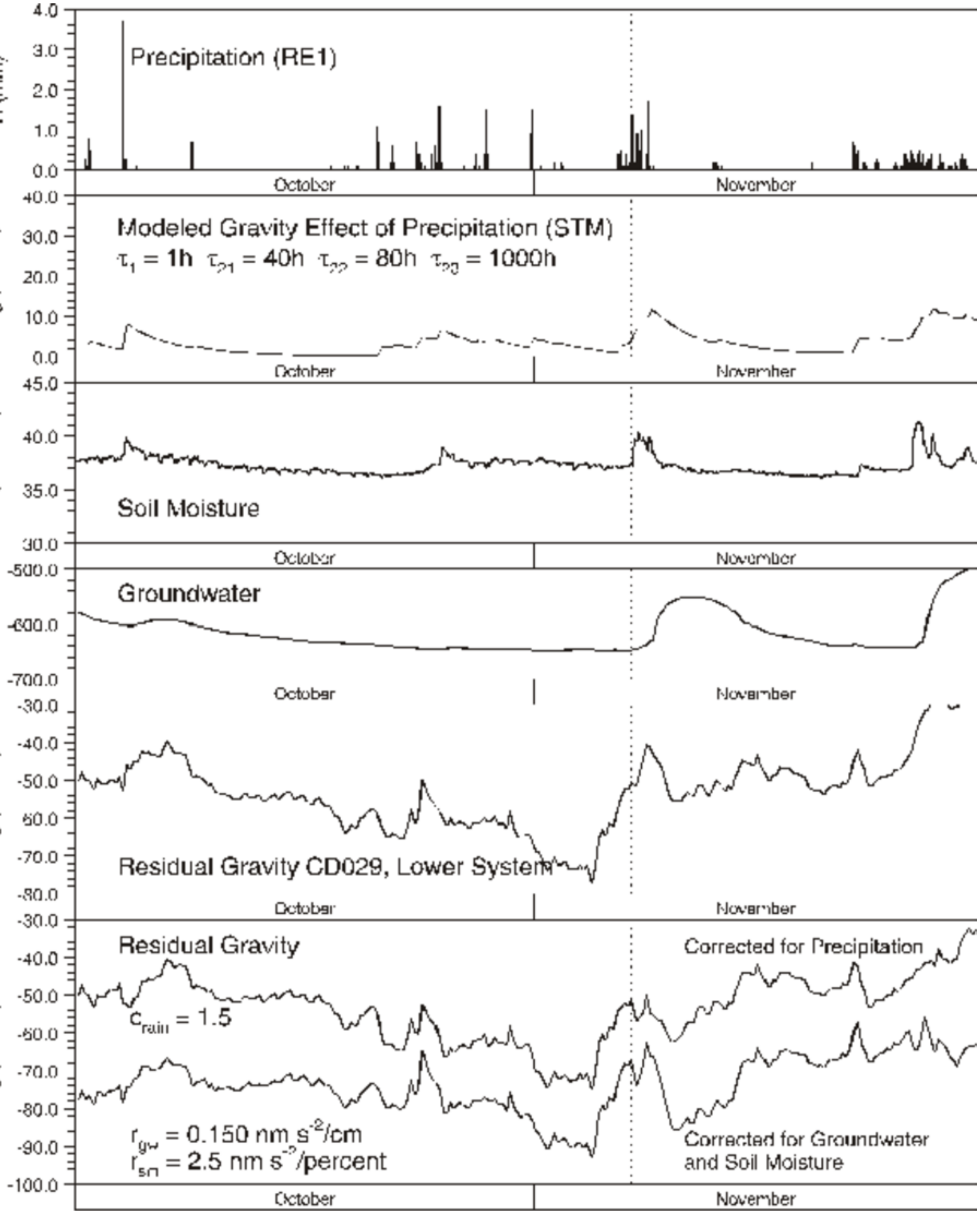

Fig. 12: Hydrological influences at Wettzell, 1.10. – 30.11.2001. Groundwater values not smoothed. The vertical dotted line marks the date November 7, 2001, 15:00 UT. In the lowermost frame two different ways of hydrological corrections are compared: firstly the modeled gravity effect of precipitation, secondly corrections derived from measured values of the groundwater level and of the soil moisture.

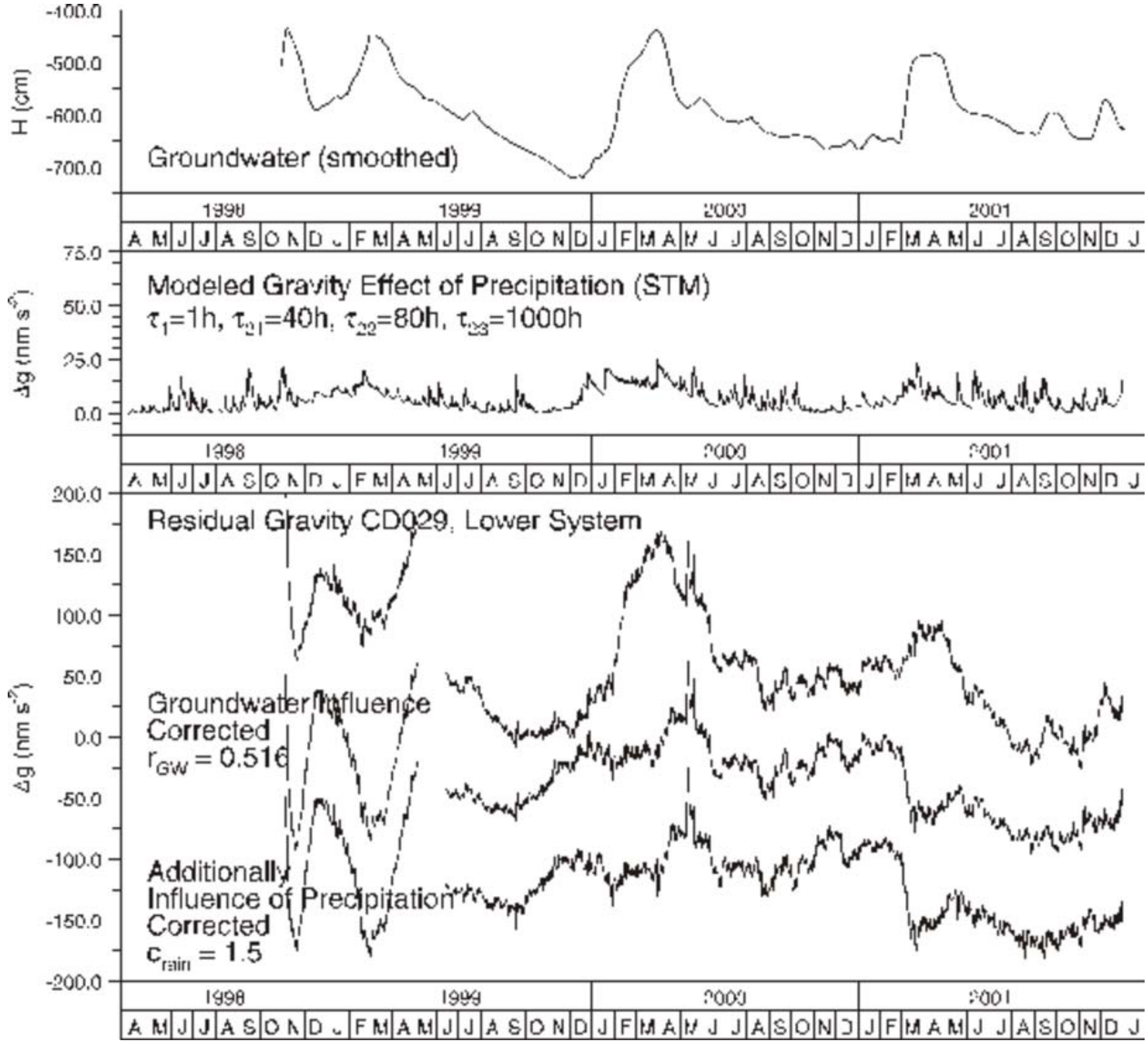

Fig. 13: Hydrological corrections, 1.4.1998 – 30.6.2001. Groundwater smoothed. The modeled gravity effect of precipitation (short-term model STM) is plotted in an enlarged scale (approx. 2:1) compared with the three curves in the lowermost frame.

8. Conclusions

- The investigations presented here generally confirm, that gravity measurements may be affected significantly by hydrological influences.
- At Wettzell an annual wave with a double amplitude of about 70 nm s^{-2} is to be expected, caused by variations of the groundwater level throughout the year. The correction of such influences is of great importance for the investigation of other long-term phenomena (e.g. gravity effect of the polar motion).
- At Wettzell the long-term gravity effects are closely correlated with changes of the groundwater level, while the modeled gravity effect of precipitation better corresponds to the short-term gravity variations.
- At Wettzell the influence of groundwater variations may be described by a linear regression model with a mean regression coefficient in the order of 0.52 nm s^{-2}/cm. However, between mid-May and mid-September the influence seems to be stronger (0.93 nm s^{-2}/cm) than in the remaining part of the year (0.25 nm s^{-2}/cm).
- If the seasonal variations of the groundwater regression coefficient are neglected, errors may arise by over- or under-compensation of the disturbing hydrological influences.

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Poster. INTERGEO, Berlin 2000

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[1] In [6] the false value τ_2 = 91 days is given instead of the right value 30 days