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Land Water Storage Changes from Ground and Space Geodesy: First Results from the GHYRAF (Gravity and Hydrology in Africa) Experiment

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Abstract—This paper is devoted to the first results from the GHYRAF (Gravity and Hydrology in Africa) experiment conducted since 2008 in West Africa and is aimed at investigating the changes in water storage in different regions sampling a strong rainfall gradient from the Sahara to the monsoon zone. The analysis of GPS vertical displacement in Niamey (Niger) and Djougou (Benin) shows that there is a clear annual signature of the hydrological load in agreement with global hydrology models like GLDAS. The comparison of GRACE solutions in West Africa, and more specifically in the Niger and Lake Chad basins, reveals a good agreement for the large scale annual water storage changes between global hydrology models and space gravity observations. Ground gravity observations done with an FG5 absolute gravimeter also show signals which can be well related to measured changes in soil and ground water. We present the first results for two sites in the Sahelian band (Wankama and Diffa in Niger) and one (Djougou in Benin) in the Sudanian monsoon region related to the recharge–discharge processes due to the monsoonal event in summer 2008 and the following dry season. It is confirmed that ground gravimetry is a useful tool to constrain local water storage changes when associated to hydrological and subsurface geophysical in situ measurements.

Key words: African monsoon, Sahel, water storage, gravimetry, GPS, MRS, GRACE.

1. Introduction

The GHYRAF (Gravity and Hydrology in Africa) project is a multi-disciplinary project that aims to better understand the water cycle in West Africa with the help of geodetic (GPS), gravity (surface and satellite-derived), geophysics (MRS) and hydrology experiments. These combined experiments are done on four specific sites on a north–south climatic gradient (see Fig. 1). The first one is located in the Sahara desert zone (Tamanrasset, Algeria) with almost no rain (less than 20 mm/year); two of them sample the Sahelian band (Wankama/Niamey and Bagara/Diffa in Niger) (indicated in orange colour on Fig. 1) with moderate annual rainfall (respectively, 560 and 350 mm/year) and the last one is in the sub-humid area of the monsoon zone (Nalohou/Djougou, Benin) with heavy rainfall (1,200 mm/year). Two of the sites (Wankama in the Niamey Square Degree mesoscale site and Nalohou close to Djougou in the upper Ouémé mesoscale site) belong to the AMMA-CATCH observation system (African Multidisciplinary Monsoon Analysis—Coupling the tropical atmosphere to the hydrological cycle) (http://www.amma-catch.org/) dedicated to evaluate the impact of anthropogenic and climatic changes on the surface water cycle (Lebel *et al.*, 2009). Table 1 summarizes the geographical coordinates of these four stations.

The project aims to set up new constraints to the problem of the soil and ground water storage changes during the monsoon cycle in Africa since our ground measurements as well as satellite ones are sensitive to the total variation of stored water (changes in the total water column of the ground, i.e. surface water, water of the unsaturated zone and groundwater). For a more detailed description of the GHYRAF project

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Members of the GHYRAF team are given in the Appendix.

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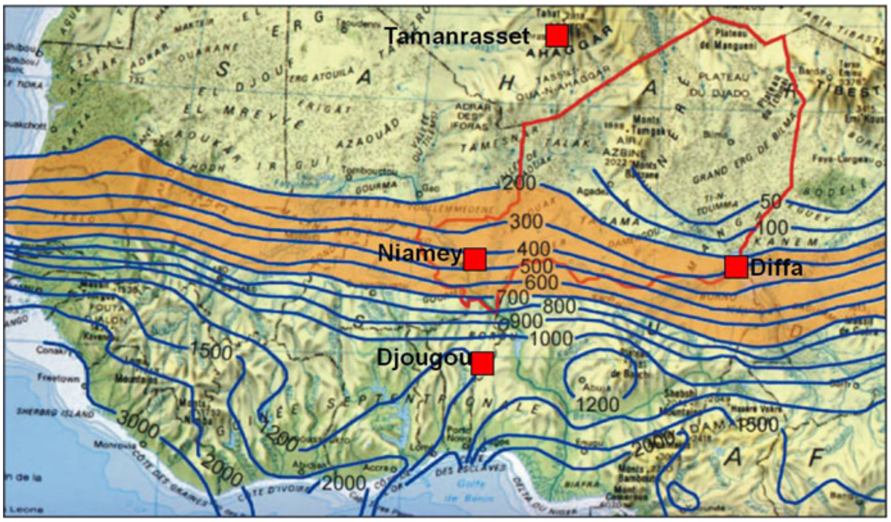

Figure 1
Location of the four principal sites investigated during the GHYRAF project. The *blue lines* are the isohyets (rainfall in mm/year, period 1950–1989 from L'Hôte and Mahé 1996) showing the strong north–south climatic gradient

characteristics we refer the reader to Hinderer *et al.* (2009).

The project started in mid-2008 and we present here the first results mainly devoted to the hydrological effects due to the 2008 monsoon period. Section 2.1 deals with the GPS observations and their ability to estimate the seasonal surface loading contribution (mainly hydrological) in West Africa. In Sect. 2.2 we show the first estimates of the water storage changes over the Niger and Lake Chad basins derived from GRACE (Gravity Recovery and Climate Experiment) satellite data and their relation to global hydrology model predictions. Section 2.3 focuses on ground gravimetry and we report on our results on each of the three sites where measurements are available. Concluding remarks are given in Sect. 3.

2. First Results from the GHYRAF Project

2.1. GPS Vertical Motion

One goal of the GHYRAF project is to measure using the GPS regional permanent network the vertical displacement due to the hydrological load caused by the monsoon. Indeed it has been shown that the precision of the current GPS processing allows the detection of the crustal deformation induced by surface loads (atmosphere, ocean and continental hydrology) (van Dam *et al.*, 2001). Figure 2 shows that the modeled vertical displacement reaches several mm according to the global hydrology model GLDAS (Rodell *et al.*, 2004).

Table 1

Location of the four specific stations investigated in the GHYRAF project and mean annual rainfall (in mm)

Location	Country	Longitude	Latitude	Mean rainfall (mm)
Tamanrasset	Algeria	5.52 E	22.78 N	20
Diffa	Niger	12.62 E	13.32 N	350
Niamey	Niger	2.17 E	13.48 N	560
Djougou	Benin	2.62 E	9.35 N	1,200

GLDAS is a modeling platform that provides estimates of land surface fluxes and storage of water and energy. We use the storage predictions from the Noah Land Surface Model (Chen *et al.* 1996), consisting of superficial soil moisture (four layers down to 2 m depth), snow and canopy water (essential to account for evapotranspiration) at a 0.25° × 0.25° spatial resolution and a 3 h time sampling. We use two distinct simulations: the first one is forced by CMAP (CPC Merged Analysis of Precipitation) (Xie *et al.* 2003) and is available at

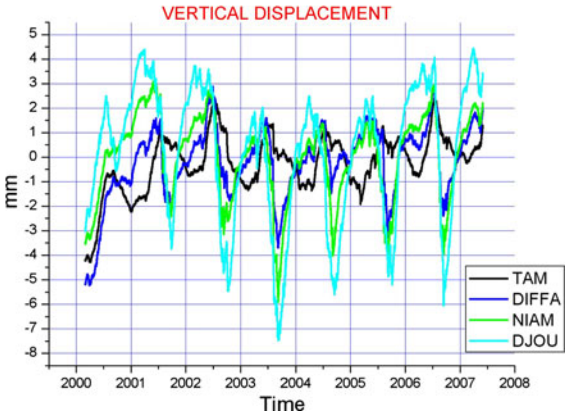

Figure 2

Predicted vertical displacement (in mm) at the four GHYRAF sites during the 2000–2008 period from the GLDAS global hydrology model

http://disc.sci.gsfc.nasa.goc/hydrology/data-holdings, and the second one is forced by TRMM (Tropical Rainfall Measuring Mission) (Hufmann *et al*. 2007) precipitation data sets.

Therefore, accurate GPS station height solutions are required and it is mandatory to process the data using a global network to obtain coordinates within a well defined reference frame. Thus, data from the AMMA-GHYRAF GPS stations (Bock *et al*., 2008) were processed over period 2005.5 to 2009.0 using the GAMIT software (Herring *et al*., 2008) as part of the TIGA GPS analysis at the University of La Rochelle (ULR) TIGA Analysis Center (TAC) (Santamaría-Gómez *et al*., in press). In this analysis, station coordinates, orbital parameters, Earth orientation parameters, 2-hourly zenith total delays, and atmospheric gradients (1/day for N/S and E/W) were estimated. The VMF1 mapping function and a priori hydrostatic delays derived from the ECMWF numerical weather model are used (Boehm *et al*., 2006). GPS height time series (shown in Fig. 3) were obtained in the ITRF2005 (Altamimi *et al*., 2007) by stacking the weekly position estimates (Santamaría-Gómez *et al*., 2009).

Figure 3 shows the GPS vertical displacements for two stations (Djougou and Niamey) where we superimposed the sum of hydrologic and atmospheric load effects computed from GLDAS water content and NCEP surface pressure data (Petrov and Boy, 2004). Despite the stronger variability in the GPS solutions, it is very obvious that there is an annual modulation of about 15–20 mm peak-to-peak. This modulation is in close agreement with the models and is well anti-correlated with rainfall at both stations. In fact, in a monsoon context, small and large scales are well correlated, so local rainfall is likely to be

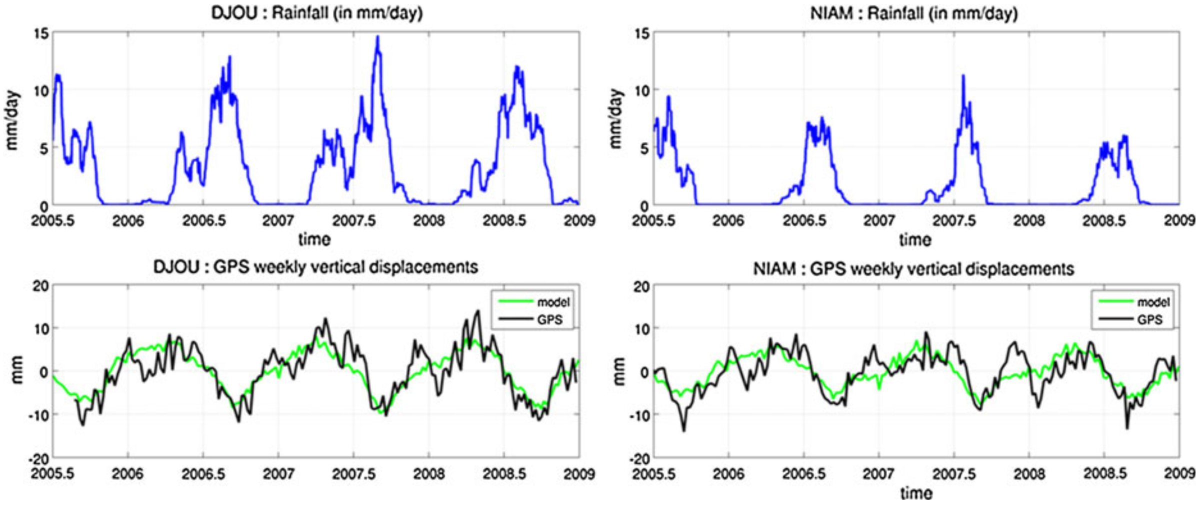

Figure 3

The rainfall (*top*) (in mm/day) and vertical displacements (*bottom*) (in mm, smoothed by 15-day running average filter) for the stations of Djougou (*left*) and Niamey (*right*) during the 2005.5–2009 period. Vertical displacements are from the predicted load (atmosphere + hydrology) (in *green*) and the observed load (in *black*) from the AMMA-GHYRAF permanent GPS network representative of what happens at larger scales and, therefore, GPS can detect such a hydrological loading signal at very large-scale (thousands of km) generated by water infiltration and storage after rain.

The correlation coefficients between GPS and GLDAS are as large as 65 and 80% for Niamey and Djougou stations respectively. The differences could be either due to limitations in the models and errors in the GPS solutions. Among the latter, some have been evidenced in studies for other parts of the world: unmodeled sub-daily signals (King *et al*., 2008), and systematic errors due to the combination procedure (Collilieux *et al*., 2007), non-tidal ocean mass loading, bedrock thermal expansion, mis-modeling of receiver antenna phase center variations (see Dong *et al*., 2002 for more details). Further work is ongoing on the analysis of these error sources.

Another interest of observing by GPS the vertical displacement at our specific stations is that we will be able to correct our ground gravity observations for this effect (free air component). Such a correction is indeed needed in any ground/satellite comparison since space gravity observations are not sensitive to this geometrical effect (Hinderer *et al*., 2006a, b; de Linage *et al*., 2007; Neumeyer *et al*., 2006). An alternative of using GPS estimates to correct the gravity data would be to use a deformation model applied to the GRACE solutions of total water storage and convert the recovered vertical deformations into gravity via the free-air gradient of -0.3086 μGal/mm. Such a method would require a precision level of at least 3 mm (1/0.3086) for the GRACE-recovered deformation in order to reach the precision level of the superconducting gravimeter (SG) gravity measurements (better than 1 μGal).

2.2. *Space Gravimetry (GRACE)*

Since its launch in April 2002, the GRACE satellites allow the recovery of Earth's time variable gravity field with temporal and spatial resolutions of, respectively, 10–30 days and larger than 400 km (Tapley *et al*., 2004). Mass variations at the Earth's surface can be uniquely retrieved from Stokes coefficients (Chao, 2005).

Figure 4 shows the annual amplitude and phase of equivalent water height variations in Africa, according to the CNES/GRGS Release 2 10-day constrained solution (Bruinsma *et al*., 2010), monthly unconstrained GSFC (Luthcke *et al*., 2006), CSR and GFZ (Flechtner, 2007) solutions. A 500 km half-width Gaussian filter has been applied to the monthly unconstrained solutions; such a post-processing is not required for the CNES/GRGS constrained solutions.

All solutions show similar features of seasonal variations in the equatorial band, with amplitudes reaching 200 mm of equivalent water height; the northern and southern hemispheres are out of phase. The N–S phase dichotomy in Africa is due to the seasonal oscillation of the Intertropical Convergence Zone across the equator. Because of the filtering, the unconstrained solutions exhibit slightly smaller amplitudes than CNES/GRGS.

The noise level in GRACE recovered continental water storage variations is estimated to a few centimeters by looking at the seasonal variations in Sahara and in the oceans, where seasonal amplitudes should be small.

In addition, GRACE solutions can be used to estimate water storage at river basin scale. Figure 5 shows the location of major river basins in Africa (derived from Jenness *et al*., 2008), and water storage variations in Lake Chad and Niger basins from GRACE and global hydrology models. The same treatment (spherical harmonic decomposition till degree $n = 60$ and 500 km half-width Gaussian filter) is applied to the different GRACE solutions and hydrology models.

Despite the different processing schemes, both solutions (CNES/GRGS and CSR) show similar temporal variations in Lake Chad and Niger river basins, with seasonal amplitude reaching about up to 150 mm of equivalent water height. GRACE observations are in agreement with GLDAS/Noah (Rodell *et al*., 2004) global hydrology model. ECMWF hydrology model (Viterbo and Beljaars, 1995) shows smaller variations than GRACE data and GLDAS model.

The Lake Chad (2.5 Mkm^2) and Niger (2.3 Mkm^2) basins are among the largest African basins as shown in Fig. 5. Because of the large scale of these basins they cannot be covered by conventional hydrological observations. Thus, satellite gravity data provide a unique opportunity to constrain the

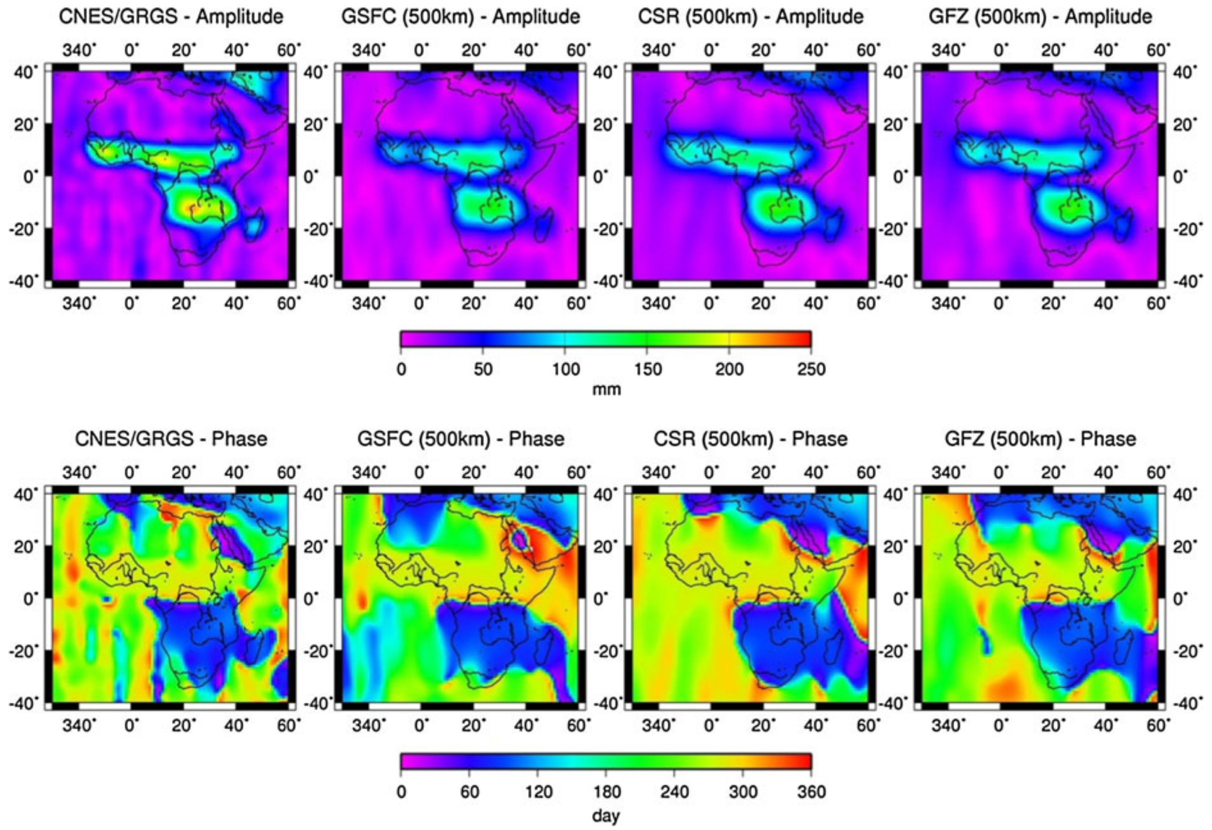

Figure 4
Amplitude (in mm) and phase (in days from 1 January) of the annual component in Africa inferred from GRACE observations according to four different processing centers (CNES/GRGS, GSFC, CSR, GFZ)

large scale water storage changes of these basins. But this is only true when averaging over large basins. By adding surface gravity measurements like in this study and relating them to water storage changes, we aim at having a better insight into hydrology models at finer scales.

As precipitation is the main forcing of soil-moisture variations, we can directly compare precipitation datasets to GRACE observations (see, for example, Crowley *et al.*, 2006). The conservation of mass provides the relation between continental water storage variations W, precipitation P, evapotranspiration E and runoff R (or more precisely the outflow in the case of Sahelian endorheic basins):

$$\frac{\partial W}{\partial t} = P - E - R \qquad (1)$$

An endorheic basin is a closed basin that does not allow any outflow to other bodies of water such as rivers or oceans. This applies to the Diffa site (outflow ends up in nearby Lake Chad) and the Wankama site (outflow/runoff end up in ponds with no outflow to the Niger River).

P is the main driver of soil moisture variations. If we assume that the sum $E + R$ is small or constant in time (e.g. E and R are periodical but out-of-phase), the time-integration of P can be directly compared to W (as observed by GRACE) after detrending. The validity of this hypothesis was shown, for instance, by Crowley *et al.* (2008) for the Amazon river basin and is demonstrated here at large wavelength scales by Fig. 5, for the Lake Chad and Niger river basins (it might not be the case at smaller spatial scales). The seasonal water storage changes deduced from CMAP dataset (also used to force the GLDAS/Noah model) are indeed the largest in amplitude but are in fair agreement with GRACE observations.

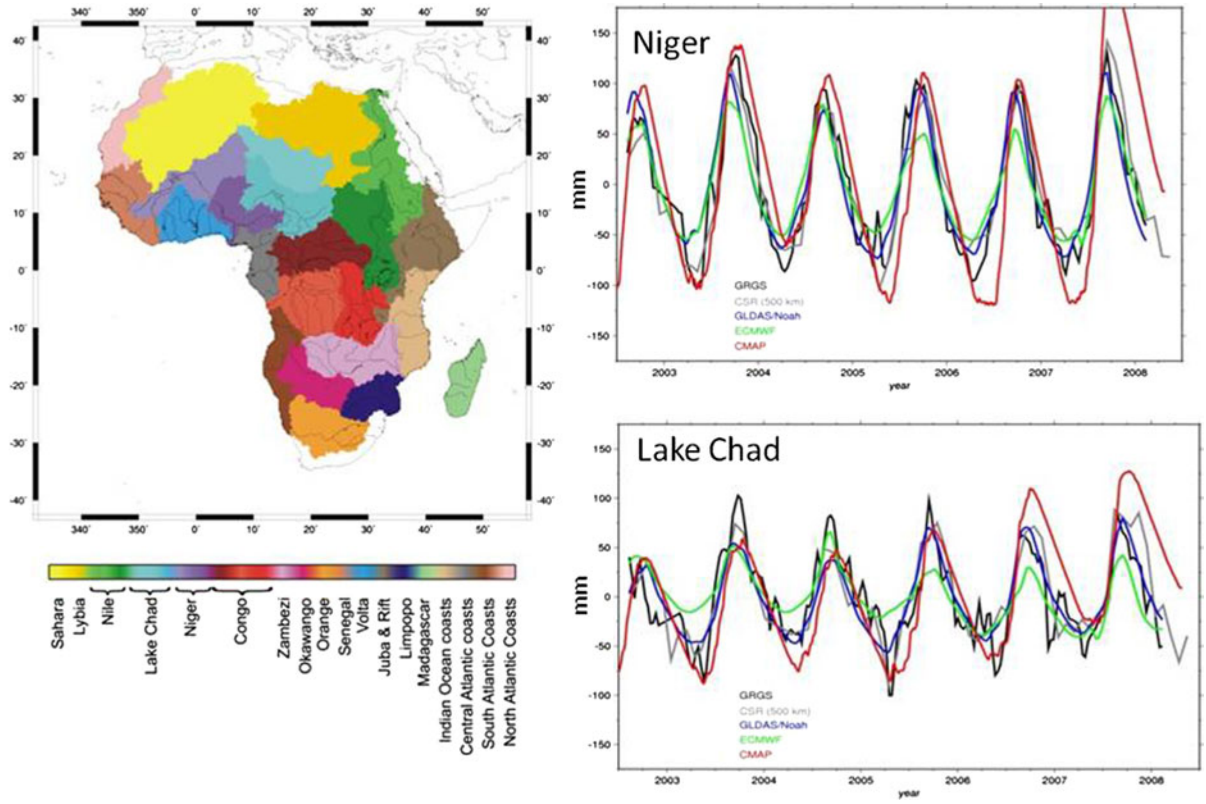

Figure 5

Location of the major hydrological basins in Africa (*left*) and estimates of the water storage changes (in mm equivalent water height) for the Niger (*right top*) and Lake Chad basins (*right bottom*) from GRACE data (CNES/GRGS and CSR solutions are respectively shown in *black and gray*), hydrology model predictions according to GLDAS/Noah (*blue*) (Rodell *et al.*, 2004) and ECMWF operational (*green*) (Viterbo and Beljaars, 1995). In *red* is shown the detrended time-integration of CMAP dataset (Xie *et al.*, 2003)

In general, E is not small compared to P depending on the integration period; at the annual time scale, for instance, E represents 80% of P in the Sudanian zone and 90% in the Sahelian zone. In contrast to equatorial areas, the runoff contribution R is likely to be negligible in arid (Sahelian) regions.

In the equatorial monsoon zone the rain is larger than the potential evapotranspiration all year long. The real evapotranspiration is, hence, equal to the potential one and is independent on rain. Hence, the cumulative rain changes are indeed directly comparable to water storage changes.

In arid (Sahelian) regions the rain is smaller than the potential evapotranspiration meaning that the real evapotranspiration is a function of the rain; as a consequence, the comparison between rain and water storage is more complicated.

A detailed comparison of GRACE spherical harmonic solutions, global hydrology models and precipitation datasets for the major African basins is given in Boy *et al.* (2011, this issue).

2.3. Ground Gravimetry

Surface gravimetric measurements can be used to investigate the underground water storage dynamics (Kroner *et al.*, 2007). This can be done by repeating absolute gravimeter measurements at specific points (Jacob *et al.*, 2008) or by performing relative gravimetry campaigns (Naujoks *et al.*, 2008). There are also a number of studies investigating various hydrological influences on fixed gravimeters such as the superconducting gravimeters of the GGP network (see e.g. Kroner and Jahr, 2006; Hasan et al., 2006; Boy and Hinderer, 2006; Hinderer et al., 2007).

2.3.1 Length Scales in Hydrology

The gravity changes (in μGal) due to the soil moisture content (GLDAS model) for the time span 2000–2008 are computed for the stations of Table 1 and shown on Fig. 6. One notices that, as expected from the climatic gradient present in West Africa (see Fig. 1), there is almost no gravity change in Tamanrasset (<1 μGal) and that, as expected, the seasonal gravity changes increase as a function of the input rainfall reaching >15 μGal peak to peak in the monsoon region (Djougou).

Since the first survey in Sahara near Tamanrasset (Algeria) was postponed due to security reasons, we have no result to report here on the so-called 'null test' where observations are done in a region where almost no gravity changes are predicted due to the lack of water storage changes. Hence, we report here only preliminary results coming from the repetition of absolute gravity measurements on the station Wankama (Niamey), Bagara (Diffa) and Nalohou (Djougou). The observed gravity changes related to the 2008 monsoonal recharge and discharge are depicted in Fig. 7 where we have also plotted the large scale predictions of the GLDAS/Noah model forced by two different meteorological forcing fields: CMAP and TRMM.

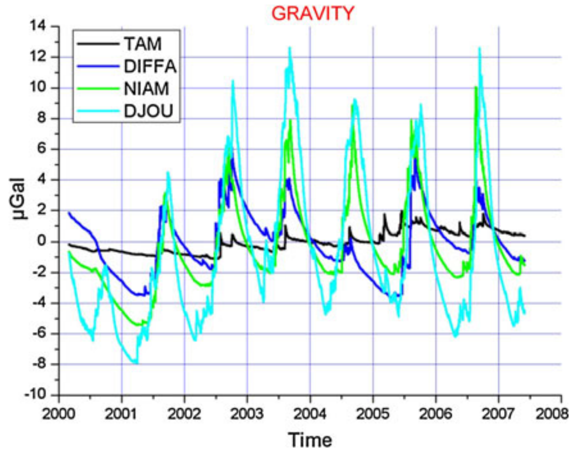

Figure 6
Predicted surface gravity changes (in μGal) at the four GHYRAF sites during the 2000–2008 period from the GLDAS global hydrology model

The question of the length scales is always important in hydrology. In Fig. 8 (top) we have computed for the GLDAS model the predictions of ground gravity changes for Niamey (13°N, 2°E). We have separated the total contribution of the GLDAS model into a local one (which is only the Newtonian attraction effect of the soil moisture present in the local pixel (simply by multiplying the local value of the soil moisture by the coefficient 42 μGal/m of equivalent water height) and a non-local one caused by the combination of the Newtonian attraction of remote masses outside the local pixel and elasto-gravitational loading effect (effect of vertical displacement + mass redistribution inside the Earth) (see de Linage et al. 2007, 2009). In fact, the local pixel is defined by the integration step in the loading computation (here 50 m), but the value of the local soil water content is identical to the model value for the pixel including the station (0.25° × 0.25°). Therefore, we neglect the contribution of the masses located at distances between 50 m and 25 km.

One can easily see from Fig. 8 (top) that the local contribution is by far the largest, the non-local term being only about 20% in amplitude (this latter term being dominated by the effect of vertical displacement). However, if we neglect this term we would overestimate the local gravity changes in terms of local soil moisture.

Figure 8 (bottom) shows that the non-local gravity changes can be derived either from the hydrology model (GLDAS) or from the GRACE observations, even if these seem to be slightly larger in Niamey.

We applied this separation scheme between local and non-local contributions to GRACE-GRGS total water content estimates (Bruinsma et al., 2010) converted into ground gravity changes. In this case, the local effect corresponds to a 400 km × 400 km cell (GRACE effective resolution). The difference in the size of the so-called local cell between GRACE (say 400 km) and the GLDAS hydrology model (50 m for the integration cell and 25 km for the uniform value of the soil water content) may explain the different amplitudes shown in Fig. 8 but this needs to be further investigated. However, it is well known that regional masses (a few tens of km) have a

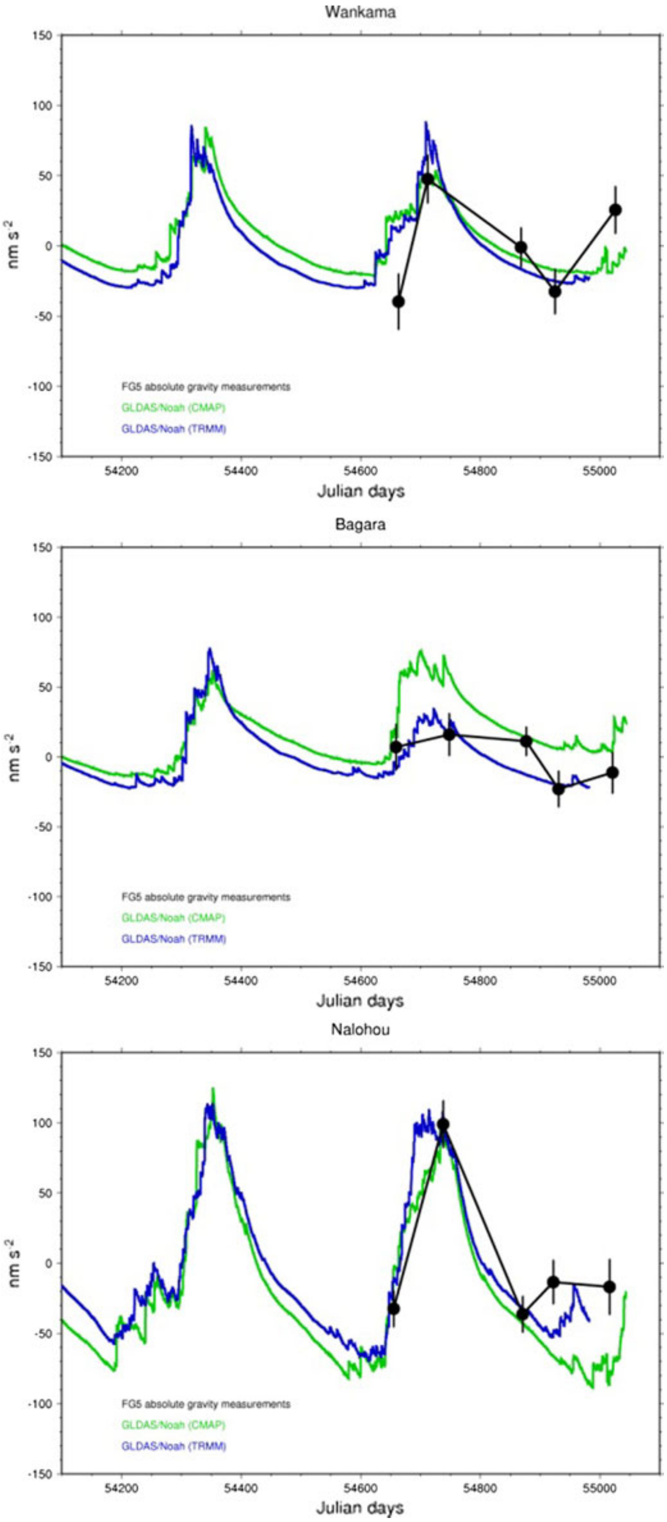

Figure 7

Predicted (GLDAS/Noah hydrology model forced by CMAP in *green* and GLDAS/Noah forced by TRMM in *blue*) and observed (FG5 measurements in *black*) gravity changes at Wankama (*top*), Bagara (*center*) and Nalohou (*bottom*) sites related to the 2008 monsoonal rainfall

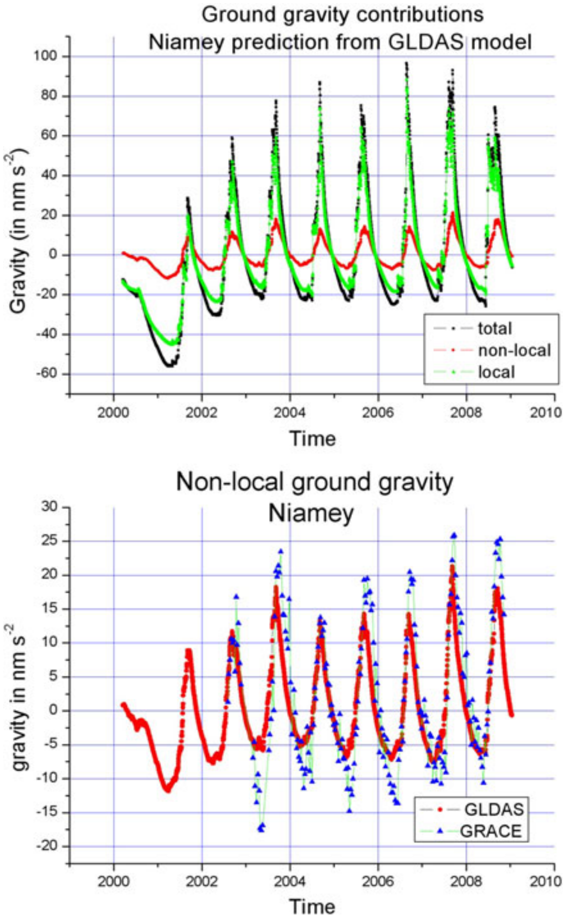

Figure 8

Top ground gravity prediction (in nm s^{-2}) from GLDAS model for Niamey (the local contribution is in *green*, the non-local one in *red* and the total in *black*). *Bottom* comparison of the non-local contribution predicted by GLDAS (*red circles*) and inferred from GRACE data (*blue triangles*)

small effect on local gravity measurements (Llubes *et al*. 2004) because the associated loading is small and because the attraction is merely horizontal and hence does not change gravity.

2.3.2 *Water Storage Changes in Wankama (Southwest Niger)*

The Wankama site is 70 km from Niamey (Niger) and belongs to the 1° × 1° Sahelian mesoscale site of AMMA-CATCH observatory (Cappelaere *et al*., 2009). This site benefits from long-term observations that have started in the early 1990s with HAPEX–Sahel experiments (Goutorbe *et al*., 1997). Various types of hydrologic variables are monitored: automatic rain gauges record rainfall every 5 min, the pond water level is measured every 20 min with a pressure sensor and every 5 min with a float, soil moisture capacity probes buried from 0.1 to 2.5 m below the surface measure every min the soil volumetric water content; the piezometric level is measured every 20 min with pressure sensors, and the runoff on small gullies every 30 s; in addition there are also regular measurements of the vegetation cycle, heat and water fluxes between atmosphere and soil.

These data are used for ecohydrologic modeling (Boulain *et al*., 2009) and for estimating the water balance components (Ramier *et al*., 2009).

The local variations of surface water (pond), shallow soil moisture and deeper aquifer storage generate a change of gravity due to the direct attraction effect. Time variations of gravity associated with water storage from May 2008 to May 2009 were modeled at FG5 point using observations of pond level and water table level (between 10 and 20 m below the soil surface as a function of the season/time period and the distance from the Wankama pond), the changes of soil moisture being assumed weak at distance from the pond due to soil crusting and Hortonian runoff (overland flow occurring when the rainfall rate is larger than the infiltration rate of the non-saturated surface layer).

This assumption is reasonable because no rainfall events occur before FG5 measurements dates and the FG5 point is located in a bare soil zone.

The water table shape is constrained by water level observations at four piezometers (Fig. 9). The water level is assumed linear between piezometers, symmetric with respect to the pond axis, and constant in the pond axis direction. The volume of the pond is calculated using its water level and a stage-area relationship derived from topography. More information on seasonal changes in the water table near the pond can be found in Favreau *et al.* (2009). In the model, the geometry of the pond was simplified by a rectangular shape which results in negligible effect on gravity. As the topography of the site is rather flat, the contribution of pond level variations on gravity change is under 3 nm s^{-2} at FG5 point, which is one order of magnitude beneath the instrumental detection limit. The specific yield of the aquifer defined as

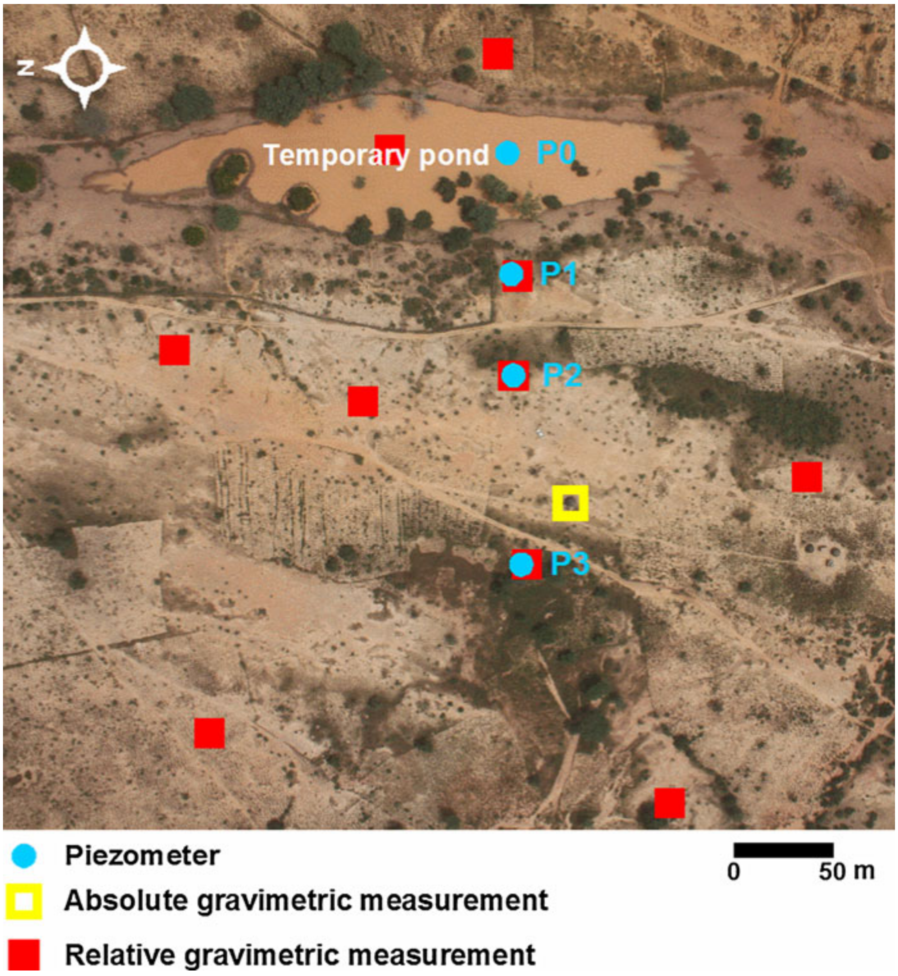

Figure 9
Aerial view (October 2008, J.-L. Rajot IRD) of the Wankama site near Niamey (Niger). The *yellow square* indicates the location of the FG5 absolute gravimetric measurement, the *blue disks* the piezometer location along a profile starting in the temporary pond (P0) and the *red squares* the location of the relative gravimetric measurements in the vicinity of the FG5 point

the ratio between the volume of water that can be extracted by gravity and the total volume of drained rock is assumed constant and varies from 1 to 15% (dashed lines from blue to red in Fig. 10a). As expected, the amplitude of the gravimetric signal is proportional to the specific yield.

We remind here that we only consider the direct attraction of the pond and water table variations in this model. Large scale effects associated with the elastic deformation of the earth and Newtonian attraction of distant loads (>500 m) are not taken into account in this calculation. To compare gravimetric measurements with the model of local water storage, we have to correct from large scale hydrological effects, as discussed in the beginning of Sect. 2.3.1. This correction is performed using either large scale hydrological models (e.g. GLDAS), or GRGS solutions of GRACE satellite data (see Fig. 8). The total gravimetric change predicted by GLDAS is computed as the convolution of Green functions with their estimate of water mass distribution. To obtain solely the large scale contribution, local effects are removed and estimated as the Bouguer anomaly due to the equivalent layer width contained in a pixel (about 25 km × 25 km for GLDAS model and about 400 km × 400 km for GRACE data).

The estimates of large scale hydrological effects on gravity only differ by 5 nm s^{-2} as can be seen

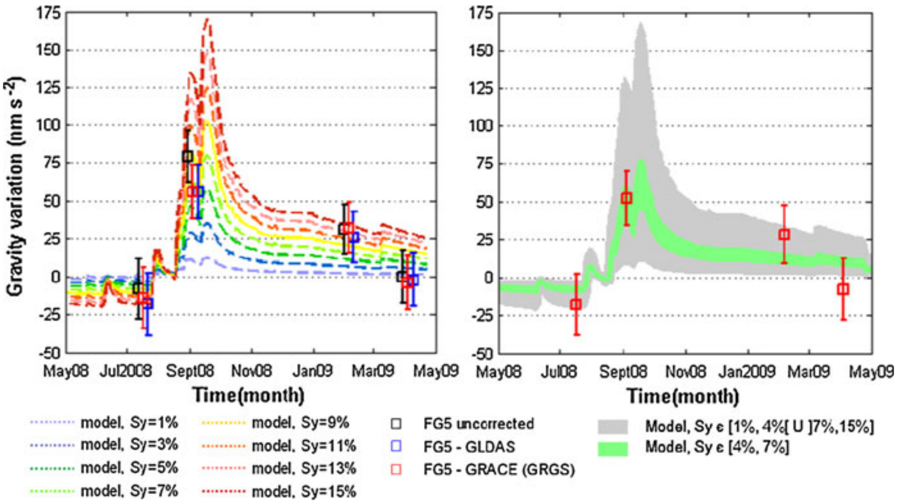

Figure 10

Synthetic gravity variations (in nm s^{-2}) at the Wankama/Niamey site caused by the changes in the water table level after the seasonal monsoon recharge in 2008. The specific yield is denoted Sy. The *squares* are the FG5 observations uncorrected for the non-local hydrology contribution (in *black*), corrected using the GLDAS model (in *blue*) and corrected using the GRACE data from CNES/GRGS (in *red*). For visibility purpose, the different values for a specific measurement considering different corrections are slightly shifted in time on the *left part*

from Fig. 10 left (differences between the blue and red squares).

The model of local water storage can now be compared to FG5 measurements (Fig. 10 left), corrected or not for large scale hydrological effects considering GLDAS and GRACE (GRGS) data. The model is within the error bars of corrected FG5 measurements for specific yield values of the aquifer ranging from 4 to 7% (Fig. 10 right). The minimum standard deviation between model and measurements reaches 13 nm s^{-2} and is obtained for a specific yield of 7% considering GRACE correction. A standard deviation of 16 nm s^{-2} is obtained for the same specific yield considering GLDAS correction. The standard deviation between model and measurements is higher when considering the corrections of large scale effects, and reaches 24 nm s^{-2} for a specific yield of 10%.

The first result derived from our study at Wankama is an estimate of the specific yield of the aquifer that ranges from 4 to 7% according to gravimetry when using a model only dependent on water table fluctuations. If one also considers a soil moisture contribution, the specific yield values may be extended to the 2 to 7% range (Pfeffer *et al.*, 2011). In addition to gravity measurements, magnetic resonance soundings (MRS) were performed in the vicinity of the FG5 site. The MRS method (Legchenko *et al.* 2002; Vouillamoz *et al.* 2008) allows measuring a MRS water content which is expected to be a good estimate of effective porosity (Lubczynski and Roy 2005; Boucher *et al.* 2009a, b) itself being generally slightly higher than specific yield. In this paper, we first consider that the aquifers are unconfined. Second, we assume that the values of MRS water content derived from field measurements are representative of the top part of the aquifer, where water table fluctuations occur, thus influencing gravity data. Third, we assume that the MRS water content value maximizes the value of the specific yield of the aquifer. Sometimes called drainage porosity (for unconfined aquifer), the specific yield quantifies the amount of water released from the aquifer by gravity forces, and thus is a key parameter for gravimetric measurements understanding. This third assumption is supported by several studies that compare MRS water content parameters with pumping tests. In a sedimentary context, the MRS water content is found to be generally higher than the specific yield estimated by pumping tests (Boucher *et al.*, 2009a, b). In a crystalline context, the study of Vouillamoz *et al.* (2005) has shown that the MRS water content can be used to give an estimate of the specific yield (in unconfined situation). In the present study, the MRS water content parameter derived from the field measurements is also called "MRS porosity" and is expressed in % of the total volume. This MRS water content is used as an input factor for gravimetric numerical modeling.

On the Wankama site, MRS results display a MRS water content ranging between 4 and 11%. This good agreement with gravimetric results is evidence for the consistency of both methods. The gravimetric method can thus be used for constraining parameterization of local hydrological modeling. To enhance our knowledge of water storage variations at this site, additional measurements with relative spring gravimeters have been performed in the rainy season in 2009 (Fig. 9) and will be analyzed to better characterize spatial heterogeneity in water storage variability.

2.3.3 Water Storage Changes in Diffa (East Niger)

The Bagara site near Diffa, in the eastern part of Niger, is located in the representative region of the Sahara–Sahel transition zone (350 mm/year of rain). Specific hydrology observations are done immediately near the location of the absolute gravimeter in Bagara and subsurface geophysics (MRS) has been applied to infer the local MRS porosity. One objective is to better understand the water recharge/discharge processes from the Komadugu-Yobe river of the sedimentary layers in Bagara and how these processes relate to the more general hydrology models like GLDAS in the region.

The Bagara site is close to the Komadugu-Yobe River, in eastern Niger (Fig. 11). The mean annual rainfall is 350 mm, but here rainfall presents a large interannual variability, for example 305, 530, 344, 279 mm, respectively, for the 2006–2009 period. Groundwater recharge is governed mainly by the Komadugu-Yobe temporary river (Gaultier, 2004), which flows between July and November, through direct infiltration at its sandy bed and from its floodzone, which is nearly 1 km wide (Fig. 11a). Rain infiltration occurs directly or via temporary ponds, and the vegetation consists of a sparse thorny savannah during most of the year. A thick (0.5–1 m) herbaceous cover grows during the rainy season,

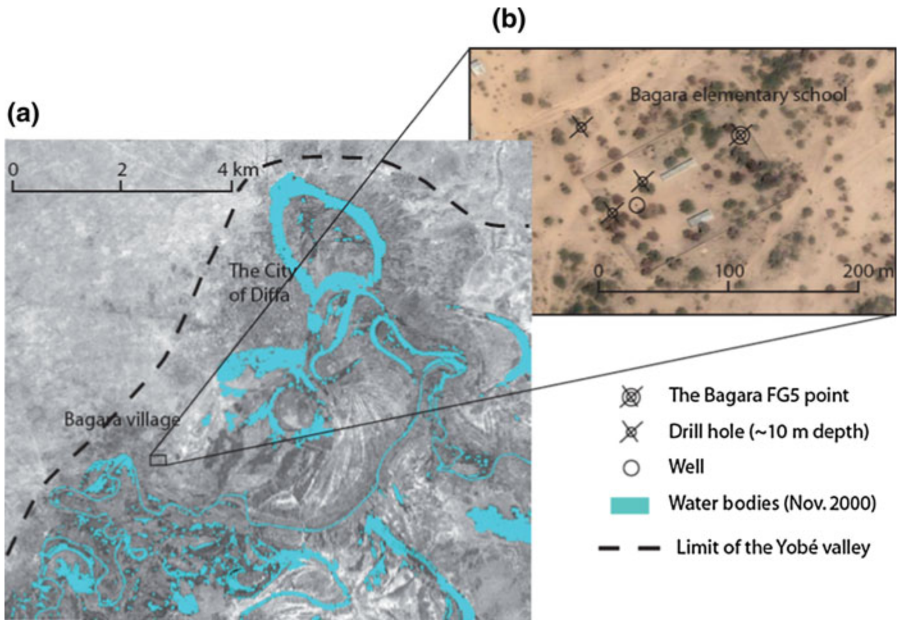

Figure 11

a Location of the Bagara site (near Diffa) in the eastern part of Niger close to Lake Chad. Bagara is close to the Komadugu-Yobe river which flows into Lake Chad at a distance of about 100 km. Flooded zone in high waters of the Komadugu-Yobe (LANDSAT data, Nov. 2000) are in blue. **b** Near surroundings of the FG5 absolute gravity measurement point. Note the scarce vegetal cover (in March) and the high density of logging data lasting from July to September, and dries out in October.

The underground water level record is clearly not continuous during the GHYRAF observation period (Fig. 12). However, previous data, collected in 1995–1997, and this record allow to define the local hydrological cycle which is characterized by a nearly 0.4 m annual amplitude and extrema in January (maximum level) and July (minimum level), which are offset relatively to the rainfall and, therefore, also to the computed GLDAS hydrological signal.

Magnetic resonance sounding (MRS) results indicate a MRS water content of nearly 25% for the whole aquifer. However, MRS content is poorly constrained in the uppermost aquifer, which is only concerned by water level fluctuations. MRS water content estimates are in the range 14–23% there, depending on the parameters adopted for the inversion, and the manual estimate is 24%. Adopting a mean MRS water content of 20% for the uppermost part of the aquifer, and making the hypothesis that it corresponds to the specific yield of the layer where the water table fluctuations are located, leads then to a 30 nm s^{-2} amplitude gravity signal, which is displayed in Fig. 12 together with the observed gravity from FG5 AG measurements and the GLDAS model. These signals are of similar amplitude, but both the gravity and the mean hydrological signal are offset in time, which cannot be accounted for by uncertainties in gravity or in water level measurements. This discrepancy persists during the dry season, when the superficial soil layer contains almost no water.

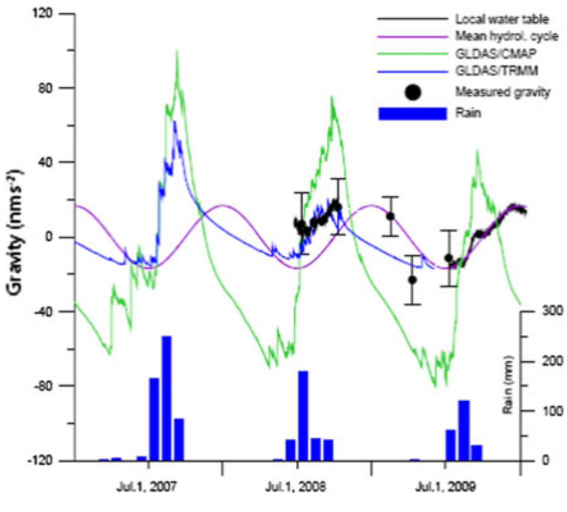

Figure 12

Seasonal gravity changes (in nm s^{-2}) for the Bagara site (near Diffa, Niger) where the black circles are the FG5 AG measurements with their uncertainties, the global hydrological model GLDAS/Noah forced by CMAP in *green*, GLDAS/Noah forced by TRMM in *blue*. The gravity changes due to the available local piezometric changes assuming a porosity of 20% are the two continuous black lines and the changes due to the mean hydrological cycle are in *pink*. We have also added the rainfall (in mm) for the period 2007–2009

The GLDAS models produce a sharp rise in the gravity signal, which is triggered by the onset of the rainy season and also a rather sharp recession curve, while both the water level and the gravity signal seem to present a smoother signal.

However, clayey layers have been commonly observed in drillholes in this area, one of these layers being found at the top of groundwater at the Bagara site. Statistical analyses of Le Coz *et al.* (2011) show that these clayey layers are of metric thickness and have a mean 300 m lateral extension. These layers correspond to the bottom of a temporary pond fed either by rainwater or by the spades of the Komadugu-Yobe river. During the dry season the pond presents a highly cracked bottom, which indicates volume change of these clayey layers with their water contents.

Therefore, it can be suspected that poroelasticity effects may occur during underground water level changes. These effects as well as diffusion effects arising from infiltration from the Komadugu-Yobe are still to be assessed with 3D models**,** when a record of at least one year duration will be available for this site.

2.3.4 Water Storage Changes in Nalohou (Benin)

The Nalohou site near Djougou (Benin) is a Soudanian site belonging to the upper Ouémé catchment (14,600 km^2) with average yearly rainfall of 1,200 mm. The upper Ouémé catchment is the wet mesoscale site of the long term hydrometeorological AMMA-Catch Observatory. At the mesoscale, rainfall and streamflow are controlled over a set of embedded catchments. To document the water budget at the local scale, several catena selected according to the land-use/cover are instrumented with piezometers

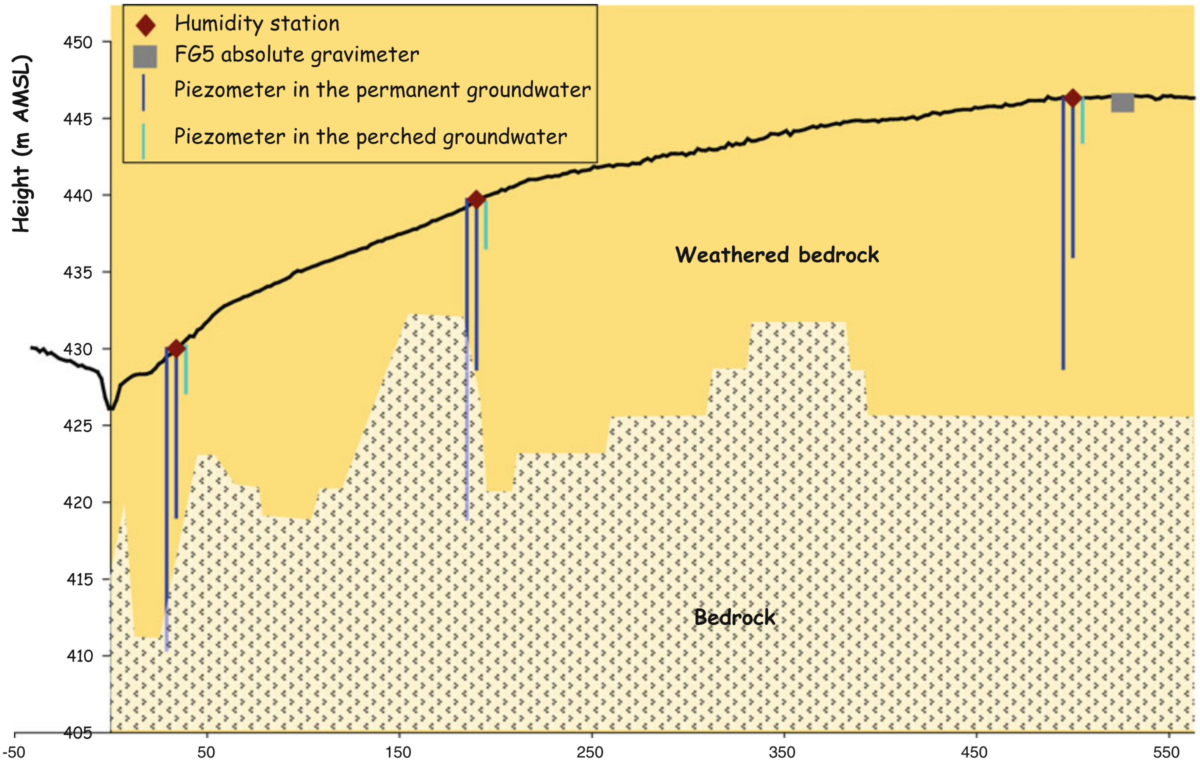

Figure 13

A sketch of the Nalohou site (near Djougou, Benin). The piezometers measuring the water table in deep permanent groundwater are in *dark blue* while those monitoring the perched and seasonal shallow groundwater are in *light blue*. The *brown diamond-shaped* indicate the humidity stations where soil moisture is observed. Finally, the location of the FG5 absolute gravimeter measurement is shown by a *grey rectangle*

screened at different depths, humidity probe stations (to monitor soil moisture of the first meter of the vadose zone) and flux stations (Guyot *et al.*, 2009). The Nalohou catena (Fig. 13), where absolute gravimetric measurements are carried out, exhibits a fallow-culture land-cover.

Combining geophysical with hydrological and geochemical data contributed to drawing up a hydrological functioning scheme (Kamagaté *et al.*, 2007). Recharged from July to September, permanent groundwater with low transmissivity and specific yield is located on the saprolite layer of the weathering profile, i.e. just above the crystalline bedrock. From September to the following June, the groundwater depletion is regular and slow (1.2 cm day^{-1}).

The general drying up of rivers in October–November follows the end of the rains and does not coincide with the lowest level of the water table (in June), reflecting the weakness or even the lack of permanent groundwater input to the base flow. Distinct geochemical signatures between base flow and the permanent groundwater provide other evidence of this feature. The origin of the base flow water has been found in a non permanent perched shallow aquifer located in the seasonally waterlogged headwaters of the streams (Séguis *et al.*, 2004, 2011). The shallow groundwater exfiltration is the dominant component of the annual discharge in the Upper Ouémé (Kamagaté *et al.*, 2007). The hypothesis proposed to explain the depletion of the permanent ground water during the dry season is tree transpiration. In a detailed analysis of evapotranspiration after an isolated rainfall event in the dry season, Guyot *et al.* (2009) demonstrate that, 1 month after the rainfall event, observed evapotranspiration rate could only be explained by a contribution of water uptake from deep soil layers (vadose or saturated zone).

Subsurface geophysics has been used to constrain better changes in water storage in the Nalohou catena. MRS survey conducted over several geological units and their respective weathered regolith has shown that significant lateral variations of MRS water content can exist over the measurement area. We found values ranging between 1.5 and 3% for most of the regolith in the area, within a noticeable exception, 10%, over quartz dykes (Descloitres *et al.*, 2011). Another attempt to estimate the specific yield has been made using mercury porosimetry method. Five samples of weathered regolith have been analysed. The results show a 20 (±5) % specific yield value. Between two dates, the water storage variations of each part (deep and shallow ground water) are the product of the difference of the piezometric levels by the specific yield. The water storage in the first meter of the vadose zone is directly estimated by the humidity probes (see Fig. 13).

Absolute gravimetric measurements have been carried out at key dates of the hydrologic cycle. In early July 2008, the permanent groundwater exhibits a low piezometric level, the perched groundwater is not yet present and the firstmeter of the vadose zone is partly dampened (see Fig. 14). Close to the end of the

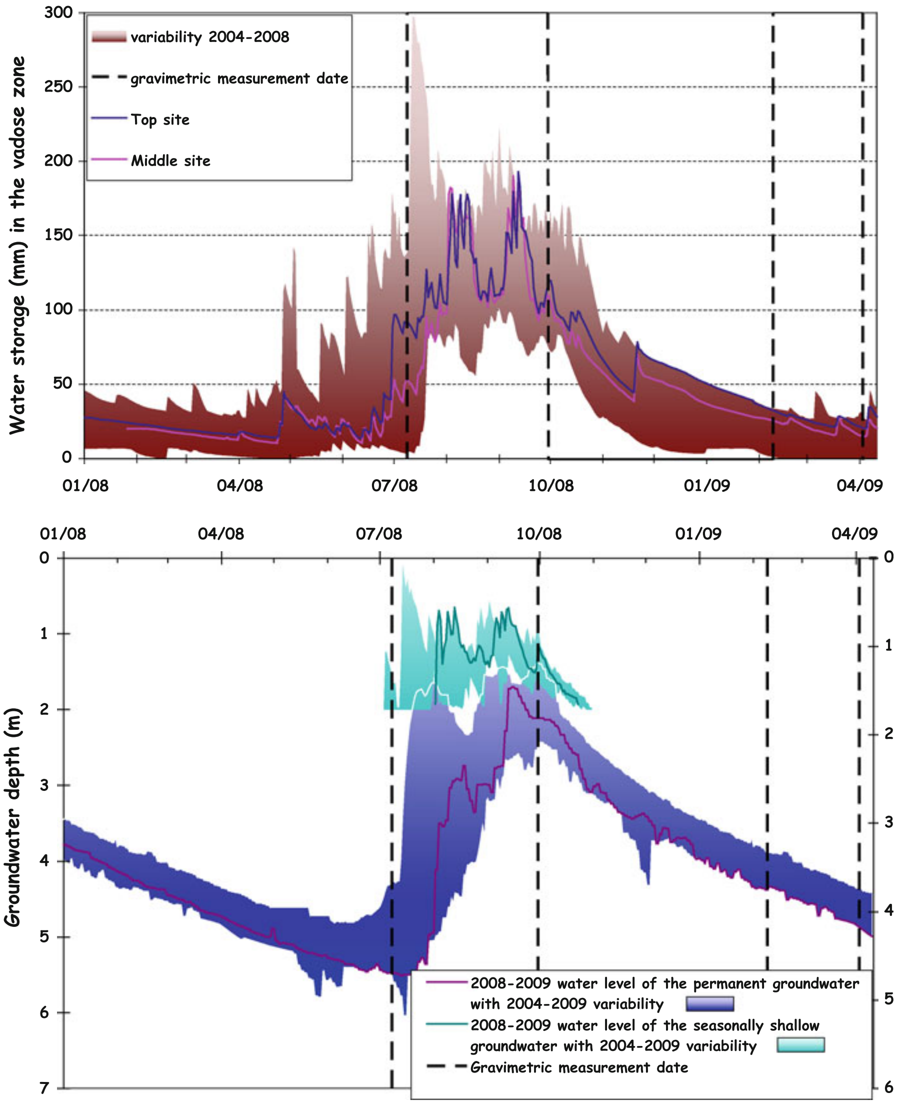

Figure 14

Dynamics of the three hydrological compartments observed close to the gravimeter site: piezometric levels of the seasonally shallow groundwater and permanent groundwater in 2008–2009 (*bottom*), water storage in the first meter of the vadose zone in top and middle sites of the catena (*top*)

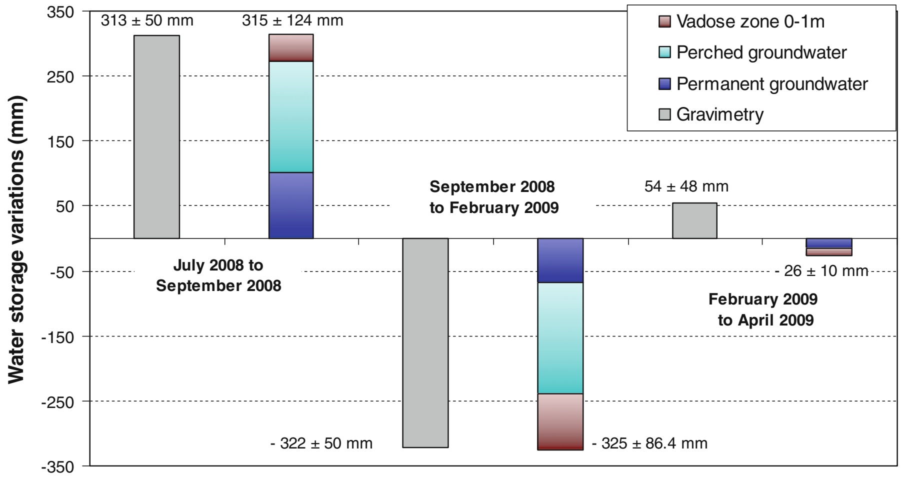

Figure 15

Water storage variations (in mm) as inferred from hydrology measurements (humidity stations in the 0–1 m vadose zone, piezometers in the perched groundwater and permanent groundwater) and from gravimetric measurements

rainy season, in mid-September 2008, the recharge of the deep groundwater has occurred, the shallow layers of the weathered mantle are saturated and the first meter of the vadose zone is now dampened. The underground storages are then the highest. Conversely, from this date to January 2009, the shallow groundwater disappears, the vadose zone is the driest and the permanent groundwater starts its depletion. In April 2009, the only change is the continuation of the permanent groundwater depletion. However, on this site, the geological units are organized in a complicated manner, i.e. the metamorphic rock and their respective regolith are organized in stripes elongated north–south, and a small dip angle is suspected (20° east) (Descloitres *et al*. 2011). This geometry could also influence the gravimetric measurements at the local scale and will be further investigated.

In Fig. 15, a good agreement between water storage variations is inferred from hydrology measurements and from gravimetric measurements. The similarity between the two estimations is high whatever the type of variation: recharge (July to September 2008) or drying-up (September 2008 to February 2009). A small discrepancy in the range of the uncertainty is observed on the last period (February to April 2009) characterised by a small depletion of the groundwater.

In the context of the GHYRAF project and the AMMA-CATCH observatory a new superconducting gravimeter (SG) has been installed in 2010 at Nalohou. This meter will be part of the GGP project (Crossley *et al*. 1999; Hinderer and Crossley 2004) and its location is very interesting in terms of network coverage (there are very few stations around the equator and only presently one in Africa). The high sampling rate of the gravimeter (1 s) will clearly enhance our domain of investigation in the spectral band and enable us to follow quite rapid hydrological events related to the monsoonal rainfalls. Further hydrogeological investigations will also be undertaken in the future (as pumping tests and vadose zone moisture monitoring using neutron probes) to obtain more independent data for comparison purpose. These investigations will lead to estimates of the specific yield independent from the ones inferred from MRS and to a better knowledge of the soil moisture in the deep vadose zone (below the first meter); this information will then allow a better estimate of the water storage changes to be compared with the surface gravity changes.

3. Conclusion

We have presented in this paper the first results from the GHYRAF (Gravity and Hydrology in Africa) experiment which started in 2008 in Niger and Benin. This project uses geodetic tools (GPS, surface and satellite gravimetry) in close connection to hydrology observations to investigate water storage changes along a climatic rainfall gradient from the Sahara to the equatorial monsoon region. The measurements from the AMMA-GHYRAF permanent GPS network in West Africa were analyzed and the comparison during the 2005–2008 period between hydrological loading predictions and observations clearly shows a nice agreement for the stations in Niamey (Niger) and Djougou (Benin). This demonstrates that GPS has the ability to retrieve annual signals of the order of 20 mm peak to peak due to continental hydrology loading. Different GRACE solutions were also used to investigate the annual signal in gravity over West Africa. The water storage changes were estimated for the Niger and Lake Chad basins showing again a nice agreement between the GLDAS/Noah global hydrology predictions, GRACE solutions and CMAP cumulative precipitation field. We have then focused on the results coming from our ground gravimetric measurements (using a FG5 absolute gravimeter) done during the 2008 monsoonal event. After showing the respective importance of local and non-local hydrology contributions to surface gravity and correcting the surface measurements for the latter contribution using GRACE satellite observations, we investigate in more details the local water storage changes in Wankama (Niger), Diffa (Niger) and Nalohou (Benin) specific sites.

In Wankama, a major result from the observed gravity changes mainly caused by changes in the piezometric level after indirect recharge processes is that the combination of both gravimetry and MRS techniques converge to infer a common specific yield value (of the order of 4–7%); this is evidence for the consistency of the two independent methods to better constrain important underground hydrodynamical parameters.

In Diffa, which is located in the Lake Chad basin and close to Komadugu-Yobe river, the observed gravity changes are smaller than the one predicted by global hydrology models but in close agreement (both in amplitude and phase) with the local piezometric level changes. It is clearly a local recharge–discharge process linked to the Komadugu-Yobe river which accounts for this rather than the mean rainfall field over the basin which explains that the soil moisture changes (and consequently the hydrology model) is shifted by several months with respect to the piezometric level.

Finally, in Nalohou, the observed gravity changes from July 2008 to April 2009 are well explained in terms of water storage changes in three specific compartments: the 0–1 m vadose zone, water level changes in temporary perched aquifers and finally water level changes in a deep permanent aquifer. The water storage budget is very consistent between the values inferred from gravimetry and the one computed from the hydrological in situ measurements.

Gravimetry appears to be a useful tool to solve some hydrological questions compared to borehole tests (being both local and invasive) or MRS (again somehow local with specific limitations due to the method). Gravimetry leads to a rapid and integrative estimate of the water storage changes provided that some simple hypotheses are made for the underground geometry. On the contrary, estimating the water storage by classical hydrology techniques requires the knowledge of piezometric changes (using boreholes), specific yield (e.g. using pumping tests or calibrated MRS) and soil moisture in the entire vadose zone (e.g. using calibrated neutron probes).

Gravimetry is also one of the few integrative methods present in hydrology (except for the surface flow measurement at the catchment outlet) and needs further investigation for a better integrated estimate of underground water storages.

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