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1 A study of the monsoonal hydrology contribution using a 8 year record (2010-2018) from
2 superconducting gravimeter OSG-060 at Djougou (Benin, West Africa)

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10

11 Abstract

12 We analyze a nearly 8-year record (2010-2018) of the superconducting gravimeter OSG-060 located at
13 Djougou (Benin, West Africa). After tidal analysis removing all solid Earth and ocean loading tidal
14 contributions and correcting for the long term instrumental drift and atmospheric loading, we obtain
15 a gravity residual signal which is essentially a hydrological signal due to the monsoon. This signal is first
16 compared to several global hydrology models (ERA, GLDAS, MERRA). Our superconducting gravimeter
17 residual signal is also superimposed onto episodic absolute gravity measurements and to space
18 gravimetry GRACE data. A further comparison is done using local hydrological data like soil moisture
19 in the very superficial layer (0-1.2 m), water table depth and rainfall. The temporal evolution of the
20 correlation coefficient between the gravity observation and both the soil moisture and the water table
21 is well explained by the direct infiltration process of rain water together with the lateral transfer
22 discharging the water table.

23 Finally we compute the water storage changes (WSC) using a simulation based on the physically-
24 based Parflow-CLM numerical model of the catchment, which solves the water and energy budget
25 from the impermeable bedrock to the top of the canopy layer using the 3D Richards equation for the
26 water transfers in the ground, the kinematic wave equation for the surface runoff, and a land surface
27 model (CLM) for the energy budget and evapotranspiration calculation.

28 This model forced by rain is in agreement with evapotranspiration and stream flow data and leads to
29 simulated water storage changes that nicely fit to the observed gravity signal. This study points out the
30 important role played by surface gravity changes in terms of a reliable proxy for water storage changes
31 occurring in small catchments.

32

33 Keywords: time variable gravity, Africa, hydrology, loading, monsoon

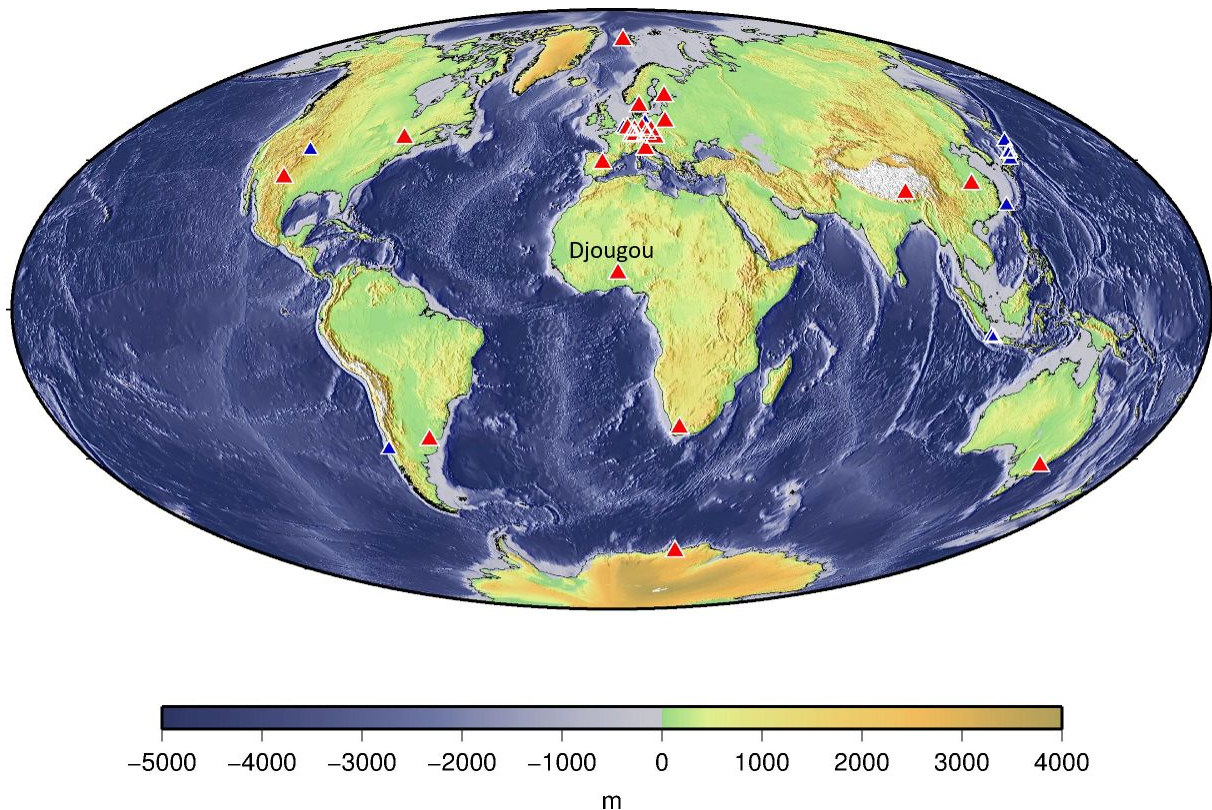
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36 Introduction

37 The superconducting gravimeter OSG-060 from GWR Instruments was installed in Nalohou, close to
 38 Djougou in northern Benin (West Africa) in July 2010. This installation was done in the frame of the
 39 GHYRAF (Gravity and Hydrology in Africa) program that lasted from 2008 to 2012 (Hinderer et al. 2012).
 40 This gravimeter is part of the IGETS (International Geodynamics and Earth Tides Service,
 41 <http://igets.u-strasbg.fr>) (see also Boy et al. 2017), under the umbrella of IAG (International
 42 Association of Geodesy).

43 Fig. 1 shows the location of the Djougou (DJ) station (the geographical coordinates of the station are
 44 9.7424 °N and 1.6056 °E) among the other stations of the international network of superconducting
 45 gravimeters (SG).
 46



47

48

49 *Fig. 1. A map of the superconducting gravimeter stations belonging to IGETS (International*
 50 *Geodynamics and Earth Tides Service, <http://igets.u-strasbg.fr>). The operational stations in 2018*
 51 *(about 20) are in red and former stations now stopped are in blue.*

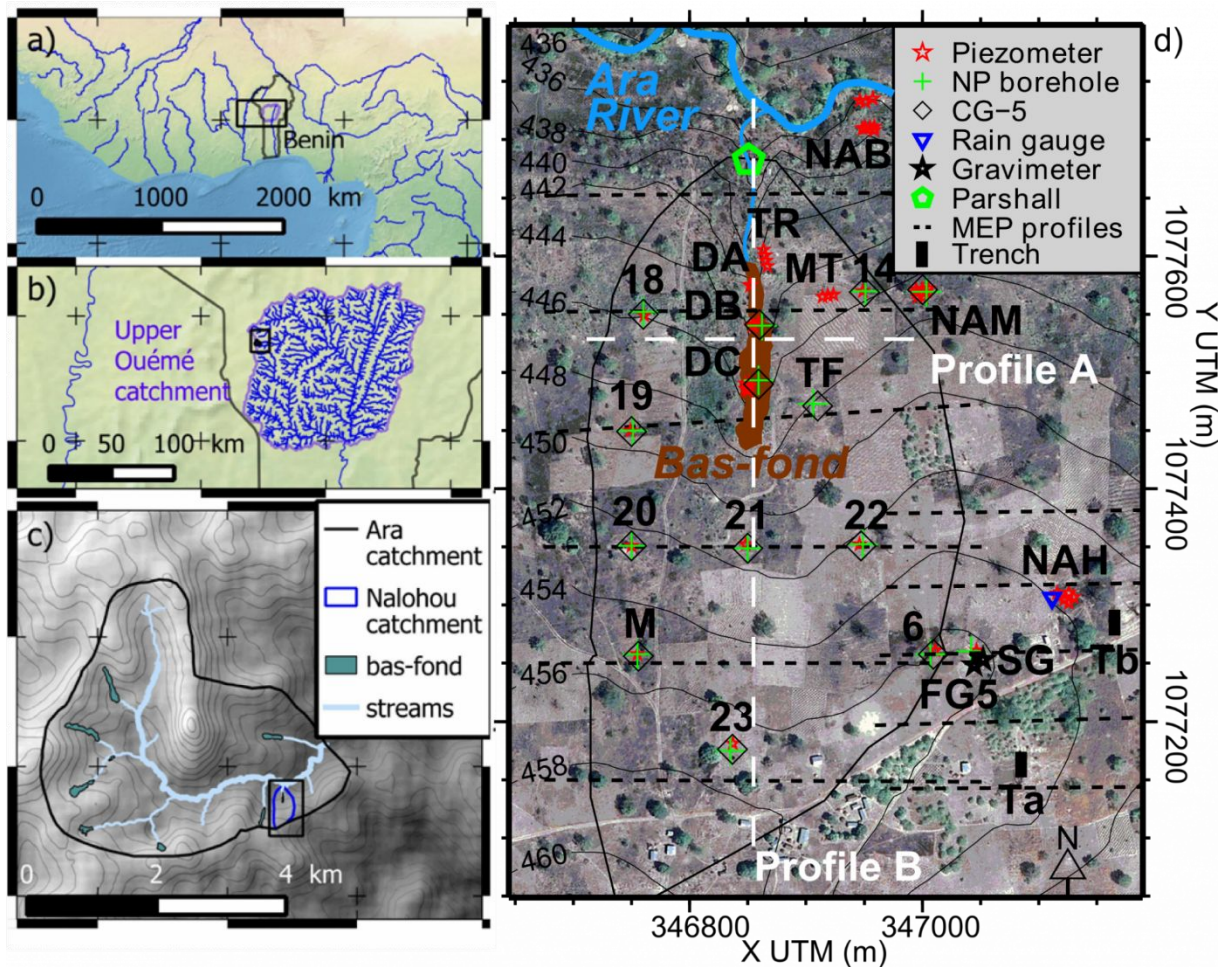
52 The location of Djougou in Benin makes this station unique for investigating the hydrology contribution
 53 of the West African monsoon. The choice of this location for installing the SG was driven by the fact
 54 that Nalohou is part of the Ara catchment (see Fig. 2) , one of the key sites in the Sudanian region
 55 monitored by AMMA-CATCH hydro-meteorological observatory (<http://www.amma-catch.org/>,
 56 AMMA-CATCH, 1990) with a high density of data available over a long time span of several decades
 57 (Galle et al. 2018).

58 The right hand side of Figure 2 (Fig. 2d) shows the location of the various hydro-meteorological
 59 instrumentation deployed (piezometers, neutron probe boreholes, rain gauge, Parshall, trenches) over
 60 the catchment as well as the gravimeter (FG5, SG-060, CG5) stations and MEP (Multi-electrode
 61 Electrical Profiling) profiles. In this study we use an absolute gravimeter FG5#206 from Micro-g
 62 Solutions Inc., and a superconducting gravimeter SG-060 from GWR Instruments Inc. .The huts for

63 episodic absolute gravity measurements (FG5#206) and continuous superconducting gravimeter
 64 monitoring (GWR OSG-060) are very close to each other (a few meters) and located on the summital
 65 part of the catchment. Since 2011 there is also a network of relative gravity stations that has been
 66 regularly repeated with a Scintrex, model CG-5 (serial number 9379) gravimeter.

67

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70

71 *Fig. 2. Location of the Ara catchment inside the Upper Ouémé catchment in North Benin and available*
 72 *hydro-meteorological and geophysical instrumentation (Hector et al. 2015); 2a) shows the upper*
 73 *Ouémé catchment in northern Benin, 2b shows the Ara catchment inside the upper Ouémé catchment,*
 74 *and 2c shows the location of the Nalohou catchment inside the Ara catchment. 2d) indicates all*
 75 *available instrumentation in hydrology and geophysics in the Nalohou catchment (WGS 84 / UTM zone*
 76 *31N projected coordinate system). NP means Neutron probe, MEP Multi-electrode Electrical Profiling,*
 77 *Parshall a Parshall flume for measuring the flow of water and Bas-Fond is the French and local name*
 78 *for an inland valley wetland.*

79



80

81 *Fig. 3. A picture of the absolute gravimeter FG5#206 (left) and superconducting gravimeter GWR OSG-*
 82 *060 (right) operating at Djougou.*

83 The main goal of installing an SG in Djougou was to monitor integrated water storage changes (WSC)
 84 in the sensitivity zone around the gravimeter by observing temporal gravity changes and compare
 85 them with point-scale hydrological measurements, such as water table depth, soil moisture sensors,
 86 or neutron probe monitoring.

87 There are several reasons to estimate water storage changes (WSC):

- 88
- 89 • To observe non-invasively a signature of the internal redistribution of water within the critical
 zone for hydrological processes identification (proxy)
 - 90 • To provide additional constraints for hydrological modeling
 - 91 • To inform ultimately on groundwater recharge and annual storage/discharge that is critical for
 92 resource managers.

93 The question of the hydrological signature in gravity has been extensively studied by many groups
 94 possessing superconducting gravimeters. It would be long to cite them all and we refer the reader to
 95 the review done in Hinderer et al. (2015), as well as in the more recent one by Van Camp et al. (2017).
 96 These studies mostly concern Europe (e.g. Creutzfeld et al. 2010; Weise and Jahr, 2018; Van Camp et
 97 al. 2006; Boy and Hinderer 2006) and hence the Djougou station is interesting by its unique location in
 98 Africa and because the investigation of monsoonal effects in West Africa has shown a clear
 99 intensification of rainfall and hydrological cycles that might be linked to climate changes (see Taylor et
 100 al. 2017; Galle et al. 2018, Nkrumah et al., 2019).

101

102 Gravity data processing

103 The gravity record has been processed jointly with air-pressure in a classical way starting with a pre-
 104 processing to remove the major disturbances (spikes, offsets, gaps, offsets) of instrumental and/or
 105 manmade origin. We refer the reader to Hinderer et al. (2015) for more details on the processing steps.

106 The gaps due to earthquakes are filled with a synthetic local tide coming from a precise tidal analysis
 107 of the 8-year data set (Hinderer et al. 2019).

108 The cleaned pressure and gravity data sets are shown on Fig. 4 for the investigated period (2010-2018).
 109 The reduction for lunisolar tides (solid Earth + ocean tidal loading), as well as for atmospheric effects
 110 and Earth's rotation leads to the gravity residuals (in black on Fig. 5). We refer the reader to Hinderer

111 et al. (2019) for more details on the solid Earth tidal model as well as on the ocean tidal model and
112 atmospheric corrections for the OSG-060 gravity record.

113 A further correction for the instrumental drift of the gravimeter (in red on Fig. 5) leads then to the
114 corrected residual signal (in blue on Fig. 5) that is reportedly of hydrological origin and characterized
115 by an annual periodicity (see Hector et al. 2014).

116 The drift assessment through least-square fitting shows that the instrumental drift of the GWR OSG-
117 060 is composed of an initial exponential term followed by a linear term that remains stable over the
118 years. This is very classical for SGs and confirms the earlier results based on a 1.5 year record of SG-
119 060 (Hinderer et al. 2014a).

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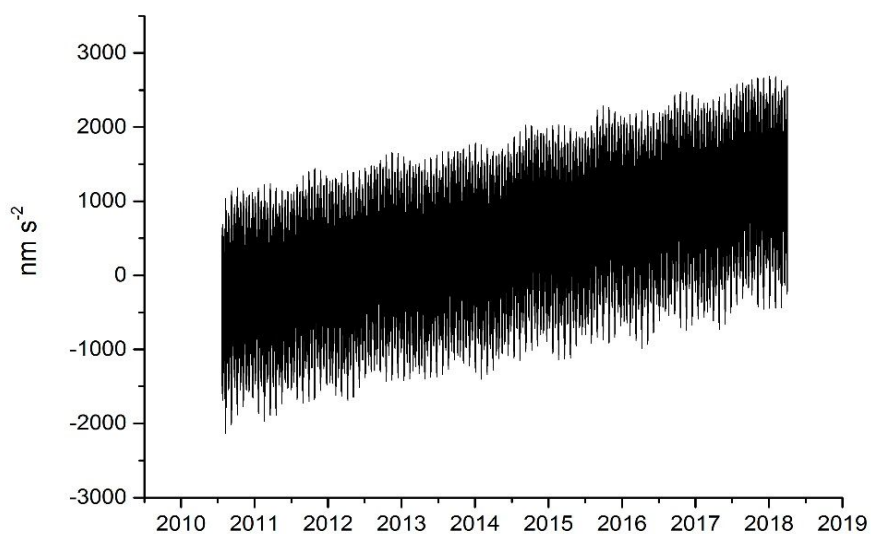
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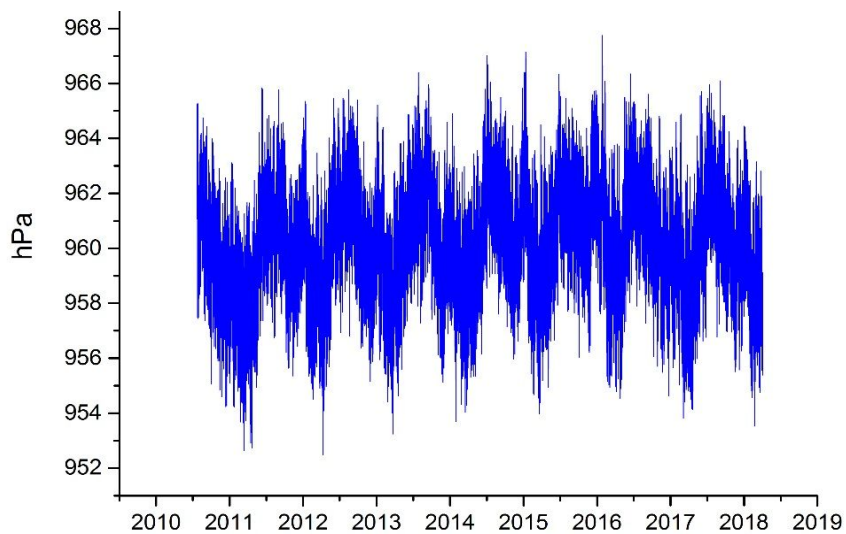
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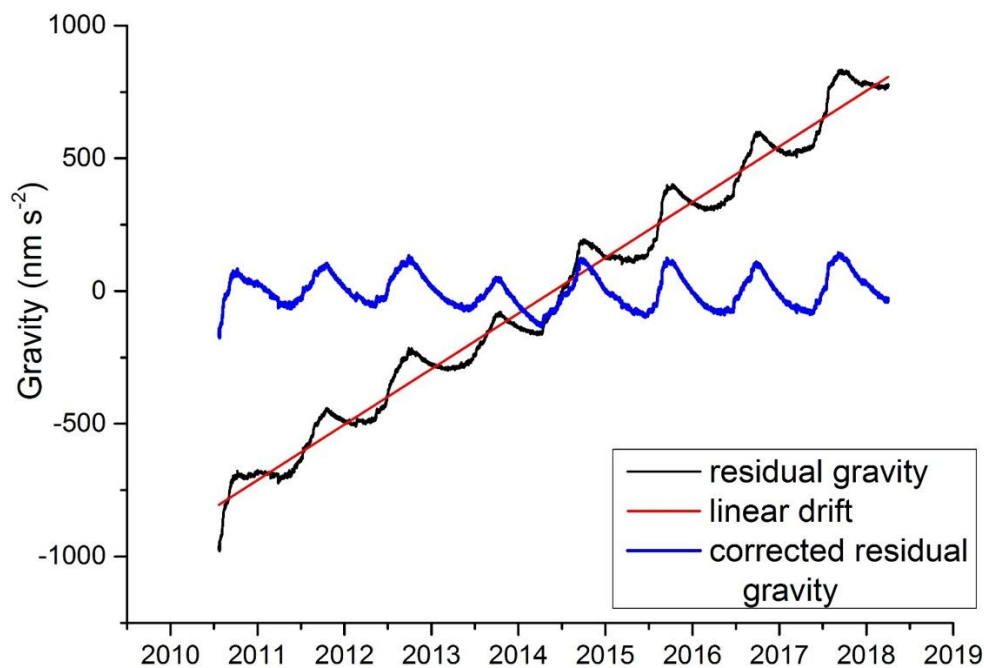
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143

144 *Fig. 4. Gravity (upper panel, in nm s^{-2}) and barometric pressure (lower panel, in hPa) observed at the*
145 *Djougou station from 2010 to 2018.*

146 The fit to an exponential function $g = g_0 + A_1 \cdot \exp(-(x-x_0)/T_1)$, where g_0 and x_0 are the starting values of
 147 gravity and time, leads to an amplitude A_1 of $-147.6 \pm 1.2 \text{ nm s}^{-2}$ and a time decay $T_1 = 13.8 \pm 0.3$ days.
 148 This exponential drift estimate was done on the residual gravity first corrected for MERRA global
 149 hydrology model (Reichle et al. 2017) (see below for this choice) because this contribution mixes up
 150 with the instrumental part and must be removed. MERRA model is here the version 2 of The Modern-
 151 Era Retrospective analysis for Research and Applications. This hydrology model is available at the EOST
 152 loading service (<http://loading.u-strasbg.fr>). The linear drift is $+213.6 \pm 0.1 \text{ nm s}^{-2}/\text{year}$ which is rather
 153 large for SGs (Hinderer et al., 2015), but linearity is very strong and apparently stable in time from our
 154 tests.



155
 156 *Fig. 5. Residual gravity signal (in black) after correction for solid Earth and ocean tidal loading,*
 157 *atmospheric effects and Earth's rotation; corrected gravity residuals (in blue) after subtracting a linear*
 158 *instrumental drift (in red).*

159
 160 Solid Earth tides, ocean tidal loading and atmospheric loading

161 We analyzed the whole dataset of gravity observations (nearly 8 years) using the Hartmann & Wenzel
 162 (1995) tidal potential catalogue. Amplitude and phase tidal parameters for groups combining
 163 inseparable constituents as well as the air pressure admittance factors were adjusted in the long
 164 period, diurnal and sub-diurnal frequency bands by means of ET34-ANA v7.1 software (Schüller 2018;
 165 Ducarme & Schüller 2018). A detailed discussion of the tidal (solid Earth + oceans) effects, as well as
 166 the atmospheric contribution to gravity, is done in Hinderer et al. (2019).

167

168 The equatorial location of Djougou station leads to strong pressure waves of thermal origin modulated
 169 in amplitude (e.g. Gegout et al. 1998; Schindelegger & Ray 2014). The air pressure also exhibits long
 170 period features among which the annual component S_a (one cycle per year) is the largest and the other
 171 terms are at S_{2a} (2 cycle per year) and S_{3a} (3 cycle per year).

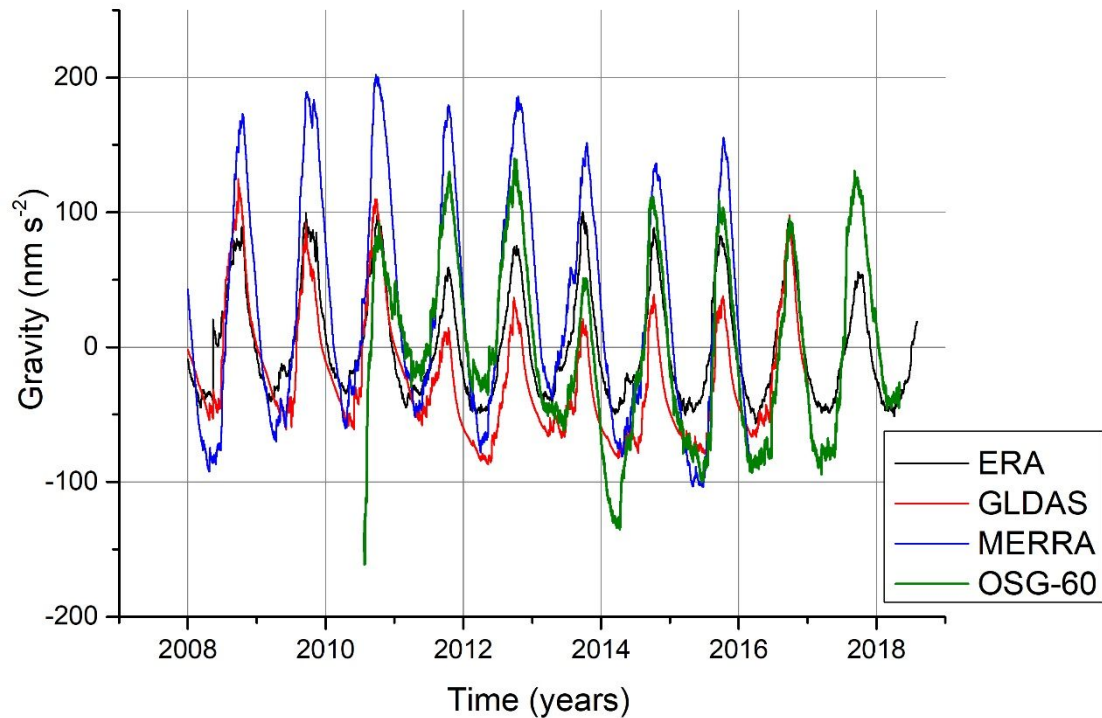
172 The gravity loading due to atmospheric pressure at Djougou takes into account the gravitational
173 attraction of the air masses as well as the elastic deformation of the Earth and hence cannot be
174 reduced to a simple function of the local pressure like in the frame of the classical concept of
175 barometric admittance (Crossley et al. 1995; Hinderer et al. 2014b) but is more complicated because
176 the non-local part involves the convolution of the pressure field worldwide with the atmospheric
177 loading Green's function (see e.g. Boy et al. 2002, 2006).

178 Different atmospheric gravity loadings were computed using ECMWF (European Centre for Medium
179 Range Weather Forecasts) operational and reanalysis (ERA interim) pressure data, assuming either an
180 inverted barometer response of the oceans (without any induced pressure effect at the ocean bottom
181 see e.g. Wunsch & Stammer 1997) or a dynamic response using TUGO-m (Carrère & Lyard, 2003). The
182 best pressure reduction was found using a hybrid approach computed by retaining the MERRA
183 modelled non-local component and replacing the local one with the observed air pressure multiplied
184 by the nominal admittance coefficient coherently with model resolution. In the MERRA model the
185 resolution is 0.625° and we used a local cell with a radius of 0.1° together with a nominal admittance
186 of $-2.21 \text{ nm}\cdot\text{s}^2/\text{hPa}$. The hybrid method enabled us to account for both very local atmospheric
187 effects, as probed by the surface pressure observations, and larger scale contributions to gravity
188 originating from the planetary thermal pressure waves.

189 Hydrological loading

190 There are several global hydrology models available at <http://loading.u-strasbg.fr>. In this study we
191 used GLDAS/Noah [Rodell et al., 2004], ECMWF operational and reanalysis (ERA interim) and MERRA2
192 [Reichle 2012; Reichle et al., 2017]. Global hydrology models are based on a land surface model (for
193 example, Noah for GLDAS) forced by atmospheric parameters, such as precipitation, temperature, long
194 and short wavelength radiations, etc. They can be run fully coupled with an atmospheric model in case
195 of the ERA interim and MERRA2 reanalysis, or independently as for GLDAS using variables from various
196 origins (atmospheric model, satellite data, etc.). The other main discrepancy is the difference between
197 operational and reanalysis model. In the first case, the model and/or the forcing can change in time,
198 whereas the entire system is stable for reanalysis.

199 All the hydrology models used in this study are providing estimates of soil moisture content in the first
200 meters, and also canopy water in the case of GLDAS/Noah. We compare all these different models as
201 they can show some discrepancies (see Figure 6), due to differences in the land surface models, but
202 also in the forcings.



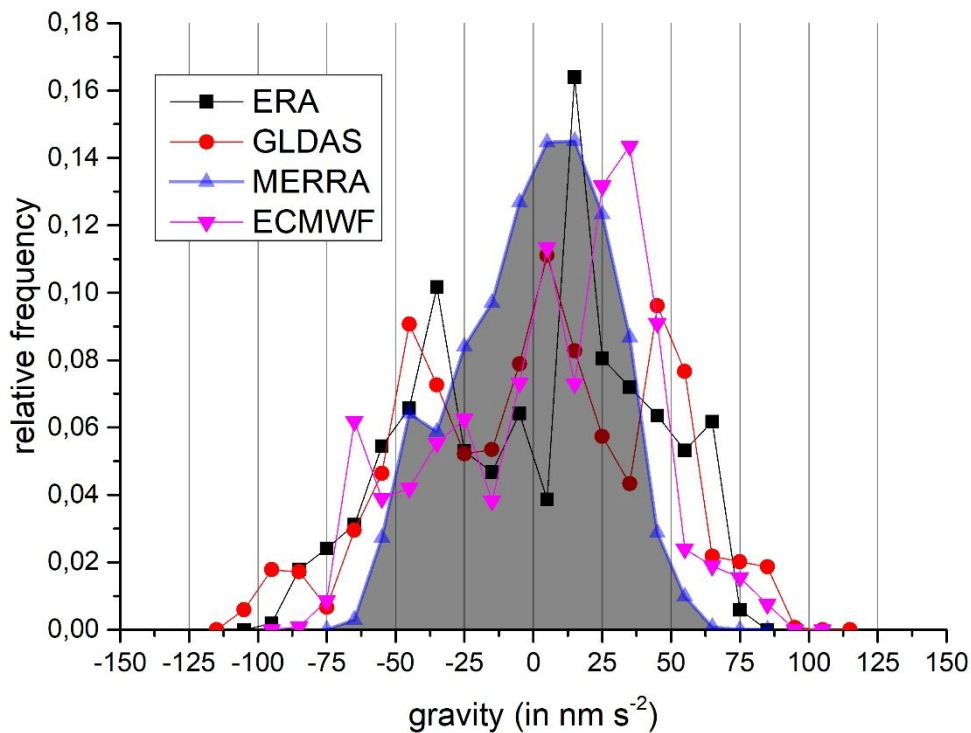
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204 *Fig. 6. Comparison of gravity changes due to hydrology according to global models (ERA, GLDAS,*
 205 *MERRA2) with superconducting gravity residuals at Djougou.*

206 For sake of comparison gravity loading from these three hydrology models, computed for the period
 207 2008-2018, are superimposed onto the SG gravity residuals (Fig. 6), which are only available after July
 208 2010 (installation of gravimeter). The beginning of the SG residuals in summer 2010 is clearly different
 209 from the hydrology predictions because of the initial instrumental drift of the SG after installation.

210 By computing the discrepancy between the observed gravity and the hydrology models we are able to
 211 find out the preferred model that leads to the best fit. This is shown by the histograms in Fig. 7
 212 depicting the differences between gravity observations and model predictions. The RMS is 42.9, 40.4,
 213 36.8 and 26.1 nm s^{-2} for models GLDAS/Noah, ERA Interim, ECMWF and MERRA2, respectively. Hence,
 214 the best model results to be clearly MERRA2.

215

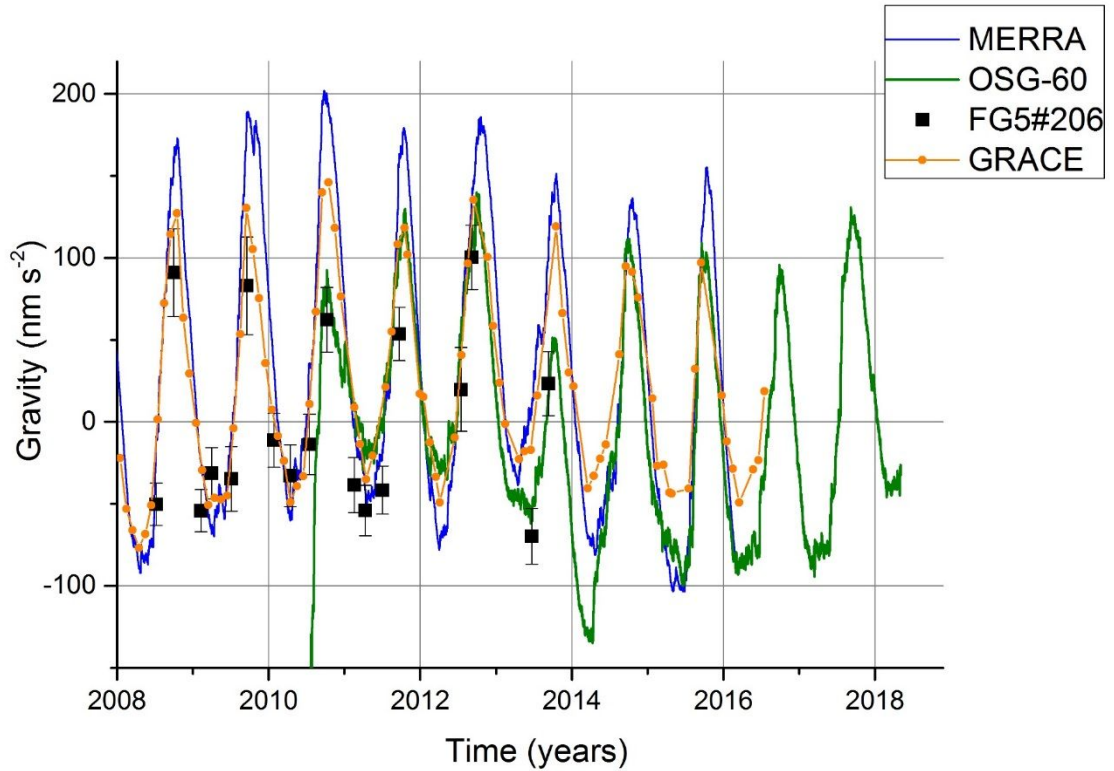


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217 *Fig. 7. Histograms of the differences between observed gravity and 4 global hydrology models.*

218 As already shown for shorter duration in previous papers (Hector et al. 2014, 2015), there is a fair
 219 agreement between the continuous superconducting gravimeter observations, episodic absolute
 220 gravity measurements and space gravimetry GRACE data that all superimpose onto global hydrology
 221 models. The comparison of MERRA hydrology model with OSG-060, FG5#206 and GRACE data is shown
 222 in Fig. 8 where the GRACE solutions come from iterated global “mascons” (Luthcke et al., 2013).

223 We use the latest version (v02.4) of the 1-degree equal area global iterated “mascon” solution
 224 provided by NASA Goddard Space Flight Center from January 2003 to July 2016. A mascon (mass
 225 concentration) represents an excess or a lack of surface mass compared to the a priori mean gravity
 226 field in a predefined region, directly inverted from the GRACE K-band range rate measurements. The
 227 excess or lack of mass is represented as a uniform water layer, expressed in centimeters of equivalent
 228 water over this area. These “mascon” solutions differ from the classical constrained or unconstrained
 229 spherical harmonic solutions, as they allow to introduce spatial constraints in the inversion of the K-
 230 band range rate residuals (Rowlands et al., 2010), and to increase the spatial resolution of the solution,
 231 as post-processing filtering is no longer required.

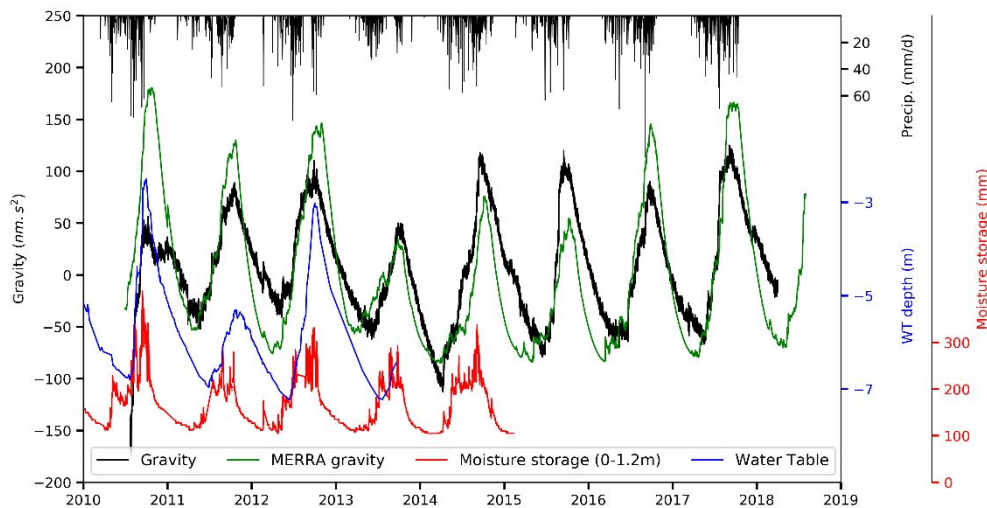


232

233 *Fig. 8. Comparison of MERRA2 hydrology model with superconducting gravimeter (OSG-060), absolute*
 234 *gravimeter (FG5#206) and GRACE data.*

235

236 One has to keep in mind that the spatial resolution of these data sets is quite different. Surface gravity
 237 is a point measurement, MERRA has a 0.625 ° grid resolution and GRACE data merely are
 238 representative of much larger scales (typically 300 x 300 km). The fact that there is a fair agreement
 239 between surface gravity and GRACE in Fig. 8 mostly comes from the fact that the hydrology loading of
 240 monsoonal origin is coherent over a wide region in West Africa, and probably also because of the
 241 specific uphill location of the gravimeter.



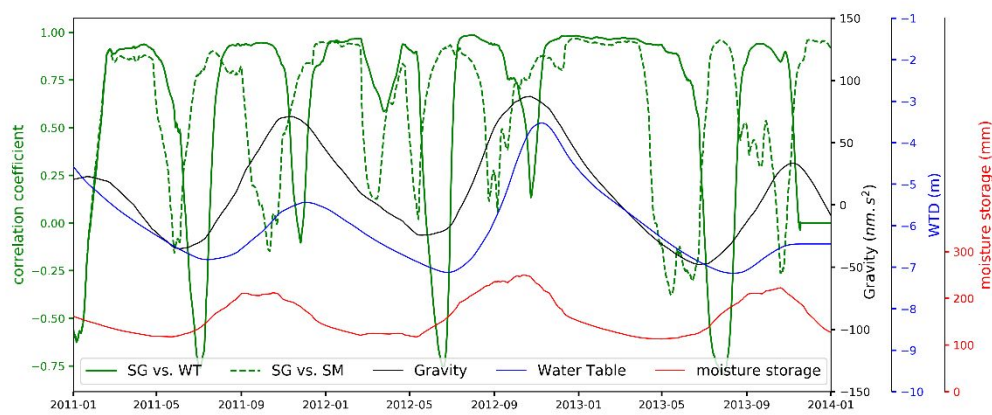
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243 *Fig. 9. Comparison of gravity observed with the superconducting gravimeter (OSG-060) (black line) and*
 244 *predicted by MERRA global hydrology model (green line), soil moisture (red line), water table depth*
 245 *(blue line) and rain data in mm/day.*

246

247 Our last absolute gravity data unfortunately was measured in 2013 and GRACE data stopped in 2016.

248 In Fig. 9 we show for the period 2010-2015 the comparison of MERRA hydrology model with gravity
 249 (OSG-060) (like in Fig. 8) but superimposed onto local hydrological data such as soil moisture (available
 250 between 0 and 1.2m using 6 probes at depths of 5, 10, 20, 40 and 60 cm, AMMA-CATCH, 2005), water
 251 table depth (AMMA-CATCH, 2003) and rain data (AMMA-CATCH 1999) in the Ara catchment available
 252 from the data base of the AMMA-CATCH observation system (Galle et al., 2018, [http://www.amma-](http://www.amma-catch.org/)
 253 [catch.org/](http://www.amma-catch.org/)).

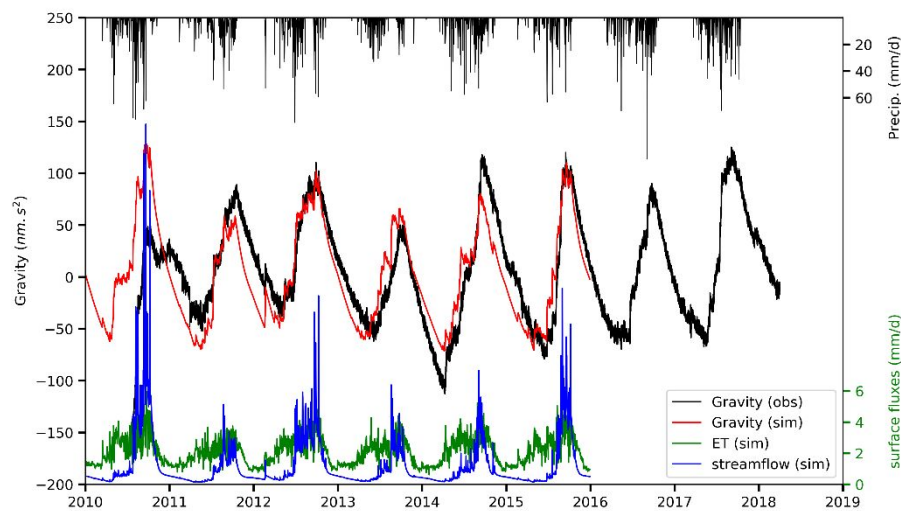


254

255 *Fig. 10. Correlation coefficient as a function of time between observed gravity (SG) and soil moisture*
 256 *(SM) and water table (WT).*

257

258 In this ground context, mainly characterized by direct water infiltration, soil moisture reacts more
 259 quickly to the rain than the deeper water table. Fig. 10 shows the correlation coefficient computed
 260 using a 2-month sliding window (to filter out the higher frequency contributions and keep only the
 261 major processes during the hydrological cycle) between SG and both water table and soil moisture. At
 262 the onset of the rain season, the level of the water table continues to decrease, the discharge being
 263 driven by the hydraulic gradient at the catchment scale (Hector et al., 2015, 2018). This results in a
 264 phase lag inducing a decorrelation of the water table and the gravity signal, due to the time offset
 265 between the yearly minima of the two series. At the same time, the rain water is being stored in the
 266 shallow soil and the correlation between soil storage and gravity takes over until the core of the rainy
 267 season, where the soil storage compartment is full (soil moisture time variability shows a plateau),
 268 while still maintaining a downward infiltration flux, recharging the water table and increasing the
 269 gravity. Thereafter the gravity correlates well to the water table, until the end of the rainy season,
 270 where gravity starts to decrease due to the system discharge by evapotranspiration, while the water
 271 table still rises in response to the slowly percolating water. During the core of the dry season, all the
 272 system discharges and both water table heights and soil moisture values are well correlated to gravity.



273

274 *Fig. 11. Modeling the WSC using a simulation of evapotranspiration (ET), streamflow and induced*
 275 *gravity effect based on Parflow-CLM model (Hector et al. 2018) and its validation through the observed*
 276 *gravity.*

277

278 This means that the transfer function between gravity and water storage changes is variable in time
 279 because several processes occur in the water table and soil moisture during the hydrological cycle
 280 driven by the monsoon; moreover the WSC are not uniform over the entire catchment as already
 281 shown by the analysis of the repeated microgravimetric network observations that could identify zones
 282 with preferential infiltration (Hector et al. 2015).

283 Finally in Fig. 11, the observed gravity is superimposed onto the WSC originating from a simulation
 284 (Hector et al. 2018) of a small headwater catchment (720 m x 300 m) encompassing the Nalohou
 285 catchment (Fig. 2) with the help of the physically-based critical zone model ParFlow-CLM (Maxwell &
 286 Miller 2005; Kollet & Maxwell 2008) run at a 20 m lateral resolution. ParFlow solves the water transfer
 287 in porous media on a gridded domain using the 3D Richards equation for the saturated and non-
 288 saturated zone, and simultaneously solves the overland flow using the kinematic wave and Manning
 289 equation on the surface cells which exhibit a positive pressure (Kollet & Maxwell 2006). ParFlow is
 290 tightly coupled to CLM, the Common Land Model (Dai et al., 2003, Maxwell & Miller 2005), a land
 291 surface model which solves the water and energy budget through the user-defined N first cells.

292 The ParFlow model is forced at a 0.5hr time step for 11 years with atmospheric and vegetation
 293 variables from the AMMA CATCH observational service; further details on the physical parametrization
 294 of the model domain as well as on the model set up can be found in Hector et al. (2018). Three
 295 additional years are used as compared to the paper by Hector et al. (2018). Simulation outputs have
 296 been extensively tested against multiple field data (streamflow, evapotranspiration, soil humidity,
 297 water storage). The SG is seated on the South-East edge of the catchment, on a saporolite unit.
 298 Therefore, only the saporolite simulation from Hector et al. (2018) is shown on Fig. 11.

299 As the SG is located on the edge of the simulation domain, no attempt to calculate the gravity effect
 300 of the simulated water storage change (WSC) is done. This would have required a finer resolution close

301 to the gravimeter, and the explicit simulation of the shelter effect as described in Deville et al. (2013)
 302 or in the detailed study by Reich et al. (2018). Instead, the simulation represents the typical behavior
 303 of a small headwater catchment composed by saporolite rock cover, an elementary hydrological unit in
 304 the area.

305 To convert the water storage changes (in mm of water equivalent) to gravity (nm s^{-2}), the best fit
306 (leading to the smallest differences in time between observations and predictions) yields a factor of
307 $0.37 \text{ nm s}^{-2}/\text{mm}$ that is lower than the classical Bouguer plate coefficient of $0.42 \text{ nm.s}^{-2}/\text{mm}$ of water
308 for a flat water layer of density 1000 kg/m^3 .

309 This difference cannot be explained by the topography effect, as computed by Hector et al., 2015 (Their
310 Fig. B1), which would imply a slightly higher coefficient of $0.44 \text{ nm.s}^{-2}/\text{mm}$. However, this is in
311 accordance with the range of coefficients found when computing the effect of the shelter (Hector et
312 al., 2014, Fig. 5) for an average depth of water storage changes between 2 and 3 meters, in agreement
313 with the actual depth range comprised between the surface and the water table. Furthermore, this
314 value is still higher than the 'rainfall admittance', the mean observed ratio of gravity increase over
315 precipitation amount computed from a representative diversity of individual rain events, of $0.22 \text{ nm.s}^{-2}/\text{mm}$.
316 This value is the lower bound for fast water storage changes occurring close to the surface and
317 for which the gravity measurement is very sensitive to the shelter extent and the sensor height above
318 ground (Hector et al., 2014). This observation clearly calls for a higher resolution simulation of the
319 surroundings of the gravimeter, explicitly simulating the shelter effect to be able to calculate directly
320 the gravity effect. Such a model would also require the simulation of the whole catchment to constrain
321 the lateral groundwater flux, responsible for the groundwater discharge.

322 The simulated water storage changes match to a reasonable extent the observed gravity changes
323 behaviour ($R^2 = 0.77$), and while the annual cycle and the inter-annual variations are overall satisfying,
324 there are clear discrepancies around specific events. This may encourage the use of the current model
325 as a correction model for data gap-filling, for long term geodetic applications, but not for high
326 frequency signal analysis, for which a higher resolution model, taking into account the local substratum
327 variability in the vicinity of the gravimeter, together with the shelter effect, is needed (see Reich et al.
328 2019).

329

330 Conclusions

331 We report on an 8-year long continuous gravity monitoring (2010-2018) by the superconducting
332 gravimeter OSG-060 at Djougou (Benin, West Africa). First, a tidal analysis using ET34-ANA v7.1
333 software enables us to remove the solid Earth tides, ocean tidal loading and Polar motion effects in
334 the gravity record. Atmospheric pressure effects are reduced by means of a hybrid model using the
335 global atmospheric model MERRA everywhere except in in the local zone, where the model pressure
336 was replaced by the observed pressure accounting for the specific admittance factor. The observed
337 residual gravity signal of hydrological origin was then investigated. We first compared this signal to
338 several global hydrology models (ERA, GLDAS, MERRA) and found that the best model (i.e. the one
339 leading to the smallest discrepancy between observations and model) is MERRA2 with a standard
340 deviation of 26.1 nm s^{-2} . The MERRA hydrology model was also compared to absolute gravity data
341 available from 2008 to 2013 and to GRACE mascons solutions between 2008 and 2016 when GRACE
342 data stopped. In a further step, the gravity signal is compared to local hydrological data like soil
343 moisture in the very superficial layer (0-1.2 m), water table depth and rainfall. The temporal evolution
344 of the correlation coefficient between the gravity observation and both the soil moisture and the water
345 table is well explained by the direct infiltration process of rain water together with the lateral transfer
346 discharging the water table. An attempt to model water storage changes was finally done using a
347 simulation based on Parflow-CLM model of the catchment. This model that is forced by rain is in
348 agreement with evapotranspiration and stream flow data and leads to simulated water storage
349 changes. These changes nicely superimpose onto gravity signal using a $0.37 \text{ nm s}^{-2}/\text{mm}$ conversion
350 factor. The next step will be to use a finer resolution model in the vicinity of the gravimeter, together
351 with the explicit simulation of the shelter effect, in order to accurately simulate the observed gravity
352 changes and use it as a gap-filling support tool.

353 The long term monitoring of WSC will help identify possible effects of land use intensification currently
 354 occurring in the area (lower duration crop rotation cycles, increased use of pesticides resulting in
 355 longer periods of soil denudation, village growth...) on groundwater recharge through increase of
 356 surface runoff. Furthermore, a major science question still unresolved in the area is whether the
 357 observed groundwater discharge during the dry season is driven by evapotranspiration only, or also by
 358 deeper drainage through permeable zones like faults. A comparative analysis of the gravity and water
 359 table decreases together with local measurements of evapotranspiration may help to further constrain
 360 this issue (Descloitres et al., 2011).

361

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