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1 **Separating climate-induced mass transfers and instrumental effects from tectonic**
2 **signal in repeated absolute gravity measurements**

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14

15 **Key Points:**

- 16 • The signature of climate-induced interannual mass transfers on repeated absolute gravity
17 measurements is estimated everywhere in the world
- 18 • Instrumental artefacts should be taken into account and mitigated as much as possible.
- 19 • In most cases, the uncertainty is estimated to $\sim 5 \text{ nm/s}^2/\text{a}$ after 10 yearly campaigns

20

21 Abstract 150 words

22 We estimate the signature of the climate-induced mass transfers in repeated absolute gravity
23 measurements based on satellite gravimetric measurements from the GRACE mission. We show
24 results at the globe scale, and compare them with repeated absolute gravity (AG) time behavior
25 in three zones where AG surveys have been published: Northwestern Europe, Canada and Tibet.
26 For 10 yearly campaigns, the uncertainties affecting the determination of a linear gravity rate of
27 change range 3-4 nm/s²/a in most cases, in absence of instrumental artefacts. The results are
28 consistent with what is observed for long term repeated campaigns. We also discuss the possible
29 artifact that can results from using short AG survey to determine the tectonic effects in a zone of
30 high hydrological variability. We call into question the tectonic interpretation of several gravity
31 changes reported from stations in Tibet, in particular the variation observed prior to the 2015
32 Gorkha earthquake.

33 1 Introduction

34 Absolute gravimeters (AG), by construction, suffer no time drift; this makes them most
35 appropriate to measure long-term surface gravity changes, which might reflect either vertical
36 ground motion or mass redistribution. AGs have for example been used to monitor slow vertical
37 ground displacements [*Mazzotti et al., 2007; Djamour et al., 2010; Van Camp et al., 2011;*
38 *Zerbini et al., 2007*] and Glacial Isostatic Adjustment [*Lambert et al., 2006; Steffen et al., 2009;*
39 *Mazzotti et al., 2011; Sato et al., 2012*]. It has also been used to study mass redistribution by
40 erosion [*Mouyen et al., 2013*] and crustal tectonics [*Mouyen et al., 2014*]. Intriguing
41 measurements of gravity changes in Tibet have been recently reported: Sun et al [2009] found
42 evidences for a gravity decrease at three stations, which they interpreted as the signature from a
43 long term thickening of the Tibetan plateau and *Chen et al.* [2015] reported a gravity increase,

44 which they attribute to preseismic processes associated to the 2015, Mw 7.8 Gorkha earthquake.
45 Such tectonic interpretation should be considered with caution in view of the possible effect of
46 non-tectonic causes, in particular surface hydrology, on absolute gravity measurements and
47 instrumental artefacts. *Yi et al.* [2016] showed that the signal observed prior to the Gorkha
48 earthquake by *Chen et al.* [2015] is most probably due to a local hydrological effect unrelated to
49 the earthquake itself.

50 Gravity measurements are indeed extremely sensible to local water storage changes, which
51 depends on very local geologic and climatic conditions, e.g. rock porosity, vegetation,
52 evaporation, and runoff rates [*Van Camp et al.*, 2006a; *Jacob et al.*, 2008; *Creutzfeldt et al.*,
53 2010a; *Lampitelli and Francis*, 2010]; the associated gravimetric signature often exceeds the
54 tectonic effects, and consequently induces non negligible time correlated signature in the gravity
55 time series [*Van Camp et al.*, 2010]. Hydrological effects are observed locally from AG
56 measurements but also at the regional or global scale from satellite gravimetric measurements or
57 GPS geodetic measurements [e.g. *Bettinelli et al.*, 2008, *Blewitt et al.*, 2001; *Chanard et al.*,
58 2014; [Ramillien et al.](#), 2004; *van Dam et al.*, 2001].

59 Separating the instrumental artifacts and the contribution of surface hydrology from
60 tectonic processes in the AG measurements is thus a major challenge. A better understanding and
61 quantification of these effects, as well as of instrumental artifacts, is in our view a prerequisite to
62 any tectonic interpretation of an AG survey. Hereafter, we first discuss instrumental artifacts and
63 next discuss hydrological effects based on satellite gravimetric measurements and comparison
64 with local AG observations in a few areas.

65 2 Instrumental artefacts

66 When different AGs are used in the same study, inter-instrument differences should be
67 taken into account, as done for example by *Lambert et al.* [2006; 2013b], or included in the
68 uncertainty budget [*Sato et al.* 2006; *Mémin et al.*, 2011, *Palinkas et al.*, 2012]. Intercomparison
69 campaigns [e.g. *Francis et al.*, 2005; 2010; [2013](#); 2015; *Jiang et al.*, 2012; *Schmerge et al.*, 2012;
70 *Vitushkin et al.*, 2002] showed that differences between FG5 and JILAg gravimeters are
71 commonly of the order of 100-150 nm/s². A difference as large as 461 nm/s² was reported for
72 one of the A10 instruments that participated in the ICAG-2001 intercomparison [*Vitushkin et al.*,
73 2002]. In other comparisons, systematic and random errors of A10 gravimeters ranged between
74 70 and 220 nm/s² [*Jiang et al.*, 2011; *Francis et al.*, 2005; [2013](#); 2015].

75 Concurrently, the uncertainty due to the setup of the AG instrument should be taken into
76 account. This noise results from instrumental setup-dependent offsets and can be due for
77 example to middling alignment of the instrument, errors in height measurement, slight
78 perturbations due to transportation or different instrument-floor couplings. For an FG5, the
79 sources of uncertainties can be represented by a normal random distribution, with a standard
80 deviation of 16 nm/s² [*Van Camp et al.*, 2005]. In some circumstances, larger, isolated systematic
81 errors due to instrumental setup may occur. For example, an error in the laser frequency can
82 induce a shift in gravity of 270 nm/s²; a malfunctioning or not calibrated clock is also possible (2
83 nm/s²/mHz for an FG5 instrument), etc. (for a comprehensive review of errors see *Niebauer et al.*
84 [1995]). This is difficult to detect but can be mitigated by sufficiently repeating the AG
85 measurements. Finally, other possible artefacts like building construction or soil sealing around
86 the gravity station may modify gravity significantly.

87 **3 Separating hydrological effects from tectonic signal**

88 Separating hydrological signature from tectonic signal in AG data can be done if either
89 (1) the hydrological signal is known with a precision sufficient to allow subtraction of the
90 hydrology signature from the AG data, (2) one disposes from sensors with a response to
91 hydrological load and tectonic effect different from that of the AG, or (3) the space-time
92 behavior of the two signals differs to such an extent that it is possible to use data processing
93 technique to separate them. The third method is most often not practical because of the sparsity
94 in time and space of AG data. Method 2 requires disposing of additional data of a different kind.

95 Method 1 requires precise independent information about hydrology. Estimating
96 subsurface water storage changes is notoriously complex, and it is even more so at the very local
97 scale, where the gravity transfer function is the most sensible. *Lambert et al.* [2006] succeeded in
98 that estimation using a single-thank soil moisture model, but this method is not easily
99 transposable. Such a modeling of hydrogeological effects requires comprehensive investigations
100 and costly in situ instrumentation for ground water measurements [*Creutzfeldt et al.*, 2010a;
101 2010b], which cannot be performed at each gravity station. In addition, correction of the
102 hydrology signature by applying global hydrological models such as the Global Land Data
103 Assimilation System [GLDAS, *Rodell et al.*, 2004] or European Re-Analysis [ERA, *Uppala et*
104 *al.*, 2005], or space-based observations from the Gravity Recovery and Climate Experiment
105 [GRACE, *Wouters et al.*, 2014] is not adequate, given their limited time and space resolution.
106 Ground water storage is indeed heterogeneous in space and variable in time at scales below the
107 spatial and temporal resolution of GRACE, preventing one from retrieving local hydrological
108 effects [*Van Camp et al.*, 2010; [2014](#)].

109 Separation of the causes of temporal variations of AG measurements and precise
110 correction of hydrogeological effects is thus not possible in most cases. Based on the spectral
111 content of modelled hydrogeological effects and of SG time series, *Van Camp et al.* [2011]
112 investigated the hydrological effects on repeated gravity measurements. They showed that the
113 time required to measure a gravity rate of change of $1 \text{ nm/s}^2/\text{a}$ at the 1σ level was of the order of
114 10 years but highly dependent on the location, assuming continuous, hourly sampled gravity time
115 series at the existing SG stations. In case of repeated absolute gravity measurements, the
116 continuity of measurements is broken, and the setup noise must be taken into account. Presently,
117 the easiest and only practical way to mitigate hydrological effects in AG measurements is to
118 perform measurements at the same epoch of the year –the impact of seasonal variations is then
119 minimized and, for a sufficiently long time period, interannual variations average out. This
120 procedure is only approximate due to long-term variability of the hydrological signal and to
121 possible long term drift of groundwater storage. The addition of superconducting gravimeter
122 (SG) information mitigates the error in the estimation of gravity rates of change caused by the
123 presence of long period, interannual, and annual signals in the AG data [*Van Camp et al.*, 2013],
124 but this remains unpractical. However, global models, as GRACE or GLDAS, can meaningfully
125 be used to investigate the spatiotemporal behavior of the hydrological signal, and gather
126 information about the possible magnitude of the hydrological signature.

127 Since 2002, GRACE has provided long enough time series to be used as in the study of
128 *Van Camp et al.* [2010]. Unlike most of the global hydrological model, GRACE integrates the
129 whole ground water content, from the saturated and unsaturated zones, producing a reliable tool
130 to estimate water storage changes. Hence, keeping in mind that the local effects can significantly
131 modify the water storage change signal both in phase and amplitude [*Van Camp et al.*, 2014],

132 GRACE can be used as a proxy in order to estimate the space-time variability of water storage
 133 changes in different climatic and hydrogeological contexts on repeated gravity measurements.
 134 This is done below by simulating repeated AG measurements performed once a year.

135 **4 Space-time variability of hydrological effects on surface gravity measurements**

136 We use monthly GRACE mass concentration (mascon) solutions from JPL [*Watkins et*
 137 *al.*, 2015; *Wiese et al.*, 2015]. The solutions are expressed on a 0.5 by 0.5 degree grid, though the
 138 actual resolution is closer to 2 degrees. As we want to avoid the influence of possible slow
 139 tectonic processes, a 1st-degree polynomial estimated at each point over the whole GRACE area,
 140 was removed, to avoid the influence of possible slow tectonic processes.

141 In this study, we only consider the Newtonian effects on the AG measurements. The
 142 deformation effect caused by the surface mass loading can be corrected using Global Navigation
 143 Satellite System (GNSS) observations [*Zerbini et al.*, 2007] and, after 5 years, is at the mm/a
 144 level [*Santamaría-Gómez and Mémin, 2015*], equivalent to 3 nm/s²/a.

145 The equivalent water height is converted into gravity signal, in nm/s², using the Bouguer
 146 factor of 4.2 nm/s² for 1 cm of water height equivalent, which has been shown to be an excellent
 147 approximation [*Creutzfeldt et al.*, 2008]. Then, we computed the Allan standard deviation [*Allan,*
 148 1966], i.e. the averaged squared differences between successive averages performed over a given
 149 time interval as a function of the interval length.

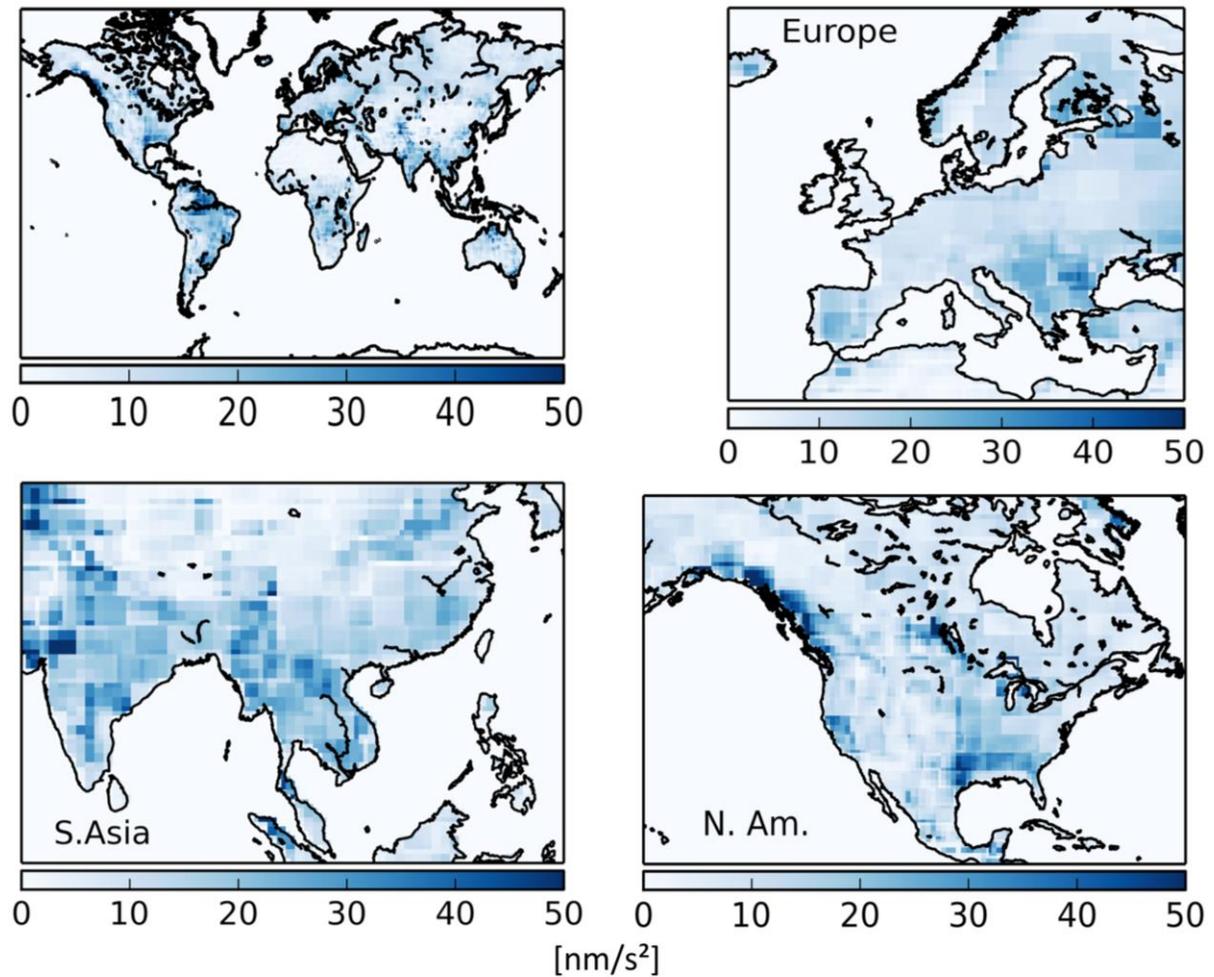
$$150 \quad \sigma_y^2(\tau) = \frac{1}{2} \langle (\bar{y}_{n+1,\tau} - \bar{y}_{n,\tau})^2 \rangle,$$

151 where the averages $\bar{y}_{n+1,\tau}$ are computed over the interval τ .

152 This statistics quantifies the impact of the timescale τ on the variability of the signal. This
153 was done on each grid cell everywhere on land but Antarctica and Greenland, for which there is
154 no solution of the JPL mascon.

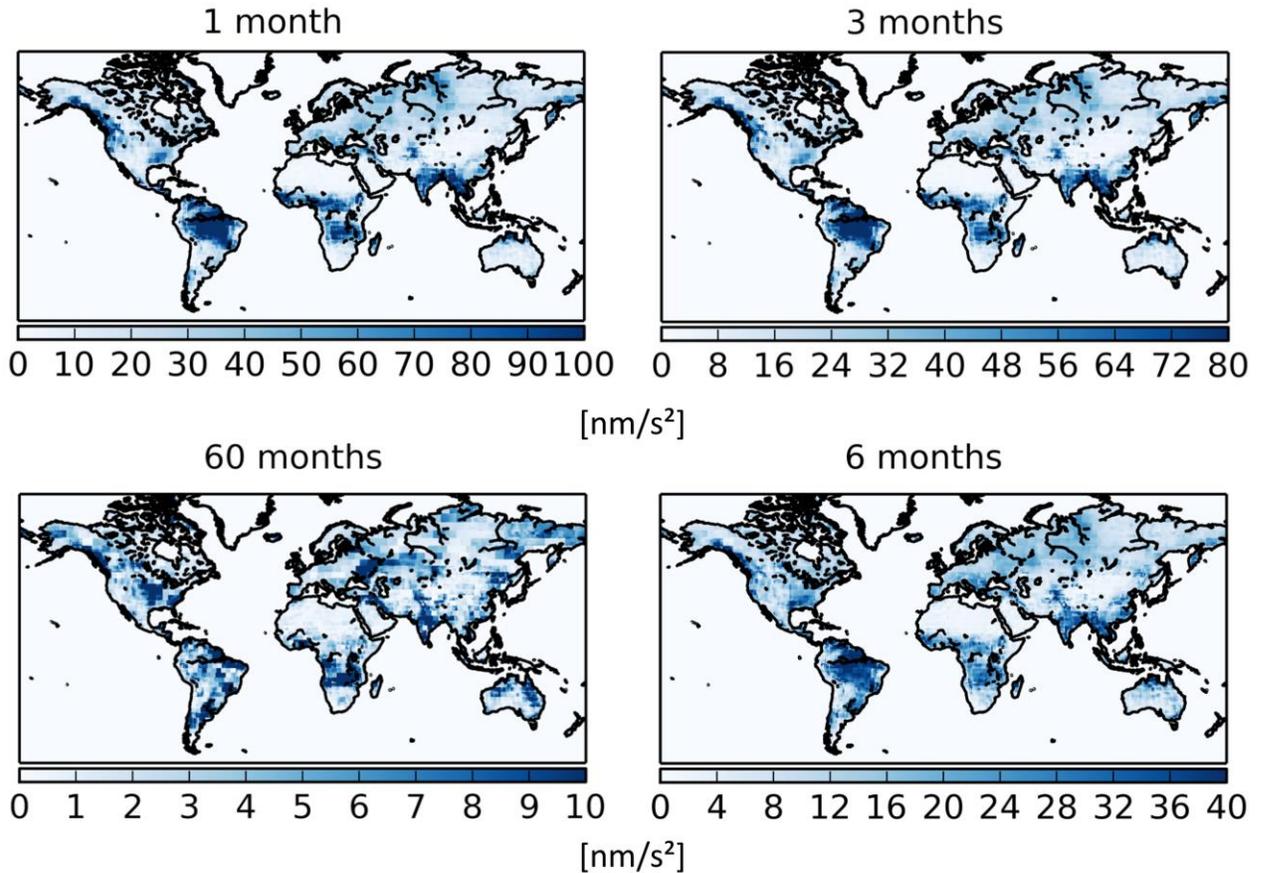
155 The Allan deviations of the gravity signature are calculated for time intervals of 12
156 months over three zones where several studies reporting on repeated AG measurements were
157 published (Figure 1): Northwestern Europe (Belgium and western Germany; *Van Camp* et al.
158 [2011], results extended to 2014 by the authors), Canada-Northern USA [*Lambert* et al., 2006;
159 2013a; 2013b; *Mazzotti* et al., 2011] and Southeast Asia (Tibet; *Sun* et al. [2009]; *Chen* et al.
160 [2016]). This is also done at time intervals of 1, 3, 6 and 60 months for the whole world (Figure
161 2). Note that the color scale has been saturated to allow a better visibility. In the supporting
162 information, Figures S1 show other zones not discussed in this paper: Central Asia, South
163 America, Africa and Oceania. Figure S2 provides the distributions shown on Figures 1 and S1.

164 The figures indicate that, in most of the cases, we can expect a standard deviation in the
165 range 10-25 nm/s² for measurements repeated once a year, due to interannual climate dynamics.
166 In other words, even when performing the measurements at the same moment every year, the
167 95% confidence interval for the interannual gravity variability, for example due to hydrological-
168 related surface load variations, is typically in the interval 20-50 nm/s².



169

170 **Figure 1.** Allan deviations of the hydrological effects on repeated gravity measurements, at the
 171 period of 12 months, which indicate the interannual variability in the whole world, Europe,
 172 Southeast Asia and North America. The hydrological effects are computed using GRACE
 173 observations, using the Bouguer conversion ratio of 4.2 nm/s^2 per cm of water. See Figures S1
 174 for South America, Central Asia, Africa and Oceania.



175

176 **Figure 2.** Allan deviations of the hydrological effects on repeated gravity measurements in the
 177 whole world, at periods of 1, 3, 6 and 60 months. The hydrological effects are computed using
 178 GRACE observations, using the Bouguer conversion ratio of 4.2 nm/s² per cm of water.

179 4.1 Northwestern Europe

180 In Northwestern Europe, Belgium and western Germany lie in a zone where GRACE
 181 indicates a 12-month Allan standard deviation of 7 nm/s². Adding up the AG setup noise, one
 182 obtains 17.5 nm/s². This uncertainty compares with the one deduced from our repeated AG
 183 measurements that provide standard deviations ranging 16-24 nm/s².

184 To better estimate this effect, as well as the influence of the number of repeated AG
 185 measurements on the trend estimate, we simulated yearly measurements performed 2, 3, 5 and 10

186 times, for durations of 2, 3, 5 and 10 years by randomly picking data from the GRACE mascon
187 solution.

188 To estimate the variability of the trend, we randomly pick 5,000,000 places in the area of
189 interest and starting dates (distributed from 30 days before to 30 days after October, 1); then we
190 compute the trend obtained from the GRACE models for those places. October 1st is chosen
191 because most of the yearly AG measurements relevant for this study are acquired around that
192 time of the year. Concurrently to the interannual mass variability effects, the instrumental setup
193 noise is taken into account by adding a normal random variable with a standard deviation of 16
194 nm/s². Table S1 provides a standard deviation averaged on the zones shown on Figures 1 and S1.

195 We also made similar simulations at the AG stations, for which we picked randomly
196 100,000 sets of N dates, around October 1st, distributed over D years ($N, D= 2, 3, 5$ and $10,$
197 $D \geq N$). For the resulting time series, we estimate the standard deviation of the GRACE time
198 series closest to the station. We end up with an average standard deviation of 1.5 ± 0.3 nm/s²/a
199 after 10 years of yearly measurements, which compares well with the actual average standard
200 deviation of 1.6 ± 1.4 nm/s²/a reported at the 9 AG stations (see Table 2 in *Van Camp et al.*
201 [2011]). Considering that GRACE does not represent precisely the space-time mass distribution
202 near the stations, and that the experimental setup is not exactly that reproduced in our test, we
203 consider that the results of this simulation are close enough to observation to be convincing and
204 to validate our approach.

205 Table S1 shows that, everywhere in the world, at least 5 AG measurements are needed
206 over a 10 year period to achieve an uncertainty smaller than 10 nm/s²/a at the one sigma level.
207 This becomes less than 5 nm/s²/a, provided one measurement is performed each year.

208 4.2 Canada, northern USA

209 In North America, the AG stations from the study of *Lambert et al.* [2013a; 2013b] and
210 *Mazzotti et al.* [2011] lie in a zone where GRACE indicates a 12-month Allan deviation ranging
211 5 nm/s^2 (Priddis, Alberta) to 37 nm/s^2 (Wausau, Wisconsin). Taking into account the AG setup
212 noise of 16 nm/s^2 , one obtains $28\text{-}40 \text{ nm/s}^2$, which compares with the uncertainties of yearly
213 repeated AG measurements that provide standard deviations ranging $25\text{-}37 \text{ nm/s}^2$ (digitized data
214 from the Figures 3a-3e in *Lambert et al.* [2005]). After 10 years, the uncertainties on the slopes
215 range $1\text{-}3 \text{ nm/s}^2/\text{a}$, which agrees with *Mazzotti et al.* [2011] reporting on uncertainties ranging 1-
216 $4 \text{ nm/s}^2/\text{a}$.

217 4.3 Southern Tibet

218 In southern Tibet, *Chen et al.* [2016] reported on gravity differences of -21 , 62 , 70 and
219 407 nm/s^2 , at 4 stations, based on measurements performed first in October 2010 or August
220 2011, and repeated once in July 2013. However, this zone experiences strong loading effects
221 from seasonal water storage changes and hydrological changes over the longer term [*Chanard et*
222 *al.*, 2015; *Hao et al.*, 2016; *Rodell et al.*, 2009]. The 12-months Allan standard deviations, which
223 indicate the interannual variability, are 26 , 17 , 17 , 21 nm/s^2 at Naqu, Lhasa, Shigatse and
224 Zhongba, respectively. There are large differences in monsoon rainfall between July-August
225 (about 120 mm of water per month in Lhasa) and October (10 mm of water per month), which
226 can induce additional hydrological effects at the 20 nm/s^2 level, according to the 1-month Allan
227 deviation. To account for this variability, another simulation of the uncertainty affecting the
228 slope estimate was performed. This includes the setup noise, considering 60 days before and
229 after October 1 (Table S2). We end up with standard deviations of 32 , 24 , 20 and $28 \text{ nm/s}^2/\text{a}$ at
230 Naqu, Lhasa, Shigatse and Zhongba, respectively. This is enough to account for the claimed
231 gravity changes at all stations but Shigatse.

232 Note that the monsoon effects can dramatically be amplified by local hydrogeological
233 effects such as floods in valleys, response of local aquifers, lakes, endorheic lakes and alluvial
234 plains; or mudflows, landslides and deposits, which may play an important role, especially in the
235 Tibetan rugged terrain. This cannot be observed directly by GRACE, and requires local
236 investigation, as done for example by *Mouyen et al.* [2013]. That paper reports on repeated AG
237 measurements in Taiwan where the observed gravity changes range -410 to $+2850$ nm/s^2 ,
238 induced by landslides and sediment accumulation triggered by a typhoon. Given the large AG
239 changes at Shigatse station do not coincide with any signal in the GRACE data, we believe, like
240 *Yi et al.* [2016] that it must reflect a local effect related either of hydrology or mass redistribution
241 by surface processes.

242 *Sun et al.* [2009] also reported repeated measurements in Tibet at three stations,
243 performed between 1990 and 2008 at the same epoch of the year: Lhasa (4 and 3 measurements
244 on two different points, -19.7 $\text{nm/s}^2/\text{a}$), Kunming (6 measurements, -14.2 $\text{nm/s}^2/\text{a}$) and Dali (10
245 measurements, -4.1 $\text{nm/s}^2/\text{a}$). Combining the hydrological effects and the setup noise, we obtain
246 uncertainties on the trend of 3, 9 and 2 $\text{nm/s}^2/\text{a}$, considering that measurements were made within
247 ± 30 days around October 1. Lhasa and, possibly, Dali may have experienced a gravity rate too
248 large (above the two-sigma level) to relate to climate dynamics. However, in these two studies in
249 Tibet, different instruments were used. *Chen et al.* [2016] made use of at least two different
250 absolute gravimeters (one FG5 and one A10), while *Sun et al.* [2009] used 5 different ones in
251 Lhasa, 2 in Kunming and 4 in Dali. This induces instrumental artefacts at a level that can reach
252 the observed signal: the reported differences affecting FG5 and JILAg instruments range up to
253 134 nm/s^2 , and up to 461 nm/s^2 for A10 gravimeters. In particular, *Francis et al.* [1995] report on
254 results from JILAg 3 and 5 instruments used by *Sun et al.* [2009]: difference of about 100 nm/s^2

255 is observed between the two instruments, and unrealistic trends in Brussels (300 nm/s² in 6
256 years) and Membach (eastern Belgium, 100 nm/s² in 3 years) could never be confirmed later on
257 [Van Camp *et al.*, 2011]. Hence, the tectonic interpretations of Sun *et al.* [2009] and Chen *et al.*
258 [2016] are questionable in our opinion, especially when the still experimental JILAg and early
259 FG5 instruments are taken into account. A detailed discussion on the offsets and uncertainties of
260 JILAg and early FG5 gravimeters are given by Palinkas *et al.* [2012]. Moreover, in Lhasa, the
261 trend is the average of two trends recorded at two different places, 800 m apart. Differences in
262 the gravity response to local hydrogeological effects at sites only 40 meters apart have been
263 reported to be as large as 100 nm/s² within a few months [Mikolaj *et al.*, 2015]. Hence, averaging
264 two trends, including one determined on only three measurements, is questionable.

265 4.4 Other zones

266 As shown by the Tables S1 and S2, in most of the cases, one needs at least 5 repeated AG
267 measurements during 10 years to achieve an uncertainty on the determination of a trend lower
268 than 10 nm/s²/a, at the one-sigma level. This decreases down to 3-4 nm/s² if the 10 yearly
269 measurements are performed. On the other hand, it is hopeless to achieve a precision better than
270 20 nm/s²/a, if only 3 measurements are performed during 3 years. Given that measurements are
271 usually not performed at exactly the same date of the year, degrees of freedom of +/-30 and +/-
272 60 days were taken into account. The 60 days cases are slightly noisier, but the increase remains
273 under the 10% level. However, those GRACE-inferred estimates represent average values in the
274 geographic zones shown on Figures 1 and S1. They do not represent local phenomena, where
275 hydrogeological effects may affect gravity at the 100-150 nm/s² level, sometimes within a few
276 hours [Van Camp *et al.*, 2006b; Meurers *et al.*, 2007]. Our results can thus be considered as a
277 lower bound of the climate-induced mass transfer uncertainty.

278 **5 Conclusions**

279 The ground water content inferred from GRACE mascon JPL solutions was used to
280 estimate the time variations of hydrological signals in repeated absolute gravity measurements.
281 This was done everywhere in the world, and the results are discussed in three zones where papers
282 report on repeated AG measurements: Northwestern Europe, Canada and Tibet. Taking into
283 account the instrumental setup noise, different time intervals (2, 3, 5, 10 years) and different
284 numbers of AG campaigns (2, 3, 5, 10), we estimate uncertainties affecting the determination of
285 a linear gravity rate of change. For 10 yearly campaigns, performed during the same epoch of the
286 year, an average uncertainty ranging 3-4 nm/s²/a can be achieved in most of the cases, in the
287 absence of instrumental artefacts and of strong local hydrogeological effects.

288 The results are consistent with the amplitude of observed gravity changes on long term
289 repeated campaigns, provided the measurement were performed with the same instrument. This
290 allows extrapolating our simulation at different locations in the world. They invite care regarding
291 the interpretation of results from short campaigns, and even more so in area prone to fluctuations
292 of hydrology and mass redistribution by surface processes. Poor calibration of the gravimeters
293 may dramatically affect this result. We draw attention on the possible offsets which can
294 significantly influence the repeated AG measurements when different instruments are used.
295 Finally, in this study, a linear trend was removed from the GRACE time series. Separating trends
296 induced by long term climate change effects from tectonic signals is a difficult issue not
297 addressed in this study.

298 **Acknowledgments and Data**

299 The data used in the references, tables and supplements and repository at
300 [http://podaac.jpl.nasa.gov/dataset/TELLUS GRACE MASCON CRI GRID RL05 V1](http://podaac.jpl.nasa.gov/dataset/TELLUS_GRACE_MASCON_CRI_GRID_RL05_V1). We
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305 **References**

- 306 Allan, D. W. (1966), The statistics of atomic frequency standards, *Proc. IEEE*, 54(2), 221–230.
- 307 Bettinelli, P., J. P. Avouac, M. Flouzat, L. Bollinger, G. Ramillien, S. Rajaure, and S. Sapkota
308 (2008), Seasonal variations of seismicity and geodetic strain in the Himalaya induced by
309 surface hydrology, *Earth Planet. Sci. Lett.*, 266(3-4), 332-344.
- 310 Blewitt, G., D. Lavalee, P. Clarke, and K. Nurutdinov (2001), A new global mode of Earth
311 deformation: Seasonal cycle detected, *Science*, 294(5550), 2342-2345.
- 312 Chanard, K., J. P. Avouac, G. Ramillien, and J. Genrich (2014), Modeling deformation induced
313 by seasonal variations of continental water in the Himalaya region: Sensitivity to Earth
314 elastic structure, *J. Geophys. Res. Solid Earth*, 119, doi:10.1002/2013JB010451.
- 315 Chen, S., M. Liu, L. Xing, W. Xu, W. Wang, Y. Zhu, and H. Li (2016), Gravity increase before
316 the 2015 Mw 7.8 Nepal earthquake, *Geophys. Res. Lett.*, 43,
317 doi:10.1002/2015GL066595.

- 318 Creutzfeldt, B., A. Güntner, T. Klügel, and H. Wziontek (2008), Simulating the influence of
 319 water storage changes on the superconducting gravimeter of the Geodetic Observatory
 320 Wettzell, Germany, *Geophysics*, 73(6), doi: 10.1190/1.2992508.
- 321 Creutzfeldt, B., A. Güntner, H. Thoss, B. Merz, and H. Wziontek (2010a), Measuring the effect
 322 of local water storage changes on in situ gravity observations: Case study of the Geodetic
 323 Observatory Wettzell, Germany, *Water Resour. Res.*, 46, W08531,
 324 doi:10.1029/2009WR008359.
- 325 Creutzfeldt, B., A. Güntner, H. Wziontek, and B. Merz (2010b), Reducing local hydrology from
 326 high-precision gravity measurements: a lysimeter-based approach, *Geophys. J. Int.*, 183
 327 (1): 178-187. doi: 10.1111/j.1365-246X.2010.04742.x.
- 328 Djamour, Y., P. Vernant, R. Bayer, H. R. Nankali, J.-F. Ritz, J. Hinderer, Y. Hatam, B. Luck, N.
 329 Le Moigne, M. Sedighi, and F. Khorrami (2010), GPS and gravity constraints on
 330 continental deformation in the Alborz mountain range, Iran, *Geophys. J. Int.*, doi:
 331 10.1111/j.1365-246X.2010.04811.x.
- 332 Francis, O., B. Ducarme, F. De Meyer, and J. Mäkinen (1995), Present stage of absolute gravity
 333 measurements in Brussels and comparison with the superconducting gravimeter drift, in
 334 Proceedings of the Workshop: Non tidal gravity changes: intercomparison between
 335 absolute and superconducting gravimeters, September 6– 8, 1994, Walferdange, Grand-
 336 Duchy of Luxembourg, *Cah. Cent. Eur. Géodyn. Séismol.*, vol. 11, edited by C. Poitevin,
 337 pp. 117–123, Cent. Eur. de Géodyn. et de Séismol., Luxembourg.
- 338 Francis, O., et al. (2005), Results of the International Comparison of Absolute Gravimeters in
 339 Walferdange (Luxembourg) of November 2003, in *International Association of Geodesy*

- 340 *Symposia Gravity, Geoid and Space Missions GGSM 2004*, Vol. 129 Jekeli, Christopher;
 341 Bastos, Luisa; Fernandes, Joana (Eds.), XVI, 368 p, Springer-Verlag, pp272-275.
- 342 Francis, O., et al. (2010), Results of the European Comparison of Absolute Gravimeters in
 343 Walferdange (Luxembourg) of November 2007, in *Gravity, Geoid and Space Missions*,
 344 *International Association of Geodesy Symposia*, Vol. 135(1), edited by S. P. Mertikas,
 345 pp. 31–36, doi:10.1007/978-3-642-10634-7_5, Springer, Berlin.
- 346 Francis, O., et al. (2013), The European Comparison of Absolute Gravimeters 2011 (ECAG-
 347 2011) in Walferdange, Luxembourg: results and recommendations, *Metrologia*, 50,
 348 (2013) 257–268, doi:10.1088/0026-1394/50/3/257.
- 349 Francis, O., et al. (2015), CCM.G-K2 key comparison, *Metrologia*, 52 07009, doi:
 350 10.1088/0026-1394/52/1A/07009.
- 351 Hao, M., J. T. Freymueller, Q. Wang, D. Cui, and S. Qin (2016), Vertical crustal movement
 352 around the southeastern Tibetan Plateau constrained by GPS and GRACE data, *Earth*
 353 *Planet. Sci. Lett.*, 437, 1-8.
- 354 Jiang, Z., et al. (2011), Final report on the Seventh International Comparison of Absolute
 355 Gravimeters (ICAG 2005), *Metrologia*, 48,, 246-260, doi: 10.1088/0026-1394/48/5/003.
- 356 Jiang, Z., et al. (2012), The 8th International Comparison of Absolute Gravimeters 2009: the first
 357 Key Comparison (CCM.G-K1) in the field of absolute gravimetry, *Metrologia*, 49(6),
 358 doi: doi:10.1088/0026-1394/49/6/666.
- 359 Jacob, T., R. Bayer, J. Chery, H. Jourde, N. L. Moigne, J.-P. Boy, J. Hinderer, B. Luck, and P.
 360 Brunet (2008), Absolute gravity monitoring of water storage variation in a karst aquifer

361 on the larzac plateau (Southern France), *J. Hydrol.*, 359(1–2), 105–117,
362 doi:10.1016/j.jhydrol.2008.06.020.

363 Lambert, A., N. Courtier, and T.S. James (2006), Long-term monitoring by absolute gravimetry:
364 tides to postglacial rebound, *J. Geodyn.*, 41(1-3), 307–317,
365 doi:10.1016/j.jog.2005.08.032.

366 Lambert, A., J. Huang, G. van der Kamp, J. Henton, S. Mazzotti, T. S. James, N. Courtier, and
367 A. G. Barr (2013a), Measuring water accumulation rates using GRACE data in areas
368 experiencing glacial isostatic adjustment: The Nelson River basin, *Geophys. Res. Lett.*,
369 40, 6118–6122, doi:10.1002/2013GL057973.

370 Lambert, A., J. Henton, S. Mazzotti, J. Huang, T.S. James, N. Courtier, and G. van der Kamp
371 (2013b), Postglacial Rebound and Total Water Storage Variations in the Nelson River
372 Drainage Basin: A Gravity-GPS Study, *Geol. Surv. Can. Open File*, OF 7317, 21 pp.

373 Lampitelli, C., and O. Francis (2010), Hydrological effects on gravity and correlations between
374 gravitational variations and level of the Alzette River at the station of Walferdange,
375 Luxembourg. *J. Geodyn.*, 49, 31–38.

376 Mazzotti, S., A. Lambert, N. Courtier, L. Nykolaishen, and H. Dragert (2007), Crustal uplift and
377 sea level rise in northern Cascadia from GPS, absolute gravity, and tide gauge data,
378 *Geophys. Res. Lett.*, 34, L15306, doi:10.1029/2007GL030283.

379 Mazzotti, S., A. Lambert, J. Henton, T. S. James, and N. Courtier (2011), Absolute gravity
380 calibration of GPS velocities and glacial isostatic adjustment in mid-continent North
381 America, *Geophys. Res. Lett.*, 38, L24311, doi: 10.1029/2011GL049846.

- 382 Mémin, A., Y. Rogister, J. Hinderer, O.C. Omang, and B. Luck (2011), Secular gravity variation
 383 at Svalbard (Norway) from ground observations and GRACE satellite data. *Geophys. J.*
 384 *Int.*, 184: 1119–1130. doi: 10.1111/j.1365-246X.2010.04922.x
- 385 Meurers, B., M. Van Camp, and T. Petermans (2007), Correcting superconducting gravity time-
 386 series using rainfall modeling at the Vienna and Membach stations and application to
 387 Earth tide analysis, *J. Geod.*, 81(11), doi:10.1007/s00190-007-0137-1.
- 388 Mikolaj, M., A. Güntner, M. Reich, S. Schröder, and H. Wziontek (2015), Portable
 389 superconducting gravimeter in a field enclosure: first experiences and results, in
 390 Proceedings of the Workshop: Hydrology, Geophysics and Geodesy – HG² A new way to
 391 manage water resources, October 23, 2015, Brussels, edited by M. Van Camp and M.
 392 Vanclooster, pp. 33-55.
- 393 Mouyen, M., F. Masson, C. Hwang, C.-C. Cheng, N. Le Moigne, C.-W. Lee, R. Kao, and W.-C.
 394 Hsieh (2013), Erosion effects assessed by repeated gravity measurements in southern
 395 Taiwan, *Geophys. J. Int.*, 192(1), 113-136. doi: 10.1093/gji/ggs019.
- 396 Mouyen, M., M. Simoes, F. Mouthereau, F. Masson, C. Hwang, and C.-C. Cheng (2014),
 397 Investigating possible gravity change rates expected from long-term deep crustal
 398 processes in Taiwan, *Geophys. J. Int.*, 198(1): 187-197. doi: 10.1093/gji/ggu133.
- 399 Nicolas, J., J.-M. Nocquet, M. Van Camp, T. Van Dam, J.-P. Boy, J. Hinderer, P. Gegout, E.
 400 Calais, M. Amalvict, and E. Calais (2006), Seasonal effect on vertical positioning by
 401 satellite laser ranging and global positioning system and on absolute gravity at the OCA
 402 geodetic station, Grasse, France, *Geophys. J. Int.*, 167, 1127–1137.

- 403 [Niebauer, T., G. Sasagawa, J. Faller, R. Hilt, and F. Klopping \(1995\), A new generation of](#)
404 [absolute gravimeters, *Metrologia*, 32, 159–180, doi:10.1088/0026-1394/32/3/004.](#)
- 405 Palinkas, V., et al. (2012), Analysis of the repeated absolute gravity measurements in the Czech
406 Republic, Slovakia and Hungary from the period 1991–2010 considering instrumental
407 and hydrological effects, *J. Geod.*, doi: 10.1007/s00190-012-0576-1.
- 408 [Ramillien, G., A. Cazenave, and O. Brunau \(2004\), Global time variations of hydrological](#)
409 [signals from GRACE satellite gravimetry, *Geophys. J. Int.*, 158\(3\), 813-826.](#)
- 410 Rodell, M., et al. (2004), The global land data assimilation system, *Bull. Am. Meteorol. Soc.*, 85,
411 381–394.
- 412 [Rodell, M., I. Velicogna, and J. S. Famiglietti \(2009\), Satellite-based estimates of groundwater](#)
413 [depletion in India, *Nature*, 460\(7258\), 999-1002, doi: 10.1038/nature08238.](#)
- 414 Sato, T., S. Miura, W. Sun, T. Sugano, J. T. Freymueller, C. F. Larsen, Y. Ohta, H. Fujimoto, D.
415 Inazu, and R. J. Motyka (2012), Gravity and uplift rates observed in southeast Alaska and
416 their comparison with GIA model predictions, *J. Geophys. Res.*, 117, B01401,
417 doi:10.1029/2011JB008485.
- 418 [Sato, T., J. Okuno, J. Hinderer, D.S. MacMillan, H.P. Plag, O. Francis, R. Falk, and Fukuda Y.](#)
419 [\(2006\), A geophysical interpretation of the secular displacement and gravity rates](#)
420 [observed at Ny-Alesund, Svalbard in the Arctic-effects of post-glacial rebound and](#)
421 [present-day ice melting, *Geophys. J. Int.*, 165, 729–743, doi: 10.1111/j.1365-](#)
422 [246X.2006.02992.x.](#)
- 423 [Santamaría-Gómez, A., and Mémin A. \(2015\), Geodetic secular velocity errors due to](#)
424 [interannual surface loading deformation, *Geophys. J. Int.*, 202, doi: 10.1093/gji/ggv190.](#)

- 425 Schmerge, D., et al. (2012), Results of the first North American comparison of absolute
426 gravimeters, NACAG-2010, *J. Geod.*, 86, doi: 10.1007/s00190-011-0539-y.
- 427 Steffen, H., O. Gitlein, H. Denker, J. Müller, and L. Timmen (2009), Present rate of uplift in
428 Fennoscandia from GRACE and absolute gravimetry, *Tectonophysics*, 474(1-2), 69–77,
429 doi:10.1016/j.tecto.2009.01.012.
- 430 Sun, W., Q. Wang, H. Li, Y. Wang, S. Okubo, D. Shao, D. Liu, and G. Fu (2009), Gravity and
431 GPS measurements reveal mass loss beneath the Tibetan Plateau: Geodetic evidence of
432 increasing crustal thickness, *Geophys. Res. Lett.*, 36, L02303,
433 doi:10.1029/2008GL036512.
- 434 Uppala, S.M., et al. (2005), The ERA-40 re-analysis, *Q. J. R. Meteorol. Soc.*, 131, 2961–3012.
- 435 Van Camp, M., S. D. P. Williams, and O. Francis (2005), Uncertainty of absolute gravity
436 measurements, *J. Geophys. Res.*, 110, B05406, doi:10.1029/2004JB003497.
- 437 Van Camp, M., M. Vanclooster, O. Crommen, T. Petermans, K. Verbeeck, B. Meurers, T. van
438 Dam, and A. Dassargues (2006a), Hydrogeological investigations at the Membach
439 station, Belgium, and application to correct long periodic gravity variations, *J. Geophys.*
440 *Res.*, 111, B10403, doi:10.1029/2006JB004405.
- 441 Van Camp, M., P. Meus, Y. Quinif, O. Kaufmann, M. vanRuymbeke, M. Vandiepenbeck, and T.
442 Camelbeeck (2006b), Karst aquifer investigation using absolute gravity, *Eos Trans. AGU*,
443 87(30), 298–298, doi:10.1029/2006EO300005.
- 444 Van Camp, M., L. Métivier, O. de Viron, B. Meurers, and S. D. P. Williams (2010),
445 Characterizing long-time scale hydrological effects on gravity for improved distinction of
446 tectonic signals, *J. Geophys. Res.*, 115, B07407, doi:10.1029/2009JB006615.

- 447 Van Camp, M., O. de Viron, H.-G. Scherneck, K.-G. Hinzen, S. D. P. Williams, T. Lecocq, Y.
448 Quinif, and T. Camelbeeck (2011), Repeated absolute gravity measurements for
449 monitoring slow intraplate vertical deformation in western Europe, *J. Geophys. Res.*, *116*,
450 B08402, doi:10.1029/2010JB008174.
- 451 [Van Camp, M., O. de Viron, and R.J. Warburton \(2013\), Improving the determination of the](#)
452 [gravity rate of change by combining superconducting with absolute gravimeter data,](#)
453 [Comput. Geosci.](#), *51*, 49-55, doi: 10.1016/j.cageo.2012.07.029.
- 454 [Van Camp M., O. de Viron, L. Métivier, B. Meurers, and O. Francis \(2014\), The quest for a](#)
455 [consistent signal in ground and GRACE gravity time series, Geophys. J. Int.](#), doi:
456 [10.1093/gji/ggt524.](#)
- 457 van Dam, T., J. Wahr, P. C. D. Milly, A. B. Shmakin, G. Blewitt, D. Lavalée, and K. M. Larson
458 (2001), Crustal displacements due to continental water loading, *Geophys. Res. Lett.*,
459 28(4), 651-654.
- 460 Vitushkin, L., et al. (2002), Results of the Sixth International Comparison of Absolute
461 Gravimeters ICAG-2001, *Metrologia*, *39*, 407–424, doi:10.1088/0026-1394/39/5/2.
- 462 [Watkins, M. M., D. N. Wiese, D.-N. Yuan, C. Boening, and F. W. Landerer \(2015\), Improved](#)
463 [methods for observing Earth's time variable mass distribution with GRACE using](#)
464 [spherical cap mascons, J. Geophys. Res. Solid Earth](#), *120*, 2648–2671,
465 [doi:10.1002/2014JB011547.](#)
- 466 Wiese D.N, D.-N. Yuan, C. Boening, F. W. Landerer, and M. M. Watkins (2015), JPL GRACE
467 Mascon Ocean, Ice, and Hydrology Equivalent Water Height RL05M.1 CRI Filtered,

468 Ver. 1. PO.DAAC, CA, USA. Dataset accessed [2016-01-15] at
469 <http://dx.doi.org/10.5067/TEMSC-OLCR5>.

470 Wouters, B., Bonin, J. A., Chambers, D. P., Riva, R. E. M., Sasgen, I., and Wahr, J. (2014),
471 GRACE, time-varying gravity, Earth system dynamics and climate change. *Rep. Prog.*
472 *Phys.*, 77(11):116801, doi:10.1088/0034-4885/77/11/116801.

473 Yi, S., Q. Wang, and W. Sun (2016), Is it possible that a gravity increase of $20 \mu\text{Gal yr}^{-1}$ in
474 southern Tibet comes from a wide-range density increase?, *Geophys. Res. Lett.*, 43,
475 doi:10.1002/2015GL067509.

476 Zerbini, S., B. Richter, F. Rocca, T. van Dam, and F. Matonti (2007), A Combination of Space
477 and Terrestrial Geodetic Techniques to Monitor Land Subsidence: Case Study, the
478 Southeastern Po Plain, Italy, *J. Geophys. Res.*, 112, B05401, doi:10.1029/2006JB004338.

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[Geophysical Research Letters]

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Supporting Information for

483 [

484 **Separating climate-induced mass transfers and instrumental effects from tectonic**

485 **signal in repeated absolute gravity measurements**

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487

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492 **Contents of this file**

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499 N/A

500 **Introduction**

501

- This supporting information contains maps of zones which are not directly discussed in the main paper: South America, Central Asia, Africa and Oceania. Figure S2 provides the distributions shown on Figures 1 and S1. The tables S1 and S2 provide detailed uncertainties on the determination of the gravity rate of change as a function of the geographic area, the duration of the measurements and the number of measurements.

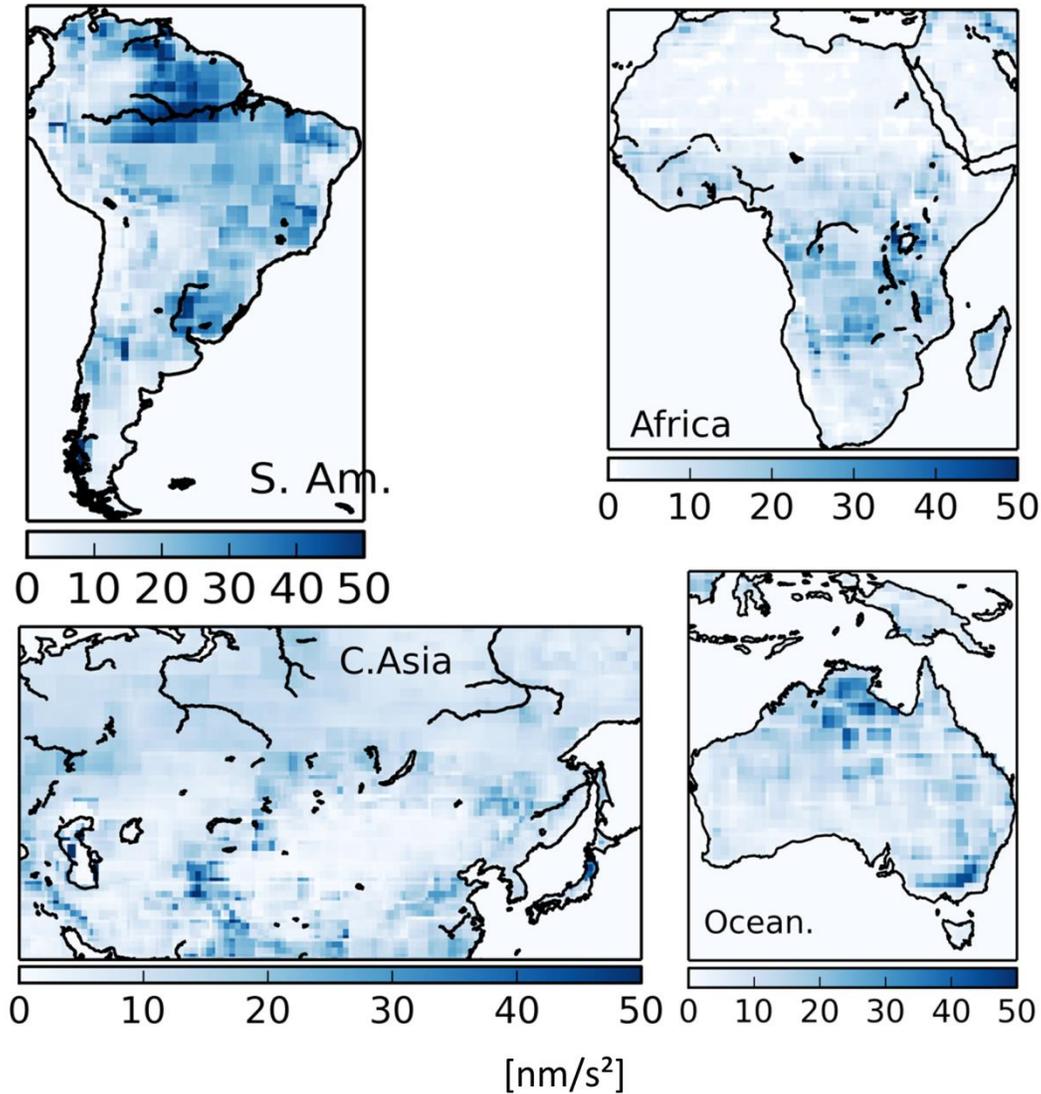
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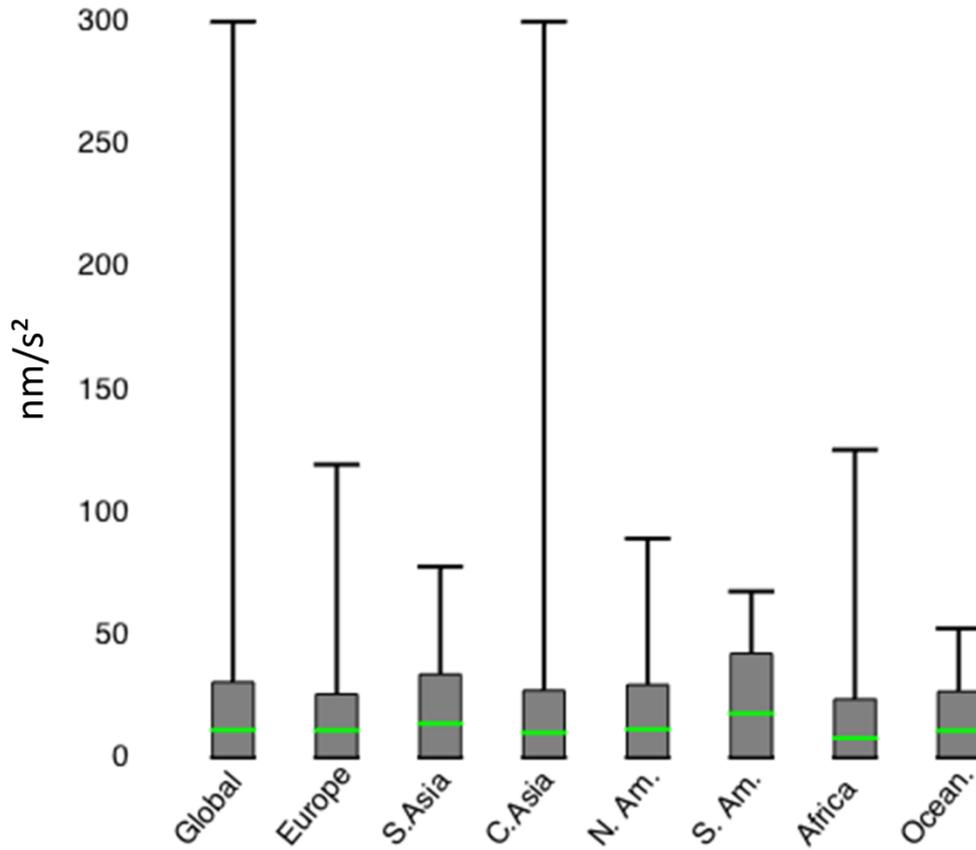
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508 **Figure S1.** Allan deviations of the hydrological effects on repeated gravity measurements, at the
 509 period of 12 months, in South America, Africa, Central Asia and Oceania. The hydrological
 510 effects are computed using GRACE observations, using the Bouguer conversion ratio of 4.2
 511 nm/s^2 per cm of water.



512

513 **Figure S2.** Box and whisker plots of the Allan standard deviations shown on Figures 1 and S1:

514 green line: median (it is indistinguishable from the average); grey boxes: 95% confidence

515 interval; whisker: upper and lower values. Scale in nm/s^2 . Most of the values are under the 50

516 nm/s^2 level.

D Duration (years)	N Number of measurements			
World	2	3	5	10
10	18	9	5	3
5	24	13	9	-
3	30	18	-	-
2	34	-	-	-
Europe				
10	23	9	5	3
5	24	13	9	-
3	30	19	-	-
2	33	-	-	-
Southeast Asia				
10	27	12	7	4
5	34	19	12	-
3	44	26	-	-
2	50	-	-	-
North America				
10	21	10	5	3
5	28	16	11	-
3	35	22	-	-
2	40	-	-	-
South America				
10	21	10	6	4
5	27	14	10	-
3	34	20	-	-
2	40	-	-	-
Central Asia				
10	20	9	5	3
5	26	14	9	-
3	34	20	-	-
2	39	-	-	-
Africa				
10	19	9	5	3
5	25	14	10	-
3	31	18	-	-
2	35	-	-	-
Oceania				
10	18	9	5	3
5	23	13	9	-
3	30	18	-	-
2	33	-	-	-

517 **Table S1.** Standard deviation (in $\text{nm/s}^2/\text{a}$) of a linear trend due to the hydrological effects as
518 inferred from GRACE, on repeated gravity measurements, performed 2, 3, 5 and 10 times.
519 When relevant, the simulation is done for durations of 2, 3, 5 and 10 years. The standard
520 deviation is obtained by averaging the standard deviations of GRACE observed at all the data

521 points of the selected area, and repeated to sum up to 5 000 000 simulated experiment on the
522 areas shown on Figures 1 and S1. As the gravity measurements cannot be performed exactly at
523 the same day of the year, the simulations allow the measurements to happen randomly from 30
524 before to 30 days after October, 1. In all case an instrumental setup noise of 16 nm/s^2 is
525 included.
526

D Duration (years)	N Number of measurements			
World	2	3	5	10
10	18	9	5	3
5	24	14	9	-
3	30	18	-	-
2	34	-	-	-
Europe				
10	18	9	5	3
5	24	14	9	-
3	30	19	-	-
2	34	-	-	-
Southeast Asia				
10	29	14	7	4
5	38	21	14	-
3	49	29	-	-
2	56	-	-	-
North America				
10	22	10	5	3
5	29	17	11	-
3	35	21	-	-
2	41	-	-	-
South America				
10	21	10	6	4
5	28	16	10	-
3	35	21	-	-
2	41	-	-	-
Central Asia				
10	21	10	5	3
5	28	16	10	-
3	36	21	-	-
2	43	-	-	-
Africa				
10	21	10	5	3
5	27	16	11	-
3	34	20	-	-
2	40	-	-	-
Oceania				
10	18	9	5	3
5	23	14	9	-
3	30	18	-	-
2	34	-	-	-

527 **Table S2.** Same as Table S1 but allowing the measurements to be performed up to 60 days
528 before and after October 1.