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Key Points:
- The signature of climate-induced interannual mass transfers on repeated absolute gravity measurements is estimated everywhere in the world
- Instrumental artifacts should be taken into account and mitigated as much as possible
- In most cases, the uncertainty is estimated to ~5 nm/s²/a after 10 yearly campaigns

Supporting Information:
- Supporting Information S1
- Figure S1
- Figure S2

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

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Abstract We estimate the signature of the climate-induced mass transfers in repeated absolute gravity measurements based on satellite gravimetric measurements from the Gravity Recovery and Climate Experiment (GRACE) mission. We show results at the globe scale and compare them with repeated absolute gravity (AG) time behavior in three zones where AG surveys have been published: Northwestern Europe, Canada, and Tibet. For 10 yearly campaigns, the uncertainties affecting the determination of a linear gravity rate of change range 3–4 nm/s^2/a in most cases, in the absence of instrumental artifacts. The results are consistent with what is observed for long-term repeated campaigns. We also discuss the possible artifact that can result from using short AG survey to determine the tectonic effects in a zone of high hydrological variability. We call into question the tectonic interpretation of several gravity changes reported from stations in Tibet, in particular the variation observed prior to the 2015 Gorkha earthquake.

1. Introduction

Absolute gravimeters (AG), by construction, suffer no time drift; this makes them most appropriate to measure long-term surface gravity changes, which might reflect either vertical ground motion or mass redistribution. AGs have, for example, been used to monitor slow vertical ground displacements [*Mazzotti et al.*, 2007; *Djamour et al.*, 2010; *Van Camp et al.*, 2011; *Zerbini et al.*, 2007] and Glacial Isostatic Adjustment [*Lambert et al.*, 2006; *Steffen et al.*, 2009; *Mazzotti et al.*, 2011; *Sato et al.*, 2012]. It has also been used to study mass redistribution by erosion [*Mouyen et al.*, 2013] and crustal tectonics [*Mouyen et al.*, 2014]. Intriguing measurements of gravity changes in Tibet have been recently reported: *Sun et al.* [2009] found evidences for a gravity decrease at three stations, which they interpreted as the signature from a long-term thickening of the Tibetan plateau, and *Chen et al.* [2016] reported a gravity increase, which they attribute to preseismic processes associated to the 2015, M_w 7.8 Gorkha earthquake. Such tectonic interpretation should be considered with caution in view of the possible effect of nontectonic causes, in particular surface hydrology, on absolute gravity measurements and instrumental artifacts. *Yi et al.* [2016] showed that the signal observed prior to the Gorkha earthquake by *Chen et al.* [2016] is most probably due to a local hydrological effect unrelated to the earthquake itself.

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

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

2. Instrumental Artifacts

When different AGs are used in the same study, interinstrument differences should be taken into account, as done, for example, by *Lambert et al.* [2006, 2013b], or included in the uncertainty budget [*Sato et al.*, 2006; *Mémin et al.*, 2011; *Palinkas et al.*, 2012]. Intercomparison campaigns [e.g., *Francis et al.*, 2005, 2010, 2013, 2015; *Jiang et al.*, 2012; *Schmerge et al.*, 2012; *Vitushkin et al.*, 2002] showed that differences between FG5 and JILAg gravimeters are commonly of the order of 100–150 nm/s^2. A difference as large as 461 nm/s^2 was reported for one of the A10 instruments that participated in the ICAG-2001 intercomparison [*Vitushkin et al.*, 2002]. In other comparisons, systematic and random errors of A10 gravimeters ranged between 70 and 220 nm/s^2 [*Jiang et al.*, 2011; *Francis et al.*, 2005, 2013, 2015].

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

3. Separating Hydrological Effects From Tectonic Signal

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

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

Separation of the causes of temporal variations of AG measurements and precise correction of hydrogeological effects is thus not possible in most cases. Based on the spectral content of modeled hydrogeological effects and of SG time series, *Van Camp et al.* [2010] investigated the hydrological effects on repeated gravity measurements. They showed that the time required to measure a gravity rate of change of 1 nm/s^2/a at the 1σ level was of the order of 10 years but highly dependent on the location, assuming continuous, hourly sampled gravity time series at the existing SG stations. In case of repeated absolute gravity measurements, the continuity of measurements is broken, and the setup noise must be taken into account. Presently, the easiest and only practical way to mitigate hydrological effects in AG measurements is to perform measurements at the same epoch of the year—the impact of seasonal variations is then minimized, and for a sufficiently long time period, interannual variations average out. This procedure is only approximate due to long-term variability of the hydrological signal and to the possible long-term drift of groundwater storage. The addition of superconducting gravimeter (SG) information mitigates the error in the estimation of gravity rates of change caused by the presence of long period, interannual, and annual signals in the AG data [*Van Camp et al.*, 2013], but this remains unpractical. However, global models, as GRACE or GLDAS, can meaningfully be used to investigate the spatiotemporal behavior of the hydrological signal and gather information about the possible magnitude of the hydrological signature.

Since 2002, GRACE has provided long enough time series to be used as in the study of *Van Camp et al*. [2010]. Unlike most of the global hydrological model, GRACE integrates the whole groundwater content, from the saturated and unsaturated zones, producing a reliable tool to estimate water storage changes. Hence, keeping in mind that the local effects can significantly modify the water storage change signal both in phase and amplitude [*Van Camp et al.*, 2014], GRACE can be used as a proxy in order to estimate the space-time variability of water storage changes in different climatic and hydrogeological contexts on repeated gravity measurements. This is done below by simulating repeated AG measurements performed once a year.

4. Space-Time Variability of Hydrological Effects on Surface Gravity Measurements

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

In this study, we only consider the Newtonian effects on the AG measurements. The deformation effect caused by the surface mass loading can be corrected using Global Navigation Satellite System (GNSS) observations [*Zerbini et al.*, 2007] and, after 5 years, is at the mm/a level [*Santamaría-Gómez and Mémin*, 2015], equivalent to 3 nm/s^2/a.

The equivalent water height is converted into gravity signal, in nm/s^2, using the Bouguer factor of 4.2 nm/s^2 for 1 cm of water height equivalent, which has been shown to be an excellent approximation [*Creutzfeldt et al.*, 2008]. Then, we computed the Allan standard deviation [*Allan*, 1966], i.e., the averaged squared differences between successive averages performed over a given time interval as a function of the interval length.

$$\sigma_y^2(\tau) = \frac{1}{2}\left\langle \left(\overline{y}_{n+1,\tau} - \overline{y}_{n,\tau}\right)^2 \right\rangle,$$

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

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

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

The figures indicate that in most of the cases, we can expect a standard deviation in the range 10–25 nm/s^2 for measurements repeated once a year, due to interannual climate dynamics. In other words, even when performing the measurements at the same moment every year, the 95% confidence interval for the interannual gravity variability, for example, due to hydrological-related surface load variations, is typically in the interval 20–50 nm/s^2.

4.1. Northwestern Europe

In Northwestern Europe, Belgium and western Germany lie in a zone where GRACE indicates a 12 month Allan standard deviation of 7 nm/s^2. Adding up the AG setup noise, one obtains 17.5 nm/s^2. This uncertainty compares with the one deduced from our repeated AG measurements that provide standard deviations ranging 16–24 nm/s^2.

To better estimate this effect, as well as the influence of the number of repeated AG measurements on the trend estimate, we simulated yearly measurements performed 2, 3, 5, and 10 times, for durations of 2, 3, 5, and 10 years by randomly picking data from the GRACE mascon solution.

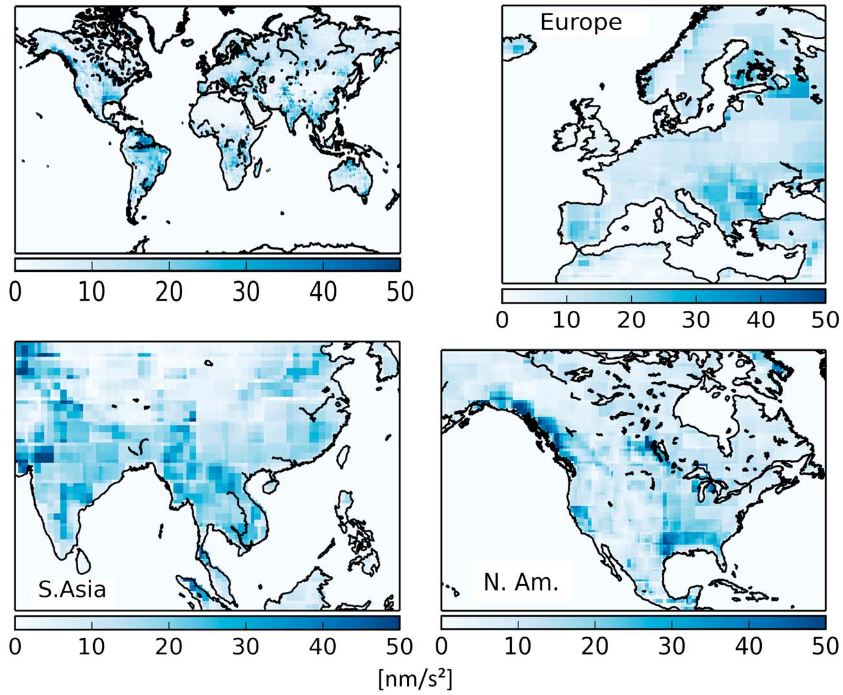

Figure 1. Allan deviations of the hydrological effects on repeated gravity measurements, at the period of 12 months, which indicate the interannual variability in the whole world, Europe, Southeast Asia, and North America. The hydrological effects are computed using GRACE observations and using the Bouguer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

To estimate the variability of the trend, we randomly pick 5,000,000 places in the area of interest and starting dates (distributed from 30 days before to 30 days after 1 October); then we compute the trend obtained from the GRACE models for those places. 1 October is chosen because most of the yearly AG measurements relevant for this study are acquired around that time of the year. Concurrently to the interannual mass

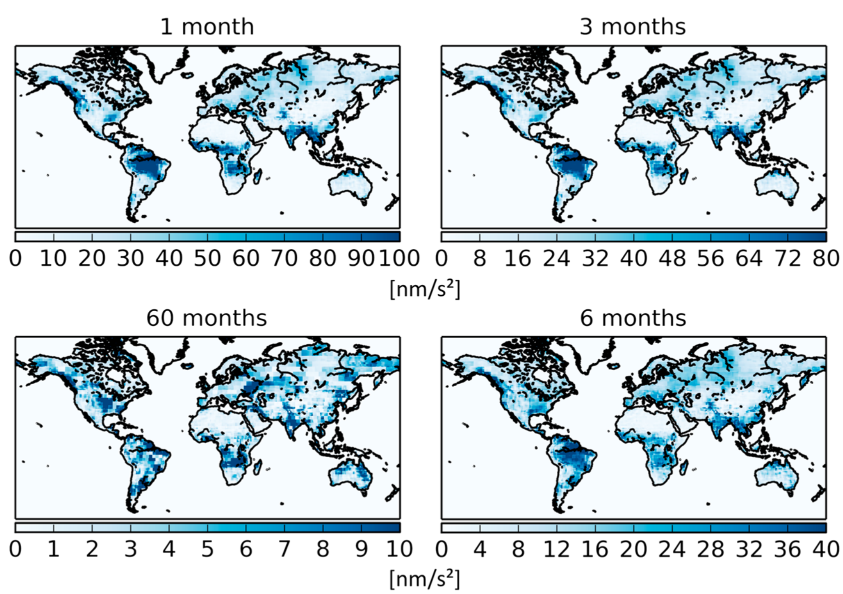

Figure 2. Allan deviations of the hydrological effects on repeated gravity measurements in the whole world, at periods of 1, 3, 6, and 60 months. The hydrological effects are computed using GRACE observations and using the Bouguer conversion ratio of 4.2 nm/s^2/cm of water.

variability effects, the instrumental setup noise is taken into account by adding a normal random variable with a standard deviation of 16 nm/s^2. Table S1 provides a standard deviation averaged on the zones shown in Figures 1 and S1.

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

Table S1 shows that everywhere in the world, at least five AG measurements are needed over a 10 year period to achieve an uncertainty smaller than 10 nm/s^2/a at the 1 sigma level. This becomes less than 5 nm/s^2/a, provided that one measurement is performed each year.

4.2. Canada, Northern USA

In North America, the AG stations from the study of *Lambert et al*. [2013a, 2013b] and *Mazzotti et al*. [2011] lie in a zone where GRACE indicates a 12 month Allan deviation ranging 6 nm/s^2 (Priddis, Alberta) to 37 nm/s^2 (Wausau, Wisconsin). Taking into account the AG setup noise of 16 nm/s^2, one obtains 17–40 nm/s^2, which compares with the uncertainties of yearly repeated AG measurements that provide standard deviations ranging 25–37 nm/s^2 (digitized data from Figures 3a–3e in *Lambert et al*. [2013b]). After 10 years, the uncertainties on the slopes range 1–3 nm/s^2/a, which agrees with *Mazzotti et al*. [2011] reporting on uncertainties ranging 1–4 nm/s^2/a.

4.3. Southern Tibet

In southern Tibet, *Chen et al*. [2016] reported on gravity differences of −21, 62, 70, and 407 nm/s^2, at four stations, based on measurements performed first in October 2010 or August 2011, and repeated once in July 2013. However, this zone experiences strong loading effects from seasonal water storage changes and hydrological changes over the longer term [*Chanard et al*., 2014; *Hao et al*., 2016; *Rodell et al*., 2009]. The 12 month Allan standard deviations, which indicate the interannual variability, are 26, 17, 17, and 21 nm/s^2 at Naqu, Lhasa, Shigatse, and Zhongba, respectively. There are large differences in monsoon rainfall between July and August (about 120 mm of water per month in Lhasa) and October (10 mm of water per month), which can induce additional hydrological effects at the 20 nm/s^2 level, according to the 1 month Allan deviation. To account for this variability, another simulation of the uncertainty affecting the slope estimate was performed. This includes the setup noise, considering 60 days before and after 1 October (Table S2). We end up with standard deviations of 32, 24, 20, and 28 nm/s^2/a at Naqu, Lhasa, Shigatse, and Zhongba, respectively. This is enough to account for the claimed gravity changes at all stations but Shigatse.

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

Sun et al. [2009] also reported repeated measurements in Tibet at three stations, performed between 1990 and 2008 at the same epoch of the year: Lhasa (4 and 3 measurements on two different points, −19.7 nm/s^2/a), Kunming (6 measurements, −14.2 nm/s^2/a), and Dali (10 measurements, −4.1 nm/s^2/a). Combining the hydrological effects and the setup noise, we obtain uncertainties on the trend of 3, 9, and 2 nm/s^2/a, considering that measurements were made within ±30 days around 1 October. Lhasa and, possibly, Dali may have experienced a gravity rate too large (above the 2 sigma level) to relate to climate dynamics. However, in these two studies in Tibet, different instruments were used. *Chen et al*. [2016] made use of at least two different absolute gravimeters (one FG5 and one A10), while *Sun et al*. [2009] used five different ones in

Lhasa, two in Kunming, and four in Dali. This induces instrumental artifacts at a level that can reach the observed signal: the reported differences affecting FG5 and JILAg instruments range up to 134 nm/s^2 and up to 461 nm/s^2 for A10 gravimeters. In particular, *Francis et al*. [1995] report on results from the JILAg #3 and #5 instruments, also used by *Sun et al*. [2009]: difference of about 100 nm/s^2 is observed between the two instruments, and unrealistic trends in Brussels (300 nm/s^2 in 6 years) and Membach (eastern Belgium, 100 nm/s^2 in 3 years) could never be confirmed later on [*Van Camp et al*., 2011]. Hence, the tectonic interpretations of *Sun et al*. [2009] and *Chen et al*. [2016] are questionable in our opinion, especially when the still experimental JILAg and early FG5 instruments are taken into account. A detailed discussion on the offsets and uncertainties of JILAg and early FG5 gravimeters is given by *Palinkas et al*. [2012]. Moreover, in Lhasa, the trend is the average of two trends recorded at two different places, 800 m apart. Differences in the gravity response to local hydrogeological effects at sites only 40 m apart have been reported to be as large as 100 nm/s^2 within a few months [*Mikolaj et al*., 2015]. Hence, averaging two trends, including one determined on only three measurements, is questionable.

4.4. Other Zones

As shown by Tables S1 and S2, in most of the cases, one needs at least five repeated AG measurements during 10 years to achieve an uncertainty on the determination of a trend lower than 10 nm/s^2/a, at the 1 sigma level. This decreases down to 3–4 nm/s^2 if the 10 yearly measurements are performed. On the other hand, it is hopeless to achieve a precision better than 20 nm/s^2/a, if only three measurements are performed during 3 years. Given that measurements are usually not performed at exactly the same date of the year, degrees of freedom of ±30 and ±60 days were taken into account. The 60 day cases are slightly noisier, but the increase remains under the 10% level. However, those GRACE-inferred estimates represent average values in the geographic zones shown in Figures 1 and S1. They do not represent local phenomena, where hydrogeological effects may affect gravity at the 100–150 nm/s^2 level, sometimes within a few hours [*Van Camp et al*., 2006b; *Meurers et al*., 2007]. Our results can thus be considered as a lower bound of the climate-induced mass transfer uncertainty.

5. Conclusions

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

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

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