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1 **Direct measurement of evapotranspiration from a forest using a superconducting**
2 **gravimeter**

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24 **Key Points (140 char):**

25 • Continuous gravity measurements reveal the evapotranspiration of a forested ecosystem
26 at the mesoscale (~50 ha).

27 • An oak-beech forest evaporates 1.7 mm of water during sunny summer days.

- 28 • Ground gravity is now able to isolate regular signals at the level of a few tenths of mm of
29 water

30 **Abstract**

31 Evapotranspiration (ET) controls the flux between the land surface and the atmosphere.
32 Assessing the ET ecosystems remains a key challenge in hydrology. We have found that the ET
33 water mass loss can be directly inferred from continuous gravity measurements: as water
34 evaporates and transpires from terrestrial ecosystems, the mass distribution of water decreases,
35 changing the gravity field.

36 Using continuous superconducting gravity measurements, we were able to identify daily gravity
37 changes at the level of, or smaller than 10^{-9} nm.s⁻² (or 10^{-10} g) per day. This corresponds to 1.7
38 mm of water over an area of 50 ha. The strength of this method is its ability to enable a direct,
39 traceable and continuous monitoring of actual ET for years at the mesoscale with a high
40 accuracy.

41 **1 Introduction**

42 Improving the assessment of the different components of the terrestrial hydrological
43 cycle remains a key challenge for geoscientists. A critical component of this cycle is
44 evapotranspiration (ET), i.e. the process whereby liquid water is converted into water vapor
45 [Robinson et al., 2003; Sun et al., 2006]. ET encompasses the evaporation flux from soil and
46 canopy, and the canopy transpiration flux [Monteith, 1965; [Shukla and Mintz, 1981](#)]. The global
47 ET is more than 85% made up of canopy transpiration, which returns more than 50% of
48 precipitation back to the atmosphere [[Oki and Kanae, 2006](#)]. In arid to semi-arid environments
49 ET can return more than 95% of the annual precipitation [Kurc and Small, 2004]; hence its
50 assessment is critical to assess recharge. ET plays a major role in terrestrial ecosystems. It
51 controls the amount of green water in the total global water balance and has therefore a major

52 impact on the global fresh water availability [*Rost et al.*, 2008]. Furthermore, ET strongly
53 controls energy transfer between the Earth and the atmosphere and hence within the global
54 climate system.

55 The direct accurate and precise measurement of diurnal ET is possible at the individual
56 plant scale, using weighing lysimeter devices [*Verstraeten et al.*, 2008; *Müller and Bolte*, 2010]
57 and at the mesoscale, i.e. the scale of a small landscape unit, using eddy-covariance flux towers
58 [*Shi et al.*, 2008; *Baldocchi and Ryu*, 2011]. Both devices are difficult to implement in
59 heterogeneous, rugged forested ecosystems. Alternatively, a lysimeter type approach was
60 proposed to measure ET at the mesoscale [*Barr et al.*, 2000]. Yet, this latter approach relies on
61 several constraining hypothesis to convert the pressure change obtained by piezometers into ET,
62 such as e.g. the presence of an aquitard, or a negligible runoff. At the regional scale, ET can only
63 be estimated indirectly, e.g. from land surface models [*Kelliher et al.*, 1993; *Rana and Katerij*,
64 2000; *Wilson et al.*, 2001; *Verstraeten et al.*, 2005], and remote sensing still requires terrestrial
65 measurements for calibration or parametrization [*Jimenez et al.*, 2011]. Such indirect regional
66 approaches rely also on strong hypotheses, not the least of which is the homogeneity of the
67 terrain and vegetation attributes in land surface model pixels, inducing a considerable uncertainty
68 in regional ET assessments [*Baldocchi and Ryu*, 2011; *Hupet et al.*, 2004]. Reducing regional ET
69 uncertainty therefore relies on the calibration of land surface model parameters, using accurate
70 and precise real ET data at ground level.

71 We propose a novel way to measure the mesoscale (about 50 ha) ET continuously, based
72 on continuous gravity monitoring. Gravity is the acceleration experienced by a body at rest at the
73 Earth surface, due to the combined gravitational forces of the Earth, the Moon, the Sun, and the
74 planets, and the centrifugal effect from the Earth rotation. Continuous gravity monitoring using

75 up-to-date instruments is precise to 1 part per 100 billion (10^{-11} g) [Van Camp et al., 2006].
76 Further, celestial mechanics can provide the relative positions of the Earth, the Moon, and the
77 Sun. The contribution from these bodies can be corrected into the gravity data down to a
78 resolution of at least 10^{-11} g [Hartmann and Wenzel, 1995; Wenzel, 1996], so that only the signal
79 from the Earth system is left in the gravity data. The Earth rotation is also monitored with high
80 accuracy, which allows a precise correction for the time variation of the centrifugal effect. The
81 atmospheric contribution can be estimated and corrected with precise meteorological data such
82 as the surface pressure. Traditional hydrology-gravity studies remove all these effects to study
83 changes in terrestrial water content, the dominant signal in the corrected gravity time-series
84 coming from the mesoscale terrestrial water content directly around the instrument [Creutzfeldt
85 et al., 2008] (Figure S1). We go one step further and remove the gravity effect of interflow losses
86 to evaluate losses caused by ET during periods without rainfall, showing that gravity time series
87 can be used as a weighing lysimeter for measuring mesoscale ET over a rain-free period.

88 **2 Continuous gravity measurements**

89 In 1995, a superconducting (or cryogenic) gravimeter (SG) [Goodkind, 1999] was
90 installed in the Membach station, eastern Belgium (50.6°N, 6.0°E, altitude: 250 m), and has been
91 continuously operating ever since. Basic processing of the SG data is done as described by
92 Hinderer et al. [2007]. The instrumental drift of the SG is corrected using repeated absolute
93 gravity measurements. In this study, tides were removed by computing tidal parameter sets using
94 the ETERNA package [Wenzel, 1996] on the gravity time series extending from 2004-06-01 to
95 2015-01-03 (3825.75 record days). The tidal potential is the Hartmann-Wenzel [Hartmann and
96 Wenzel, 1995] catalog with 7761 waves. The adjusted tidal parameters make it possible to
97 compute a tidal signal which includes both the solid Earth tide and ocean loading effects. The

98 atmospheric loading effects were corrected by using a linear admittance factor also provided in
99 the ETERNA package. It amounts to $-3.302 \text{ nm}\cdot\text{s}^{-2} \text{ hPa}^{-1}$. An annual modulation effect on the
100 atmospheric S3 tide remained after removing the tidal and atmospheric effects. It was removed
101 by fitting two harmonics with frequencies of (3 cpd + 1 cpy) and (3 cpd - 1 cpy) on the gravity
102 residuals [Polzer et al., 1996].

103 **3 Soil moisture**

104 The station is located about fifty meters below the surface (Figure S2). The area is one of
105 deciduous forest (Figure S3) and experiences a marine temperate climate (Cfb in the climate
106 scheme of Köppen–Geiger [Peel et al., 2007]) (Figure S4). Given the position of the nearby
107 river, the low saturated hydraulic conductivity and the low porosity of the bedrock in which the
108 station is excavated [Van Camp et al., 2006], the diurnal signal coming from nearby aquifers or
109 river is expected to be smaller than 0.1 nm/s^2 , i.e. much smaller than the ET signature.

110 Since 2004, three soil moisture time domain reflectometry (TDR) probes at 30, 45 and 60
111 cm below the surface allow for a continuous monitoring of the gravimetric water content (GWC,
112 the mass of water per unit mass of dry soil) in the partially saturated soil, 48 m above the SG
113 [Van Camp et al., 2006]. The corresponding time series, which measures the local-scale water
114 saturation of the soil, shows a seasonal pattern with steps during rainfall events [Van Camp et al.,
115 2006; Meurers et al., 2007]. Focusing on a dry period, of which a short sample is plotted in red
116 on Figure S5, we observe that the soil moisture decreases only during the day. This signature is
117 expected from evapotranspiration during dry days [Schelde et al., 2011].

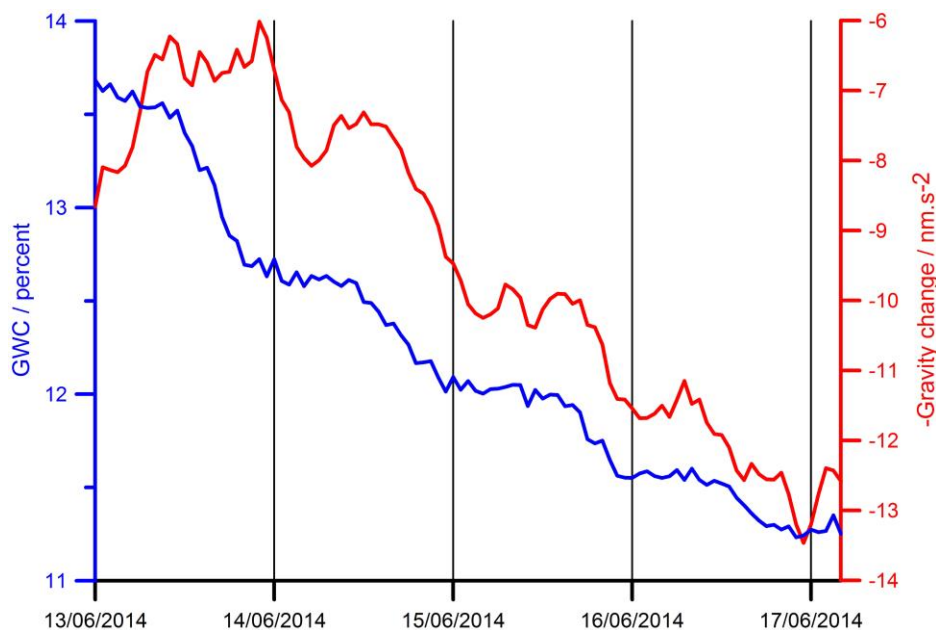
118 A small soil moisture increase is seen overnight, probably due to hydraulic lift effects
119 [Caldwell et al., 1998], vapor condensation, capillary water redistribution, or imperfect
120 temperature correction of the probes. The soil moisture probes only allow the first 60 cm of the

121 soil to be investigated. For this reason we want to study the potential of gravity measurements to
122 assess ET at the mesoscale around the station.

123 **4 Modeling the gravity effect of groundwater**

124 Measuring the gravity signature of ET is a metrological challenge, as the expected signal
125 is at the level of a few millimeters of water in a temperate deciduous forest [*Kosugi et al., 2006*].
126 For the diurnal cycle, the geophysical noise, mostly caused by hydrogeological effects and
127 imperfect correction of atmospheric factors, amounts to 0.4 nm.s^{-2} , corresponding to 1.0 mm of
128 water. Hence the expected ET signal is at the limit of the precision level of terrestrial
129 measurements [*Van Camp et al., 2005*], and can only be evidenced at particularly favorable
130 times (Figure 1A). To enhance the signal in the time series, a stacking process over at least a few
131 dozen of days was needed to isolate the signal (Figures 1B and 1C).

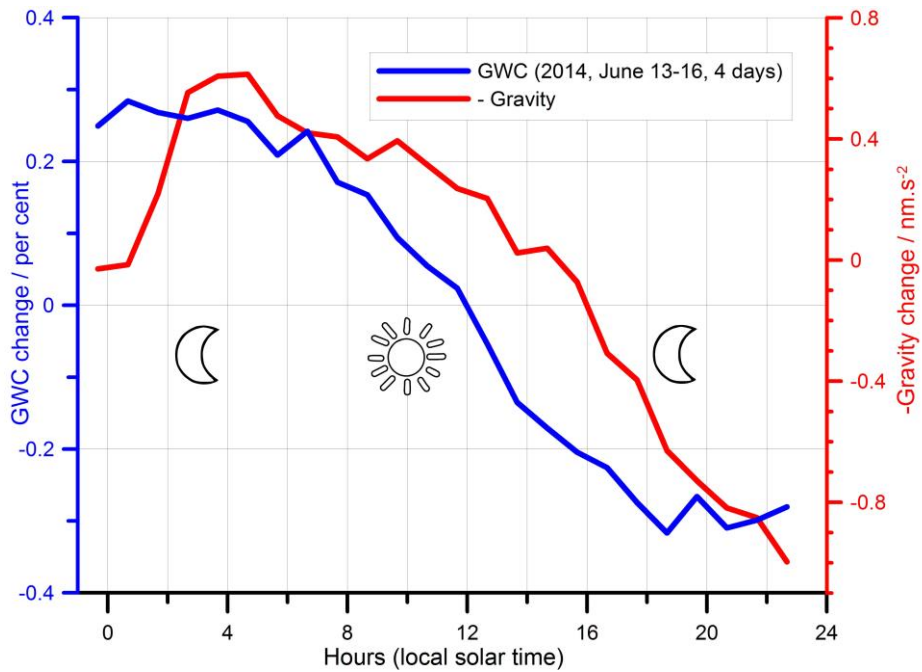
132



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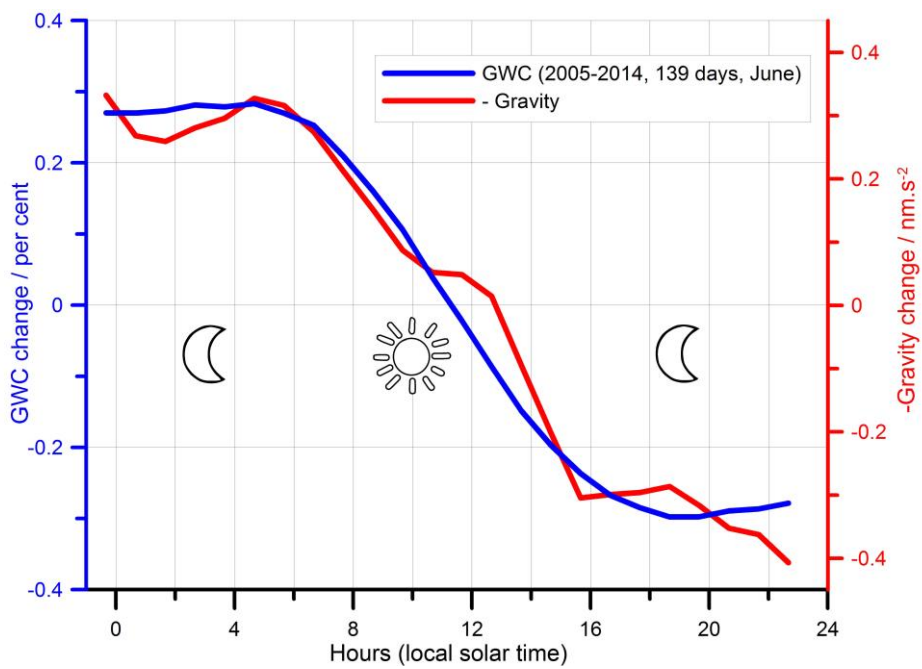
(A)



135

136

(B)



137

138

(C)

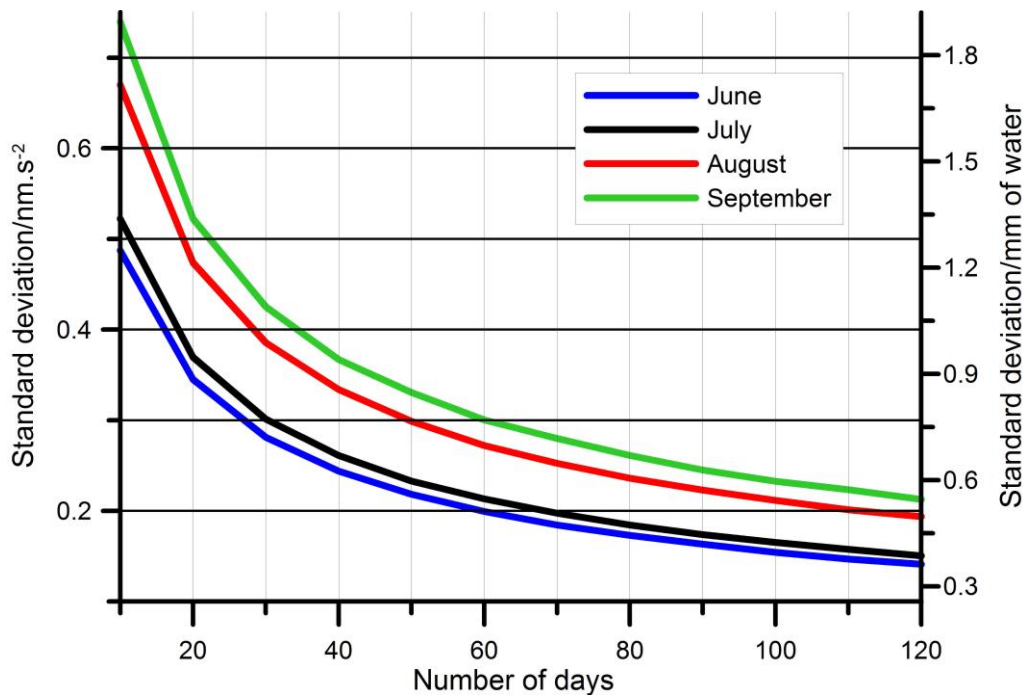
139

140

Figure 1. Gravity water content (blue, in %) and inverted gravity signal (red, in nm.s^{-2}); the actual gravity signal increases because the gravimeter is underground, below the

141 surface soil moisture). Time is in days (A) and hours (B, C, local solar time). (A) Series
142 during 4 days in June 2014. An decrease in gravity of about 2 nm.s^{-2} , equivalent to a loss
143 of 5 mm of water, is observed during the day; (B) stacked values as shown on (A); (C)
144 stacked values for 139 dry days. The stacking is performed in the months of June from
145 2005 to 2014. Between 4:40 and 17:40 the GWC diminishes by -0.57 ± 0.02 percentage
146 point and gravity increases by $0.66 \pm 0.14 \text{ nm/s}^2$, which is equivalent to 1.7 ± 0.3 mm of
147 water. The subsurface lateral flow was separated from the diurnal ET signal by removing
148 a linear trend fitted over the nighttime pattern.

149 Figure 2 shows the error on the gravity signal calculated as a function of the number of
150 days. This is done for June, July, August and September, during which more than 120 data
151 values are available. The errors were estimated by the Monte-Carlo method using 100,000
152 random resamples [Robert and Casella, 2004]. A precision of 0.2 nm.s^{-2} , equivalent to 0.5 mm
153 of water, is already obtained after 60 days in June and 70 days in July, while 120 days or more
154 are necessary for August and September, as ET decreases when summer fades to fall (Figure S6).



155

156 **Figure 2.** The standard deviation of the daily gravity changes as a function of the number
 157 of days. This provides the number of days necessary to measure the daily gravity change,
 158 for the 4 months of which more than 120 data are available. A precision of 0.2 nm/s²,
 159 equivalent to 0.5 mm of water, is obtained when 60 days or are available in June and 70
 160 in July.

161 From 2005 to 2014, we selected dry periods, i.e. periods when the soil moisture data
 162 exhibits step-like behavior as on Figure S5. This resulted in 139 days in June, i.e. the month
 163 experiencing the strongest ET effect (Figure S6). We averaged the gravity values separately for
 164 each hour of the day, to obtain an averaged diurnal cycle. The averaged cycle is illustrated for
 165 both the soil moisture and the gravity in Figures 1B and 1C. On Figure 1C, the stair-like
 166 behavior is clear in the stacked soil moisture data, as well as the small increase during the night.
 167 The stair-like behavior in the gravity data is also present. From July to September, the signal
 168 decreases and falls within the error bars, making it difficult to extract.

169 Note that the TDR probes and the gravimeter do not perform the same kind of
170 measurement, otherwise there would be no challenge in obtaining the ET, and it would long be
171 public knowledge. At the Membach station, the TDR probes clearly show fast changes in the
172 shallowest zone above 60 cm. Given the hydrogeological context in the weathered zone,
173 drainage is quite efficient and TDRs cannot reflect the water dynamics in the whole unsaturated
174 weathered zone (1-10 m thick [*Van Camp et al.*, 2006]), nor in neighboring zones. We only use
175 the GWC as a measurement of the saturation conditions of the first 60 centimeters, allowing us
176 to identify dry periods. In the gravity signal, there is a residual slope, visible during the night,
177 caused by the subsurface lateral flow. This flow was separated from the diurnal ET signal by
178 removing a linear trend fitted over the nighttime behavior. This flow is caused by an ongoing
179 interflow (subsurface lateral flow) process at the base of the weathered zone lower than the soil
180 moisture probes [*Kosugi et al.*, 2006; *Davies-Smith et al.*, 1988]. This interflow occurs in lower
181 layers of the ground and is consequently not observed by the TDR probes, except just after
182 strong rainfalls.

183 From those average days, we estimate the daily gravity increase associated to the ET at the
184 level of 0.66 ± 0.14 nm/s². Note that gravity increases because the gravimeter is located
185 underground, below the surface soil moisture. This corresponds to an average of 1.7 ± 0.3 mm of
186 water over the area. Details on the conversion of nm/s² to mm of water are available in the
187 supporting information [*Okabe*, 1979].

188 This value compares with what is expected in such a Cfb humid, temperate climate
189 [*Baldocchi et al.*, 2011], and with the 1.9 ± 0.2 mm estimate from an eddy covariance tower in a
190 similar forest in Vielsalm (50.3°N, 6.0°E, altitude: 450 m), 34 km south of Membach [*Soubie*,
191 2014]. Comparing Membach and Vielsalm is only indicative, given that (1) the techniques are

192 different, (2) ET depends on the stand (Douglas fir and beeches in Vielsalm [Aubinet et al.,
193 2001]), topography, altitude, soil conditions, canopy density, age and forest management, (3) ET
194 inferred from the flux tower includes rainy days.

195 This also compares with the potential ET (PET) of 3.9 mm estimated by using the
196 Penman–Monteith equation, considering PET as the maximum ET (see supporting information,
197 equation [Allen et al., 1998; Verstraeten et al., 2005]. PET is the amount of evaporation that
198 would occur if sufficient water was available. The PET and the ET inferred from the gravity
199 changes are computed on the same dry days. This differs from the eddy covariance estimates,
200 which are computed taking all the days of the month into account.

201 **5 Discussions**

202 In the subsurface, evapotranspiration is a major hydrological phenomenon that occurs in dry
203 days, which is well illustrated by the GWC data at the Membach station. Considering that this
204 phenomenon must be linked to changes in the water distribution around the gravimeter, it is
205 theoretically possible to retrieve the associated signature in the gravity signal. Several questions,
206 however, remain concerning those results:

207 First, are those results robust and reproducible elsewhere? We successfully tested the robustness
208 for the Membach station in many ways by taking different years and different times of the year.
209 It is not possible to infer from the available data if the same can be achieved in other stations. We
210 applied our method to one other station, Walferdange, in Luxembourg, and we obtained similar
211 results. However, based on this single comparison, we cannot conclude that the method would
212 work at every site. Considering the level of the signal, reproducing these results in another
213 station will require working closely with the operator of the station.

214 Also, can we be sure that the obtained signature is indeed linked to evapotranspiration?
215 Considering that (1) the amplitude is of the right order of magnitude, (2) the signal cannot be
216 retrieved at winter time when ET is reduced, (3) the signal disappears when it is raining, (4) as
217 soon as we avoid rainy days, the diurnal gravity signal shows this signature that only exists
218 during the day, we can have some confidence in the results.

219 Finally, what is the scope of this study if it only applies to one or two stations? We consider that,
220 even in this case, this study is useful for three reasons:

221 (1) From the measurement point of view, it is interesting to show that an appropriate correction
222 of the data enables a signal to be retrieved down to a resolution of a few tenths of nm/s^2 ;

223 (2) This study provides for the first time a direct measurement of evapotranspiration integrated
224 over a deciduous forest area, a result interesting in its own right;

225 (3) New methods to estimate evapotranspiration can be validated and calibrated on a site where
226 SG gravity provides an independent estimate. Note that Membach is probably not an ideal case
227 given that the topography and the geology of the subsurface (i.e. silty soil combined with
228 sandstone blocks and gravels) are likely to cause a strong subsurface lateral flow which is likely
229 to disrupt the signal. We think that the ideal site would be in a flat forested area (if possible,
230 installing the gravimeter in a shaft), with lower underground hydraulic conductivity.

231 **6 Conclusions**

232 We have shown that liquid water losses can be directly inferred from continuous gravity
233 measurements: as water evaporates and transpires from terrestrial ecosystems, the mass
234 distribution varies through the system, changing its gravity field.

235 Using continuous superconducting gravity measurements, we were able to identify
236 average daily changes in gravity at the level of, or smaller than $10^{-9} \text{ nm.s}^{-2}$ (or 10^{-10} g) per day.
237 Considering the topography around the gravimeter, this corresponds in June, from 2005 to 2014,
238 to an average of 1.7 mm of water per sunny day over an area of 50 ha. The strength of this
239 method consists in its ability to ensure a direct, traceable and continuous monitoring of actual ET
240 for years at the mesoscale ($\sim 50 \text{ ha}$) with a precision of a few tenths of mm of water.

241 This can be performed in rugged forested areas with a precision of a few tenths of mm of
242 water. The method is, therefore, complementary to the well-known eddy covariance method

243 which often suffers from methodological uncertainty due to poor footprint modeling. This study
244 provides also a way to assess the quality of the gravity time series and the applied corrections.

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255 website of the Royal Observatory of Belgium:
256 <http://seismo.oma.be/en/gravimetry/observations/online-database>.

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