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Direct measurement of evapotranspiration from a forest using a superconducting gravimeter

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Key Points (140 char):

- Continuous gravity measurements reveal the evapotranspiration of a forested ecosystem at the mesoscale (~50 ha).
- An oak-beech forest evaporates 1.7 mm of water during sunny summer days.

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

Abstract

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

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

1 Introduction

Improving the assessment of the different components of the terrestrial hydrological cycle remains a key challenge for geoscientists. A critical component of this cycle is evapotranspiration (ET), i.e. the process whereby liquid water is converted into water vapor [*Robinson* et al., 2003; *Sun* et al., 2006]. ET encompasses the evaporation flux from soil and canopy, and the canopy transpiration flux [*Monteith*, 1965; *Shukla and Mintz,* 1981. The global ET is more than 85% made up of canopy transpiration, which returns more than 50% of precipitation back to the atmosphere [*Oki and Kanae,* 2006]. In arid to semi-arid environments ET can return more than 95% of the annual precipitation [Kurc and Small, 2004]; hence its assessment is critical to assess recharge. ET plays a major role in terrestrial ecosystems. It controls the amount of green water in the total global water balance and has therefore a major impact on the global fresh water availability [*Rost* et al., 2008]. Furthermore, ET strongly controls energy transfer between the Earth and the atmosphere and hence within the global climate system.

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

We propose a novel way to measure the mesoscale (about 50 ha) ET continuously, based on continuous gravity monitoring. Gravity is the acceleration experienced by a body at rest at the Earth surface, due to the combined gravitational forces of the Earth, the Moon, the Sun, and the planets, and the centrifugal effect from the Earth rotation. Continuous gravity monitoring using up-to-date instruments is precise to 1 part per 100 billion (10^{-11} g) [*Van Camp* et al., 2006]. Further, celestial mechanics can provide the relative positions of the Earth, the Moon, and the Sun. The contribution from these bodies can be corrected into the gravity data down to a resolution of at least 10^{-11} g [*Hartmann and Wenzel*, 1995; Wenzel, 1996], so that only the signal from the Earth system is left in the gravity data. The Earth rotation is also monitored with high accuracy, which allows a precise correction for the time variation of the centrifugal effect. The atmospheric contribution can be estimated and corrected with precise meteorological data such as the surface pressure. Traditional hydrology-gravity studies remove all these effects to study changes in terrestrial water content, the dominant signal in the corrected gravity time-series coming from the mesoscale terrestrial water content directly around the instrument [*Creutzfeldt* et al., 2008] (Figure S1). We go one step further and remove the gravity effect of interflow losses to evaluate losses caused by ET during periods without rainfall, showing that gravity time series can be used as a weighing lysimeter for measuring mesoscale ET over a rain-free period.

2 Continuous gravity measurements

In 1995, a superconducting (or cryogenic) gravimeter (SG) [*Goodkind*, 1999] was installed in the Membach station, eastern Belgium (50.6°N, 6.0°E, altitude: 250 m), and has been continuously operating ever since. Basic processing of the SG data is done as described by *Hinderer* et al. [2007]. The instrumental drift of the SG is corrected using repeated absolute gravity measurements. In this study, tides were removed by computing tidal parameter sets using the ETERNA package [*Wenzel*, 1996] on the gravity time series extending from 2004-06-01 to 2015-01-03 (3825.75 record days). The tidal potential is the Hartmann-Wenzel [*Hartmann and Wenzel*, 1995] catalog with 7761 waves. The adjusted tidal parameters make it possible to compute a tidal signal which includes both the solid Earth tide and ocean loading effects. The atmospheric loading effects were corrected by using a linear admittance factor also provided in the ETERNA package. It amounts to -3.302 $nm.s^{-2}$ hPa^{-1}. An annual modulation effect on the atmospheric S3 tide remained after removing the tidal and atmospheric effects. It was removed by fitting two harmonics with frequencies of (3 cpd + 1 cpy) and (3 cpd - 1 cpy) on the gravity residuals [*Polzer* et al., 1996].

3 Soil moisture

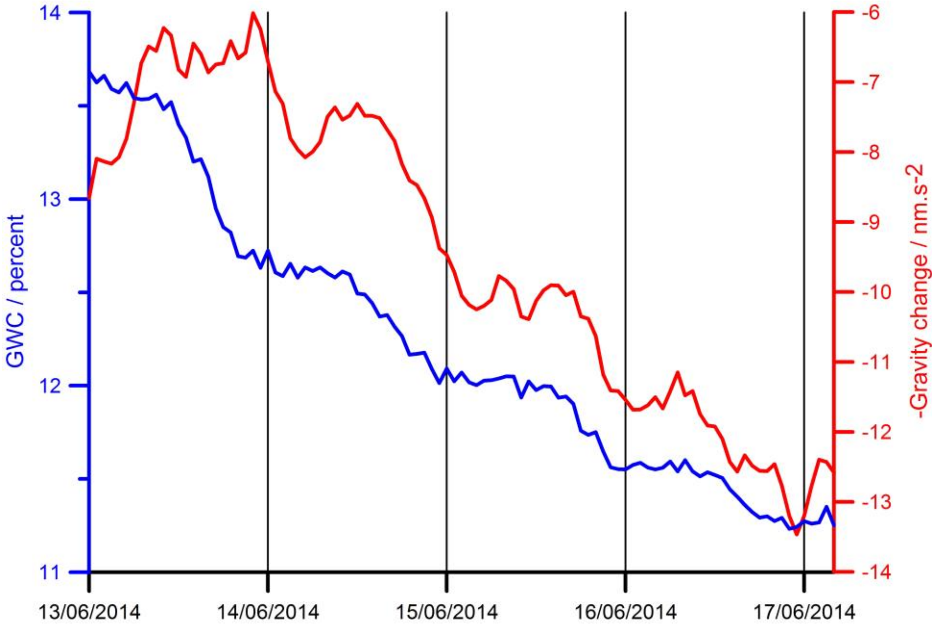
The station is located about fifty meters below the surface (Figure S2). The area is one of deciduous forest (Figure S3) and experiences a marine temperate climate (Cfb in the climate scheme of Köppen–Geiger [*Peel* et al., 2007]) (Figure S4). Given the position of the nearby river, the low saturated hydraulic conductivity and the low porosity of the bedrock in which the station is excavated [*Van Camp* et al., 2006], the diurnal signal coming from nearby aquifers or river is expected to be smaller than 0.1 nm/s², i.e. much smaller than the ET signature.

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

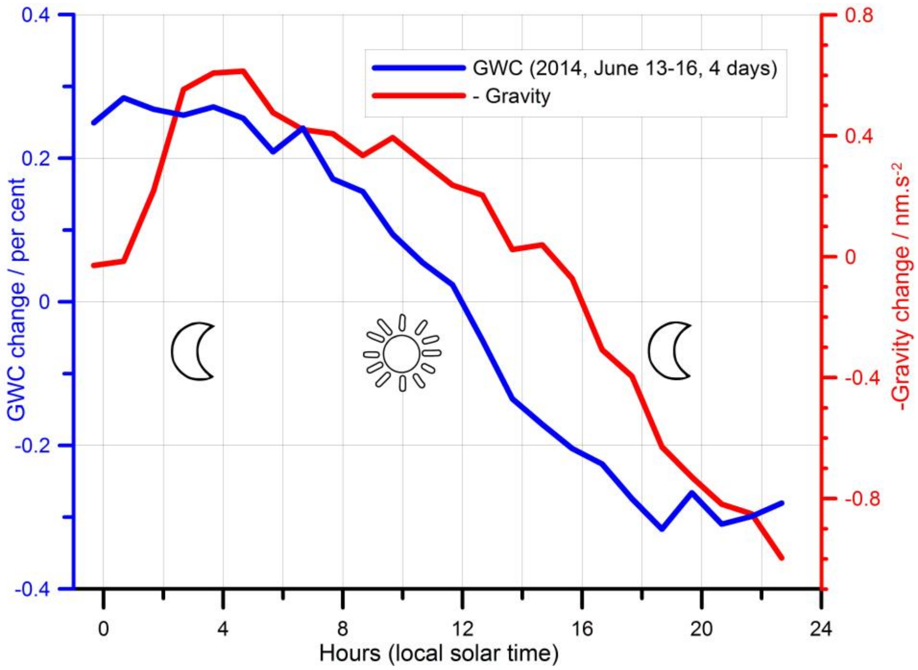
A small soil moisture increase is seen overnight, probably due to hydraulic lift effects [*Caldwell* et al., 1998], vapor condensation, capillary water redistribution, or imperfect temperature correction of the probes. The soil moisture probes only allow the first 60 cm of the soil to be investigated. For this reason we want to study the potential of gravity measurements to assess ET at the mesoscale around the station.

4 Modeling the gravity effect of groundwater

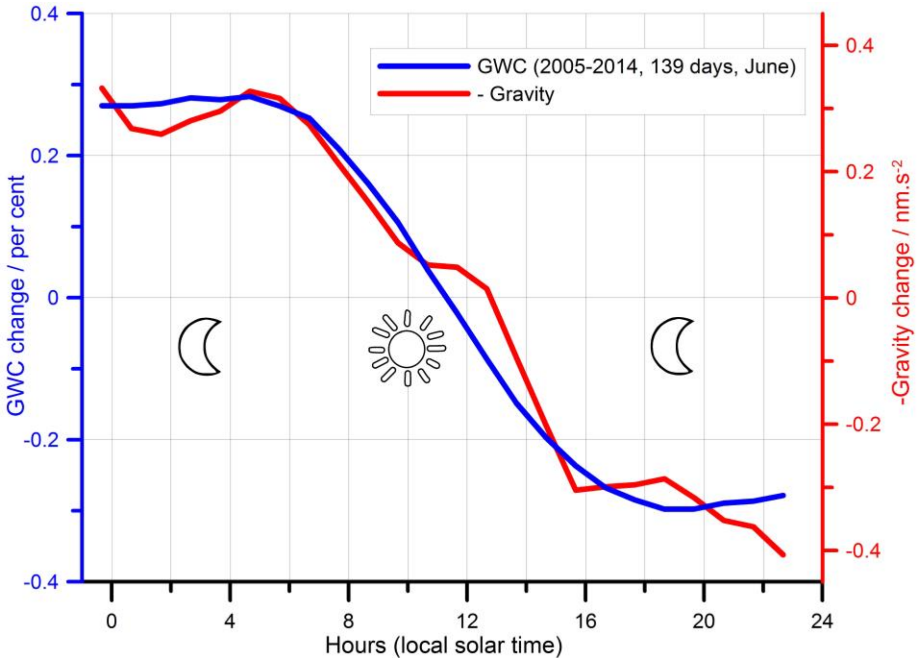
Measuring the gravity signature of ET is a metrological challenge, as the expected signal is at the level of a few millimeters of water in a temperate deciduous forest [*Kosugi* et al., 2006]. For the diurnal cycle, the geophysical noise, mostly caused by hydrogeological effects and imperfect correction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



(A)



(B)



(C)

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

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

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

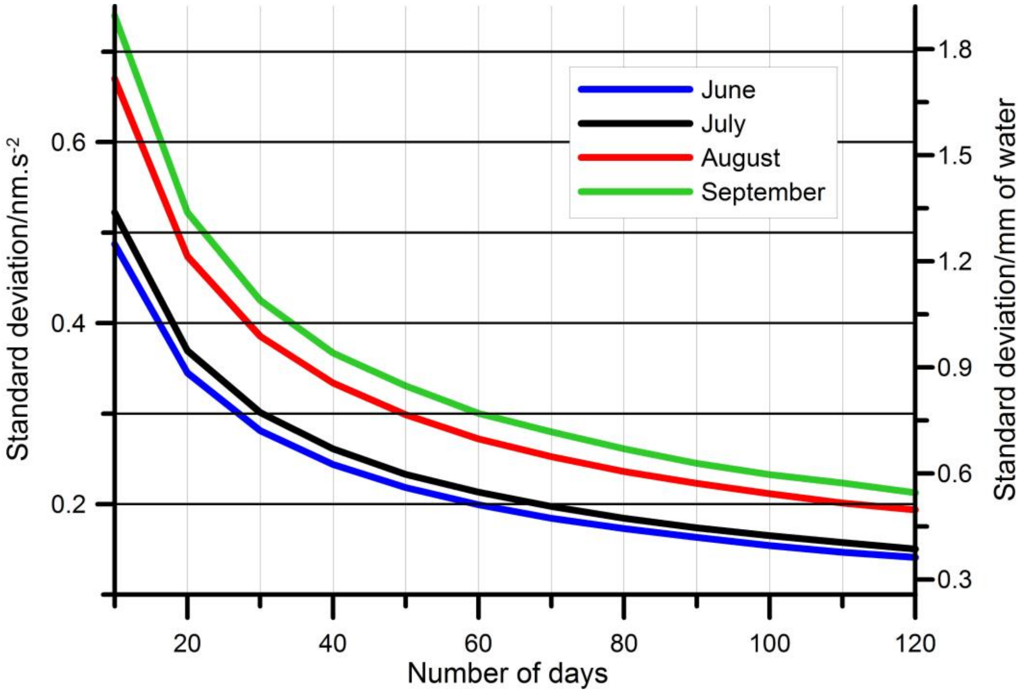


Figure 2. The standard deviation of the daily gravity changes as a function of the number of days. This provides the number of days necessary to measure the daily gravity change, for the 4 months of which more than 120 data are available. A precision of 0.2 nm/s², equivalent to 0.5 mm of water, is obtained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

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

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

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

This value compares with what is expected in such a Cfb humid, temperate climate [*Baldocchi* et al., 2011], and with the 1.9±0.2 mm estimate from an eddy covariance tower in a similar forest in Vielsalm (50.3°N, 6.0°E, altitude: 450 m), 34 km south of Membach [*Soubie*, 2014]. Comparing Membach and Vielsalm is only indicative, given that (1) the techniques are different, (2) ET depends on the stand (Douglas fir and beeches in Vielsalm [Aubinet et al., 2001]), topography, altitude, soil conditions, canopy density, age and forest management, (3) ET inferred from the flux tower includes rainy days.

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

5 Discussions

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

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

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

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

(1) From the measurement point of view, it is interesting to show that an appropriate correction of the data enables a signal to be retrieved down to a resolution of a few tenths of nm/s²;

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

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

6 Conclusions

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

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

This can be performed in rugged forested areas with a precision of a few tenths of mm of water. The method is, therefore, complementary to the well-known eddy covariance method which often suffers from methodological uncertainty due to poor footprint modeling. This study provides also a way to assess the quality of the gravity time series and the applied corrections.

Acknowledgments and Data

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