

Signals of mass redistribution observed at the South African Geodynamic Observatory Sutherland

C. Kroner¹, H. Pflug¹, S. Werth¹, A. Güntner², B. Creutzfeldt², P. Fourie³, Ph. Charles³

1. Helmholtz Centre Potsdam GFZ German Research Centre for Geosciences, kroner@gfz-potsdam.de, pflug@gfz-potsdam.de, swerth@gfz-potsdam.de
2. Helmholtz Centre Potsdam GFZ German Research Centre for Geosciences, guentner@gfz-potsdam.de, creutzfeldt@gfz-potsdam.de
3. South African Astronomical Observatory, pah@sao.ac.za, pac@sao.ac.za

ABSTRACT

Since the year 2000 a superconducting gravimeter (SG) has been operating at the South African Geodynamic Observatory Sutherland (SAGOS). It is one of the few instruments installed in the southern hemisphere and presently the only one of its kind on the African continent. Time-dependent gravity observations carried out with superconducting gravimeters are long-term stable and of high resolution ($\sim 1 \text{ nm/s}^2$ in the time domain) have thus the potential to provide constraints for hydrological models since they completely contain the changes in all water storage components in contrast to hydrological point observations. Esp. in combination with satellite-derived temporal gravity field variations as from the GRACE mission they provide a powerful tool for the investigation of changes in continental water storage.

SAGOS is located on a hill in the Karoo, a semi-arid area with an average annual precipitation in the range of 200 to 400 mm.

A seasonal effect on gravity related to local hydrological variations is clearly seen in the SG record. It is in the order of magnitude of several nm/s^2 . Depending on the hydrological model the large-scale hydrological impact on gravity amounts to 10 – 20 nm/s^2 with or without a pronounced seasonal variation. Substantial differences exist between both, the amplitudes and the features of the gravity changes derived from global hydrological models. The same applies to the observed hydrology-related gravity changes and the model-based gravity variations. The results of the recently initiated investigations will contribute to an improved local and regional quantification of hydrological dynamics and thus establish additional means for the management of the valuable resource water.

Key words: temporal gravity variations; superconducting gravimetry; continental water storage

INTRODUCTION

Time-dependent gravity observations have the potential to provide constraints for hydrological modelling as they fully contain the changes in all water storage components in contrast to hydrological point observations. Results in e.g. Wahr et al. (2004), Schmidt et al. (2005), Werth et al. (2009) or Swenson and Wahr (2009) emphasize the applicability of the monthly gravity field solutions derived from GRACE to changes in the continental water storage. State-of-the-art large-scale hydrology models, however, have deficiencies in representing the total temporal and spatial variations of continental water storage due to missing adequate large-scale monitoring systems on the one hand, and difficulties in modelling soil moisture fields in general on the other hand.

The satellite-derived data set can be enhanced and assessed by continuous terrestrial gravity observations deploying superconducting gravimeters (SG) providing an even more versatile tool for dynamic process studies.

In recent years efforts have been made to combine SG observations for Europe (Crossley et al., 2005, 2009; Neumeyer et al., 2008; Weise et al., 2009). A main issue regarding the terrestrial data is the separation of local (distances \leq a few km from the instrument) and regional hydrological impacts. This can be achieved by an appropriate local hydrological model. On the other hand the dependency on local phenomena can be deployed for the study of small-scale hydrological processes as e.g. associated with rain events and the subsequent percolation.

In a recent research project the successful deployment of terrestrial gravity observations for the assessment of local hydrological modelling could be shown (Creutzfeldt et al., 2008; Naujoks, 2008; Naujoks et al., 2008). By three-dimensional gravimetric modelling into which hydrological changes are incorporated as density changes the understanding of the observed gravity variations is improved and constraints for the hydrological modelling are provided.

Based on the recent experiences the application of terrestrial gravity observations to hydrological studies will be extended to the Karoo region. At the South African Geodynamic Observatory Sutherland (SAGOS; 32.38°S, 20.81°E, 1759 m above msl) a superconducting gravimeter is operating since spring 2000. A clear hydrological impact on gravity is found albeit the location in a semi-arid region with an average annual precipitation between 200 and 400 m.

Local hydrological effects

Regarding the effect of changes in local hydrology on gravity the time-scale and local topography (typically zone < 1 km from the instrument) need to be considered. The observatory is located on a hill which rises approximately 150 – 200 m above the surrounding area. The observatory is covered by a soil-gravel layer for temperature screening (Figure 1). On a time-scale of up to a couple of days soil moisture variations related to rain events are predominantly visible in the gravity record (Figure 2). Due to the coverage and the lowered gravimeter pier most of the topography in the immediate vicinity of the instrument (few tens of meters) is above sensor level which leads to the observed anti-correlation between the gravity residuals (gravity data reduced for all known effects except hydrology, cf. Kroner et al., 2009) and hydrological variations. In the gravity record rain events are visible as distinct peaks. A rough relation of 1 mm rain corresponds to 0.5 nm/s² gravity decrease can be inferred. Variations of the groundwater table (Fig. 2, piezometer at a distance of ~50 m from the gravimeter) have a smaller gravity effect possibly because of the depth of the water table (about 60 m below the gravimeter) and the limited spatial correlation length of water level variations at these short time scales.



Figure 1. View of SAGOS.

At longer time scale, from weeks to years, the area increases in which coherent changes in water storage occur, which thus leads to a significant impact on gravity. This becomes visible when comparing gravity residuals with water table variations at a site in the valley 2-3 km away from the gravimeter and with filtered air tempera-

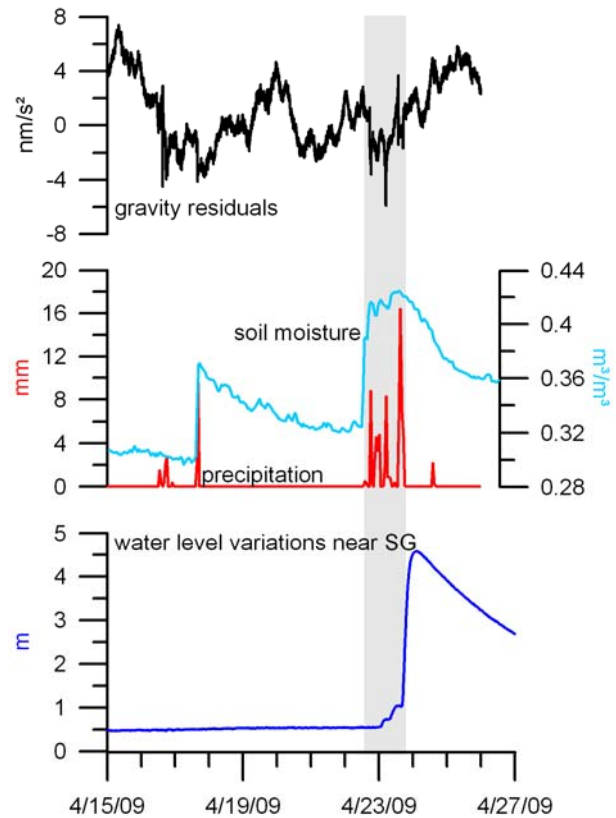


Figure 2. Gravity residuals, precipitation, soil moisture (depth 0-0.4 m) and relative water level changes in the vicinity of the SG during a period with rain events. The grey bar is for better comparison.

ture data as an indicator for seasonal soil moisture variations (Figure 3). The water table variations are characterized by a seasonal variation. Around February/March 2005 there was a dry spell which led to a substantial decrease of the water level by about 2 m. These groundwater dynamics may be a good indicator of soil moisture and groundwater depletion in a larger area around the gravimeter and, thus, a highly correlated gravity decrease is seen for this period. An empirical reduction of the water table effect with a regression coefficient leads to gravity residuals which still exhibit, among other inter-annual and seasonal signals, such as a pronounced about annual variation of 10-15 nm/s² peak-to-peak-amplitude. This variation has the wrong sign with respect to the seasons in order to originate from regional changes in continental water storage. Comparing gravity and air temperature an anti-correlation emerges. By rule of thumb, high temperature means low soil moisture content on a seasonal scale. From the gravity increase with soil moisture decrease follows that the main, but by no means exclusive, impact area has to be again the immediate gravimeter vicinity.

Large-scale hydrological impacts

The impact of large-scale changes in continental water storage is exemplarily estimated from two global hydrological models, the WaterGAP Global Hydrological Model (WGHM; Döll et al., 2003; Güntner et al., 2007) and the Global Land Data Assimilation System (GLDAS; Rodell et al., 2004). Both models are available in daily time steps. The WGHM has a spatial resolution of 0.5°, the GLDAS model a resolution of 1°. A main difference between the two hydrological models exists in the hydrological compartments considered. In contrast to GLDAS the WGHM includes the components surface and groundwater table storage. The load-

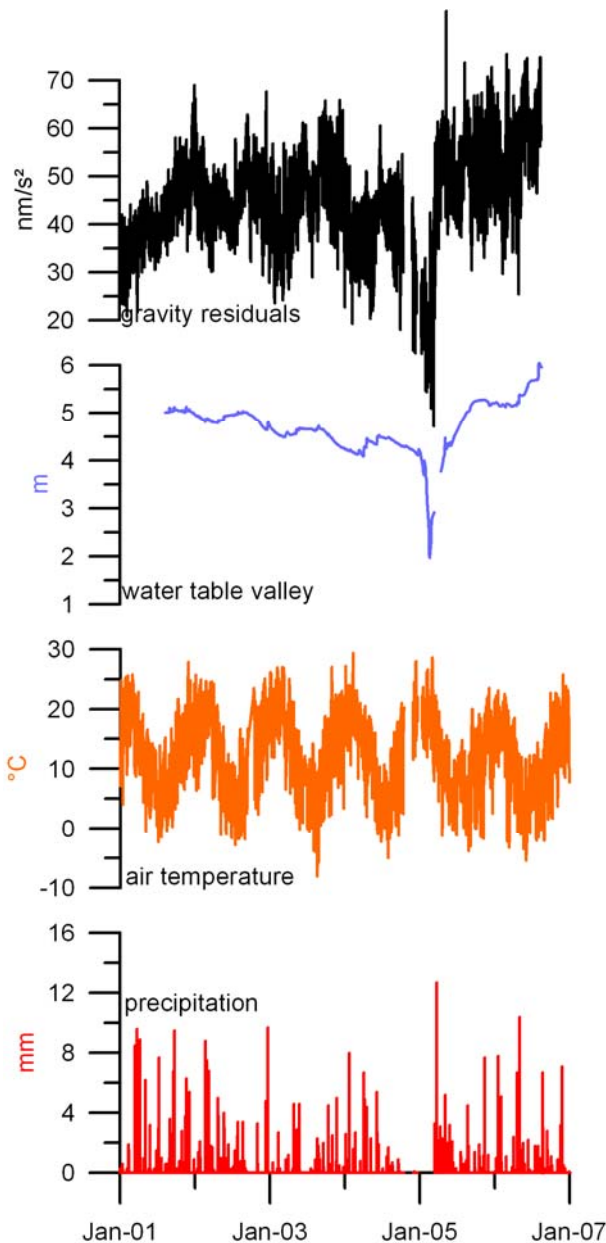


Figure 3. Gravity residuals, relative water level changes observed at one site in the valley, filtered air temperature (25 h) and precipitation between Jan. 2001 and Dec. 2006.

ing effect, attraction and deformation part, is computed

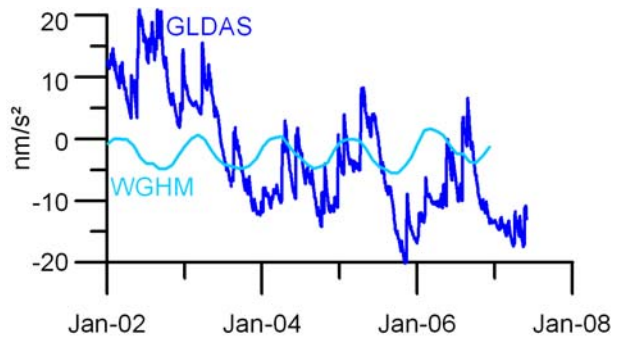


Figure 4. Gravity variations at SAGOS derived from the global hydrological models WGHM and GLDAS.

by use of Green’s function (Farrell, 1972; Francis and Dehant, 1987) assuming an earth structure according to PREM (Dziewonski and Anderson, 1981).

In Figure 4 the gravity variations at Sutherland derived from the hydrological models are given. Substantial discrepancies exist with regard to amplitude and features. There is approximately a factor of 5 between the peak-to-peak-amplitudes. The modelled gravity changes are in both cases in an order of magnitude that they should be detectable in the observed gravity variations without any difficulty. Presently no obvious agreement between the data sets is evident. The existing discrepancies emphasize the necessity for research with respect to hydrological processes in the Karoo region.

CONCLUSIONS

From recent studies it has emerged that valuable constraints can be inferred from high-precision stationary observations with superconducting gravimeters for hydrological modelling on different spatial and temporal scales. Based on previous good experiences at European stations the SG observations at SAGOS are to be deployed for hydrological studies. In the gravity record hydrologically induced changes of several nm/s^2 and more can be identified. They are related to both, rain events and principle changes in water storage in the area around the gravimeter.

From global hydrological models significant gravity variations are derived at Sutherland station which should be detectable in the SG data. Between the modelled effects substantial discrepancies exist, likewise with observed gravity, which underlines the necessity for further research.

In a first step the gravity observations will be used as one constraint in local hydrological studies. For this a local hydrological network has been recently established. Later on the SG data will be combined with

GRACE-derived temporal gravity variations for hydrological investigations on regional scale.

ACKNOWLEDGMENTS

We thank P. Döll and the GGFC Special Bureau for Hydrology for providing the WGHM and GLDAS data used in this study.

REFERENCES

- Creutzfeldt, B., Güntner, A., Klügel, T., Wziontek, H., 2008, Simulating the influence of water storage changes on the superconducting gravimeter of the Geodetic Observatory Wettzell, Germany: *Geophysics* 73(6), WA95-WA104.
- Crossley, D., Hinderer, J., Boy, J.-P., 2005, Time variation of the European gravity field from superconducting gravimeters: *Geophysical Journal International*, 161(2), 257-264.
- Crossley, D., de Linage, C., Boy, J.-P., Hinderer, J., 2009, Ground validation of GRACE data using the GGP Network: *Journal of Geodynamics*, accepted.
- Döll, P., Kaspar, F., Lehner, B., 2003, A global hydrological model for deriving water availability indicators: model tuning and validation: *Journal of Hydrology*, 270, 105-134.
- Dziewonski, A.M. and Anderson, D.L., 1981, Preliminary reference earth model (PREM): *Physics of the Earth and Planetary Interiors*, 25(4), 297-367.
- Farrell, W.E., 1972, Deformation of the earth by surface loads: *Review on Geophysics*, 10, 761-797.
- Francis, O. and Dehant, V., 1987, Recomputation of the Green's functions for tidal loading estimations: *Bulletin d'Information des Marées Terrestres*, 100, 6962-6986.
- Güntner, A., Stuck, J., Werth, S., Döll, P., Verzano, K., Merz, B., 2007, A global analysis of temporal and spatial variations in continental water storage. *Water Resources Research*, 43(5), W05416.
- Kroner, C., Thomas, M., Dobslaw, H., Abe, M., Weise, A., 2009, Seasonal effects of non-tidal oceanic mass shifts in observations with superconducting gravimeters: *Journal of Geodynamics*, accepted.
- Naujoks, M., 2008, Hydrological information in gravity: observation and modelling: PhD-thesis, Institute of Geosciences, Friedrich-Schiller-University Jena.
- Naujoks, M., Weise, A., Kroner, C., Jahr, T., 2008, Detection of small hydrological variations in gravity by repeated measurements with field gravimeters: *Journal of Geodesy*, 82 (9), 543-553.
- Neumeyer, J., Barthelmes, F., Kroner, C., Petrovic, S., Schmidt, R., Virtanen, H., Wilmes, H., 2008, Analysis of gravity field variations derived from superconducting gravimeter recordings, GRACE satellite and hydrological models at selected European sites: *Earth, Planets and Space*, 60, 1-14.
- Rodell, M., Houser, P.R., Jambor, U., Gottschalck, J., Mitchell, K., Meng, C.-M., Arsenault, K., Cosgrove, B., Radakovich, J., Bosilovich, M., Entin, J.K., Walker, J.P., Lohmann, P., Toll, D., 2004, The Global Land Data Assimilation System: *Bulletin of the American Meteorological Society*, 85 (3), 381394.
- Schmidt, R., Flechtner, F., Güntner, A., König, R., Meyer, U., Neumayer, K.-H., Petrovic, S., Reigber, Ch., Zhu, S.-Y., 2005, Surface mass variability from GRACE and hydrology: *Geophysical Research Abstracts*, 7, 04736.
- Swenson, S. and Wahr, J., 2009, Monitoring the water balance of Lake Victoria, East Africa, from space: *Journal of Hydrology*, 370(1-4), 163-176.
- Wahr, J., Swenson, S., Zlotnicky, V., Velicogna, I., 2004, Time-variable gravity from GRACE: First results, *Geophysical Research Letters*, 31, L11501.
- Weise, A., Kroner, C., Abe, M., Ihde, J., Jentsch, G., Naujoks, M., Wilmes, H., Wziontek, H., 2009, Terrestrial gravity observations with superconducting gravimeters for validation of satellite-derived (GRACE) gravity variations: *Journal of Geodynamics*, accepted.
- Werth, S., Güntner, A., Petrovic, S., Schmidt, R., 2009, Integration of GRACE mass variations into a global hydrological model: *Earth and Planetary Science Letters*, 277(1-2), 166-173.