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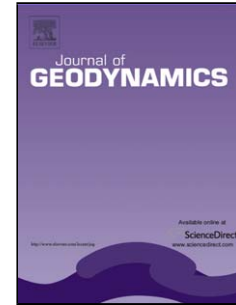
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## Gravity field variations from superconducting gravimeters for GRACE validation

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### Abstract

The network of superconducting gravimeters (SG) of the ‘Global Geodynamics Project’ (GGP) offers the unique opportunity to supplement and validate the gravity field variations derived from the GRACE satellite mission. Because of the different spatial and temporal resolution of the gravity data a combination of all data sets can be used to retrieve a maximum of information regarding mass transfers especially related to hydrology which is deployable as constraint for hydrological modelling.

For a consistent combination of the data sets the gap between terrestrial data of superconducting and absolute gravimeters (AG) and from satellite data has to be bridged. A successful combination of SG and AG data could be realized for several stations which resulted in time series of highest accuracy and long-term stability.

In principle, the same reductions applied to GRACE data have to be taken into account for the terrestrial data. The separation of local hydrological effects in SG observations is crucial for the comparison with satellite-derived gravity data. It is shown that even for stations with a hydrological challenging situation such as Moxa/Germany local hydrology-induced effects can be successfully modelled.

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Currently, the study focuses on Europe with its dense and long-term observation network. Regarding the consistency of the SG gravity variations they are representative for a larger region. From a comparison with GRACE-derived gravity field changes, and the variations due to hydrological models a principle good agreement emerges.

*Keywords:* temporal gravity field variations, superconducting gravimetry, GGP, GRACE, hydrological gravity effects

## **1. Introduction**

Gravity data from terrestrial as well as from satellite-derived observations contain valuable information about mass transports mainly due to the global hydrology. The combination of terrestrial observations with superconducting gravimeters (SG) and repeated absolute gravity measurements (AG) offers the unique opportunity to supplement and evaluate temporal gravity field variations derived from the GRACE satellite mission. First comparisons were done by e.g. Boy and Hinderer (2006), Hinderer et al. (2006, 2009), Neumeyer et al. (2006b, 2008), and Crossley et al. (2009).

The resulting data base can be used for studies of mass transport phenomena related to hydrology and geodynamic processes on different temporal and spatial scales. One essential task prerequisite is the separation of local effects from large-scale ones in the terrestrial data (e.g. Creutzfeld et al., 2008, Naujoks et al., 2008; Longuevergne et al., 2009). This study will contribute e.g. to the utilization of gravity data for regional quantification of hydrological dynamics and to derive constraints to hydrological models which simultaneously will lead to an improved reduction of hydrological signals in gravity observations.

Due to the different spatial and temporal resolution of the data sets, a procedure needs to be developed for a consistent combination. The challenging task requires terrestrial gravity time series of highest precision and long-term stability, which can be achieved only by the combination of superconducting and absolute gravimeter observations.

The present study focuses on Europe and benefits from the dense and long-term terrestrial observation network of SG (Fig. 1) within the 'Global Geodynamics Project' (GGP, Crossley et al., 1999), despite the small gravity changes due to hydrological mass storage to be expected (Crossley et al., 2005; Schmidt et al., 2008).

## **Figure 1**

### **2. Consistent combination of SG and AG measurements**

The SG time series have been reprocessed according to predefined standards providing a consistent processing and a documentation especially with regard to offset removals. The data sets presently available cover the period from 2003 to 2006 corresponding to the selected period for GRACE.

The sensor of the SG is known to provide a high resolution and a low and very stable zero reference drift, which must be precisely estimated to determine long-term changes in gravity. Due to its relative measuring principle the SG needs to be precisely calibrated. In contrast AGs are based on direct realization of physical standards for length and time. Thus, a drift can be excluded, but regular supervision of the AG instruments is necessary especially after maintenance.

The combination of the measurements of both gravimeter types allows the determination of instrumental properties and results in a reliable and precise continuous gravity time series with long-term stability. Wziontek et al. (2009) used for some SG stations an improved combination approach: Drift and scale function are estimated for

the SG and offset checks are carried out for the AG simultaneously based on primary observations within a least squares procedure, avoiding reductions of time-variable constituents in the gravity signal. The results are drift corrected gravity time series with a high resolution, for example for the SG time series Bad Homburg in Fig. 2.

## Figure 2

### 3. Reductions for the consistent combination of gravity time series

For the consistent combination of terrestrial and satellite-derived gravity variations the same reductions applied to GRACE data have to be considered for the terrestrial time series. Fig. 3 shows the gravity residuals for several SG stations after reduction of earth and ocean tides, atmospheric effects, and polar motion signal. The specifications of the reductions are given in Kroner et al. (2009). The effects of atmospheric variations are reduced using data from ECMWF. The attraction effect is removed by a 3D-modelling up to a spherical distance of  $5^\circ$  (Neumeyer et al., 2004, 2006a; Abe et al., 2009; Klügel and Wziontek, 2009). For the remaining parts of the Earth's surface the reduction is based on surface pressure (Merriam, 1992), which is used as well for the reduction of the atmospheric loading. Not applied up to now are reductions with respect to the non-tidal ocean mass redistribution, which are presently suffering from uncertainties due to a rough grid (Kroner et al., 2009), and the ocean pole tide effect, which is with  $< 2 \text{ nm/s}^2$  at European SG sites smaller than the uncertainties of other long-period signals (Chen et al., 2008, 2009).

After applying the reductions the remaining variations mainly contain signals due to hydrology (Fig. 3). For a regionalized interpretation of the SG time series the central European gravity residuals are expected to show a similar behaviour. Currently, a

seasonal signal emerges with maxima in winter to spring with deviations in amplitude. The signal varies between 60 nm/s<sup>2</sup> at Bad Homburg and 150 nm/s<sup>2</sup> at Wetzell. But for example at Moxa there is nearly no seasonal signal noticeable, which is also found for individual years in Membach. For Strasbourg the seasonal signal even seems to be anti-correlated to large-scale hydrology, with maxima in autumn to early winter (Longuevergne et al., 2009). Actually, it is well known that the global hydrological signal is concealed by local hydrological effects at some sites, when the local effect is different from the regional contribution, for example for subsurface stations like Strasbourg (Boy and Hinderer, 2006) and Membach (Meurers et al., 2007).

### Figure 3

#### 4. Reduction of local hydrological effects

Apart from global and regional effects, terrestrial data contain the impact of local mass changes. Checking for local hydrological effects is therefore required. At surface stations these effects primarily depend on heterogeneities below the sensor. In the case of subsurface stations or considerable topography, as e.g. for Moxa, where due to the hilly surroundings a major portion of the topography is above gravimeter level (Fig. 4), the attraction effect of local hydrology strongly depends on the local topography.

Typically, the local effect from an area of a few 100 m around the gravimeter reaches the order of magnitude of a few 10 nm/s<sup>2</sup>, depending on the local hydrological situation as well as the local topography. The modelling of a local reduction is essential in order to separate local and large-scale contributions. Studies in this regard have been carried out for Vienna, Wetzell (Creutzfeld et al., 2008) and for the subsurface SG sites Strasbourg (Boy and Hinderer, 2006; Longuevergne et al., 2009) and Membach (Van Camp et al., 2006; Meurers et al., 2007).

**Figure 4**

At the SG station Moxa, gravity changes due to local hydrology have been detected by repeated observations with relative gravimeters (LCR) of very high quality in a local network (Naujoks et al., 2008). Based on the conceptual hydrological model J2000 a local hydrological model has been developed for the catchment area of the small creek Silberleite in the valley of Moxa observatory (Krause et al., 2009). The main hydrological storages are most effective from the first few meters below surface due to the real topography with the SG installed at the bottom of the valley (Fig. 4). The hydrological variations are introduced as density changes in the soil and upper weathering layers into a high-resolution 3D gravity model of the 2 km x 2 km area (Naujoks et al., 2009). This novel combination of hydrological and 3D gravity modelling provides gravity variations in hourly time steps whose accuracy is assessed by the observed gravity changes in the local network. By considering gravity differences only the impact of local hydrological variations is regarded. From the modelling emerges a maximum effect during winter until snow melt, mostly occurring in March, which reaches  $54 \text{ nm/s}^2$  (Fig. 5). The contributions of individual parts of the area are separated: About 30 % of the local hydrological effect is caused by variations in the very near area within 90 m radius around the observatory. About 70 % of the local hydrological effect originates from a zone of 250 m radius.

After the reduction of the local hydrological effect in the gravity residuals of the SG at Moxa a seasonal signal in the order of 35 - 40  $\text{nm/s}^2$  appears (Fig. 6), which was masked before and is expected from large-scale hydrology.

**Figure 5**



**Figure 6****5. Large scale hydrological effects**

As for local hydrology also for regional hydrology a certain impact from topography, above and below the gravity sensor, might be expected. Using monthly values of the WaterGap Hydrological Model WGHM (Döll et al., 2003; Güntner et al., 2007) and GTOPO30 (<http://edc.usgs.gov/>) for topography estimates of the gravity effect for several European sites are carried out. A regional area with a radius of 2000 km, covering most of Europe, is defined. A local area of 1 km radius is excluded where the approximation of a thin water layer is not valid. The regional hydrological effects obtained with and without consideration of topography differ in the range of only 1 - 2 nm/s<sup>2</sup>, shown exemplarily for Moxa (Fig. 7). Thus, the topography is negligible for the regional hydrological effect. The global hydrological effect for areas of greater distance than 2000 km is with 7 - 8 nm/s<sup>2</sup> not negligible for Central Europe. The total non-local hydrological effect amounts to 30 - 38 nm/s<sup>2</sup>.

**Figure 7****6. Comparison of terrestrial and satellite-derived gravity field variations and gravity changes from a global hydrological model**

First comparisons are carried out with regard to common signal content of observed terrestrial and satellite-derived (GRACE) gravity variations on the one hand and with gravity changes based on large-scale hydrological models on the other hand. Fig. 8 shows the data sets of monthly values obtained for Moxa, Bad Homburg, and Medicina from 2003 to 2006. For Moxa the terrestrial gravity residuals are reduced for local hydrology (Fig. 6).

The residuals of the SG observations show a very good agreement, demonstrating that the signals are representative for a larger region and originate from the same source. For a comparison with the GRACE-derived gravity changes the monthly solutions by GFZ (RL04) are used, smoothed by Gaussian filter of half-widths analogous to the degrees  $l_{fl} = 10, 13, \text{ and } 20$  (Neumeyer et al., 2008; Schmidt et al., 2008). A principle good agreement with the terrestrial SG gravity residuals exists for the degrees  $l_{fl} = 10$  and  $l_{fl} = 13$ . In contrast the GRACE solutions with a lower amount of filtering, i.e.  $l_{fl} = 20$ , contain more fluctuations which are not present in the monthly means of the terrestrial time series. The contribution of vertical deformation due to loading of global hydrology which is not observed by the satellites is added to the GRACE data to make both series comparable (Neumeyer et al., 2006b).

### Figure 8

The two observed time series correspond to the gravity changes derived from the global hydrological model WGHM (Döll et al., 2003; Güntner et al., 2007). This confirms the assumption that the signal in the gravity variations is mainly caused by global hydrological variations. Deviations between the various time series, which are found in amplitude for some months, as well as phase lags with regard to the occurrence of minima and maxima, require further investigations.

## 7. Conclusions

An essential result is the consistence of the long-term variations of the SG gravity residuals at some central European SG sites, despite the great distances of several 100 km. Thus, regionalisation is permitted. Furthermore, the SG residuals and the

gravity changes from the satellite mission GRACE are in agreement. The same is found for the gravity variations derived from global hydrology (WGHM).

Complex local hydrological conditions are an obstacle which can be overcome as has been exemplarily shown for the SG site Moxa. This effect can mask the seasonal signal of global hydrology. Concerning the estimation of large-scale effects from hydrological models the consideration of the regional topography results in a negligible impact for Central Europe.

Further research will comprise

- to improve the agreement between terrestrial and GRACE observations by rescaling and changes in the filtering of the satellite data.
- to extend the studies to further global hydrological models. Constraints for hydrological models will be derived by a separation of the hydrological effects from different areas, in a first step for a regional model of Europe.
- to identify common characteristic spatial and temporal patterns in the gravity and hydrological time series by Principal Component Analysis and EOF analysis.

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**Fig. 1:** Stations of superconducting gravimeters in Central Europe for comparison with GRACE and superconducting gravimeter at the Geodynamic Observatory Moxa/Germany.

**Fig. 2:** Combination of SG and AG data at station Bad Homburg 2002-2006 ( $10 \text{ nm/s}^2 = 1 \text{ } \mu\text{Gal}$ ).

**Fig. 3:** Gravity residuals from superconducting gravimeters at some European stations.

**Fig. 4:** Sketch of topography around Moxa observatory including the main hydrological processes.

**Fig. 5:** Local hydrological effect at Moxa observatory with contribution of different zones around the SG (Naujoks et al., 2009).

**Fig. 6:** Gravity residuals with (—) and without (---) reduction of the local hydrological effect (---) estimated from a local model for Moxa (Naujoks et al., 2009).

**Fig. 7:** Monthly hydrological gravity effect computed for a regional zone with and without topography, a global area and the total effect for Moxa observatory, using the global hydrological model WGHM.

**Fig. 8:** Comparison of terrestrial gravity residuals (monthly mean) from SG observations with monthly GRACE solutions using different filtering (see text, sect. 6) and with gravity variations derived from modelled changes in continental water storage (WGHM) for stations Moxa (after local hydrological reduction), Bad Homburg, and Medicina. The contribution of vertical deformation due to loading of global hydrology not observable by satellites was added to the GRACE data for the comparison.

Figure 1





Figure 2

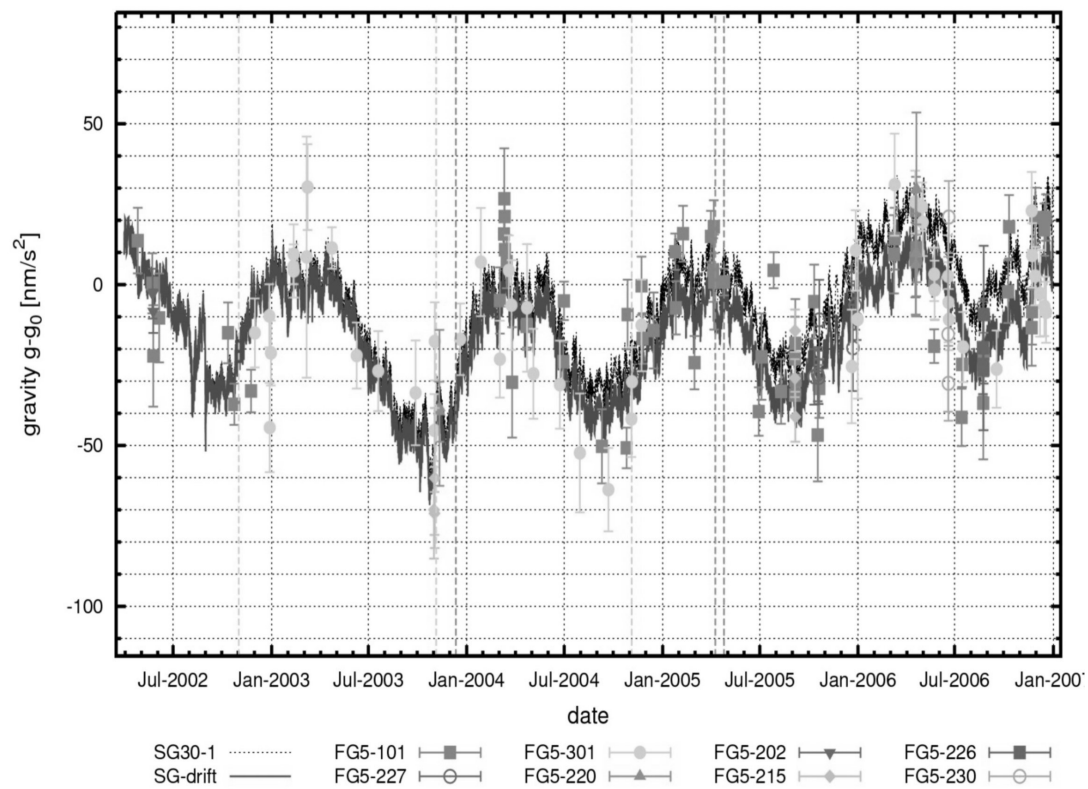


Figure3

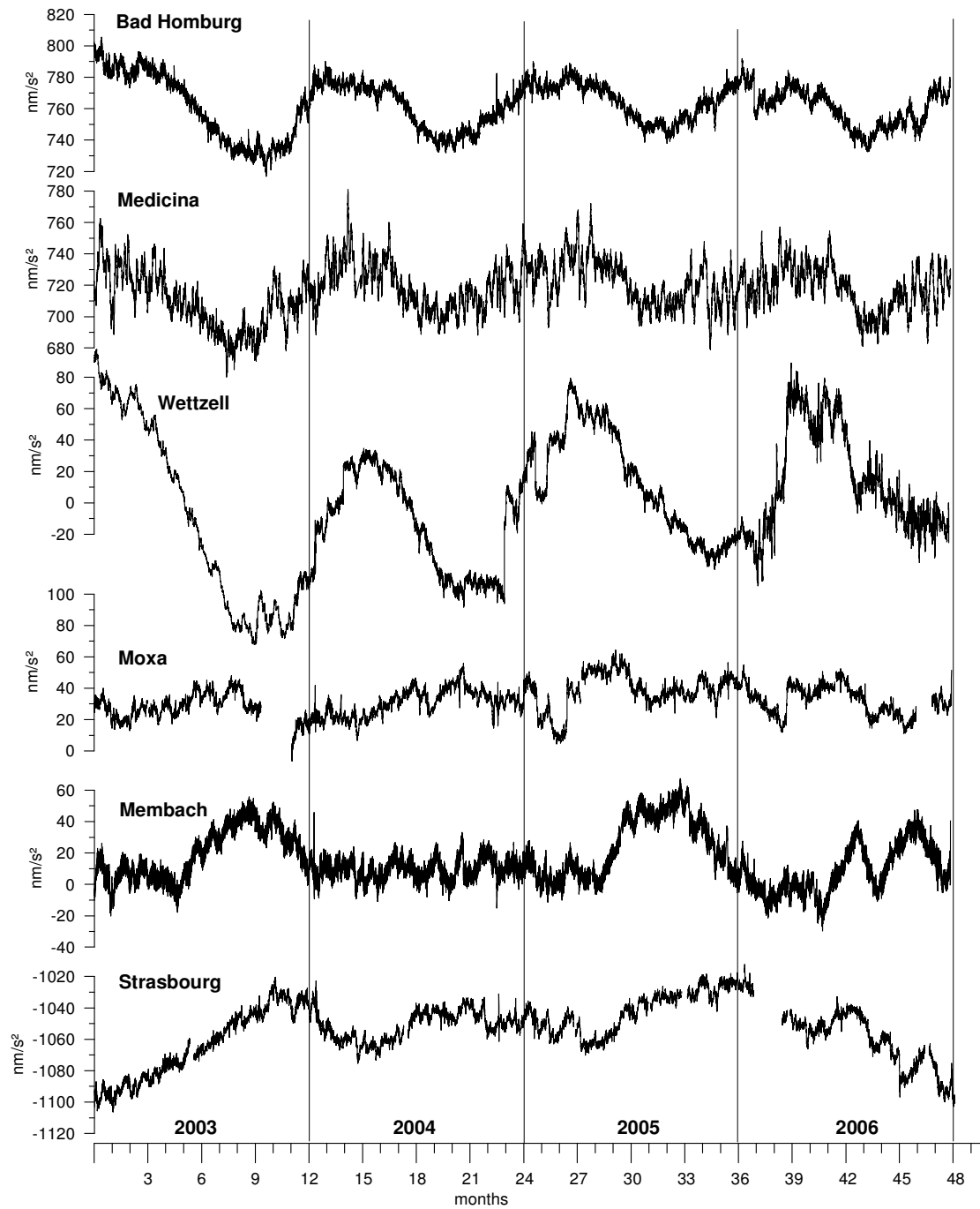
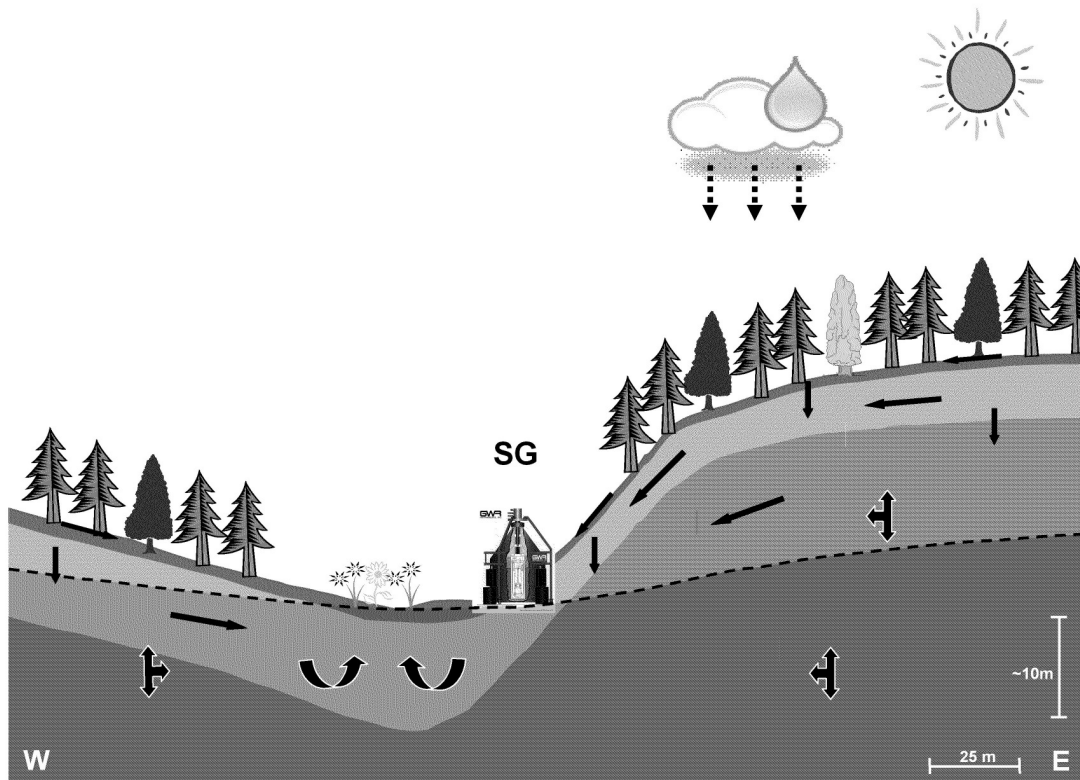


Figure 4



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Figure 5

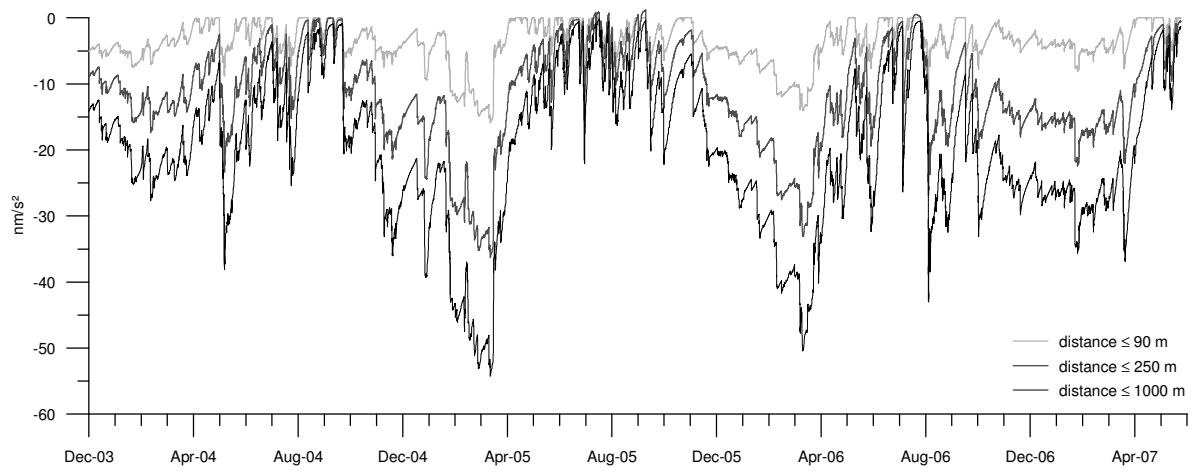


Figure 6

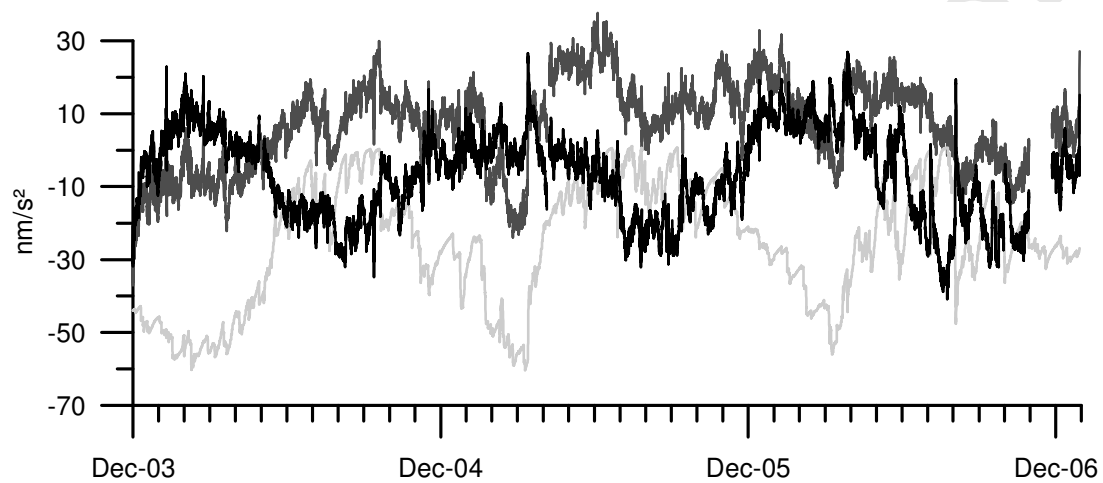


Figure 7

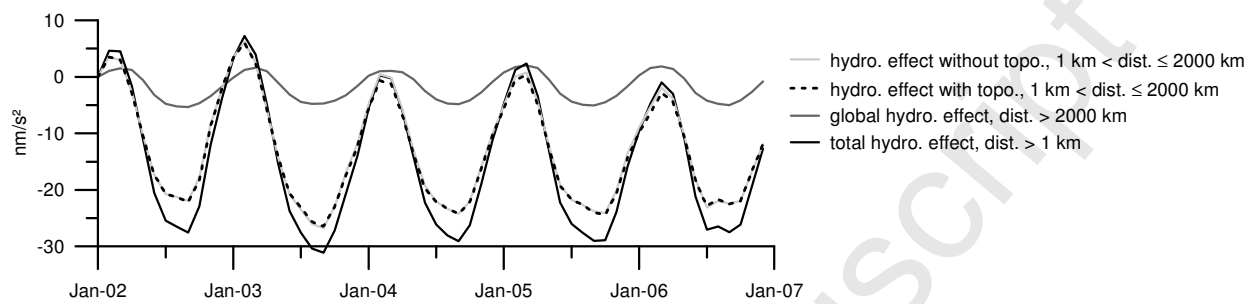


Figure 8

