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Total water storage dynamics derived from tree-ring records and terrestrial gravity observations

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S U M M A R Y

For both societal and ecological reasons, it is important to understand past and future subsurface water dynamics but estimating subsurface water storage is notoriously difficult. In this pilot study, we suggest the reconstruction of subsurface water dynamics by a multi-disciplinary approach combining hydrology, dendrochronology and geodesy. In a first step, nine complete years of high-precision gravimeter observations are used to estimate water storage changes in the subsurface at the Geodetic Observatory Wettzell in the Bavarian Forest, Germany. The record is extended to 63 years by calibrating a hydrological model against the 9 years of gravimeter observations. The relationship between tree-ring growth and water storage changes is evaluated as well as that between tree-ring growth and supplementary hydrometeorological data. Results suggest that tree-ring growth is influenced primarily by subsurface water storage. Other variables related to the overall moisture status (e.g., Standardized Precipitation Index, Palmer Drought Severity Index, streamflow) are also strongly correlated with tree-ring width. While these indices are all indicators of water stored in the landscape, water storage changes of the subsurface estimated by depth-integral measurements give us the unique opportunity to directly reconstruct subsurface water storage dynamics from records of tree-ring width. Such long reconstructions will improve our knowledge of past water storage variations and our ability to predict future developments. Finally, knowing the relationship between subsurface storage dynamics and tree-ring growth improves the understanding of the different signal components contained in tree-ring chronologies.

1. Introduction

In many parts of the world, water stored in the subsurface as groundwater or soil moisture is the main fresh water source not only for drinking water and food production but also for natural vegetation. Global change is expected to alter rainfall and temperature patterns and, as consequence of the tight linkage between climate and hydrological cycle, will affect terrestrial water storage in its spatial as well as temporal distribution. For example, heat waves and droughts are likely to become more intense and frequent (e.g., Meehl and Tebaldi, 2004; Schär et al., 2004; Sheffield and Wood, 2008), which will have a significant impact on the water availability. Furthermore, water storage anomalies can have a positive feedback on heat waves by amplifying these extremes (e.g., Hirschi et al., 2011; Vautard et al., 2007). Observational knowledge of the past is necessary to improve our understanding of the environmental system and the prediction of future developments thus allowing more efficient water resource management (Woodhouse and Lukas, 2006).

Despite the importance of subsurface water storage, measuring its dynamics still remains a challenge. Often point measurements of groundwater levels and soil moisture, which are spatially highly variable due to structural and textural heterogeneity of the subsurface, are extrapolated to an extent where the uncertainties make a clear interpretation of patterns and dynamics impossible. This is especially true in areas with deep unsaturated zones where soil moisture data become even more important. In this context, the novel data sets from high-precision gravimeters (Goodkind, 1999; Niebauer et al., 1995) are promising, as these gravimeter measurements are influenced by subsurface water storage changes (e.g., Boy and Hinderer, 2006; Creutzfeldt et al., 2010a; Jacob et al., 2008; Kroner and Jahr, 2006; Meurers et al., 2007; Van Camp et al., 2006) and allow for the depth-integrated estimation of water storage change over the entire footprint (Creutzfeldt et al., 2012).

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These data sets give an insight into the integral response dynamics of the subsurface system, integrating over the different compartments from the surface to the groundwater instead of small scale dynamics of point measurement likely to be affected by local heterogeneities or by the measurement technique itself. However, due to the novelty of this method, only relatively short time series are available. In order to understand the long-term variability, long time series of subsurface water storage need to be reconstructed.

Tree-ring records such as width, density or isotope composition have proved to be a valuable source to provide long-term proxy data on environmental conditions (e.g., Cook and Kairiukstis, 1990; Hughes et al., 2011; Schweingruber, 1996), since temperature and water supply are the dominant factors controlling tree growth (Kozlowski and Pallardy, 1997). As the water supply of trees is based on subsurface water both from the saturated and the unsaturated zone, trees are a natural archive of subsurface water storage information. Dendrochronologies have been used to infer precipitation records, or different hydro-meteorological indices, such as Standardized Precipitation Index (SPI) or Palmer Drought Severity Index (PDSI) (e.g., Kagawa et al., 2003; Meko et al., 1995; Miller et al., 2006; Stahle and Cleaveland, 1992; Wilson et al., 2005). Furthermore, runoff time series have been reconstructed based on tree-ring chronologies making use of the direct relationship between the hydrological system state (water storage) and its response (discharge; e.g., Loaiciga et al., 1993; Meko and Woodhouse, 2011; Woodhouse et al., 2006). However, only a few studies focused on the relationship of single storage components, like groundwater or soil moisture to tree-ring data (e.g. Anderson et al., 2012; Bogino and Jobbágy, 2011; Briffa and Wigley, 1985; Ferguson and George, 2003; Kagawa et al., 2003; Perez-Valdivia and Sauchyn, 2011; Yin et al., 2008). These studies found good correlations between tree rings and parameters such as soil moisture (Anderson et al., 2012; Yin et al., 2008) and groundwater depth (Bogino and Jobbágy, 2011; Ferguson and George, 2003). As mentioned by Anderson et al. (2012) reconstructions of soil moisture are not yet common, because existing soil moisture data are limited both spatially and temporally. To the best of our knowledge, no study has investigated the relationship of tree-ring growth and subsurface water storage variation. Furthermore, except for groundwater level measurements, in the above-mentioned studies only modelled soil moisture data or soil moisture proxies were compared to tree ring data.

In this pilot study, we will investigate the relationship between subsurface water storage change and tree-ring width, where water storage change is expressed using the minimum observed water storage of the study period as the baseline. Water storage change is measured by a superconducting gravimeter in combination with an absolute gravimeter from 2000 to 2009 in the Southeast of Germany (Creutzfeldt et al., 2012). On the one hand, these depth-integrated measurements allow for a direct comparison of subsurface storage dynamics and tree-ring growth. On the other hand, the same data set of gravimetric data is used to calibrate a hydrological model (Creutzfeldt et al., 2010b). This model is then run for the entire period of available climatic data (1947–2009). The resulting time series of subsurface storage dynamics also allow us to investigate the relationship of tree-ring growth and water storage change in the context of other climate time series, hydrological data or environmental indices. A statistical model is constructed relating tree-ring width to the amount of water stored in the subsurface. This statistical model is then applied directly to time series of tree-ring width to reconstruct subsurface water storage dynamics for the period 1900 to 2009. Hence, we show how the combination of tree-ring data, superconducting gravimeter data and hydrological modelling allows reconstructing long time series of water storage dynamics.

2. Material and methods

2.1. Research site and hydro-meteorological data

The study area surrounds the superconducting gravimeter of the Geodetic Observatory Wettzell, operated by the Federal Agency for Cartography and Geodesy (BKG; Schlüter et al., 2007). The Geodetic Observatory Wettzell is located in the Bavarian Forest at a mid-mountain range in the Southeast of Germany (Fig. 1). The area is characterized by undulating highlands with grassland and fields and steep long slopes dominated by forests. The Geodetic Observatory Wettzell and the immediate surrounding area are dominated by grassland, interspersed with some groves. At a distance of 250 m, mixed forest stands containing *Picea abies* (L.) H. Karst. (spruce), *Abies alba* Mill. (fir), *Fraxinus excelsior* L. (ash), *Betula pendula* Roth (birch) and *Quercus sp.* (oak) trees can be found, however, the dominant tree species is spruce. The soils are predominantly Cambisols, partly acidified and leached. Distinct characteristics of the soils are their periglacial weathering cover (Grams, 2010; Völkel, 1995). The geology consists of acidic metamorphic rocks (biotite-gneiss), which generally shows a seamless transition toward the surface into a fractured zone followed by a saprolite cover consisting mainly of weathered gneiss (Raum, 2002).

The study area is characterized by a temperate climate with a mean annual precipitation of 995 mm, a potential evapotranspiration of 577 mm, and a mean annual temperature of 7 °C. Precipitation, air temperature, air humidity and snow depth have been measured continuously since 1947 at the hydropower plant Höllenstein, which is located at a distance of 2 km from the research site. Since 2000, climate and groundwater piezometer data are also available from the comprehensive monitoring station at the observatory. Streamflow was measured at the nearby stream gauge Kötzting (river Weißer Regen; catchment size 224 km^2) for the period of 1947–2009. Data were processed to daily, monthly and yearly time series and potential evapotranspiration (Thornthwaite, 1948), Standardized Precipitation Index (SPI)

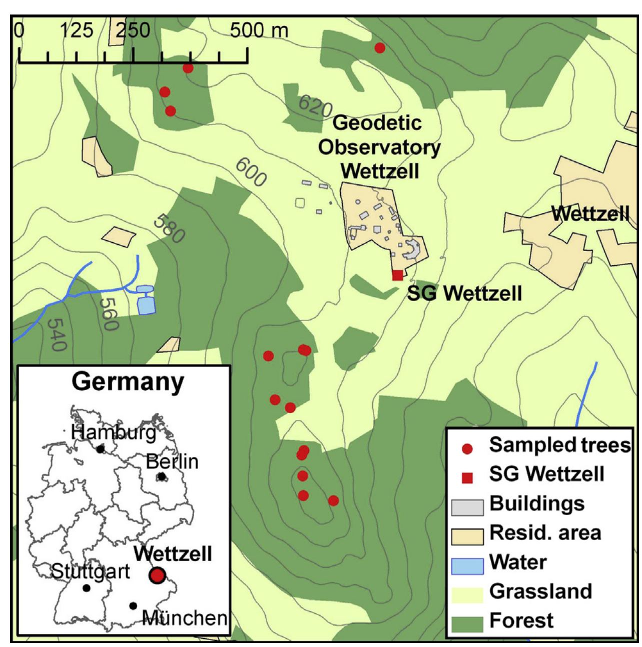

Fig. 1. The study area with spatial arrangement of the instrumentation, sampled trees and the land use around the Geodetic Observatory Wettzell. The inset map displays the location of the study area in Germany in combination with major cities (black dots) and the federal states of Germany (grey lines).