Introduction of a Superconducting Gravimeter as Novel Hydrological Sensor for the Alpine Research Catchment Zugspitze

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Abstract. The Zugspitze Geodynamic Observatory Germany has been set up with a worldwide unique installation of a superconducting gravimeter at the summit of Mount Zugspitze. With regard to hydrology, this karstic high-alpine site is largely dominated by high precipitation amounts and a long seasonal snow cover period with significant importance for water supply to its forelands, while it shows a high sensitivity to climate change. However, regarding the majority of alpine regions
20 worldwide there is only weak knowledge on temporal water storage variations due to only sparsely distributed hydrological and meteorological point sensors and the large variability and complexity of alpine signals. This underlines the importance of well-equipped areas such as Mount Zugspitze serving as natural test laboratories for an improved monitoring, understanding and prediction of alpine hydrological processes. The observatory superconducting gravimeter OSG 052 supplements the existing sensor network as a novel hydrological sensor system for the direct observation of the integral gravity effect of total
25 water storage variations in the alpine research catchment Zugspitze. Besides the experimental setup and the available datasets, the required gravimetric prerequisites are presented such as calibration, tidal analysis and signal separation of the superconducting gravimeter observations from the first 2 years. The snowpack is identified as primary contributor to seasonal water storage variations and thus to the gravity residuals with a signal range of up to 750 nm/s² corresponding to 1957 mm snow water equivalent measured at a representative station at the end of May 2019. First hydro-gravimetric sensitivity analysis
30 are based on simplified assumptions of the snowpack distribution within the area around Mount Zugspitze. These reveal a snow-gravimetric footprint of up to 4 km distance around the gravimeter with a dominant gravity contribution from the snowpack in the Partnach spring catchment. This study already shows that the hydro-gravimetric approach can deliver important and representative integral insights into this high-alpine site. This work is regarded as a concept study showing preliminary gravimetric results and sensitivity analysis for upcoming long-term hydro-gravimetric research projects.

1 Introduction

One of the grand societal challenges is ensuring a sufficient water supply under climate change conditions. The European Alps are of crucial importance to supply water for ecological, energy and societal purposes and with a relatively large fraction of annual precipitation received and stored, they are often referred to as water towers (Immerzeel et al., 2020; Beniston et al., 2018; Viviroli et al., 2007). The IPCC (2014) indicates that "in many regions, changing precipitation or melting snow and ice are altering hydrological systems, affecting water resources in terms of quantity and quality", thereby emphasizing the need for efficient future water management strategies, even in currently water secure regions (see also Immerzeel et al., 2020). To develop such strategies, a comprehensive understanding and quantification of changing hydrological processes in mountainous regions, including short- and long-term observations and model predictions are urgently required.

However, due to the high installation and maintenance costs of monitoring equipment, and often harsh environmental conditions causing instrument failure and difficult accessibility, hydro-meteorological observatories and subsequent data for high-alpine catchments are scarce. The Partnach spring catchment in the southeast of the summit of Mount Zugspitze, also known as the Research Catchment Zugspitze (RCZ), belongs to one of the best-instrumented high-alpine catchments for monitoring snow hydrological processes (Bernhardt et al., 2018). Due to a special geological karst situation, the entire catchment is solely drained by the Partnach spring, and can therefore be regarded as a natural lysimeter, allowing for detailed water balance studies (Wetzel, 2004; Rappl et al., 2010). Given this unique geological situation and the available instrumentation, the RCZ is part of the GEWEX International Network of Alpine Research Catchments (INARCH; Pomeroy et al., 2015).

The environmental research station Schneefernerhaus (UFS), located in the RCZ, is easily accessible with cable cars, and operates a dense hydro-meteorological sensor network jointly with the German Weather Service (DWD) and the Bavarian Avalanche Warning Service (LWD) including a portable LiDAR sensor for spatially distributed snow height monitoring (see subsection 2.2 for details). Detailed water balance and karst water discharge studies at the Partnach spring have investigated runoff responses to rainfall and snowmelt dynamics and characterized the karst groundwater aquifer (Hürkamp et al., 2019; Morche and Schmidt, 2012; Rappl et al., 2010; Wetzel, 2004). Numerous snow-hydrological studies further investigated the spatiotemporal dynamics of snow cover and the snow water equivalent (SWE) (Bernhardt et al., 2018), combining monitoring techniques, such as terrestrial photography (Härer et al., 2013 and 2016), remote sensing (Härer et al., 2018) or LiDAR observations (Weber et al., 2016, 2020, and 2020a) with different complex snow-hydrological modelling. Some limitations arising from these studies were the small number of cloud-free remote sensing scenes in the visible and near-infrared spectrum to derive spatially distributed snow cover maps at high temporal resolutions, and the limited spatial extent of the terrestrial photography and LiDAR observations in the RCZ (Härer et al., 2016; Weber et al., 2016, and 2020). Both, photography and

LiDAR observation techniques are not able to measure the hydrologically relevant SWE value directly, but rather rely on additional snow density data from local snow pit or snow weight measurements.

70   The last years of terrestrial gravimetric research have seen a transformation of SG installations from low noise sites for the analysis of global geophysical phenomena to specific sites of interest for the monitoring of near-surface mass transport processes. These include the development of SGs as hydrological sensors for the direct, integral and non-invasive monitoring of total water storage variations in a radius of up to 4 km around the SG in a minimized field enclosure (Güntner et al., 2017). Just recently, Chaffaut et al. (2020) reported about an SG installation in a lower mountain catchment in the French Vosges for
75   the analysis of water storage dynamics. In this catchment, however, seasonal snow cover plays a minor role. In addition, SGs are applied in connection with absolute gravimeters (AGs) and relative spring gravimeters (RGs) in hybrid approaches for hydro-gravimetry (Naujoks et al., 2010) and even for volcano monitoring (Carbone et al., 2019) and geothermal mass movements (Schäfer et al., 2020). These hybrid approaches exploit the advantages of the various types of gravimeters with the AGs providing long-term gravity changes, SGs for the continuous high-precision temporal gravity changes at the measurement
80   sites and RGs for additional spatiotemporal variations in the area of interest.

Any available catchment data can be either used directly to analyse the dynamics of individual components of the catchment water balance, or used in combination with snow-hydrological models where it can provide information on the initial and boundary conditions and also information relevant for model parameters, as well as important data to calibrate the model.
85   While snow cover and snow height data are able to condition the model behaviour to some degree (Weber et al., 2020a), it has recently been shown that integral data from satellite (Bahrami et al., 2020) and terrestrial gravimetry (Güntner et al., 2017) that provide footprint averaged time series of terrestrial water storage anomaly (TWSA) can greatly improve the identification of water balance components and relevant hydrological processes in the catchment.

90   Gravimetric methods are already applied in the RCZ. Episodic AG observations have been carried out since 2004 with a FG5 absolute gravity meter by the Leibniz University Hannover (LUH) for the analysis of long-term gravity changes at Mount Zugspitze and for a long-range gravimeter calibration base (Timmen et al., 2006; Peters et al., 2009). Timmen et al. (2021) estimate a geophysical trend of -20 nm/s²/yr. with an uncertainty of 3 nm/s²/yr. (single standard deviation 1σ) from AG observations between 2004 and 2019 as a consequence of Alpine mountain uplift and hydrological mass loss. Monthly RG
95   observations have been done with a transportable spring gravimeter since 2014 by the Technical University of Munich (TUM) for the analysis of periodic permafrost changes and cavity detection in a tunnel (Kammstollen) of Mount Zugspitze (Scandroglio et al., 2019). The most important gap in the hybrid gravimetric approach has now been closed by the installation of the SG at the summit of Mount Zugspitze enabling the separation of short-term, seasonal, interannual and long-term gravity changes.

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The overall research question to be discussed in this study is to what extent the OSG 052 can contribute to a better understanding of hydrological processes in high-alpine catchments. This addresses the benefits and improvements of the hydro-gravimetric approach but also its limitations. After a presentation of the available data sets from gravimetry to hydrology and meteorology in the RCZ (section 2), the applied gravimetric methods for the separation of the hydrological signal from the

105 gravity observations are shown (section 3). Section 4 contains the hydro-gravimetric results and sensitivity analysis with regard to various water storage components. Section 5 summarizes the main results and provides an outlook on future hydro-gravimetric projects.

2 Observations

Mount Zugspitze is Germany's highest mountain with an altitude of 2962 m. There are half a million tourists every year and

110 correspondingly high media attention. The worldwide unique setup of the Zugspitze Geodynamic Observatory Germany at the summit of Mount Zugspitze (Figure 1) is explained including all relevant sensors and datasets. In addition, the available hydrological and meteorological datasets from the alpine research catchment Zugspitze are introduced.

2.1 The Zugspitze Geodynamic Observatory Germany

The Zugspitze Geodynamic Observatory Germany (ZUGOG) has been set up by the German Research Centre for Geosciences

115 (GFZ) at the summit of Mount Zugspitze in a former laboratory of the Max Planck Institute for Extraterrestrial Physics (MPE), which was built in 1963 for the observation of cosmic rays (Figure 2). The 10 m high tower-like aluminium structure of the lab with an area of approx. 50 m² has a very steep roof to keep it free from snow. In addition, the position at the summit prevents hydrological mass variations above the sensor and simultaneously increases the hydro-gravimetric footprint. Inside the lab, there is a measuring room with two concrete piers on the ground floor. While the first concrete pier is occupied by the

120 SG, the second one is intended for absolute and relative gravimeters as well as other instruments. On the first floor are basic sleeping facilities for overnight stays if necessary. A ventilation has been installed in order to reduce the heat produced by the compressor of the SG. This is necessary as the lab itself heats up considerably during sunny days. In addition, a thermally insulated box has been built around the SG including heaters to keep the sensor at a stable ambient temperature of around 25°C. Temperature and humidity sensors have been installed in the lab. The power supplies of all electronics and compressor

125 are secured by uninterruptible power supplies (UPS). The lab is accessible all year round with cable cars from Germany and Austria. The UFS provides personnel and technical support as well as infrastructure during maintenance trips.
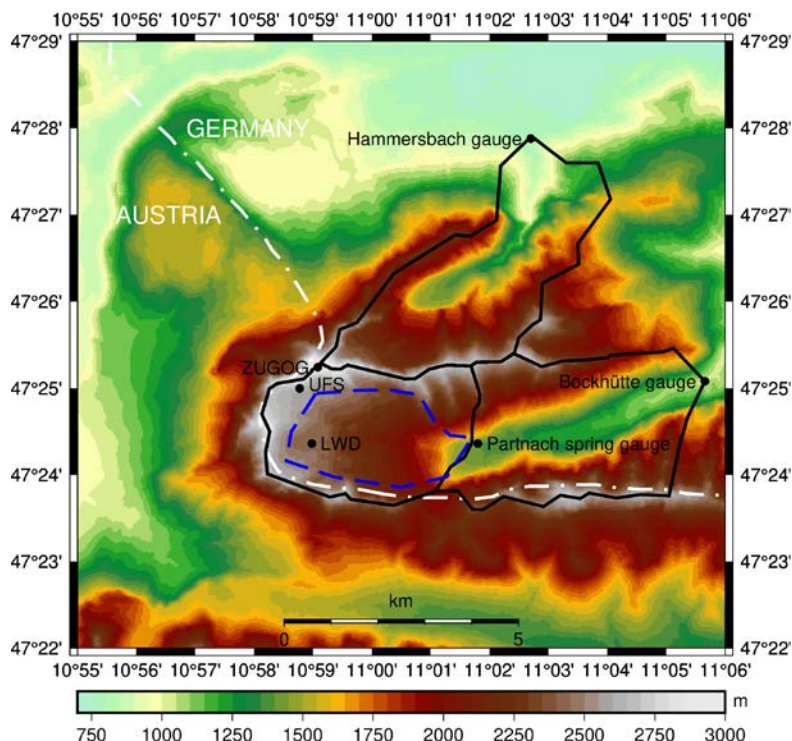
Figure 1: Topographic heights around the Zugspitze Geodynamic Observatory Germany (ZUGOG), the Environmental Research
130 **Station (UFS) and the hydro-meteorological station (LWD), the alpine catchments (black lines) Partnach spring (11 km²) as part of**
Bockhütte (25 km²) with their corresponding gauge stations as well as the Hammersbach catchment (14 km²) with its planned gauge
station, and the estimated groundwater body below Zugspitzplatt (blue dashed line)

In September 2017, the OSG 052 was warmed up to room temperature at its former location in Sutherland, South Africa, and
sent to the manufacturer GWR Instruments, Inc. in San Diego for refurbishment after observing in parallel with the dual sphere
135 OSG D-037 between 2008 and 2017 (Förste et al., 2016). The refurbishment of the 10 years old SG at GWR included the
thermal levellers, an upgrade of the electronics from version GEP-2 to GEP-3, a modification of the dewar to enable cooling
from room temperature down to 4 K with the accompanying refrigeration system, a replacement of the GPS antenna and a
barometer specifically calibrated for a working altitude of 3000 m as well as an Intel mini Personal Computer for the operation
of the UIPC software under Windows 7.

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Figure 2: Top left: The Zugspitze Geodynamic Observatory Germany (ZUGOG) with GNSS station in front; top right: OSG 052
150 **installed on the ground floor at ZUGOG, bottom left: ZUGOG with snow height sensors and snow scale in front; bottom right:**
ZUGOG with a winter view of a part of the alpine research catchment Zugspitze including the Northern and Southern Schneeferner
glaciers.

After returning to GFZ, the OSG 052 has been moved to ZUGOG in September 2018 by truck, cogwheel train and helicopter

at operating temperatures of 4 K. The first weeks of gravity observations with the OSG 052 showed an instrumental

155 malfunction with a very large negative drift of about -50 nm/s²/day and several small offsets. This led to the decision at the

end of October 2018 to warm up and re-cool the SG in order to eliminate the abnormal drift. However, the cooling process

stopped at 160 K, and the dewar had to be pumped out to recreate a proper vacuum. After that, the temperatures started to

decrease again and, finally, the levitation of the sphere could be completed and the SG has been in nominal operation since 29

December 2018. ZUGOG is part of the International Geodynamics and Earth Service (IGETS; Boy et al., 2020) providing

160   Level 1 raw gravity and atmospheric pressure data with sampling rates of 1 s and 1 minute (Voigt et al., 2019) on a regular basis to the publicly accessible IGETS data base hosted by GFZ (Voigt et al., 2016). In addition, the continuous Global Navigation Satellite Systems (GNSS) station ZUGG (Ramatschi et al., 2019) has been installed at 9 Sep 2018 nearby the lab for monitoring of deformations (Figure 2 top left) and is recording since then.

165   For the monitoring of local hydrological and meteorological variations, several environmental sensors have been installed. A snow scale and three laser-based snow height sensors have been installed in front of the lab in order to quantify the accumulated snow masses on this horizontal plane during the winter months. After the experiences from the first winter 2018/2019, the pole with the snow height sensors had to be extended from 2.5 to 4 m (Figure 2 bottom left). Another laser-based snow height sensor has been installed with a view to the slope directly below the SG. Laser-based sensors have been preferred instead of

170   the widely used ultrasonic sensors because the snow cover is not horizontal. A small meteorological station outside the lab observes temperature and humidity as well as wind speed and direction. All data sets are parts of a remotely controlled monitoring system.

2.2 Hydrological and meteorological datasets in the research catchment Zugspitze

ZUGOG is connected to the UFS as the home base of a large research consortium operating a dense hydrological and

175   meteorological sensor network for more than 20 years. Long-term meteorological datasets are available on hourly to yearly basis from the Climate Data Center (CDC) of DWD for the station at the summit of Mount Zugspitze (Station ID 5792) including relative humidity, air temperature, precipitation height and form, wind speed and direction and air pressure. LWD provides several hydrological and meteorological datasets from a station at the Zugspitzplatt at an altitude of 2420 m including the SWE of the snowpack recorded by a snow scale. Moreover, in the last few years three further meteorological stations were

180   set up at the Zugspitzplatt as well as on two mountain ridges in the frame of the Virtual Alpine Observatory project (VAO).

Gauge stations have been set up for the observation of the discharge at Partnach spring and Bockhütte (Figure 1), while another gauge station is planned for the Hammersbach catchment. The Partnach spring catchment (RCZ) covers an area of about 11 km² located in the Northern Limestone Alps. Its main characteristics are a mean annual precipitation sum of 2080 mm and an

185   average temperature of -4.5°C regarding the climatic reference period 1981 to 2010 (Weber et al., 2016). The altitudes vary between 2962 m (summit of Mount Zugspitze) and 1430 m at Partnach spring where the catchment is exclusively drained due to the special geological karst situation being therefore regarded as a natural lysimeter. Germany's highest glacier remains - the Northern and Southern Schneeferner – are also located in the RCZ as well as permafrost in the rock walls of Mount Zugspitze (Krautblatter et al., 2010). The RCZ is part of the Bockhütte catchment with an area of 25 km². The Hammersbach

190   catchment covers an area of 14 km² in northeastern direction from Mount Zugspitze and includes the Höllentalferner glacier. Karst hydrological characteristics can be found in Lauber and Goldscheider (2014).

All datasets are compiled in the Alpine Environmental Data Analysis Center (AlpEnDAC) as part of the VAO. Overall, this high-alpine region has one of the highest densities of meteorological stations worldwide and serves therefore as an ideal reference for testing new measurement and modelling approaches.

3 Gravimetric methodology

The essential prerequisite for the application of the OSG 052 as a hydrological sensor is the separation of the hydrological signal from the raw gravity observations. The required steps are explained on the basis of the continuous time series from 29 Dec 2018 to 31 Dec 2020 (2 years of observation).

3.1 Pre-processing and calibration

Raw gravity observations are voltage variations in 1 s sampling along with the observed barometric pressure variations and stored in daily files of the Tsoft format (Van Camp et al., 2005). These are compiled into monthly files and converted into the GGP format of IGETS. Short data gaps up to 10 s are interpolated linearly on the full signal. For the decimation from 1 s to 1 min sampling, a double precision Chebyshev filter "g1s1m" with a filter length of 1009 s is applied (Crossley, 2010). For the reduction of the gravity data and the removal of spikes and offsets as well as the filling of longer gaps, the programs DETIDE and DESPIKE of ETERNA 3.4 (Wenzel, 1997) are used. Besides some steps on 7 Jan 2019 during the final centering of the sphere, the time series has shown only two additional steps on 24 Oct 2019 during a simulated power failure for UPS testing and on 7 Dec 2020 after exchanging the CMOS battery on the GEP remote card, which were eliminated manually with the program Tsoft. Overall, the SG shows a very stable performance. Finally, the monthly files in 1 min sampling are further decimated to one long time series in 1 h sampling by the program DECIMATE.

For the transition from voltage to gravity variations, the amplitude factor of the OSG 052 has been determined on the basis of two absolute gravimeters and one calibrated spring gravimeter (Table 1). The first estimation was done in 2011 at Sutherland with FG5-301 by the German Federal Agency for Cartography and Geodesy (BKG). In order to validate this result after repeated transport of the SG and refurbishment at GWR, the second estimation was done in Sep 2018 at ZUGOG with FG5X-220 by LUH (Timmen et al., 2021), however, with a reduced accuracy due to the malfunction of the SG at this time (see section 2.1). Hence, a third estimation was carried out in Sep and Oct 2019 at ZUGOG on the basis of the relative spring gravimeter CG6-69 of GFZ calibrated in the gravimeter calibration system Hannover (Timmen et al., 2020). Within a least-squares adjustment, the amplitude factor of OSG 052 and a best-fitting polynomial reflecting the irregular drift of the CG6 were determined. The full period of 4 weeks of co-located measurements was divided into blocks from 2 to 4 days with and without overlap and polynomial degrees of 2 and 3. The best fitting solution (smallest standard deviation for the amplitude factor) was found to be for blocks of 3 days, polynomials of degree 3 and 50 % overlap. The final amplitude factor is -749.59 nm/s²/V (1σ=0.22 nm/s²/V) as a weighted mean from calibrations 1-3. The achieved accuracy should be sufficient with regard to the

hydro-gravimetric analysis. Amplitude factor deviations of 1 nm/s²/V correspond to 1.3 x 10⁻³ relative and 1 nm/s² absolute

225   gravity deviations for maximum gravity residuals of 800 nm/s² which can be used as measure for the accuracy of the gravity

observations at ZUGOG.

The time delay of the OSG 052 was determined within a step response experiment developed by GWR on 1 March 2019 at

ZUGOG. 16 introduced step voltages were analysed with the program ETSTEP of ETERNA 3.4 (Wenzel, 1997) and the time

230   delay was estimated to 10.53 s (1σ=0.03 s).

Table 1: Amplitude factors of the OSG 052 estimated from three methods

No of calibration	Method	Site	Period	Amplitude factor [nm/s²/V]	1σ uncertainty [nm/s²/V]
1	FG5-301 (BKG)	Sutherland	23-26 Nov 2011	-748.3	0.5
2	FG5X-220 (LUH)	Zugspitze	15-20 Oct 2018	-746.68	1.30
3	CG6-69 (GFZ)	Zugspitze	27 Sep-24 Oct 2019	-750.03	0.25
Mean value				-749.59	0.22

The instrumental drift of the OSG 052 has not been determined yet. The first absolute measurements cannot be used as

235   reference value for the drift estimation, as the SG had to be warmed up and cooled again for re-initialisation at the end of

December 2018 (section 2.1). Hence, there is no connection to the current continuous SG time series and the second absolute

measurements at 26-27 Sep 2019 (Timmen et al., 2021). For the preliminary analysis shown in this study, the drift is assumed

to be zero and no trend is subtracted from the SG time series. Further absolute gravity measurements are planned with the

FG5X-220 for 2021, which is required for the adequate determination of the rather small drift of some nm/s²/yr.

240   **3.2 Tidal analysis**

In order to reduce the gravity effects from solid Earth and ocean tides, a local tidal model was computed based on 2 years of

observations (29 Dec 2018 – 31 Dec 2020) with the program ANALYZE of ETERNA 3.4 (Wenzel, 1997) for the analysis of

monthly, diurnal, semidiurnal and shorter tidal waves. The estimated amplitude factors and phase leads according to the

ETERNA wave grouping for a 1-year gravity time series are displayed in Table 2. The numerical high-pass filtering and a

245   Hann window usually applied for the analysis of diurnal and semi-diurnal waves were deactivated for the simultaneous analysis

of the monthly waves resulting in higher standard deviations for the shorter waves. Instead, a Chebyshev polynomial of degree

2 was applied in order to eliminate any long-term instrumental trend signal or long-term variations in gravity. Longer tidal

waves (half year periods and longer) are considered by nominal values, i.e. amplitude factors of 1.16 and phases 0°. It should

be noted that these results could be reproduced by ET34-ANA-V80 (Schueller, 2020) with very small differences. However,

250   modifications with regard to wave group modelling including higher tidal potential degrees and additional tidal constituents

have not been carried out yet but are planned for the future on the basis of longer time series. Along with the tidal waves, the

single admittance factor between gravity and barometric pressure was determined with -3.6506 nm/s²/hPa (1σ=0.0393 nm/s²/hPa). In order to reduce the large seasonal gravity signal, a second admittance factor was determined between gravity and the snow water equivalent (SWE) with 0.2965 nm/s²/mm (1σ=0.0007 nm/s²/mm; cf. section 4.2). The gravity variations

255 induced by solid Earth and ocean tides are predicted with the local tidal parameters from Table 2 and shown for the analysed period in Figure 3 (top right).

Table 2: Estimated amplitude factors and phase leads from a least-squares adjustment of 23 tidal waves based on 2 years of gravity observations with OSG 052 at ZUGOG

Frequencies [cpd]		Wave	Theoretical Amp.[nm/s²]	Amplitude factor	Std	Phase lead [°]	Std [°]
from	to						
0.020885	0.054747	MM	21.1656	1.01201	0.18789	9.1622	10.6146
0.054748	0.091348	MF	40.0581	1.11718	0.04843	5.8775	2.4845
0.091349	0.122801	MTM	7.6699	1.42938	0.16566	-6.1562	6.6347
0.122802	0.501369	MQM	1.2250	1.24028	0.60193	5.1859	27.8178
0.501370	0.911390	Q1	59.3059	1.14954	0.00152	-0.1425	0.0756
0.911391	0.947991	O1	309.7475	1.15060	0.00031	0.0454	0.0154
0.947992	0.981854	NO1	24.3484	1.14980	0.00302	0.3313	0.1505
0.981855	0.998631	P1	144.1019	1.15094	0.00066	0.0240	0.0327
0.998632	1.001369	S1	3.4048	1.38514	0.03875	23.9574	1.6028
1.001370	1.023622	K1	435.4574	1.13835	0.00022	0.1490	0.0110
1.023623	1.035379	TET1	4.6578	1.15618	0.02065	1.1388	1.0233
1.035380	1.057485	J1	24.3569	1.15438	0.00384	0.0779	0.1905
1.057486	1.071833	SO1	4.0394	1.13676	0.02372	0.9770	1.1951
1.071834	1.470243	OO1	13.3201	1.15354	0.00642	0.1334	0.3188
1.470244	1.880264	2N2	10.5279	1.15943	0.00249	2.4868	0.1229
1.880265	1.914128	N2	65.9181	1.17379	0.00053	2.0941	0.0260
1.914129	1.950419	M2	344.2804	1.18640	0.00011	1.5090	0.0052
1.950420	1.984282	L2	9.7321	1.17467	0.00407	1.7836	0.1984
1.984283	2.002736	S2	160.1632	1.18501	0.00023	0.1346	0.0112
2.002737	2.451943	K2	43.5108	1.18753	0.00087	0.4461	0.0422
2.451944	3.381378	M3	4.5825	1.07740	0.00484	-0.0481	0.2573
3.381379	4.347615	M4	0.0566	0.25408	0.25504	95.3389	57.5061
4.347616	7.000000	M5	0.0007	29.93575	20.46948	30.4792	39.1786

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3.3 Non-tidal gravity reductions

Besides tidal variations, the gravity observations include significant non-tidal effects shown in Figure 3. For a more detailed compilation of temporal gravity field variations see e.g. Voigt et al. (2016a). The signal admittance factor from the tidal analysis of -3.6506 nm/s²/hPa includes the maximum correlated signal between observed gravity and barometric pressure. For

265 a refined modelling of gravity variations induced by mass redistributions in the atmosphere, the Atmospheric attraction computation service (Atmacs; Klügel and Wziontek, 2009) provides effects from local to global scales with a temporal resolution of 3h based on 3D ECMWF weather data. However, the limited spatial resolution of the weather models of 7 km

for Europe shows that the complex topography around the station cannot be represented sufficiently. Therefore, the local part from Atmacs is not used. Instead, a single admittance factor is estimated between the gravity observations reduced by regional and global atmospheric effects (i.e. the local atmospheric effect) and barometric pressure variations with -2.9190 nm/s²/hPa (1σ=0.0274). This is the local atmospheric effect which is added to the regional and global parts from Atmacs. A future task is to consider the complex alpine topography in the area around the gravimeter either by using a weather model with a higher spatial resolution or by setting up a local model based on an array of available barometers (Riccardi et al., 2007). Additional hourly barometric pressure observations are also available from the DWD stations Zugspitze (2964 m) and Garmisch-Partenkirchen (719 m) as well as from UFS (2656 m), Zugspitzkamm (2805 m) and Schneefernerkopf (2875 m).

Temporal variations of the Earth's rotation vector with respect to the Earth's body are described by the pole coordinates and the Earth rotation angle and provided as Earth orientation parameters (EOP) by the International Earth Rotation and Reference Systems Service (IERS). For the computation of the thereby induced gravity variations, the program PREDICT of ETERNA 3.4 (Wenzel, 1997) is applied with the long term file EOP 14 C04 (IAU1980) provided by the International Earth Rotation and Reference Systems Service (IERS) and amplitude factors set to 1.16 considering the elastic properties of a deformable solid Earth.

Non-tidal ocean loading at Mount Zugspitze is caused by the attraction of non-tidal water mass variations in the Atlantic Ocean and the Mediterranean Sea and the vertical displacement of the Earth's crust due to the loading of these water masses. For the computation of this effect, the Matlab toolbox mGlobe v1.1.0 (Mikolaj et al., 2016) is applied on the basis of 3-hourly total ocean bottom pressure anomalies (dataset "oba") from the GRACE Atmosphere and Ocean De-aliasing Level-1B (AOD1B RL06) products (Dobslaw et al., 2017).

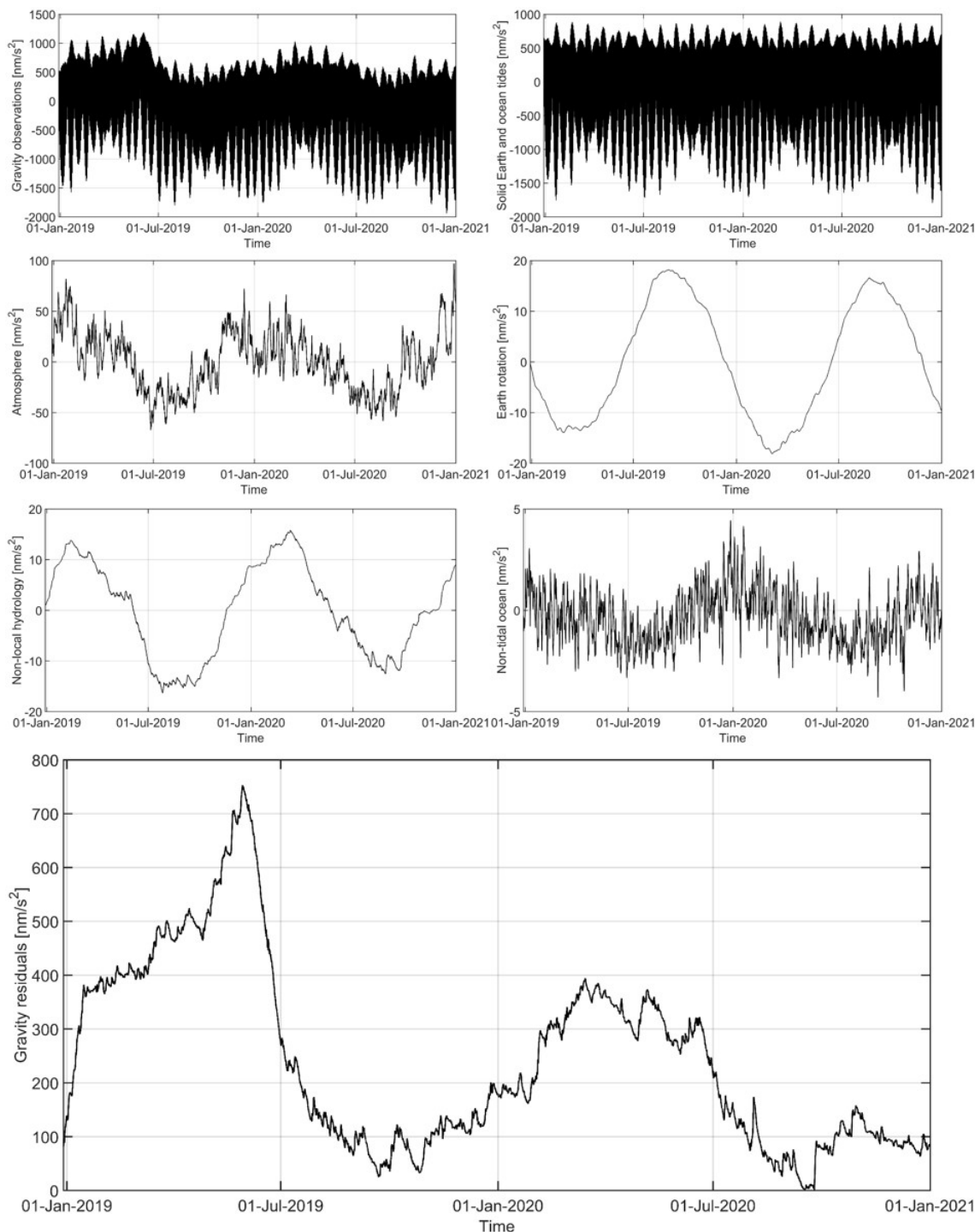
Hydrological gravity variations can be subdivided into those from local scales (up to several meters around the gravimeter) over alpine catchment scales (from several meters to kilometers) to non-local scales (from several kilometers). Non-local hydrological gravity variations include both attraction effects and surface loading, while for local to catchment scales only the attraction effects from mass redistributions is considered. The non-local hydrology is provided by the EOST Loading Service (Boy, 2015) using the Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2; Gelaro et al., 2017) with spatial resolutions of 0.5° and 0.625° in latitude and longitude, respectively, and 1-hour temporal resampling.

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Figure 3: Signal separation from gravity observations (top left) to gravity residuals (bottom) by reducing gravity variations induced by solid Earth and ocean tides, atmospheric mass redistributions, Earth rotation, non-local hydrological and non-tidal ocean mass redistributions. Please note the different scaling of the axes.

Figure 3 shows the process of signal separation from gravity observations of OSG 052 to gravity residuals by reducing all
305 shown and explained effects for the period from 29 Dec 2018 to 31 Dec 2020. These gravity residuals are the primary target
signal for hydro-gravimetric studies at Mount Zugspitze reflecting predominantly total water storage variations on different
scales. An exceptionally large seasonal gravity range of up to 750 nm/s² is visible. Typically, the gravity residuals of SGs in
Central Europe show seasonal variations of around 100 nm/s² range (Abe et al., 2012). However, it should also be noted that
the gravity residuals also include uncertainties in the model-based signal separation, which are typically at the level of a few
310 nm/s² root-mean-square error (Mikolaj et al., 2019). In addition, non-hydrological signals from alpine geological mass
redistributions are also included in the gravity residuals. Typical examples are avalanches, rockfalls and landslides occurring
on time scales from seconds to days. Regular controlled avalanche blasting with an impact of approx. -5 nm/s² on the gravity
signal have already been noticed. On long time scales, the impact of mountain uplift and its separation from climate-driven
long-term hydrological variations are challenging (Timmen et al., 2021).

315

An essential task is the reduction of local hydrological signals in order to enhance the sensitivity towards the catchment scale.
While the steep roof of the lab and its position above the slope at the summit are very advantageous, most disturbing signals
are expected from snow masses on a horizontal plane with an area of 5 m x 10 m directly in front of the lab (Figure 2 bottom
left) where a local snow monitoring network has been set up. A first estimation of the maximum signal from snow heights of
320 4 m and densities of 300 kg/m³ reveals a significant gravity effect of 25 nm/s² with a seasonal character superimposed by
somewhat smaller event-like signals during heavy snowfall events. As this is only a fraction of 1:30 with regard to the total
gravity residual range and due to initial problems as a consequence of very harsh conditions during winter 2018/19 (frozen
snow height sensors, torn cables, too low sensor pole height), a model-based description of the local snowpack situation has
not yet been set up completely.

325 **4 Hydro-gravimetric results and sensitivity analysis**

The subsequent hydro-gravimetric analysis based on the gravity residuals from Figure 3 (bottom) focus, for the first time, on
a high-alpine region largely dominated by seasonal snow cover. The gravity residuals reflect the total water storage variations
from local to catchment scales as the balance of precipitation, glacial melt, retention in the karst, runoff and evapotranspiration.
At Mount Zugspitze, this includes a large annual precipitation of approx. 2000 mm with 80 % as snowfall from autumn to late
330 spring above approx. 1800 m, leading to a profound seasonal snow storage. The discharge measured at the gauges, is largely
characterized by a high-alpine snowmelt runoff regime. The discharge peaks occur in summer and include besides large
portions of melted snow also components of rainfall events, and to a minor extent melted ice from the Northern and Southern
Schneeferner as well as the Höllentalferner glaciers (Hagg et al., 2012) and from thawing permafrost below the summit of
Mount Zugspitze (Krautblatter et al., 2010). Moreover, the water storage in the vadose and phreatic zones and subsequently
335 also the discharge are influenced by the geological karst situation in this region. Evapotranspiration has a large geographical

heterogeneity of the determining parameters on catchment scale (Wetzel 2004). At the surface of the highly karstified limestone of this region, only short distances of overland flow can be observed. Accordingly evapotranspiration is reduced due to lacking surface storage capacities in soils or fine-grained sediments.

340   The large complexity and variability of the hydrological parameters show the high potential of continuous gravity observations providing the integral signal of all mass redistributions in the vicinity of the gravimeter and serving as constrains for the hydrological modelling on catchment scale. The following hydro-gravimetric analysis should be regarded as a preliminary concept study to demonstrate potentials and limitations of integrating gravimetric signals into analyses of high-alpine hydrological processes.

345   **4.1 Water balance**

The gravity residuals from the hydro-gravimetric approach in Figure 3 (bottom) provide the first continuously and precisely observed time series of water storage variations at Mount Zugspitze. From the first 2 years of observations, the high interannual variability of water storage maxima can be determined with 752 nm/s² at 29 May 2019 and 393 nm/s² at 14 Mar 2020 significantly differing in time of year and in amplitude by a factor of two due to seasonal snowpack variations. The seasonal
350   minima, however, are very close in time and amplitude with a difference of -24 nm/s² between 16 Sep 2020 and 21 Sep 2019, respectively, fitting very well with the estimated trend of -20 nm/s²/yr. estimated from absolute gravity observations between 2004 and 2019 by Timmen et al. (2021). They suggest that the main contribution is caused by glacier diminishing, and a smaller part is explained by mountain uplift (1 mm causes -2 nm/s²). With a multi-year continuous gravity time series from OSG 052, it is possible to study the evolution of seasonal and - in combination with absolute gravity observations - also long-
355   term water storage variations.

However, for the hydrological decomposition of the gravity residuals into individual water storage components, complementary data from meteorological and hydrological techniques are needed. The gravimetric method is known to be most sensitive to local mass variations in vertical direction with a signal attenuations by $1/r^2$ (r being the distance between
360   gravimeter and source mass) and further attenuation towards increasing horizontal directions. Hence, the essential question is how sensitive the gravity residuals are with regard to individual water storage components from local to catchment scales. This question will be addressed in the following sections.

4.2 Snowpack

Representative observations of the snow water equivalent (SWE) for the Zugspitzplatt are available from the LWD station
365   (Figure 1). The spatiotemporal variations of the snowpack around the summit of Mount Zugspitze are the main contributors to the gravity residuals from autumn to spring. Figure 4 shows the gravity residuals, the SWE multiplied by the estimated

regression factor between gravity residuals and SWE of 0.298 nm/s²/mm (1σ = 0.003 nm/s²/mm). The high correlation of 0.969 between the gravity residuals and SWE is clearly visible and both are following similar seasonal patterns.

370   In general, the winter seasons of 2018/19 and 2019/20 were very different. The first winter season is characterized by a sharp increase in SWE in mid-January as well as in the second half of May due to massive snowfall. The maximum SWE is extraordinary high, with a value of 1957 mm measured at the LWD station, compared to an annual mean of the maximum SWE at approx. 1350 mm since the installation of the snow scale in 2014 until now. Contrary, the second winter season with a maximum SWE of 1147 mm at the LWD station reflects more a winter with a rather small to normal amount of snow. While

375   in 2019 the seasonal gravity and SWE maxima coincide at 29 May, there is a difference of more than one month between gravity and SWE maxima in 2020, i.e. 14 Mar and 19 Apr, respectively. However, in 2020 there was no distinctive SWE peak rather a longer period with maximal SWE values between these two dates. Higher temperatures during April 2020 led to an early onset of snowmelt in the lower part of the catchment with beginning recharge of the karst water body and increasing runoff at Partnach spring.

380

Despite the high correlation between gravity and SWE from the LWD station at Zugspitzplatt, there are still significant additional signals remaining with a range of 250 nm/s². The reasons are quite manifold. First, the single point observations of the SWE at LWD station are not fully representative for the large variations of the snowpack and its distribution at catchment scale particularly considering the altitude and temperature gradient within the area. Second, signals from other water storage

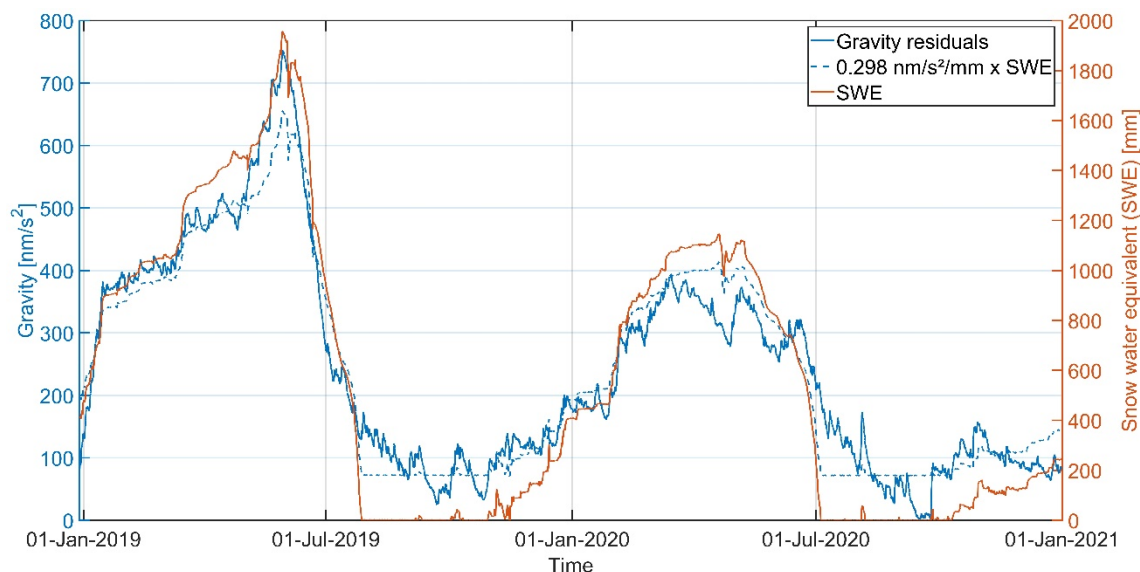
385   components are not considered within the regression analysis. This applies particularly to the snow-free summer season starting in July.

390

Figure 4: Gravity residuals (solid blue), snow water equivalent (solid red) from LWD station at Zugspitzplatt and SWE multiplied with estimated regression factor of 0.298 nm/s²/mm between gravity residuals and snow water equivalent (dashed blue line)

The essential question is how representative the locally observed gravity residuals are with regard to the snowpack of the whole catchment. For this purpose, a sensitivity analysis of a very simple snowpack distribution assumption in the surroundings

395 are carried out exemplarily for the times of maximum seasonal gravity residuals at 29 May 2019 and 14 Mar 2020. In order to take into account the topography for the spatial snow distribution, the high-resolution digital terrain model DGM50/M745 by BKG from 2006 with a grid spacing of 1" x 1" (20 m longitude x 30 m latitude) is used. Following assumptions are made for the snowpack distribution at the specific dates:

1. Computing the gravity effect from topography by integration of all rectangular prisms of 20 m x 30 m areas and
400   constant heights.

2. Initially putting a homogeneous snowpack of maximum SWE of 1957 mm and 1075 mm, respectively, on top of every rectangular prism for the topography.

3. Linearly decreasing the snowpack on slopes with a value of 50 % at 45° slope and 0 % at 90° slope.

4. Further linearly decreasing the snowpack for lower elevations between 2000 and 1500 m with 0 % snowpack at 1500
405   m (only valid for the late spring of the examples).

Figure 5 shows the assumed spatial distribution of the snowpack around Mount Zugspitze (left) and the resulting gravity contributions at the ZUGOG gravimeter site from the individual rectangular prisms (right) with the essential results summarised in Table 3. The assumed snow distributions provide gravity values of 764 nm/s² (752 nm/s² observed) and 420

410 nm/s² (393 nm/s² observed), respectively, for the dates 29 May 2019 and 14 Mar 2020 corresponding to deviations of 2 % and 6 %. The gravity contributions from all snow covered prisms coloured from yellow to deep red (>10^{-3} nm/s²) in Figure 5 are

defined as snow-gravimetric footprint with contributions of 99.4 % (29 May 2019) and 98.0 % (14 Mar 2020), respectively, to the total gravity effects from all modelled snow masses. With omissions between 4 and 8 nm/s², future snowpack analysis and modelling should thus focus on these areas.

415

The results show that the gravimeter observations are sensitive to the snowpack on catchment scales up to 3.5 km horizontal and 4 km slant distances to the gravimeter with a resulting snow-gravimetric footprint of approx. 40 km² (Figure 5). The major contribution comes from prisms in the RCZ with 71 % in both examples. The Hammersbach catchment has a much less significant contribution of 6 % only, as this lies on the opposite side of Mount Zugspitze and has very steep slopes near the
420 summit. The additional gravity contribution from the snowpack in the remaining eastern parts of the Bockhütte catchment is negligible. The remaining 23 % contribution to the total gravity signal from snow masses comes mainly from the area northwest from ZUGOG but should be much less in reality as there should be less snow in this area due to very steep slopes and prevailing westerly winds.

425 As the sensitivity diminishes with increasing distances from the gravimeter site, the individual contribution of the snow covered areas in the RCZ are analysed being coloured from yellow to deep red ($>10^{-3}$ nm/s²) in Figure 5. The left chart of Figure 6 shows a majority of 58 % from the deep red zone around ZUGOG including two prisms directly below the gravimeter which contribute with 308 nm/s² reduced by 60 nm/s² masking out the area below the ZUGOG building. These effects in the close vicinity should be much smaller in reality compared to our very simple assumption of snow distribution, as the maximum
430 snowpack at the summit is certainly less than the values from the LWD station due to usually strong winds at the summit ridge, which are neglected up to this point. For the setup of more detailed snowpack description in the direct vicinity, a high resolution DTM with a grid spacing of 1 m x 1 m will be used in the future in combination with a detailed 3D surveying of the buildings at the summit (sections 2.1 and 3.3). The right chart of Figure 6 without the two prisms below the gravimeter shows a far more uniformly distributed contribution. This should be considered as target distribution for a thorough gravimetric evaluation of
435 the spatiotemporal snowpack modelling especially in the RCZ in the future.

Based on this concept study, the description of the snowpack distribution will be refined in future studies for the entire Zugspitze region and the three catchments. The aim is to set up snowpack models such as SNOWPACK/Alpine3D (Lehning et al., 2006) or use cold region hydrological model frames like the Canadian Hydrological Model (CHM, Marsh et al., 2020)
440 at this location, and, in addition, to statistically describe the main snowpack distribution via LiDAR measurements, similar as presented in Grünewald et al. (2013). With these approaches, we will improve the descriptions of the spatial snowpack distribution in this very complex high-alpine terrain by including detailed descriptions of the snowpack itself, the effect of energy balance on the snowpack, potential wind redistributions as well as further meteorological and gravimetrical influences on the snow cover regarding elevation, aspect and slope – and of course by using the gravity residuals as boundary conditions.

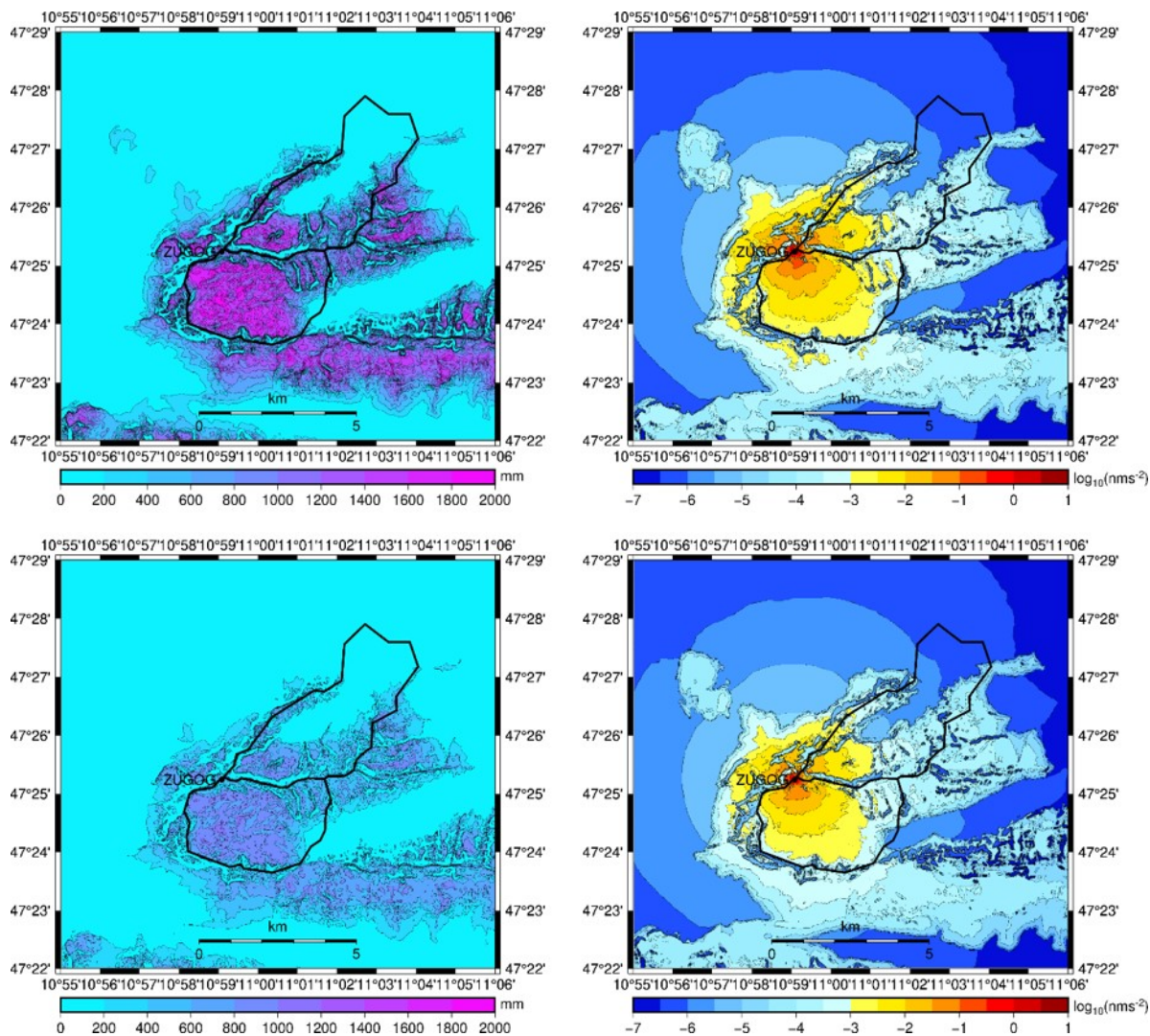



Figure 5: Modelled snowpack at maximum seasonal gravity residuals (left) at 29 May 2019 (top) and 14 Mar 2020 (bottom), respectively, and resulting gravity contributions from individual rectangular prisms with regard to the ZUGOG (right). The boundaries of the Partnach spring and Hammersbach catchments are shown as black line.

Table 3: Maximum gravity residuals from SG observations and gravity contributions from modelled snowpack of various areas with regard to ZUGOG at maximum seasonal gravity residuals at 29 May 2019 and 14 Mar 2020

Area	29 May 2019		14 Mar 2020	
	Δg [nm/s²]	Δg [%]	Δg [nm/s²]	Δg [%]
Total	763.9	100.0	420.4	100.0
Snow-gravimetric footprint (yellow to deep red areas in Figure 5)	759.5	99.4	411.9	98.0
Partnach spring catchment (RCZ)	542.0	71.0	297.6	70.8
Hammersbach catchment	46.3	6.1	25.5	6.1

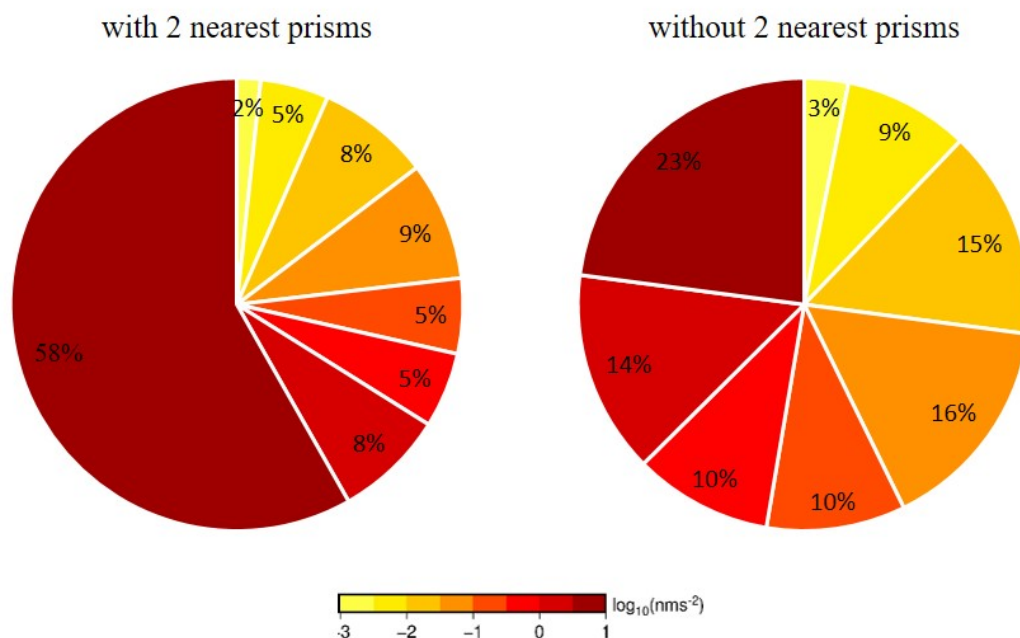



Figure 6: Percentages of the gravity contributions from yellow to deep red areas according to the colour palette in Figure 5 with two prims directly below ZUGOG (left) and without (right) at 29 May 2019

4.3 Karst groundwater

Besides snow distribution and snow water equivalent, liquid water balance in the karstified RCZ is influencing the SG signal. Throughout the year, a typical course of runoff with four characteristic periods can be observed (Figure 7). From the end of October to April no recharge of the karst system takes place and the Partnach spring is falling dry. With rising temperatures in April, melting processes are beginning in the lower parts of the catchment and first meltwater pulses can be observed at the Partnach River gauge. Melting period in the upper part of RCZ starts later in May lasting until the beginning of July. The karst system of RCZ is mainly fed by meltwater and discharge at the Partnach spring is continuously high. Liquid precipitation leads to pronounced runoff peaks on top of the increased basal discharge level. During this period of time, runoff at the Partnach spring is a mixture of meltwater from areas with increasing elevations and liquid precipitation. After melting ends, long lasting rainfall and storm precipitation are dominating runoff characteristics with steep rising and falling limbs. The well-developed karst system of RCZ with conduit flow causes these rapid runoff reactions of the Partnach spring. With lowering temperatures during autumn, snow accumulation starts in higher elevations of RCZ and recharge of karst groundwater is reduced because liquid precipitation is more seldom. Sometimes daily melting cycles of the glacier remains (Northern and Southern Schneeferner) can be observed during this usually dry period. At the end of autumn, low temperatures and snowfall in higher elevations are terminating recharge and karst groundwater head is falling step by step beneath the level of the Partnach spring.

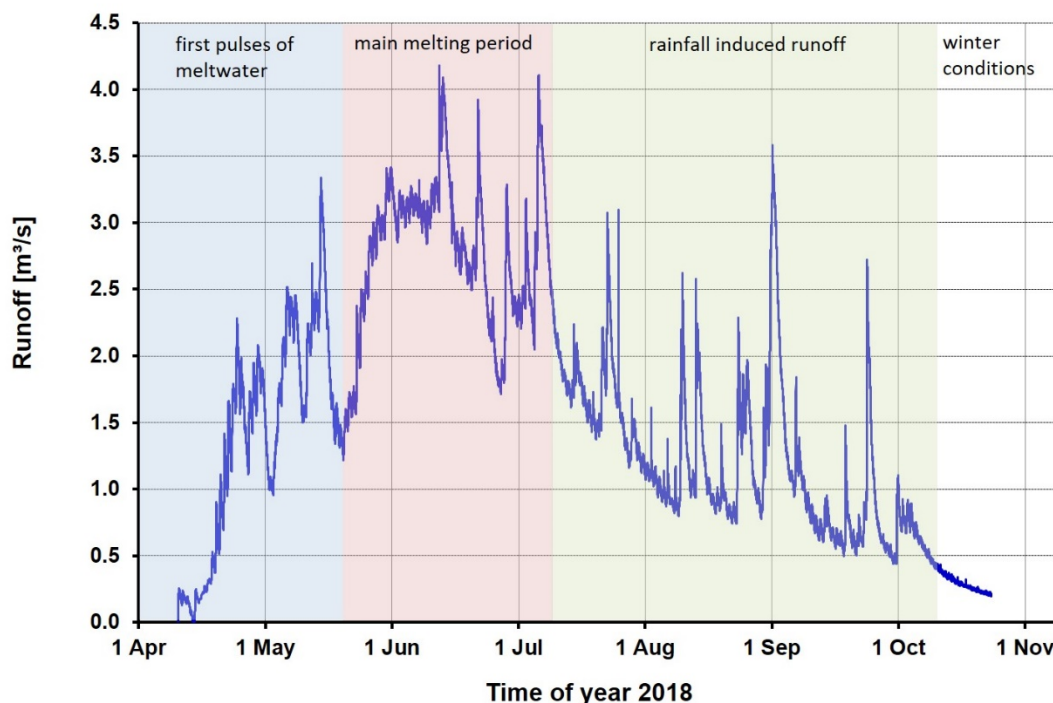



Figure 7: Runoff characteristics of the Partnach spring during 2018.

During seasonal snowmelt periods in spring and especially after the snowpack has fully disappeared in summer (27 Jul 2019
475 and 4 Jul 2020, respectively), other signals become the main contributors to the water storage variations observed by the
gravimeter. The largest part of the melting snow fills the vadose zone of the karstified underground body down to an altitude
of 1440 m below the Zugspitzplatt (Figure 1). If the groundwater level is rising with beginning recharge of the vadose zone,
the runoff starts at the Partnach spring which is well observed by a gauge station. From the seasonal gravity minima at 21 Sep
2019 and 16 Sep 2020, respectively, being very close in time despite the very different snow masses, a large variability in the
480 runoff processes as a consequence of the seasonal snowpack can be stated.

For the hydrological interpretation of gravity signals from ZUGOG, it is crucial to quantify the water volume stored in the
vadose karst zone of RCZ. Thereto pseudo-continuous depletion curves were constructed by splicing short falling hydrograph
intervals together (e.g. Lamb and Beven, 1997). The recession constant "α" was calculated for several years, because recession
485 behaviour of the Partnach spring varies from year to year due to unknown processes in the karst system (Figure 8). Based on
a mean recession constant "α", a water storage model for the vadose karst zone was developed by an addition of daily discharge
volumes during the depletion period. As Figure 8 shows, storage volume in the vadose zone varies between 1.6 and 3.38 x 10^6
m³. Under the assumption of a homogeneous layer of a 6 km² wide groundwater body (Figure 1), these numbers correspond
to groundwater heights of 0.27 and 0.56 m, respectively. Sensitivity analysis with regard to the ZUGOG site reveal

490 corresponding gravity values between 12 and 24 nm/s², respectively. With an uncertainty of a few nm/s², the gravimetric approach should be able to distinguish interannual groundwater height variations.

Besides seasonal runoff and corresponding karst groundwater variations, rainfall events on time scales from hours to days produce significant peak-like signals not only in the runoff but also in the gravimetric time series. A homogeneous layer of 1

495 mm precipitation height on top of the digital terrain model applied (section 4.2) would result in a gravity increase of 0.9 nm/s². This shows that the gravity variations can be used as reference for the estimation of the total sum of precipitation in this alpine terrain with large variability in precipitation instead of using point measurements with precipitation collectors. The same hydro-gravimetric approach might be applied to the estimation of daily evapotranspiration rates during dry days in late summer (August and September), when the seasonal runoff has mainly finished. However, maximum evapotranspiration rates do not

500 exceed 2-3 mm/day inducing a gravity effect of 1.8 to 2.7 nm/s² at the ZUGOG gravimeter site which is at the limit of what can be observed by the gravimeter.

In addition, glacier melting and permafrost degradation also contribute to groundwater and runoff with predominant climate-driven long-term signals but also significant interannual variations e.g. as a consequence of very dry and hot summers

505 (Scandroglio et al., 2019). In addition, cavities inside Mount Zugspitze filled with water through permafrost degradation could be problematic depending on the distance and direction to the gravimeter and their sizes. However, ZUGOG is located above the southern slope of Mount Zugspitze, while permafrost is mostly situated at the northern part. These additional signals will be best captured by the combination of absolute, superconducting and relative gravimetry and other geodetic techniques in a future hybrid approach. Thus, the whole summit area could be covered by a gravity network, constrained by the SG at ZUGOG,

510 and observed regularly within episodic campaigns.

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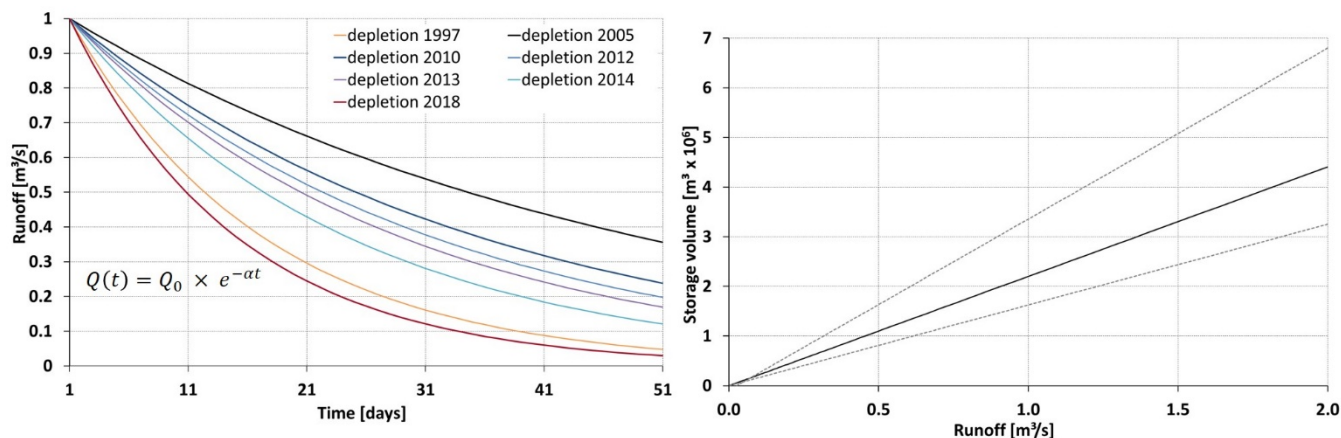
Figure 8: Depletion curves of the karst groundwater of RCZ for selected years (left) and calculated storage volumes of the groundwater body at different levels of runoff (right). The solid line shows the relationship for a mean recession constant "α" of 0.4 and the dashed lines are enclosing the range of one standard deviation.

5 Summary and conclusions

The superconducting gravimeter OSG 052 has been introduced as a novel hydrological sensor within a worldwide unique installation at the summit of the high-alpine Mount Zugspitze (2962 m). For the first time, a high-quality and publicly available continuous gravity time series of the water storage variations for two years around Mount Zugspitze is provided for an improved understanding of high-alpine catchment processes. As the discharge of the main three high-alpine catchments with their respective gauges at the Partnach spring, Bockhütte and Hammersbach (projected) are largely influenced by seasonal snow cover from autumn to spring, the spatiotemporal variations of the snowpack are the main contributor to the gravity residuals. Sensitivity analysis on the basis of a simplified assumption on snow distribution in this area reveal a snow-gravimetric footprint of 3.5 km horizontal and 4 km slant distances around the gravimeter covering an area of 40 km². The large range of gravity residuals up to 750 nm/s² corresponds to the maximum of 1957 mm snow water equivalent on 29th May 2019, measured at the LWD station located on the Zugspitzplatt. This result, together with the low uncertainty of the gravity residuals of a few nm/s², enables various detailed future hydro-gravimetric analysis for this high-alpine site at Mount Zugspitze. As the snow masses from the Partnach spring catchment (RCZ) contribute to more than 2/3 of the total gravity signal, this catchment will be the main focus for future investigations.

During the mainly snow-free season in summer, other water storage components dominate the gravity residuals. Runoff and karst groundwater variations are driven not only by snowmelt and rain but also by glacier melting and permafrost degradation. While the discharge of the Partnach spring and Bockhütte catchments are well observed by gauge stations, the estimation of catchment-wide total rainfall amounts and evapotranspiration rates might strongly benefit from including the gravity residuals into the analysis.

However, the hydro-gravimetric approach shows also a few limitations. The setup of a more detailed and small scale snowpack description, especially in the direct vicinity, is essential in order to increase the sensitivity towards the whole catchment. The

545 sensitivity to the hydrological mass variations depends on the distances and directions from the gravimeter. For the separation of individual water storage components, additional information from hydro-meteorological monitoring and modelling is always required. Nevertheless, the well-equipped high-alpine research catchment Zugspitze is a very good home base for upcoming long-term hydro-gravimetric studies.

550 The required steps within an upcoming hydro-gravimetric research project can be divided into monitoring, modelling and prediction. The essential prerequisite is to ensure the continuous high-quality operation of the OSG 052 and all associated sensor systems at ZUGOG as well as the hydrological and meteorological sensors in the three relevant catchments with focus on the RCZ. For an enhanced gravimetric monitoring, additional absolute gravity measurements provide the SG drift and support long-term studies. The GNSS station nearby ZUGOG reveals the long-term vertical displacement of the site. It is

555 further intended to install a continuously recording spring gravimeter in a vertical distance of 500 m below OSG 052 inside Mount Zugspitze in a technical room next to the rails of the cogwheel train to quantify the ongoing mass redistributions inside the mountain. In addition, the integration of episodic relative gravity measurements both from the tunnel of Mount Zugspitze and from the RCZ would be highly beneficial in a future hybrid gravimetric approach in order to better capture the spatiotemporal gravity variations on catchment scales – and with this for a more thorough constraining of the hydrological

560 model.

For an improved gravimetric modelling, the artificial snow-hydrological mass variations in the direct vicinity of the gravimeter have to be reduced by local monitoring and modelling. With regard to atmospheric gravity effects, the complex alpine topography surrounding ZUGOG has to be taken into account either by using a weather model with a higher spatial resolution

565 or by setting up a local model based on an array of available barometers. Modelling both effects with an uncertainty of a few nm/s² (1σ) leads to an improved signal separation with the gravity residuals being even more representative for the hydrology of the RCZ. As the snowpack signal dominates the gravity residuals, a large focus will be on high-resolution modelling of the spatiotemporal variations of the snowpack amount and distribution as well as the coupling with a hydrological model including the description of the karst zone. In addition to continuous point measurements and in order to allow spatial model validation,

570 a LiDAR installation is planned to track continuously the spatial distribution of snow height in the upper part of the RCZ as well as snow mapping using current remote sensing approaches.

The essential task is to develop an efficient physically based, spatially distributed karst-snow-hydrological model describing relevant physical processes in the RCZ. This will answer the question how robust the estimated gravimetric footprint is with

575 regard to real snowpack distribution conditions. A "forward operator" for the gravimeter should be included which allows

observed temporal gravity variations (as well as other model outputs such as runoff, snow pattern etc.) to be used for inverse modelling and conditioning the uncertainties of all predicted processes and states. This will illuminate to what extent the observed gravity variations are able to condition the prediction of snow- and karst-hydrological states and processes in the catchment. Different time scales have to be distinguished, as precipitation events (solid, liquid) and lateral snow distribution

580   induce short-term signal alterations, while evapotranspiration, sublimation, snow melting processes and groundwater recession take place on longer time scales. It will be a challenge to explore whether and to what extend these processes can be disentangled by combining gravimetric and other available information.

The overall aim of such projects is to develop the hydro-gravimetric technique for an improved understanding and a better

585   predictability of alpine mass redistributions on catchment scales which can be transferred to other alpine research catchments worldwide. Finally, an improved knowledge of hydrological variations on catchment scales enhances the resolution of large-scale hydrological variations and reduces the spatial and temporal gap to the satellite mission GRACE-FO (Gravity Recovery and Climate Experiment – Follow On), launched in May 2018, which provides gravity variations with a spatial resolution of 300 x 300 km² and a temporal resolution of 1 month.

590   **Data availability**

Raw gravity and atmospheric pressure data from the OSG 052 at ZUGOG are published (Voigt et al. 2019) and available from the IGETS data base hosted by the Information System and Data Center at GFZ (URL: https://isdc.gfz-potsdam.de/igets-data-base/). The subsequent gravity residuals and all auxiliary data from ZUGOG can be provided upon request from the author. Hydro- and meteorological datasets of the area around Mount Zugspitze and beyond are available from the Alpine

595   Environmental Data Analysis Center (AlpEnDAC) as part of the VAO (URL: https://www.alpendac.eu).

Author contribution

CV: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Visualization, Writing – original draft preparation, review & editing. **KS, FK, KFW:** Conceptualization, Investigation, Methodology, Writing – original draft preparation, review & editing. **LT:** Data curation, Formal analysis,

600   Writing – review & editing. **TR:** Data curation, Project administration, Resources, Writing – review & editing. **HP, NS:** Data curation, Project administration, Writing – review & editing. **CF, FF:** Funding acquisition, Project administration, Resources, Writing – review & editing.

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