Detailed Response on all comments on manuscript HESS-2021-78

Dear Bettina Schaefli, Dear Anonymous Referees, Dear David Crossley,

First of all, we would like to sincerely appreciate your constructive and valuable expert comments on our manuscript. These help us to largely improve our manuscript.

Please find our responses in green.

Editor Initial Decision: Start review and discussion (08 Mar 2021) by Bettina Schaefli
Comments to the Author:
Dear Authors
thanks for the submission of this interesting work. I have at this stage some very minor comments, which you might want to consider (your choice, I do not need an answer):
Fig. 1 does not show any river network, unusual for a hydrology paper;

Authors: Fig. 1 was modified and enhanced with the river network. In addition, we added the two glaciers Nördlicher Schneeferner and Höllentalferner. We have also added a profile (see comment by David Crossley) and the Eibsee.

Fig. 3 does not properly say what each subplot shows, which is not ideal for the reader.

Authors: Fig. 3 was modified accordingly using (a), (b),… Same for all other figures with subplots.

Fig. 7: is there really zero flow as implied by the figure before April 2018 or simply no measurements? Could specify obs. period in the caption.

Authors: The April data just weren't fully plotted. These were added to the figure.

And finally: there is no agreement on the use of the word runoff but I, personally, think it is good to use streamflow when you talk about streamflow rather than runoff on the hillslope scale.

Authors: We will use the term „spring discharge" throughout revised manuscript

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Comment on hess-2021-78

Anonymous Referee #1

Referee comment on "Introduction of a Superconducting Gravimeter as Novel Hydrological Sensor for the Alpine Research Catchment Zugspitze" by Christian Voigt et al., Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2021-78-RC1, 2021

Continuously measuring gravity changes in a high altitude Alpine site is a première, and these integrative measurements will provide new information on the ice-snow-water mass balance. More specifically, the combination of continuous, relative measurements with the superconducting gravimeter and occasional ones with an absolute instrument should provide valuable information on long-term changes informing about erosional processes, and ice and water mass changes.

Such a study is in principle worth publishing in HESS, but presently, it suffers from different shortcomings.

The bibliography is not complete.
Some parts are wordy; the information could be better structured. Often the authors beat around the bush, go back and forth, making it difficult to focus on the main project

that is, I presume, constraining the snow mass model. Overall, this paper rather looks like a field report, a plea for funding or in the best case, a feasibility study, which is not the purpose of a scientific paper. For example, do we need the details on the way the instrument was moved? Moreover, some parts are probably interesting for an audience of geodesists, but here, one should not forget that the paper will be mostly read by hydrologists.
It is very necessary to dispose at the very least of two absolute gravity measurements to determine the drift of the superconducting gravimeter and incidentally, confirm the calibration factor. The authors and colleagues have the skills and material to do the job, so, I urge the authors to perform the absolute measurements that will provide the healthy and solid foundations required to support their case. Without this, the inferred gravity changes will remain speculative, especially when those changes are discussed at the nm/s² level.
What is exactly the scientific question? Installing an SG in Alpine context? This is not a scientific goal. Evidencing the ability of an SG to monitor changes in water mass balance? Building a terrain model of the Newtonian effect of snow? This has been done in numerous studies. Instead, you should modify the title and focus on the investigation of the snow and water mass balance, and the novel results one could infer from it. But, this can only be achieved with a longer time series, appropriate modelling (e.g., the authors propose to build a model as SNOWPACK -do it!) and appropriate ancillary measurements (e.g. LIDAR for snow thickness).

Authors (updated from AC1 of open discussion): We fully agree on the necessary steps which are planned within an upcoming research project. The only disagreement is on the opinion whether the current concept status is worth to be published in HESS or not. We face your several comments point by point below but comment on your major issues already here. These are:

1. Missing second absolute gravity measurements: It is true that the so far missing second absolute measurements leave room for certain speculation. To be honest, these should have been carried out at end of September 2020. However, the laser of the FG5 was broken and had to be sent back to the manufacturer, while the rest of the FG5 has spent the winter up there. The second absolute measurements were carried out from 29 March to 1 April 2021 for the SG drift estimation. Those will be included into the revised version of the manuscript.With this, the gravimetric part can be regarded as finalized within the revised version of our manuscript.

2. Concept status vs. final results: As we have written in the abstract "this work is regarded as a concept study showing preliminary gravimetric results and sensitivity analysis for upcoming long-term hydro-gravimetric research projects." The introduction of section 4 specifies: "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." The aim of this manuscript is indeed to introduce our SG (and its publicly available dataset) as a hydrological sensor into a high-alpine research catchment (as the title says), which has never been done before because of several practical difficulties and not knowing whether such a site provides any meaningful results from the gravimeter. This interdisciplinary manuscript should help to bring together the expertise of gravimetry and alpine hydrology by addressing the following important questions:

    1. What are the required ingredients to set up a SG in a high-alpine area and use it as a hydrological sensor?
    2. How are the gravimetric observations and the gravity residuals composed at this specific site?
    3. Which hydrological masses and changes are visible to which extent from the summit above the research catchment?

4. What are the benefits and the limitations of the hydro-gravimetric approach at this site?

In our opinion, addressing these questions is essential in terms of extent and accuracy before setting up a complex hydrological model of the research catchment. In addition, we strongly believe that our findings are of interest for the community of alpine hydrologists already at this preliminary state to evaluate whether the hydro-gravimetric approach could be valuable for their own research areas or not.

3. Detailed methods section: This is an inherent problem of interdisciplinary manuscripts. From a geophysicist's or geodesist's perspective, the detailed explanations on the gravity observations and the signal separation procedure might be a bit boring and lengthy and there is certainly potential to shorten this section. From a hydrologist's perspective, however, this section could be very exciting providing a step-by-step description how to get hydrological signals out of raw gravity observations. In a revised version we will try to find a better balance between these two perspectives.

Additions: We believe that "Audience = 'solely' hydrologists" is not generally true. (1) Indeed, we address hydrologists to think of applying gravimetry as a useful tool in their alpine area of interest. But if hydrologists are not interested in technical details, they can easily skip this section and just take the gravity residuals provided in Fig. 3. (2) We would also like to encourage the gravimetry community to think of similar projects, and we think that from this perspective it does make sense to provide technical details on problems especially in such a high-alpine area. And (3) we try to foster collaborations between hydrologists and geodesists/geophysicists with our manuscript, and thus our work shows all the ingredients which brought us all the way to get proper gravimetric results to be used by hydrologists.

See also my numerous comments in the annotated pdf.

I recommend rejection as presently, much more work should be done but I would be pleased to revise an improved version of this work when (1) the absolute gravity measurements are performed and (2) a more comprehensive investigation of the snow and water mass balance is done. Of course, more time is needed but this is often the case in geodesy, where one looks at slow processes.

Please also note the supplement to this comment:
https://hess.copernicus.org/preprints/hess-2021-78/hess-2021-78-RC1-supplement.pdf

Numerous comments from PDF supplement:

L. 18: high precipitation and long seasonal snow cover
→ Quantify (mm/yr) and quantify

Authors: Sentence was modified accordingly: "a large mean annual precipitation of 2080 mm and a long seasonal snow cover period of 9 months"

LL. 25-27: 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.
→ Is it really relevant into an abstract? this is essentially standard processing

Authors: The sentence was shortened accordingly: "Besides the experimental setup and the available datasets, the gravimetric methods based on the first 27 months of observations are presented."

LL. 32-34: 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

→ 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~~

Authors: First sentence modified: "This shows that…"

Second sentence: This is an important sentence to prepare and guide the audience and this is why this should not be removed in our opinion. By the way, concept studies are common practice in hydrological journals.

LL: 36: One of the grand societal challenges is ensuring a sufficient water supply under climate change conditions.
~~→ One of the grand societal challenges is ensuring a sufficient water supply under climate change conditions.~~

LL. 39-43: The IPCC (2014) indicates that "in many regions, changing precipitation or melting snow and ice 40 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.

→ Such a political introduction is rather good for a project proposal or a report. Here, the main interest should remain scientific: assessing ground water availability is a challenging task, with or without climate change. I'd rather focus on the Alpine context as you do before and after.

Authors: We don't understand why we shouldn't provide such a societal motivation for our research.

LL. 68: LiDAR observation techniques are not able to measure the hydrologically relevant SWE value directly,

→ I don't understand this point: if the LIDAR needs other data, why do you use it? As stated further on (L570), you are willing to develop this tool. Is it the combination of LIDAR+gravity which will make it successful? Clarify.

Authors: Sentence was modified accordingly: "Both, photogrammetry and LiDAR observation techniques are only capable of measuring snow heights but not hydrologically relevant SWE values directly and thus rely on additional snow density data from local snow pit or snow weight measurements."

L. 74: you may mention the SG installed to monitor karst sytems in France and Belgium or to investigate the water storage in the USA:

Fores, B., Champollion, C., Le Moigne, N., Bayer, R., & Chéry, J. (2016). Assessing the precision of the iGrav superconducting gravimeter for hydrological models and karstic hydrological process identification. Geophysical Journal International, 208(1), 269–280. https://doi.org/10.1093/gji/ggw396

Watlet A., Van Camp M., Francis O., Poulain A., Rochez G., Hallet V., Quinif Y., Kaufmann O., Gravity monitoring of underground flash flood events to study their impact on groundwater recharge and the distribution of karst voids, Water Resources Res., doi:10.1029/2019WR026673, 2020.

Kennedy, J., T. P. A. Ferré, A. Güntner, M. Abe, and B. Creutzfeldt (2014), Direct measurement of subsurface mass change using the variable baseline gravity gradient method, Geophys. Res. Lett., 41, doi:10.1002/2014GL059673

Authors: This paragraph was modified accordingly: "These include the development of SGs as hydrological sensors for the direct, integral and non-invasive monitoring of water storage variations in a minimized field enclosure at Wettzell, Germany (Güntner et al., 2017) and near Tucson, Arizona, USA (Kennedy et al., 2014) as well as SG installations for the monitoring of karst hydrological processes at the Larzac plateau, France (Fores et al., 2017), and at Rochefort, Belgium (Watlet et al., 2020). Creutzfeldt et al. (2013) use SG measurements at Wettzell, Germany, for the estimation of storage-discharge-relationships in a small headwater catchment. Very recently, Chaffaut et al. (2020) have reported about an SG installation at the summit of the Strengbach catchment in the French Vosges for the analysis of water storage dynamics. In this catchment, however, seasonal snow cover only plays a minor role."

In addition, we added Hinderer et al. (2015) at the end of this paragraph.

LL. 81-84: 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.

→ quite complicated statement. Make this simplier.

Authors: Probably the transition from last paragraph and context were unclear. Paragraph switched.

L. 118: In addition, the position at the summit prevents hydrological mass variations above the sensor and simultaneously increases the hydro-gravimetric footprint.

→ It is also the case in Chaffaut et al, 2020. It's not common, so it is worth mentioning this.

Authors: First mentioning of Chaffaut et al. (2020) was modified (see above): "Very recently, Chaffaut et al. (2020) have reported about an SG installation at the summit of the Strengbach catchment in the French Vosges for the analysis of water storage dynamics. In this catchment, however, seasonal snow cover only plays a minor role." In addition, Chaffaut et al. (2020) were added after this sentence: "In addition, the position at the summit prevents hydrological mass variations above the sensor and simultaneously increases the hydro-gravimetric footprint (cf. Chaffaut et al., 2020)."

LL: 121-124: 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.

→ A ventilation ~~has been installed in order to~~ reduces 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 includes heaters to keep the sensor at a stable temperature of around 25°C. Temperature and humidity sensors are installed in the lab.

→ What is "stable"? +/- 1°C? Anyway, the SGs look quite robust vs. temperature changes.

Authors: The sentence was modified accordingly: "to keep the sensor at a stable ambient temperature of around 25°C (±1°C)."

L. 130: Figure 1

→ The quality is poor, and the coordinates on the axis are confusing. Improve the resolution and legibility (black texts are difficult to read)

Authors: The resolution of the figure should just be a matter of the PDF conversion. Originally it has a resolution of 600 dpi. We changed most of the text colour from black to white for an improved legibility. As we don't understand why the coordinate axes should be confusing (GMT standard), we left them as they were.

L. 135: The refurbishment of the 10 years old SG at GWR included the thermal levellers,

→ There was none? Make this clear. The levelers are standard parts of SGs, as far as I know.

Authors: The thermal levellers have been refurbished. Sentence was modified: "This [the maintenancce] included the refurbishment of the thermal levellers,…"

LL. 153-155: 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.

→ 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.

Authors: Why not mention this? In our opinion, this shows the large effort of moving such a device to the summit of a high-alpine mountain in terms of organisation, manpower, costs etc.

LL. 155-158: 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.

→ Again, are all those technical details useful? If you really want to mention them, then you may (1) explain that it's expected to have to re-vacuum the Dewar after it warmed up and (2) tell us why after new cooling everything is all right. But I'm convinced that in the very best case, this is relevant to a technical paper.

Authors: As the referees surely knows, there have been serious drift issues with transporting SGs at 4K at that time (Schäfer et al. 2020). We mention this for three reasons: (1) We would like to raise awareness to station operators to rethink of moving their SGs "cold" or "warm" and (2) we want to explain why the publicly available data is of less quality until 29 Dec 2018, and (3) we wanted to explain why the first absolute measurements from Sep 2018 cannot be used for drift estimation.

Schäfer, F., Jousset, P., Güntner, A., Erbas, K., Hinderer, J., Rosat, S., Voigt, C., Schöne, T., and Warburton, R.: Performance of three iGrav superconducting gravity meters before and after transport to remote monitoring sites, Geophys. J. Int., 223, 959-972, doi:10.1093/gji/ggaa359, 2020.

The original sentences are: "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."

After consultation with Richard Warburton (GWR) we modified these: "At the end of October 2018, the instrument was warmed then re-cooled after abnormal drift was observed. The manufacturer (GWR) now recommends that SGs be transported at room temperature, and the Dewar be evacuated just prior to cooling with the refrigeration system. According to GWR, development is currently in progress to eliminate these requirements."

LL. 161-163: 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.

→ ~~has been~~
→ Wordy sentence: "A GNSS station measures since Sept 9, 2018".

Authors: The sentence was modified accordingly.

LL. 165-167: 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.

→ ~~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.

→ which plane?

L. 169: Another laser-based snow height sensor has been installed with a view to the slope directly below the SG.

→ has a view

Authors: We mean the horizontal plane in front of the lab. We rephrased the paragraph: "Several environmental sensors monitor local hydrological and meteorological variations. A snow scale and three laser-based snow height sensors quantify the accumulated snow masses on this horizontal plane installed in front of the lab during the winter months (Figure 2c). 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. Another laser-based snow height sensor has a view to the slope directly below the SG. Laser-based sensors have been preferred instead of 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."

L. 175: Long-term meteorological datasets are available on hourly to yearly basis from the Climate Data Center.

→ Do you mean for the last 20 years?

Authors: The sentence was modified: "Long-term meteorological datasets since 1900…"

L. 182: Gauge stations have been set up for the observation of the discharge at Partnach spring and Bockhütte

→ Gauge stations monitor

Authors: The sentence was modified accordingly.

L. 184: Its main characteristics are a mean annual precipitation sum of 2080 mm

→ mean annual precipitation of 2080 mm

Authors: modified.

LL. 186-187: at Partnach spring where the catchment is exclusively drained due to the special geological karst situation being therefore regarded as a natural lysimeter.

→ Partnach spring that drains the whole catchment

Authors: modified

→ Make another sentence here, and provide some more details on this case: how are you sure that everything drains towards that spring? it's probably explained in Krautblatter but you may say something here. If this spring is a natural lysimeter, why then performing gravity measurements? Looking further in the paper, I see that the interpretation of the spring flow is not so straightforward, so I'd be more careful here.

Authors: The lysimeter characteristics have already been proven and are well-established as stated in the Introduction: "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 and water movement studies (Wetzel, 2004; Rappl et al., 2010)."

L. 209: shows a very stable performance

→ Subjective statement. What do you mean? Which drift? How does it compare with Peterson's noise model NLNM?

Authors: This sentence is indeed subjective and aimed at the few disruptions. It was removed. Btw. noise levels have been analysed on an EGU poster (Voigt et al., 2019) but these are out of scope of the hydrological analysis presented here on the basis of 1h decimated data.

Voigt, C., Pflug, H., Förste, C., and Flechtner, F.: The Zugspitze Geodynamic Observatory Germany – Installations and First Data Analysis. Geophysical Research Abstracts Vol. 21, EGU2019-8605-1, 2019

L. 210: DECIMATE

→ Which filter?

Authors: The sentence was extended: "…DECIMATE using symmetrical numerical FIR lowpass filters "N2H1M001" and "N14H5M01" from ETERNA 3.4."

LL: 212-224: 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 hydro-gravimetric analysis.

→ Very long paragraph, plenty of technical details, this would become much more simple and elegance would rule should you perform a calibration during a next visit of the AG.

Authors: At the end of March 2021, we had only a time window for 4 days parallel observations for the determination of the second absolute value to be used for the SG drift estimation. We don't see any need in carrying out a fourth calibration, as the results are accurate enough for our hydrological purposes (as we have shown). Instead, we think that the alternative procedure of calibrating a SG on the basis of a well-calibrated relative gravimeter was quite successful and should be mentioned. E.g., there is a full paper recently published in JGeod. by Antokoletz et al. (2020, https://doi.org/10.1007/s00190-020-01402-7) on standard AG-SG-measurements and the estimated calibration factor at La Plata. Why shouldn't we write just one – indeed quite technical - paragraph on different ways to successfully estimate the calibration factor?

LL. 224-226: Amplitude factor deviations of 1 nm/s²/V correspond to 1.3 x 10-3 relative and 1 nm/s² absolute 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.

→ This is quite conservative given Table 1.

→ I do not understand this.

Authors: There are deviations between the single calibration factor estimations of up to 3.35 nm/s²/V. With a lower weight on the uncertain second estimation, we hope to get near the true calibration vector within 1 nm/s². The last sentence was rephrased: "The achieved accuracy should be sufficient with regard to gravity residuals with a range of 750 nm/s² (Figure 3g), as amplitude factor deviations of 1 nm/s²/V correspond to maximum deviations of 1 nm/s² in gravity residuals, which can be used as measure for the accuracy of the gravity observations at ZUGOG."

LL. 228-230: 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 delay was estimated to 10.53 s (1σ=0.03 s).

→ Incidentally it's a pity you analyze such a reduced number of steps while the modern electronics of GWR now allows producing hundreds of steps, and it's easy to analyze them automatically (see with GWR). But, in this hydrological study the precision on the phase is not of concern.

Authors: We are aware of this. But as this SG is mainly intended for hydrological analysis, our intention was to not spend too much time on this issue.

LL. 236-239: 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.

→ This is really quite problematic! Tedious paragraph. To make it simple: perform the required measurements before publishing.

Authors: In the meantime, we have carried out the second set of absolute measurements at the end of March 2021 with the FG5-X-220 by Leibniz University Hannover. The estimated SG drift is -30 nm/s² for the period of 1.5 years between the two absolute sets (so -20 nm/s²/yr). So, based on these two absolute measurements, we cannot disprove our null hypothesis for the drift. We have modified the whole paragraph from LL. 234:

"The instrumental drift of the OSG 052 is determined based on two absolute determinations with FG5X-220 by LUH at 26-27 Sep 2019 and 30-31 Mar 2021 with 2477 and 5166 drops, respectively (Figure 3g). The instrumental uncertainty (long-term stability) of each g determination is estimated with 20 nm/s² (1σ) (Timmen et al., 2021). From the comparison, a SG drift of -20 nm/s²/yr is estimated. The null hypothesis of a zero drift assumption cannot be disproved statistically. With the knowledge that the SG drift should be small and linear towards increasing gravity, no drift is applied in the following hydro-gravimetric analysis. Further absolute measurements planned for the future will increase the redundancy of the drift estimation and longer temporal differences between the absolute measurements will make the drift estimation more robust. Unfortunately, the first absolute measurements from 15-20 Oct 2018 cannot be used as additional reference value for the drift estimation, as the SG had to be warmed up and cooled again for re-initialisation at the end of Dec 2018 (section 2.1), so that there is no connection to the current continuous SG time series."

L. 242: ANALYZE of ETERNA 3.4

→ Why not directly use Schüller? The comparison of the different softwares is not relevant here. Audience = hydrologists. And statements such as "with very small differences" should be quantified, if still relevant.

Authors: We have started with ET345-ANA-V60. But then there were every few months updates and it was not easy to follow all these in time. As we are quite familiar with ETERNA 3.4, we decided to do the tidal analysis with this program and to just validate whether we get the same results out of ET34-ANA-V80. But if we use this one, we will certainly be asked why we didn't do any modified wave grouping etc. In total, the tidal analysis provides sufficient results for our purposes. We have removed the reference to Schueller's program in the manuscript.

L.257 Table 2

→ Is it really necessary in such a paper? Why not just mentioning the efficiency of the tidal correction by using the appropriate parameters, together with Tsoft that is widely used by the hydrologists?

Authors: Our intention was to provide these results to be used by other groups doing relative gravimetry in this area.

L. 261: Non-tidal gravity reductions

→ You should refer here to the review study of Mikolaj et al., 2019 (10.1029/2018JB016682)

Authors: This was added to the sentence: ", while Mikolaj et al. (2019) quantify time-domain uncertainties for the different gravity reductions." In addition this is also referenced in a later sentence: "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 nm/s² root-mean-square error (Mikolaj et al., 2019)."

LL. 270-271: 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.

→ Unclear. See the clear explanation of Mikolaj et al: "The disadvantage of global models is the lower temporal resolution compared to in situ pressure, potentially leading to insufficient modeling of processes at shorter periods. This issue is addressed in a separate analysis combining in situ pressure with global models as recommended in the Atmacs model"

Authors: This is exactly what we have done but obviously our description was too short or unclear. We modified the paragraph: "In order to account for the limited spatial resolution and to improve the temporal resolution, the following procedure is used. The gravity observations are reduced by the effects of solid Earth and ocean tides, Earth rotation and SWE variations as well as regional and global atmospheric effects from Atmacs. In this way, the gravity residuals primarily reflect the effects of local atmospheric mass redistributions. The admittance factor between these gravity residuals and the observed barometric pressure variations is estimated to -2.9190 nm/s²/hPa (1σ=0.0274). For the total atmospheric reduction, the local part of Atmacs is replaced by this admittance factor multiplied by the observed pressure variations in 1h sampling and added to the regional and global atmospheric effects from Atmacs."

In addition, the statement on future tasks was shifted to Summary and Conclusions.

LL. 284-288: 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).

→ One can refer to Figure 3 but you can already provide here some basic values: peak-to peak variations, mains frequencies. Hence, hydrologists will know whether it's relevant or not to apply such a process.

Authors: This sentence was modified: "For the computation of these small effects with a range of 5 nm/s², 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) and shown in Figure 3e."

LL. 290-295: 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.

→How precise are these models? Don't we add noise rather than improving the signal?

Authors: There is a corresponding note provided along with the gravity residuals: "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 nm/s² root-mean-square error (Mikolaj et al., 2019)."

L. 302: atmospheric mass redistributions

→ Does it include both local and global effects?

Authors: The question should be answered above. All effects from local to global are included.

L. 307: An exceptionally large seasonal gravity range

→ Why exceptional? Maybe, it is usual at Zugspitze. What is rather true, it that such a variation is not common at other gravity observatories.

Authors: "Exceptionally large" compared to other SG installations. The sentence was modified: "An exceptionally large seasonal gravity range of up to 750 nm/s² is visible compared to other SG installations in Central Europe with seasonal variations of approx. 100 nm/s² range."

LL. 308-314: 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 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).

→ Not really relevant here, given the small size of this effect. This must be discussed before.

→ This is confusing. Again, all those small effects should be discussed either before or in a discussion section. The main point here is hydrology (if you can rule out landslides)

→ Refer to erosional processes investigated by Mouyen et al. 2013(10.1093/gji/ggs019): they observed up to about 2800 nm/s² gravity changes due to landslides in Taiwan.

Authors: We don't agree. The overall result of this section are the gravity residuals. And now we discuss the uncertainties that are included in these gravity residuals. These are (1) uncertainties from the models applied, and (2) signals that might be still included. → No modifications.

LL. 338-339: Accordingly, evapotranspiration is reduced due to lacking surface storage capacities in soils or fine-grained sediments.

→ This is true, I presume, in the absence of snow. Is it often the case?

Authors: We are actually not sure, if you mean the frequency or the time span of absence of snow with your question in the comment. Anyway, we changed the respective paragraph to better explain why less evapotranspiration occurs also in the summer months in high alpine catchments: "The same hydro-gravimetric approach might be applied to the estimation of daily evapotranspiration rates (Van Camp et al., 2016) during dry days in late summer (August and September), when snow melt of the seasonal snow pack has mainly finished. In general, evapotranspiration is small in high-alpine areas, especially due to less available soil moisture in shallow alpine soils or even the absence of soils at all, sparse vegetation and less demand of plants and decreases with increasing altitude (Gurtz et al., 1999, https://doi.org/10.1002/(SICI)1099-1085(19991215)13:17<2751::AID-HYP897>3.0.CO;2-O). Maximum evapotranspiration rates of 2-3 mm/day for high alpine environments inducing a gravity effect of 1.8 to 2.7 nm/s^2 at the ZUGOG gravimeter site are at the limit of what can be observed by the gravimeter."

L. 340: show the high potential

→ It does not show the potential of gravity measurements. It's the very nature of gravity measurements and more generally, geodetic ones, to integrate different effects. We do not need the Zugspitze to learn about that. Modify this sentence, please.

Authors: The focus is on the very large complexity and variability in this area and an eagerly awaited desire for an integral picture. We modified the sentence: "The large complexity and variability of the hydrological parameters make the hydrological modelling very difficult. Continuous gravity observations provide the integral signal of all mass redistributions in the vicinity of the gravimeter and should thus be highly beneficial serving as constrains for the hydrological modelling on catchment scale."

L. 348: with 752 nm/s^2

→ nm/s^2 is no water storage variation

Authors: This sentence was modified: "The gravity residuals from the hydro-gravimetric approach in Figure 3g provide the first continuously and precisely observed time series **induced by** water storage variations at Mount Zugspitze."

LL. 349-355: variations. The seasonal minima, however, are very close in time and amplitude with a difference of -24 nm/s^2 between 16 Sep 2020 and 21 Sep 2019, respectively, fitting very well with the estimated trend of -20 nm/s^2/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/s^2). 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 term water storage variations.

→ I do not accept this statement: in the absence of absolute gravity measurements this remains speculative. You do not know which transient effects may modify the general trend previously determined by the absolute gravity measurements (e.g., the exceptional snow cover, or the repeated drought in Europe in 2019 and 2020). And I can certainly not accept the values provided in this whole paragraph as granted, given the unconstrained drift.

→ This is no novel information and to illustrate the combination of AG and SG you may refer to Van Camp et al. 2013 10.1016/j.cageo.2012.07.029

Authors: see statement above on the second set of absolute measurements.

LL. 357-362: 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 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.

→ wordy paragraph. Simplify and refer e.g; to Creutzfeldt et al., 2008 (10.1190/1.2992508)

Authors: The reference was added to the paragraph and the paragraph was modified: "According to Newton's law of gravitation, the gravimetric method is known to be most sensitive to local mass variations with a signal attenuations by $1/r^2$ (r being the distance between gravimeter and source mass). As gravimeters are solely sensitive in vertical direction, attenuations occur for mass variations towards horizontal direction (Creutzfeldt et al., 2008)."

L. 368: regression factor between gravity residuals and SWE

→ How do you separate the water as snow and the water percolating in the ground? SWE might be 0 while the ground remains plenty of water.

Authors: This has not been separated yet. This is just the SWE measured by a snow scale at the LWD station (as explained).

L. 368: The high correlation of 0.969 between the gravity residuals and SWE is clearly visible and both are following similar seasonal patterns.

→ provide significance

Authors: The sample size of 19771 is added.

L. 370: Sharp increase

→ quantify

Authors: Sharp increase of approx. 300 nm/s² (added).

LL. 381-382: 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.

→ You need to discuss this in much more details: when do we observe the largest differences? The best agreement?

Authors: This paragraph was modified: "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. During periods of massive snowfall this leads to remaining signals of up to 150 nm/s². Moreover, rain events during the short summer season cause rapid gravity increases of up to 100 nm/s² followed by an equally fast but only partial decrease and a slower subsequent decline due to the lagged drainage back to the gravity level before the specific rain event (Timmen et al., 2021). Second, signals from other water storage components are not considered within the regression analysis with the major remaining signals of up to 200 nm/s² occurring during the main melting periods and corresponding runoff from May to July and additional signals of up to 100 nm/s² during the short snow free summer season (Figure 6)."

LL. 384-385: Second, signals from other water storage components are not considered within the regression analysis.

→ see my comment on L368. Why don't you use the water flow at the Partnach spring?

Authors: Runoff data from Partnach spring gauge are not available for the year 2019. And the logged data from spring 2020 to now is not yet available. The paragraph on the gauge stations in section 2.2 was enhanced accordingly: "Gauge stations monitor the discharge at Partnach spring and Bockhütte (Figure 1), while another gauge station is planned for the Hammersbach catchment. However, massive snowfall and corresponding runoff in spring 2019 have severely damaged the gauge station at Partnach spring and the data for the year 2019 is completely missing. After several visits to the site, the station is not yet fully back operational again. In spring 2020, a gauge logger without remote control has been installed temporarily, so that the data gap does not become even larger. While the 2019 data gap is trying to be filled with runoff measurements from the Bockhütte gauge station, a comprehensive maintenance of the Partnach spring station is planned for summer 2021."

L. 422: there should be less snow

→ If it is "less", then where are the remaining 23%?

Authors: The paragraph was modified: "The assumed spatial distribution of the snowpack suggests that the remaining 23 % contribution to the total gravity signal come from snow masses of the nearby summit area northwest from ZUGOG. However, the local snowpack distribution in the direct vicinity of the SG needs special attention due to artificial snow accumulations around the summit."

LL. 425-426: As the sensitivity diminishes with increasing distances from the gravimeter site, the individual contribution of the snow covered areas in the RCZ are analysed.

→ Would it be interesting to discuss this also in term of elevation, as snow disappears earlier at low elevation? Or are the data of the snow cover sufficiently precise to take this into account?

Authors: Elevation is one component of snow model (see bullet 4 in section 4.2).

LL. 428: reduced by 60 nm/s² masking out the area below the ZUGOG building.

→ What do you mean? An umbrella effect?

Authors: There is just no snow below the building.

L. 456: Karst groundwater

→ Karst is by itself very complicated, presenting e.g. non-linear effects. Is this likely to make even more difficult the separation between ground water and snow/ice? On the other hand, I agree that the presence of a spring acting as a lysimeter is quite interesting, and I also agree that the numerous facilities at the Zugspitze station makes it possible to install an SG, but at least, this potential complexity should be discussed in the introduction and/or discussion.

Authors: Corresponding sentences were added to the summary/discussion: "On the one hand, the hydrological composition of dominating snow cover, melting glaciers and degrading permafrost as well as karst groundwater is very complex and demanding. On the other hand, the RCZ is among the best equipped high-alpine catchments with lysimeter characteristics and now supplemented by a superconducting gravimeter on top of it. This combination is what makes it very interesting and unique worldwide."

LL. 461-464: 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.

→ By using the recession model is it possible to separate the transient rainfall effects from the snow melt? Hence integrating the spring flow for some weeks would provide a proxy for the snow cover, is it?

Authors: The separation of snow melt and rainfall contribution is difficult for a number of reasons, one is that rainfall can be temporarily stored within the snow pack, and released later. This would not produce any pronounced peak in the spring discharge. Also, the catchments spans a range of 1500 m in altitude, so the melting processes and snow pack height distribution are highly variable in space and time.

L. 473: Figure 7: Runoff characteristics

→ Why do not you show the 2019-20 series? this would be relevant to the SG series and allow us to see the influence of the exceptional snow cover on the spring discharge.

Authors: The data is unfortunately not available for this period (see section 2.2).

LL.477-478: 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.

→ ?

Authors: We will use the term 'spring discharge' instead of 'runoff', which might have been misleading in this context.

LL. 486-487: a water storage model for the vadose karst zone was developed by an addition of daily discharge volumes during the depletion period.

→ How is it achieved? Does it take into account this specific site?

Authors: We rephrased this sentence to be more specific and clearer: "Based on a mean recession constant "α", the storage volume of the vadose zone was calculated to vary between 1.6 and 3.38 x 10^6 m^3 (Figure 7b)"

LL. 496-497: 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.

→ This is not new, see Delobbe et al., 2019, (10.5194/hess-23-93-2019).
Please provide values: what is the actual change in gravity during rainfall? Can you infer an admittance?

Authors: The reference was added. The sentence before provides the theoretical admittance factor from the topography: 0.9 $nm/s^2/mm$ rain.

LL. 500-501: at the ZUGOG gravimeter site which is at the limit of what can be observed by the gravimeter.

→ About evapotranspiration and gravity refer to Van Camp et al., 2016 (10.1002/2016GL070534.)

Authors: Thank you. Added.

L. 540: might strongly benefit

→ Aren't you sure?

Authors: Changed to "will strongly benefit"

LL. 543-544: 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.

→ could remote-sensing tools help? You mentionned this in the introduction, but is it really impossible to use it as complementary information, esp. for long-term changes? You also mention LIDAR hereafter... Please merge those two parts (here and L570)

Authors: The whole chapter of summary and discussion was modified.

LL. 550-554: 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 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.~~

→ This is appropriate for a request for funding.

Authors: The whole chapter of summary and discussion was modified.

L. 555: install a continuously recording spring gravimeter

→ I suppose, a gPhone? Provide a reference. Only this instrument can ensure long-term (relative) stability.

Authors: Unfortunately, a gPhone is not available. Instead, our ZLS-Burris spring gravimeter will be equipped with AGEScont software.

LL. 563-565: 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 or by setting up a local model based on an array of available barometers.

→ Is it really a priority? As you write further, the essential task is to build the spatially distributed hydrological model.

Authors: The local hydrological model is of highest priority. But we think that it is also worth improving the atmospheric reductions.

Comment on hess-2021-78
Anonymous Referee #2

Referee comment on "Introduction of a Superconducting Gravimeter as Novel Hydrological Sensor for the Alpine Research Catchment Zugspitze" by Christian Voigt et al., Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2021-78-RC2, 2021

I found the presentation of preliminary data from the ZUGOG observatory to be an interesting extension of the microgravity method into alpine environements. To my knowledge it is the first deployment of its kind in the high alpine environment and presents unique considerations concerning the spatial sensitivity of the instrument. I do not share the novelty or significance concerns of RC1; I think the preliminary presentation is inline with other publications (e.g., https://doi.org/10.5194/essd-11-1501-2019) and rapid publication is of greater benefit to those who might consider similar deployments (myself included).

The paper hints at the fact that a mountain-top deployment is both an advantage and disadvantage - increase in sensitivty to distant mass change is accompanied by an (unwanted) increase at near distance. Perhaps the ideal location would be in a flatter region atop a mountain (of course in most cases it's limited by infrastructure). I agree with the proposal to collect gradient data between meters to better define the region of sensitivity.

I agree that a second send of AG measurements will greatly improve the manuscript by constraining the drift rate.

Authors (response to referee #1): In the meantime, we have carried out the second set of absolute measurements at the end of March 2021 with the FG5-X-220 by Leibniz University Hannover. The estimated SG drift is -30 nm/s² for the period of 1.5 years between the two absolute sets (so -20 nm/s²/yr). So, based on these two absolute measurements, we cannot disprove our null hypothesis for the drift. We have modified the whole paragraph from LL. 234:

"The instrumental drift of the OSG 052 is determined based on two absolute determinations with FG5X-220 by LUH at 26-27 Sep 2019 and 30-31 Mar 2021 with 2477 and 5166 drops, respectively (Figure 3g). The instrumental uncertainty (long-term stability) of each g determination is estimated with 20 nm/s² (1σ) (Timmen et al., 2021). From the comparison, a SG drift of -20 nm/s²/yr is estimated. The null hypothesis of a zero drift assumption cannot be disproved statistically. With the knowledge that the SG drift should be small and linear towards increasing gravity, no drift is applied in the following hydro-gravimetric analysis. Further absolute measurements planned for the future will increase the redundancy of the drift estimation and longer temporal differences between the absolute measurements will make the drift estimation more robust. Unfortunately, the first absolute measurements from 15-20 Oct 2018 cannot be used as additional reference value for the drift estimation, as the SG had to be warmed up and cooled again for re-initialisation at the end of Dec 2018 (section 2.1), so that there is no connection to the current continuous SG time series."

Creutzfeldt (2013) is an important reference for the discussion on the relation between spring discharge, storage, and gravimetry.

Creutzfeldt, B., Troch, P., Güntner, A., Ferré, T. P. A., Graeff, T., & Merz, B. (2013). Storage-discharge relationships at different catchment scales based on local high-precision gravimetry. Hydrological Processes, 28(3), 1465–1475. https://doi.org/10.1002/hyp.9689

Authors: Added: "Creutzfeldt et al. (2013) use SG measurements at Wettzell, Germany, for the estimation of storage-discharge-relationships in a small headwater catchment,…"

Does the very high correlation between the residuals and SWE have implications for the uniformity of the snowpack? I think that's an important aspect of this deployment, that because the gravity meter integrates over a large area, it inherently "smooths" the heterogeneous snowpack. But probably there is a level of heterogeneity where the assumption of uniform snowpack is not valid?

Authors: The question regarding the high correlation between SG residuals and SWE is justified. This was also a bit surprising for us at the beginning. However, the large SWE quantities of up to 2000 mm dominate the hydrological mass variations in this area by far. So the general good agreement between the SG residuals and the SWE from a single but quite representative hydro-meteorological station is initially positive. In addition, in Figure 4 and as stated in the paragraph from line 381, SG residuals and SWE show highly significant differences of 250 nm/s² range which leaves a lot of room for analysis on the variability of the snowpack but also on liquid contributors. Finally, the SG residuals show a lot more short-term variations than the SWE especially during and after snow events indicating plenty of more information included.

We modified the paragraph: "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. During periods of massive snowfall this leads to remaining signals of up to 150 nm/s². Moreover, rain events during the short summer season cause rapid gravity increases of up to 100 nm/s² followed by an equally fast but only partial decrease and a slower subsequent decline due to the lagged drainage back to the gravity level before the specific rain event (Timmen et al., 2021). Second, signals from other water storage components are not considered within the regression analysis with the major remaining signals of up to 200 nm/s² occurring during the main melting periods from May to July (Figure 6)."

I encourage the authors to explore the relation between SWE-corrected residuals and spring discharge (e.g., in a figure). Although the discussion of recession constant is useful for bounding the thickness of groundwater storage, that could also be done by integrating spring discharge and dividing by area.

Authors: The note on the relation of SWE-corrected SG residuals and spring discharge at the Partnach spring is fair and a figure would be desirable. Unfortunately, the massive snow masses (and corresponding dischargein spring 2019 have damaged the sensors at the Partnach spring gauge station and this is why there is a lack of data for our relevant SG period. So this can only be part of upcoming analysis.

The paragraph on the gauge stations in section 2.2 was enhanced accordingly: "Gauge stations monitor the discharge at Partnach spring and Bockhütte (Figure 1), while another gauge station is planned for the Hammersbach catchment. However, massive snowfall and corresponding runoff in spring 2019 have severely damaged the gauge station at Partnach spring and the data for the year 2019 is completely missing. After several visits to the site, the station is not yet fully back operational again. In spring 2020, a gauge logger without remote control has been installed temporarily, so that the data gap does not become even larger. While the 2019 data gap is trying to be filled with runoff measurements from the Bockhütte gauge station, a comprehensive maintenance of the Partnach spring station is planned for summer 2021."

The figures are well prepared and relevant to the text.

Fig. 5: Although the figure is useful for showing the asymmetry of the gravimeter footprint, the magnitude of the contribution to g of each individual prism isn't useful, and the log colorbar-scaling can be misleading. Suggest showing instead the cumulative sensitivity contours—i.e., the region within which 30% of the signal originates, 60%, 90%, etc.

Authors: Figure 5 was modified accordingly. On the right, the cumulative snow-gravimetric sensitivities are shown as contour plots up to 99.87 and 99.76%, respectively, for the 2 examples of seasonal gravity maxima in 2019 and 2020. These omit a gravity residuals of 1 nm/s² along with the estimated uncertainty of the gravimetric method. These are the snow-gravimetric footprints.

490: Do 0.27 and 0.56 m refer to thicknesses of free-standing water (i.e., terrestrial water storage)? "Groundwater heights" would imply the values depend on the porosity of the porous media, as measured in a monitoring well.

KS/FK: Authors: We changed it to: " …, these numbers correspond to water level changes of 0.27 and 0.56 m, respectively, that can be translated into groundwater level changes depending on the aquifer porosity."

495: Why is the precipitation admittance factor (90 µGal/m) so much higher than the SWE admittance factor (29.8 µ/m)? It may be interesting to discuss how the former is much higher than the infinite slab, and the latter lower.

Authors: The higher rain admittance factor can be explained by the homogeneous layer of 1mm precipitation over the whole area, while the SWE admittance factor depends on the SWE observed by one snow scale which is known to provide maximum values for the area. However, the distribution of the SWE is very homogeneous (as can be seen from our snowpack model). So there is no maximum SWE all over the area.

The paragraph was supplemented accordingly: "The higher precipitation admittance factor (factor 3 compared to 0.298 nm/s²/mm for the SWE) results from the large geographical heterogeneity of the SWE in the RCZ. The SWE of the snowpack recorded by the snow scale at the LWD station provides maximum SWE values, while precipitation is set as a homogeneous layer."

505: "Problematic" is unclear.

Authors: The sentenced was modified: "In addition, cavities inside Mount Zugspitze filled with water through permafrost degradation might lead to disturbances of the gravimetric signal on catchment scale depending on the distance and direction to the gravimeter and their sizes."

526-529: This sentence is unclear (its difficult to tell how the first part justifies the latter).

Authors: The whole chapter of summary and discussion was modified.

572-582: I found this paragraph to be vague and of limited importance.

Authors: The whole chapter of summary and discussion was modified.

Comment on hess-2021-78
David Crossley

Community comment on "Introduction of a Superconducting Gravimeter as Novel Hydrological Sensor for the Alpine Research Catchment Zugspitze" by Christian Voigt et al., Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2021-78-CC1, 2021

I read the paper with great interest as an example of SG measurements at extreme high topographic variations. Contrary to Reviewer#1, I believe this paper is ready to be published as a preliminary analysis of some difficult measurements. It is unrealistic to demand all papers must be textbook ready when ongoing developments are of some interests to the community. So I thought that rejection was too harsh.

There were however some useful comments in this review. I agree the writing is repetitious in some concepts as similar topics are commented on several times in different sections. It would pay dividends if the authors kept comments tightly under each of their subsections, instead of back-and-forth referencing.

Authors: We modified the whole manuscript to eliminate or at least largely reduce redundancies.

Also the bibliography needs attention. Generally the figures are appropriate.

Authors: A lot of references were added (see also referee report #1)

A few observations:

Figure 1: the topography; maybe add a profile EW or NS to give some sense of how fast it is falling off for the first km or 2 around the station? This pertains very much to the integration of the mass effect of the snow and water.

Authors: Figure 1 was modified and enhanced with a topographic profile through the station showing the local situation. You will see that the slope is steep toward the North and the height difference to the valley is almost 1500 m, while on the other side towards the RCZ the slope is not so steep and the flatter Zugspitzplatt is on a height difference of 700 m. So by far the largest contributions can be expected from the snow masses there.

Table 2: The tidal results are presented with almost no comments. What are the X-vectors for the various OTL waves?

Authors: We decided to print our estimations of the partial tidal waves to be applied from other groups doing relative and absolute gravimetry in this area for their reductions. The focus should be on how to get adequate gravity residuals from your observations for hydro-gravimetric analysis and not so much to interpret partial tidal waves. Btw Referee #1 would like us to significantly reduce the technical details from our paper.

Figure 3: it would be better to label each panel by letters (a), (b) … and then refer to these in the caption.

Authors: Done. As in every Figure with subplots.

Figure 4: like Reviewer#2 I was surprised at the high correlation between the SG and SWE from such a simple Bouguer model. With all the mass variations below the station the departure from a Bouguer plate is extreme, and nearby snow mass variations should be quite significant close to the station, offset by significant lack of mass further from the SG. This needs more attention/discussion.

Authors (as above for Referee #2): The question regarding the high correlation between SG residuals and SWE is justified. This was also a bit surprising for us at the beginning. However, the large SWE quantities of up to 2000 mm dominate the hydrological mass variations in this area by far. So the general good agreement between the SG residuals and the SWE from a single but quite representative hydro-meteorological station is initially positive. In addition, in Figure 4 and as stated in the paragraph from line 381, SG residuals and SWE show highly significant differences of 250 nm/s² range which leaves a lot of room for analysis on the variability of the snowpack but also on liquid contributors. Finally, the SG residuals show a lot more short-term variations than the SWE especially during and after snow events indicating plenty of more information included.

We modified the paragraph: "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. During periods of massive snowfall this leads to remaining signals of up to 150 nm/s². Moreover, rain events during the short summer season cause rapid gravity increases of up to 100 nm/s² followed by an equally fast but only partial decrease and a slower subsequent decline due to the lagged drainage back to the gravity level before the specific rain event (Timmen et al., 2021). Second, signals from other water storage components are not considered within the regression analysis with the major remaining signals of up to 200 nm/s² occurring during the main melting periods from May to July (Figure 6)."

I didn't see any elevation correction for the local pressure admittance (Boy et al, 2002). This would be interesting because the nominal admittance is modified at high elevations due to the reduced density of the air column (compared to the values given on the IGETS/EOST loading website). An arrays of barometers is probably not rewarding, especially in this difficult terrain.

Authors: This is exactly what we have done but obviously our description was too short or unclear. We modified the paragraph: "In order to account for the limited spatial resolution and to improve the temporal resolution, the following procedure is used. The gravity observations are reduced by the effects of solid Earth and ocean tides, Earth rotation and SWE variations as well as regional and global atmospheric effects from Atmacs. In this way, the gravity residuals primarily reflect the effects of local atmospheric mass redistributions. The admittance factor between these gravity residuals and the observed barometric pressure variations is estimated to -2.9190 nm/s²/hPa (1σ=0.0274). For the total atmospheric reduction, the local part of Atmacs is replaced by this admittance factor multiplied by the observed pressure variations in 1h sampling and added to the regional and global atmospheric effects from Atmacs."

Overall, this paper is well worth revising, especially with the new AG calibration for the drift (the previous AG gradient doesn't mean much over 2004-2019) and SG scale factor.

Authors (response to referee #1): In the meantime, we have carried out the second set of absolute measurements at the end of March 2021 with the FG5-X-220 by Leibniz University Hannover. The estimated SG drift is -30 nm/s² for the period of 1.5 years between the two absolute sets (so -20 nm/s²/yr). So, based on these two absolute measurements, we cannot disprove our null hypothesis for the drift. We have modified the whole paragraph from LL. 234:

"The instrumental drift of the OSG 052 is determined based on two absolute determinations with FG5X-220 by LUH at 26-27 Sep 2019 and 30-31 Mar 2021 with 2477 and 5166 drops, respectively (Figure 3g). The instrumental uncertainty (long-term stability) of each g determination is estimated with 20 nm/s² (1σ) (Timmen et al., 2021). From the comparison, a SG drift of -20 nm/s²/yr is estimated. The null hypothesis of a

zero drift assumption cannot be disproved statistically. With the knowledge that the SG drift should be small and linear towards increasing gravity, no drift is applied in the following hydro-gravimetric analysis. Further absolute measurements planned for the future will increase the redundancy of the drift estimation and longer temporal differences between the absolute measurements will make the drift estimation more robust. Unfortunately, the first absolute measurements from 15-20 Oct 2018 cannot be used as additional reference value for the drift estimation, as the SG had to be warmed up and cooled again for re-initialisation at the end of Dec 2018 (section 2.1), so that there is no connection to the current continuous SG time series."
Regarding the calibration factor: We don't see any need in carrying out a fourth calibration, as the results are accurate enough for our hydrological purposes (as we have shown).

Christian Voigt on behalf of the team of authors (7 May 2021)