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Quantifying the Central European Droughts in 2018 and 2019 With GRACE Follow-On

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Key Points:
- GRACE-FO quantifies continental water mass anomalies in continuation of the GRACE mission (2002–2017)
- GRACE-FO observes a water storage deficit of 112 and 145 Gt in 2018 and 2019 in Central Europe relative to the average conditions
- These deficits amount to 73% and 94% of the mean amplitude of seasonal water storage variations, respectively

Supporting Information:
- Supporting Information S1
- Figure S1
- Figure S2
- Figure S3
- Figure S4
- Figure S5
- Figure S6

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Abstract The GRACE-FO satellites launched in May 2018 are able to quantify the water mass deficit in Central Europe during the two consecutive summer droughts of 2018 and 2019. Relative to the long-term climatology, the water mass deficits were -112 ± 10.5 Gt in 2018 and -145 ± 12 Gt in 2019. These deficits are 73% and 94% of the mean amplitude of seasonal water storage variations, which is so severe that a recovery cannot be expected within 1 year. The water deficits in 2018 and 2019 are the largest in the whole GRACE and GRACE-FO time span. Globally, the data do not show an offset between the two missions, which proves the successful continuation of GRACE by GRACE-FO and thus the reliability of the observed extreme events in Central Europe. This allows for a joint assessment of the four Central European droughts in 2003, 2015, 2018, and 2019 in terms of total water storage deficits.

Plain Language Summary During the droughts of 2018 and 2019, Central Europe had a water deficit of about 112 and 145 Gt compared to an average year. As the water storage differences between winter and summer is about 150 Gt, the drought-related deficit amounts to 73% and 94% of these annual variations. These mass variations can be observed with the twin satellite missions GRACE (Gravity Recovery and Climate Experiment, 2002–2017) and its successor GRACE Follow-On (launched May 2018). With the satellite observations, the change in the total water storage can be estimated, including ground water, soil water content, and surface waters such as lakes and rivers. During the 21st century, Central Europe experienced four major droughts in 2003, 2015, 2018, and 2019, and we document the severity of the more recent droughts with respect to earlier events. We also find no systematic offset between the GRACE and GRACE-FO observations, so that the available satellite gravity record extends now over 18 years already.

1. Introduction

Satellite gravimetry is the only remote sensing technique available today that provides quantitative estimates of water storage changes at regional to global scales, independent of whether these are exposed at the Earth's surface or occurring in the deep subsurface. The Gravity Recovery and Climate Experiment (GRACE, 2002–2017) satellite mission measured tiny variations in the distance between two twin satellites trailing each other in a polar orbit at very low (500 km) altitudes (Tapley et al., 2019). GRACE applications in hydrology were manifold, such as quantifying the contributions of the continental ice sheets to sea level rise (Velicogna & Wahr, 2006), groundwater changes (Frappart & Ramillien, 2018), water storage capacity and flood potential (Reager & Famiglietti, 2009), or drought effects, for example, in California's Central Valley (Famiglietti et al., 2011). The monitoring of water mass anomalies from space initiated with GRACE is being continued by the GRACE-FO mission (Landerer et al., 2020) launched in May 2018.

Since the launch of GRACE-FO, Central Europe experienced two severe droughts in 2018 and 2019. In the summer months of 2018, Central and Northern Europe experienced exceptionally dry conditions (Toreti et al., 2019) with parts of Central Europe receiving less than 50% of the long-time mean precipitation (European Drought Observatory, 2018). Combined with a heat wave in July and August, this led to a severe drought in the region. In addition to the long-lasting effects of the 2018 drought event, parts of Central Europe again experienced below-average precipitation in 2019 and heat waves in June and July 2019, leading to the second drought in two consecutive years (European Drought Observatory, 2019). The water deficit had severe consequences for agricultural productivity, forest management, and industrial production, with the latter cut back by disrupted transport on inland water ways due to extremely low water levels. The associated heat waves also had severe impacts on the health conditions of the population. Comprehensive

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information on the extent, severity, and impact of the droughts is needed to guide future large-scale water management decisions. The recent conditions should also be set into the context of earlier drought events in the area such as the European heat wave of 2003 (Andersen et al., 2005; Seitz et al., 2008), which was exceptionally hot and dry all over Central Europe leading to widespread water scarcity at that time (Laaha et al., 2017).

There is no universal definition of drought, as it largely depends on the discipline and the area of application. Commonly, meteorological, hydrological, agricultural, and socioeconomic droughts are distinguished (Wilhite & Glantz, 1985). This study deals with hydrological droughts, which is the shortage of surface or subsurface water compared to a reference that is considered to represent "normal" conditions for a given time period of the past. Many drought investigations seek to characterize deviations from the "normal" via standardized drought indices (Heim, 2002). Many operational drought indices focus on meteorological quantities, as, for example, the Standardized Precipitation Index (SPI) (e.g., McKee et al., 1993; Pietzsch & Bissolli, 2011), the Standardized Precipitation Evapotranspiration Index (SPEI) (Vicente Serrano, 2010), or a combination of those (Ziese et al., 2014). Hydrological droughts of the surface water scarcity are characterized by the Surface Water Supply Index (SWSI) (Shafer & Dezman, 1982) or the Streamflow Drought Index (SDI) (Nalbantis & Tsakiris, 2009). Indices indicating drying of soil moisture are usually based on precipitation and evapotranspiration observations and associated numerical modeling, like the series provided by the European Drought Observatory (EDO) (Horion et al., 2012).

GRACE gravity data have also been used before to define global drought indices. Houborg et al. (2012) introduced a percentile index for the North American Drought Monitor. Thomas et al. (2014) proposed a standardized index that incorporates not only the absolute value of the water mass deficit but also the duration of the drought. Zhao et al. (2017) proposes an index that explicitly considers both GRACE measurement and leakage errors. A comprehensive assessment of GRACE-based drought indices has been recently provided by Gerdener et al. (2020). Cammalleri et al. (2019) showed that a shortage of precipitation, as indicated by meteorological drought indices, can be used as a local proxy to hydrological droughts observed with GRACE.

In this work we investigate the capability of GRACE-FO to identify and quantify the water mass deficit of the two exceptionally dry summers 2018 and 2019 in Central Europe. We classify these events in the context of 18 years of GRACE and GRACE-FO observations and discuss the reliability of the newly available GRACE-FO estimates. We also compare a drought index based on satellite gravity data to independent soil moisture and lake level indices and discuss potential and limitations of a GRACE-based index with respect to more conventional hydrometeorologic indicators.

2. Processing of GRACE/GRACE-FO Data

We use 178 monthly GRACE and GRACE-FO gravity fields from the GFZ RL06 time series (Dahle et al., 2019), given in Stokes coefficients expanded up to degree and order 96 that cover the time frame April 2002 until November 2019. Coefficients of degree 2 and order 0 are replaced by estimates from Satellite Laser Ranging (König et al., 2019). We further subtract a model of glacial isostatic adjustment (Klemann et al., 2008), insert approximated degree 1 terms following Bergmann-Wolf et al. (2014), remove an aliased tidal signal at a period of 161 days, and apply time-variable decorrelation filters (Horvath et al., 2018) with different smoothing widths (i.e., the stronger VDK3 and the weaker VDK5).

The Stokes coefficients are subsequently synthesized on a global 1° latitude-longitude grid. To reduce the impact of spatial leakage, trends as well as annual and semiannual signals are filtered with VDK5, whereas residual month-to-month variability is filtered with the somewhat stronger VDK3 version of Horvath et al. (2018). In contrast to mascon solutions, no spatial leakage correction is applied. Coseismic gravity changes associated with three megathrust earthquakes are empirically estimated and removed. The resulting gridded terrestrial water storage (TWS) estimates are publicly available from the GravIS portal (gravis.gfz-potsdam.de, Zhang et al., 2019). From the gridded data, a mass anomaly time series is aggregated for Central Europe (CE), which is defined in this study as the region between 4° and 24° eastern longitude and between 45° and 55° northern latitude, thereby ranging from Netherlands to Poland and from the Alps to the coast of the Baltic Sea. The size of the land area is approximately 1.45 million square km. The mass anomaly time series are provided with an uncertainty estimation, which will be given for all mass anomaly values in this study.

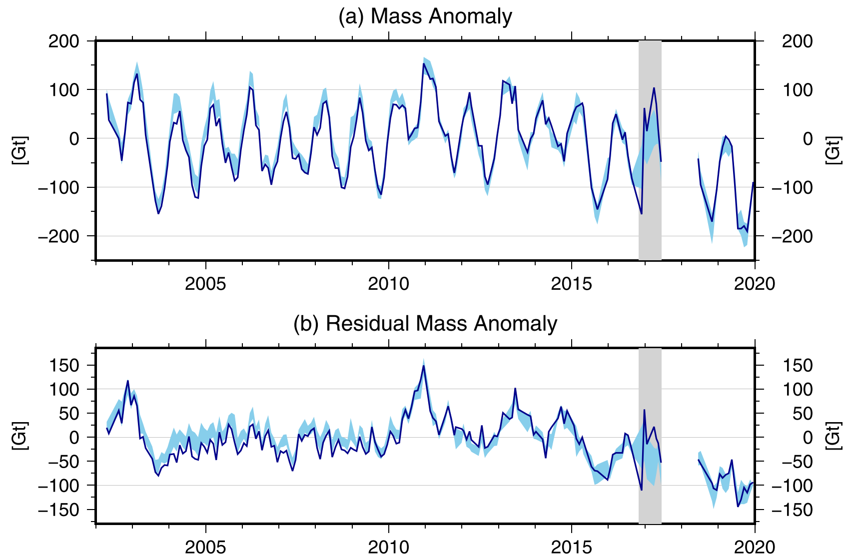

Figure 1. (a) Total water storage (TWS) anomaly time series observed over CE with GRACE and GRACE-FO; (b) the TWS anomaly reduced for annual signal component (dark blue: GFZ RL06 solution; light blue: range of six GRACE/GRACE-FO solutions; standard deviation around ensemble mean; gray: GRACE end-of-life period).

3. Water Mass Deficits From GRACE/GRACE-FO

Apart from a strong seasonal signal, the GRACE-based mass anomaly time series for CE shows distinct minimal values of TWS during the summer-to-autumn periods of 2003, 2015, 2018, and 2019 (Figure 1). In July 2019, GRACE-FO documents with -146 ± 12 Gt the largest deficit of water mass observed in CE so far of the past 18 years. The gap between maximum and minimum of the seasonal signal amounts to 154 Gt, meaning that the overall deficit in 2019 corresponds to 95% of this seasonal oscillation. Note that in the year 2018, GRACE-FO solutions are only available for June, July, October/November (mean epoch 31 October), and November (mean epoch 15 November), so that the seasonal minimum might have been missed. In November 2018 the deficit amounted to -113 ± 10.5 Gt, corresponding to 73% of the seasonal signal. From the whole GRACE and GRACE-FO data record, these two very recent years show the largest water mass deficit observed so far. We note that even the exceptionally high amount of snowfall in the Alps and a conventionally humid winter elsewhere in Europe were not able to restore the water storage to the pre-drought conditions, thereby providing important insights into the cumulative stress of repeated dry periods on the hydrological systems. In contrast, the extremely hot summer of the year 2003 just had a maximum deficit in September of -80 ± 10 Gt. Year 2015 exhibited another drought in the satellite record with a mass deficit of -83 ± 15 Gt peaking in December. Compared to the other events discussed above, the drought in 2015 persisted over the longest period of time until finally a recovery of the water storage deficit relative to the mean seasonality occurred which was only in middle of 2016.

To further assess the uncertainty of these results, we also use three additional recent (compatible with GFZ RL06) global spherical harmonics solutions from GRACE and GRACE-FO processed by Center for Space Research (Bettadpur, 2018; Save, 2019b), Jet Propulsion Laboratory (Yuan, 2018, 2019), and Technical University of Graz (Kvas et al., 2019). For completeness, we also consider the global mascon solutions published by CSR (Save, 2019a; Save et al., 2016) and JPL (Watkins et al., 2015; Wiese et al., 2016, 2018). The spread of these six different solutions is characterized for each month by the standard deviation of the mass anomalies around the ensemble mean, which is displayed as shaded area in Figure 1. We note that GFZ RL06 used in this paper typically fits well into this uncertainty range. Some exceptions are notable, in particular during the early years of the GRACE mission. During the GRACE end-of-life months from November 2016 to June 2017, the data quality degraded due to the loss of the accelerometer data on one spacecraft (Bandikova et al., 2019), which leads to an increased spread among the series. Those months are therefore ignored in the following analysis.

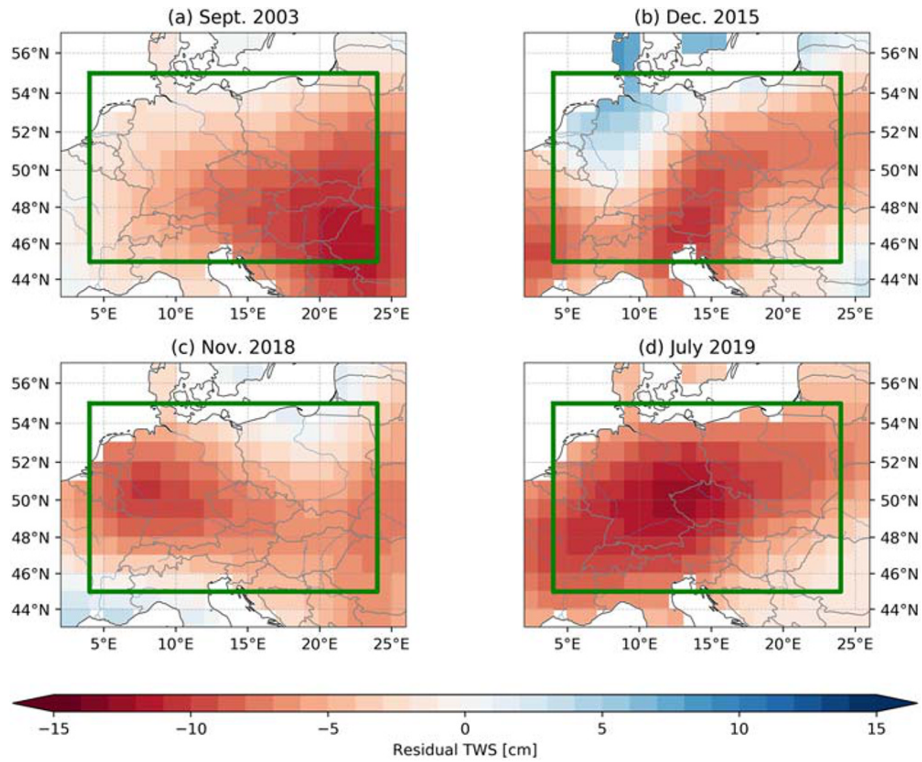

Figure 2. Residual TWS anomaly (annual signal reduced) for (a) September 2003, (b) December 2015, (c) November 2018, and (d) July 2019. The green box marks the area of CE.

Besides total water storage anomalies estimated over the whole region of Central Europe, satellite gravimetry also provides some information on the spatial distribution of the water deficits, here given for each drought year at the month of seasonal minimum in TWS (Figure 2). In November 2018, the drought conditions were most severe in the western part of Germany. The Baltic coast region in Poland even had slightly above-average water storage conditions. In July 2019, the drought was centered in eastern Germany and Poland. However, the drought was more widespread across CE in 2019, since many regions affected by the previous dry summer did not yet recovered to the full extent. In 2003, the biggest water deficit was detected in the southeast of Europe. The drought of 2015 instead was centered in Austria, while the coastal regions and northwest Germany experienced above-average water storage conditions.

While November 2018 was the overall driest month in 2018, the region of southwestern Germany and neighboring countries saw an even larger drought earlier that year (Figure S5). Similarly, the northwestern part of CE exhibited an even more severe water deficit in August 2019, or Austria and the Adriatic coast were drier in August than in September 2003. The spatiotemporal pattern of water storage evolution in 2003 compared to 2019 shows that conditions were much more severe in 2019, both in terms of maximum deficits and the duration of the drought. Unfortunately, the spatiotemporal evolution of the droughts in 2015 and 2018 cannot be fully tracked due to several missing GRACE/GRACE-FO monthly solutions in those years.

4. Comparison With Soil Moisture and Lake Level Indices

In order to relate the GRACE and GRACE-FO results to other hydrometeorological observations, we utilize both a publicly available drought index for soil moisture and a specifically calculated index based on lake level in situ observations. Compared to GRACE/GRACE-FO, soil moisture and surface water storage represent only a certain compartment of the terrestrial water storage. It should be noted, however, that the storage variations of large unregulated lakes can be considered as an integral representation of the overall water storage dynamics of the river basins that drain into the lakes and, thus, compare fairly well to the TWS variations measured by GRACE and GRACE-FO.

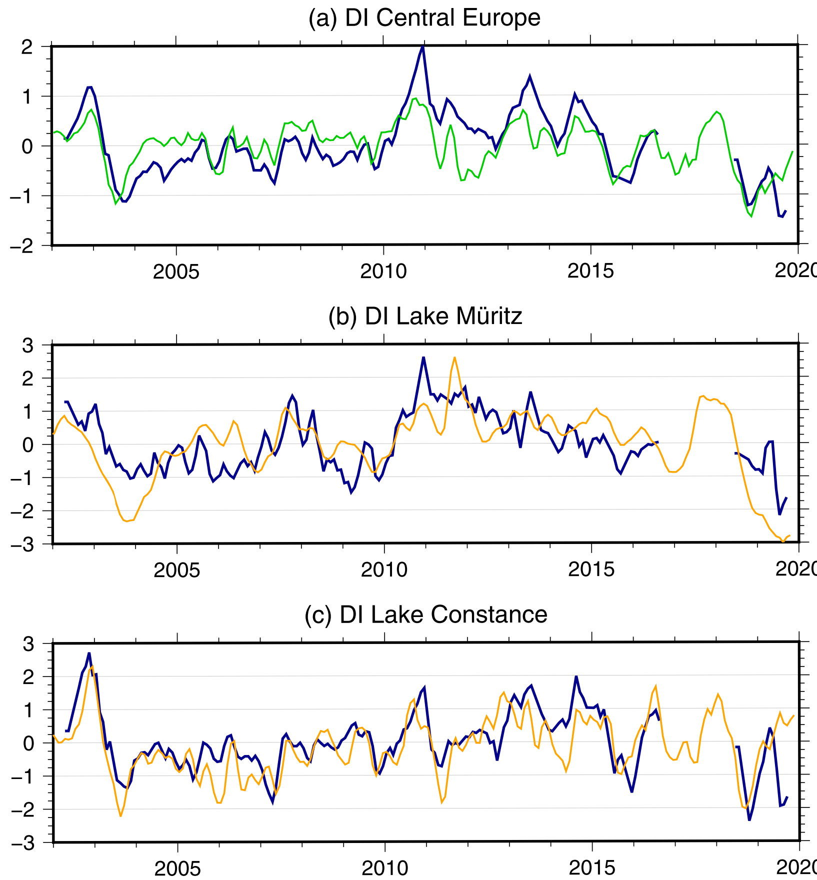

Figure 3. Comparison of DI-TWS (blue lines) to other drought indices: (a) DI-SM (green) and (b and c) DI-LL (orange) of Lake Müritz and Lake Constance.

We use the soil moisture index of the European Drought Observatory (EDO) (Horion et al., 2012), given for Europe on a (5 km)^2 equal-area grid with a temporal resolution of 10 days. The index is based on the plant available soil moisture between wilting point and field capacity as simulated with the hydrological model LISFLOOD (van der Knijff et al., 2010). The corresponding soil depth varies spatially with the rooting depth of the dominant land cover. Here, the index values (DI-SM) are standardized at each time step by subtracting the long-term mean of the time step μ_i (i.e., its climatology) and dividing by the standard deviation σ_i of the time step over the entire soil moisture time series:

$$\text{DI -SM}_{i,j}^{EDO} = \frac{\text{SM}_{i,j} - \mu_i}{\sigma_i}. \tag{1}$$

We adjust the original reference time period of the index (1995–2018) to the temporal mean of all GRACE and GRACE-FO months used in this study and calculate monthly means to aligned to the epochs of the satellite gravimetry solutions. Note that the index values after March 2019 are based on a new model version, which is not yet fully validated.

We also use lake water level observations of Lake Constance in the southwest and Lake Müritz in the northeast of Germany, which are the two largest lakes in the country. The lake water level time series are given between January 2000 and October 2019 with a daily resolution. We convert them to monthly-mean values and normalize each gauge time series to the lake level index (DI-LL) similarly as DI-SM. As before, only months with available GRACE/GRACE-FO data are used for the normalization.

For comparison, we transform the gridded TWS data to a standardized anomaly index for each grid cell similar to the soil moisture index introduced above. The epochs of the TWS data are the mean epochs of data

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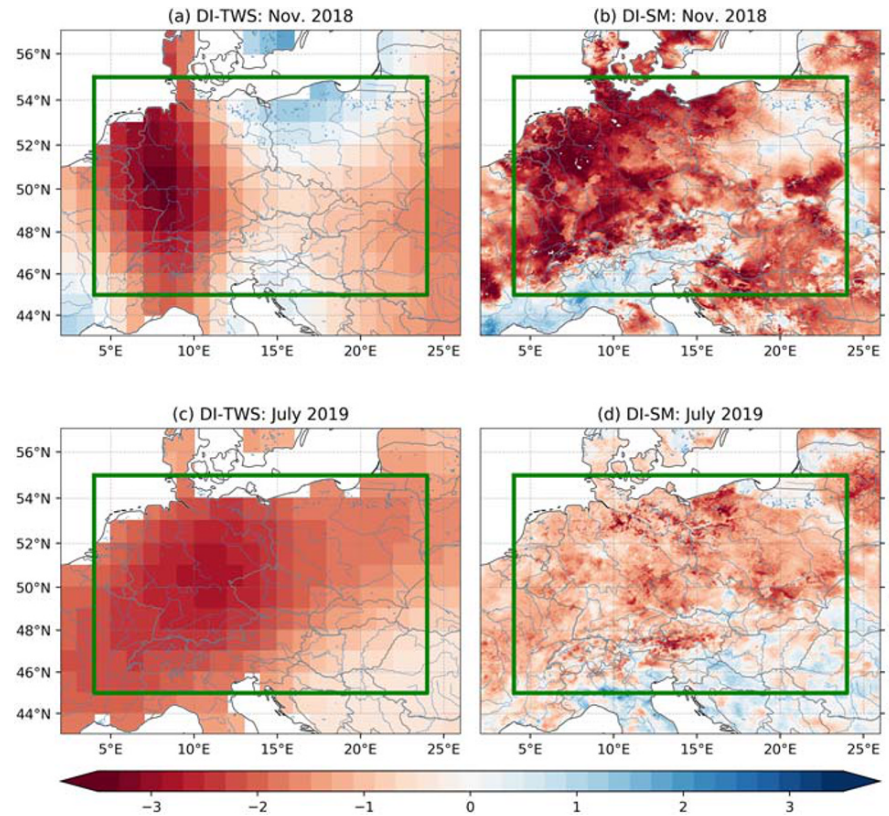

Figure 4. Spatial patterns of (a) DI-TWS and (b) DI-SM for November 2018 and for July 2019 (c and d).

acquisition that are not always aligned with calendar months. In these cases the data are assigned to the month of the mean epoch for the normalization. This index will further be referred to as DI-TWS.

Area-average time series for CE were calculated for DI-TWS and DI-SM and smoothed with a 3-month moving average filter to suppress high-frequency variations (Figure 3a). While both summer droughts of 2018 and 2019 are clearly indicated by minimum values of DI-TWS, the summer 2019 was not as dry as 2018 in terms of DI-SM soil moisture. The drought in the very hot summer of 2003 is captured by both indices but with a time lag and a longer persistence of DI-TWS compared to DI-SM, indicating a larger memory effect of TWS as compared to soil moisture.

DI-LL of Lake Müritz and Lake Constance is now compared to DI-TWS of the respective grid cells that encompass the lakes. Overall, the interannual variations of DI-TWS are similar to those of DI-LL for both cases (Figures 3b and 3c) with a slightly higher correlation for Lake Constance (0.69). For Lake Müritz (correlation 0.62), both indices show their overall minimum value in summer 2019. For Lake Constance, both DI-LL and DI-TWS similarly represent the 2018 drought but differ markedly in the case of the 2019 drought with a recovery of DI-LL but another minimum of DI-TWS. The high water level of Lake Constance during summer 2019 as represented by DI-LL is caused by the runoff of snow melt from the Alps feeding Lake Constance after an exceptionally snow-rich winter.

For November 2018 and July 2019, we compare the spatial distribution of the indices DI-TWS and DI-SM in Figure 4. It should be noted that DI-TWS captures large-scale effects only, while DI-SM has a significantly higher spatial resolution (Figure 4). In 2018, the general pattern of driest conditions in western Germany is reflected by both indices. However, a wet pattern along the coast of the Baltic Sea is more pronounced in DI-TWS. The correlation between DI-TWS and DI-SM on a 1° grid is 0.83 in 2018. In 2019, the two indices agree on the center of the dry region in eastern Germany/western Poland and a rather moist area in southeastern Europe. For July 2019, the spatial correlation between the grids is 0.88. A further comparison to precipitation-based drought indices is given in Supporting Information S1, which largely corroborates the results presented above.

5. Discussion

We showed that the residual water storage anomaly observed by GRACE and GRACE-FO over CE ranges between 151 and −145 Gt, with an typical error of 7 to 22 Gt associated to a single monthly-mean estimate as provided with the GFZ solutions. Even under consideration of those uncertainties, the most recent summers of 2018 and 2019 were the driest in the combined GRACE and GRACE-FO data record. The water storage deficit of the droughts in 2003 and 2015 are with -80 ± 16 Gt and -87 ± 16 Gt clearly less severe. It will be interesting to see how the storage situation will further evolve during the upcoming 2020 summer period.

To assess the data continuity between GRACE and GRACE-FO, we compare the GRACE/GRACE-FO TWS data with TWS data reconstructed from precipitation Humphrey and Gudmundsson (2019). We find that GRACE-FO TWS is very close to the reconstructed TWS and no offsets are detected (Figure S6). Thus, we conclude that GRACE-FO consistently continues the GRACE time series and that the extreme events observed in CE by GRACE-FO in 2018 and 2019 are not impacted by data biases or other spurious effects of the new satellite mission.

The spatial patterns of GRACE-based water storage deficits indicate that the summer droughts of 2003 and 2019 had a larger spatial extent throughout CE than the 2015 and 2018 events. Based on GRACE-FO, the latter was regionally more severe in southwestern Germany and neighboring countries. Also, southern Europe experienced above-average wet conditions in 2018 (Toreti et al., 2019). In 2015, the GRACE-based patterns with predominant water deficits in particular in the eastern parts of CE are similar to patterns of precipitation deficits given in Orth et al. (2016) and the focus area of the drought from a hydrological perspective reported by Laaha et al. (2017).

Due to the filtering necessary in GRACE/GRACE-FO data processing, water mass signals are spread out over larger areas, thereby reducing the spatial resolution. Signals can either leak into the region of interest from the outside or, vice versa, signals inside the area can leak to the outside, which is called leakage-in or leakage-out, respectively (Klees et al., 2007). We investigated the effect of leakage for our study area by comparing the mass anomaly and the residual mass anomaly time series for CE based on all VDK filtered fields between VDK2 to VDK6. Overall, no significant difference is visible between the filters, especially not during the summer drought periods. This indicates that spatial leakage does not dominate the uncertainties in the study region. This is also supported by the rather small spread of the ensemble that also includes two mascon solutions with sophisticated leakage corrections. In September 2003, for instance, the difference between the strongest (VDK2) and the weakest filter (VDK6) is 7 Gt only, in November 2018 4.5 Gt, and in July 2019 14 Gt. In the latter case, a positive water storage anomaly over southwestern France leaks into the CE study area when using the strong VDK2 filter and thereby spuriously reduces the drought severity.

The comparison between the three different indices shows both advantages and limitations of drought identification with satellite gravity data. All indices indicate droughts in different hydrological storages. Temporal lags of different extent can be observed between the water mass in surface water, soil moisture, and TWS. However, only TWS indicates possible shortages in the amount of water potentially available in a certain region and therefore shows a stronger memory effect than, for example, precipitation, soil moisture, or surface water (Creutzfeldt et al., 2012). This memory effect and the slight dampening of the signal might be caused by the deep groundwater included in TWS, which has an overall slower response compared to soil moisture or surface water. Because of this, the persistence of the 2018 drought well into 2019 is clearly observable with satellite gravity data, since the winter precipitation was obviously not sufficient to recharge the large total water deficit. Since soil moisture was already restored to the predrought level, this index misses this potentially important information for the long-term water availability. Local surface water observations can be influenced strongly by local effects not observed by TWS such as the aftermath of the heavy snowfall in winter 2018/2019 on Lake Constance. Nevertheless, the general correspondence among the different indices is very good, thereby further indicating the reliability of GRACE-FO.

6. Conclusions

In this work, we quantified the total water storage deficit over Central Europe during the droughts of 2018 and 2019 with GRACE-FO. Compared to the long-term mean climatology, the deficits are −112 ± 10.5 Gt and −145 ± 12 Gt, respectively. This amounts to over 73% and 95% of the mean seasonal storage change in this region. In terms of soil moisture the drought of 2019 was less severe than 2018 but, the winter 2018/2019 could not sufficiently recharge the deep storages, which led to the even higher deficit in 2019. With GRACE-FO we can also observe the regional intensity of droughts. While the 2018 event was centered in southwest Germany and neighboring countries, the drought in 2019 affected mostly parts of Poland, eastern Germany, and the Czech Republic until July before spreading westward in August. Overall, in 2019 the drought affected all of CE while the eastern part of CE was less affected in 2018.

The two earlier droughts of 2003 and 2015 are also put into perspective with more recent data. Unfortunately, no GRACE-FO data are available for several months during 2018, so that the peak deficit in that year might have been missed. The drought of 2015 lasted the longest but only with a maximum water deficit of 54% of the maximum 2019 deficit.

The comparison of three different drought indices, namely, a soil moisture index, an index derived from surface water level gauges, and the gravity-based TWS index gave evidence of all drought events in any of them, albeit with partly differing dynamics of the water cycle components represented by the respective indices. Furthermore, as the GRACE-FO TWS data for CE closely matches the expected TWS of a long-term reconstruction, we are confident that GRACE-FO provides a reliable, offset-free, and unique view on the impact of the two consecutive drought years on the water budget in Central Europe. GRACE-FO therefore successfully continues the time series of regional water mass anomalies secured by the GRACE satellite mission.

Data Availability Statement

GRACE and GRACE-FO gridded TWS data are freely available over the GFZ portal GravIS (https://gravis.gfz-potsdam.de/home). The EDO drought index, generated using Copernicus Emergency Management Service information (2019), can interactively be viewed online (at https://edo.jrc.ec.europa.eu). Water level gauge data of Lake Müritz and Lake Constance were provided by the *Wasserstraßen- und Schifffahrtsverwaltung des Bundes* (WSV) via the *Bundesanstalt für Gewäcurren;sserkunde*(BfG, https://www.bafg.de/EN/06_Info_Service/01_WaterLevels/waterlevels_node.html) on request.

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References

Andersen, O. B., Seneviratne, S. I., Hinderer, J., & Viterbo, P. (2005). GRACE-derived terrestrial water storage depletion associated with the 2003 European heat wave. *Geophysical Research Letters*, *32*, L18405. https://doi.org/10.1029/2005GL023574

Bandikova, T., McCullough, C., Kruizinga, G. L., Save, H., & Christophe, B. (2019). GRACE accelerometer data transplant. *Advances in Space Research*, *64*(3), 623–644. https://doi.org/10.1016/j.asr.2019.05.021

Bergmann-Wolf, I., Zhang, L., & Dobslaw, H. (2014). Global eustatic sea-level variations for the approximation of geocenter motion from GRACE. *Journal of Geodetic Science*, *4*(1), 37–48. https://doi.org/10.2478/jogs-2014-0006

Bettadpur, S. (2018). GRACE UTCSR Level-2 processing standards document (for Level-2 product release 0006), grace. ftp://isdcftp.gfz-potsdam.de/grace/DOCUMENTS/Level-2/

Cammalleri, C., Barbosa, P., & Vogt, J. V. (2019). Analysing the relationship between multiple-timescale SPI and GRACE terrestrial water storage in the framework of drought monitoring. *Water (Switzerland)*, *11*(8), 1672. https://doi.org/10.3390/w11081672

Creutzfeldt, B., Ferré, T., Troch, P., Merz, B., Wziontek, H., & Güntner, A. (2012). Total water storage dynamics in response to climate variability and extremes: Inference from long-term terrestrial gravity measurement. *Journal of Geophysical Research*, *117*, D08112. https://doi.org/10.1029/2011JD016472

Dahle, C., Murböck, M., Flechtner, F., Dobslaw, H., Michalak, G., Neumayer, K. H., et al. (2019). The GFZ GRACE RL06 monthly gravity field time series: Processing details and quality assessment. *Remote Sensing*, *11*(18), 2116. https://doi.org/10.3390/rs11182116

European Drought Observatory (2018). Drought in central-northern Europe—September 2018 (*Tech. Rep.*). JRC European Drought Observa tory (EDO).

European Drought Observatory (2019). Drought in Europe—August 2019 (*Tech. Rep.*). JRC European Drought Observatory.

Famiglietti, J. S., Lo, M., Ho, S. L., Bethune, J., Anderson, K. J., Syed, T. H., et al. (2011). Satellites measure recent rates of groundwater depletion in California's Central Valley. *Geophysical Research Letters*, *38*, L03403. https://doi.org/10.1029/2010GL046442

Frappart, F., & Ramillien, G. (2018). Monitoring groundwater storage changes using the Gravity Recovery and Climate Experiment (GRACE) satellite mission: A review. *Remote Sensing*, *10*(6), 829. https://doi.org/10.3390/rs10060829

Gerdener, H., Engels, O., & Kusche, J. (2020). A framework for deriving drought indicators from the Gravity Recovery and Climate Experiment (GRACE). *Hydrology and Earth System Sciences*, *24*(1), 227–248. https://doi.org/10.5194/hess-24-227-2020

Heim, R. R. (2002). A Review of Twentieth-century drought indices used in the United States. *Bulletin of the American Meteorological Society*, *83*(8), 1149–1166. https://doi.org/10.1175/1520-0477-83.8.1149

Horion, S., Saiote Carrão, H. M., Singelton, A., Barbosa Ferreira, P., & Vogt, J. (2012). JRC experience on the development of drought information systems (*Tech. Rep.*.). Publications Office of the European Union.

Horvath, A., Murböck, M., Pail, R., & Horwath, M. (2018). Decorrelation of GRACE time variable gravity field solutions using full covariance information. *Geosciences*, *8*(9), 323. https://doi.org/10.3390/geosciences8090323

Houborg, R., Rodell, M., Li, B., Reichle, R., & Zaitchik, B. F. (2012). Drought indicators based on model-assimilated Gravity Recovery and Climate Experiment (GRACE) terrestrial water storage observations. *Water Resources Research*, *48*, W07525. https://doi.org/10.1029/2011WR011291

Humphrey, V., & Gudmundsson, L. (2019). GRACE-REC: A reconstruction of climate-driven water storage changes over the last century. *Earth System Science Data*, *11*(3), 1153–1170. https://doi.org/10.5194/essd-11-1153-2019

Klees, R., Zapreeva, E. A., Winsemius, H. C., & Savenije, H. H. G. (2007). The bias in GRACE estimates of continental water storage variations. *Hydrology and Earth System Sciences*, *11*(4), 1227–1241. https://doi.org/10.5194/hess-11-1227-2007

Klemann, V., Martinec, Z., & Ivins, E. R. (2008). Glacial isostasy and plate motion. *Journal of Geodynamics*, *46*(3-5), 95–103. https://doi.org/10.1016/j.jog.2008.04.005

König, R., Schreiner, P., & Dahle, C. (2019). Monthly estimates of C(2,0) generated by GFZ from SLR satellites based on GFZ GRACE/GRACE-FO RL06 background models ((*Tech. Rep.*). GFZ Data Services.

Kvas, A., Behzadpour, S., Ellmer, M., Klinger, B., Strasser, S., Zehentner, N., & Mayer-Gürr, T. (2019). ITSG-Grace2018: Overview and evaluation of a new GRACE-only gravity field time series. *Journal of Geophysical Research: Solid Earth*, *124*, 9332–9344. https://doi.org/10.1029/2019JB017415

Laaha, G., Gauster, T., Tallaksen, L. M., Vidal, J. P., Stahl, K., Prudhomme, C., et al. (2017). The European 2015 drought from a hydrological perspective. *Hydrology and Earth System Sciences*, *21*, 3001–3024. https://doi.org/10.5194/hess-21-3001-2017

Landerer, F. W., Flechtner, F. M., Save, H., Webb, F. H., Bandikova, T., Bertiger, W. I., et al. (2020). Extending the global mass change data record: GRACE follow-on instrument and science data performance. *Geophysical Research Letters*, *47*, e2020GL088306. https://doi.org/10.1029/2020GL088306

McKee, T. B., Doesken, N. J., & Kleist, J. (1993). *The relationship of drought frequency and duration to time scales* (Vol.17, pp. 179–183). Paper presented at Proceedings of the 8th Conference on Applied Climatology.

Nalbantis, I., & Tsakiris, G. (2009). Assessment of hydrological drought revisited. *Water Resources Management*, *23*(5), 881–897. https://doi.org/10.1007/s11269-008-9305-1

Orth, R., Zscheischler, J., & Seneviratne, S. I. (2016). Record dry summer in 2015 challenges precipitation projections in Central Europe. *Scientific Reports*, *6*(1), 1–8. https://doi.org/10.1038/srep28334

Pietzsch, S., & Bissolli, P. (2011). A modified drought index for WMO RA VI. *Advances in Science and Research*, *6*, 275. https://doi.org/10.5194/asr-6-275-2011

Reager, J. T., & Famiglietti, J. S. (2009). Global terrestrial water storage capacity and flood potential using GRACE. *Geophysical Research Letters*, *36*, L23402. https://doi.org/10.1029/2009GL040826

Save, H. (2019a). CSR GRACE RL06 Mascon Solutions. Texas Data Repository Dataverse. https://doi.org/10.18738/T8/UN91VR

Save, H. (2019b). GRACE Follow-On CSR Level-2 Processing Standards Document For Level-2 Product Release 06, GRACE-FO. ftp://isdcftp.gfz-potsdam.de/grace-fo/DOCUMENTS/Level-2/

Save, H., Bettadpur, S., & Tapley, B. D. (2016). High-resolution CSR GRACE RL05 mascons. *Journal of Geophysical Research: Solid Earth*, *121*, 7547–7569. https://doi.org/10.1002/2016JB013007

Seitz, F., Schmidt, M., & Shum, C. K. (2008). Signals of extreme weather conditions in Central Europe in GRACE 4-D hydrological mass variations. *Earth and Planetary Science Letters*, *268*(1-2), 165–170. https://doi.org/10.1016/j.epsl.2008.01.001

Shafer, B. A., & Dezman, L. E. (1982). Development of a Surface Water Supply Index (SWSI) to assess the severity of drought conditions in snowpack runoff areas. Paper presented at Proceedings of the 50th Annual Western Snow Conference, Reno, NV.

Tapley, B. D., Watkins, M. M., Flechtner, F., Reigber, C., Bettadpur, S., Rodell, M., et al. (2019). Contributions of GRACE to understanding climate change, *9*(5), 358–369. https://doi.org/10.1038/s41558-019-0456-2

Thomas, A. C., Reager, J. T., Famiglietti, J. S., & Rodell, M. (2014). A GRACE-based water storage deficit approach for hydrological drought characterization. *Geophysical Research Letters*, *41*, 1537–1545. https://doi.org/10.1002/2014GL059323

Toreti, A., Belward, A., Perez-Dominguez, I., Naumann, G., Luterbacher, J., Cronie, O., et al. (2019). The exceptional 2018 European water seesaw calls for action on adaptation. *Earth's Future*, *7*, 652–663. https://doi.org/10.1029/2019EF001170

van der Knijff, J. M., Younis, J., & de Roo, A. P. J. (2010). LISFLOOD: A GIS-based distributed model for river basin scale water balance and flood simulation. *International Journal of Geographical Information Science*, *24*(2), 189–212. https://doi.org/10.1080/13658810802549154

Velicogna, I., & Wahr, J. (2006). Measurements of time-variable gravity show mass loss in Antarctica. *Science*, *311*(5768), 1754–1756. https://doi.org/10.1126/science.1123785

Vicente Serrano, S. M., J. I. (2010). A multiscalar drought index sensitive to global warming: The standardized precipitation evapotranspiration index. *Journal of Climate*, *23*(7), 1696–1718.

Watkins, M. M., Wiese, D. N., Yuan, D.-N., Boening, C., & Landerer, F. W. (2015). Improved methods for observing Earth's time variable mass distribution with GRACE using spherical cap mascons. *Journal of Geophysical Research: Solid Earth*, *120*, 2648–2671. https://doi.org/10.1002/2014JB011547

Wiese, D. N., Landerer, F. W., & Watkins, M. M. (2016). Quantifying and reducing leakage errors in the JPL RL05M GRACE mascon solution. *Water Resources Research*, *52*, 7490–7502. https://doi.org/10.1002/2016WR019344

Wiese, D. N., Yuan, D. N., Boening, C., Landerer, F. W., & Watkins, M. M. (2018). JPL GRACE mascon ocean, ice, and hydrology equivalent water height release 06 coastal resolution improvement (CRI) filtered Version 1.0.

Wilhite, D. A., & Glantz, M. H. (1985). Understanding the drought phenomenon: The role of definitions. *Water International*, *10*(3), 111–120. https://doi.org/10.1080/02508068508686328

Yuan, D.-N. (2018). GRACE JPL Level-2 processing standards document for Level-2 product release 06, GRACE. ftp://isdcftp.gfz-potsdam.de/grace/DOCUMENTS/Level-2/

Yuan, D.-N. (2019). GRACE follow-on JPL Level-2 processing standards document for Level-2 product release 06, JPL. ftp://isdcftp.gfz-potsdam.de/grace-fo/DOCUMENTS/Level-2/

Zhang, L., Dobslaw, H., Dill, R., & Boergens, E. (2019). GFZ GravIS RL06 continental water storage anomalies. V. 0001. *GFZ Data Services*. https://doi.org/10.5880/GFZ.GRAVIS_06_L3_TWS

Zhao, M., Geruo, A., Velicogna, I., & Kimball, J. S. (2017). A global gridded dataset of GRACE drought severity index for 2002–14: Comparison with PDSI and SPEI and a case study of the Australia millennium drought. *Journal of Hydrometeorology*, *18*(8), 2117–2129. https://doi.org/10.1175/JHM-D-16-0182.1

Ziese, M., Schneider, U., Meyer-Christoffer, A., Schamm, K., Vido, J., Finger, P., et al. (2014). The GPCC Drought Index—A new, combined and gridded global drought index. *Earth System Science Data*, *6*(2), 285–295. https://doi.org/10.5194/essd-6-285-2014