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Key Points:
- GRACE-FO is extending the 15-year GRACE record of global monthly mass change at an equivalent precision and spatiotemporal sampling
- Since its launch in 2018, GRACE-FO has observed large water storage and ice mass changes driven by interannual climate anomalies
- GRACE-FO's instrument/flight system performance has largely improved over GRACE. The novel laser ranging instrument works successfully

Supporting Information:
- Supporting Information S1
- Figure S1
- Figure S2
- Figure S3
- Figure S4
- Figure S5
- Figure S6
- Figure S7
- Figure S8
- Figure S9

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Extending the Global Mass Change Data Record: GRACE Follow-On Instrument and Science Data Performance

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Abstract Since June, 2018, the Gravity Recovery and Climate Experiment Follow-On (GRACE-FO) is extending the 15-year monthly mass change record of the GRACE mission, which ended in June 2017. The GRACE-FO instrument and flight system performance has improved over GRACE. Better attitude solutions and enhanced pointing performance result in reduced fuel consumption and gravity range rate post-fit residuals. One accelerometer requires additional calibrations due to unexpected measurement noise. The GRACE-FO gravity and mass change fields from June 2018 through December 2019 continue the GRACE record at an equivalent precision and spatiotemporal sampling. During this period, GRACE-FO observed large interannual terrestrial water variations associated with excess rainfall (Central US, Middle East), drought (Europe, Australia), and ice melt (Greenland). These observations are consistent with independent mass change estimates, providing high confidence that no intermission biases exist from GRACE to GRACE-FO, despite the 11-month gap. GRACE-FO has also successfully demonstrated satellite-to-satellite laser ranging interferometry.

Plain Language Summary Mass change is a fundamental climate system indicator and provides an integrated global view of how Earth's water cycle and energy balance are evolving. The Gravity Recovery and Climate Experiment (GRACE) mission monitored mass changes every month from 2002 through 2017. Since June 2018, GRACE Follow-On (GRACE-FO) continues this data record, tracking and monitoring changes in ice sheets and glaciers, near-surface and underground water storage, as well as changes in sea level and ocean currents. GRACE-FO instruments have been successfully calibrated and are providing new monthly mass change observations at a consistent spatial resolution and data quality with GRACE. Since its launch, GRACE-FO has measured record land water storage changes in 2018 and 2019 in response to extreme heat waves and droughts over Europe and Australia, as well as to extreme rainfall events over the United States and Middle East. In the summer of 2019, GRACE-FO measured record-level Greenland mass loss rates. A novel laser ranging interferometer was successfully demonstrated on GRACE-FO, laying the groundwork for improved future satellite gravity observations.

1. Introduction

For more than 15 years, the Gravity Recovery and Climate Experiment (GRACE) mission, a collaboration between the National Aeronautics and Space Administration (NASA) and the German Aerospace Centre (DLR), provided monthly observations of changes in ice sheets and glaciers, near-surface and underground water storage, as well as changes in sea level and ocean currents. Mass change observations are fundamental indicators of large-scale climate dynamics and provide an integrated global view of how Earth's water cycle and energy balance are evolving (e.g., Reigber et al., 2002; Rodell et al., 2018; Tapley et al., 2004, 2019). The importance of mass change observations was underscored in the 2018 Decadal Survey report (NASEM, 2018)

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as one of five “most important” measurements for NASA to obtain in the next decade and the only one for which continuity with the existing record is recommended as a top priority.

Prior to the Decadal Survey, NASA's Climate Architecture Report (NASA, 2010) recognized mass change as a critical climate data record and recommended a gap filler between GRACE and a higher-capability mission, GRACE-2 (NASA, 2010), recommended in the US 2007 Decadal Survey (NRC, 2007). In response, NASA and GFZ (Helmholtz Centre Potsdam GFZ German Research Centre for Geosciences) jointly pursued the GRACE Follow-On (GRACE-FO) mission with the primary objective of continuing and extending global measurements of monthly gravity and surface mass changes from GRACE, as well as continuing observations of atmospheric soundings from Global Positioning System (GPS) radio occultations for the operational provision of vertical atmospheric temperature/humidity profiles to weather services (e.g., Anlauf et al., 2011; Pingel et al., 2010). A secondary objective was to demonstrate for the first time satellite-to-satellite laser ranging (Abich et al., 2019) as an enabling technology for future GRACE-like missions and a demonstrator for the Laser Interferometer Space Antenna (LISA).

To minimize the possibility of a gap in the data record, a heritage architecture similar to GRACE was chosen, with a mission lifetime of 5 years after launch. This allowed for rapid development with architectural modifications limited to lessons learned from GRACE. The twin GRACE-FO satellites were built by Airbus Defence and Space in Germany and launched as part of a commercial rideshare agreement with Iridium Inc. from Vandenberg Air Force Base, California, on a Space-X Falcon 9 rocket on 22 May 2018. The first GRACE-FO science data were obtained on 27 May 2018, and as of January 2020, 17 monthly gravity fields and corresponding mass change maps have been processed and released (Supporting Information, Figure S1).

2. Measurement and Ground Data System Configuration and Performance

The GRACE-FO measurement concept is similar to that of GRACE: two identical satellites (GF1 and GF2) in a near-polar orbit, separated along-track between 170–270 km, at an initial altitude of approximately 491.5 km (Table S1). After drifting apart for 4 days after launch to a separation distance of 216 km, a drift-stop maneuver was performed and the two satellites were yaw-rotated by 180° to align the ranging instruments in relative boresight for nominal science ranging operations. The satellite orbits are allowed to naturally evolve and decay, but regular orbit maintenance maneuvers will be performed throughout the mission duration to keep the satellites in relative fine-pointing alignment and at nominal separation distance between 170 and 270 km.

The satellite system performance requirements were adopted from GRACE, which allowed for a minimization of cost, risk, and schedule. Changes to the original GRACE designs were implemented to mitigate previously identified in-flight performance issues, either engineering or scientific, to account for hardware obsolescence, or accommodate the laser ranging interferometer (LRI). Each satellite carries attitude sensors via three star cameras (SCAs) and an angular rate-sensing inertial measurement unit (IMU), as well as one precise accelerometer (ACC) in the satellite's mass center to measure non-gravitational forces, for example, from solar radiation pressure and drag, as from attitude orbit control system (AOCS) activations via magnetorquers or cold-gas thrusters. These signals need to be removed from the intersatellite range changes to estimate the gravity field. A GPS receiver for precise orbit determination (POD) and precise time tagging is combined with a dual frequency K/Ka-band microwave instrument (MWI) to track intersatellite range variations. The LRI measures range variations in parallel, allowing for a direct comparison of the two ranging observations. The measurement system design and requirements for each subsystem are described in more detail in Kornfeld et al. (2019).

The use of three SCA heads per spacecraft on GRACE-FO reduces the susceptibility to partial Sun and/or Moon blinding, minimizing periods where only one head is available. From launch through September 2019, at least two SCA heads were available 99.5% (three SCA heads 71.5%; two heads 28%) of the time per spacecraft, resulting in more precise attitude solutions compared with GRACE (which only had two and no functional IMUs). The SCA and IMU data are combined for an optimal attitude product (SCA1B) via a Kalman filter (Harvey & Sakumura, 2019; Wen et al., 2019), yielding an SCA noise level about a factor 2 lower than on GRACE (Table S2). Similarly, the GRACE-FO SCAs and IMUs are providing improved attitude solutions compared with GRACE (Figure S2). The improved attitude measurements have significantly

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enhanced the overall GRACE-FO AOCS pointing performance, such that angular spacecraft variations with respect to the line of sight are reduced by 55% (roll) to 95% (yaw) compared with GRACE (Figure S3). In combination with the improved AOCS actuation and control, fuel consumption during nominal operations is reduced by up to 75% (Table S1) compared with GRACE.

The ACCs are an updated heritage design from previous geodetic missions. Electrostatic measurements of a 72 g proof-mass displacement along the three linear and three angular directions are used to infer non-gravitational accelerations, which in the current flight environment are typically on the order of tens of nm/s^2 (linear) and several micro-rad/s^2 (angular). The in-orbit performance of the GF1 ACC is as good or slightly better than that of the original GRACE ACCs. Some large, spurious accelerations occur away from thruster firings with geographical and beta-angle (angle between satellite orbit and vector to the Sun—defines time spent in direct sunlight) dependencies. While no definitive cause for these outliers has been identified yet, they are robustly removed based on threshold detection ($\pm[1.5, 1.0, 3.0] \times 10^{-7}$ m/s^2 for [x, y,z] directions, respectively) to avoid aliasing into the ACC Level-1B products. Outliers on GRACE were attributed to thermally induced "twangs" from foil on the satellite bottom (e.g., Peterseim et al., 2014), but design changes on GRACE-FO should avoid this particular mechanism. The GF2 ACC is underperforming relative to GF1. Starting on 21 June 2018, bias jumps and noise that are highly correlated across all six ACC axes have degraded the measurements. The GF2 ACC still measures real non-gravitational accelerations, and an optimal calibration approach is currently being developed to reduce noise and at least partially utilize GF2 ACC measurements in future Level-1 data releases. In the meantime, starting 21 June 2018, all non-gravitational GF2 accelerations are modeled by using ACC observations from GF1 and thruster information from GF2 to predict the GF2 non-gravitational accelerations, similar to what was done during the last seven GRACE months (Bandikova et al., 2019). In addition to this ACC "full transplant," calibrations are applied to accurately capture thruster-imparted accelerations, using results from in-orbit thruster calibration maneuvers. As these calibrations are specific to GRACE-FO, a new ACC data product called "ACT1B" has been released (instead of the "ACC1B" from GRACE).

The performance of the radiometric K/Ka-band ranging and GPS orbit positioning system, combined in the MWI, meets expectations. GPS antenna phase-center maps have been derived, and the calculated POD performance is consistent or even slightly better than what was achieved for GRACE (Dahle, Flechtner et al., 2019; Yuan, 2019). On 22 October 2018, the GF2 MWI was switched to the redundant instrument processing unit (IPU) A-side after the B-side malfunctioned on 19 July 2018. As a consequence, the nominal science data stream was interrupted for nearly 100 days and no Level-2 products could be derived for August, September, and a portion of October 2018. The technology demonstration LRI is fully operational and working well. The LRI measures range variations better than 10 $nm/\sqrt{(Hz)}$ at 40 mHz, well below the white noise displacement precision capability goals (Abich et al., 2019). LRI-specific science data processing includes the removal of occasional LRI phase jumps that are coincident with attitude control thruster activations, which occur up to a few times per orbit revolution (Abich et al., 2019). LRI science ranging data have been acquired concurrently with the K/Ka band range (KBR) measurements from the MWI. Both measurements are converted and provided as range, range rates, and range accelerations, with data edits and various corrections applied (e.g., light-time and scale corrections, antenna offsets relative to the center of mass; see Wen et al., 2019 for details).

The ground segment for GRACE-FO is similar to GRACE. The German Space Operations Center (GSOC) of the DLR, with ground stations in Weilheim and Neustrelitz, Germany, as well as GFZ's satellite receiving station in Ny-Ålesund, Spitsbergen (Norway), provide real-time monitoring of the spacecraft status during satellite overflights, as well as pass-wise downlinks of stored housekeeping and science data. The received telemetry is directly transmitted to DLR's Raw Data Center (RDC) in Neustrelitz, Germany, and provided to the Physical Oceanography Distributed Active Archive Center (PO.DAAC) at JPL in Pasadena (US), the Information System and Data Center (ISDC) at GFZ in Potsdam (Germany), as well as to the University of Texas Center for Space Research (UTCSR) for archiving, monitoring, and analysis. Further processing from instrument data to gravity field and mass change products is done by the analysis centers of the joint Science Data System (SDS).

The GRACE-FO SDS converts the raw (Level 0) spacecraft and instrument telemetry into observations (Level 1) needed to compute monthly gravity fields (Level 2). At Level 1, the sensor data are processed at

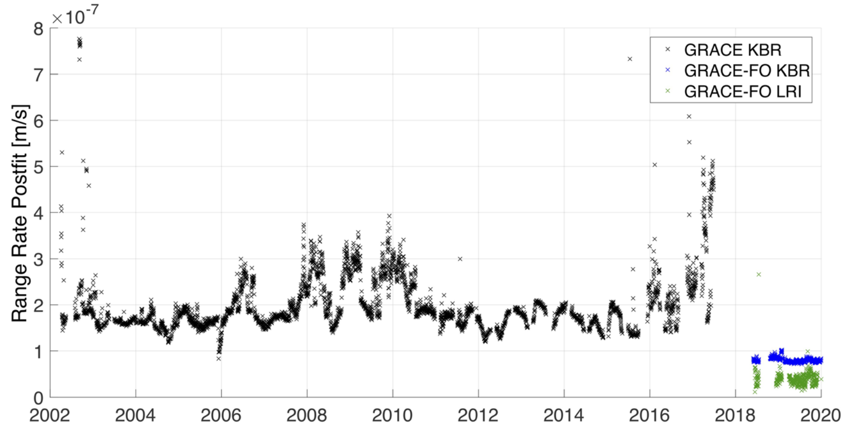

Figure 1. Daily RMS of K/Ka band range rate post-fit residuals for GRACE (black) and GRACE-FO (blue), as well as GRACE-FO LRI range rate post-fit residuals (green).

JPL to provide all necessary inputs to derive monthly time variations in the gravity field as well as to determine the orbit and static gravity field. At Level 2, monthly average estimates of the Earth gravitational potential are derived in the form of unconstrained spherical harmonic geopotential coefficients (both degree and order 60 × 60 and 96 × 96), or for mass concentration blocks with a priori constraints to most effectively reduce errors (e.g., Save et al., 2016; Watkins et al., 2015). Consistent with GRACE, the GRACE-FO SDS solves for monthly gravity field variations relative to a static background model, using forward models of submonthly variability from oceanic and solid Earth tides, atmospheric and dynamic ocean bottom pressure variations for de-aliasing (Dobslaw et al., 2017), as well as pole tide signals. Note that GRACE and GRACE-FO products are based on consistent background models and conventions (currently RL06 Level-2 processing standards), and no further cross-calibration is required as long as this consistency is maintained. While the nominal solution span is aligned with calendar months, some GRACE-FO monthly solutions are missing several days during a month (June and July 2018), or span across neighboring calendar months to ensure sufficient data coverage during science data gaps (i.e., October 2018, February 2019). Further Level-1 and Level-2 processing details are provided in the respective GRACE-FO SDS Level-1 and Level-2 Handbooks. In the following, we discuss a first performance assessment of the GRACE-FO gravity and mass change fields, as well as mission science results over the first 17 data months after launch.

3. Gravity and Mass Change Performance Assessment

The GRACE-FO monthly gravity field performance is assessed with several metrics: (1) the internal consistency of the measurement data and the data fits to the derived gravity fields, (2) the behavior of the gravity field error variances at different spatial scales, and (3) comparison of these quantities to the GRACE data record.

First, we assess internal consistency of satellite measurements by comparing the root mean square differences (RMSDs) differences between KBR-observed and GPS-derived intersatellite range as a metric of the POD quality. The KBR-GPS RMSD for GRACE (1.7 mm in 2008) and GRACE-FO (1.6 mm in 2019) are of comparable magnitude (Figure S4). These small values highlight the high accuracy achieved in the GRACE and GRACE-FO orbit solutions. The GRACE-FO KBR gravity field post-fit residual levels, a measure of how well the observed intersatellite range variations fit the estimated gravity fields, are about a factor 2 smaller than for GRACE (Figure 1). This is consistent with an overall lower noise level on the GRACE-FO KBR system, in conjunction with the improved AOCS performance. Similarly, the very low measurement noise of the LRI (Abich et al., 2019) results in even lower post-fit residuals from LRI-based gravity fields, at approximately 50% relative to the GRACE-FO KBR (Figure 1). While the instrument noise level of the LRI ranging observations is approximately a factor 30 smaller than for the MWI, the smaller improvement of the LRI post-fit residuals relative to the KBR post-fit residuals likely reflects remaining submonthly signal that is not accounted for in the de-aliasing models and would thus be common to KBR and LRI. However,

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the significantly lower LRI measurement noise provides an opportunity to detect submonthly gravity variations from fast atmosphere and ocean processes directly in the intersatellite range changes and benchmark de-aliasing models against these observations to improve the model and in turn reduce the associated errors in the monthly gravity field solutions. A detailed comparison of KBR and LRI monthly gravity fields is beyond the scope of this paper, but a first assessment of monthly LRI gravity fields (Pie et al., 2019) yields consistent results with the KBR-based monthly gravity fields, up to degree and order 180. As on GRACE, the C_{20} gravity coefficient for GRACE-FO is recommended to be substituted with satellite laser ranging (SLR) observations. Recent improvements in SLR processing (Loomis et al., 2019) have led to new SLR-C_{20} estimates that are provided in Technical Note 14 (TN-14), replacing the previously recommended Technical Note 11 (TN-11; Cheng et al., 2013). Since the C_{30} gravity harmonic also appears to have higher noise levels in the GRACE-FO data (Loomis et al., 2020), an SLR-based C_{30} alternative estimate, consistently processed with GRACE-FO RL06 data standards, is now also provided in TN-14 for substitution. This replacement is particularly relevant for estimates of Antarctic mass change budgets, as the C_{30} coefficient is maximally contributing in the spherical harmonic synthesis at the South Pole (Loomis et al., 2020). Initial tests indicate that an improved ACC transplant procedure (e.g., modeling each satellite's drag to account for differential non-gravitational accelerations) has the potential to significantly improve the estimation of deficient low-degree harmonics such as C_{30}. Geocenter gravity coefficients, required for the surface mass change estimates, are provided for each SDS solution in Technical Note 13 (TN-13; Sun et al., 2016).

Second, we evaluate gravity and mass change errors as a function of spatial scale to assess the continuity of the data record between the two gravity missions. The formal error estimates of Level-2 data products tend to underestimate actual errors due to simplified assumptions regarding instrument noise and the absence of background model errors in the stochastic modeling (e.g., Dahle, Murböck et al., 2019). A more realistic empirical error estimate is based on the residuals of the gravity and mass change fields after removing a fit consisting of linear trend, annual and semiannual terms, as well as the well-known S2 tidal alias (Ray & Luthcke, 2006; Seo et al., 2008). Note that when including the S2 alias in the fit (as a sinusoid of its aliased 161-day period), a phase offset of 100° is applied between GRACE and GRACE-FO. Tidal aliases do not have the same phase in GRACE and GRACE-FO monthly gravity fields as the GRACE-FO nodal plane at launch was not aligned to any specific phase offset with respect to GRACE. We assess the monthly fit residuals at different spatial scales by first smoothing the mass change observations with a Gaussian filter between 100 and 1,000 km, at 100 km increments. The coefficients of the fit terms are estimated via least squares for both GRACE and GRACE-FO simultaneously for a total of 180 monthly gravity maps spanning April 2002 to December 2019. This relatively simple fit model does not account for non-rectilinear interannual variations, which are more strongly expressed over land than over oceans. Thus, to avoid interpreting longer-period interannual real climate signal residuals as errors, we limit the averaging to the global ocean area. The error characteristics of the first year of GRACE-FO gravity fields are consistent with the monthly fields obtained from GRACE at all spatial scales (Figures 2 and S5). At 300 km spatial smoothing, and with an empirical post-processing filter included to remove correlated errors (e.g., Swenson & Wahr, 2006) applied, the signal content for all three spherical harmonic solutions is very consistent and errors reduce to approximately 14 to 17 mm liquid water equivalent (LWE; Figure 2). At spatial scales below 300 km, the GRACE-FO errors are lower than GRACE errors, consistent with overall lower noise levels in the KBR data, which dominate the overall measurement system error budget at high frequencies and smaller spatial scales. For comparison, consistently estimated error levels of the JPL Mascon solution (i.e., same smoothing, no additional decorrelation) are lower at all spatial scales (e.g., RMS_e^{ocean} = 9 mm at 300 km), highlighting the overall superior correlated error removal using a priori constraints compared with empirical filters. During its 15-year mission duration, the performance of GRACE varied due to changes in the performance of different subsystems on the spacecraft (e.g., Dahle, Murböck et al., 2019). The first 2 years experienced higher errors mainly due to the use of only a single SCA, followed by a long period of low errors from 2004 through 2010. Finally, from 2011 through 2017, the errors increased again as thermal control was disabled due to power constraints, non-gravitational effects increased at lower altitudes, and one ACC was unavailable in the last seven mission months. The global ocean mean fit residual RMSD at 300 km Gaussian smoothing clearly reveals these error regimes (Figure 2b). The 2018/2019 GRACE-FO error levels (approximately 15 mm RMS) are consistent with GRACE, just slightly higher than error levels during the years 2004 to 2010 (approximately 14 mm RMS). The current GRACE-FO errors can likely be reduced further as

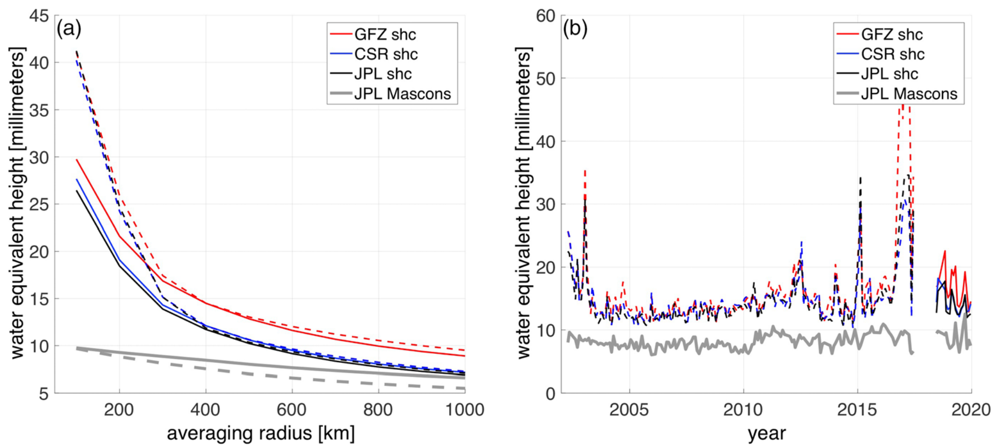

Figure 2. (a) RMS error (see text for details) over the global ocean for the three SDS GRACE (April 2002 to June 2017, dashed) and GRACE-FO (June 2018 to December 2019, solid) spherical harmonic solutions (SHC) and for the JPL Mascons, for different Gaussian averaging radii, which to first order is representative of the spatial resolution of the filtered data. A decorrelation filter (Swenson and Wahr, 2006) has been applied to SHC fields. (b) Evolution of GRACE and GRACE-FO errors at 300 km smoothing radius. Geocenter and C_{20}/C_{30} contributions are not included (see text for details; see Figure S5 for smoothing-only version).

instrument and data calibrations (e.g., KBR phase center calibration, ACC transplant and calibration) are further refined. Again, we note that mascon approaches provide improved error suppression throughout the different error regimes.

Third, the residuals in GRACE and GRACE-FO mass change observations after removing the fit contain errors as well as real geophysical signals, in particular over land and ice regions (e.g., Rodell et al., 2018; Tapley et al., 2019). A global map of the residuals' RMS (Figure 3a) of the 17-month GRACE-FO mass change fields provides more geophysical insight into the spatial distribution of errors and residuals and forms the basis for a first assessment of data continuity across the 11-month intermission data gap. The RMS of fit residuals maps into regions with well-known interannual signals and/or non-linear trends (Rodell et al., 2018), in particular over land (Figures 3a–3e). The period during the first year of GRACE-FO data was marked by strong positive North Atlantic Oscillation conditions throughout 2018 and into early 2019, as well as by weak to moderate El Niño/Southern Oscillation (ENSO) conditions from late 2018 into mid-2019 (Blunden & Arndt, 2019). Years 2018 and 2019 are among the four warmest in the last 100 years (NOAA, 2019). These processes impact precipitation and evaporation patterns as well as water use and as such have the potential to cause significant anomalies in terrestrial water storage (TWS) as well as land ice mass, and in turn, gravity anomalies

Five signals that deviate from long-term TWS trends and average annual cycles stand out (Figure 3a): (1) Central United States, (2) Central Europe, (3) North-East Australia, (4) the Middle East, and (5) Greenland. Validation of the time-variable satellite gravity observations with independent in situ measurements is challenging due to the integral nature of the satellite gravimetric measurements, but indirect and semi-independent methods such as reconstructions of TWS have recently become available (e.g., Humphrey & Gudmundsson, 2019) to evaluate the TWS basin anomalies. These statistical models are trained with GRACE observations, using meteorological forcing of precipitation and temperature as input parameters, and provide total aggregated TWS changes. We use an extended reconstructed TWS into the GRACE-FO time period, but without using GRACE-FO data in the initial calibration of the reconstruction model (Humphrey & Gudmundsson, 2019, personal communication). This approach enables us to verify that no intermission bias exists, as well as to verify that the GRACE-FO TWS signals are realistic and of geophysical origin.

1. Over the Central United States, the Mississippi River Basin featured a record-high water storage anomaly in May 2019 during the wettest US year in over a century. Since national record keeping began in 1895, the period from June 2018 through June 2019 was the wettest ever recorded (964 mm precipitation total; NOAA, 2019), with much of the excess rainfall concentrated in the upper Midwest region.

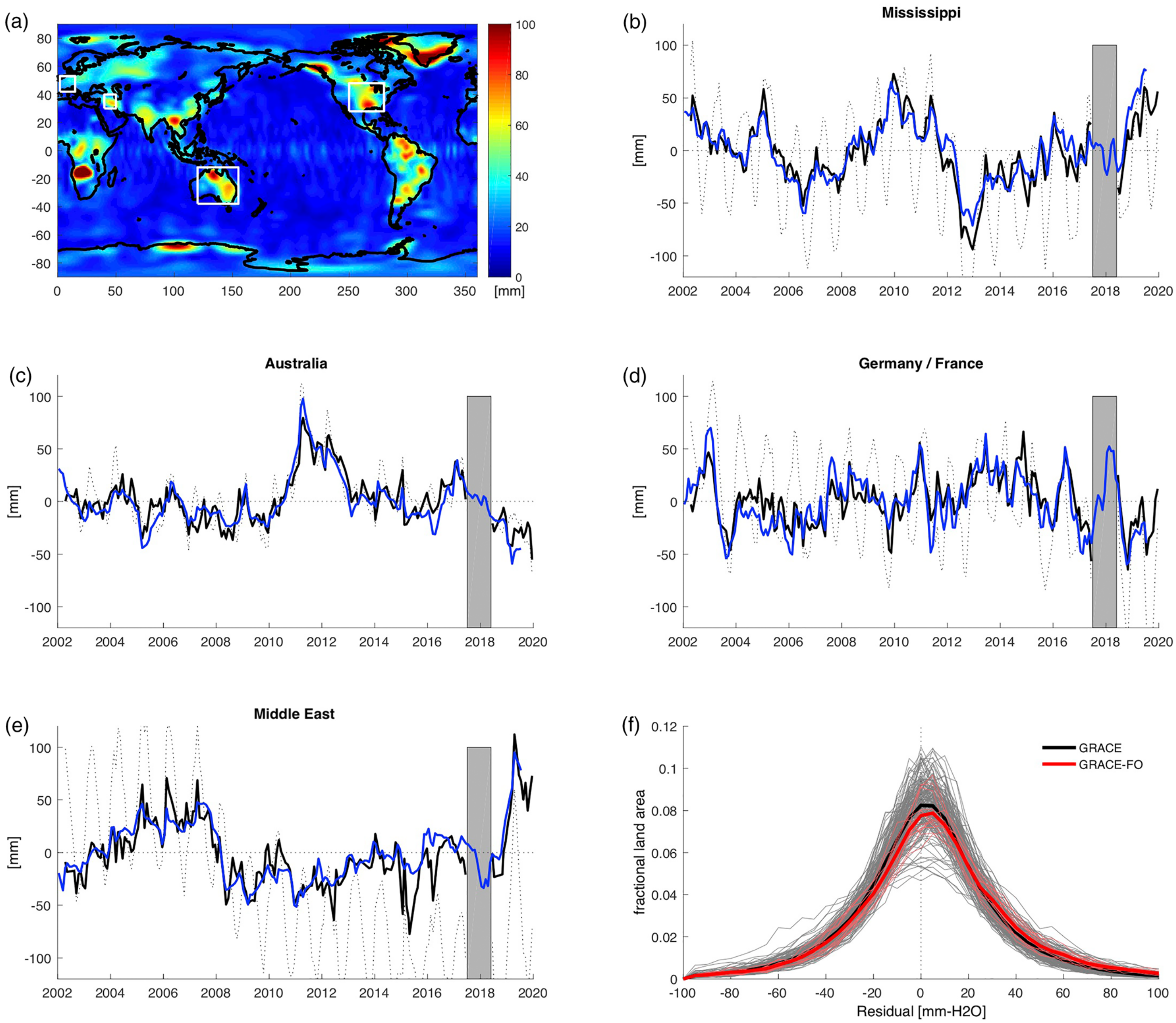

Figure 3. (a) Spatial distribution of the RMS of GRACE-FO June 2018 to December 2019 (mean of JPL, CSR, GFZ RL06 solutions; see Figures S6–S8 for individual centers). (b–e) Corresponding basin-mean TWS anomalies from GRACE and GRACE-FO (black) and from a TWS reconstruction (blue). The regional anomalies in GRACE-FO agree well with the reconstruction, indicating that they are physical and that no GRACE/GRACE-FO bias exists. Solid: mean annual signal and trends removed; dotted: full GRACE and GRACE-FO monthly anomaly (see text for details); intermission gap between GRACE and GRACE-FO indicated by gray bar. (f) Histogram ofthe residuals between the reconstruction and GRACE (grey) and GRACE-FO (red) TWS observations.

2. Conversely, Europe experienced an exceptionally dry and hot summer in 2018 (Blunden & Arndt, 2019; European Drought Observatory, 2018, 2019), leading to regional water shortages and hindering commercial river shipping as water levels dropped (e.g., Rösner et al., 2019). The lack of precipitation is clearly captured in the negative GRACE-FO-observed TWS anomalies. Although the observed TWS recovered somewhat during the 2018/2019 winter, the low TWS levels extend into the 2019 summer, which again saw anomalously high temperatures in June and July (NOAA, 2019).
3. Over NE Australia, lower than average rainfall starting in 2017 and extending into 2018 resulted in significant TWS reductions and drying in 2018 and 2019 (NOAA, 2019). The low TWS values recorded by GRACE-FO in 2018–2019 contrast with the record-high TWS during 2011 to 2012 and highlight the large interannual precipitation variability and corresponding TWS changes over this region (e.g., Boening et al., 2012).

4. The Middle East region (Iran/Iraq) experienced anomalously high rainfall starting in early 2019 (NOAA, 2019), which is reflected in large TWS anomalies. This rainfall follows years of below-average TWS in this region. It will be particularly interesting if deeper TWS can be recharged with this precipitation surplus to predrought levels, or if the excess rainfall mostly evaporates or runs off.

For all regions, the TWS reconstruction agrees well with the GRACE-FO non-seasonal anomalies in amplitude and phase, suggesting that the observed TWS changes are real geophysical responses of TWS to water cycle variability. On a global scale, the distribution of the residuals between the reconstruction and observations is consistent between GRACE and GRACE-FO (Figure 3f), providing high confidence that the GRACE-FO data record is unbiased relative to GRACE.

5. The most prominent mass change trends over the 15-year GRACE data record are associated with significant ice loss over Greenland and Antarctica (Figure S9). GRACE-FO recorded a reduced Greenland mass loss rate in late 2018 relative to the long-term trend from GRACE, followed by rapid accelerated mass loss in 2019. As for TWS, an assessment with surface mass balance (SMB) methods (Velicogna et al., 2020) and reanalysis (Ciracì et al., 2020) for ice caps and glaciers find no bias across the GRACE/GRACE-FO gap.

4. Summary

GRACE-FO has been providing monthly global mass change observations since June 2018. Satellite-to-satellite laser ranging was successfully demonstrated with the first-time technology demonstration LRI. Key metrics of the instrument and flight system performance have improved from GRACE, in particular for the MWI and AOCS subsystems which feature lower signal-to-noise ratios. While additional calibrations are needed for the ACCs, in particular on GF2, an effective calibration/transplant approach for the GF2 ACC yields GRACE-FO data products that perform as well or better than GRACE. This ACC "full transplant" approach for GF2 is expected to provide high-quality science results throughout the 5-year prime GRACE-FO mission duration. Fuel resources on board the satellites in early 2020 are sufficient to manage the GRACE-FO orbit to minimize differential non-gravitational forces between GF1 and GF2, while maximizing lifetime.

The assessment of the global mass change fields through December 2019 has demonstrated that GRACE-FO is extending the original GRACE record at an equivalent precision and spatiotemporal sampling. Precipitation and temperature-driven TWS reconstructions and SMB comparisons compare well with GRACE-FO observations and provide confidence that no intermission biases exist. GRACE-FO has already detected significant modulations of interannual and long-term water storage variability due to excess precipitation (e.g., US Midwest, Middle East), drought (e.g., Central Europe, Australia), as well as changes in ice mass trends (e.g., Greenland). The joint analysis of the GRACE-FO mass change observations with complementary Earth observations (e.g., ice height changes from NASA's IceSat-2 mission, surface deformation with GNSS sensors, ocean temperature profiles with Argo floats) will enable detailed process studies of glacier and ice sheet melt and mass change, land water storage and groundwater recharge, and the global sea level budget and its partitioning (Tapley et al., 2019). The combined GRACE and GRACE-FO data record is approaching two decades and is an essential global observing system to quantify and attribute ongoing mass change and transport and to provide essential information to project these changes into the future.

Data Availability Statement

More information about GRACE-FO can be found at https://gracefo.jpl.nasa.gov and at https://www.gfz-potsdam.de/en/grace-fo. GRACE and GRACE-FO Level-1 data, Level 2 spherical harmonic gravity coefficients and the Technical Notes TN-13 and TN-14 are available at NASA's PO.DAAC (https://podaac.jpl.nasa.gov), and GFZ's ISDC (https://isdc.gfz-potsdam.de/grace-fo-isdc/). All handbooks are available at https://podaac-tools.jpl.nasa.gov/drive/files/allData/gracefo/docs/.

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