Novel Along-Track Processing of GRACE Follow-On Laser Ranging Measurements Found Abrupt Water Storage Increase and Land Subsidence During the 2021 March Australian Flooding

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Abstract Following extreme drought during the 2019–2020 bushfire summer, the eastern part of Australia suffered from a week-long intense rainfall and extensive flooding in March 2021. Understanding how much water storage changes in response to these climate extremes is critical for developing timely water management strategies. To quantify prompt water storage changes associated with the 2021 March flooding, we processed the low-latency (1–3 days), high-precision intersatellite laser ranging measurements from GRACE Follow-On spacecraft and determined instantaneous gravity changes along spacecraft orbital passes. Such new data processing detected an abrupt surge of water storage approaching 60–70 trillion liters (km$^3$ of water) over a week in the region, which concurrently caused land subsidence of ~5 mm measured by a network of ground GPS stations. This was the highest speed of ground water recharge ever recorded in the region over the last two decades. Compared to the condition in February 2020, the amount of recharged water was similar but the recharge speed was much faster in March 2021. While these two events together replenished the region up to ~80% of the maximum storage over the last two decades, the wet antecedent condition of soils in 2021 was distinctly different from the dry conditions in 2020 and led to generating extensive runoff and flooding in 2021.

Plain Language Summary The monthly mean snapshots of global gravity field and surface mass variation (“mascon”) from the GRACE and GRACE Follow-On spacecraft missions are problematic to accurately quantify abrupt water storage changes and flooding by intense rainfall. This study demonstrates a new use of the GRACE Follow-On data to measure immediate water storage changes by computing instantaneous gravity change along spacecraft orbital passes. This new application is also shown for low-latency (a few days) data processing to assess surface mass changes immediately after extreme events. The results found that the eastern parts of Australia experienced the highest speed of ground water recharge ever recorded in the region and the wet antecedent condition of soils yielded extensive flooding in 2021.

1. Introduction

During the week of 17th to 23rd of March in 2021, the eastern New South Wales (NSW) and the southern Queensland states of Australia received the heaviest rainfall since national recording started in 1900. The high-pressure system developed in the Tasman Sea between Tasmania and New Zealand and stagnated over the week, continuously supplying moisture to the easterly air flow to the eastern coast of NSW (N.B. the counterclockwise flow from the high-pressure system in the southern hemisphere). The trough and low-pressure system along the NSW coast strengthened the moist flow causing persistent heavy rainfall over the week. The total amount of the weekly rainfall was well above 100 trillion liters (1 trillion liter = 1 km$^3$) over the eastern half of NSW according to the Bureau of Meteorology rain gauge record (http://www.bom.gov.au/jsp/awap/rain/index.jsp). This is equivalent to 30% of average yearly rainfall over the last
two decades. The entire coast of NSW and much of inland areas experienced the unprecedented flooding (Bureau of Meteorology, 2021).

The areas affected by the 2021 March heavy rainfall include the northern Murray-Darling basin (see also a map in Figure 3a for a geographic location). The basin holds up to ~20 trillion liters of public water storage in lakes, reservoirs and dams, supplying water resources to over 2.2 million people in four different states and has been the home to nearly 40% of the Australian agricultural products (Murray-Darling Basin Authority, 2021). During the millennium drought in 2001–2009, the public storage was less than 30% of the capacity until the 2010–2012 La Nina rainfall replenished the basin. Since then, the water storage has been declining and exhibited a record low level during the bushfire summer (December–February) in 2019–2020, when many of the dams in the upper basin showed less than 10% of their capacity according to Water Reporting Summaries for Murray-Darling Basin Catchments (http://www.bom.gov.au/water/nrtwreporting). Suddenly, in February 2020, the substantial rainfall recharged the dry basin without causing extensive flooding, followed by more intense rainfall accompanying flooding in March 2021.

How much water was stored and how fast the region was recharged from the 2021 March heavy rainfall event are important for assessing water availability in the basin and evaluating the reasons for the abrupt and extensive flooding. We examined the GRACE Follow-On (GRACE-FO) data of surface mass (gravity) changes. The onboard sensors including microwave (K-/Ka-Band) and laser (Nd:YAG) ranging interferometer systems detect minute perturbation of intersatellite distance between two spacecraft along the orbit, ~490 km above the sea level (Abich et al., 2019; Landerer et al., 2020). For example, the intersatellite distance is reduced by excess mass (relative to a previous reference state), such as flood water, as the satellites fly over the positive water mass anomaly and thus, produce a negative anomaly in intersatellite ranging measurements. The standard Level-2 (L2) and Level-3 (L3) data of monthly snapshots of gravity field and surface mass variation ("mascon") are derived from the analysis of these intersatellite ranging data (Level-1B; L1B) with the spatial resolution of 300–500 km (smaller toward the pole) and the uncertainty of 1–2 cm in equivalent water height (Tapley et al., 2019; Watkins et al., 2015; Yuan, 2019). The "monthly" L2 and L3 global snapshots, however, will be problematic to accurately quantify the amount of water storage change associated with the 2021 March rainfall, because the rainfall was substantial only over the third week of March. Finer temporal sampling of water storage changes from such an intense rainfall is critical to understanding how the Australian land mass responds to extreme weather events, and to monitor and manage the available water resources.

Instead, we use L1B measurements of instantaneous distance changes between two spacecraft to determine the corresponding surface water storage variations across March in 2021. Moreover, we deliberately present the analysis based on the Quick-Look (QL) L1B data with a typical data latency of only 1–3 days (Wen et al., 2019), for immediate quantification of water storage change by the rainfall. The total storage changes were estimated every few days over the eastern NSW and its vicinity whenever there was close satellite coverage, in contrast to every month for L2 and L3 global solutions. The results were compared with different L2 and L3 data products as well as land surface model outputs. We also discuss vertical land motion caused by the 2021 March rainfall load from the network of continuously operating GPS stations throughout the states of southern Queensland, NSW and Victoria (VIC).

2. Data and Methods

2.1. Quick Look (QL) L1B Data

This study utilized the QL (version 00) data provided by the Jet Propulsion Laboratory’s Level-1 processing (Wen et al., 2019). QL Level-1 data is processed similarly to the publicly released version 04 data (i.e., with identical processing steps and a daily cadence); however, the data latency is reduced to typically 1 day (i.e., the L1B data for yesterday is processed and available today). Data latency of the version 04 and QL L1B datasets are driven by the availability of the GPS orbit and clock solutions (Bertiger et al., 2020), denoted FLINN. These GPS orbit and clock solutions enable the computation of the GRACE-FO precise orbit determination (POD) solution, which provides highly accurate orbits and time corrections for the GRACE/GRACE-FO satellites (Bertiger et al., 2010; Wen et al., 2019), necessary for Level-1 processing. Version 04 data uses the
“final” FLINN solutions which are typically available with a latency of approximately 2 weeks. To facilitate reduced latency, the QL data set uses the “Rapid” FLINN solutions, which are available within 1 day.

Differences between the version 04 and QL data sets are driven by differences in the FLINN products and are typically within the measurement noise as presented in Figure 1. Once the L1B datasets are available, Level-2 processing is also performed. Note that the latency of the Level-2 processing is the main driver for latency of the water storage analysis and is itself driven by the availability of the background models, primarily atmosphere and ocean dealiasing (AOD) (Dobslaw et al., 2017). AOD datasets are typically published with a latency of 1–2 days; therefore, the Level-2 processing of the dynamic orbit can be performed within a similar timeframe (1–3 days allowing for validation and verification of the Level-2 processing).

2.2. Along-Track Gravity Data Processing

We have developed a method to determine the time series of line-of-sight gravity difference (LGD) inferring gravity changes associated with mass variations on the surface of the Earth. They are instantaneous, relative gravity perturbation between two satellites along the orbital trajectory (Ghobadi-Far et al., 2018). First, the dynamic orbit (time series of position and velocity vectors) of two GRACE-FO satellites are computed using the reference geopotential field model and other gravitational force models (such as tidal forces) as well as non-gravitational force measurements available as L1B accelerometer and attitude data (Yuan, 2019). The computed orbit is used to form range-rate \( \dot{r} = \dot{x}_{12} \cdot e_{12} \), where \( \dot{x}_{12} \) is the velocity vector difference and \( e_{12} \) is the unit vector of line-of-sight between two satellites. The residual range-rate is, then, computed by subtracting the computed range-rate from the measured range-rate (L1B data). The measurements are available from laser ranging interferometer (LRI) and microwave instrument (MWI). The residual range-rate time series from both LRI and MWI data are numerically differentiated to get residual range-acceleration. Finally, the LGD time series are computed by applying a time-domain filtering (convolution) to residual range-acceleration with the transfer function developed in Ghobadi-Far et al. (2018). We demonstrated that such LGD time series can be computed directly from the L1B LRI measurements of intersatellite distance change with the uncertainty of a few 0.1 nm/s² (Ghobadi-Far et al., 2020).

Figure 2 presents examples of LGD data from LRI and MWI. Both LGD data from MWI and LRI are consistent until 10 mHz, where the MWI LGD starts to deviate due to increased K-/Ka-band ranging system noise. The present version of LRI L1B data extends the measurements valid to 20–30 mHz but still shows larger...
high frequency noise than the predicted noise in Abich et al. (2019). Part of the reason for this noise is frequent thrust-firing signals that have been imperfectly modeled in the accelerometer L1B data, as described in Wen et al. (2019) and Ghobadi-Far et al. (2020).

3. Measurements of Instantaneous Gravity Changes by the 2021 March Rainfall

Unlike monthly gravity snapshots, the along-track LGD time series can be employed to study instantaneous (sub-monthly) changes in terrestrial water storage. For this event of the 2021 March rainfall, we deliberately used the QL L1B data to demonstrate the possibility of detecting water storage change as quickly as possible with a few days of latency. Figure 3 shows examples of the LGD data across the eastern NSW in March 2021. The ground tracks of the descending orbit are shown in Figure 3a and the corresponding LGD data are presented in Figure 3b. It was found that the GRACE-FO satellites repeat within 0.6° of ground tracks in longitude in this month. A total of four sets of distinct ground tracks are shown with each set including two “repeat” tracks with 11 days of time difference. From west to east (inland to coast), the black lines show the tracks on the “rainy” days of 22nd, 17th, 23rd, and 18th, while the gray lines show the ones on the “clear” days of 11th, 6th, 12th, and 7th (i.e., 11 days prior to the corresponding rainy days). Note that the rain was severe for the week from 17th to 23rd of March.

The LGD time series (Figure 3b) represent the instantaneous gravity anomalies on different days with respect to the monthly mean of February 2021. The LGD change of $-2 \text{ nm/s}^2$ was observed between 11th and 22nd along the inland ground track (westernmost in Figure 3a). Substantial water storage increase was detected there after the rainfall; the “negative” LGD change means mass “increase.” The similar change was also observed along the coast between 12th and 23rd. The difference between 6th and 17th was relatively modest since this was only the beginning of the rainfall. The last one between 7th and 18th is smaller since this was farther from the land (i.e., gravitational signal from terrestrial water storage attenuates with distance to satellites). Other changes were also seen from the LGD data mostly over the ocean, north and south of the eastern Australia, indicating unmodeled ocean mass signals not correctly predicted by the applied AOD models.

The LGD gravity change measurements were compared with the prediction from the monthly mean gravity field solutions (L2) and the mascon solutions (L3) as well as with the land surface model (LSM) outputs of soil water storage changes in Figure 4. Computation (forward modeling or synthesis) of the LGD time series from the L2 spherical harmonic series, the L3 surface mass grid, and the LSM outputs is trivial and discussed in Section 3 of Han (2013). For the synthesis, high frequency GRACE and GRACE-FO L2 and L3 data errors are naturally attenuated, and thus no filter is needed. It is noteworthy to mention that the computed LGD from the L2 and L3 data does represent only the monthly mean anomaly. Figure 4a presents a total of 11 LGD data overpassing the eastern NSW and its vicinity extended to the ocean from the descending orbit, on different days including five days before the rainfall and six days after. The LGD data present an emergence of the negative anomaly (“mass surplus”), up to $-3 \text{ nm/s}^2$, starting from 17th and afterward. The computed LGD time series from the L2 and L3 data predicted only one third of the magnitude of the LGD measurements during the days after the rainfall. The use of L2 and L3 data would result in significantly underestimated water storage variations within March.

The LGD data of instantaneous gravity changes are more consistent with the LSM outputs of soil moisture storage change as shown in Figure 4b; here we utilized the available model outputs of modern-era retrospective analysis for research and applications version 2 (MERRA-2) (Gelaro et al., 2017), global land data assimilation system (GLDAS/NOAH) (Rodell et al., 2004), and Australian water resources assessment landscape (AWRA-L) (Frost et al., 2018), evaluated at a daily time step. For the days before the heavy rainfall
started, the daily model storage anomalies were less than $-1 \text{ nm/s}^2$, and they are consistent with the LGD data as well as the L2 and L3 data. However, unlike the monthly results (L2 and L3), the models follow the LGD observations of sudden increase of the negative anomaly centered around the eastern NSW during and after the rainy days. The agreement of sub-monthly gravity changes between the LGD data and the LSM results implies the signals found in LGD are associated with the prompt water storage change by the rainfall. Among different models, GLDAS/NOAH predicts consistently a larger storage increase than MERRA-2 or AWRA-L, and the GRACE-FO LGD measurements. In addition, GLDAS/NOAH and MERRA-2 predict the storage increase at the higher latitudes than what the LGD measurements and AWRA-L indicate (identified by different latitudes of the anomaly peaks in Figure 4b). These model differences are certainly discernable from the LGD measurements. The similar conclusion can be drawn from the LGD data of the ascending orbit (Figure 5).

4. How Much of the Rain Water Was Stored?

The region of water loading is represented by four spherical discs in the inset of Figure 6a, covering the southeast part of Queensland and much of the eastern NSW. This region was chosen based on the MERRA-2 model storage change as shown in the background map with color (red indicating $>10 \text{ cm equivalent water height}$). The total area of the spherical discs is $\sim 608,000 \text{ km}^2$; $152,000 \text{ km}^2$ with each disc roughly equal to one “pixel” (spatial resolution) of GRACE & GRACE-FO data.

All LGD data time series with the ascending and descending ground tracks overpassing the selected region within 200 km in longitude were used to determine daily mean estimates of surface mass change. There is
an estimate only when there is an overpassing arc of data. Uniform water height over each of the spherical discs was assumed. The Green's function between the water height parameters and the LGD data are formed on the basis of spherical harmonic expansion (Han, 2013). The spatial correlation of the water height parameters is implicitly imposed by applying a regularized inversion. The optimal regularization parameter is determined empirically using the synthetic LGD data (e.g., Sprlak et al., 2020). Spatially smoothed water height changes for all four spherical discs were determined from the overpassing LGD data. There was a total of 12 estimates irregularly sampled in March as shown in Figure 6a, as the time series of total surface mass change in giga tonne (or a trillion liters of water). The GRACE-FO LGD observations detected increased storage up to 60–70 trillion liters of water just in the week since the heavy rainfall began. The LGD water storage estimates in March are in accordance with the MERRA-2 model soil moisture storage changes (Figure 6a). The additional surface water storage computed from the Muskingum-Cunge runoff routing method adds 10–20 trillion liters depending on flood wave propagation celerity (Cunge, 1969; David et al., 2011). A tight constraint on the celerity is not feasible due to the amount of runoff relative to the LGD estimate error. The total cumulative rainfall in the region over the same period was about ~110 trillion liters (Bureau of Meteorology, 2021). The LGD observation and the MERRA-2 model found that more than half of the weekly rainfall infiltrated into soils. A total of 20 trillion liters (~20%) of rainwater became runoff and swamped the coastal regions and inland areas across NSW and Queensland, and the rest (30% or less) evaporated. Additional comparison of the LGD data with other models is presented in Figure 6b with the model outputs of AWRA-L and GLDAS/NOAH (AWRA-L was calibrated with in-situ stream gauge records).
Historically, over the last two decades, the region including the northern Murray-Darling basin exhibited the maximum water storage up to $\sim 160$ trillion liters for the 2012 (southern) spring-winter period and the minimum was observed in the recent 2019–2020 bushfire summer; see GRACE & GRACE-FO observation and the GLDAS/NOAH model results in Figure 7. During the millennium drought period (2001–2009), the storage was on average 60 trillion liters above the recorded minimum storage. The 2010–2012 La Nina replenished nearly the whole Australian continent (Fasullo et al., 2013) and filled the region with up to 160 trillion liters of water. Since then, the water storage had been declining in general (except for 2016) reaching the record minimum in the 2019–2020 summer.

In February 2020, long waited rainfall persisted over the whole month and recharged the dry soils with 60 trillion liters of water. This single event raised the overall storage to the level observed during 2013–2017. In March 2021, the similar amount of rainfall as the cumulative rainfall in February 2020, but much more intense only over a week, fell over the region. The 2021 March rain added another 60–70 trillion liters of water storage to the region only over a week or so (see the GRACE-FO LGD estimates in black in Figure 7). This was the record highest speed of ground water recharge that has ever been observed over the last two decades. At the end of March 2021, the water storage in the region was measured to be around 130 trillion liters above the minimum storage. The vast area of the eastern NSW and its vicinity rapidly recovered from the lowest water level during the 2019–2020 bushfire summer. The region was recharged up to the point nearly 80% of the maximum storage only in 14 months primarily by two major rainfall events in February 2020 and March 2021.
Figure 6. (a) The line-of-sight gravity difference estimates of total water storage changes (black circles with 2-sigma error bars) over the four spherical discs shown in the inset. A total of 12 estimates irregularly sampled in March was found from the ascending and descending track measurements. They are presented with the zero mean over the days before 16th of March (i.e., before the heavy rainfall start). The maximum storage of \( \sim 70 \) trillion liters of water was observed at the end of the rainfall (1 trillion liter = 1 km\(^3\)). Different color curves indicate the synthetic storage changes computed from the modern-era retrospective analysis for research and applications version 2 (MERRA-2) soil moisture storage (blue) and additional storage from the runoff routing with different routing celerity of 1.5, 0.7, and 0.1 m/s (red, yellow, and purple, respectively). The runoff-generated water storage (except the lowest celerity case) is computed to be about 10 trillion liters while the soil moisture storage is 60–70 trillion liters. (b) Similar to (a), but including the model soil moisture storage from global land data assimilation system (GLDAS/NOAH) and Australian water resources assessment landscape (AWRA-L). The GLDAS/NOAH and AWAR-L are over- and under-predicting the storage change from MERRA-2, by \( \sim 10 \) giga tonnes.

Figure 7. The observed (red) and model (blue) water storage variation in the same region over almost two decades; they are from three different monthly mean L3 mascon solutions of GRACE and GRACE Follow-On (GRACE-FO) (note data gap in 2017 between two missions) and from daily mean global land data assimilation system soil moisture storage. The GRACE-FO line-of-sight gravity difference estimates were also added in March 2021 (black). The abrupt change of up to 70 trillion liters (70 km\(^3\)) during the rainy week of March 2021 is the most extreme increase of storage observed during the last two decades in this region.
5. Land Subsidence by the Water Storage Load

The elastic lithosphere deforms spontaneously responding to surface mass load. This deformation is dominant at a large spatial scale and measurable, when the load is spatially extensive, by a network of continuously operating (CORS) GPS stations (Argus et al., 2014; Han, 2017; Razeghi et al., 2019). We used daily mean position solutions (Blewitt et al., 2018) from a number of Australian CORS GPS stations in NSW, VIC, and southern Queensland to independently estimate the magnitude and timing of changes in water storage. Given such a short period of intense rainfall, we analyzed the daily time series of the vertical position solutions to find short-term deformation signals within March 2021. The average vertical land motion (VLM) between two periods of 1st to 16th of March and of 17th to 31st of March was determined from daily GPS positions at every site to examine the VLM within March particularly after the heavy rainfall started on March 17 (Figure 8a). The GPS time series indicate how much the land deformed vertically after the heavy rainfall while the VIC ones had no statistical change.
rainfall throughout the states. The uncertainty of the VLM estimates is around 2 mm for all sites. It was found that many of NSW stations subsided by 4–6 mm, most of them are statistically significant based on the statistical t-test. However, the GPS estimates of VLM at most of VIC stations are not statistically significant, that is, no change.

The GPS measurements of sub-monthly VLM are used to validate the GRACE-FO results. Using the GRACE-FO LGD estimates of water storage changes, which is about 60 trillion liters on average during the last two weeks of March, we computed the synthetic VLM at each of the GPS sites. To be consistent with GPS measurements in terms of signal content, we also computed the additional elastic deformation due to atmosphere and ocean mass loading by using the AOD model (Dobslaw et al., 2017). We added the AOD results to the GRACE-FO estimates in order to compute the total elastic deformation by all non-tidal surface mass loads (Figure 8b). Significant subsidence within March 2021 found mostly in NSW is generally comparable with the GPS measurements. The AOD loading effect is only ~20% of the total effect, confirming the observed VLM are primarily rainfall induced.

The original daily GPS time-series of vertical position solutions from the 10 representative sites from north to south (top to bottom) are presented in Figure 8c; each time series has the coordinates noted at the end. The time series covers four months from January to April in 2021. The 17th of March was marked with a purple vertical line. The mean positions two weeks before and after that day are marked in black horizontal lines. The first six time series belonging to southern Queensland and NSW exhibit significant subsidence after the rainfall. In contrast, the bottom four time series belonging to VIC do not present any statistically significant change. The NSW state-wide subsidence of ~5 mm associated with the March rainfall was clearly observed by the CORS GPS stations and is in accordance with the calculated elastic deformation with the GRACE-FO LGD estimates of water storage changes. These basic results reinforce the observation of the eastern NSW region having the highest water loading by the rainfall.

### 6. Discussion

A total of ~100 trillion liters of rainfall fell over the eastern NSW and the coastal areas for a week. The clay-rich vertosol soils dominant in the eastern Australia (Australian Water Resources Assessment, 2012) were able to capture and hold nearly 60% of the total rainfall, recharging an extensive area including the northern Murray-Darling basin. This was in addition to a similar amount of recharge from the 2020 February rainfall, but over two months. These two consecutive events alone replenished the region at nearly 80% of the maximum storage observed in 2012 after the exceptionally strong 2010–2012 La Nina (Figure 7).

The monthly rainfalls in February 2020 and in March 2021 were similar (Figure 9a), however, the flooding in 2021 was much more severe and extensive (Bureau of Meteorology, 2021). In 2020, the rainfall started with the driest condition of soils just after the 2019–2020 bushfire summer producing little runoff and thus no substantial flooding. In contrast, in 2021, the soils were saturated by holding water as much as 40% of the maximum storage in 2012. The runoff was generated more effectively because the antecedent soil condition was already wetter in 2021 (Figure 9b). This is likely the reason for extensive flooding in 2021 compared to 2020 (Bureau of Meteorology, 2021). These two contrasting consequences from the similar rainfalls are excellent examples of demonstrating how antecedent soil moisture condition governs runoff and flooding (Crow et al., 2018; Wyatt et al., 2020) and reiterating this is important to implement into flood forecasting and warning practices.

The mass change observations from GRACE and continuing with GRACE-FO measured the critical point of soil wetness from which the flood likelihood increases in the region (Figure 9b). The data are also important for quantifying total water storage over extensive areas beyond the government regulated public water storages that amount to only a fraction of total water storage. The comprehensive examination of such large areas (from GRACE-like observations) needs to be incorporated into calculation of water availability and management of water resources, as it will affect interaction among rivers, wetlands, floodplains, and reservoires as whole environmental systems.

As a technical advancement, this study demonstrated a new methodology of scientifically utilizing high-precision laser ranging measurements for higher temporal sampling of surface mass changes. The
standard spatial analysis (i.e., global gravity field recovery) over a month period such as L2 and L3 data processing would produce a biased estimate when characteristic time scales of mass change processes are shorter than a month. Our proposed time-domain (along-track) analysis will lead to better quantification of such processes. Furthermore, we exploited the low-latency (within 1–3 days) QL L1B data to examine the feasibility of immediate assessment of extreme events such as flooding, even earlier than the land surface model results with the latency of a couple of months due to available meteorological forcing data. Such QL data processing can promote timely assessment of severe weather events and natural hazards as important applications of the GRACE-FO mission.

A new streamlined along-track data processing chain is proposed to facilitate utilization of superb laser ranging measurements for advanced quantification of rapid Earth system changes. Alternate geophysical and climate models can be assessed against the laser data as we demonstrated with MERRA-2, GLDAS/NOAH, and AWRA-L. Prompt evaluation of such models will be critical for improved computation and forecasting (e.g., improved weather forecasting based on land condition). The GRACE & GRACE-FO data set of instantaneous mass changes (LGD) are optimal to assimilate into different weather and climate models by updating and predicting the model state parameters as frequently as possible, instead of using a monthly adjustment.

**Data Availability Statement**

All data including GRACE-FO Level-1B and Level-2 data used in this study are publicly available at https://podaac.jpl.nasa.gov/GRACE. The GLDAS land surface model results are from https://ldas.gsfc.nasa.gov/gldas. The MERRA-2 data are available at https://disc.gsfc.nasa.gov/datasets?project=MERRA-2. The AWRA-L results are from http://www.bom.gov.au/water/landscape. The continuous Australian GPS sites used in this study, as well as the specific agency responsible for operating these sites, are available from http://geodesy.unr.edu.

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**Figure 9.** (a) Time series of the cumulative rainfall during 2003–2021, computed each year, over the impacted region (four spherical discs in Figure 6a). Two extrema in 2010 and 2019 are shown in addition to the cases in 2020 and 2021. They were from the meteorological forcing data used in the global land data assimilation system (GLDAS/NOAH) model. The monthly rainfall totals in February 2020 and in March 2021 are similar, but the flooding in 2021 was much more extensive and severe. (b) The ratio of runoff divided by precipitation (Q/P) is shown over soil water storage, computed from GLDAS/NOAH, during 2003–2021, and in 2020 and 2021 separately. It highlights the runoff during the heavy rainfall period in March 2021 more effectively generated flooding due to the relatively large pre-existing soil water storage (40% and above of the maximum storage observed in the last two decades).
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References

Abich, K., Abramovici, A., Amparan, B., Baatzsch, A., Okishiho, B. B., Bar, D. A., et al. (2019). In-orbit performance of the GRACE Follow-On laser ranging interferometer. Physical Review Letters, 123, 031101. doi:10.1103/PhysRevLett.123.031101

Argus, D. F., Fu, Y., & Landerer, F. W. (2014). Seasonal variation in total water storage in California inferred from GPS observations of vertical land motion. Geophysical Research Letters, 41, 1971–1980. doi:10.1002/2014GL059579

Australian Water Resources Assessment. (2021). Report summary. Bureau of Meteorology.

Bertiger, W., Bar-Sever, Y., Dorney, A., Haines, B., Harvey, N., Hemmerberg, D., et al. (2020). GipsyX/RTGx, a new tool set for space geodetic operations and research. Advances in Space Research, 66, 469–489. doi:10.1016/j.asr.2020.04.015

Bertiger, W., Desai, S. D., Haines, B., Harvey, N., Moore, A. W., Owen, S., & Weiss, J. P. (2010). Single receiver phase ambiguity resolution with GPS data. Journal of Geodesy, 84(5), 327–337. doi:10.1007/s00190-010-0371-9

Blewitt, G., Hammond, W. C., & Kruizinga, G. (2019). Harnessing the GPS data explosion for interdisciplinary science. Eos, 99, 485. https://doi.org/10.1029/2019EO104623

Bureau of Meteorology. (2021). Special climate statement 74—Extreme rainfall and flooding in eastern and central Australia in March 2021. Retrieved from http://www.bom.gov.au/climate/current/statements/

Crow, W. T., Chen, R., Reichle, R. H., Xia, Y., & Liu, Q. (2018). Exploiting soil moisture, precipitation, and streamflow observations to evaluate soil moisture/runoff coupling in land surface models. Geophysical Research Letters, 45, 4869–4878. doi:10.1029/2018GL077193

Cunge, J. A. (1969). On the subject of a flood propagation computation method (Muskingum method). Journal of Hydraulic Research, 7, 205–230. https://doi.org/10.1080/00221686909500264

David, Ç., Maidment, D. R., Niu, G.-Y., Yang, Z.-L., Habets, F., & Elkhouh, V. (2011). River network routing on the NHIDPlus dataset. Journal of Hydrometeorology, 12, 913–934. https://doi.org/10.1175/2011Jhm1345.1

Dobslaw, H., Bergmann-Wolf, I., Dill, R., Poropat, L., Thomas, M., Dahle, C., et al. (2017). A new high-resolution model of non-tidal atmosphere and ocean mass variability for de-aliasing of satellite gravity observations: AOD1B RL06. Geophysical Journal International, 211, 263–269. https://doi.org/10.1093/gji/ggx302

Fasullo, J. T., Boening, C., Landerer, F. W., & Nerem, R. S. (2013). Australia’s unique influence on global sea level in 2010–2011. Geophysical Research Letters, 40, 4368–4373. https://doi.org/10.1002/2013GL058445

Frost, A. J., Ramchurn, A., & Smith, A. (2018). The Australian landscape water balance model (AWRA-L v6). Technical description of the Australian water resources assessment landscape model version 6. Bureau of Meteorology Technical Report.

Ghobadi-Far, K., Han, S. C., Weller, S., Loomis, B. D., Luthcke, S. B., Mayer-Gürr, T., & Behzadpour, S. (2018). A transfer function between borehole tiltmeter measurements uniquely distinguish short-wavelength gravitational perturbations. Geophysical Research Letters, 47, e2020GL089445. https://doi.org/10.1029/2020GL089445

Ghobadi-Far, K., Han, S. C., Weller, S., Loomis, B. D., Luthcke, S. B., Mayer-Gürr, T., & Behzadpour, S. (2018). A transfer function between line-of-sight gravity difference and GRACE intersatellite ranging data and an application to hydrological surface mass variation. Journal of Geophysical Research: Solid Earth, 123, 9186–9201. https://doi.org/10.1029/2018JB016088

Han, S.-C. (2013). Determination and localized analysis of intersatellite line of sight gravity difference: Results from the GRAIL primary mission. Journal of Geophysical Research: Planets, 118, 2323–2337. https://doi.org/10.1002/2013JE004402

Han, S.-C. (2017). Elastic deformation of the Australian continent induced by seasonal water cycles and the 2010–2011 La Niña determined using GPS and GRACE. Geophysical Research Letters, 44, 2763–2772. https://doi.org/10.1002/2017GL072999

Landerer, F., Flechtner, F. M., Save, H., Webb, F. H., Bandikova, T., Bertiger, W. L., et al. (2020). Extending the global mass change data record: GRACE Follow-On instrument and science data performance. Geophysical Research Letters, 47, e2020GL088306. doi:10.1029/2020GL087299

Murray-Darling Basin Authority. (2021). The 2020 basin plan evaluation.

Razeghi, M., Han, S.-C., McClusky, S., & Sauber, J. (2019). A joint analysis of GPS displacement and GRACE geopotential data for simultaneous estimation of geocenter motion and gravitational field. Journal of Geophysical Research: Solid Earth, 124, 12241–12263. https://doi.org/10.1029/2019Jb016808

Roddier, M., Houser, P. R., Jambor, U., Gottschalch, J., Mitchell, K., Meng, C.-J., et al. (2004). The global land data assimilation system. Bulletin of the American Meteorological Society, 85, 381–394. https://doi.org/10.1175/BAMS-85-3-381

Sprlak, M., Han, S.-C., & Featherstone, W. (2020). Integral inversion of GRAIL inter-satellite gravitational accelerations for regional recovery of the lunar gravitational field. Advances in Space Research, 65, 630–649. https://doi.org/10.1016/j.asr.2020.01.003

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

Watkins, 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, 2648–3267. https://doi.org/10.1002/2014Jb01547

Wen, H., Kruizinga, G., Palk, M., Landerer, F., Bertiger, W., Sakumura, C., et al. (2019). Gravity Recovery and Climate Experiment Follow-On (GRACE-FO) level-1 data product user handbook. JPL D-56935. NASA Jet Propulsion Laboratory, California Institute of Technology. Retrieved from https://podac.touca.jpl.nasa.gov/drive/files/allData/gracefo/docs/GRACE-FO_L1_Handbook.pdf

Wyatt, B. M., Ochsner, T. E., Krueger, E. S., & Jones, E. T. (2020). In-situ soil moisture data improve seasonal streamflow forecast accuracy in rainfall-dominated watersheds. Journal of Hydrology, 590, 125404. https://doi.org/10.1016/j.jhydrol.2019.125404

Yuan, D.-N. (2019). GRACE Follow-On JPL level-2 processing standards document for level-2 product release 06, Jet Propulsion Laboratory, California Institute of Technology.