Water Cycle Science Enabled by the GRACE and GRACE-FO Satellite Missions

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Abstract

Satellite observations of the time-variable gravity field revolutionized the monitoring of large-scale water storage changes beginning with the 2002 launch of the Gravity Recovery and Climate Experiment (GRACE) mission. Most hydrologists were skeptical of the satellite gravimetry approach at first, but validation studies assuaged their concerns and high-profile, GRACE-based groundwater depletion studies caused an explosion of interest. The importance of GRACE observations for hydrologic and cryospheric science became so great that GRACE Follow On (GRACE-FO) jumped NASA's Earth Science mission queue and launched in 2018. A third Mass Change mission is currently under development. Here we review key milestones in satellite gravimetry's progression from the fringes of hydrology to being a staple of large-scale water cycle and water resources studies and the sole source of observations of what is now an 'Essential Climate Variable', terrestrial water storage.

Water intersects practically every sub-discipline of Earth science as well as being essential to all life on Earth. The heterogeneities of the water cycle largely determine the distribution of ecological systems and human populations around the world and have important implications for agriculture, natural hazards, and meteorology. Therefore, it may be surprising that there was no viable method for measuring large scale, seasonal to interannual fluctuations of water across the continents prior to the twenty-first century. Direct and indirect observations of precipitation, arguably the most important water cycle observable, have been collected since the middle of the second millennium, if not earlier[1]. By the late 1800s, attempts were being made to estimate the balance of precipitation, evapotranspiration, and runoff from the continents. However, despite the physics of infiltration, soil drainage, groundwater flow, and baseflow having been characterized a century or more earlier[2], implying significant subsurface water storage dynamics, scientists failed to acknowledge the importance of changes in water stored on and in the land as a major component of continental water balance until a 1992 study constructed a global, monthly climatology of soil water content[3].

Twentieth century hydrologists largely ignored terrestrial water storage (TWS) as a variable for a few reasons. First, at a time when improving general circulation and weather forecast models was a primary goal of numerical modelers, accurate simulation of TWS was not considered important so long as the simulated moisture state of the surface served effectively as a lower boundary condition for the atmosphere. For decades, the land surface was simplified numerically to behave as a ‘bucket’ of water beneath the atmosphere[4]. Second, save for the terrestrial water budget equation (see Global Water Budget Analysis, below), hydrologists rarely considered the concept of TWS; they instead were concerned with its components. Related to that, measuring large scale changes in TWS using conventional methods has always been a challenge because it comprises multiple components, each with its own considerations. In particular, snow water equivalent (the product of snow depth and snow density) is highly variable in space, and snow tends to be deepest in the least accessible locations: polar regions and on the tops of mountains[5]. Soil moisture is highly variable both spatially and temporally, and measuring wetness below the surface soil layer requires digging a hole or inserting a long probe using a hydraulic press[6]. In situ soil moisture monitoring networks are highly concentrated in the northern midlatitudes, providing very little coverage outside of 30°N to 60°N[7]. Lake and river channel water storage is relatively easy to estimate, but only if measurements are recorded and shared. Outside of the wet tropics, surface water is typically a small component of TWS change[8]. Vegetation water storage changes are typically much smaller than soil moisture changes[9]. Finally, the standard method for monitoring groundwater storage variations is to drill down into an aquifer, install a piezometer, and record water level or piezometric head variations. Owing to cost, logistics, and political impediments (most nations do not share what groundwater measurements they have[10]), it would be impossible to establish globally representative, automated networks with sufficient density to monitor any of these variables satisfactorily. Even the USGS's near-real time groundwater monitoring network has major gaps in the western U.S. (Figure 1). The International Groundwater Resources Assessment Centre (IGRAC), which aspires to serve as a clearinghouse for global groundwater data, houses records from fewer than 35 countries representing far less than half the world's land surface (Figure 1). While numerous additional groundwater observational records exist, most are either restricted from distribution or not digitized and centralized. Given these challenges and despite its true significance as an indicator of water resources availability and hydroclimatic change, TWS quantification and understanding would have remained in limbo absent the introduction of a game-changing observational advancement.

Satellite Gravimetry

Geodesists have long recognized that both static features and temporal variations in Earth's gravity field, which reflect heterogeneities in the distribution of solid, liquid, and atmospheric mass, perturb the paths of Earth-orbiting satellites in predictable ways[11–14]. In the 1960s they conceived the idea of measuring these orbit perturbations precisely in order to infer time varying mass variations in the land, ocean, and atmosphere[15]. Satellite laser ranging (i.e., precise tracking of the distances from ground stations to an orbiting satellite) enabled the first global mapping of Earth's gravity field and continues to provide time varying gravity information which is superior to that of GRACE/FO at the largest scales[14,16]. A compendium of studies[17] laid the scientific foundation for launching a dedicated, time-variable gravimetry mission, demonstrating the potential value for hydrology and other disciplines and describing possible satellite instruments and configurations for such a mission. The preferred architecture comprised identical twin satellites in a polar, low Earth orbit, one following the other with 100-220 km separation. Orbital perturbations caused by gravitational variations would be quantified using micron-level tracking of the intersatellite distance (range) by microwave interferometers aboard both satellites. Non-gravitational accelerations, such as those caused by atmospheric drag, would be measured by highly precise accelerometers. Soon thereafter, GRACE, which was jointly supported by the German space agency, was selected by NASA to be one of its first Earth System Science Pathfinder projects.

A seminal pre-launch study[18] introduced a technique for translating gravimetry measurements from GRACE into changes in terrestrial water storage (TWS) and provided the equations necessary to extract region-specific TWS anomaly time series from global gravity field solutions expressed using spherical harmonics (a series of functions that describe anomalies on a sphere, in which higher degrees and orders represent progressively smaller constituents of the anomalies). Subsequent studies[19,20] explored this potential in depth, comparing anticipated uncertainty in the TWS retrievals with model- and in situ observation-based estimates of TWS changes at various spatial scales. They concluded that the approach would be viable depending on the size of the region and the amplitude of the TWS variations. It was also demonstrated that changes in groundwater storage could be isolated from the TWS data, given modeled or observed estimates of soil moisture and other TWS components as needed[21].

GRACE Mission – The Early Years

GRACE[22] launched on 17 March 2002 to the delight of the geodesy, cryosphere, and ocean science communities. Cryospheric scientists used GRACE to generate startling new estimates of the rates of ice losses from Greenland, Antarctica, and the Alaskan glaciers[23–26]. Oceanographers used it to improve their understanding and quantification of sea level changes[27–29]. Meanwhile, most hydrologists, if they had heard of the mission at all, fretted that GRACE's spatial (>150,000 km^2 at mid-latitudes[30,31]) and temporal (monthly) resolutions were too coarse, and they were befuddled by its non-instantaneous, vertically integrated TWS anomaly data. Further, non-geodesists were concerned that the retrievals could be contaminated by unknown or poorly modeled sources of mass change in Earth's crust and mantle.

Discord and controversy in the hydrology community are not unusual, so perhaps the initial resistance to GRACE is not surprising. Multiple sub-disciplines compete for primacy and funding, and GRACE was likely viewed as additional competition, for example by soil moisture enthusiasts who, at the time, were advocating for their own mission. Further, the characteristics of GRACE-based TWS data did not lend themselves to comparisons with or incorporation into grid-based hydrological models. The developers of these models were already busy evaluating and arguing the merits of global versus regional modeling, physics-based versus conceptual modeling, the use of empirically based parameters versus calibration, and complex, high resolution, computationally expensive models versus simplified approaches.

While hydrologists were certainly unfamiliar with data products having characteristics like those of GRACE, their concerns were largely unfounded. Mass changes attributable to viscoelastic mantle and crustal deformation occur over long enough timescales that they are non-factors in monthly to interannual terrestrial mass change, with two notable exceptions. First, glacial isostatic adjustment (GIA) can be significant in polar and near-polar regions that were covered by ice during the last glacial maximum. The gravitational effects can be removed reasonably well[32] using models of GIA[33,34] although errors in these models can be an issue for hydrological studies in regions with significant rates of GIA[35]. Second, major earthquakes (magnitude > 8) produce both step function (coseismic) and exponential (postseismic) signals in mass anomaly time series, whose removal from the GRACE data is further complicated by their wavelike spatial patterns[36]. Fortunately, only a handful of major earthquakes have occurred in the GRACE era, and their effects are limited in time and space[37]. In addition to redistribution of TWS, the other main drivers of mass and gravitational change are circulations of the atmosphere and oceans. Both of these are modeled and removed from the observed gravity signal when TWS is the target observable, but errors stemming from the models continue to be a major component of the error budget of the derived TWS anomalies[18,19,38]. Within the terrestrial mass changes that remain, seasonal and interannual changes in vegetation biomass have been shown to be at or below GRACE's uncertainty threshold[9]. That leaves groundwater, soil moisture, surface waters, snow, ice, and permafrost as the primary components of TWS retrieved from GRACE gravity observations. Of those, seasonal variability is dominated by surface water in the wet tropics, by snow in alpine and high latitude regions, and by soil moisture most elsewhere[8]. Transitioning across interannual to decadal timescales, soil moisture's transient influence wanes and groundwater and ice trends eventually dominate the changes, save for loss of water from major surface water bodies such as the Aral and Caspian Seas[39,40] and filling of manmade reservoirs[41].

Despite the skepticism, a handful of researchers described and evaluated new hydrological applications for GRACE, such as the use of GRACE-based TWS observations for closing the water budget and estimating regional mean evapotranspiration[42] (ET) and net water flux[43] (precipitation minus ET) at the land-atmosphere interface. Also introduced were methods for using GRACE and other data to estimate river discharge[44,45] and high latitude seasonal snow mass[46]. GRACE TWS data revealed an anti-correlation of TWS variations during 2002-2006 in the Amazon and Congo River basins[47]. They were employed to evaluate the water storage variations simulated by climate models[48], while numerous other studies evaluated the GRACE TWS time series using ground-based observations and models[49–52]. During this same period, two studies[53,54] demonstrated the ability to isolate groundwater storage changes from GRACE TWS data using in situ or modeled soil moisture and snow water equivalent. The first GRACE data assimilation experiments were performed[55] enabling the TWS components to be separated while also achieving spatial and temporal downscaling of the coarse resolution GRACE observations. Nevertheless, only a tiny fraction of the hydrology community embraced GRACE during its early years.

Onset of the era of GRACE hydrology

A major impediment to the uptake of GRACE data by hydrologists was the necessity of enlisting geodesists to process the level-2 GRACE data (i.e., gravity field solutions) and derive TWS time series. The monthly level-2 gravity field solutions were delivered as sets of spherical harmonic coefficients, and few, if any, hydrologists were familiar with that mathematical construct, capable of applying destriping techniques to remove correlated errors[56], and able to apply Gaussian averaging kernels[57] for computing regional time series and associated uncertainty estimates.

That situation changed when the first 1° gridded GRACE TWS anomaly fields[58] began to be distributed. They included numerous caveats and warnings; for example, the method used to derive the fields was optimized for the ocean, not for the land. Further, users were admonished that a TWS time series for an individual 1° grid cell was meaningless on its own; it was necessary to average the gridded data over sufficiently large regions in order to overcome spatial correlation errors associated with the data processing (Gaussian smoothing). In fact, geodesists' fear of such products being misused was one of the main reasons they had not previously been developed. Nevertheless, the original gridded product freed hydrologists to perform GRACE-based studies on their own, and as a result, the number of such studies began to grow.

Over time, geodesists became increasingly uncomfortable with the way the first gridded product was being used and the failure of many hydrologists to acknowledge its deficiencies when drawing conclusions. In particular, gravity signal "leakage" from adjacent, large, and imperfectly modeled gravitational phenomena such as ocean tides had not been minimized in the gridded product through advanced geodetic processing or properly accounted in hydrologists' error budgets, and the Gaussian smoothing and destriping caused damping of the dynamic range of TWS that was particularly troublesome for water balance studies. Further, geodesists argued that a consistent comparison between modeled or independently observed hydrological phenomena and GRACE TWS anomalies required the former to be converted to spherical harmonics and Gaussian smoothed in the same way as the latter. Hydrologists saw little practical benefit to this approach beyond validation, and argued that gridded or otherwise preprocessed TWS products were imperative for maximizing GRACE data uptake and enabling the mission to reach its potential as a tool for hydrology. Discussions between these two factions at the Second GRACE Hydrology Workshop[59] in November 2009 sparked the development of a gridded TWS anomaly product that was better suited for land hydrology and was accompanied by a set of scale factors intended to counteract the signal damping[60]. Just as importantly, data and a short routine were provided for estimating uncertainty in the resulting monthly TWS anomalies when averaged over a region of interest. This uncertainty decreases dramatically as the size of the region increases, and it is also much smaller near the poles, where the satellite ground tracks are close, than near the equator. Since then, many other geodesy teams have introduced their own level-3 TWS products, catering to the needs of hydrologists[61–65].

Two headline-making publications[66,67] helped to dissolve hydrologists' remaining hesitancy and pique their interest in GRACE. They described shocking rates of groundwater depletion occurring in northern India (Figure 2), driven by groundwater extractions to support irrigated agriculture in a semi-arid climate. While it was known from local reports that groundwater levels were declining, the intensity and scale of declines had not previously been quantified due to the inaccessibility of in situ observations. Considering that over 100 million live in the affected region and that its agricultural output underpins the food supply for all of India, the potential consequences of dewatering the aquifers cannot be overstated. The two publications and the extensive media coverage surrounding them drew worldwide attention to the issue and engendered scores of follow-on studies[68–71]. According to *Web of Science*, in the prior decade (1999-2008) there had been 174 publications with both "groundwater" and "India" in the title. There were 832 in the decade that followed. Scientists who were previously unconvinced began to comprehend the power of satellite gravimetry as a tool for seeing "beneath the surface" in a way that no other approach could, providing unique and essential value for the field of hydrology. Figure 3 illustrates the steady growth of journal publications on GRACE and GRACE FO (hereafter GRACE/FO) hydrology since 2002. Clearly, there are far too many to cite here. What cannot be inferred from Figure 3 is that, prior to around 2010, a majority of these publications were written by non-hydrologists. Similarly, while early GRACE-based hydrological studies tended to focus on comparison and evaluation, starting around 2009, as discussed below, an increasing number of studies explored scientific and practical applications.

Contributions of GRACE to the study of groundwater

Following the formulas of the original Indian groundwater depletion studies[66,67], researchers investigated other regions where notable TWS declines were seen in the GRACE data, often due to groundwater pumping. In particular, GRACE was applied to provide new estimates of known groundwater depletion in California's Central Valley[72,73]. Considering that about one quarter of the food consumed in the U.S. comes from the Central Valley, monitoring and preserving its groundwater is crucial. The GRACE-based studies and associated media coverage once again drew renewed attention to groundwater depletion, likely contributing to the passage of California's 2014 Sustainable Groundwater Management Act. Several groups focused on another critical source of water for irrigated agriculture in the U.S., the High Plains aquifer[74–76]. Over the past two decades, this aquifer, which supports "the breadbasket of America", has been stable or gaining water in the north, while water stored in the central and southern portions has been slowly and steadily declining since records began in the middle of the 20th century[77]. Others quantified groundwater losses in the North China plain[78–80], another important agricultural region where withdrawals for irrigation have been outpacing recharge. Several studies discussed substantial decreases in surface water and groundwater in the Middle East caused by a combination of drought and irrigated agriculture[81–84]. Scientists also evaluated groundwater storage variations and depletion in the Great Lakes basin[85], the Colorado River basin[86], and across Africa[87–90], among other regions. Still other authors began to develop global assessments of groundwater storage changes based on GRACE data[40,91–94]. Figure 4 displays a global map of 20-year trends in TWS based on GRACE and GRACE-FO observations[61]. TWS declines in several of the regions, such as those previously noted, can be attributed at least in part to groundwater depletion to support irrigated agriculture, in some cases exacerbated by recent drought[40]. Finally, as the only truly global source of TWS observations, GRACE first made possible a sub-section on groundwater and terrestrial water storage in the *Bulletin of the American Meteorological Society*'s annual "State of the Climate" report in 2011[95], and it has been included ever since.

Global Water Budget Analysis

Hydrologists have aspired to close the water budget (see equation 1, below) from global to catchment scales for more than a century[2,96,97]. However, prior to the launch of GRACE, with few exceptions[98] water budget analyses relied on the assumption that changes in TWS are insignificant on annual and longer timescales. This assumption was enticing because the collocated, in situ observations of groundwater, soil moisture, and, in some cases, snowpack and surface water necessary to estimate interannual changes in TWS were extremely scarce[20]. Analysis of the first few years of GRACE data provided ample evidence that the assumption of annual steady state of TWS was flawed at both river basin and global scales, and that interannual changes in TWS caused compensating changes in mean sea level[99–101].

In addition to the change in storage, ΔTWS, closing the terrestrial water budget requires estimates of the net fluxes into and out of a study region (often a catchment or river basin bounded by topography across which lateral flows are negligible):

$$\Delta \mathrm{TWS} = \mathrm{P} - \mathrm{ET} - \mathrm{Q} \qquad (1)$$

where P, ET, and Q are accumulated precipitation, evapotranspiration, and runoff. Given knowledge of three of the variables, the fourth can be estimated as a residual. Early GRACE-based studies estimated ET, which is difficult to measure directly, as the residual[42,102]. However, because ΔTWS represents the change between instantaneous TWS values at the start and end of the flux accumulation period, while GRACE/FO provides monthly mean TWS anomalies, the approach requires either complex mathematics[42], a multi-month moving window approach[103], or higher tolerance for error. Similarly, a combined atmospheric-terrestrial water budget can be used to estimate atmospheric convergence (P-ET) as a residual:

$$P - ET = Q + \Delta TWS + \Delta AMC \qquad (2)$$

where ΔAMC is the change in total atmospheric moisture content, which is typically assumed to be negligible[43]. The resulting ET and P-ET estimates have proven useful for evaluating modeled and remote sensing-based fluxes[104–109], at least in terms of magnitude or bias. The approach even helped to resolve a scientific debate. Hydrologists had disagreed on the strength of the seasonal cycle of ET in tropical regions, where water and energy are typically abundant throughout the year[110,111]. The observed seasonality of TWS provided by GRACE was the key innovation that enabled the matter to be put to rest, as the water budget residual ET indicated that the seasonal cycle in Brazil and central Africa was relatively weak and less dynamic than that depicted by most models[105]. Unfortunately, the scarcity of river discharge observations (from basins large enough for GRACE/FO to resolve) limits the applicability of this approach. That’s one reason scientists use GRACE/FO TWS data together with atmospheric analysis model-based convergence to estimate river discharge as a water budget residual[44,45]. However, the long term mean magnitude of the resulting estimates is almost entirely controlled by the simulated convergence, with GRACE/FO TWS primarily acting to modulate the seasonal cycle.

Another innovative application of the water budget approach is to estimate accumulated snowfall in high latitude or alpine regions. This can be accomplished with the aid of modeled ET and modeled or observed Q. Both are generally small in comparison with P at high latitudes/altitudes during the winter prior to spring thaw, such that errors in a water budget residual are likewise small. In other words, ΔTWS is mostly attributable to P in equation 1. The resulting regional scale, monthly estimates of snowfall are valuable because precipitation is under-sampled in cold regions and snowfall is notoriously challenging to measure due to gauge undercatch, which itself is difficult to estimate. The study that introduced this approach determined that the undercatch corrections in one popular, global precipitation dataset were too large[112]. However, other GRACE-based studies have shown that precipitation products underestimate cold season precipitation by 30-50% in the Himalayas[113] and that undercatch corrections applied in well-known products are both necessary and highly variable in the Arctic[114]. Another concluded that four meteorological datasets generally underestimated P even after undercatch corrections had been applied[115].

When estimates of all the budget variables are available, they can be used within a water balance framework to constrain each other, thereby improving each individual estimate. Among the first to apply this approach with GRACE data, a 2009 study estimated Mississippi River discharge as a water budget residual, showing that it significantly exceeded gauged discharge, and used the results to bias-correct satellite-derived precipitation[116]. A follow-up study over ten global river basins similarly attributed most of the non-closure error to the precipitation data[117]. In 2015, a multi-institutional investigation used observation-based datasets including GRACE data within a variational framework to enforce simultaneous water and energy budget closure over continents, ocean basins, and worldwide, on monthly mean and annual mean (2001-2010) timescales[118,119]. The approach successfully reduced bias in all of the estimated fluxes and storage changes. Results showed that unconstrained annual terrestrial and atmospheric water budgets closed with considerably less than 10% imbalance (relative to precipitation) in most cases, however, on a mean monthly timescale, water budget imbalance approached or exceeded 20% in North America, Eurasia, and Australia. Building on this technique, studies with larger suites of input datasets produced gridded, global results[120] and results over longer periods[121]. Rather than constraining the flux estimates, other investigators have computed the mass imbalance arising from different combinations of inputs to the water budget equation as a way to help select appropriate combinations of datasets for regional hydrological studies[122].

Because the Earth is a closed system, it has long been known that changes in the mass of water stored in the oceans, land, and atmosphere must sum to zero. However, prior to GRACE, there was no way to perform an observation-based accounting. The literature is rich with GRACE-informed studies of the responses of ice sheets and sea level to climate change[123,124]. GRACE similarly enabled quantification of non-ice sheet, terrestrial water contributions to seasonal and interannual variations in sea level. A 2016 study demonstrated the use of GRACE data over land and ocean in a global least-squares inversion, together with ocean altimetry and steric data from ocean reanalyses and other data sets, to constrain the sea level budget including the TWS contribution to sea level[125]. It has also been shown that non-ice TWS largely controls seasonal and interannual variations of the land-ocean water balance[126]. Another study estimated that, during 2002-2014 at the global scale, hydroclimate related increases in non-ice TWS acted to reduce the rate of sea level rise by about 15% after removing the effects of irrigation-enhanced groundwater depletion[127]. It was concluded that this was consistent with regional increases in precipitation that drove flooding and drought recovery events in several locations globally. Ironically, in the year after that study ended there was a huge decrease in non-ice sheet TWS (Figure 5), and it has not recovered to its earlier dynamic range[128]. While it is possible that extreme glacier melt accounted for the sudden decline, recent analyses do not implicate that as the primary driver[129,130], leaving liberation of unfrozen forms of TWS as the likely culprit. Supporting that hypothesis, a subsequent study concluded that TWS in endorheic basins (which are often semi-arid to arid) declined by about 106 Gt/yr during 2002-2016[131] – water which would ultimately enter the ocean. TWS fluctuations cause seasonal mass variations in sea level, whose annual range of about 34 mm is comparable to about a decade of long-term barystatic level rise[132]. Non-secular interannual variations in sea level also are largely driven by irregular gains and losses of TWS around the world. For example, a powerful El Nino in 2011 caused an excess of TWS in the southern hemisphere, including record flooding Australia, which in turn produced a temporary decline in global mean sea level[101,133]. Prior to GRACE, explanations for such a decline would have derived from circumstantial evidence.

Because shifts in the water cycle will be among the most visible and consequential effects of climate change, understanding its variations and predicting how it is likely to change in the future are key goals for hydrologists and climate scientists[118]. A study of the first eight years of GRACE data showed that observed TWS variations were consistent with known wet/dry precipitation patterns associated with El Nino and La Nina[134]. Another study found evidence in the GRACE data for water cycle acceleration, which has long been predicted as a consequence of climate change[135]. Certain regional trends observed by GRACE/FO (Figure 4) have similarly been flagged as possible climate change impacts[40]. Further, global TWS itself seems to govern atmospheric carbon dioxide growth, with faster growth in drier years[136], revealing one of possibly many TWS-climate feedback loops.

Integration of GRACE data into hydrological models

Early in the mission, hydrological models were frequently used to validate the retrieval of TWS changes from the GRACE gravity observations[57,137–139] and to refine retrieval algorithms[140,141]. Later, such models helped identify the processes controlling the observed TWS changes[8,52,142,143]. As hydrologists became satisfied that GRACE was, in fact, measuring what the geodesists claimed, the retrieved TWS began to be used to validate hydrological models[144–146]. For example, it was shown that many land surface models, particularly those lacking a groundwater variable, have insufficient storage capacity to represent the true, full dynamic range of TWS[147,148].

While most GRACE-based studies have relied on in situ observations, model output, or simplifying assumptions to isolate variations in groundwater or the other components of TWS, scientists recognized that auxiliary data and hydrological models could be used more holistically to extract groundwater information from GRACE observations. In particular, a Kalman smoother based data assimilation approach[55] was introduced for integrating GRACE derived TWS data into a land surface model, thus enabling spatial and temporal downscaling and vertical disaggregation of the TWS components. Just as importantly for practical, operational applications, data assimilation permitted extrapolation to near-real time based on the meteorological inputs[55], whereas standard GRACE TWS products were typically released 2-5 months after the time of observation.

Subsequent efforts developed techniques for assimilating GRACE data into different land surface models[149–154]. Others improved on the original Kalman smoother data assimilation by enabling assimilation of gridded (as opposed to basin average) GRACE data[155,156]. This was important because it minimized spatial artifacts associated with pre-defined regions (i.e., river basin boundaries) and better utilized the spatial information contained in the data products. Still, it was shown that the lack of vertical stratification in the GRACE data could lead to mischaracterization of subsurface processes[157] which further could cause errors in the assimilated output[158]. Simultaneous assimilation of GRACE TWS, Soil Moisture and Ocean Salinity (SMOS) or Soil Moisture Active Passive (SMAP) soil moisture, Moderate Resolution Imaging Spectroradiometer (MODIS) or Advanced Microwave Scanning Radiometer (AMSR) snow, and other remote sensing data holds promise for overcoming such issues while also improving horizontal downscaling[159–164]. As an alternative to data assimilation, GRACE data have also been used to inform and calibrate hydrological models[165–169].

Practical Applications

Monitoring drought was recognized early in the mission as a practical application of GRACE data, though multiple years of observations were needed to develop a baseline for quantifying wet or dry extremes[170–173]. GRACE data assimilation was the foundation for the first routinely delivered GRACE-based soil moisture and groundwater drought/wetness indicator maps for the contiguous United States[174]. These indicators were presented as wetness percentiles relative to the range of conditions at each specific location and time of year in a 60+ year historical model simulation. This enabled GRACE data to become useful for operational drought monitoring, and the indicator maps began to be consulted by the authors of the U.S. Drought Monitor[175]. In addition to their improved spatial resolution, a key to the adoption of GRACE data assimilation products by drought, water resources, and agricultural decision-makers was their weekly, near-real time availability[175,176]. Few operational applications can make use of data older than about 2 weeks[177]. GRACE/FO data assimilation was later expanded to cover all continents except Antarctica, serving as the basis for weekly, global, root zone soil moisture and groundwater wetness/drought indicator maps[10], which were unprecedented (Figure 6). One-to-three month forecasts of the same, for the contiguous U.S., are also available, initialized by GRACE-FO data assimilation[178]. Several GRACE-only drought indices have been proposed as well, mostly quantifying drought relative to the historical range of season- and location-specific conditions[179–184].

Wet extremes can be detected and quantified in the same ways as dry extremes, and some of the indicators described above are meant to serve both purposes[10,174,180]. Using GRACE, studies have investigated major flood events around the world[185–187]. Further, owing to the importance of elevated water levels as a precursor to severe flooding, scientists have introduced means for assessing flood vulnerability based on the current TWS anomaly relative to the water holding capacity of the land inferred from the GRACE data record[188,189]. It has also been demonstrated through a case study in the Missouri River basin that snow water equivalent, soil moisture, and groundwater output from a GRACE data assimilating land surface model[174] have the potential to improve the predictability of flood events[190].

Ongoing GRACE/FO research may create additional opportunities for practical applications that could be developed in the future for user-specific needs. For instance, application of the water budget approach for ET has been used to estimate water consumption during the summer season in the upper and lower Colorado River Basins[191]. Remote detection of water usage would be valuable for agricultural monitoring and optimization purposes. As another example, GRACE/FO data assimilation-based soil moisture estimates show promise as potential predictors of fire season intensity and burned area[192] and could perhaps be incorporated into an operational framework for wildfire early warning[193]. Similarly, such estimates have shown promise for predicting slope stability and landslide vulnerability[194]. Finally, groundwater assessments that utilize GRACE/FO other remote sensing and in situ observations could be used for operational groundwater monitoring or even groundwater change prediction[195–197].

Future Prospects

In contrast to the skepticism that many scientists had about GRACE when it launched in 2002, by the 2010s its importance as a tool for studying the water cycle, cryosphere, and oceans had become so clear that NASA, together with its partner, the German Space Agency, prioritized launching GRACE-FO above several other mission concepts that had been recommended by a 2007 U.S. National Research Council report[198]. Moreover, the subsequent decadal report[199] ranked a third Mass Change (satellite gravimetry) mission among its top five Earth science mission priorities for the following decade, in order to avoid a gap in the data record and to potentially improve upon GRACE/FO in terms of spatial resolution, temporal resolution, and/or accuracy. GRACE-FO added an experimental laser interferometer to increase the precision of the inter-satellite range measurements (above that of the primary instrument, a microwave interferometer). The laser has been a success, however, the principal source of error limiting improved resolution at a given level of accuracy is spatial-temporal undersampling of high frequency mass variations in the atmosphere and oceans[200] (i.e., “aliasing”). Overcoming aliasing is expected to require a constellation of two or more GRACE-like satellite pairs[177]. While that may not materialize in the immediate future, extension of the satellite gravimetry-based TWS data record by GRACE-FO and a subsequent

Mass Change mission will support improved understanding of water cycle variability and change associated with natural variations, climate change, direct human impacts, and even implementation of water management policy[201].

References

1. Strangeways, I. A history of rain gauges. *Weather* **65**, 133–138 (2010).
2. Peters-Lidard, C. D. *et al.* 100 Years of Progress in Hydrology. *Meteorological Monographs* **59**, 25.1-25.51 (2018).
3. Mintz, Y. & Serafini, Y. v. A global monthly climatology of soil moisture and water balance. *Clim. Dyn.* **8**, 13–27 (1992).
4. Manabe, S. Climate and the ocean circulation: I. The atmospheric circulation and the hydrology of the Earth's surface. *Mon. Weather Rev.* **97**, 739–774 (1969).
5. Brown, R. D., Fang, B. & Mudryk, L. Update of Canadian Historical Snow Survey Data and Analysis of Snow Water Equivalent Trends, 1967–2016. *Atmosphere-Ocean* **57**, 149–156 (2019).
6. Wilson, D. J. *et al.* Spatial distribution of soil moisture over 6 and 30cm depth, Mahurangi river catchment, New Zealand. *J. Hydrol. (Amst.)* **276**, 254–274 (2003).
7. Dorigo, W. A. *et al.* The International Soil Moisture Network: a data hosting facility for global in situ soil moisture measurements. *Hydrol. Earth Syst. Sci.* **15**, 1675–1698 (2011).
8. Getirana, A., Kumar, S., Girotto, M. & Rodell, M. Rivers and Floodplains as Key Components of Global Terrestrial Water Storage Variability. *Geophys. Res. Lett.* **44**, 10,359-10,368 (2017).
9. Rodell, M., Chao, B. F. F., Au, A. Y. Y., Kimball, J. S. S. & McDonald, K. C. C. Global biomass variation and its geodynamic effects: 1982-98. *Earth Interact.* **9**, 1–19 (2005).
10. Li, B. *et al.* Global GRACE Data Assimilation for Groundwater and Drought Monitoring: Advances and Challenges. *Water Resour. Res.* **55**, 7564–7586 (2019).
11. Kaula, W. M. Tests and combination of satellite determinations of the gravity field with gravimetry. *J. Geophys. Res.* **71**, 5303–5314 (1966).
12. Yoder, C. F. *et al.* Secular variation of Earth's gravitational harmonic J2 coefficient from Lageos and nontidal acceleration of Earth rotation. *Nature* **303**, 757–762 (1983).
13. Gutierrez, R. & Wilson, C. R. Seasonal air and water mass redistribution effects on LAGEOS and Starlette. *Geophys. Res. Lett.* **14**, 929–932 (1987).

14. Chao, B. F. & O'Connor, W. P. Global surface-water-induced seasonal variations in the Earth's rotation and gravitational field. *Geophys. J. Int.* **94**, 263–270 (1988).

15. Kaula, W. M. *The Terrestrial Environment: Solid Earth and Ocean Physics, Application of Space and Astronomic Techniques, Report of a Study at Williamstown*. (1970).

16. Loomis, B. D., Rachlin, K. E., Wiese, D. N., Landerer, F. W. & Luthcke, S. B. Replacing GRACE/GRACE-FO With Satellite Laser Ranging: Impacts on Antarctic Ice Sheet Mass Change. *Geophys. Res. Lett.* **47**, (2020).

17. National Research Council. *Satellite Gravity and the Geosphere*. (National Academies Press, 1997).

18. Wahr, J., Molenaar, M. & Bryan, F. Time variability of the Earth's gravity field: Hydrological and oceanic effects and their possible detection using GRACE. *J. Geophys. Res. Solid Earth* **103**, 30205–30229 (1998).

19. Rodell, M. & Famiglietti, J. S. S. Detectability of variations in continental water storage from satellite observations of the time dependent gravity field. *Water Resour. Res.* **35**, 2705–2723 (1999).

20. Rodell, M. & Famiglietti, J. S. S. An analysis of terrestrial water storage variations in Illinois with implications for the Gravity Recovery and Climate Experiment (GRACE). *Water Resour. Res.* **37**, 1327–1339 (2001).

21. Rodell, M. & Famiglietti, J. S. The potential for satellite-based monitoring of groundwater storage changes using GRACE: The High Plains aquifer, Central US. *J. Hydrol. (Amst.)* **263**, 245–256 (2002).

22. Tapley, B. D., Bettadpur, S., Ries, J. C., Thompson, P. F. & Watkins, M. M. GRACE measurements of mass variability in the Earth system. *Science (1979)* **305**, 503–505 (2004).

23. Tamisiea, M. E., Leuliette, E. W., Davis, J. L. & Mitrovica, J. X. Constraining hydrological and cryospheric mass flux in southeastern Alaska using space-based gravity measurements. *Geophys. Res. Lett.* **32**, 1–4 (2005).

24. Velicogna, I. & Wahr, J. Greenland mass balance from GRACE. *Geophys. Res. Lett.* **32**, 1–4 (2005).

25. Chen, J. L., Wilson, C. R. & Tapley, B. D. Satellite gravity measurements confirm accelerated melting of Greenland ice sheet. *Science (1979)* **313**, 1958–1960 (2006).

26. Luthcke, S. B. *et al.* Recent greenland ice mass loss by drainage system from satellite gravity observations. *Science (1979)* **314**, 1286–1289 (2006).

27. Chambers, D. P., Wahr, J. & Nerem, R. S. Preliminary observations of global ocean mass variations with GRACE. *Geophys. Res. Lett.* **31**, 13 (2004).

28. Chen, J. L., Wilson, C. R., Tapley, B. D., Famiglietti, J. S. & Rodell, M. Seasonal global mean sea level change from satellite altimeter, GRACE, and geophysical models. *J. Geod.* **79**, 532–539 (2005).

29. Nerem, R. S., Leuliette, É. & Cazenave, A. Present-day sea-level change: A review. *Comptes Rendus - Geoscience* **338**, 1077–1083 (2006).

30. Rowlands, D. D. *et al.* Resolving mass flux at high spatial and temporal resolution using GRACE intersatellite measurements. *Geophys. Res. Lett.* **32**, 1–4 (2005).

31. Wahr, J., Swenson, S. & Velicogna, I. Accuracy of GRACE mass estimates. *Geophys. Res. Lett.* **33**, 6 (2006).

32. Velicogna, I. & Wahr, J. Measurements of time-variable gravity show mass loss in Antarctica. *Science (1979)* **311**, 1754–1756 (2006).

33. Peltier, W. R. Global glacial isostasy and the surface of the ice-age earth: The ICE-5G (VM2) model and GRACE. *Annu. Rev. Earth Planet. Sci.* **32**, 111–149 (2004).

34. IVINS, E. R. & JAMES, T. S. Antarctic glacial isostatic adjustment: a new assessment. *Antarct. Sci.* **17**, 541–553 (2005).

35. Forman, B. A., Reichle, R. H. & Rodell, M. Assimilation of terrestrial water storage from GRACE in a snow-dominated basin. *Water Resour. Res.* **48**, (2012).

36. Han, S. C., Sauber, J., Luthcke, S. B., Ji, C. & Pollitz., F. F. Implications of postseismic gravity change following the great 2004 Sumatra-Andaman earthquake from the regional harmonic analysis of GRACE intersatellite tracking data. *J. Geophys. Res. Solid Earth* **113**, (2008).

37. Ghobadi-Far, K. *et al.* Gravitational Changes of the Earth's Free Oscillation from Earthquakes: Theory and Feasibility Study Using GRACE Inter-satellite Tracking. *J. Geophys. Res. Solid Earth* **124**, 7483–7503 (2019).

38. Hardy, R. A., Nerem, R. S. & Wiese, D. N. The Impact of Atmospheric Modeling Errors on GRACE Estimates of Mass Loss in Greenland and Antarctica. *J. Geophys. Res. Solid Earth* **122**, 10,440-10,458 (2017).

39. Chen, J. L. *et al.* Long-term Caspian Sea level change. *Geophys. Res. Lett.* **44**, 6993–7001 (2017).

40. Rodell, M. *et al.* Emerging trends in global freshwater availability. *Nature* **557**, 651–659 (2018).

41. Wang, X., de Linage, C., Famiglietti, J. & Zender, C. S. Gravity Recovery and Climate Experiment (GRACE) detection of water storage changes in the Three Gorges Reservoir of China and comparison with in situ measurements. *Water Resour. Res.* **47**, 12 (2011).

42. Rodell, M. *et al.* Basin scale estimates of evapotranspiration using GRACE and other observations. *Geophys. Res. Lett.* **31**, (2004).

43. Swenson, S. & Wahr, J. Estimating large-scale precipitation minus evapotranspiration from GRACE satellite gravity measurements. *J. Hydrometeorol.* **7**, 252–270 (2006).

44. Syed, T. H. H. *et al.* Total basin discharge for the Amazon and Mississippi River basins from GRACE and a land-atmosphere water balance. *Geophys. Res. Lett.* **32**, 1–5 (2005).

45. Syed, T. H. H., Famiglietti, J. S. S., Zlotnicki, V. & Rodell, M. Contemporary estimates of Pan-Arctic freshwater discharge from GRACE and reanalysis. *Geophys. Res. Lett.* **34**, (2007).

46. Frappart, F., Ramillien, G., Biancamaria, S., Mognard, N. M. & Cazenave, A. Evolution of high-latitude snow mass derived from the GRACE gravimetry mission (2002-2004). *Geophys. Res. Lett.* **33**, 2 (2006).

47. Crowley, J. W., Mitrovica, J. X., Bailey, R. C., Tamisiea, M. E. & Davis, J. L. Land water storage within the Congo Basin inferred from GRACE satellite gravity data. *Geophys. Res. Lett.* **33**, 19 (2006).

48. Swenson, S. C. & Milly, P. C. D. Climate model biases in seasonally of continental water storage revealed by satellite gravimetry. *Water Resour. Res.* **42**, 3 (2006).

49. Hinderer, J., Andersen, O., Lemoine, F., Crossley, D. & Boy, J.-P. Seasonal changes in the European gravity field from GRACE: A comparison with superconducting gravimeters and hydrology model predictions. *J. Geodyn.* **41**, 59–68 (2006).

50. Swenson, S., Yeh, P. J. F., Wahr, J. & Famiglietti, J. A comparison of terrestrial water storage variations from GRACE with in situ measurements from Illinois. *Geophys. Res. Lett.* **33**, 16 (2006).

51. Strassberg, G., Scanlon, B. R. & Rodell, M. Comparison of seasonal terrestrial water storage variations from GRACE with groundwater-level measurements from the High Plains Aquifer (USA). *Geophys. Res. Lett.* **34**, (2007).

52. Syed, T. H. T. H., Famiglietti, J. S. J. S., Rodell, M., Chen, J. & Wilson, C. R. C. R. Analysis of terrestrial water storage changes from GRACE and GLDAS. *Water Resour. Res.* **44**, (2008).

53. Yeh, P. J.-F. P. J. F., Swenson, S. C. C., Famiglietti, J. S. S. & Rodell, M. Remote sensing of groundwater storage changes in Illinois using the Gravity Recovery and Climate Experiment (GRACE). *Water Resour. Res.* **42**, (2006).

54. Rodell, M. *et al.* Estimating groundwater storage changes in the Mississippi River basin (USA) using GRACE. *Hydrogeol. J.* **15**, 159–166 (2007).

55. Zaitchik, B. F. B. F., Rodell, M. & Reichle, R. H. R. H. Assimilation of GRACE terrestrial water storage data into a land surface model: Results for the Mississippi River basin. *J. Hydrometeorol.* **9**, 535–548 (2008).

56. Swenson, S. & Wahr, J. Post-processing removal of correlated errors in GRACE data. *Geophys. Res. Lett.* **33**, 8 (2006).

57. Wahr, J., Swenson, S., Zlotnicki, V. & Velicogna, I. Time-variable gravity from GRACE: First results. *Geophys. Res. Lett.* **31**, 11 (2004).

58. Chambers, D. P. Evaluation of new GRACE time-variable gravity data over the ocean. *Geophys. Res. Lett.* **33**, 17 (2006).

59. Rodell, M., Famiglietti, J. S. J. S. & Scanlon, B. R. B. R. Realizing the potential of satellite gravimetry for hydrology. *Eos (Washington DC)* **91**, 96 (2010).

60. Landerer, F. W. & Swenson, S. C. Accuracy of scaled GRACE terrestrial water storage estimates. *Water Resour. Res.* **48**, 11 (2012).

61. Watkins, M. M., Wiese, D. N., Yuan, D. N., Boening, C. & Landerer, F. W. Improved methods for observing Earth’s time variable mass distribution with GRACE using spherical cap mascons. *J. Geophys. Res. Solid Earth* **120**, 2648–2671 (2015).

62. Wiese, D. N., Landerer, F. W. & Watkins, M. M. Quantifying and reducing leakage errors in the JPL RL05M GRACE mascon solution. *Water Resour. Res.* **52**, 7490–7502 (2016).

63. Save, H., Bettadpur, S. & Tapley, B. D. High-resolution CSR GRACE RL05 mascons. *J. Geophys. Res. Solid Earth* **121**, 7547–7569 (2016).

64. Loomis, B. D., Luthcke, S. B. & Sabaka, T. J. Regularization and error characterization of GRACE mascons. *J. Geod.* **93**, 1381–1398 (2019).

65. Boergens, E., Dobslaw, H. & Dill, R. COST-G GravIS RL01 Continental Water Storage Anomalies. V. 0004. GFZ Data Services. *V. 000* **4**, (2020).

66. Rodell, M., Velicogna, I. & Famiglietti, J. S. Satellite-based estimates of groundwater depletion in India. *Nature* **460**, (2009).

67. Tiwari, V. M., Wahr, J. & Swenson, S. Dwindling groundwater resources in northern India, from satellite gravity observations. *Geophys. Res. Lett.* **36**, L18401 (2009).

68. Soni, V. Groundwater loss in India and an integrated climate solution. *Curr. Sci.* **102**, 1098 (2012).

69. Chinnasamy, P., Hubbart, J. A. & Agoramoorthy, G. Using remote sensing data to improve groundwater supply estimations in Gujarat, India. *Earth Interact.* **17**, 1–17 (2013).

70. Chen, J., Li, J., Zhang, Z. & Ni, S. Long-term groundwater variations in Northwest India from satellite gravity measurements. *Glob. Planet. Change* **116**, 130–138 (2014).

71. Prakash, S., Gairola, R. M., Papa, F. & Mitra, A. K. An assessment of terrestrial water storage, rainfall and river discharge over Northern India from satellite data. *Curr. Sci.* **107**, 1582–1586 (2014).

72. Famiglietti, J. S. S. *et al.* Satellites measure recent rates of groundwater depletion in California's Central Valley. *Geophys. Res. Lett.* **38**, 3 (2011).

73. Scanlon, B. R. *et al.* Groundwater depletion and sustainability of irrigation in the US High Plains and Central Valley. *Proc. Natl. Acad. Sci. U.S.A.* **109**, 9320–9325 (2012).

74. Strassberg, G., Scanlon, B. R. & Chambers, D. Evaluation of groundwater storage monitoring with the GRACE satellite: Case study of the High Plains aquifer, central United States. *Water Resour. Res.* **45**, 5 (2009).

75. Longuevergne, L., Scanlon, B. R. & Wilson, C. R. GRACE hydrological estimates for small basins: Evaluating processing approaches on the High Plains aquifer, USA. *Water Resour. Res.* **46**, 11 (2010).

76. Breña-Naranjo, J. A., Kendall, A. D. & Hyndman, D. W. Improved methods for satellite-Based groundwater storage estimates: A decade of monitoring the high plains aquifer from space and ground observations. *Geophys. Res. Lett.* **41**, 6167–6173 (2014).

77. Luckey, R. R., Gutentag, E. D. & Weeks, J. B. Water-level and saturated-thickness changes, predevelopment to 1980. *in the High Plains aquifer in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming* **652**, 2 (1981).

78. Feng, W. *et al.* Evaluation of groundwater depletion in North China using the Gravity Recovery and Climate Experiment (GRACE) data and ground-based measurements. *Water Resour. Res.* **49**, 2110–2118 (2013).

79. Feng, W., Shum, C. K., Zhong, M. & Pan, Y. Groundwater storage changes in China from satellite gravity: An overview. *Remote Sens. (Basel)* **10**, 674 (2018).

80. Huang, Z. *et al.* Subregional-scale groundwater depletion detected by GRACE for both shallow and deep aquifers in North China Plain. *Geophys. Res. Lett.* **42**, 1791–1799 (2015).

81. Longuevergne, L., Wilson, C. R., Scanlon, B. R. & Crétaux, J. F. GRACE water storage estimates for the middle east and other regions with significant reservoir and lake storage. *Hydrol. Earth Syst. Sci.* **17**, 4817–4830 (2013).

82. Voss, K. A. K. A. *et al.* Groundwater depletion in the Middle East from GRACE with implications for transboundary water management in the Tigris-Euphrates-Western Iran region. *Water Resour. Res.* **49**, 904–914 (2013).

83. Forootan, E. *et al.* Separation of large scale water storage patterns over Iran using GRACE, altimetry and hydrological data. *Remote Sens. Environ.* **140**, 580–595 (2014).

84. Joodaki, G., Wahr, J. & Swenson, S. Estimating the human contribution to groundwater depletion in the Middle East, from GRACE data, land surface models, and well observations. *Water Resour. Res.* **50**, 2679–2692 (2014).

85. Huang, J. *et al.* Detectability of groundwater storage change within the Great Lakes Water Basin using GRACE. *J. Geophys. Res. Solid Earth* **117**, (2012).

86. Castle, S. L. S. L. *et al.* Groundwater depletion during drought threatens future water security of the Colorado River Basin. *Geophys. Res. Lett.* **41**, 5904–5911 (2014).

87. Lee, H. *et al.* Characterization of terrestrial water dynamics in the Congo Basin using GRACE and satellite radar altimetry. *Remote Sens. Environ.* **115**, 3530–3538 (2011).

88. Ahmed, M., Sultan, M., Wahr, J. & Yan, E. The use of GRACE data to monitor natural and anthropogenic induced variations in water availability across Africa. *Earth Sci. Rev.* **136**, 289–300 (2014).

89. Ramillien, G., Frappart, F. & Seoane, L. Application of the regional water mass variations from GRACE satellite gravimetry to large-scale water management in Africa. *Remote Sens. (Basel)* **6**, 7379–7405 (2014).

90. Nanteza, J., de Linage, C. R., Thomas, B. F. & Famiglietti, J. S. Monitoring groundwater storage changes in complex basement aquifers: An evaluation of the GRACE satellites over East Africa. *Water Resour. Res.* **52**, 9542–9564 (2016).

91. Jin, S. & Feng, G. Large-scale variations of global groundwater from satellite gravimetry and hydrological models, 2002-2012. *Glob. Planet. Change* **106**, 20–30 (2013).

92. Döll, P., Müller Schmied, H., Schuh, C., Portmann, F. T. & Eicker, A. Global-scale assessment of groundwater depletion and related groundwater abstractions: Combining hydrological modeling with information from well observations and GRACE satellites. *Water Resour. Res.* **50**, 5698–5720 (2014).

93. Chen, J., Famiglietti, J. S., Scanlon, B. R. & Rodell, M. Groundwater Storage Changes: Present Status from GRACE Observations. in *Remote Sensing and Water Resources* (eds. Cazenave, A., Champollion, N., Benveniste, J. & Chen, J.) 207–227 (2016).

94. Richey, A. S. *et al.* Uncertainty in global groundwater storage estimates in a Total Groundwater Stress framework. *Water Resour. Res.* **51**, (2015).

95. Rodell, M., Chambers, D. P. & Famiglietti, J. S. Groundwater and Terrestrial Water Storage [in ‘State of the Climate in 2010’]. *Bull. Am. Meteorol. Soc.* **92**, (2011).

96. Voeikov, A. I. *Klimaty zemnogo shara, v Osobennosti Rossii (Climates of the Earth, Particularly of Russia).* (Kartograficheskoe Zavedenie A. Il’ina, 1884).

97. Murray, J. On the total annual rainfall on the land of the globe, and the relation of rainfall to the annual discharge of rivers. *Scott. Geogr. Mag.* **3**, 65–77 (1887).

98. Mintz, Y. & Serafini, Y. v. A global monthly climatology of soil moisture and water balance. *Clim. Dyn.* **8**, 13–27 (1992).

99. Ramillien, G. *et al.* Land water storage contribution to sea level from GRACE geoid data over 2003-2006. *Glob. Planet. Change* **60**, 381–392 (2008).

100. Llovel, W. *et al.* Terrestrial waters and sea level variations on interannual time scale. *Glob. Planet. Change* **75**, 76–82 (2011).

101. Boening, C., Willis, J. K., Landerer, F. W., Nerem, R. S. & Fasullo, J. The 2011 la Nia: So strong, the oceans fell. *Geophys. Res. Lett.* **39**, 19 (2012).

102. Ramillien, G. *et al.* Time variations of the regional evapotranspiration rate from Gravity Recovery and Climate Experiment (GRACE) satellite gravimetry. *Water Resour. Res.* **42**, 10 (2006).

103. Landerer, F. W., Dickey, J. O. & Güntner, A. Terrestrial water budget of the Eurasian pan-Arctic from GRACE satellite measurements during 2003-2009. *J. Geophys. Res. Atmospheres* **115**, (2010).

104. Ferguson, C. R., Sheffield, J., Wood, E. F. & Gao, H. Quantifying uncertainty in a remote sensing-based estimate of evapotranspiration over continental USA. *Int. J. Remote Sens.* **31**, 3821–3865 (2010).

105. Rodell, M., Mcwilliams, E. B. E. B., Famiglietti, J. S. J. S., Beaudoing, H. K. H. K. & Nigro, J. Estimating evapotranspiration using an observation based terrestrial water budget. *Hydrol. Process.* **25**, 4082–4092 (2011).

106. Trenberth, K. E. & Fasullo, J. T. North American water and energy cycles. *Geophys. Res. Lett.* **40**, 365–369 (2013).

107. Long, D., Longuevergne, L. & Scanlon, B. R. Uncertainty in evapotranspiration from land surface modeling, remote sensing, and GRACE satellites. *Water Resour. Res.* **50**, 1131–1151 (2014).

108. Bhattarai, N. *et al.* An automated multi-model evapotranspiration mapping framework using remotely sensed and reanalysis data. *Remote Sens. Environ.* **229**, 69–92 (2019).

109. Eicker, A. *et al.* Daily GRACE satellite data evaluate short-term hydro-meteorological fluxes from global atmospheric reanalyses. *Sci. Rep.* **10**, 1–10 (2020).

110. Hasler, N. & Avissar, R. What controls evapotranspiration in the Amazon basin? *J. Hydrometeorol.* **8**, 380–395 (2007).

111. da Rocha, H. R. *et al.* Patterns of water and heat flux across a biome gradient from tropical forest to savanna in Brazil. *J. Geophys. Res. Biogeosci.* **114**, (2009).

112. Swenson, S. Assessing high-latitude winter precipitation from global precipitation analyses using GRACE. *J. Hydrometeorol.* **11**, 405–420 (2010).

113. Behrangi, A., Gardner, A. S., Reager, J. T. & Fisher, J. B. Using GRACE to constrain precipitation amount over cold mountainous basins. *Geophys. Res. Lett.* **44**, 219–227 (2017).

114. Behrangi, A., Singh, A., Song, Y. & Panahi, M. Assessing Gauge Undercatch Correction in Arctic Basins in Light of GRACE Observations. *Geophys. Res. Lett.* **46**, 11358–11366 (2019).

115. Robinson, E. L. & Clark, D. B. Using Gravity Recovery and Climate Experiment data to derive corrections to precipitation data sets and improve modelled snow mass at high latitudes. *Hydrol. Earth Syst. Sci.* **24**, 1763–1779 (2020).

116. Sheffield, J., Ferguson, C. R., Troy, T. J., Wood, E. F. & McCabe, M. F. Closing the terrestrial water budget from satellite remote sensing. *Geophys. Res. Lett.* **36**, 7 (2009).

117. Sahoo, A. K. *et al.* Reconciling the global terrestrial water budget using satellite remote sensing. *Remote Sens. Environ.* **115**, 1850–1865 (2011).

118. Rodell, M. *et al.* The observed state of the water cycle in the early twenty-first century. *J. Clim.* **28**, 8289–8318 (2015).

119. L'Ecuyer, T. S. *et al.* The observed state of the energy budget in the early twenty-first century. *J. Clim.* **28**, (2015).

120. Hobeichi, S., Abramowitz, G. & Evans, J. Conserving land-atmosphere synthesis suite (CLASS). *J. Clim.* **33**, 1821–1844 (2020).

121. Zhang, Y. *et al.* A Climate Data Record (CDR) for the global terrestrial water budget: 1984–2010. *Hydrol. Earth Syst. Sci.* **22**, 241–263 (2018).

122. Lehmann, F., Vishwakarma, B. D. & Bamber, J. How well are we able to close the water budget at the global scale? *Hydrol. Earth Syst. Sci.* **26**, 35–54 (2022).

123. Tapley, B. D. *et al.* Contributions of GRACE to understanding climate change. *Nat. Clim. Chang.* **9**, 358–369 (2019).

124. Chen, J. *et al.* Applications and Challenges of GRACE and GRACE Follow-On Satellite Gravimetry. *Surv. Geophys.* **43**, 305–345 (2022).

125. Rietbroek, R., Brunnabend, S.-E., Kusche, J., Schröter, J. & Dahle, C. Revisiting the contemporary sea-level budget on global and regional scales. *Proc. Natl. Acad. Sci. U.S.A.* **113**, 1504–1509 (2016).

126. Cáceres, D. *et al.* Assessing global water mass transfers from continents to oceans over the period 1948–2016. *Hydrol. Earth Syst. Sci.* **24**, 4831–4851 (2020).

127. Reager, J. T. *et al.* A decade of sea level rise slowed by climate-driven hydrology. *Science (1979)* **351**, 699–703 (2016).

128. Rodell, M. & Wiese, D. Groundwater and terrestrial water storage [in 'State of the Climate in 2020']. *Bull. Am. Meteorol. Soc.* **102**, S65–S66 (2021).

129. Wouters, B., Gardner, A. S. & Moholdt, G. Global glacier mass loss during the GRACE satellite mission (2002-2016). *Front. Earth Sci. (Lausanne)* **7**, 96 (2019).

130. Ciracì, E., Velicogna, I. & Swenson, S. Continuity of the Mass Loss of the World's Glaciers and Ice Caps from the GRACE and GRACE Follow-On Missions. *Geophys. Res. Lett.* **47**, 9 (2020).

131. Wang, J. *et al.* Recent global decline in endorheic basin water storages. *Nat. Geosci.* **11**, 926–932 (2018).

132. Chandanpurkar, H. A. *et al.* The Seasonality of Global Land and Ocean Mass and the Changing Water Cycle. *Geophys. Res. Lett.* **48**, 7 (2021).

133. Fasullo, J. T., Boening, C., Landerer, F. W. & Nerem, R. S. Australia's unique influence on global sea level in 2010-2011. *Geophys. Res. Lett.* **40**, 4368–4373 (2013).

134. Phillips, T., Nerem, R. S., Fox-Kemper, B., Famiglietti, J. S. & Rajagopalan, B. The influence of ENSO on global terrestrial water storage using GRACE. *Geophys. Res. Lett.* **39**, 16 (2012).

135. Eicker, A., Forootan, E., Springer, A., Longuevergne, L. & Kusche, J. Does GRACE see the terrestrial water cycle "intensifying"? *J. Geophys. Res.* **121**, 733–745 (2016).

136. Humphrey, V. *et al.* Sensitivity of atmospheric CO2 growth rate to observed changes in terrestrial water storage. *Nature* **560**, 628–631 (2018).

137. Andersen, O. B. & Hinderer, J. Global inter-annual gravity changes from GRACE: Early results. *Geophys. Res. Lett.* **32**, 1–4 (2005).

138. Schmidt, R. *et al.* GRACE observations of changes in continental water storage. *Glob. Planet. Change* **50**, 112–126 (2006).

139. Kusche, J., Schmidt, R., Petrovic, S. & Rietbroek, R. Decorrelated GRACE time-variable gravity solutions by GFZ, and their validation using a hydrological model. *J. Geod.* **83**, 903–913 (2009).

140. Chen, J. L. L., Rodell, M., Wilson, C. R. R. & Famiglietti, J. S. S. Low degree spherical harmonic influences on Gravity Recovery and Climate Experiment (GRACE) water storage estimates. *Geophys. Res. Lett.* **32**, 1–4 (2005).

141. Werth, S., Güntner, A., Schmidt, R. & Kusche, J. Evaluation of GRACE filter tools from a hydrological perspective. *Geophys. J. Int.* **179**, 1499–1515 (2009).

142. Reager, J. T. & Famiglietti, J. S. Characteristic mega-basin water storage behavior using GRACE. *Water Resour. Res.* **49**, 3314–3329 (2013).

143. Pokhrel, Y. N., Fan, Y., Miguez-Macho, G., Yeh, P. J.-F. & Han, S.-C. The role of groundwater in the Amazon water cycle: 3. Influence on terrestrial water storage computations and comparison with GRACE. *J. Geophys. Res. Atmospheres* **118**, 3233–3244 (2013).

144. Ngo-Duc, T., Laval, K., Ramillien, G., Polcher, J. & Cazenave, A. Validation of the land water storage simulated by Organising Carbon and Hydrology in Dynamic Ecosystems

(ORCHIDEE) with Gravity Recovery and Climate Experiment (GRACE) data. *Water Resour. Res.* **43**, 4 (2007).

145. Alkama, R. *et al.* Global evaluation of the ISBA-TRIP continental hydrological system. Part I: Comparison to GRACE terrestrial water storage estimates and in situ river discharges. *J. Hydrometeorol.* **11**, 583–600 (2010).

146. Güntner, A. Improvement of Global Hydrological Models Using GRACE Data. *Surv. Geophys.* **29**, 375–397 (2008).

147. Scanlon, B. R. *et al.* Global models underestimate large decadal declining and rising water storage trends relative to GRACE satellite data. *Proc. Natl. Acad. Sci. U.S.A.* **115**, E1080–E1089 (2018).

148. Scanlon, B. R. *et al.* Tracking Seasonal Fluctuations in Land Water Storage Using Global Models and GRACE Satellites. *Geophys. Res. Lett.* **46**, 5254–5264 (2019).

149. Eicker, A., Schumacher, M., Kusche, J., Döll, P. & Schmied, H. M. Calibration/Data Assimilation Approach for Integrating GRACE Data into the WaterGAP Global Hydrology Model (WGHM) Using an Ensemble Kalman Filter: First Results. *Surv. Geophys.* **35**, 1285–1309 (2014).

150. van Dijk, A. I. J. M., Renzullo, L. J., Wada, Y. & Tregoning, P. A global water cycle reanalysis (2003-2012) merging satellite gravimetry and altimetry observations with a hydrological multi-model ensemble. *Hydrol. Earth Syst. Sci.* **18**, 2955–2973 (2014).

151. Tangdamrongsub, N., Steele-Dunne, S. C., Gunter, B. C., Ditmar, P. G. & Weerts, A. H. Data assimilation of GRACE terrestrial water storage estimates into a regional hydrological model of the Rhine River basin. *Hydrol. Earth Syst. Sci.* **19**, 2079–2100 (2015).

152. Shokri, A., Walker, J. P., van Dijk, A. I. J. M. & Pauwels, V. R. N. Performance of Different Ensemble Kalman Filter Structures to Assimilate GRACE Terrestrial Water Storage Estimates into a High-Resolution Hydrological Model: A Synthetic Study. *Water Resour. Res.* **54**, 8931–8951 (2018).

153. Nie, W. *et al.* Assimilating GRACE Into a Land Surface Model in the Presence of an Irrigation-Induced Groundwater Trend. *Water Resour. Res.* **55**, 11274–11294 (2019).

154. Tangdamrongsub, N., Jasinski, M. F. & Shellito, P. J. Development and evaluation of 0.05g terrestrial water storage estimates using Community Atmosphere Biosphere Land Exchange (CABLE) land surface model and assimilation of GRACE data. *Hydrol. Earth Syst. Sci.* **25**, 4185–4208 (2021).

155. Kumar, S. V. S. v *et al.* Assimilation of Gridded GRACE terrestrial water storage estimates in the North American land data assimilation system. *J. Hydrometeorol.* **17**, 1951–1972 (2016).

156. Girotto, M., de Lannoy, G. J. M. G. J. M., Reichle, R. H. R. H. & Rodell, M. Assimilation of gridded terrestrial water storage observations from GRACE into a land surface model. *Water Resour. Res.* **52**, 4164–4183 (2016).

157. Meixner, T. *et al.* Implications of projected climate change for groundwater recharge in the western United States. *J. Hydrol. (Amst.)* **534**, (2016).

158. Girotto, M. *et al.* Benefits and pitfalls of GRACE data assimilation: A case study of terrestrial water storage depletion in India. *Geophys. Res. Lett.* **44**, (2017).

159. Su, H., Yang, Z. L., Dickinson, R. E., Wilson, C. R. & Niu, G. Y. Multisensor snow data assimilation at the continental scale: The value of Gravity Recovery and Climate Experiment terrestrial water storage information. *J. Geophys. Res. Atmospheres* **115**, (2010).

160. Tian, S. *et al.* Improved water balance component estimates through joint assimilation of GRACE water storage and SMOS soil moisture retrievals. *Water Resour. Res.* **53**, 1820–1840 (2017).

161. Zhao, L. & Yang, Z. L. Multi-sensor land data assimilation: Toward a robust global soil moisture and snow estimation. *Remote Sens. Environ.* **216**, 13–27 (2018).

162. Girotto, M. *et al.* Multi-sensor assimilation of SMOS brightness temperature and GRACE terrestrial water storage observations for soil moisture and shallow groundwater estimation. *Remote Sens. Environ.* **227**, 12–27 (2019).

163. Tangdamrongsub, N. *et al.* Multivariate data assimilation of GRACE, SMOS, SMAP measurements for improved regional soil moisture and groundwater storage estimates. *Adv. Water Resour.* **135**, 103477 (2020).

164. Wang, J., Forman, B. A., Girotto, M. & Reichle, R. H. Estimating Terrestrial Snow Mass via Multi-Sensor Assimilation of Synthetic AMSR-E Brightness Temperature Spectral Differences and Synthetic GRACE Terrestrial Water Storage Retrievals. *Water Resour. Res.* **57**, 9 (2021).

165. Lo, M. H., Famiglietti, J. S., Yeh, P. J. F. & Syed, T. H. Improving parameter estimation and water table depth simulation in a land surface model using GRACE water storage and estimated base flow data. *Water Resour. Res.* **46**, (2010).

166. Sun, A. Y. A. Y., Green, R., Rodell, M. & Swenson, S. Inferring aquifer storage parameters using satellite and in situ measurements: Estimation under uncertainty. *Geophys. Res. Lett.* **37**, (2010).

167. Xie, H., Longuevergne, L., Ringler, C. & Scanlon, B. R. Calibration and evaluation of a semi-distributed watershed model of Sub-Saharan Africa using GRACE data. *Hydrol. Earth Syst. Sci.* **16**, 3083–3099 (2012).

168. Hu, L. & Jiao, J. J. Calibration of a large-scale groundwater flow model using GRACE data: a case study in the Qaidam Basin, China. *Hydrogeol. J.* **23**, 1305–1317 (2015).

169. Huang, Y. *et al.* Estimation of human-induced changes in terrestrial water storage through integration of GRACE satellite detection and hydrological modeling: A case study of the Yangtze River basin. *Water Resour. Res.* **51**, 8494–8516 (2015).

170. Andersen, O. B., Seneviratne, S. I., Hinderer, J. & Viterbo, P. GRACE-derived terrestrial water storage depletion associated with the 2003 European heat wave. *Geophys. Res. Lett.* **32**, 1–4 (2005).

171. Yirdaw, S. Z., Snelgrove, K. R. & Agboma, C. O. GRACE satellite observations of terrestrial moisture changes for drought characterization in the Canadian Prairie. *J. Hydrol. (Amst.)* **356**, 84–92 (2008).

172. Chen, J. L., Wilson, C. R., Tapley, B. D., Yang, Z. L. & Niu, G. Y. 2005 drought event in the Amazon River basin as measured by GRACE and estimated by climate models. *J. Geophys. Res. Solid Earth* **114**, (2009).

173. Leblanc, M. J., Tregoning, P., Ramillien, G., Tweed, S. O. & Fakes, A. Basin-scale, integrated observations of the early 21st century multiyear drought in Southeast Australia. *Water Resour. Res.* **45**, 4 (2009).

174. Houborg, R., Rodell, M., Li, B., Reichle, R. & Zaitchik, B. F. B. F. Drought indicators based on model-assimilated Gravity Recovery and Climate Experiment (GRACE) terrestrial water storage observations. *Water Resour. Res.* **48**, 7 (2012).

175. Wardlow, B. D. *et al.* Remote sensing of drought: emergence of a satellite-based monitoring toolkit for the United States. in *Remote Sensing of Water Resources, Disasters, and Urban Studies* (ed. Thenkabail, P. S.) 367–400 (CRC Press, 2015).

176. Bernknopf, R. *et al.* The Value of Remotely Sensed Information: The Case of a GRACE-Enhanced Drought Severity Index. *Weather, Climate, and Society* **10**, 187–203 (2018).

177. Wiese, D. N. *et al.* The Mass Change designated observable study: overview and results. *Earth and Space Science* **l**, (2022).

178. Getirana, A. *et al.* GRACE improves seasonal groundwater forecast initialization over the United States. *J. Hydrometeorol.* **21**, 59–71 (2020).

179. Long, D. *et al.* GRACE satellite monitoring of large depletion in water storage in response to the 2011 drought in Texas. *Geophys. Res. Lett.* **40**, 3395–3401 (2013).

180. Long, D. *et al.* Drought and flood monitoring for a large karst plateau in Southwest China using extended GRACE data. *Remote Sens. Environ.* **155**, 145–160 (2014).

181. Thomas, A. C. A. C., Reager, J. T. J. T., Famiglietti, J. S. J. S. & Rodell, M. A GRACE-based water storage deficit approach for hydrological drought characterization. *Geophys. Res. Lett.* **41**, 1537–1545 (2014).

182. Thomas, B. F. *et al.* GRACE Groundwater Drought Index: Evaluation of California Central Valley groundwater drought. *Remote Sens. Environ.* **198**, 384–392 (2017).

183. Zhao, M., Geruo, A., Velicogna, I. & Kimball, J. S. 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. *J. Hydrometeorol.* **18**, 2117–2129 (2017).

184. Gerdener, H., Engels, O. & Kusche, J. A framework for deriving drought indicators from the Gravity Recovery and Climate Experiment (GRACE). *Hydrol. Earth Syst. Sci.* **24**, 227–248 (2020).

185. Chen, J. L., Wilson, C. R. & Tapley, B. D. The 2009 exceptional Amazon flood and interannual terrestrial water storage change observed by GRACE. *Water Resour. Res.* **46**, (2010).

186. dutt Vishwakarma, B., Jain, K., Sneeuw, N. & Devaraju, B. Mumbai 2005, Bihar 2008 Flood Reflected in Mass Changes Seen by GRACE Satellites. *Journal of the Indian Society of Remote Sensing* **41**, 687–695 (2013).

187. Abelen, S., Seitz, F., Abarca-del-Rio, R. & Güntner, A. Droughts and Floods in the La Plata Basin in Soil Moisture Data and GRACE. *Remote Sens. (Basel)* **7**, 7324–7349 (2015).

188. Reager, J. T. & Famiglietti, J. S. Global terrestrial water storage capacity and flood potential using GRACE. *Geophys. Res. Lett.* **36**, 23 (2009).

189. Reager, J. T., Thomas, B. F. & Famiglietti, J. S. River basin flood potential inferred using GRACE gravity observations at several months lead time. *Nat. Geosci.* **7**, 588–592 (2014).

190. Reager, J. T. J. T. *et al.* Assimilation of GRACE terrestrial water storage observations into a land surface model for the assessment of regional flood potential. *Remote Sens. (Basel)* **7**, 14663–14679 (2015).

191. Castle, S. L. *et al.* Remote detection of water management impacts on evapotranspiration in the Colorado River Basin. *Geophys. Res. Lett.* **43**, 5089–5097 (2016).

192. Jensen, D. *et al.* The sensitivity of US wildfire occurrence to pre-season soil moisture conditions across ecosystems. *Environ. Res. Lett.* **13**, 014021 (2018).

193. Farahmand, A. *et al.* Satellite hydrology observations as operational indicators of forecasted fire danger across the contiguous United States. *Natural Hazards and Earth System Sciences* **20**, 1097–1106 (2020).

194. Felsberg, A. *et al.* Global Soil Water Estimates as Landslide Predictor: The Effectiveness of SMOS, SMAP, and GRACE Observations, Land Surface Simulations, and Data Assimilation. *J. Hydrometeorol.* **22**, 1065–1084 (2021).

195. Ahmed, M. *et al.* Integration of GRACE (Gravity Recovery and Climate Experiment) data with traditional data sets for a better understanding of the time-dependent water partitioning in African watersheds. *Geology* **39**, 479–482 (2011).

196. Iqbal, N., Hossain, F., Lee, H. & Akhter, G. Integrated groundwater resource management in Indus Basin using satellite gravimetry and physical modeling tools. *Environ. Monit. Assess.* **189**, 128 (2017).

197. Sun, A. Y. Predicting groundwater level changes using GRACE data. *Water Resour. Res.* **49**, 5900–5912 (2013).

198. National Research Council. *Earth science and applications from space: National imperatives for the next decade and beyond*. *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond* (C. (Available at, 2007). doi:10.17226/11820.

199. National Academies of Science, Engineering, and M. *Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space*. *Thriving on Our Changing Planet* (Thriving on our changing planet: A decadal strategy for Earth observation from space., DC: The National Academies Press, 2019). doi:10.17226/24938.

200. Han, S. C., Jekeli, C. & Shum, C. K. Time-variable aliasing effects of ocean tides, atmosphere, and continental water mass on monthly mean GRACE gravity field. *J. Geophys. Res. Solid Earth* **109**, (2004).

201. Bhanja, S. N. S. N. *et al.* Groundwater rejuvenation in parts of India influenced by water-policy change implementation. *Sci. Rep.* **7**, 1–7 (2017).

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Author Contributions

M.R. prepared the review article outline. M.R. and J.T.R. designed the figures and wrote the manuscript.

Competing Interest Declaration

The authors claim no competing financial or non-financial interests.

Additional Information

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Figure Captions

Figure 1. Inadequacy of in situ groundwater observation availability. Global map: locations of groundwater observation wells whose records are archived by the International Groundwater Resources Assessment Centre. Inset map: locations of the U.S. Geological Survey's Groundwater Climate Response Network wells.

Figure 2. Terrestrial Water Storage depletion in India. Groundwater withdrawals to support irrigated agriculture in a large region of northern India (corresponding to large rates of TWS decline indicated by warm colors in panel a) have caused TWS to be depleted over the past 20+ years (time series in panel b) as observed by the GRACE (blue) and GRACE-FO (dark yellow) satellite missions. Values are reported as equivalent height of water (cm) relative to the long-term mean.

Figure 3. Growth of GRACE hydrology publications. Yearly numbers of journal publications containing in their abstracts either "Gravity Recovery and Climate Experiment" or “GRACE satellite” and “water” or one of several other hydrology related terms. Source: Web of Science.

Figure 4. Global trends in terrestrial water storage. Mean rates of change of TWS (cm yr-1) based on GRACE and GRACE-FO observations from April 2002 to May 2022. The map was smoothed with a 150 km radius Gaussian filter for the purpose of visualization, but the base product has a native 3° resolution.

Figure 5. Global terrestrial water storage anomalies over time. Global average, non-seasonal terrestrial water storage anomalies from GRACE (blue) and GRACE-FO (dark yellow), in cm equivalent height of water, relative to a 2003-2020 mean baseline. Mascons containing TWS declines in Antarctica, Greenland, the Gulf Coast of Alaska, and polar islands associated with ice sheet and glacier losses were excluded from the average.

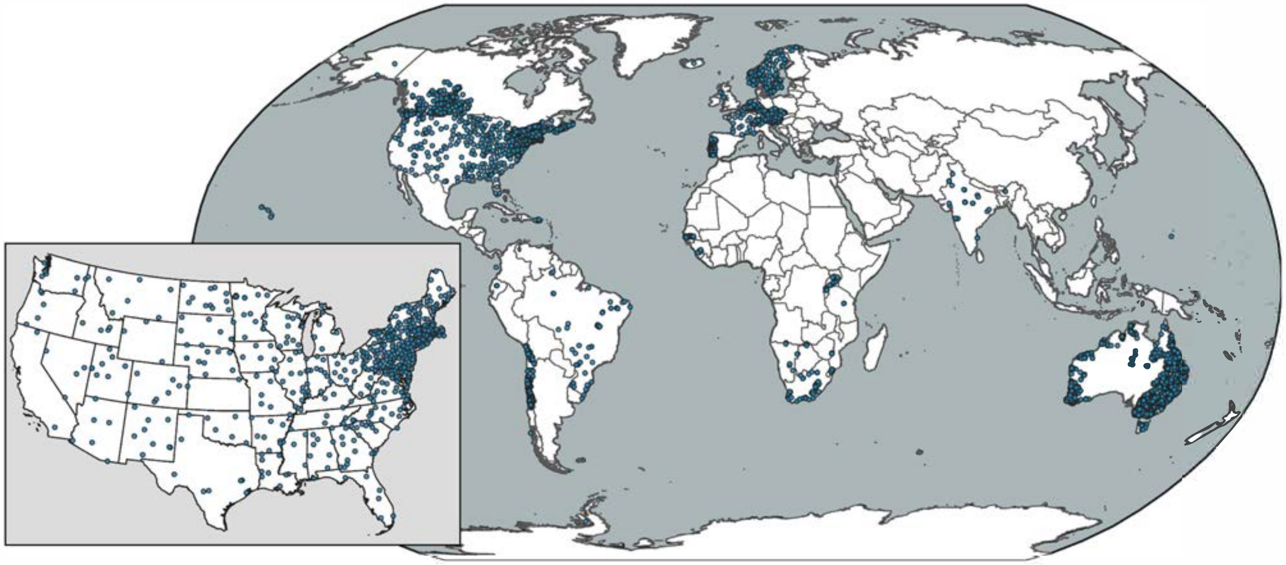
Figure 6. Global drought and wetness monitoring products. Wetness percentiles on 25 July 2022 (relative to the period 1948-2012) for (a) surface soil moisture, (b) root zone soil moisture, and (c) shallow groundwater, based on output from a GRACE and GRACE-FO data assimilating land surface model. As an example, a value of 5 indicates that the location was drier than present only 5% of the time in this week of the year during 1948-2012. The maps are generated weekly and made available from https://nasagrace.unl.edu/.

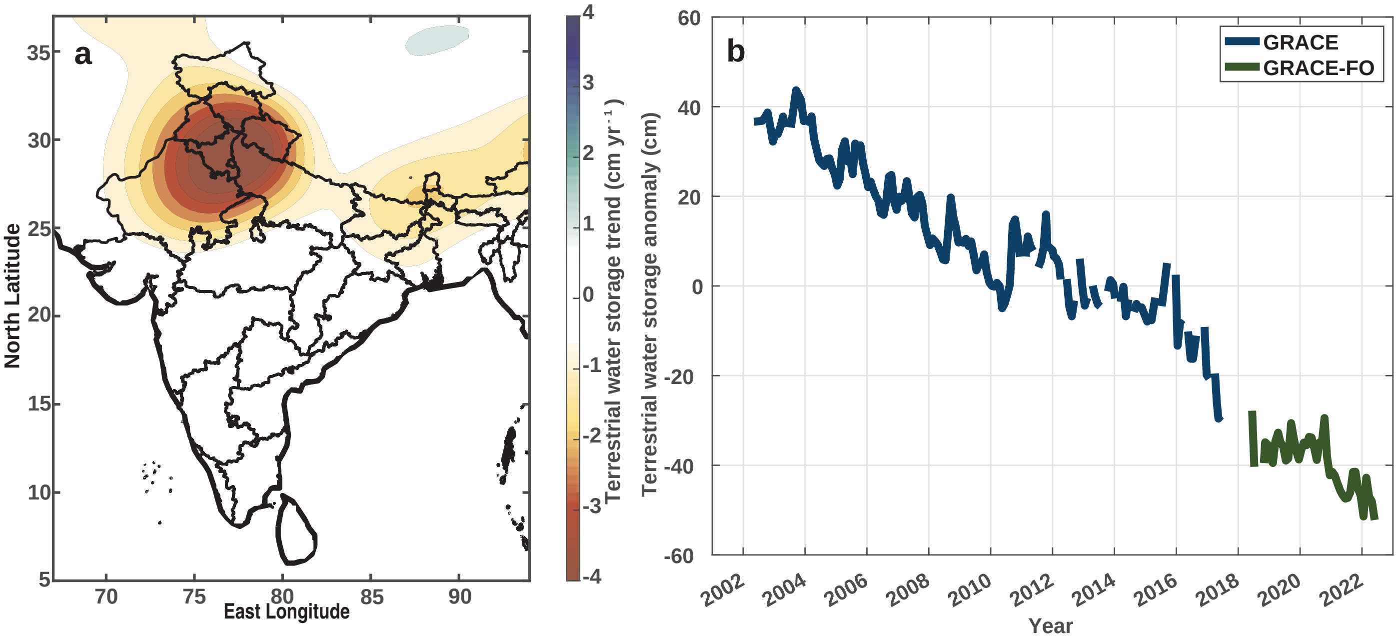
Methods

Figures 2, 4, and 5 were created using the Jet Propulsion Laboratory’s (JPL) monthly mass 3-degree gridded mascon RL06 version 02 dataset[61] from April 2003 to April 2022 (December 2021 in the case of Figure 5). For Figures 2a and 4, the data were smoothed using a 300 km Gaussian to improve the visualization. For Figure 2b, the data were averaged over a previously defined area of TWS decline in northern India[40] while simultaneously fitting a climatology and a trend to the timeseries at each pixel. For Figure 5, the data were averaged over the global land surface excluding Antarctica, Greenland, the Gulf Coast of Alaska, and polar islands, and the mean seasonal cycle was removed[128].

Data Availability

The well locations mapped in Figure 1 are available from the U.S. Geological Survey's Groundwater Water Climate Response Network website and the International Groundwater Resources Assessment Centre's website. The JPL RL06_v02 gridded monthly mass data used Figures 2, 4, and 5 is identical to that which is available from the NASA/JPL GRACE Tellus website[61]. Figure 3 was created from a citation report that searched for journal articles containing "GRACE satellite" or "Gravity Recovery and Climate Experiment" and one of nine hydrology-related terms, performed on the Web of Science website. Figure 6 was constructed from images available on the University of Nebraska-Lincoln National Drought Mitigation Center's NASA GRACE website[10,174].

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North Latitude
East Longitude
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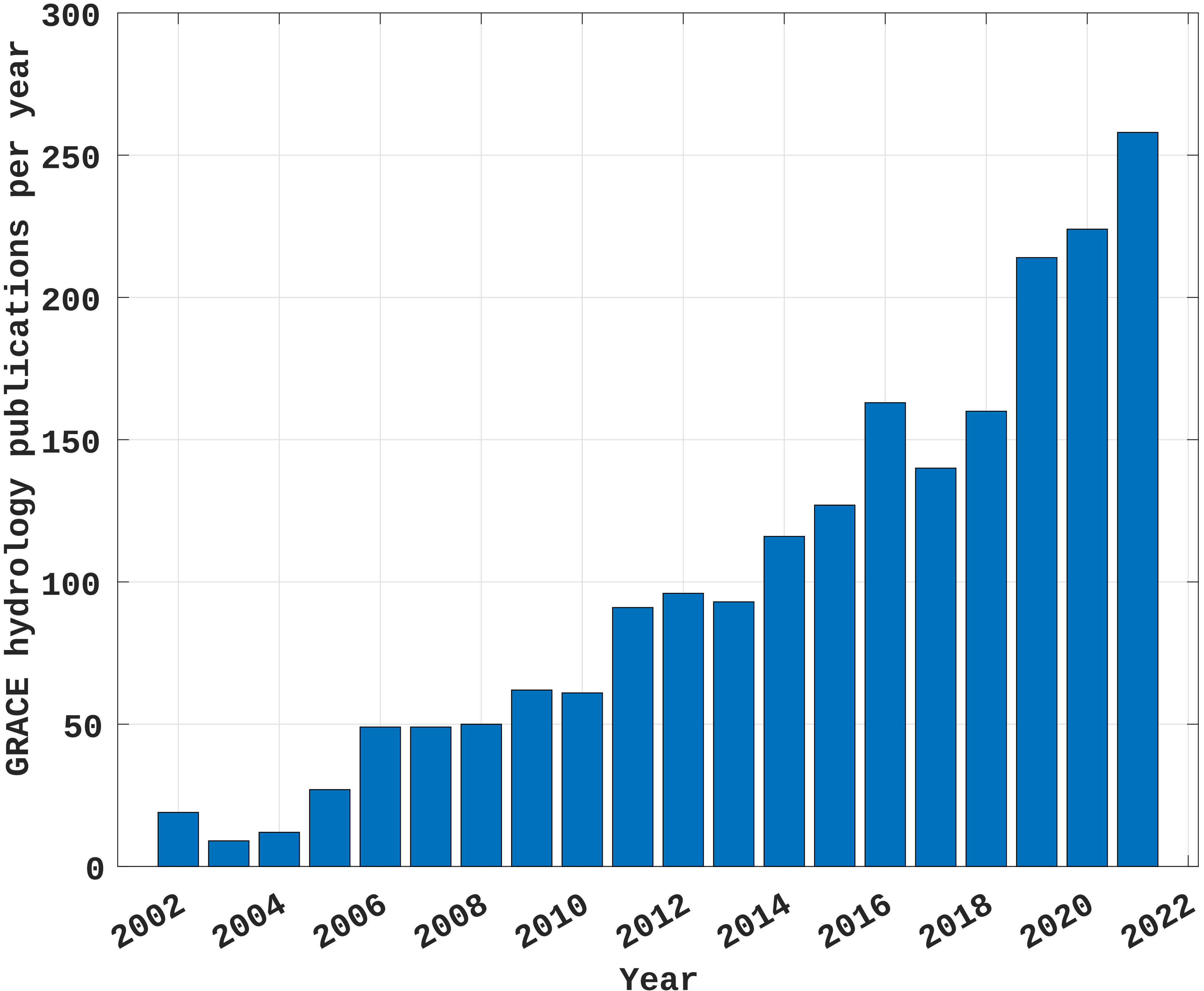
-1
-2
-3
-4
Terrestrial water storage trend (cm yr⁻¹)
b
GRACE
GRACE-FO
60
40
20
0
-20
-40
-60
Terrestrial water storage anomaly (cm)
2002
2004
2006
2008
2010
2012
2014
2016
2018
2020
2022
Year


GRACE hydrology publications per year
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300
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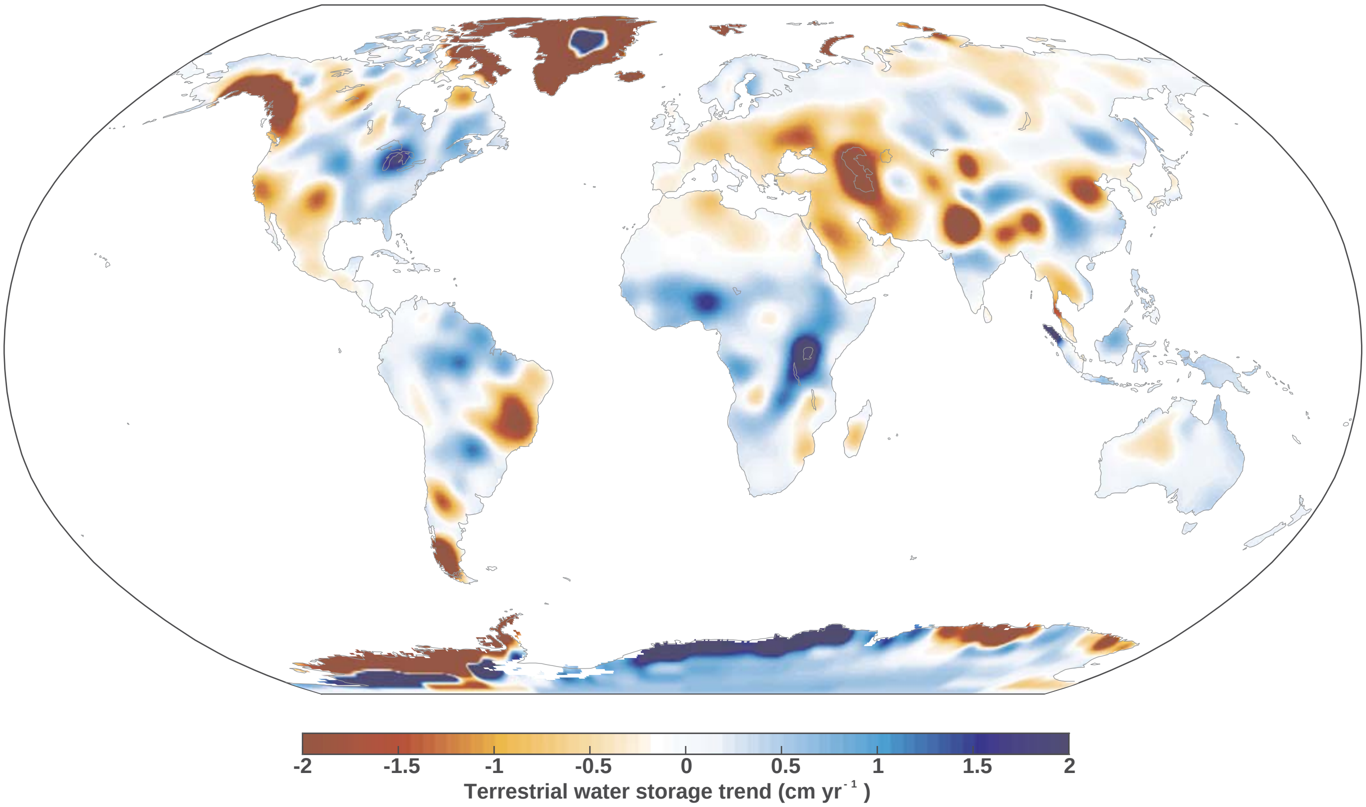
2022
Year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-0.5
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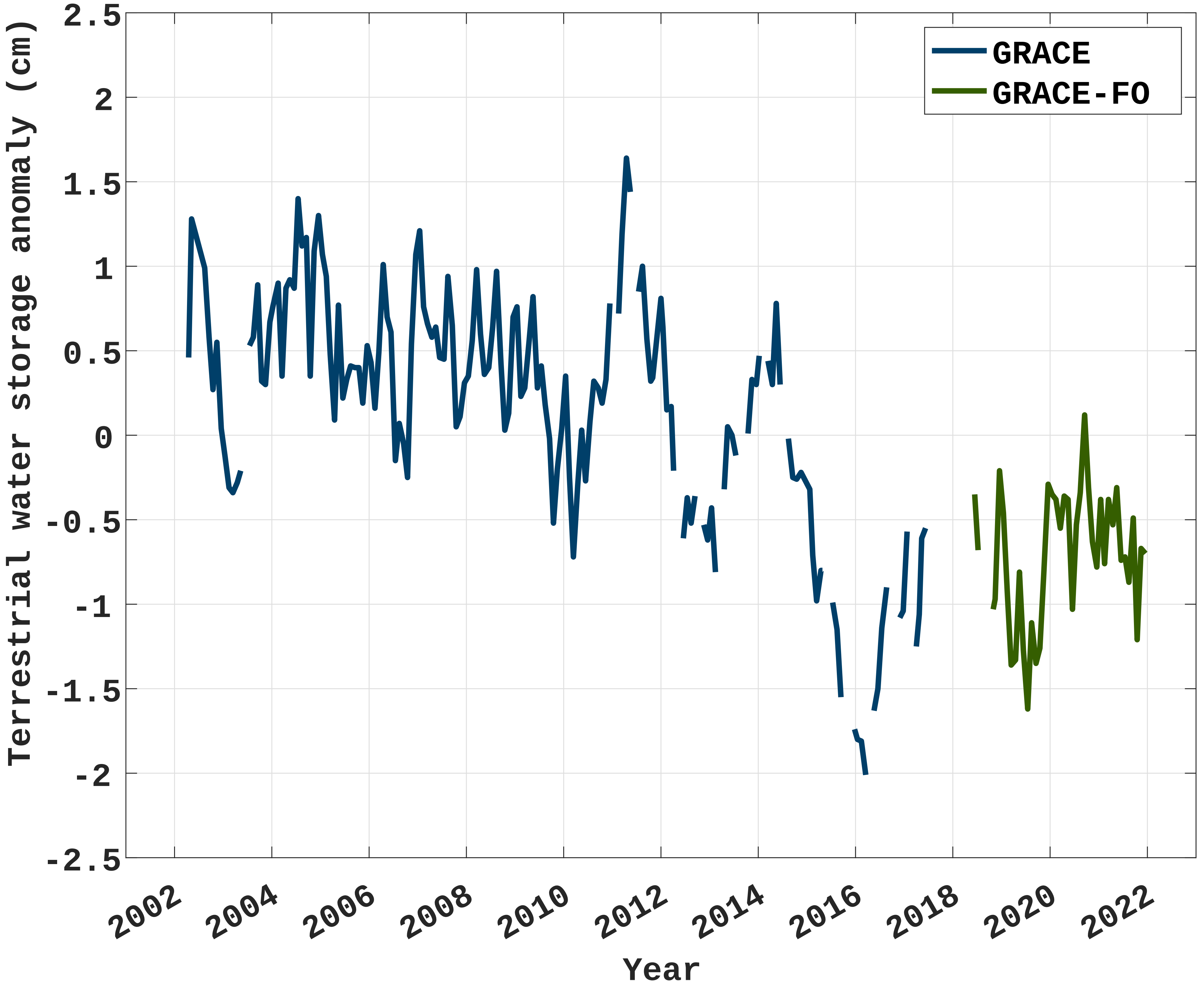
1
1.5
2
Terrestrial water storage trend (cm yr^{-1})


Terrestrial water storage anomaly (cm)
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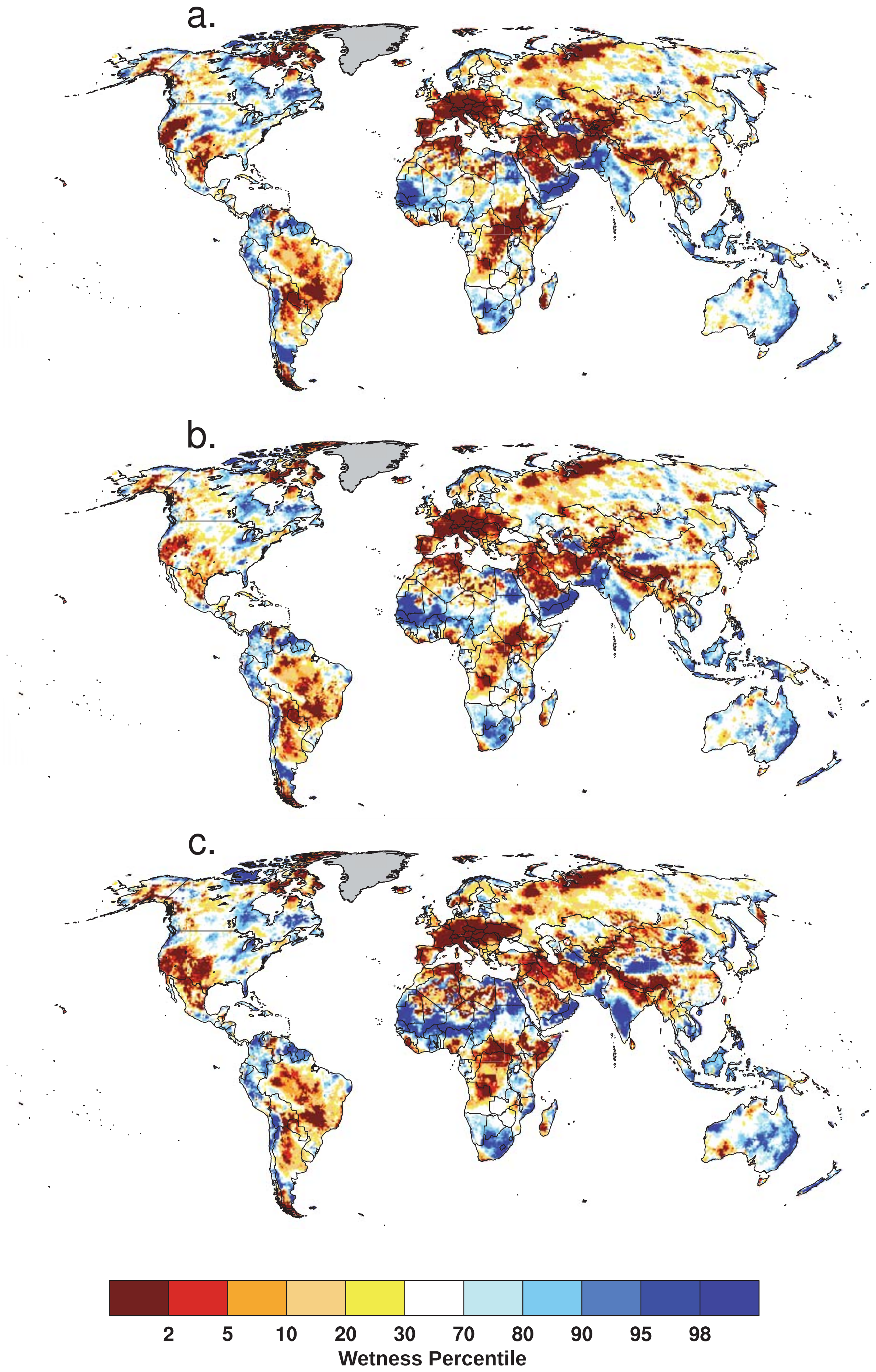
Year
GRACE
GRACE-FO


a.
b.
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2
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Wetness Percentile