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Contributions of GRACE to understanding climate change

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Author contributions
All authors contributed the writing and editing of the paper; Introduction (B.D.T., C. R., S.B., M.W. and I.S.), Ice Sheets and Glaciers (I.S., A.G. and I.V.), Terrestrial Water Storage (J.F., M.R., J.T.R, and S.S.), Sea-Level Change and Oceans Dynamics (D.C., F.L., C.B., H.D. and I.S.), Climate service applications (F.F., C.D., D.W. and M. R.) and Future of mass transport observations (B.D.T., F.L., M.W., F.F. and I.S.); overall editing & internal review E.R.I. and M.E.T; Box 1 (NASA/JPL, I. S.); Fig. 1 (H.S.), Fig. 2 (I.S.), Fig. 3 (I.S. and M.R.), Fig. 4 (D.C.) and Fig. 5 (M.R.). I.S. handled implementing the comments of three anonymous reviewers.

Competing financial interests
The authors declare no competing financial interests.

Additional information
The GRACE data used in this paper are freely available from the websites of the Science Data Systems Centers. The GRACE gravity field data products (Level 2 data) as well as supporting documentation may be accessed at http://podaac.jpl.nasa.gov/grace and http://isdc.gfz-potsdam.de/grace. User-friendly, gridded maps of mass change (Level 3 data) are available from https://grace.jpl.nasa.gov/ (JPL), http://www2.csr.utexas.edu/grace/ (CSR) and http://gravis.gfz-potsdam.de/home (GFZ). GRACE Follow-On data will be provided through the same portals once available. The reader is encouraged to use all data sets available.
A list of GRACE related publications is available under https://grace.jpl.nasa.gov/publications/ and https://www.gfz-potsdam.de/en/grace/. Videos of the GRACE-Follow On pre-launch briefing and the launch is available under https://www.youtube.com/watch?v=qYJt-6uHVcM and https://www.youtube.com/watch?v=I_0GgKfwCSk, respectively (both sources last accessed September 15, 2018).
The figures and updates to published values presented in this paper are based on the following data sets and processing.
Fig. 1. Global representation of the trends and variability in ice and water mass recovered by GRACE within 15 years. The plot is based on the 1-arc degree mascon solution by CSR RL05M[4]. A linear trend, annual and semi-annual model is fit to each pixel for the entire mission duration, assuming temporally uniform uncertainties. The temporal linear part of that fit is mapped in a and b the standard deviation shown in c is calculated after the removal of the temporal linear trend. The trends have been corrected for glacial-isostatic adjustment using the model of Peltier et al.[12] computed by Wahr(should this be Wahr, rather than A?) et al.[124].
Fig. 2 and *Ice sheets and glaciers*. Time series of ice sheet mass change are based on GRACE Level 2 data of CSR RL05 obtained with an inversion approach based on forward modelling [18,125]. For Antarctica the GIA correction is AGE1[125] (ca. 48 ± 28 Gt/yr), for Greenland it is GGG1D [126](ca. 17 Gt/yr).Uncertainties are calculated based on the formal monthly uncertainties provided by the processing centers, scaled by the RMS residual after subtracting temporal fluctuations longer than three months. Temporal linear trends for the entire GRACE period are estimated using uncertainty-weighted least squares. Annual balances are estimated using an unweighted piecewise linear model with breakpoints on January 1st. Uncertainties for the temporal linear trends and the annual balances are obtained by error propagation.
Fig. 3 and *Terrestrial water storage*. Time series of zonal mean of the terrestrial water storage anomalies in mid latitudes are based on CSR RL05M Mascons[4]. Uncertainties are calculated as RMS residual of the zonal mean after subtracting the linear trend, offset, annual and sub-annual temporal components and fluctuations shorter than five months. The RMS uncertainty (ca. 2 cm equivalent water height along the latitude, 2-SD) is then used to scale the formal, time-dependent uncertainties provided by the processing center CSR. Then the temporal model is refit and propagated uncertainties are calculated. The annual amplitude is shown on the right part of the figure. The anomalies shown in the left part of the figure are the residuals with respect to the fitted temporal model.
Fig. 4 and *Sea-level change and ocean dynamics*. Global Mean Sea-level (GMSL) and its components. GSML from altimetry is based on data provided by the University of Colorado (http://sealevel/colorado.edu) [87]. Ocean mass changes are derived from GRACE Level 2 data of three processing centers (CSR RL05, JPL RL05 and GFZ RL05) using an averaging kernel method and scaling[98], available from the University of South Florida (http://http://xena.marine.usf.edu/~chambers/SatLab/Home.html). Global mean steric sea level anomalies are based on Argo data provided by NOAA (https://www.nodc.noaa.gov/OC5/3M_HEAT_CONTENT/basin_fsl_data.html). To unify the temporal sampling, we adopt three-month (seasonal) averages, which is limited by sampling period of the Argo data obtained from NOAA. These were computed after first fitting and removing annual and semi-annual sinusoids from the altimetry and GRACE monthly averages. An annual and semi-annual sinusoid was also estimated and removed from the 3month thermometric time-series for consistency. The correction for glacial-isostatic adjustment to the GRACE data is based on the ICE5G ice model[12], computed by Wahr et al.[124]. Further details can be found in Chambers et al. 2017[92].

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Preface

Time-resolved satellite gravimetry has revolutionized understanding of mass transport in the Earth system. Since 2002, the Gravity Recovery and Climate Experiment (GRACE) has enabled monitoring of the terrestrial water cycle, ice sheet and glacier mass balance, sea level change and ocean bottom pressure variations and understanding responses to changes in the global climate system. Initially a pioneering experiment of geodesy, the time-variable observations have matured into reliable mass transport products, allowing assessment and forecast of a number of important climate trends and improve service applications such as the U.S. Drought Monitor. With the successful launch of the GRACE Follow-On mission, a multi decadal record of mass variability in the Earth system is within reach.

Global observations of water and ice mass redistribution in the Earth system at monthly to decadal time scales are critical for understanding the climate system and for investigating its change. Together with other observations, they provide information on Earth's energy storage, ocean heat content, land surface water storage and ice sheet response to global warming. Interactions between the different climate system components involve mass variations in continental surface and sub-surface water storage (rivers, lakes, ground water, snow cover and polar ice sheets and mountain glaciers), as well as the mass redistribution within and between ocean and atmosphere. These mass movements are inherent to the evolution of droughts, floods, large-scale ocean currents, ice sheets and glacier change and sea level rise. Launched in 2002, the Gravity Recovery and Climate Experiment (GRACE) satellite mission[1] added a unique observable to the existing suite of Earth observations: time-resolved gravity measurements of global mass redistribution, a fundamental building block crucial to understanding the complex interactions and transitions involved in today's changing climate.

Measurement principle of GRACE mission

The GRACE mission was launched on March 17, 2002 in a collaboration between the National Aeronautics and Space Administration (NASA) and the German Aerospace Center (DLR), in response to recommendations resulting from decades of study[2,3]. The primary objective of GRACE was to apply monthly-aggregated measurements of the Earth's gravity field to track mass changes in the hydrosphere, cryosphere and oceans. In contrast to single satellite approaches with one dedicated sensor, GRACE uses a constellation of two satellites, orbiting one behind the other, featuring a suite of measurement systems (see Box 1). The fundamental measurement is derived from micron level tracking of the satellite-to-satellite distance, which varies due to individual gravitational attractions on the satellites as they overfly the Earth's surface.

After a month, the collected measurements allow an estimate of a global spherical harmonic model of the Earth's gravity field, which is then used to estimate mass changes on the Earth surface. Processing choices made by the Science Data System (SDS) centers and the users can lead to differences between mass time series from GRACE[4–6]. To ease the use of GRACE data in diverse Earth science applications, the SDS centers now provide quality-controlled gridded and basin-integrated mass change products (Level 3 data) (Additional information).

Success of a pioneering mission

The GRACE science mission ended on October 12, 2017 due to battery failure, after providing paradigm-shifting near-continuous measurements for over 15 years – ten years longer than the nominal mission lifetime. The mission data record provides 163 monthly solutions of the time varying gravity field out of 187 months possible, along with a highly accurate mean field. For the first time, GRACE enabled the quantification of mass trends and mass fluctuations of terrestrial water storage, continental aquifers, and glaciers and ice sheets (Fig. 1), and enlightened our view of large-scale mass redistribution associated with glacial isostatic adjustment and earthquakes. With this data, GRACE contributed to quantifying global and regional changes, from both natural variability and anthropogenic influence, in the hydrological cycle, ice sheet mass balance, ocean circulation and sea-level change. The following review highlights some representative breakthroughs, selected from numerous scientific publications based on GRACE observations in the fields of cryosphere, hydrology and ocean sciences, as well as in service applications.

Ice sheets and glaciers

Today's changes in continental ice mass sensitively indicate active transitions in the atmosphere and oceans that have, in the past centuries to millennia, sustained ice sheets and glaciers as stable geographic features. As the oceans and atmosphere have warmed over the past decades, ice sheets and glaciers have experienced increased melting[7]. Outlet glaciers that terminate in the ocean and that have experienced increased subaqueous melting have sped up (increased rates of discharge) in response to reduced buttressing at glacier fronts. These changing oceanic and atmospheric conditions have led to sharp increases in rates of mass loss from nearly all glacierized regions on Earth[8,9], causing more than half of the global mean sea-level rise[10].

Without GRACE, satellite observations are restricted to measuring changes of the ice sheet surface with radar (ERS-1/2, Envisat, CryoSat-2) and laser (ICESat 1/2) altimetry, which are influenced by changes in the surface properties and firn compaction and provide only indirect measurements of the net mass change (precipitation – evaporation – runoff – ice discharge). Alternatively, the components of the net mass change can be addressed by estimating precipitation and runoff with regional climate models and measuring discharge with Interferometric Synthetic Aperture Radar (InSAR)[11] and optical feature/speckle tracking. GRACE provided the first direct measurement of ice mass change. While altimetry estimates are restricted to multi-annual trends of height change due to sampling issues and their sensitivity to snow at the ice sheet surface, GRACE-derived ice sheet and glacier mass changes are obtained with an unprecedented temporal resolution of one month. The long-term mass trends for the ice sheets derived from GRACE are less influenced by sampling issues or unknown surface properties than the other methods[9].. However, particularly for Antarctica, problems remain in correcting for often poorly known mass redistribution related glacial isostatic adjustment (GIA) -- a slow rebound of the Earth's underlying lithosphere and mantle following readjustment from past ice sheet retreat[12,13].

Mass balance of Greenland and Antarctica

Within two years after mission launch, GRACE data analysis revealed a clear signal of ice-mass loss in Greenland and Antarctica[14,15]. Mass trends became more robust and accurate with extension of the mission measurement period to longer than five years. Increased quality of the gravity field solutions themselves also contributed to this robustness[16]. Further GRACE analysis isolated the largest mass imbalance in southeast Greenland[5] and the Amundsen Sea Embayment, West Antarctica[17]. Over the GRACE life span, the mass loss in Greenland encompassed the entire margin of the ice sheet. In Antarctica, the Amundsen Sea Embayment of the ice sheet dominates the mass loss in response to changed oceanic conditions (Fig. 1).

The Greenland GRACE time series are in general accord with independent estimates derived from satellite altimetry and the component approach. This allowed the inference that 60% of the total mass loss is due to enhanced melt production in response to Arctic warming trends, while 40% is due to an increase in ice-dynamic outflow[7,11,18]. With the increasing length of the GRACE time series, acceleration of mass loss was inferred to be statistically significant for some regions of both ice sheets[19]. However, although an acceleration of mass loss is expected as the ice sheets adapt to increasing global temperatures, Wouters et al.[27] showed that natural variability of the ice sheet mass can lead to a misinterpretation of the accelerations deduced from satellite records covering one or two decades. Recent years have shown reduced annual mass loss of the Greenland ice sheet (Fig. 2), decreasing the values of acceleration detected through the year 2012[20]. For many regions, the significance and cause of the variations in the mass change are still are matter of debate.

As an update to previous studies, we note that during the period April 2002 to June 2017, Greenland showed an negative average annual balance of −258 ± 26 Gt/yr (2-SD; propagated and GIA uncertainty), with a measured year-to-year variability of ±137 Gt/yr (±53 % w.r.t. the average). For the Antarctic ice sheet, the average annual mass balance determined by GRACE is −137 ± 41 Gt/yr (2-SD; propagated and GIA uncertainty), with a considerably larger year-to-year variability of ±208 Gt/yr (Fig. 2). The largest ice-mass loss is caused by a speed-up of glaciers feeding into the Amundsen Sea Embayment, for which GRACE recorded mass changes of – 120 ± 14 Gt/yr (2-SD) with an acceleration of – 7 ± 2 Gt/yr^2 (2-SD; Fig. 2).

Mass signatures of changes in global atmospheric circulation

Apart from the long-term trends, GRACE enabled a direct relation of inter-annual fluctuations in the mass of the ice sheets and the global variability in atmospheric circulation patterns. For example, the anomalous melt event in Greenland in 2012 (Fig. 2) was driven by the advection of warm air from the mid-latitudes due to strong atmospheric blocking conditions over Greenland[21]. GRACE showed that estimates of melt-enhanced mass loss were double in 2012 (−543 ± 27 Gt/yr, 2-SD), compared to the average for 2003–2011 (Fig. 2).

It has also been shown that West Antarctic accumulation fluctuations from GRACE correlate well with El Niño Southern Oscillation (ENSO) modulated moisture flux to the continent[22]. Atmospheric pressure patterns create southward moisture transport that delivered snowfalls of 300 Gt in 2009 and 2011 along the Atlantic Sector of the Antarctic ice sheet[29]. With the extended mission data, Mémin et al.[23] used GRACE measurements to identify a periodic signal of about four to six years in the coastal precipitation, connected to the Antarctic Circumpolar Wave and ENSO. For the cold regions of the Earth, GRACE measurements of large-scale accumulation variations are important for validating the net continental balance of moisture flux in weather and climate models[24], which otherwise are largely dependent on sparse and expensive in-situ networks.

Monitoring glacier fluctuations and trends with global coverage

GRACE has proven to be an invaluable tool for the challenging measurement of mass trends of glacier regions outside of Greenland and Antarctica. Even though glaciers are highly localized features, the imprint of their collective imbalance is well detected in the regional gravity field. Advantageous for recovering these small-scale features is the higher spatial resolution of GRACE in high latitudes which is possible with denser ground track spacing.

Thus, GRACE helped identify a large bias in the *in situ* glacier-monitoring network, which traditionally aggregate individual measurements to estimate glacier contributions to sea level rise[8]. Furthermore it has been shown that GRACE-derived trends in glacier mass are in accord with satellite laser altimetry[25–27] and surface mass balance models[26,28]. Regionally, trends were successfully quantified for Alaska[29,30], Patagonia[31,32], Iceland, Canadian Arctic and Svalbard[16], and later for all glaciated regions[8,33].

Terrestrial water storage

Among the most impactful contributions of the GRACE mission has been in the unveiling of Earth's changing freshwater landscape, which has profound implications for water, food and human security. Global estimates of GRACE trends, such as the one shown in Fig. 1 suggest increasing water storage in high and low latitudes (wetting), with decreasing storage in mid-latitudes (drying)[34,35]. Though the GRACE record is relatively short, this observation of large-scale changes in the global hydrological cycle has been an important early confirmation of the changes predicted by climate models through the 21st century[36,37]. Nevertheless, projections of future water availability remain quite model dependent and require a systematic evaluation of soil moisture trends from models, such as Coupled Model Intercomparison Project Phase 5 (CMIP5), with GRACE and other measurements. Wetting in high and low latitudes, drying mid-latitudes, and falling water tables in mid-latitude aquifers[38], all indicate potential changes in future access to fresh water, with implications for the sustainability of water for humane consumption, irrigation and food security and industrial uses. Of the world's 37 largest aquifer systems, 13 were found to be suffering critical depletion during the GRACE observational period[38].

Terrestrial water storage and climate variability

Measurements of continental water mass change from GRACE have been examined in the context of climate variability in several recent studies[34,35,39–42]. As an example, Fig. 3 (right panel) shows that the GRACE-derived zonal mean of the annual amplitude of the terrestrial water storage (TWS) – that is the sum of snow, ice, surface water, soil moisture and groundwater – ranges between ± 17 cm equivalent water height. As indicated in Fig. 3, climate driven perturbations of annual TWS variation are often associated with flood[43,44] and drought[45–47] years in low to mid-latitudes. GRACE TWS data also helped to establish the current state of the water cycle[48] so that ongoing and future hydro-climatic change can be detected. Further, since 2011 such zonal mean water mass plots have been included in annual climate reports as indicators of TWS and groundwater variability[49].

The importance of terrestrial water storage variability to understanding climate is also exemplified by the fact that the global sea level record contains substantial annual variability around an underlying secular trend. Natural variability in TWS can be a significant source or sink in the global ocean mass budget, of similar order to the Greenland Ice Sheet, which contributed on average in the GRACE period 0.7 mm each year to sea-level rise (see Fig. 2). The fluctuations in TWS influences on sea level range from interannual to decadal time scales[50], masking or augmenting the underlying trend[20,34], or even reversing sign of the rate of sea-level rise when more water is stored on the continents[44]. This interplay between land

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water storage and sea level is of critical importance in interpreting the global sea level record.

A recent study correlated that annual variations in TWS with the rate of carbon uptake by the land[51]. The study concluded that the growth rate of atmospheric carbon dioxide is faster during dry years than during wet years, and that terrestrial water storage is a better indicator of these rates than precipitation. This fascinating development further demonstrates the interdisciplinary utility of the GRACE measurements and suggests pathways for the improvement of climate models.

Detecting trends of anthropogenic groundwater depletion

Embedded within the drying mid-latitudes, hot spots for water loss during the GRACE mission emerge (Fig. 1), many of which correspond to the world's major aquifer systems. GRACE-derived changes have enabled large-scale water balance closure[48,52,53] and the first-ever estimates of groundwater storage changes from space[54,55]. These studies confirm excessive rates of groundwater depletion from individual aquifers[56–61] around the world[35,38,62,63]. Rodell et al.[35] provide a comprehensive attribution of all the major GRACE-observed hydrological trends to natural variations, anthropogenic climate change, or to human water management practices.

Hydrological flux estimation and climate model improvement

TWS change, precipitation, runoff, and evapotranspiration are all essential elements of the water cycle and are difficult to quantify, particularly at a global scale. Applying mass conservation, GRACE measurement of the TWS change allows the derivation of basin-scale flux estimates of evapotranspiration[52,64], river discharge[65] and precipitation minus evapotranspiration[66]. In cold mountainous regions, monthly-mean precipitation estimates based on GRACE appear to be advantageous, particularly in the winter months when uncertainties in conventional hydrometeorological observing systems are large due to the presence of light rain, snow, and mixed-phase precipitation [24]. TWS changes from GRACE together with meteorological data are critical for characterizing streamflow in ungauged river basins[67], or for estimating important land-atmosphere interactions.

GRACE trend and amplitude data can be used to validate[68] or calibrate[69] the land component of global climate models (i.e. land surface model) and evaluate their performance. For example, GRACE measurements helped to identify model shortcomings[42,70], and to refine both model structural elements and parameters[68,71,72]. GRACE terrestrial water storage information now provides a new assimilation component for land-surface model simulation[5,73–78].

The 15-year GRACE record yields insight into the normal range of wet-to-dry-season variation, as well as into excursions from normal wet conditions [43,79] and normal dry conditions[47,80]. The length of the available time-series reveals a detailed spatial picture of the response of TWS variations to atmospheric energy and water fluxes at sub-seasonal to inter-annual time-scales[40] and to natural climatic oscillations such as El Niño and La

Niña[81,82]. Even the estimation of probabilistic return frequencies of regional hydrometeorological extremes is possible[83].

Including GRACE TWS information in a simple model of flood potential can increase early warning lead times by as much as an entire season or more[79]. GRACE-derived drought indices result in longer estimates of drought persistence, relative to indices based only on meteorological fields and surface variables, such as temperature, precipitation and stream flow[47,80]. GRACE-based TWS have contributed to the evaluation of different development stages of a global coupled Earth System Model designed to facilitate operational climate predictions at time-scales from several months to up to ten years[84].

Sea-Level change and oceans dynamics

Sea-level rise is a profound and direct consequence of a warming climate: within this century global mean sea-level rise may accelerate to 10 mm/yr[85] a rate unprecedented during the last 5000 years[86]. Different physical processes cause this increase: the ocean warming leads to volumetric expansion, and continental ice loss causes mass inflow to the ocean. Since 1993, satellite altimetry - primarily the TOPEX/Poseidon and Jason missions - has provided global measurements of the sea surface height, indicating a global average rate of sea level rise of 3.1 mm/yr in the past 25 years[20,87] (1993 to 2017). With GRACE and autonomous Argo floats[88], it is possible to directly measure the individual steric and mass change components, respectively, and to assess the sea-level budget with independent measurements on the global scale. By placing a constraint on ocean mass change, GRACE can indirectly constrain the estimate of Earth’s energy imbalance, which is a fundamental global metric of climate change[89].

Global mean sea-level budget

Prior to GRACE, the mass component of the sea level budget was estimated from a residual between altimeter (total) sea level and thermal expansion measurements[90]. Despite higher noise level in the early data, Chambers et al.[91] estimated ocean mass changes from GRACE. Today, GRACE is used routinely together with ocean hydrographic profiles from Argo for examining the global sea level budget[20], enhancing our understanding of how the contributions are changing over time. Fig. 4 shows that from 2005 to 2017 the total sea level trend of 3.8 ± 0.7 mm/yr measured by altimetry results from a 2.5 ± 0.4 mm/yr mass inflow (GRACE) and 1.1± 0.2 mm/yr volumetric expansion (Argo) (update from Chambers et al.[92]; see Additional information). However, some discrepancies between the different GRACE products exist, which are discussed in more detail in a recent assessment of the World Climate Research Programme[20].

Resolving long-term accelerations in the data is highly relevant for validating sea-level projections, but requires sufficient knowledge for correction of inter-annual fluctuations arising from natural climate modes. For example, multi-year variations are visible in the altimeter record that are statistically related to ENSO (Fig. 4), but could not be clearly attributed to either heating or ocean mass changes[93]. GRACE provided accurate estimates of the part of the variability caused by the relocation of ocean mass, along with the identification of its continental source region[44]. Fasullo et al. [94] took this investigation further and used ancillary data to explain how the mass exchange is related to ENSO and other atmospheric drivers, linking the exchanges to the characteristic time scales of terrestrial watersheds.

Ocean heat content and deep ocean warming

The heat uptake by the ocean is the largest sink for the Earth's energy increase from rising CO_2 concentrations[89]. Temperature profiles by Argo floats provide a reliable estimate of the ocean heat continent[95]; however, the Argo data coverage excludes ocean depths below 2000 m, the marginal seas and is sparse under sea ice and ice shelves. Together with other observations, GRACE is able to provide an estimate of the ocean heat budget in an indirect approach. GRACE, altimetry and Argo indicate that most of the warming occurs in the upper 2000 m of the ocean on a global scale, leading to a thermosteric sea-level rise of 0.9±0.15 mm/yr between 2005 and 2013[96]. The trends at ocean depths below 2000 m are inferred by subtracting the sum of the total GRACE mass trends and Argo warming trends above 2000 m from the altimeter measurements of total sea-level change. The result showed only small changes on a global scale[96] that were not statistically significant. For the full water column, the study relates the global change of the ocean heat content to an energy imbalance of 0.64 ± 0.44 W m^{-2}.

Closing the sea-level budget regionally remains challenging, and even more so inferring deep-ocean warming trends. The subtropical South Pacific, however, is an example, where the indirect method is confirmed with sparse in situ observations. There, observations indicate a significant heat uptake in the depths below 2000 m[97], attributed to long-term changes in atmospheric circulation driving the deep-reaching circulation[97]. To place tighter constraints on the deep ocean warming will require spatiotemporally improved observations; such as more accurate gravity fields, improved altimetry estimates near the coast and in polar regions, Argo measurements of deep ocean and in ice regions, and improved estimates of glacial-isostatic adjustment.

Ocean dynamics and overturning circulation

Over the oceans, GRACE measures changes in the mass of the total water column exerted on the ocean floor, the ocean bottom pressure (OBP). From spatial OBP gradients, geostrophic bottom currents can be derived where very few in-situ bottom pressure observations exist. In addition, in-situ sensors cannot provide reliable long-term observations due to chronic sensor drift. GRACE has overcome this severe spatial sampling and temporal resolution problem. The data have been used to infer large-scale oceanic transports on a global, continuous, and month-to-month basis[98]. This is useful particularly in remote areas like the Southern Ocean, where in-situ data are extremely sparse and often limited to a few ship transects or repeat-measurements at single locations like the Drake Passage. As an example, for the Antarctic Circumpolar Current (ACC), bottom currents derived from GRACE were used to estimate the barotropic transport variations of the ACC, which varies significantly on annual to interannual time scales[99,100]. High resolution models of the ACC, in turn, demonstrate the role of the current in modulating melting of West Antarctic ice shelves through Circumpolar Deep Water (CDW) intruding onto the Antarctic continental shelves[101].

GRACE is particularly important for Arctic Ocean considerations, where perpetual sea-ice cover limits both the sampling of the sea-surface heights with altimeters and the use of Argo floats. In addition, altimetry satellites are often placed into inclined orbits, typically lacking coverage higher than latitude 66°. OBP from GRACE together with ocean modelling showed that wintertime mass increase in the Arctic Ocean is mainly a consequence of southerly winds through Fram Strait, and to a lesser extent through Bering Strait, causing northward geostrophic current anomalies[102]. Moreover, GRACE and ocean modelling showed that non-seasonal mass variations in the Arctic are an effect of the wind-driven redistribution of water, and not caused by modulations in fresh water flux[103].

In the northwestern part of the Pacific, GRACE allowed the inference of barotropic variations of large-scale oceanic gyre circulations, which act with periods of days to several years [104,105] in response to changes in the surface wind stress over the whole North Pacific Region[106]. The results helped to improve the representation of the high-frequency general ocean circulation in global numerical models that are also used as background information in the GRACE gravity field determination [107]. Recent resolution improvements of the GRACE-based bottom pressure estimates even allowed the characterization of the spin-up and slow-down of the much smaller Argentine Gyre, which is energized by interactions between the mean flow of the ACC and the local meso-scale eddy field[108].

The Atlantic Meridional Overturning Circulation (AMOC) is a major feature of Earth's climate system, and is essential for Earth's northward ocean heat transport. It also has a strong bottom current associated with the deep return flow of North Atlantic Deep Water that provides an accurate measure of the overall AMOC transport. Landerer et al.[109] have recently demonstrated that interannual fluctuations in this lower limb of the AMOC can be derived from GRACE-based OBP variations. This opens the prospect for using satellite gravimeter observations for monitoring this important current feature on a broader scale and provide crucial information on its long-term evolution.

Climate service applications

Apart from improving our understanding of the climate system components, GRACE time series of mass storage changes have been used to support an operational climate service. The limitation of the coarse spatial and temporal resolution of the GRACE data for agricultural and societal needs can be overcome by data assimilation into models. Recently, progress has been made in shortening the time lag of the availability of GRACE data to near-real time, breaking ground for new climate forecast services.

Operational drought monitoring

Drought monitoring tools are highly dependent on the availability and quality of precipitation, streamflow, and other observations and indicators of water availability. For example, the premier drought-monitoring tool in the U.S. is the U.S. Drought Monitor (USDM; http://drought.unl.edu/), which provides weekly maps of drought conditions based on a synthesis of in situ data, remote sensing products, and reports from state climatologists and other local experts[110]. Initially the USDM incorporated almost no information on groundwater or terrestrial water storage and only modelled estimates of soil moisture. In 2011, NASA scientists began to deliver wetness/drought indicators for shallow groundwater and surface and root zone soil moisture based on the assimilation of GRACE terrestrial water storage data into a land surface model[80]. Integration of GRACE TWS data and other observations within a land data assimilation system has been shown to produce significant improvement in the accuracy of the results. In addition, the assimilation takes advantage of the higher resolutions and increased timeliness of the meteorological fields and model to enable spatial, temporal, and vertical downscaling of GRACE TWS data[43,111]. Gridded maps are now routinely produced at 0.125° within 24 hours of real time for operational drought monitoring.

Flood forecasting developments

The use of gravity to detect water saturated storage conditions in soils has led to an application of GRACE in the monitoring of regional "flood potential"[43,79,111]. To be most effective, flood forecasting systems require near-real time data to estimate the probability of flood events and to predict their evolution for the application in risk and emergency management. The European Union funded European Gravity Service for Improved Emergency Management (EGSIEM) project[112] has developed such daily near real-time gravity products, along with GRACE-based wetness indicators. Operational test runs were performed between April and June 2017 within DLŔs Center for Satellite-based Crisis Information, complemented by hindcast experiments of historical flood events. The historical flood analysis demonstrated a significant improvement in the early flood warning using GRACE-derived wetness indicators. Knowledge of the preconditioning of elevated water storage markedly increased the lead times of early flood warning by up to six weeks prior to peak flow, e.g., for the flooding of the Mississippi in 2011[79] and the Danube in 2006 and 2010[113]. The GRACE-derived wetness indicators were also included in a pre-operational way in the Forecast Viewer of the Global Flood Awareness System (GloFAS; http://www.globalfloods.eu/), jointly developed by the European Commission and the European Centre for Medium-Range Weather Forecasts (ECMWF). Recent studies have also demonstrated the effectiveness of assimilated GRACE TWS measurements for seasonal wildfire prediction in the United States[114].

Continuation of the mass transport observations

As the GRACE mission results became accepted, the user community strongly recommended the continuation of the mass transport time series[115,116], prioritizing improvements of the satellites and prolonging of the measurement over revolutionizing the mission concept with the risk of multi-year gaps in the temporal coverage. NASA and GFZ responded to this user request in 2010, and on May 22, 2018, the successor mission GRACE-FO (Follow-On) was successfully launched from Vandenberg Airforce Base, California, USA on a Space-X Falcon 9 rocket (https://youtu.be/Tvdz5yFSwCY, last accessed 4 September 2018).

The GRACE-Follow On Mission

While the nominal mission lifetime is again five years, additional operation lifetime is expected based on satellite and instrument design and the influence of solar activity on the apmospheric induced decay of the spacecraft. During a significant portion of the GRACE mission, the solar flux was very benign – a condition that may not repeat itself in the coming years of GRACE-FO.

The GRACE-FO satellites are equipped with evolved versions of GRACE instrumentation (KBR, GPS, star camera, accelerometer). But the mission also features a novel Laser Ranging Interferometer (LRI)[117], measuring the satellite-to-satellite distance in parallel with the KBR instrument. The LRI has a design precision that is approximately 26 times better than the KBR on GRACE[117] - even though the quality of the GRACE/GRACE-FO gravity fields depends upon a suite of measurements, as explained in Box 1, the LRI has the potential for increasing the accuracy[118]. The successful demonstration of the LRI will establish its potential for use in future GRACE-like gravity missions[119]. However, future mission concepts go beyond developments in the instrumentation. Studies show the potential of constellations of satellite pairs for improving the temporal and spatial resolution limitations associated with the single pair mission[120,121]. The orbit constellation approach would open new possibilities to measure directly the short-term mass fluctuations that, to some extent, degrade the current gravity field solutions.

Relevance for climate sciences and climate services

Within 15 years, GRACE has evolved from pioneering concept demonstration into a system for reliably delivering mass transport products. These data and products enabled over two thousand peer-reviewed studies (archives listed in Additional information), of which many are cited in IPCC AR5[37], as they significantly contributed to our understanding of climate change. Currently, GRACE mass transport data directly or indirectly contribute to many Essential Climate Variables (ECVs) and should be adopted as primary ECV of the Global Climate Observing System[122].

Continuing data collection with GRACE-FO will be essential to attribute anthropogenic impacts on ice loss, sea-level rise and ocean heat uptake, and to quantify global changes in the severity and frequency of droughts and flood events. More accurate gravity fields provided in near-real time would stimulate new climate service applications, crucial to regional water management, flood, drought and snow/ice melt prediction, providing a data basis for political decisions or emergency management.

Recognizing the important utility for satellite gravity observations for Earth science, the recent 2017 NASA Decadal Survey[115] (https://science.nasa.gov/earth-science/decadalsurveys) has recommended a *mass change continuity mission* among the top five priorities for continued Earth observations. In retrospect, the launch of GRACE on 17 March 2002 provided a truly unique variable to the suite of Earth observations – the mission's legacy of a 15-year record of mass transport in the climate system will serve as a essential baseline for future generations.

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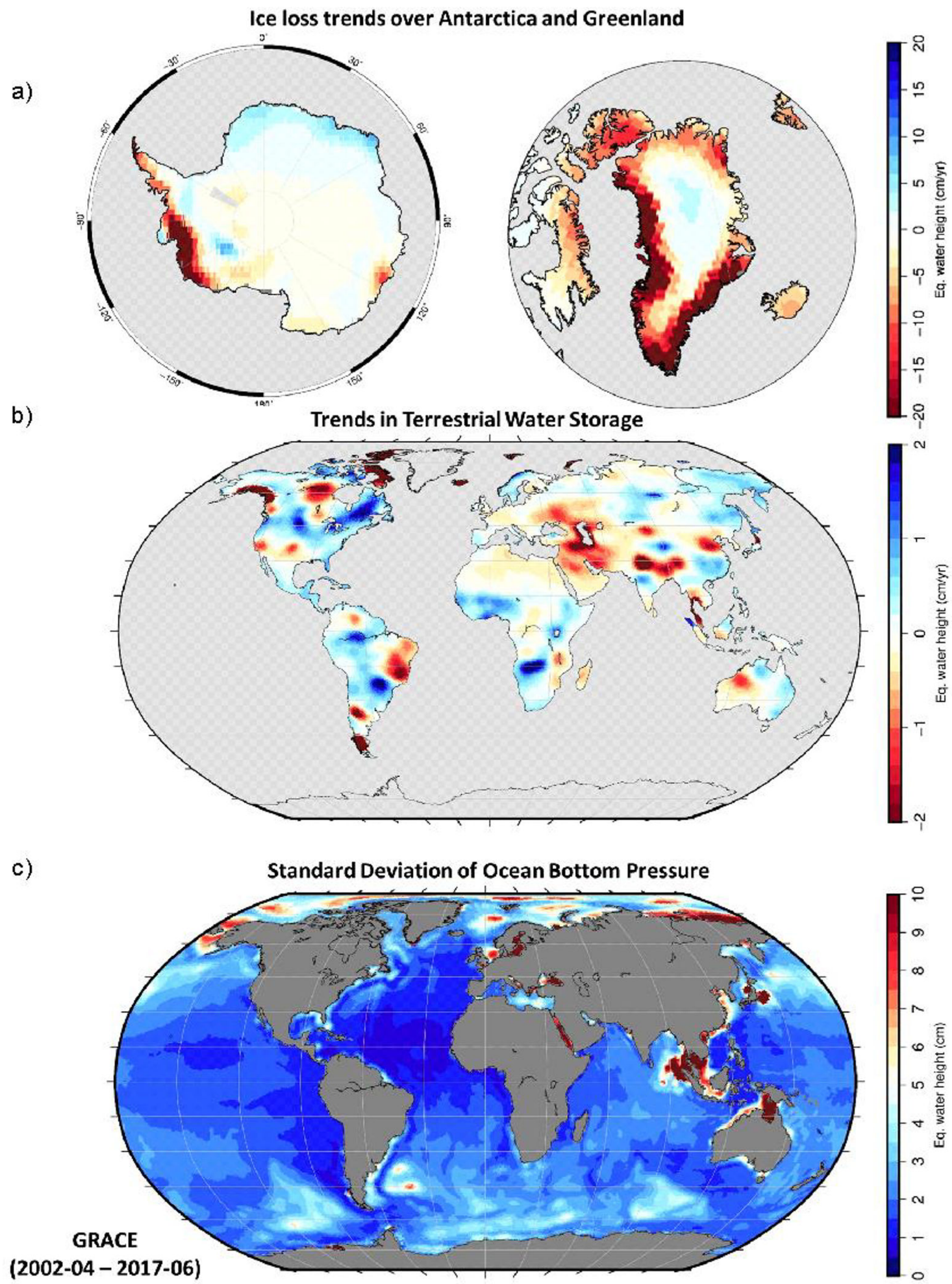


Fig. 1:

Global representation of trends and variability in ice and water mass recovered by GRACE over 15 years. a, the trend maps over Antarctica, Greenland and the part of the Arctic mainly represent changes in ice mass. b, the trend map mainly represents changes in the terrestrial water storage, as well as large trends due to glacier ice loss from continental areas, such as Alaska, Patagonia, Arctic Canada, etc.. The trends of the terrestrial water storage are partially related to climate variability causing floods and droughts, but also reflect e.g. long-term changes in groundwater depletion by human activity. c, standard deviation of the ocean bottom pressure obtained as the sum of mainly high resolution information of the ocean background model used in the GRACE data processing plus corrections of the background model from GRACE[107],which are particularly relevant in the southern oceans and the Arctic Ocean[4]. From the color scale on the plots a, b, the red colors represent mass loss and the blue represents mass gain. In plot c, the color scales represent variability with the highest variability shown by the red colors. The data source is CSR RL05M[4] Mascons. A glacial-isostatic adjustment (GIA) correction[124] has been subtracted in a and b. Details on the data shown are presented in Additional information.

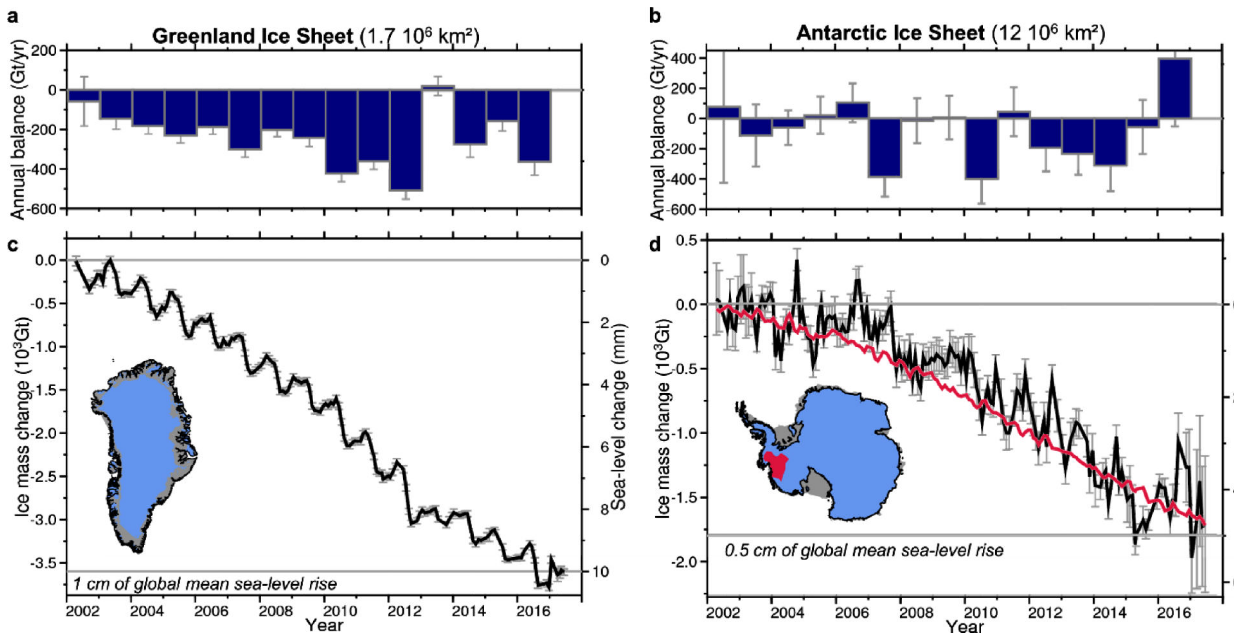


Fig. 2.

GRACE observations of mass change of the Polar ice sheets between April 2002 and June 2017. Annual mass balance of the a, Greenland Ice Sheet and the b, Antarctic Ice Sheet. Time series of mass change of the, c, Greenland Ice Sheet and the, d, Antarctic Ice Sheet (black), as well as the region of the Amundsen Sea Embayment only (red). Updated from Sasgen et al.[18,125]. The data source is CSR RL05. Details on the data shown are presented in Additional information.

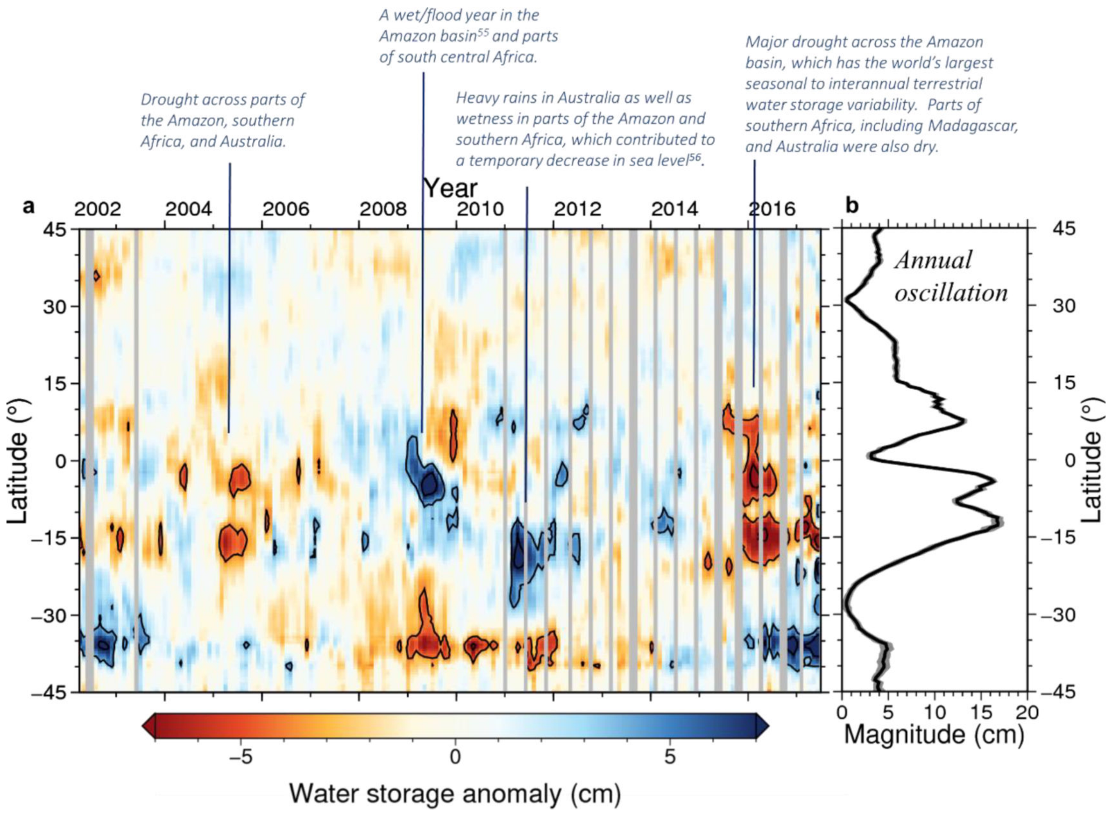


Fig. 3:

GRACE zonal mean of terrestrial water storage anomalies (cm equivalent water height) for April 2002 to June 2017. a, The time series of anomalies after subtracting an annual periodic component, offset and linear trend. Contour levels are at ± 4 and ± 8 cm. b, The magnitude of the annual oscillation. Based on CSR RL05M Mascons[4]. Details on the data shown are presented in Additional information.

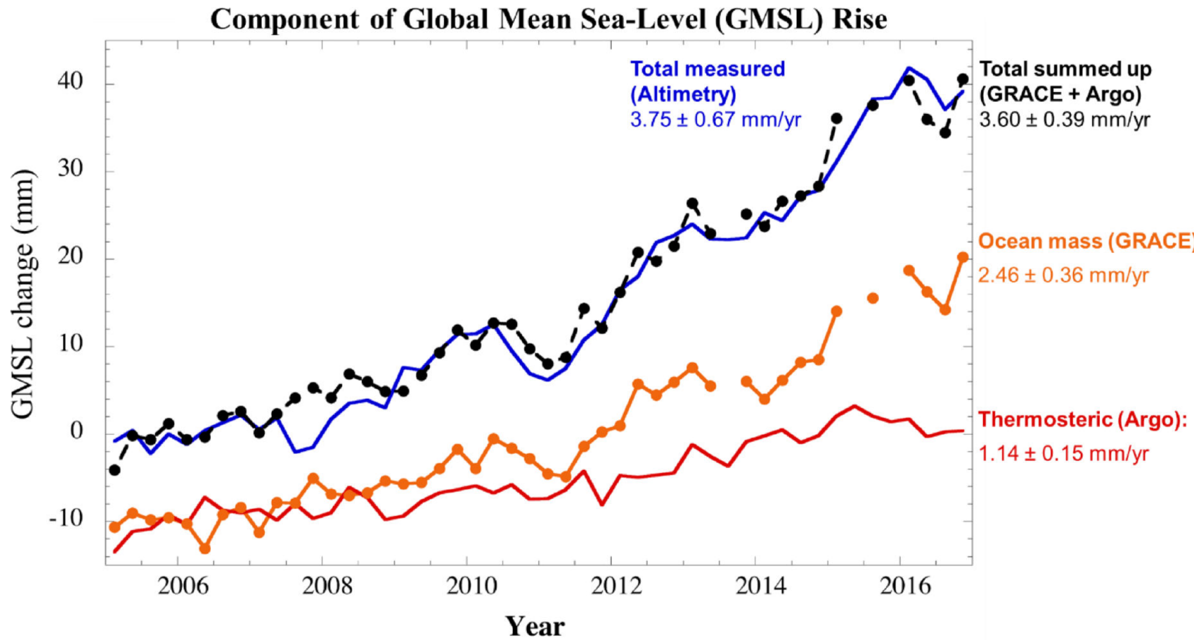


Fig. 4:

Global mean sea-level (GMSL) observed with satellite altimetry, GRACE and Argo floats for the time period 2005 until end of 2016. Shown are the observed sea-level change from altimetry (black) and the total sea-level change (blue) calculated as the sum of the mass (orange) and volume (red) components. The ocean mass changes are recovered with GRACE, temperature-driven volume (thermosteric) changes are estimated from Argo floats. The black line shows the sum of the mass and volume changes. The values represent three-month (seasonal means), i.e. January, February March; April, May, June; July, August, September; October, November, December. Updated from Chambers [92]. Details on the data shown are presented in Additional information.

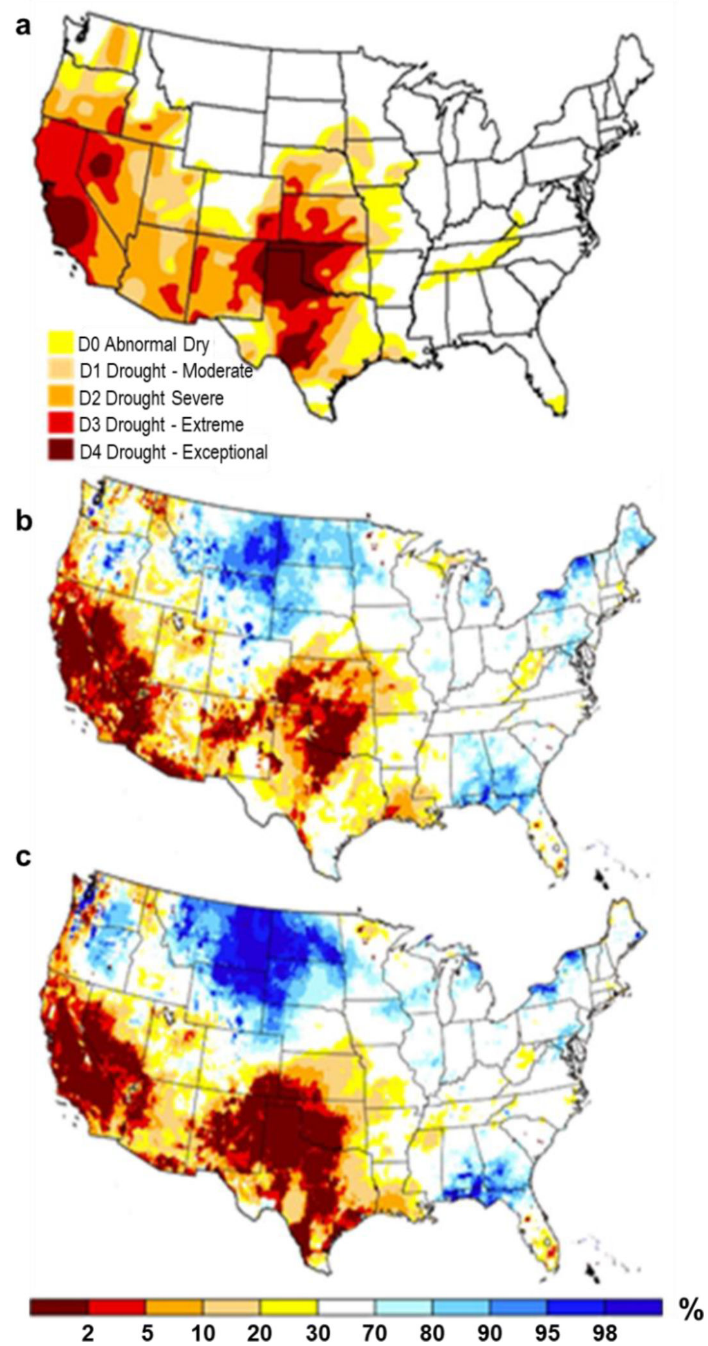
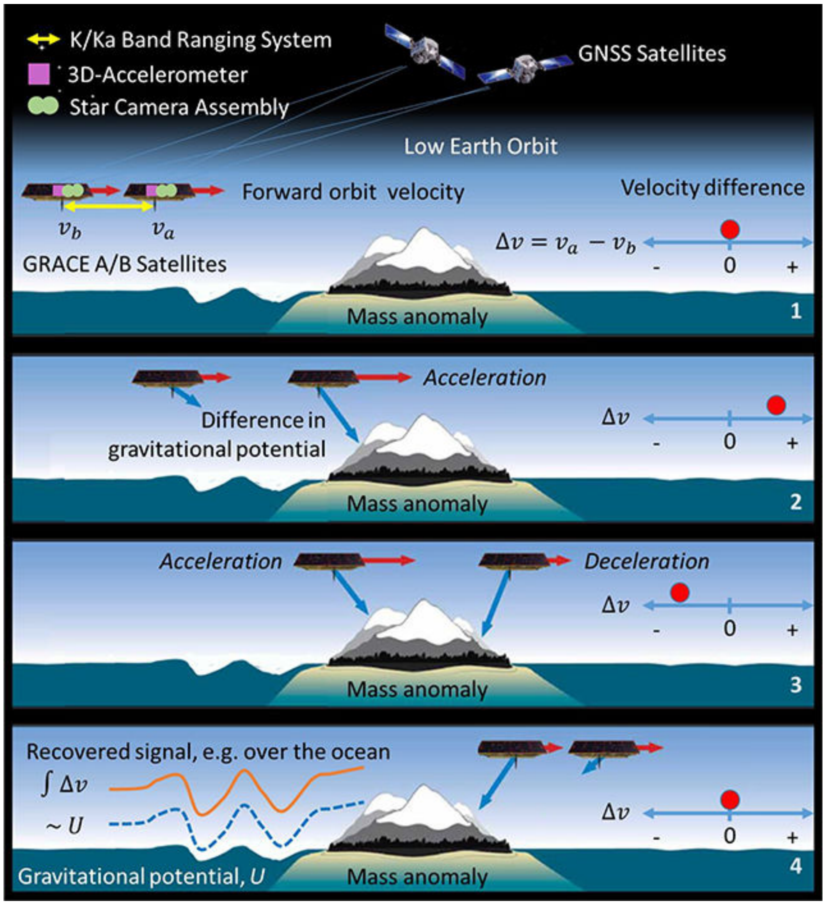


Fig. 5:

Operational drought monitoring supported by GRACE. a, Comparison of the U.S. Drought Monitor map for 20 May 2014 with the, b, GRACE data assimilation based root zone soil moisture and, c, shallow groundwater wetness/drought indicators for 19 May 2014. The scale bar for the latter two describes current wet or dry conditions, expressed as a percentile showing the probability of a given location being dryer at present than at the same time of year during the period of record from 1948 to the present.



Box 1:

The GRACE and GRACE-Follow-On measurement is implemented by two identical satellites (GRACE A/B) orbiting one behind the other in a near-polar orbit plane. The along-track separation is kept within a range of 220 ± 50 km. The satellites experience positive and negative gravitationally induced along-track accelerations due to the varying mass distribution underneath. Each satellite will experience the effects of the local mass, i.e. the associated change in a surface of constant gravitational potential U, at slightly different times, causing a differential acceleration. The differential acceleration in turn causes distance (range) variations and velocity differences Δv that are proportional to the mass attraction. The relative distance between the satellites is measured with micron level precision by a high accuracy inter-satellite K/Ka band ranging system. An accurate three-axis accelerometer measures the effects of all non-gravitational forces acting on each satellite, including atmospheric drag, direct and Earth reflected solar radiation pressure and thrusting. A GPS receiver on each satellite provides position and time synchronization, and a dual star camera assembly gives information on the satellites' orientation in space. The satellites overfly the entire Earth surface within approximately 30 days, allowing monthly estimates of a global gravity model with a surface spatial resolution of typically 300 km with an accuracy of 2 cm[123].