CLIMATE CHANGE

Celestial whispers: NASA grace missions transforming water and climate science

The GRACE missions have transformed mass change monitoring, revealing vital insights into groundwater dynamics, ice melt, and sea-level rise by tracking Earth's gravity changes.

 Ashraf Rateb · October 12, 2024

As we deepen our understanding of the world, our capacity to shape it evolves as well. This wisdom is evident in the scientific and technological progress of the 21st century. A prime example is the GRACE (Gravity Recovery and Climate Experiment) missions, which have revolutionized our perception and management of the planet’s most valuable resource: water. GRACE’s ability to measure subtle changes in Earth’s gravity has provided critical insights into hidden aquifer dynamics, melting ice sheets, and rising sea levels, helping us address urgent environmental challenges.

> *With our thoughts, we make the world*
>
> — SHAKYAMUNI BUDDHA

GRACE, a pair of satellites, was a successful collaboration between NASA and the German Aerospace Center. Launched in March 2002 with an initial mission objective of five years, it far exceeded expectations, operating until 2017 and delivering 15 years of continuous monthly measurements of mission with even greater precision.

But how does GRACE work? Imagine GRACE as a weighing scale in the sky. As water moves across the Earth—whether as groundwater, ice, or oceans—it causes small changes in gravity in those areas. When mass shifts, such as during floods or ice melts, the gravitational pull in those regions increases. These changes slightly alter the distance between the two satellites, which is measured by a highly precise K-band microwave ranging system. By continuously recording these shifts, GRACE provides monthly snapshots of how Earth's gravity changes, offering valuable data for scientists.

GRACE's measurements are crucial across various landscapes. On land, it tracks groundwater depletion, floods, and droughts. In polar regions, it monitors the melting of the ice sheets and glaciers. Over the oceans, it measures mass changes that contribute to sea-level rise. Additionally, GRACE detects subtle shifts in the solid Earth, such as movements caused by earthquakes and the slow rise of land after being compressed by ancient ice sheets during the last Ice Age.

insufficient for developing reliable and actionable frameworks. By integrating multiple lines of evidence from satellites, models, and ground verification—and by embracing and quantifying uncertainties—we can effectively address environmental challenges and shape a sustainable future.

— ASHRAF RATEB

The quantity measured by GRACE is known as *the Total Water Storage (TWS)*, which represents the total sum of water stored in the terrestrial system, including *snow, ice, surface water, soil moisture, and groundwater.* By using additional data, scientists can further break down this total to understand specific components. One of GRACE's groundbreaking achievements is its ability to *map freshwater availability* (Figure 1) and reveal the effects of *groundwater abstraction*, often linked to irrigation, *climate variability*, and *extreme weather events* on TWS.

For example, *Figure 1* highlights red areas that indicate regions with persistent declining trends in water storage, including the southwestern United States, Middle East, North Africa, Northern India, and North China Plain. In contrast, the blue areas reflect *positive trends* in water storage, as natural *climate variability*—chaotic changes in the climate system—or by *anthropogenic climate change*. This remains a puzzle, and researchers are working to put together the pieces.

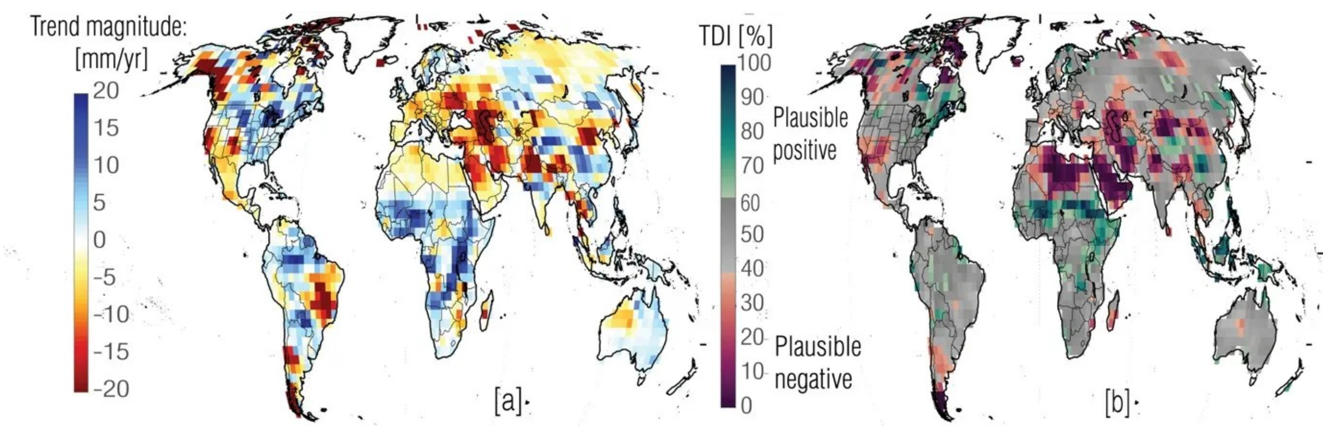


Figure 1. Trendiness of total water storage demonstrates the yearly average of a 3-degree grid scale using NASA JPL mascons. The trend magnitude is shown in mm/year (left) over 21 years (04/2002–01/2022), and the *Trend Direction Index (TDI)* (right) indicates the likelihood of the trend moving upward. Green colors reflect persistent upward trends, while red (<50%) indicates trends moving downward. A TDI of 50% reflects equal plausibility of the trend moving in either direction. Gray colors are used to highlight areas of extreme trends.
Credit: Ashraf Rateb

Beyond tracking these trends, GRACE provides a deeper understanding of the change in intensity of wet and dry spells and their effects on global water resources. Mapping the timing and spatial distribution of *ice melting and accretion*, along with their contributions to sea level rise, is one of

In addition to these direct applications, scientists have been using GRACE data to calibrate and validate Earth system models, or blend it with other geodetic data, to improve our understanding of hydrological processes (e.g., aquifer dynamics, floods) and to evaluate the impacts of human interventions and climate change on water resources. GRACE–TWS was officially recognized by the *World Meteorological Organization* in 2022 as an *Essential Climate Variable*, highlighting its critical role in understanding and addressing various aspects of *water resources* and the impacts of *climate change* and *human interventions*.

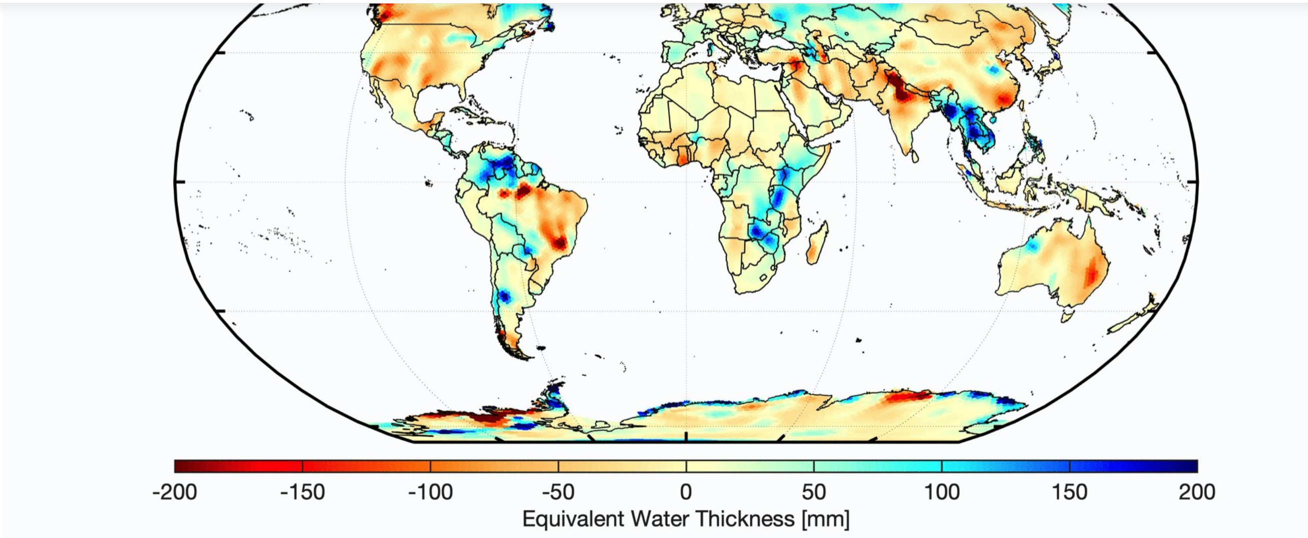


Figure 2. Total Water Storage (TWS) surplus (wet) and deficit (dry) in mm, accounting for changes beyond seasonal and linear patterns. Data is from the University of Texas at Austin, Center for Space Research, using GRACE-Follow On mission mascon solutions.
Credit: Ashraf Rateb

Recent advancements in GRACE science focus on enhancing spatiotemporal resolution to explore new applications, including understanding pre-flood conditions. The Center for Space Research at the University of Texas conducted an experiment to improve GRACE's temporal resolution by generating five-day solutions, providing better insights into flood generation and water storage impacts. Results show that antecedent conditions in Terrestrial Water Storage (TWS), derived from five-day sampling, significantly improve pre-flood and active flood

The study found that floods triggered by saturation-excess runoff—due to persistent rainfall, monsoons, snowmelt, or rain-on-snow events—show detectable TWS increases 15 to 50 days before and during floods. Additionally, these new data enable quicker mapping of post-flood water storage changes, which is vital for assessing recovery from tropical cyclones and other sub-monthly weather extremes. These experiments pave the way for developing new datasets that could enhance future operational flood monitoring systems. GRACE data, though costly and complex to process, have become more accessible and valuable for hydrologists and climatologists, thanks to efforts by scientific centers over the past two decades.

Recommendations

Although GRACE missions have greatly advanced our knowledge of Earth's water systems, their spatial resolution (approximately 300 km) and vertically integrated TWS measurements constrain detailed local analyses and differentiation of water storage components. To enhance GRACE

1. **Develop advanced data fusion techniques incorporating AI with emphasis on uncertainty quantification and causal Inference**

Advanced data fusion methodologies that combine GRACE data with hydroclimate variables (e.g., soil moisture) and high-resolution remote sensing data from satellites such as Sentinel-1, SMAP, and SWOT can yield deeper insights into specific aquifers and surface water bodies. This integrated approach improves monitoring, especially in remote or underserved regions, and helps downscale TWS information to finer spatial scales.

When downscaling TWS information using machine learning and AI algorithms, prioritizing uncertainty quantification and causal inference is crucial. By rigorously assessing data and model uncertainties and understanding the causal relationships between variables, researchers can enhance the reliability and interpretability of the results. Incorporating auxiliary local data further improves the model accuracy and ensures that insights are valid and actionable for targeted water management

2. **Develop real-time or near-real-time water scarcity and flood forecasting indices using enhanced GRACE data integrated with hydroclimate forecasts**

Building on the efforts of organizations such as NASA and the National Drought Mitigation Center, real-time water scarcity indices have been developed by integrating GRACE data with hydrological model forecasts. This integration can improve drought monitoring and support proactive water resource management. Similarly, enhancing flood forecasting capabilities is possible through the augmentation of daily and five-day GRACE data when operationalized. By incorporating high-temporal-resolution GRACE observations into flood prediction models, it's feasible to improve the detection of pre-flood conditions and active flood events. This approach enables more timely and effective responses to flooding, reducing the impacts on communities and infrastructure.

Conclusions

By overcoming GRACE data limitations with innovative strategies, researchers, policymakers, and environmental organizations can improve uncertainty quantification and causal inference ensures that insights are reliable and actionable, enabling better decision-making on global and local levels.

The future of GRACE-like data looks promising as upcoming satellite generations will refine these measurements, further boosting our capacity to manage water resources in a changing climate. NASA plans to launch GRACE-Continuity (GRACE-C) by 2028, continuing the legacy of past missions. Additionally, NASA and the European Space Agency are collaborating on the Mass Change and Geosciences International Constellation (MAGIC) mission, featuring four satellites in pairs, which will further advance our ability to monitor Earth's gravity and water systems.

With these exciting advancements on the horizon, our ability to monitor Earth's water systems will reach new heights, providing crucial insights for smarter resource management and effective climate action. The legacy of the GRACE missions continues to inspire innovation, empowering us to protect our planet for future generations.

Journal reference

Rateb, A., Save, H., Sun, A. Y., & Scanlon, B. R. (2024). Rapid mapping of global flood precursors and impacts using novel five-day GRACE solutions. *Scientific Reports*, *14*(1), 13841. https://doi.org/10.1038/s41598-024-64491-w

CLIMATE CHANGE ENVIRONMENTAL SCIENCE GEODESY GRACE MISSIONS
GRACE SATELLITES GRACE-FOLLOW ON GROUNDWATER DYNAMICS HYDROLOGY
ICE MELT MONITORING NASA NATURAL HAZARDS REMOTE SENSING
SCIENTIFIC REPORTS SEA-LEVEL RISE THE UNIVERSITY OF TEXAS AT AUSTIN
WATER RESOURCE MANAGEMENT

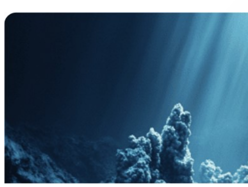
Ashraf Rateb is a Research Assistant Professor at the Bureau of Economic Geology, University of Texas at Austin. His research focuses on the intersection of geodesy and hydroclimate, with an emphasis on understanding water resource dynamics and the impact of climate change.

You might be interested in

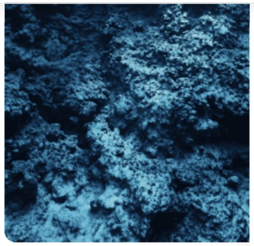
September 19, 2024

How marine life responds to the challenges of climate change

Marine life faces pressure from human-caused changes like ocean warming and acidification, with new studies showing surprising impacts on marine ecosystems.



August 19, 2024



regions

Discover how microbes in deep water create methane hydrates by degrading organic carbon, a crucial natural process with significant environmental implications.

August 9, 2024

Ukraine’s agriculture faces dual threats of invasion and climate change

The study examines the impact of the invasion and climate change on Ukraine's irrigated agriculture.

Breakthrough research, delivered straight to your inbox.