

# Monitoring Groundwater Changes for Water Resources Management

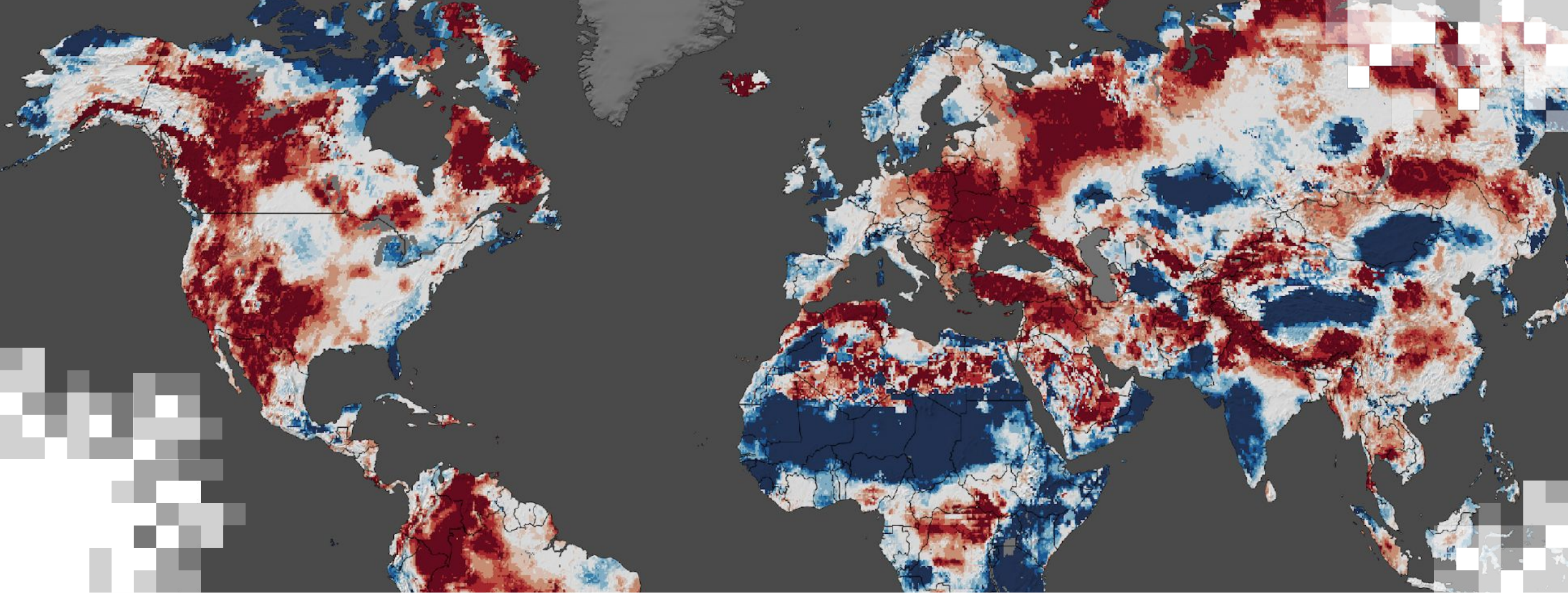
Part 1: Overview and Analysis of NASA Terrestrial Water Storage Data from GRACE/GRACE-FO

ARSET Host: Amita Mehta (612, GESTAR II)

Guest Speaker: Matthew Rodell (610, NASA-GSFC)

April 23, 2026





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# About ARSET

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- Trainings include a variety of applications of satellite data and are tailored to audiences with a variety of experience levels.



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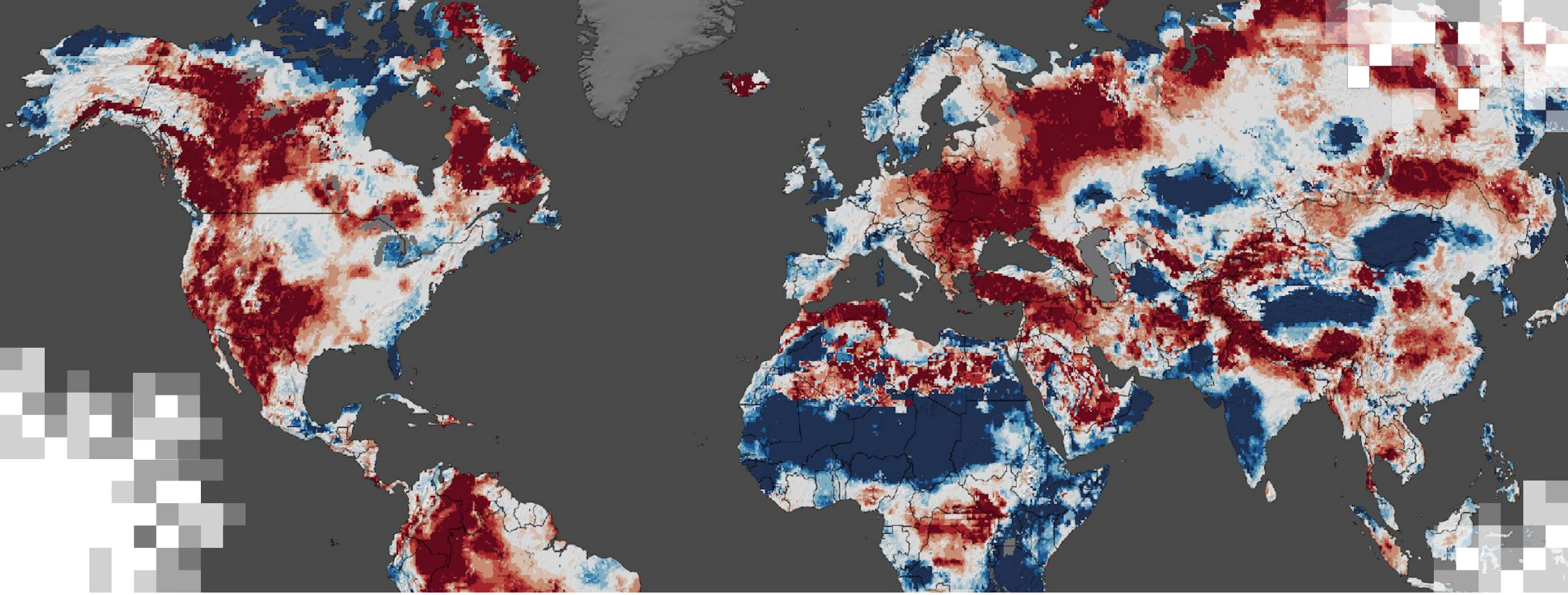
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# About ARSET Trainings

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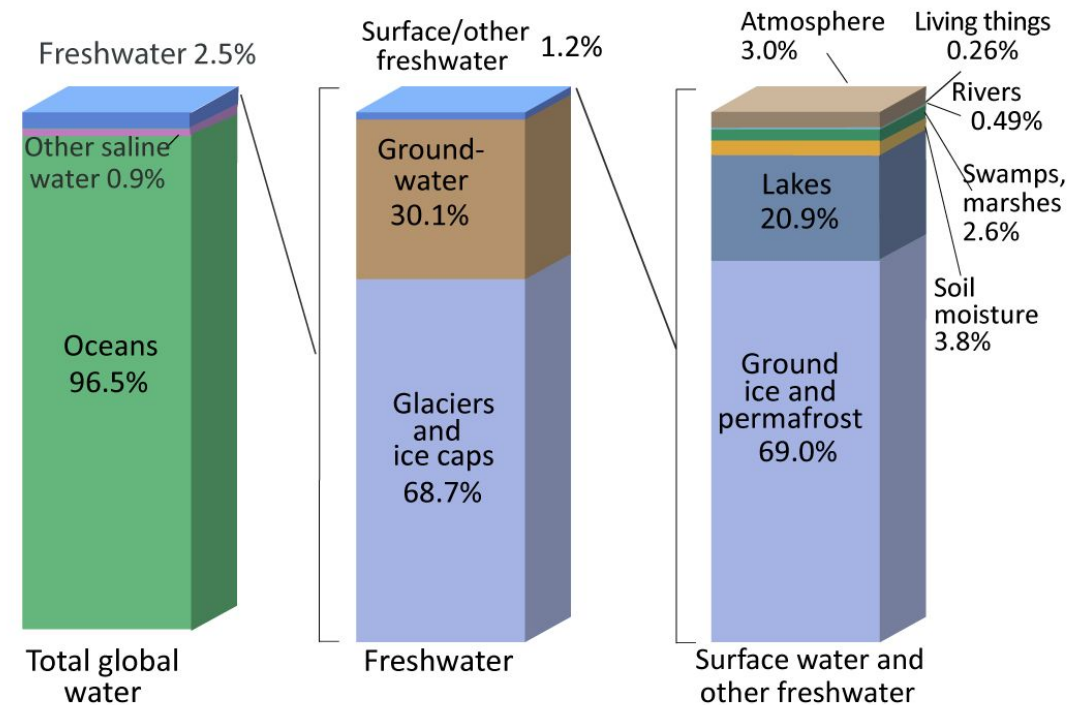


## **Monitoring Groundwater Changes for Water Resources Management Overview**

# What is Groundwater?

- Groundwater is water from precipitation that percolates into the soil and moves downward to fill cracks and openings in rocks and sand.
- Groundwater makes up about 30% of the global freshwater.

## Where is Earth's Water?



Source: [Water in Crisis: A Guide to the World's Freshwater Resources](#)

Source: [National Groundwater Association](#)

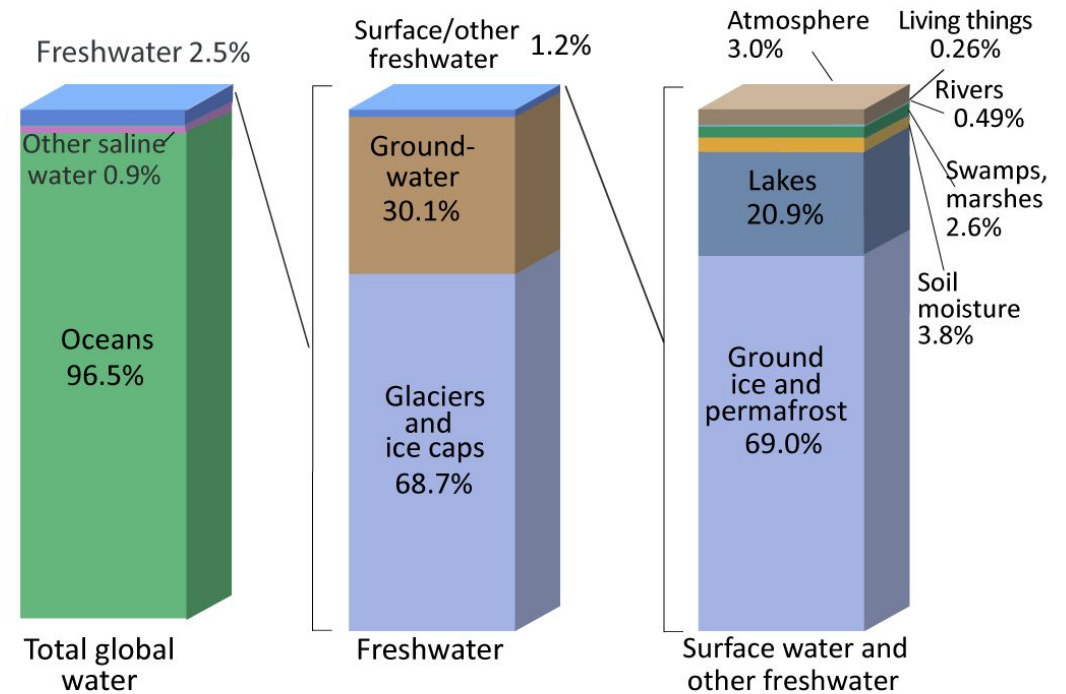


# What is Groundwater?

- Groundwater ages range from months to millions of years.
- The total groundwater volume in the upper 2 km of continental crust is approximately 22.6 million km<sup>3</sup>, of which 0.1–5.0 million km<sup>3</sup> is less than 50 years old\*.

- The most extracted resource worldwide
- A renewable resource, depends on regional environmental conditions

## Where is Earth's Water?



Source: [Water in Crisis: A Guide to the World's Freshwater Resources](#)

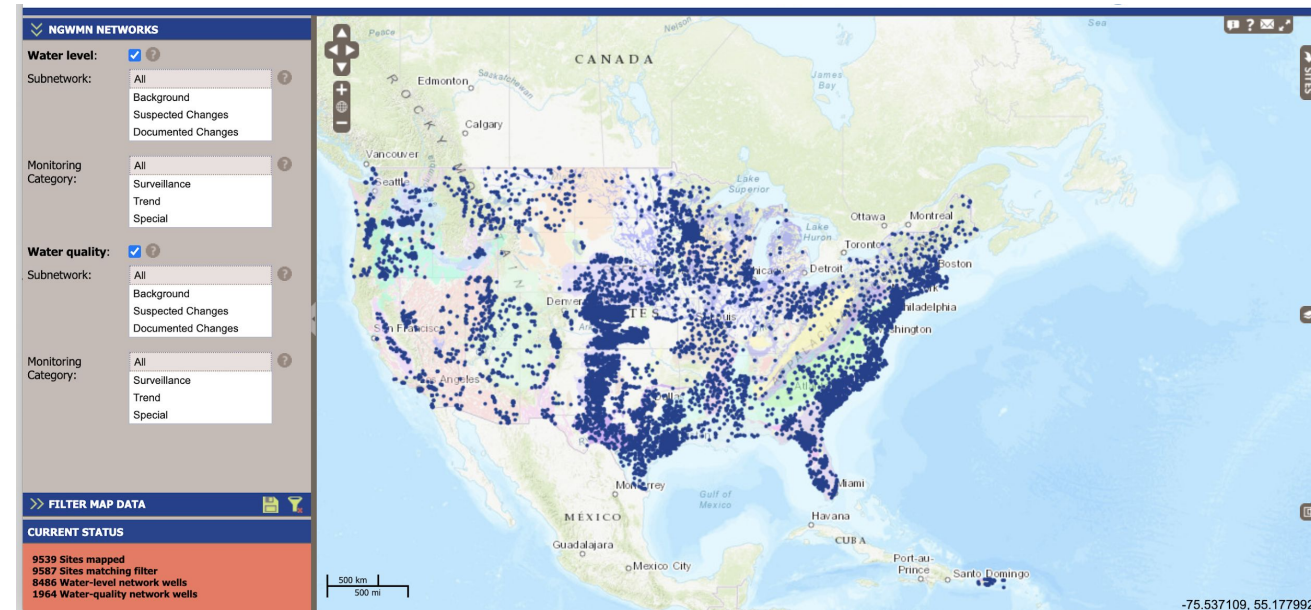
[National Ground Water Association \(NGWA\)](#)

\*[Gleeson et al., \(2016\)](#)



# Monitoring Groundwater: GRACE/GRACE-FO

- Traditionally, water wells are used for monitoring groundwater levels.
- There are no direct measurements of groundwater from remote sensing observations.
- Measurements from **GRACE** and **GRACE-FO** satellites are used to estimate **total terrestrial water changes**.
- These measurements are used to **derive global, large-scale groundwater** (~150,000 km<sup>2</sup>) changes by using additional hydrological information.

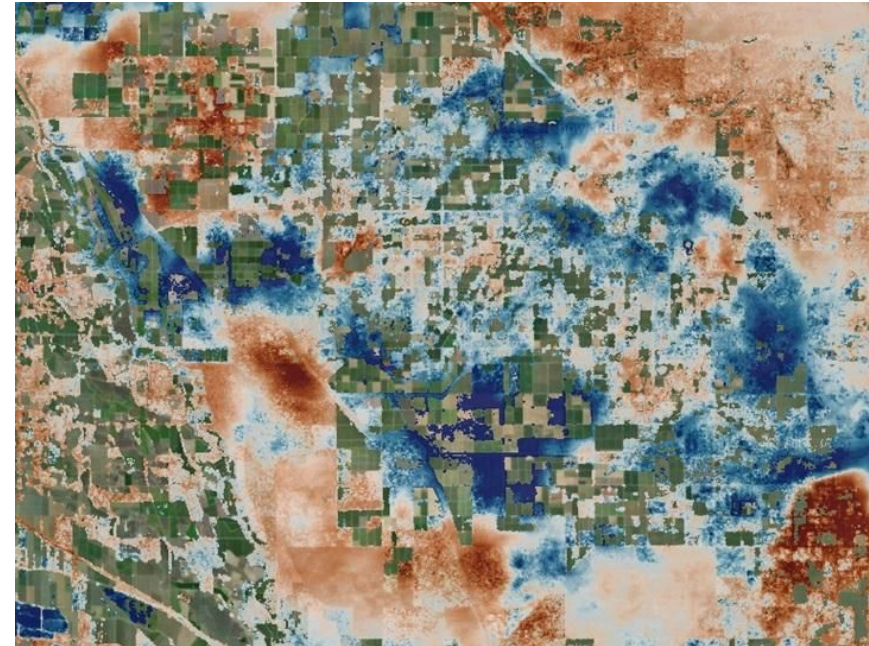


[National Groundwater Monitoring Network](#)



# Monitoring Groundwater: GLDAS & OPERA DISP

- Global Land Data Assimilation System (GLDAS) assimilates GRACE/(-FO) data to derive global groundwater data.
- Additionally, Synthetic Aperture Radar (SAR) measurements from Sentinel-1 are used to derive Surface Displacement (DISP) indicating groundwater changes and are available from Observational Product for End-Users from Remote Sensing Analysis (OPERA).



OPERA Displacement Product



# Training Learning Objectives

By the end of this training, participants will be able to:

- Identify characteristics of groundwater quantity datasets from GRACE/GRACE-FO, GLDAS, and OPERA Displacement (DISP).
- Access, analyze, and visualize GRACE/GRACE-FO data to monitor seasonal to interannual changes in large-scale total terrestrial water storage.
- Access, analyze, and visualize GLDAS data to monitor interannual to interdecadal changes in groundwater at regional scale.
- Map surface subsidence related to groundwater extraction with OPERA DISP data.
- Recognize applications of these groundwater datasets, available at multiple spatial and temporal scales, for monitoring drought and flood conditions, and for planning groundwater resources for a variety of uses.



# Prerequisites

- [Fundamentals of Remote Sensing](#)
- [Groundwater Monitoring using Observations from NASA's Gravity Recovery and Climate Experiment \(GRACE\) Missions.](#)



# Training Outline

## Part 1

Overview and  
Analysis of NASA  
Terrestrial Water  
Storage data from  
GRACE/GRACE-FO

April 23, 2026

## Part 2

Overview and  
Applications of GLDAS  
Groundwater data  
products at Regional  
Scale

April 28, 2026

## Part 3

Overview and  
Applications of  
OPERA-DISP to Monitor  
Groundwater  
Changes

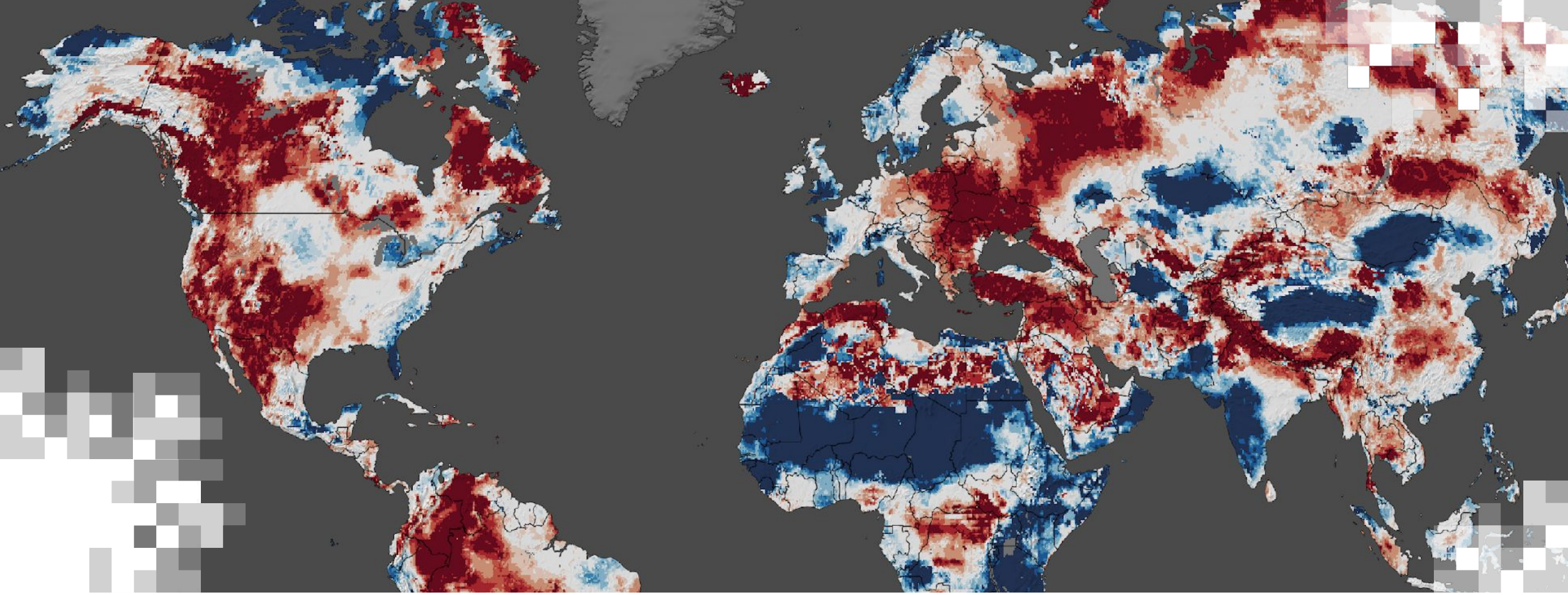
April 30, 2026

## Homework

Opens April 30 – Due May 15 – Posted on Training Webpage

A certificate of completion will be awarded to those who attend all live sessions and complete the homework assignment(s) before the given due date.





**Part 1**  
**Overview and Analysis of NASA Terrestrial Water Storage data**  
**from GRACE/GRACE-FO**

# Part 1 Objectives

By the end of Part 1, participants will be able to:

- Identify characteristics of terrestrial water storage data sets from GRACE/GRACE-FO.
- Monitor seasonal and interannual changes in terrestrial water storage using GRACE/FO Analysis Tool.



# Part 1 Outline

- Overview of GRACE(-FO) Missions
- GRACE(-FO) Data products
- GRACE(-FO) Data Applications
- Terrestrial Water Storage Data Visualization:
  - Demonstration: [GRACE\(-FO\) Data Analysis Tool](#)



# How to Ask Questions

- Please put your questions in the Questions box and we will address them at the end of the webinar.
- Feel free to enter your questions as we go. We will try to get to all the questions during the Q&A session after the webinar.
- The remainder of the questions will be answered in the Q&A document, which will be posted to the training website about a week after the training.

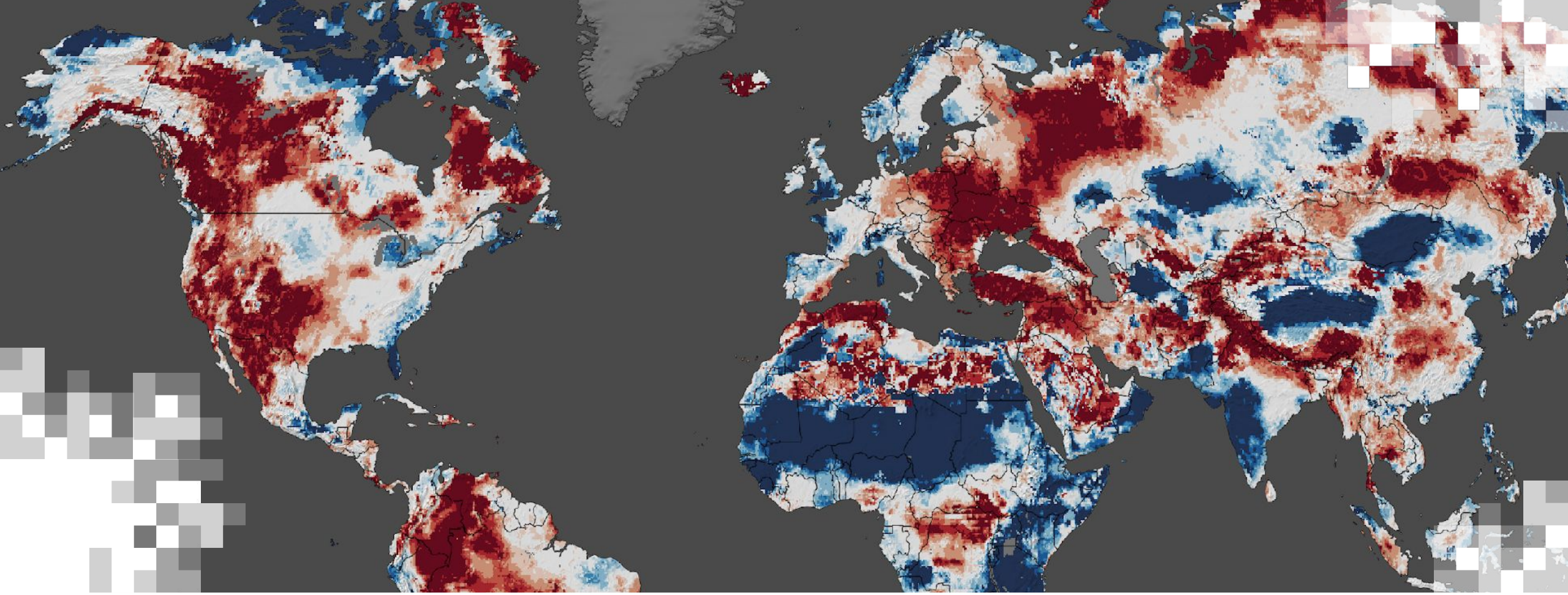


# Part 1 – Trainer

## Dr. Matthew Rodell

Deputy Director of Earth Sciences for  
Hydrosphere, Biosphere, and  
Geophysics (NASA/GSFC)

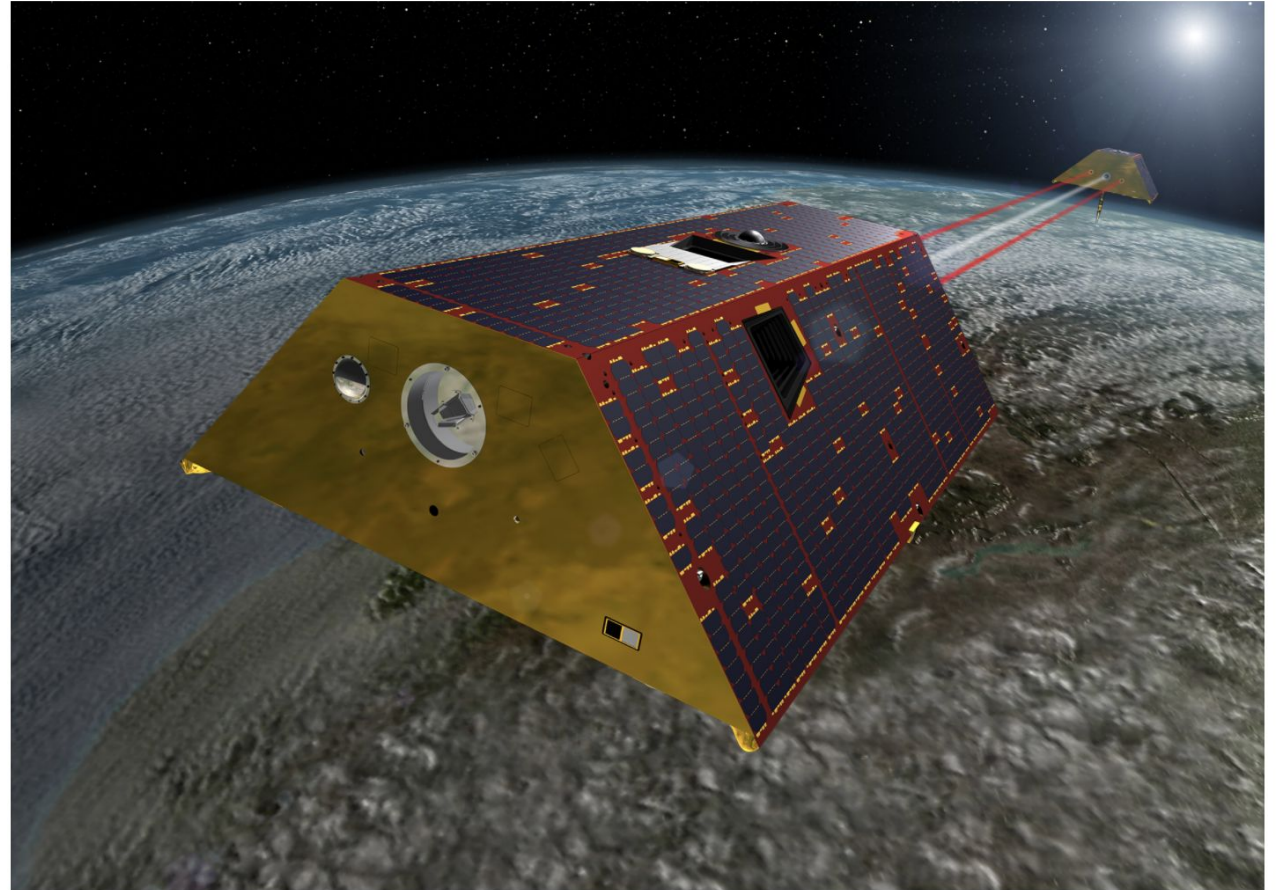




**Part 1:  
Overview of GRACE(-FO) Missions**

# GRACE & GRACE-FO

- [GRACE](#) and [GRACE-FO](#) are satellite missions jointly developed by NASA and the German Aerospace Center (DLR).
- Both are twin satellite systems in near-polar orbits.
- Each consists of two identical satellites orbiting about 220 km apart, at 500 km altitude.
- The satellites observe all regions of the Earth at different local times over a 30-day period.

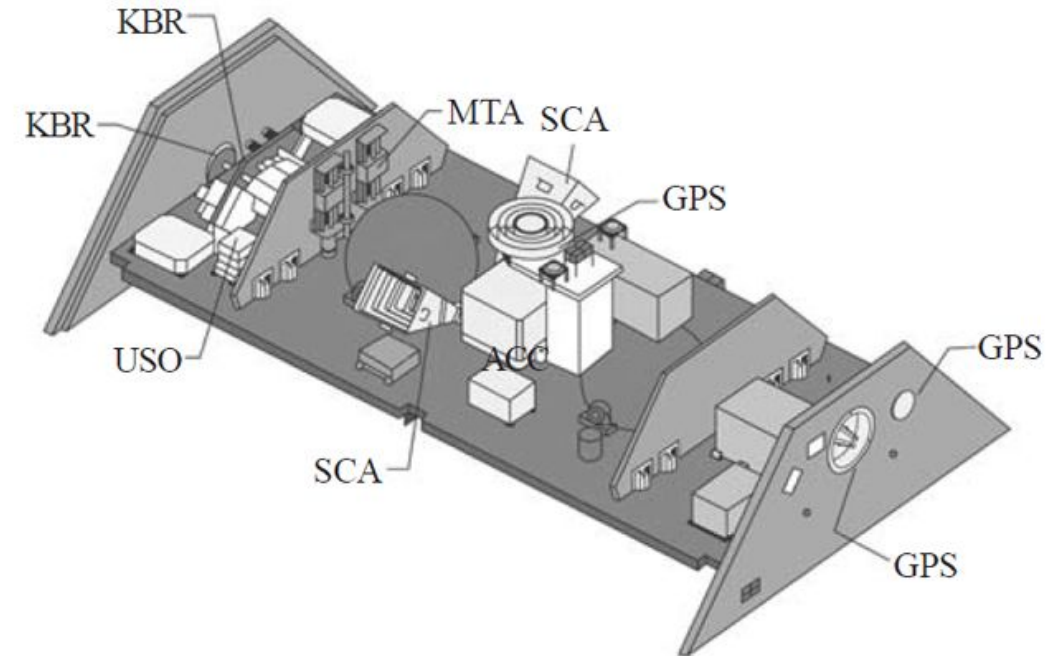


Like GRACE, the twin GRACE-FO satellites will follow each other in orbit around the Earth, separated by about 137 miles (220 km). Seen in an artist's rendering. Credit: NASA



# GRACE & GRACE-FO

- Provide global coverage
- GRACE: March 17, 2002 to October 12, 2017
- GRACE-FO: May 22, 2018 to Present
- Primary Sensors:
  - Microwave K-band Ranging Instrument
  - Accelerometers
  - Global Positioning System Receivers

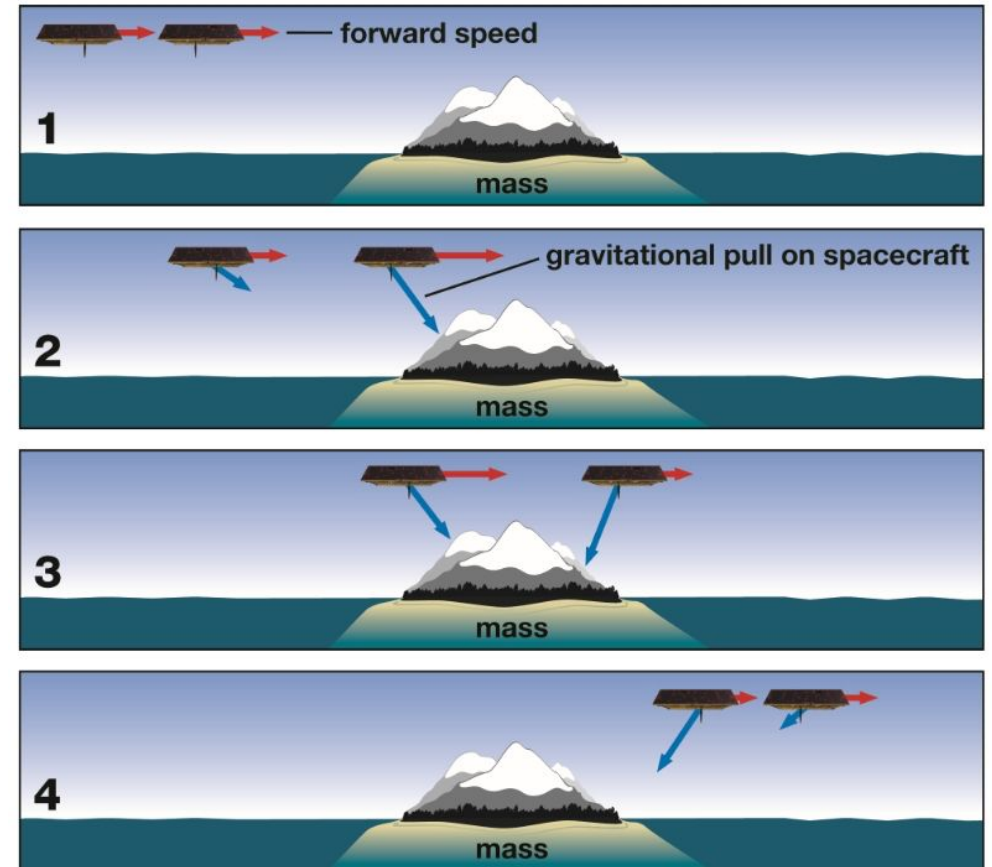


## NASA GRACE MISSION



# GRACE & GRACE-FO Measurements

- As the twin satellites orbit the Earth, the distance between them is affected by gravity anomalies (differences in mass concentration).
- The microwave ranging system is designed to measure these variations with high precision.
- The Global Positioning System (GPS) receivers determine the exact position of the satellites over the Earth.
- The accelerometers measure non-gravitational accelerations (such as those due to atmospheric drag).



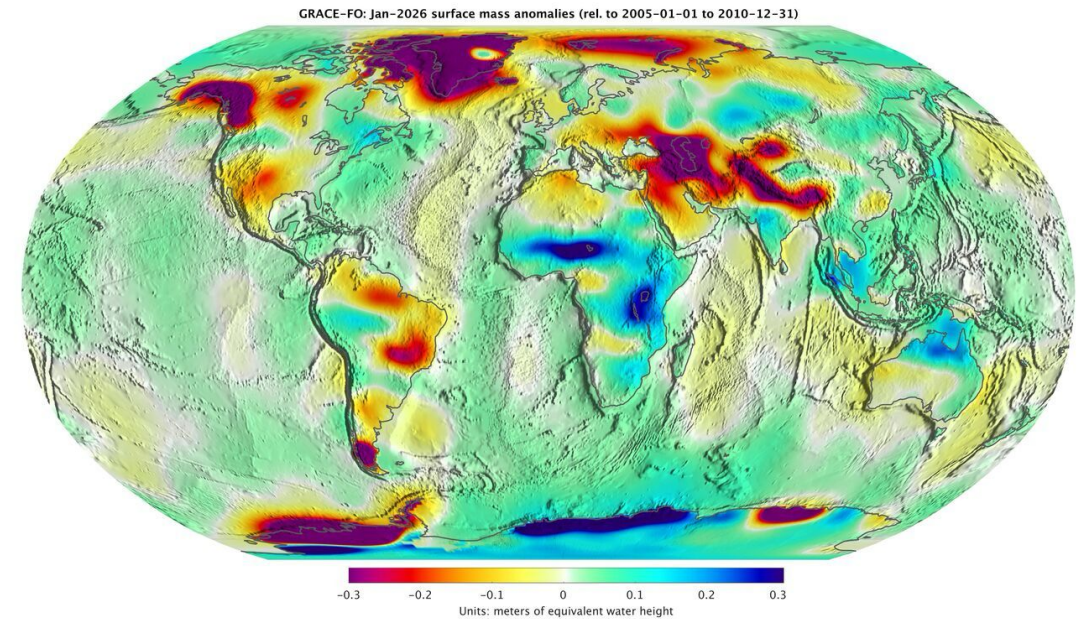
How GRACE-FO Measures Gravity



# From Gravity to Terrestrial Water

- Fundamentals of physics are used to translate GRACE(-FO) measurements (distance between the satellites) to gravity or mass concentration.
- Subtle shifts in Earth's gravity occur, primarily dominated by water movements from one place to another on and under land, in the ocean, and in the atmosphere.
- After accounting for atmospheric, oceanic, and solid Earth mass redistributions, variations in gravity observed by GRACE(-FO) are interpreted as terrestrial water storage (TWS) changes.

## Terrestrial Water Storage Anomaly (TWSA) Data from March 2015 to March 2016



[GRACE-FO TWS Anomaly for January 2026](#)

Reference: [The Gravity of Water](#)



# GRACE Terrestrial Water Storage Data

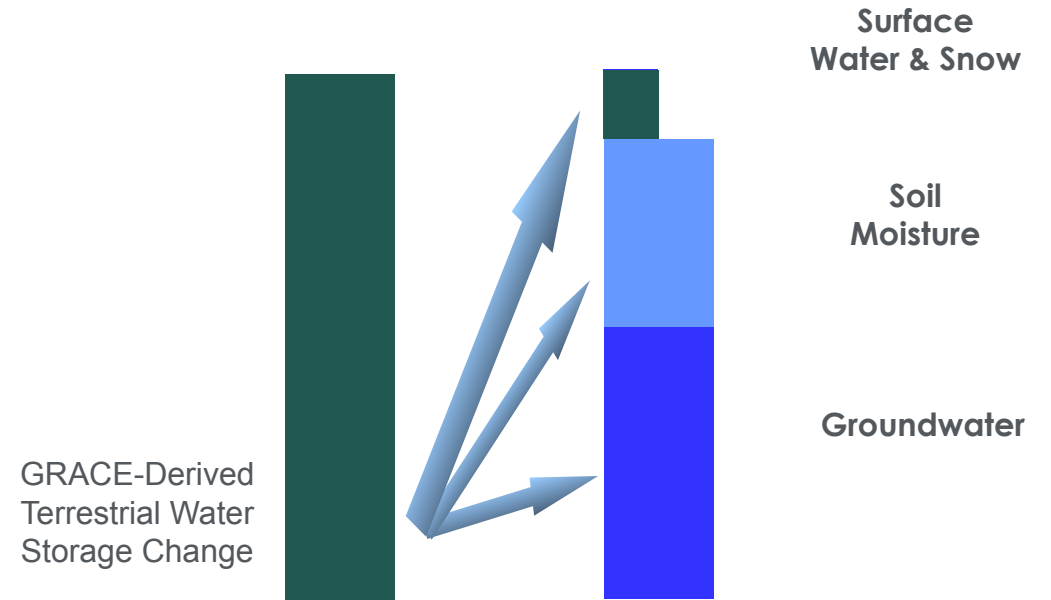
- The TWS data are provided in cm (or mm) of equivalent water thickness.
- GRACE Level-3 (terrestrial water storage anomaly) data have an effective spatial resolution of about 100,000-150,000 km<sup>2</sup>.
- For convenience, the TWS data are often provided on 1°x1° or 0.5°x0.5° resolution grids
- However, they are not meant to be interpreted at that high resolution; averaging over a sufficiently large region (>100,000 km<sup>2</sup>) is necessary for results to be meaningful.
- Errors in monthly TWS anomalies are estimated to be 1-2 cm over >300,000 km<sup>2</sup> regions.

## [GRACE\(-FO\) Data](#)



# From Terrestrial Water to Groundwater

- Terrestrial water is the sum of groundwater, soil moisture, surface water, snow, and ice
- GRACE measures total column terrestrial water (TWS) and cannot distinguish between these components
- Incorporating GRACE(-FO) derived TWS anomalies into land surface models as a constraint (i.e., data assimilation) enables vertical, horizontal, and temporal disaggregation



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Government sponsorship acknowledged.



# From Terrestrial Water to Groundwater: Water Balance Approach

$$P - ET - Q = \Delta TWS \text{ [terrestrial water balance]}$$

$$\Delta TWS = \Delta GW + \Delta SM + \Delta SWE + \Delta SW$$

$$\Delta GW = \Delta TWS - \Delta SM - \Delta SWE - \Delta SW$$

$P$  = precipitation

$ET$  = evapotranspiration

$Q$  = river discharge

$\Delta TWS$  = **change in terrestrial water storage [from GRACE]**

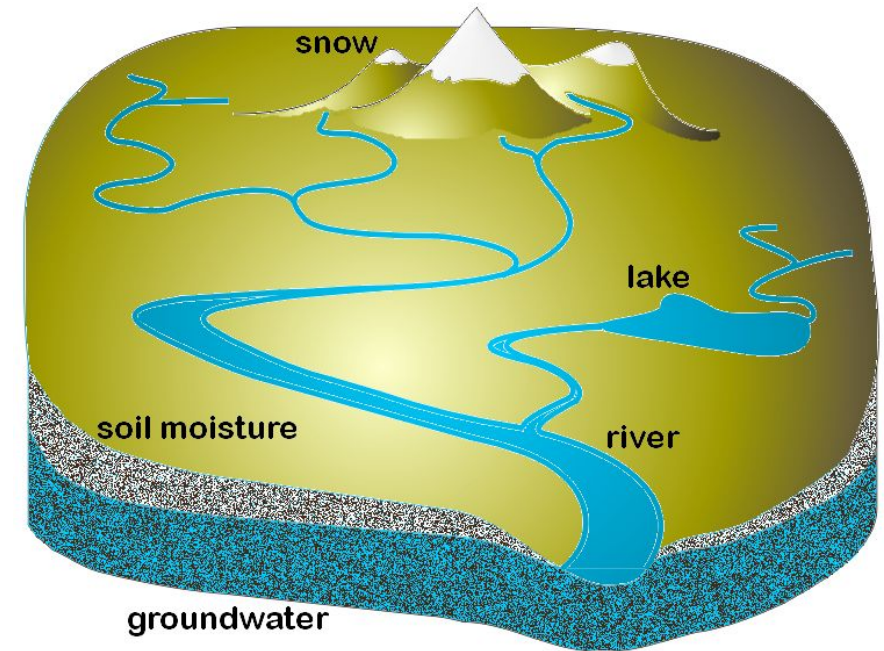
$\Delta GW$  = change in groundwater storage [unknown]

$\Delta SM$  = change in soil moisture

$\Delta SWE$  = change in snow water equivalent

$\Delta SW$  = change in surface water storage

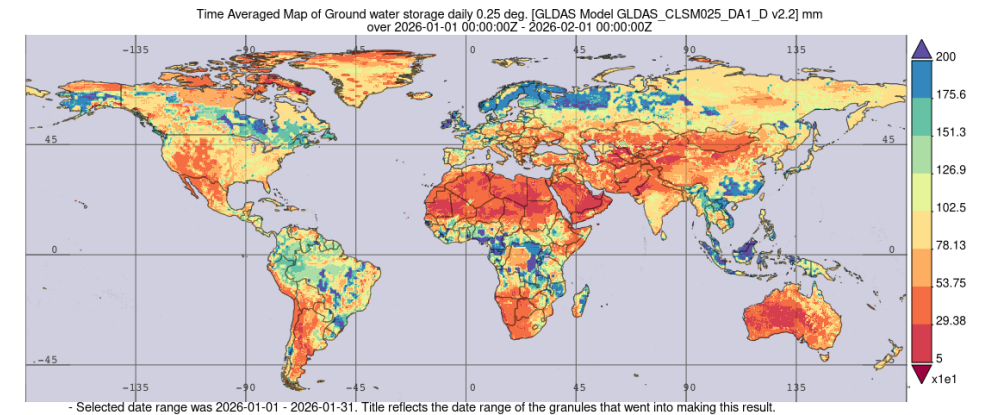
[ $\Delta SM$ ,  $\Delta SWE$ ,  $\Delta SW$  from in situ observations or models]



# From Terrestrial Water to Groundwater: Data Assimilation

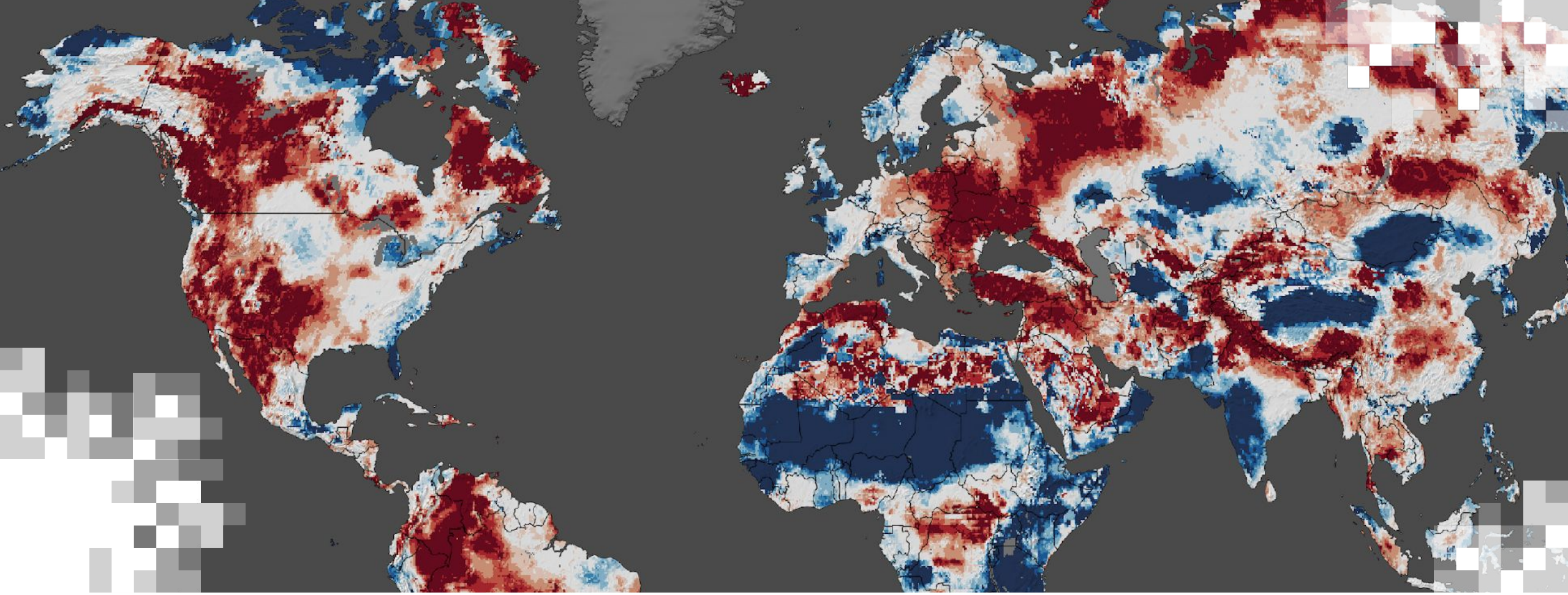
- An alternative to the water balance equation (previous slide) for isolating groundwater storage changes, is GRACE (-FO) TWS data assimilation
- GLDAS Version 2.2 assimilates GRACE (-FO) TWS data and provides all the water budget components, including groundwater

## GLDAS-v2.2 Groundwater Storage (mm)



January 2026





## GRACE(-FO) Data Products

# GRACE and GRACE-FO Data Access

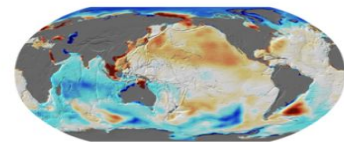
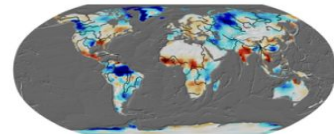
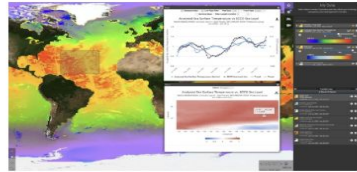
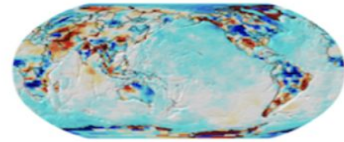
The following websites provide detailed information and access to GRACE/GRACE-FO data:

- [GSFC Mascon Product](#)
- [JPL data portal](#)
- [GFZ data portal](#)
- [GRACE website at University of Texas at Austin Center for Space Research \(CSR\)](#)



# JPL GRACE Data Portal

## [DATA Access](#)



## Options

### **GRACE/GRACE-FO Monthly Mass Grids – JPL Global Mascons**

Global surface mass changes (land + oceans)

### **Interactive GRACE/GRACE-FO Data Browser**

This data browser allows the interactive retrieval of GRACE & GRACE-FO Land over river basins, as well as the evaluation of long-term trends and mean seasonal amplitudes.

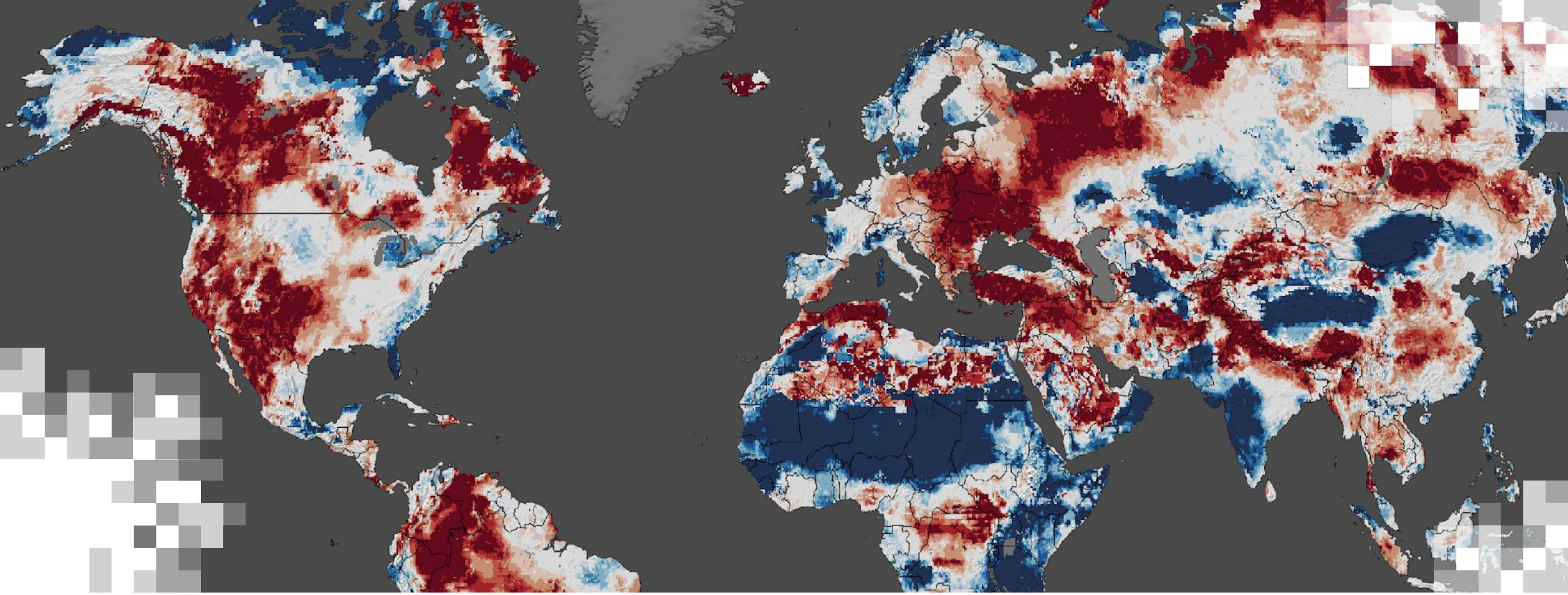
### **GRACE Monthly Mass Grids – Land**

Land water storage from GRACE is updated monthly and is provided on 1-degree global grids.

### **GRACE Monthly Mass Grids – Ocean**

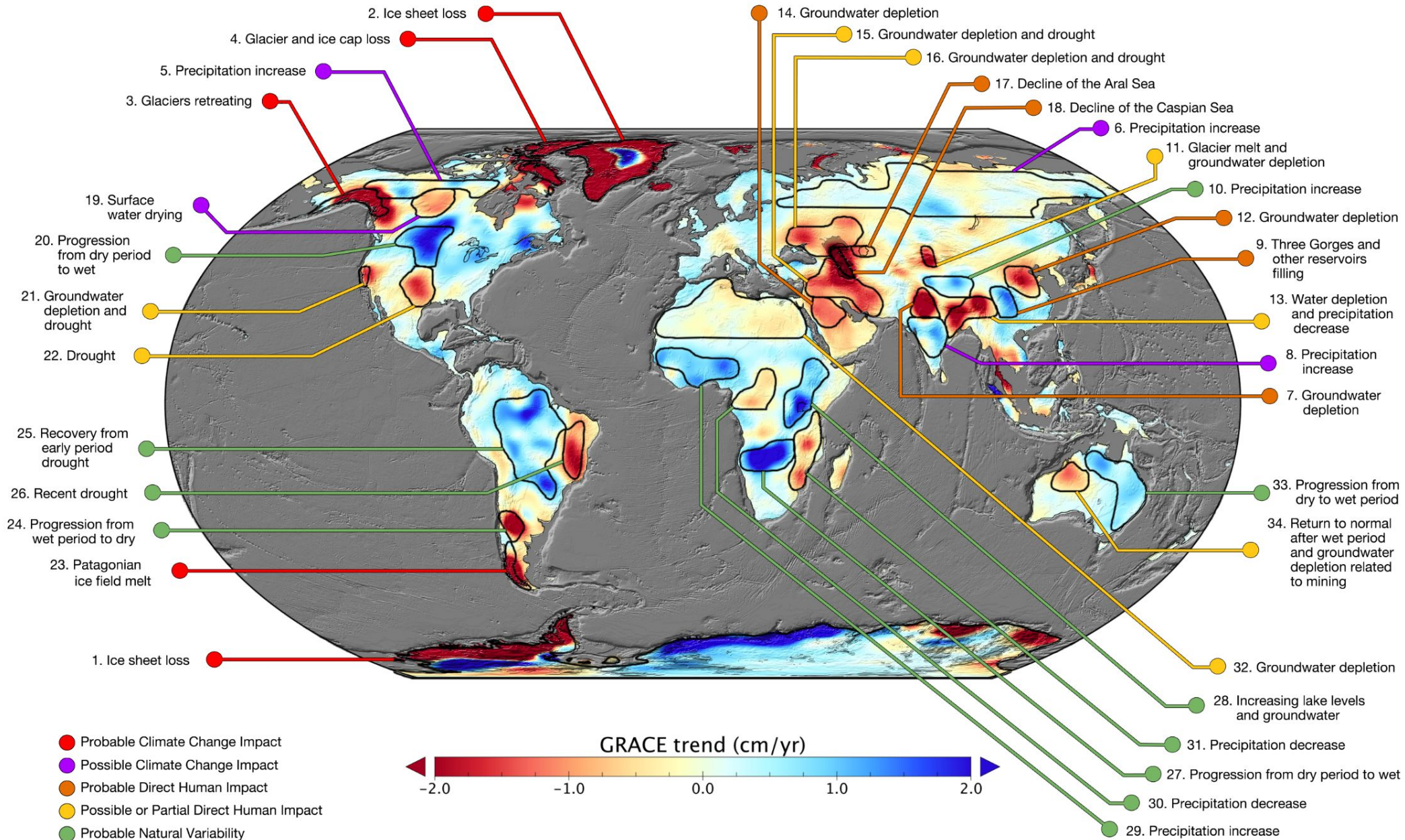
Ocean bottom pressure from GRACE is updated monthly and is provided on 1-degree global grids.





## GRACE(-FO) Applications

# Emerging Trends in Freshwater Resources Based on GRACE



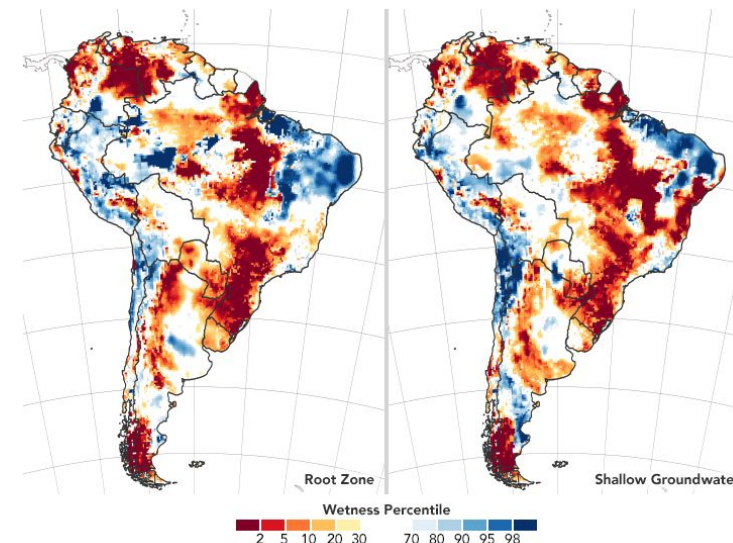
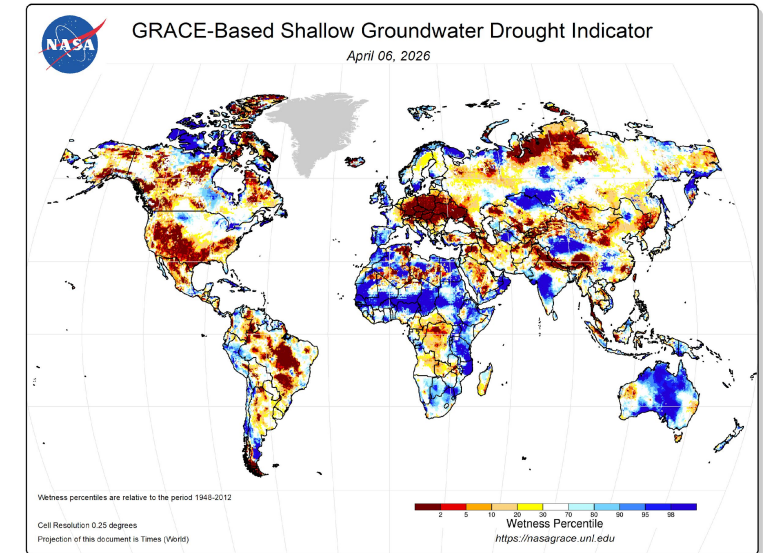
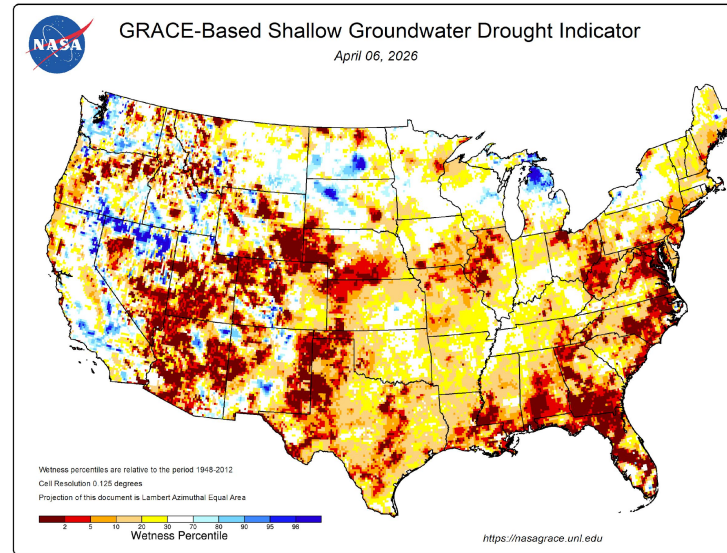
Left: Rate of Change of Terrestrial Water Storage (TWS) as an Equivalent Height of Water (cm/yr) from GRACE, 2002 - 2016

Rodell, M., J.S. Famiglietti, D.N. Wiese, J.T. Reager, H.K. Beaudoin, F.W. Landerer, and M.-H. Lo, 2018: Emerging trends in global freshwater availability, *Nature*, **557**, 651-659.



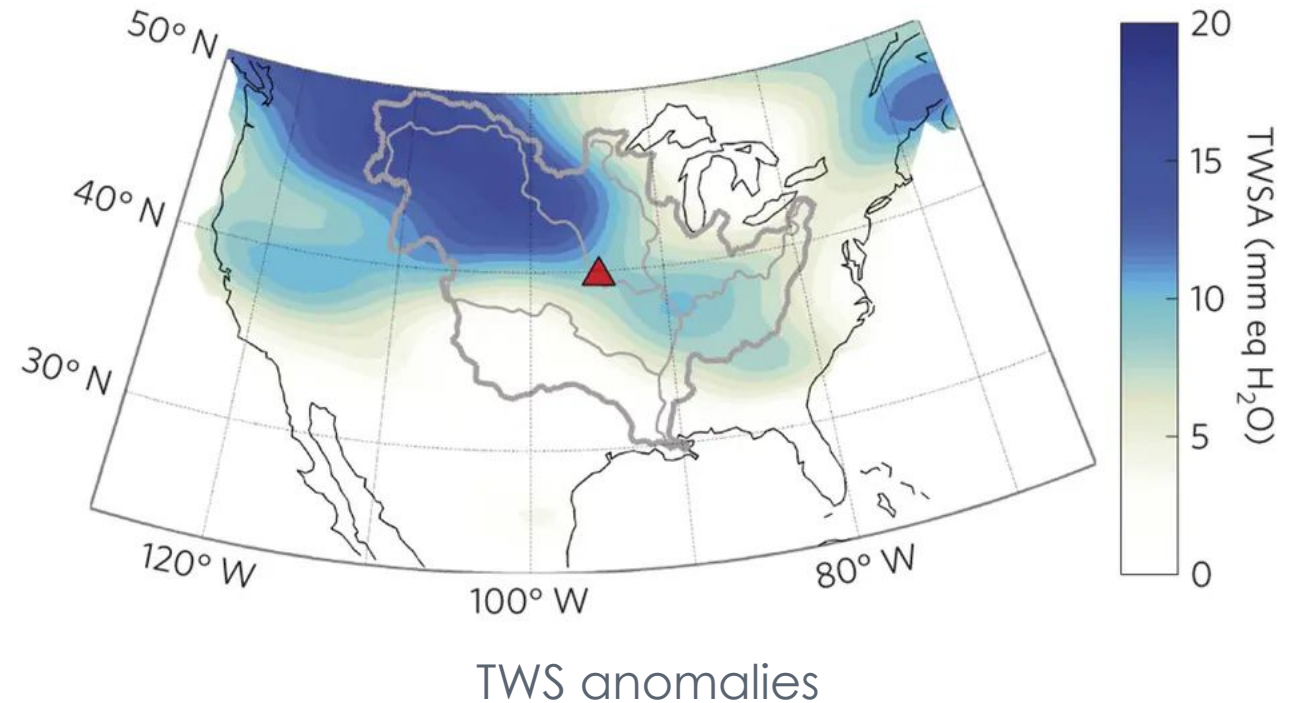
# GRACE and GRACE-FO for Drought Monitoring

- [GRACE-based Drought Indicators](#) for the continental U.S. and world
- [GRACE-FO based TWS shows drought conditions](#) in Brazil's Mato Grosso do Sul, São Paulo, and Paraná states, according to several news reports. Likewise, drought conditions are shown in northern Argentina, Chile, Colombia, and Venezuela.



# GRACE-Based Flood Potential

- GRACE observations are useful for assessing flood vulnerability [flood vulnerability](#) globally.
- GRACE TWS data indicate where levels may be near or above the capacity of the land to store water.
- Additional precipitation above the storage capacity can produce excess runoff and flooding.

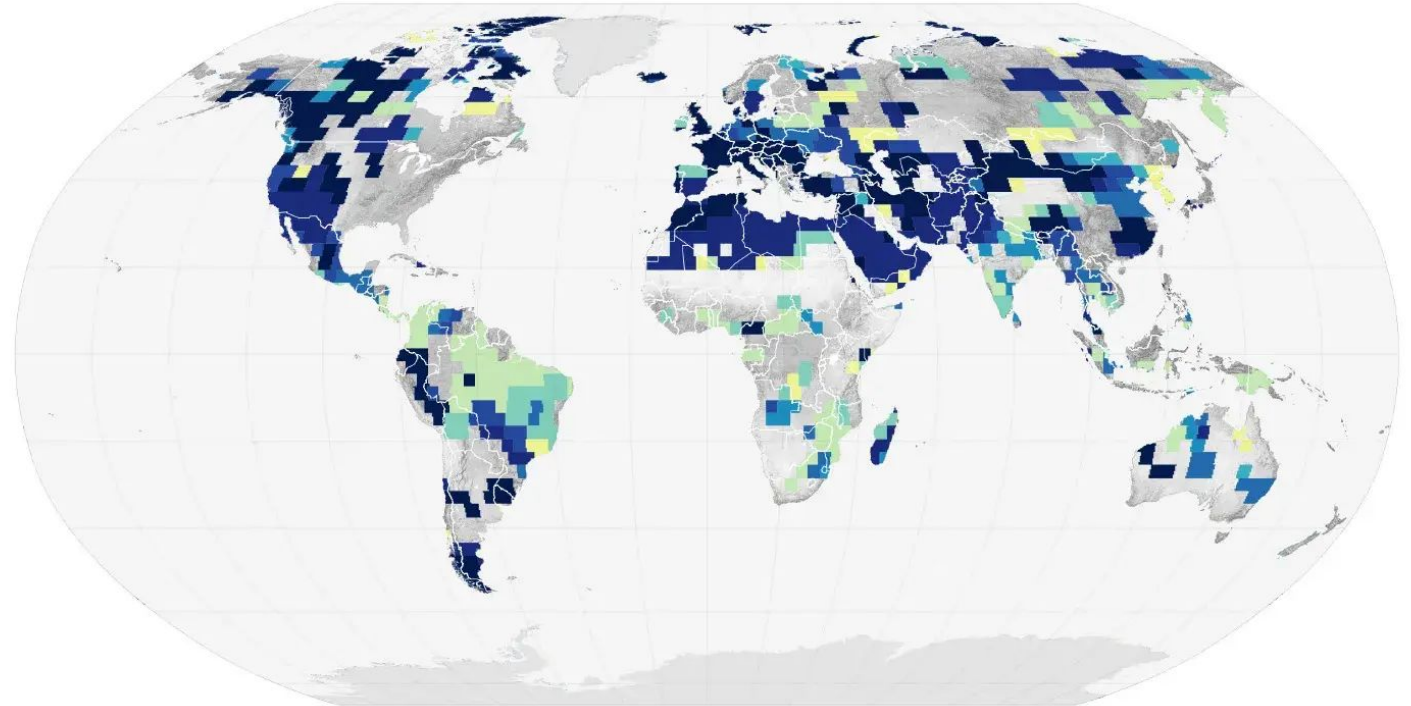


Source: Reager et al., 2014: Nature Geoscience.



# GRACE (-FO) Monitors TWS Changes Globally

- [An abrupt decline](#) in global TWS occurred in 2015
- A significantly large portion of the global land surface hit its 23-year minimum in the nine years since 2015.
- These were also the nine warmest years in the modern temperature record.

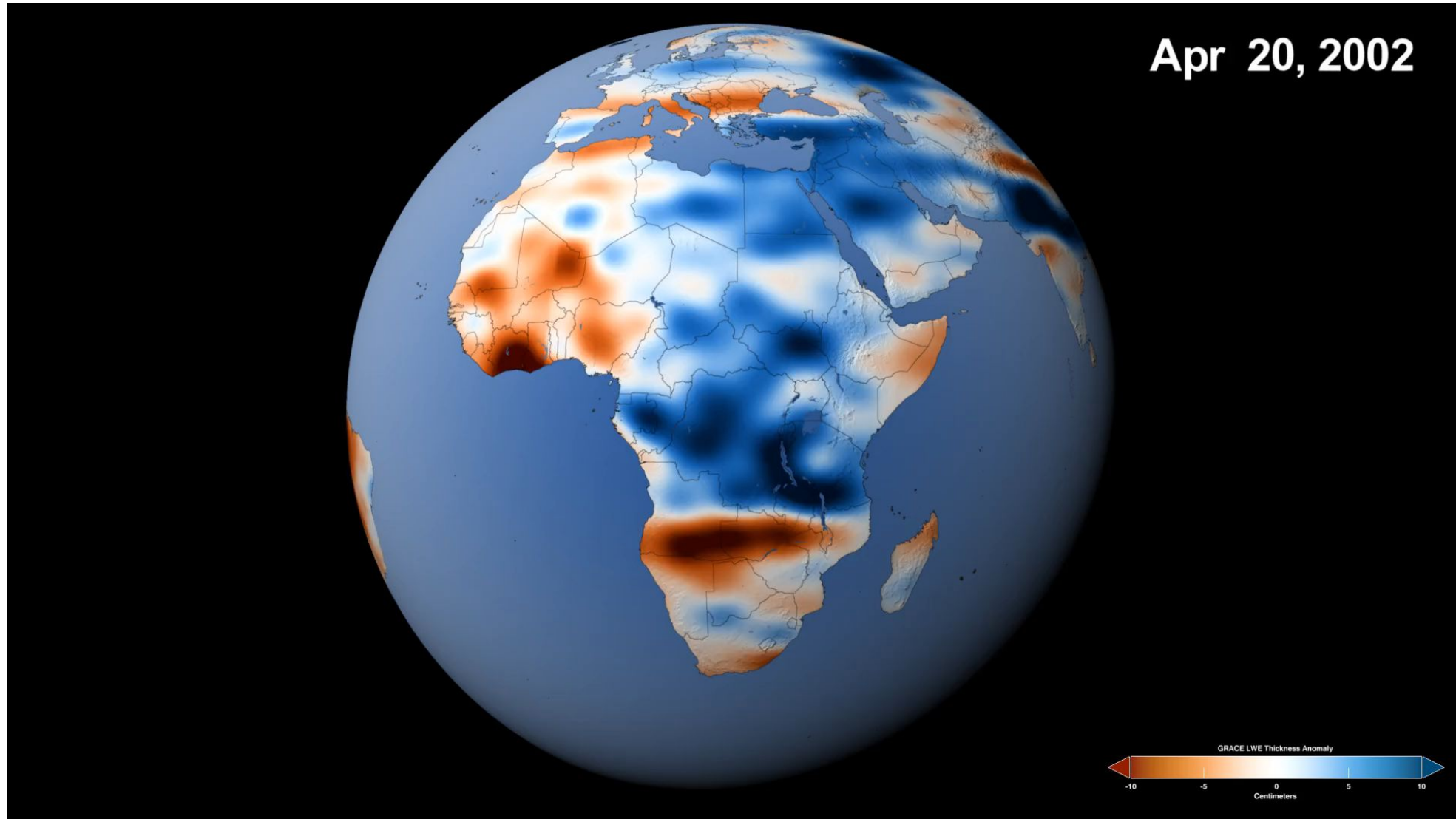


Rodell, M., and Coauthors, 2024: An abrupt decline in global terrestrial water storage and its relationship with sea level change. *Surv. Geophys.*, 45, 1875–1902, <https://doi.org/10.1007/s10712-024-09860-w>.

Image Credit: NASA Earth Observatory/ Wanmei Liang  
Data Courtesy: Mary Michael O'Neill

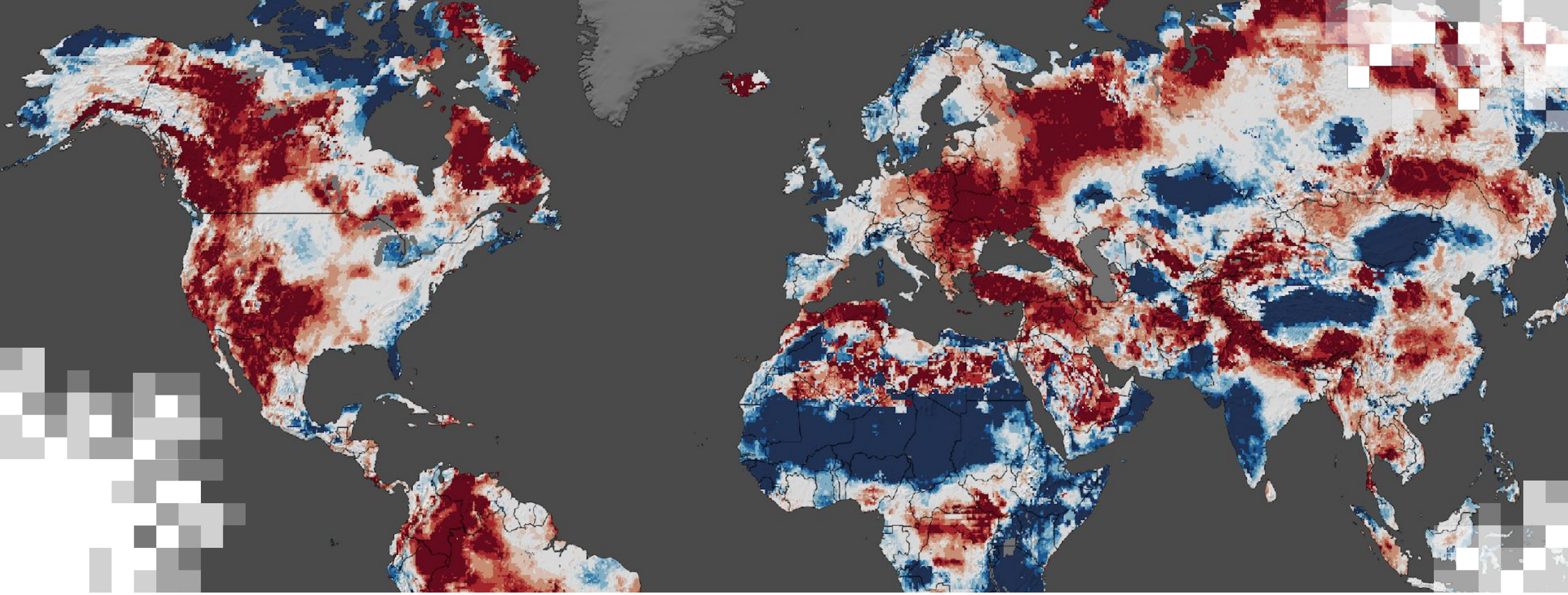


# GRACE (-FO) Tracks Terrestrial Water Storage - Africa



[NASA SVS](#)



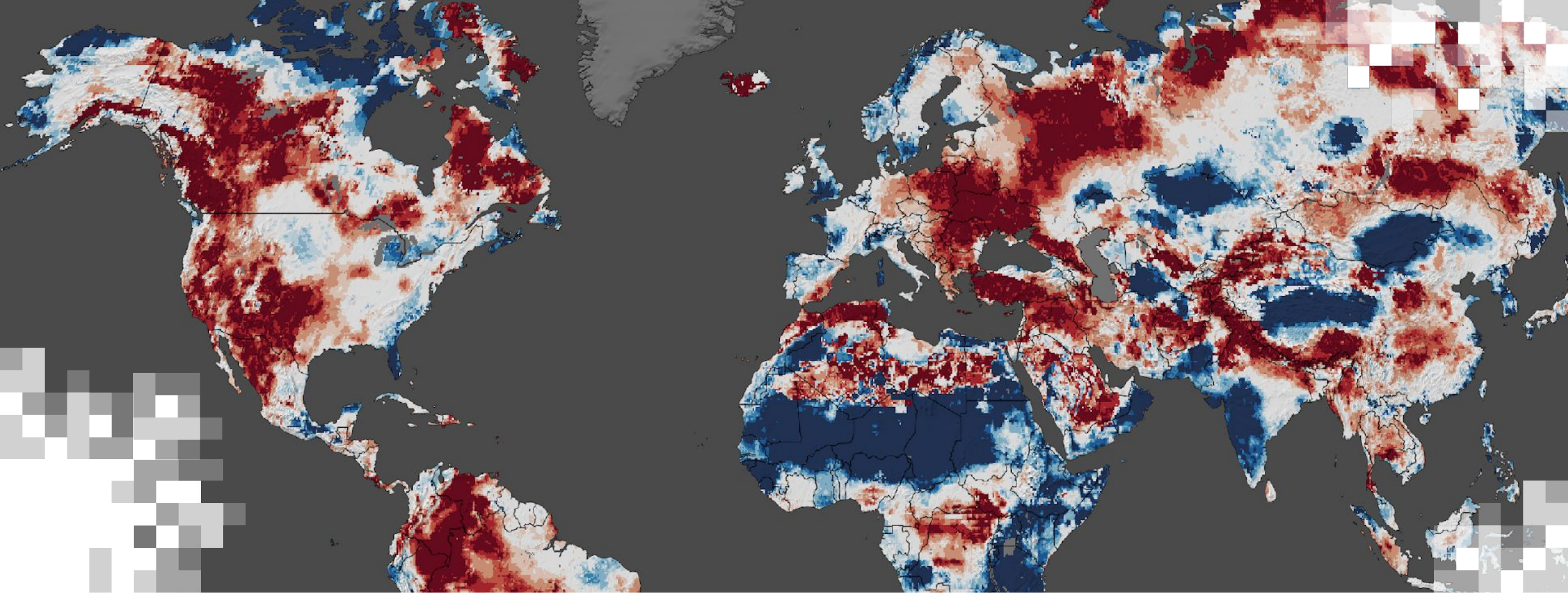


**Demonstration**  
**Terrestrial Water Storage Data Visualization:**  
**[GRACE\(-FO\) Data Analysis Tool](#)**

# Demonstration: Outline for GRACE/GRACE-FO Data Analysis Tool

- Learn to navigate the GRACE Data Analysis Tool.
- View terrestrial water storarge (TWS) maps and time series using the Data Analysis Tool.
- Examine month-by-month variations in TWS for a selected region.
  - Case Study Regions: Colorado River Basin, Ogallala Aquifer





## Part 1: Summary

## Summary: About GRACE(-FO)

- GRACE and GRACE-FO provide unique measurements of variations in mass or gravity changes over Earth's surface, producing monthly maps of the gravity field.
- These variations in gravity are primarily related to the movement of terrestrial water, and they are interpreted in terms of change in equivalent water thickness or terrestrial water storage (TWS).
- Using the GRACE TWS along with model-based hydrologic components groundwater can be estimated.
- GRACE data are used to obtain TWS and groundwater change information globally and have been useful in monitoring flood and drought conditions, and large-scale groundwater depletion.



## Summary: Limitations

- GRACE and GRACE-FO based TWS and groundwater are available globally, but the spatial resolution is  $\sim 150,000 \text{ km}^2$  and can not resolve smaller watersheds.
- The TWS or water equivalent depth are measured in cm (or mm), much smaller compared to the Earth's radius (6,378 km) and have estimated uncertainty of about 1-2 cm.
- When changes in gravity are caused by mass redistribution in the solid Earth, such as in a large earthquake or due to effects of glacial processes on the mantle, it is necessary to first remove these effects from the gravity measurements before deriving the TWS thickness.



# Looking Ahead to Part 2

- Overview of Ground Water Data from GLDAS v. 2.2



# Homework and Certificates

- **Homework:**

- One homework assignment
- Opens on 04/30/2026
- Access from the [training webpage](#)
- Answers must be submitted via Google Forms
- **Due by 05/15/2026**

- **Certificate of Completion:**

- Attend all three live webinars (attendance is recorded automatically)
- Complete the homework assignment by the deadline
- You will receive a certificate via email approximately two months after completion of the course.



# Acknowledgements

## Dr. Matthew Rodell

Deputy Director of Earth Sciences for  
Hydrosphere, Biosphere, and  
Geophysics (NASA/GSFC)



# Contact Information

## Trainers:

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- Amita Mehta
  - [amita.v.mehta@nasa.gov](mailto:amita.v.mehta@nasa.gov)

- [ARSET Website](#)
- [ARSET YouTube](#)

For questions, comments, or to share how you have applied our trainings to your work or studies, email [nasa.arset@gmail.com](mailto:nasa.arset@gmail.com)

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1. Send an email with no subject line to [arset-join@lists.nasa.gov](mailto:arset-join@lists.nasa.gov).
2. Follow the instructions sent in response.



# Resources

- [Getirana, A., M. Rodell, S. Kumar, H. K. Beaudoin, K. Arsenault, B. Zaitchik, H. Save, and S. Bettadpur, 2020: GRACE improves seasonal groundwater forecast initialization over the United States. \*J. Hydrometeor.\*, 21, 59–71.](#)
- [Landerer and Swenson, 2012: Accuracy of scaled GRACE terrestrial water storage estimates, \*WATER RESOURCES RESEARCH\*, VOL. 48, W04531.](#)
- [NCAR Climate Data Guide.](#)
- [Reager, J. T., B. F. Thomas, J. S. Famiglietti, 2014: River basin flood potential inferred using GRACE gravity observations at several months lead time. \*Nature Geoscience\*, 7\(8\), 588-592.](#)
- [Rodell, M., and J. T. Reager, 2023: Water cycle science enabled by the GRACE and GRACE-FO satellite missions. \*Nature Water\*, 1, 47–59.](#)
- [Swenson, S. C. 2012: GRACE monthly land water mass grids NETCDF RELEASE 5.0. Ver. 5.0. PO.DAAC, CA, USA.](#)





**Thank You!**

