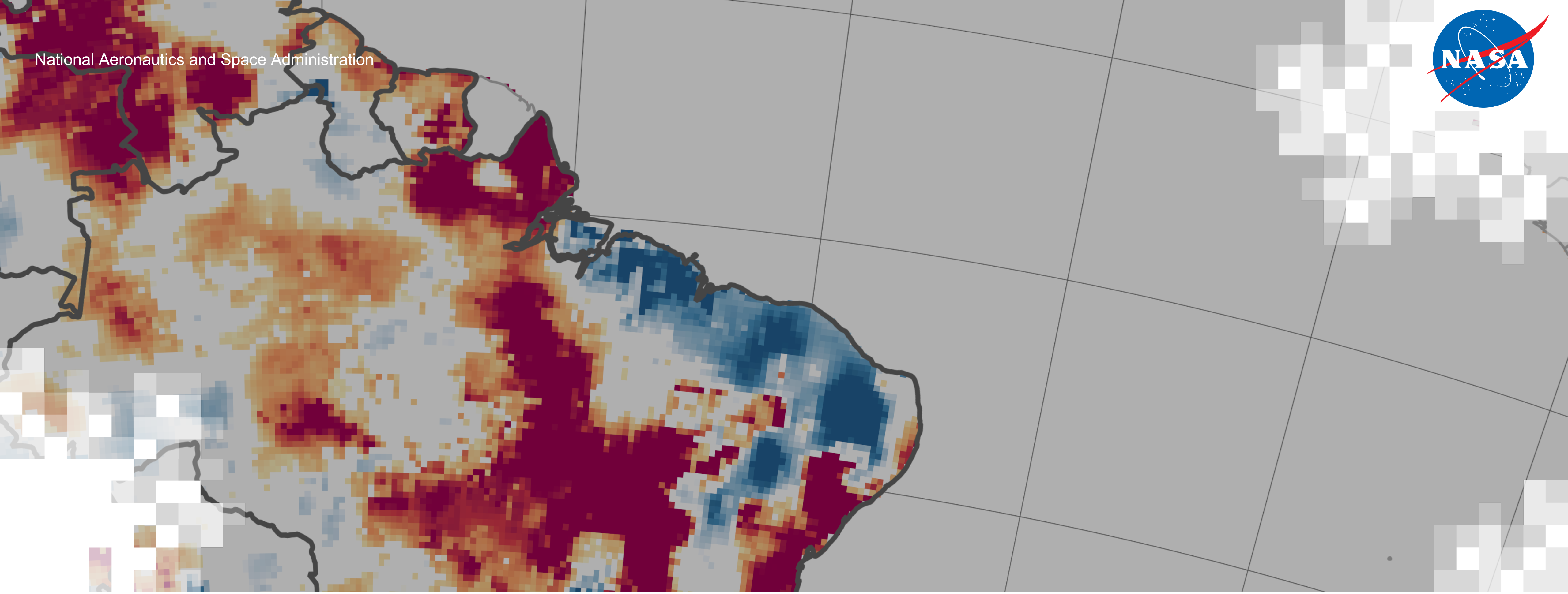
National Aeronautics and Space Administration



# Groundwater Monitoring using Observations from NASA's Gravity Recovery and Climate Experiment (GRACE) Missions

Amita Mehta, Erika Podest, Sean McCartney

June 25, 2020

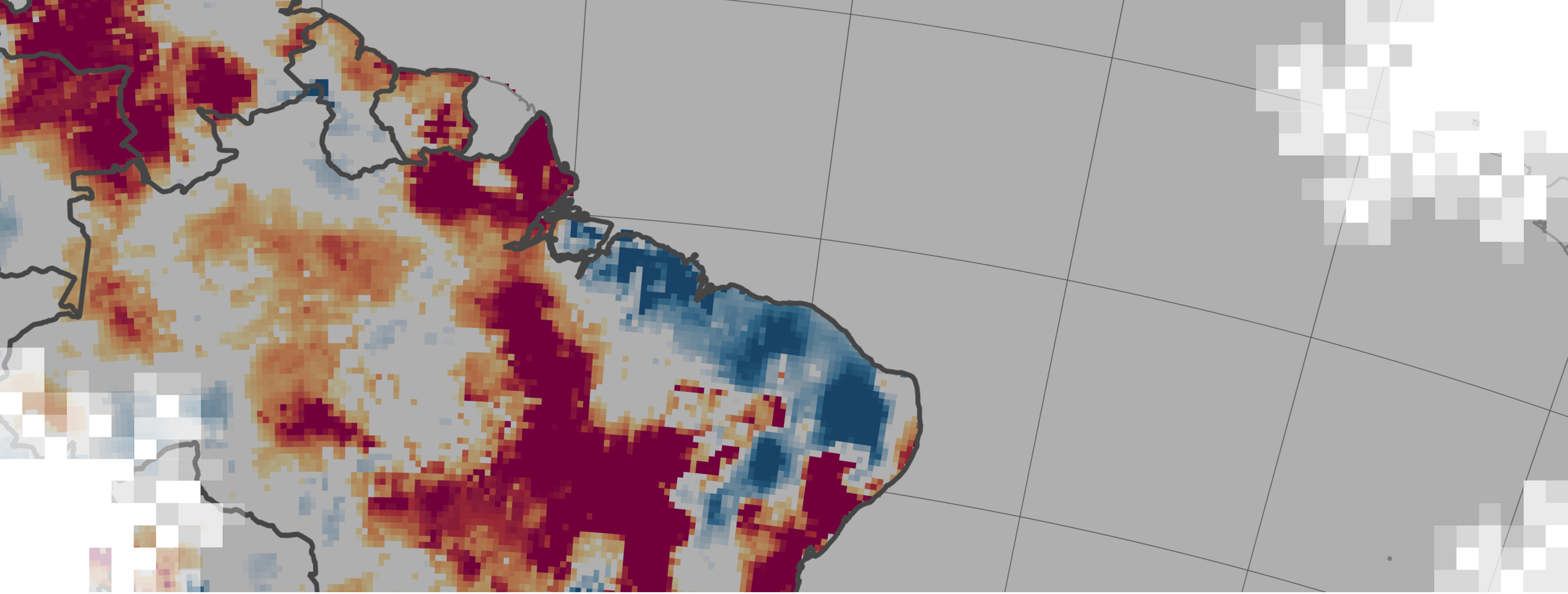
APPLIED REMOTE SENSING TRAINING PROGRAM
TRAIN - EMPOWER - ADVANCE

# Objectives

- Provide an overview of GRACE missions
- Demonstrate how to access and analyze GRACE terrestrial water storage data

# Outline

- About ARSET
- Description of Groundwater
- Overview of GRACE and GRACE-Follow On (FO) Missions
- Examples of GRACE Groundwater Applications
- Demonstration: GRACE Groundwater Data Access and Analysis

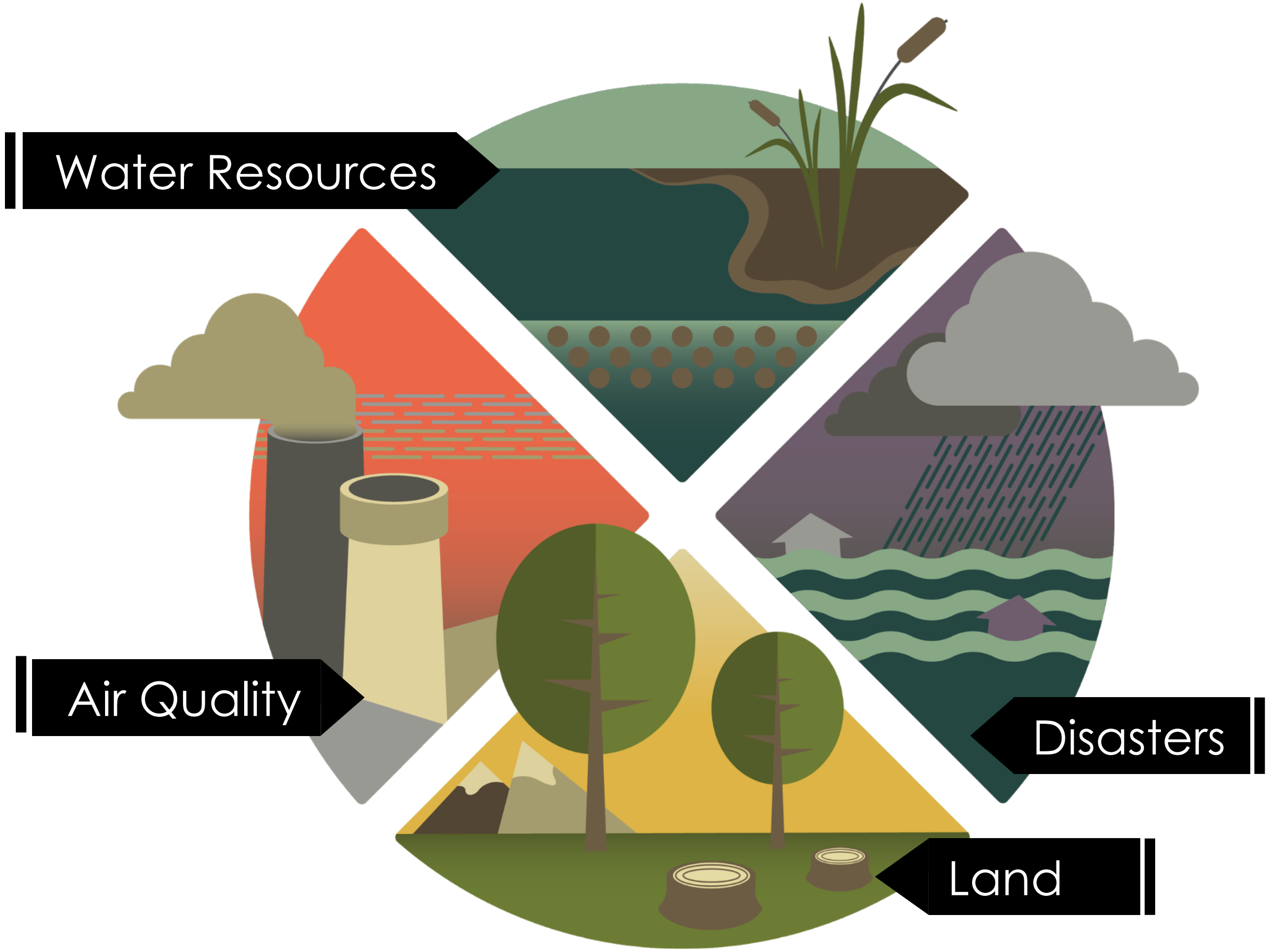


# About ARSET

# NASA's Applied Remote Sensing Training Program (ARSET)

http://arset.gsfc.nasa.gov/

- Part of NASA's Applied Sciences Capacity Building Program
- Empowering the global community through online and in-person remote sensing training
- Topics for trainings include:
  - Air Quality
  - Disasters
  - Land
  - Water Resources

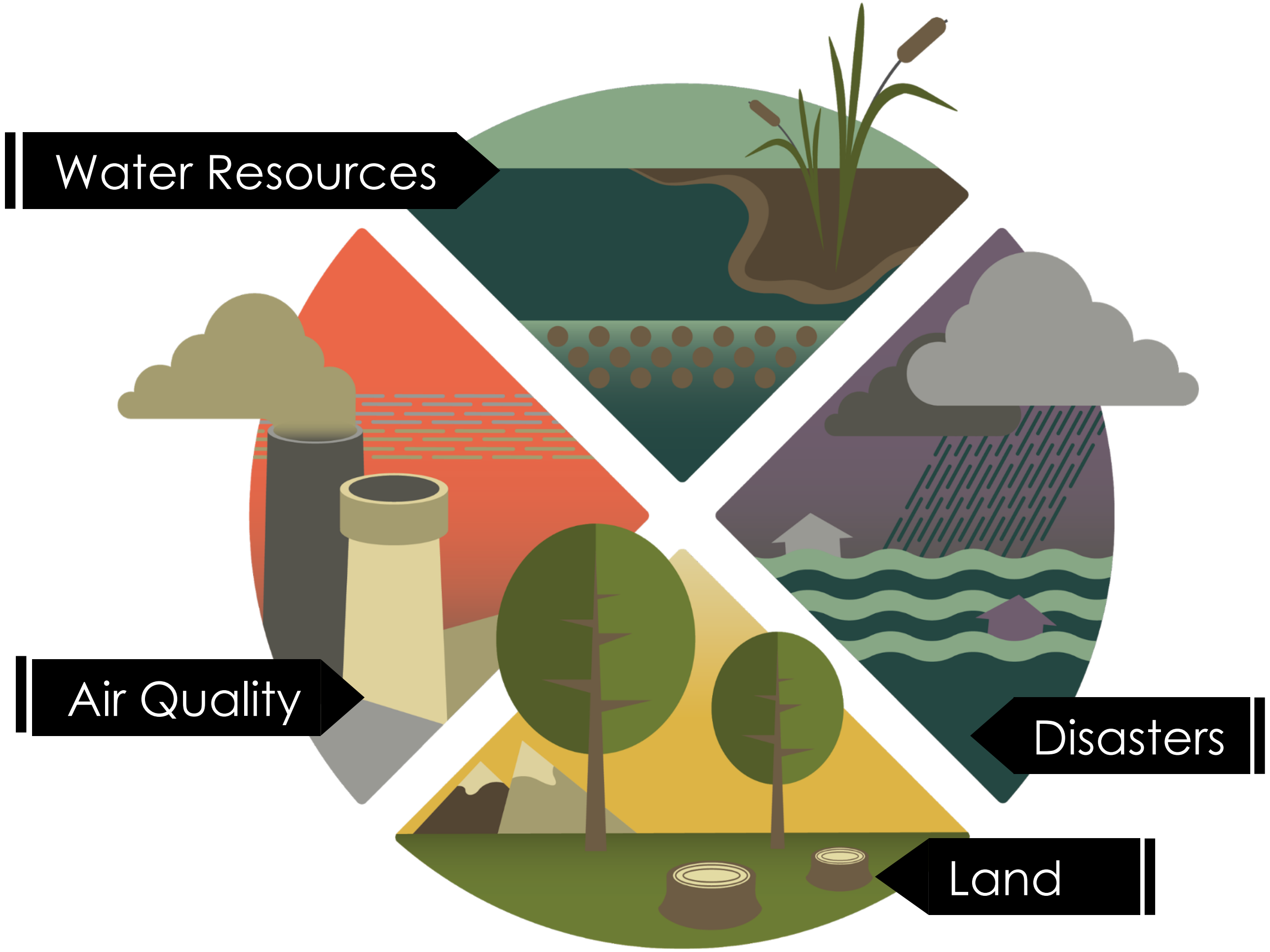


# NASA's Applied Remote Sensing Training Program (ARSET)

http://arset.gsfc.nasa.gov/

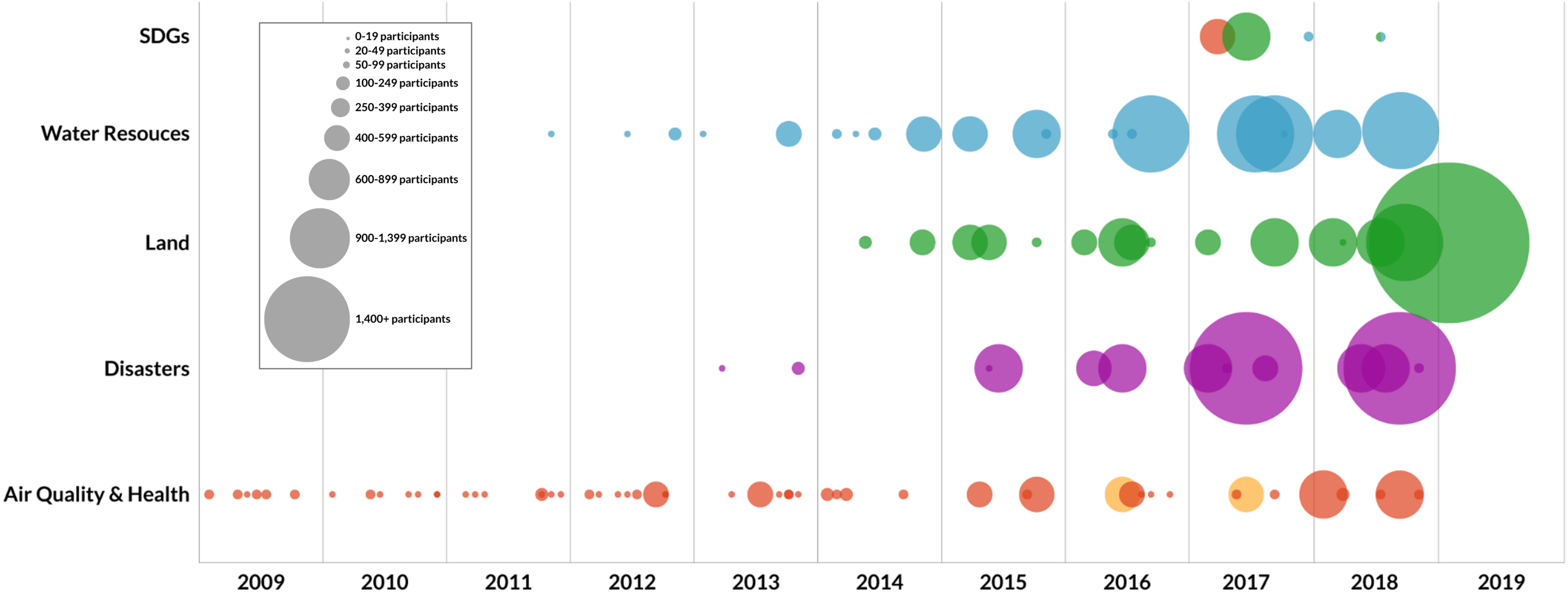
- ARSET's goal is to increase the use of Earth science in decision-making through training for:
  - Policy makers
  - Environmental managers
  - Other professionals in the public and private sector

All ARSET materials are freely available to use and adapt for your curriculum. If you use the methods and data presented in ARSET trainings, please acknowledge the NASA Applied Remote Sensing Training (ARSET) program.



# ARSET Trainings

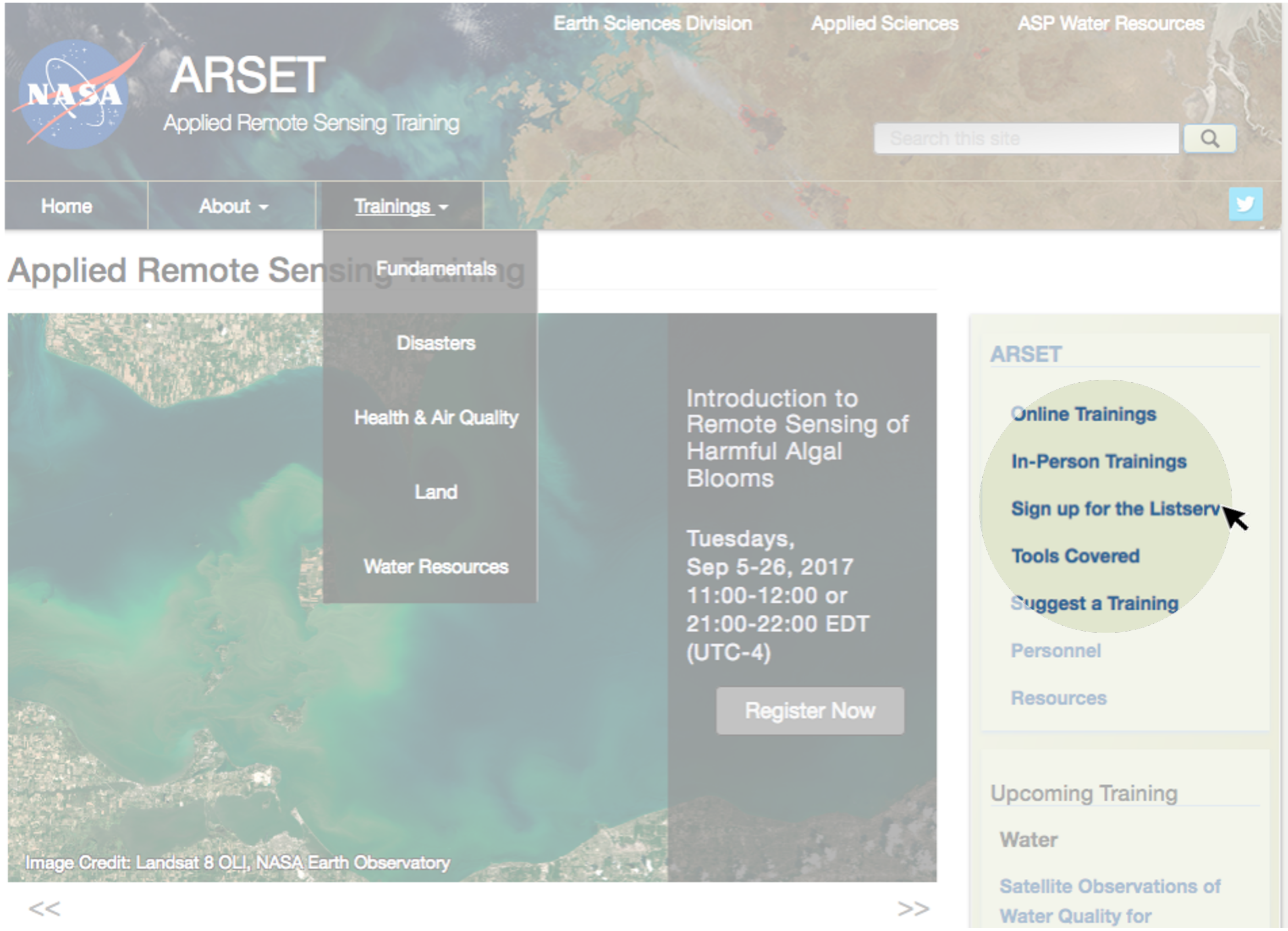
150+ trainings
40,000+ participants
170 countries
7,500+ organizations

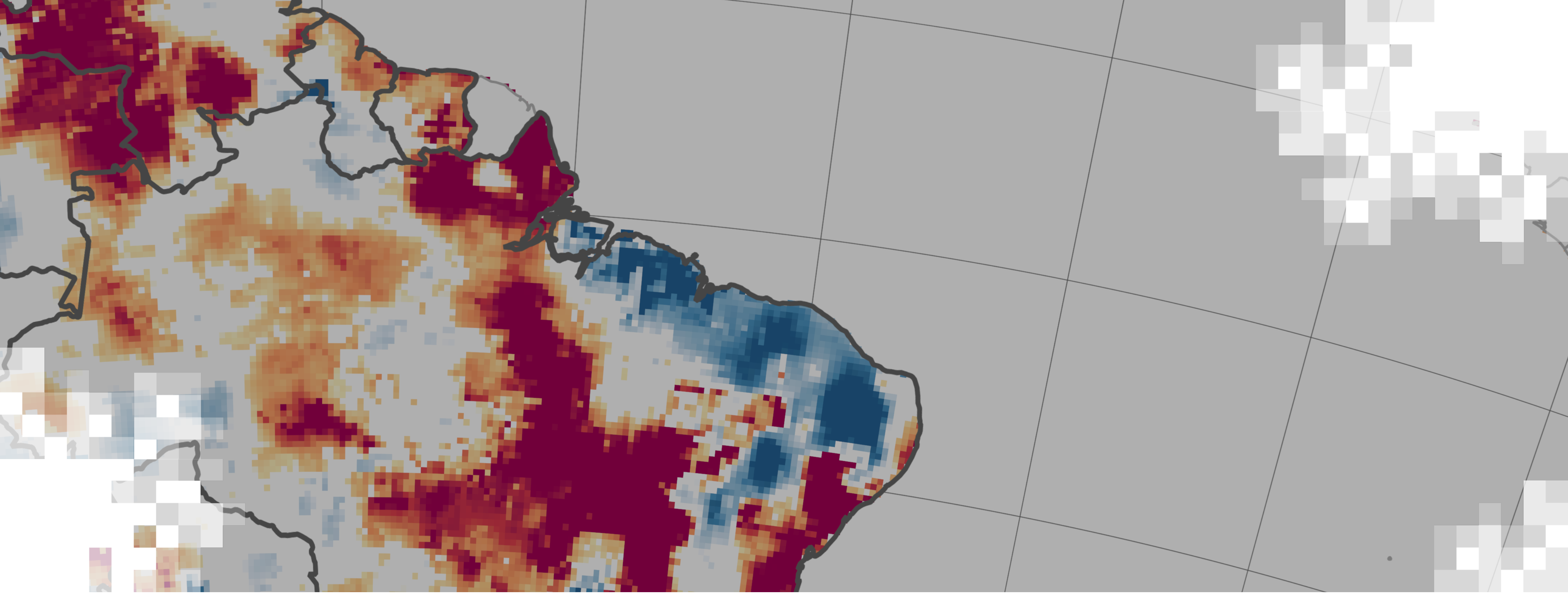



* Bubble size corresponds to number of attendees

# Learn More About ARSET

http://arset.gsfc.nasa.gov/

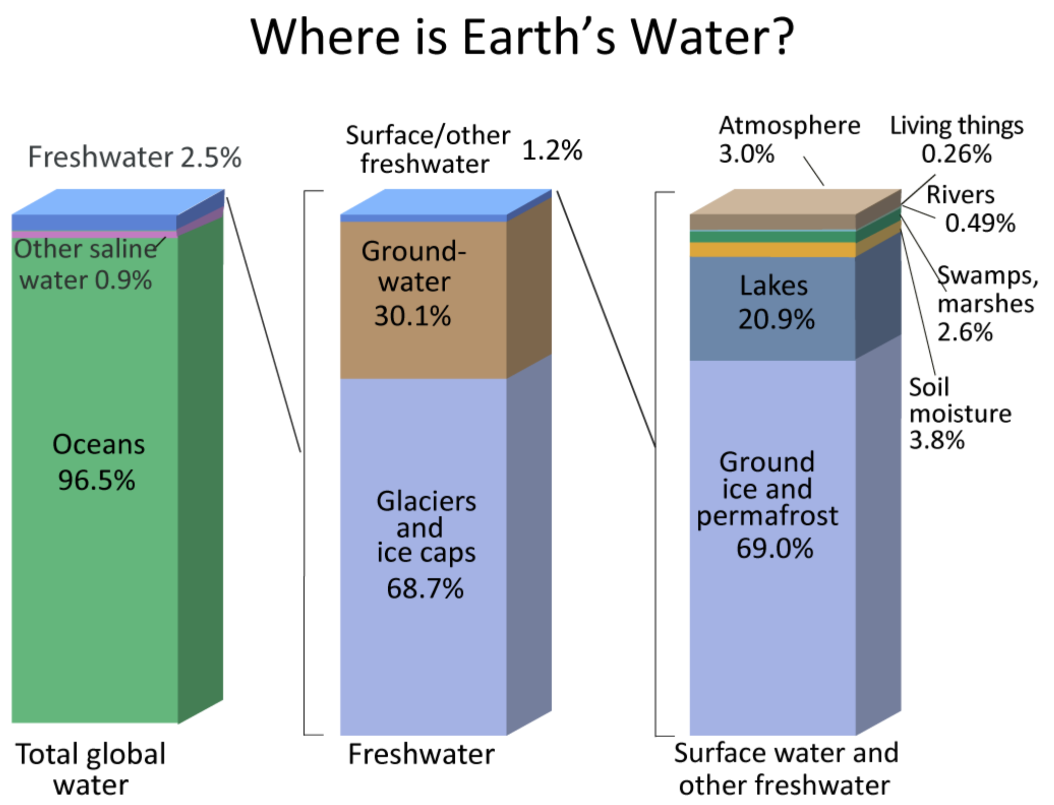




# Description of Groundwater

# What is Groundwater?

- https://www.ngwa.org/
- 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.
- Groundwater ages range from months to millions of years.



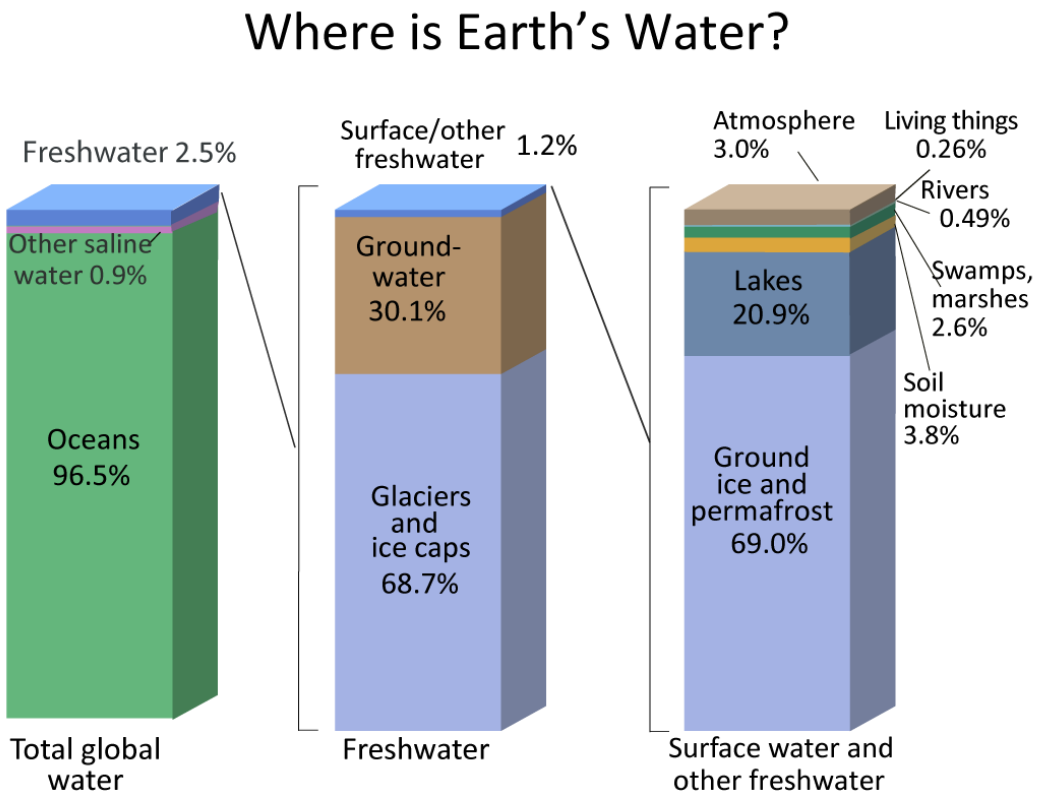

Source: Igor Shiklomanov's chapter "World fresh water resources" in Peter H. Gleick (editor), 1993, Water in Crisis: A Guide to the World's Fresh Water Resources. (Numbers are rounded).

Gleeson, T., Befus, K., Jasechko, S. *et al.* 2016: The global volume and distribution of modern groundwater. *Nature Geosci* **9**, 161–167 (2016). https://doi.org/10.1038/ngeo2590

# What is Groundwater?

- https://www.ngwa.org/
- The total groundwater volume in the upper 2 km of continental crust is approximately 22.6 million km$^3$, of which 0.1–5.0 million km$^3$ is less than 50 years old (Gleeson et al., 2016).

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




Source: Igor Shiklomanov's chapter "World fresh water resources" in Peter H. Gleick (editor), 1993, Water in Crisis: A Guide to the World's Fresh Water Resources. (Numbers are rounded).

# Groundwater Usage

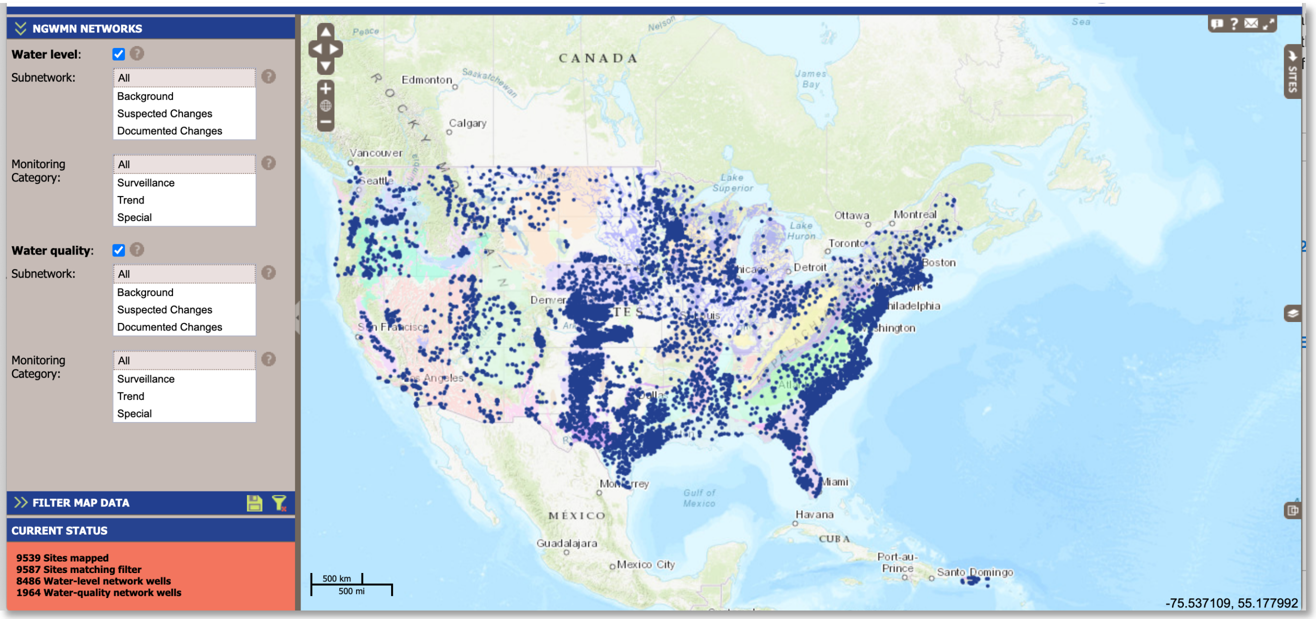
- https://www.ngwa.org/
- Globally about 50% of drinking water is obtained from groundwater withdrawal.
- Approximately 70% of the groundwater withdrawal is used for agriculture.
- Globally, about 38% of land uses groundwater for irrigation.
- Monitoring groundwater is crucial for water resources management.

**The 15 nations with the largest estimated annual groundwater extractions (2010)[7] are:**

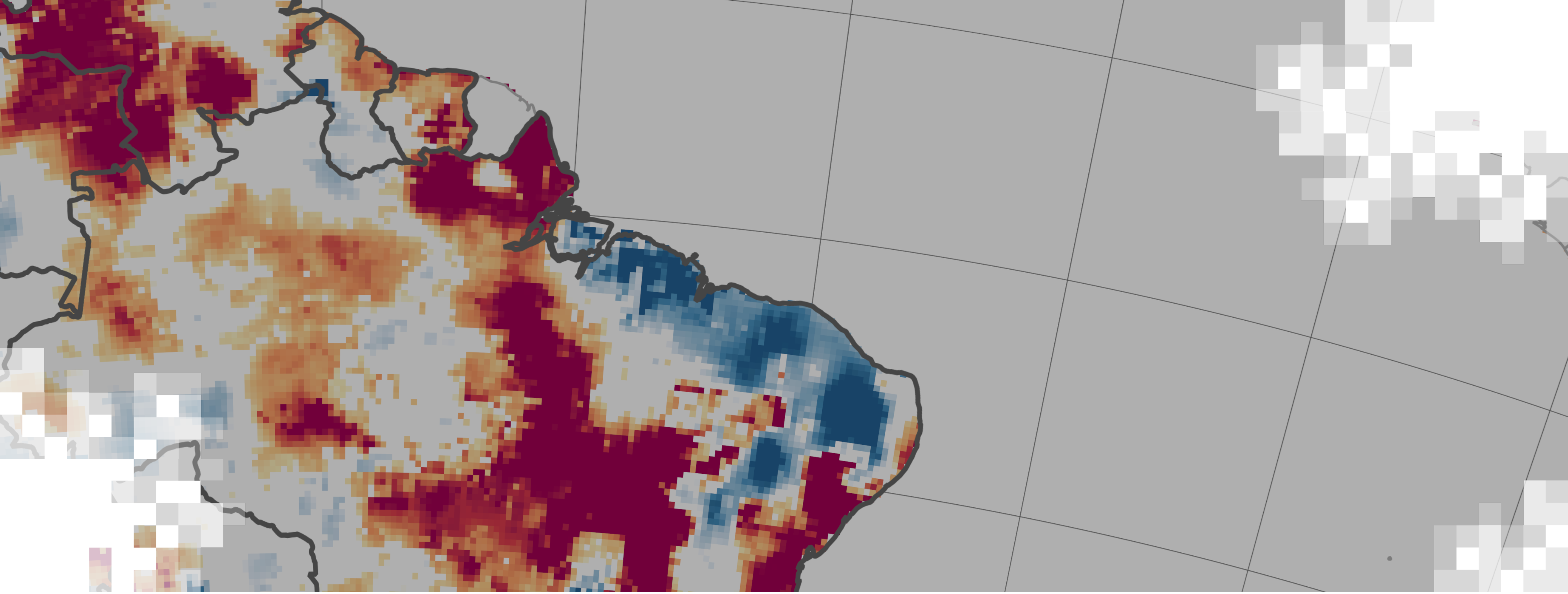
| Country | Population 2010 (in thousands) | Groundwater extraction | | | |
|---|---|---|---|---|---|
| | | Estimated groundwater extraction 2010 (km³/yr) | Breakdown by sector | | |
| | | | Groundwater extraction for irrigation (%) | Groundwater extraction for domestic use (%) | Groundwater extraction for industry (%) |
| India | 1224614 | 251.00 | 89 | 9 | 2 |
| China | 1341335 | 111.95 | 54 | 20 | 26 |
| United States | 310384 | 111.70 | 71 | 23 | 6 |
| Pakistan | 173593 | 64.82 | 94 | 6 | 0 |
| Iran | 73974 | 63.40 | 87 | 11 | 2 |
| Bangladesh | 148692 | 30.21 | 86 | 13 | 1 |
| Mexico | 113423 | 29.45 | 72 | 22 | 6 |
| Saudi Arabia | 27448 | 24.24 | 92 | 5 | 3 |
| Indonesia | 239871 | 14.93 | 2 | 93 | 5 |
| Turkey | 72752 | 13.22 | 60 | 32 | 8 |
| Russia | 142985 | 11.62 | 3 | 79 | 18 |
| Syria | 20411 | 11.29 | 90 | 5 | 5 |
| Japan | 126536 | 10.94 | 23 | 29 | 48 |
| Thailand | 69122 | 10.74 | 14 | 60 | 26 |
| Italy | 60551 | 10.40 | 67 | 23 | 10 |

# Monitoring Groundwater

- 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 have been used to estimate monthly, total surface, and groundwater depth since 2002 at a resolution of ~150,000 km$^2$.
- These measurements are used to derive global, large-scale groundwater distribution by using additional hydrological information.



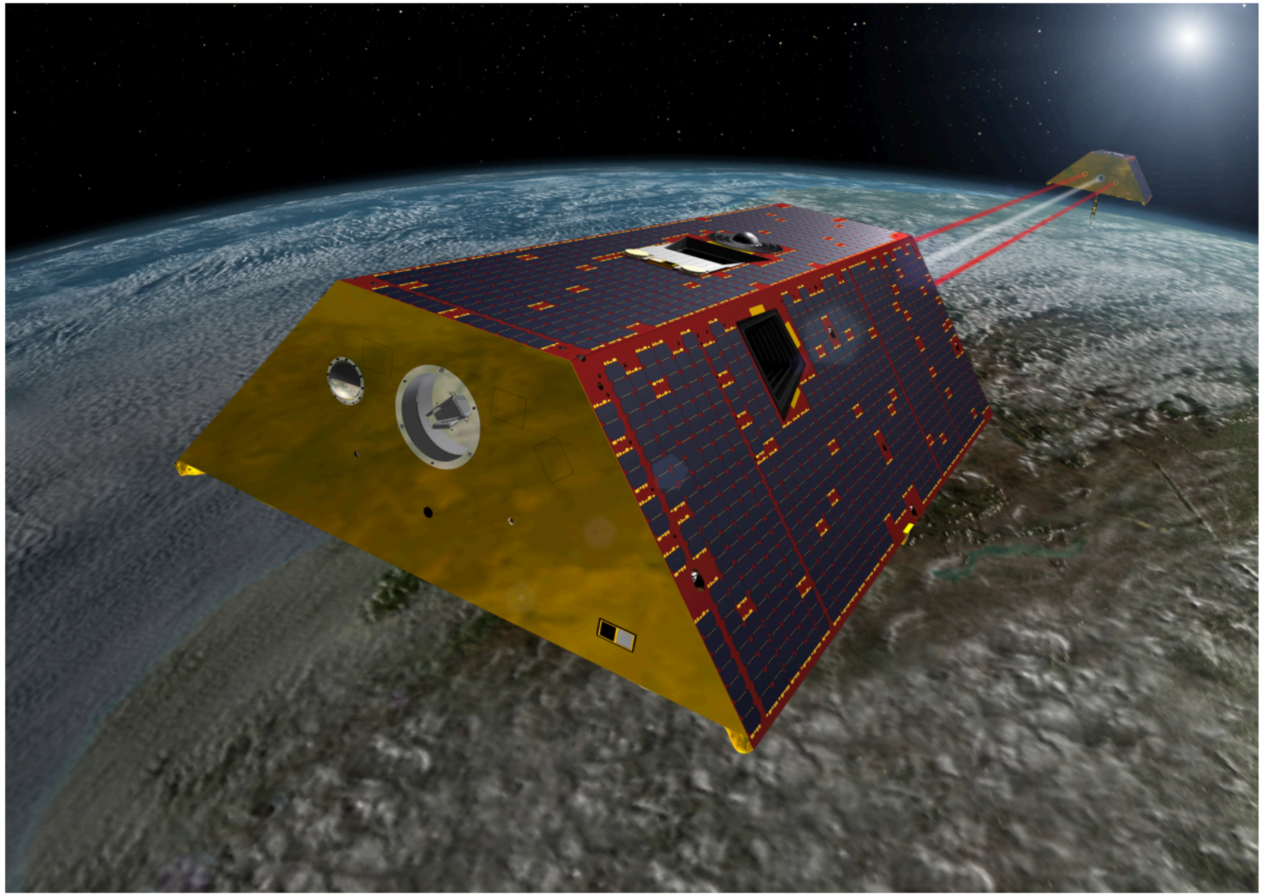

https://cida.usgs.gov/ngwmn/index.jsp



# Overview of GRACE & GRACE-FO Missions

# GRACE & GRACE-FO

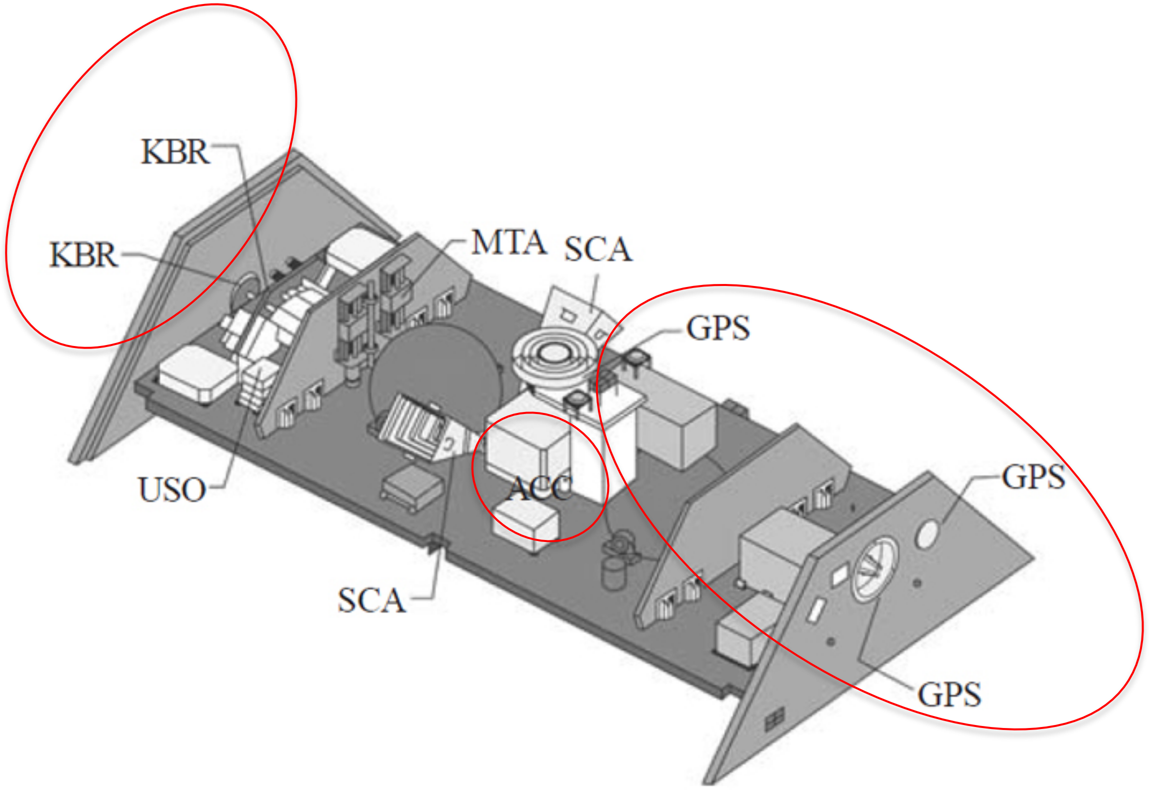
- https://grace.jpl.nasa.gov/mission/grace/
- https://gracefo.jpl.nasa.gov/mission/overview/
- GRACE and GRACE-FO are joint satellite missions between NASA and the German Aerospace Center (DLR).
- Both are twin satellite systems in polar, sun-synchronous orbits.
- Each consists of two identical satellites orbiting about 220 km apart.



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

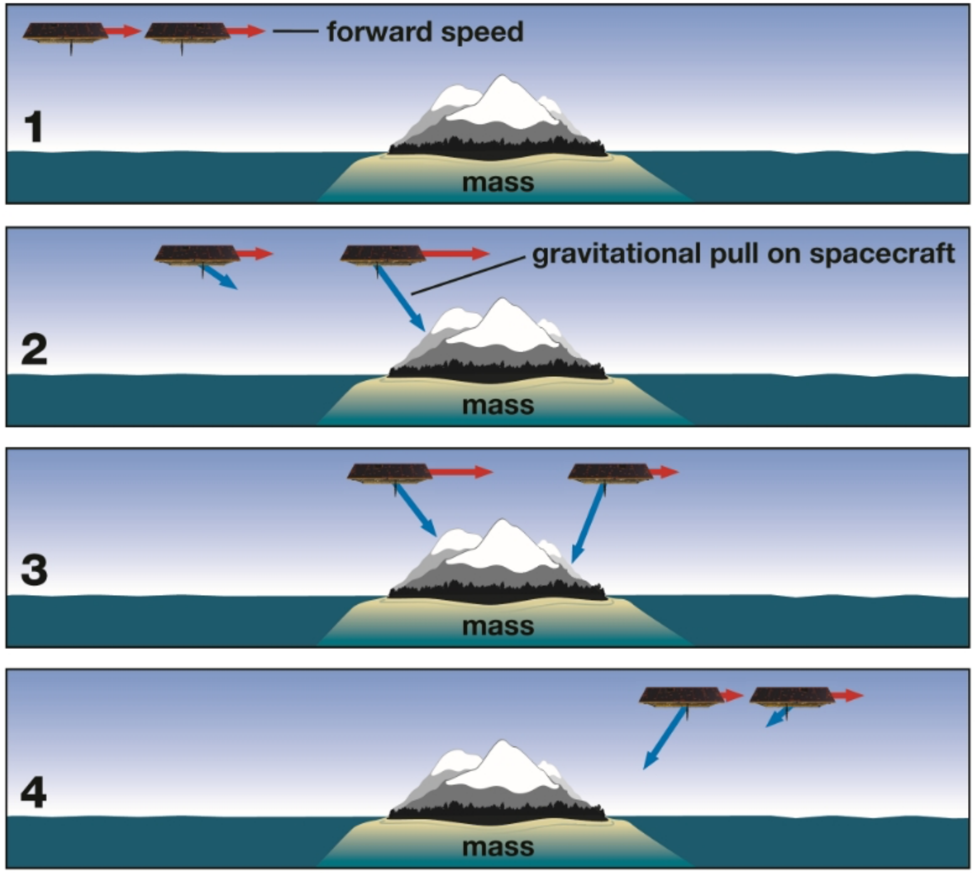
- https://grace.jpl.nasa.gov/mission/grace/
- https://gracefo.jpl.nasa.gov/mission/overview/
- Provides global coverage
- GRACE: March 17, 2002 to October 12, 2017
- GRACE-FO: May 22, 2018 to present
- Primary Sensors:
  - Microwave K-band Ranging Instrument
  - Accelerometers
  - Global Positioning System Receivers




https://www.nasa.gov/mission_pages/Grace/spacecraft/index.html

# GRACE & GRACE-FO Measurements

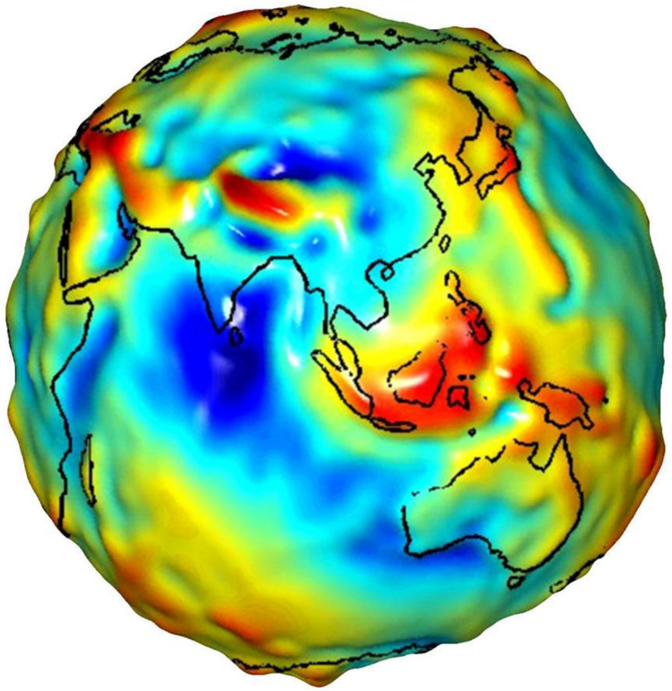
- As the twin satellites orbit around the Earth, the distance between them is affected by gravity anomalies (change in mass concentration).
- The microwave ranging system is designed to measure these variations with high precision.
- The Global Positioning System (GPS) receivers determine the exact position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




https://gracefo.jpl.nasa.gov/resources/50/how-grace-fo-measures-gravity/

# From Gravity to Terrestrial Water

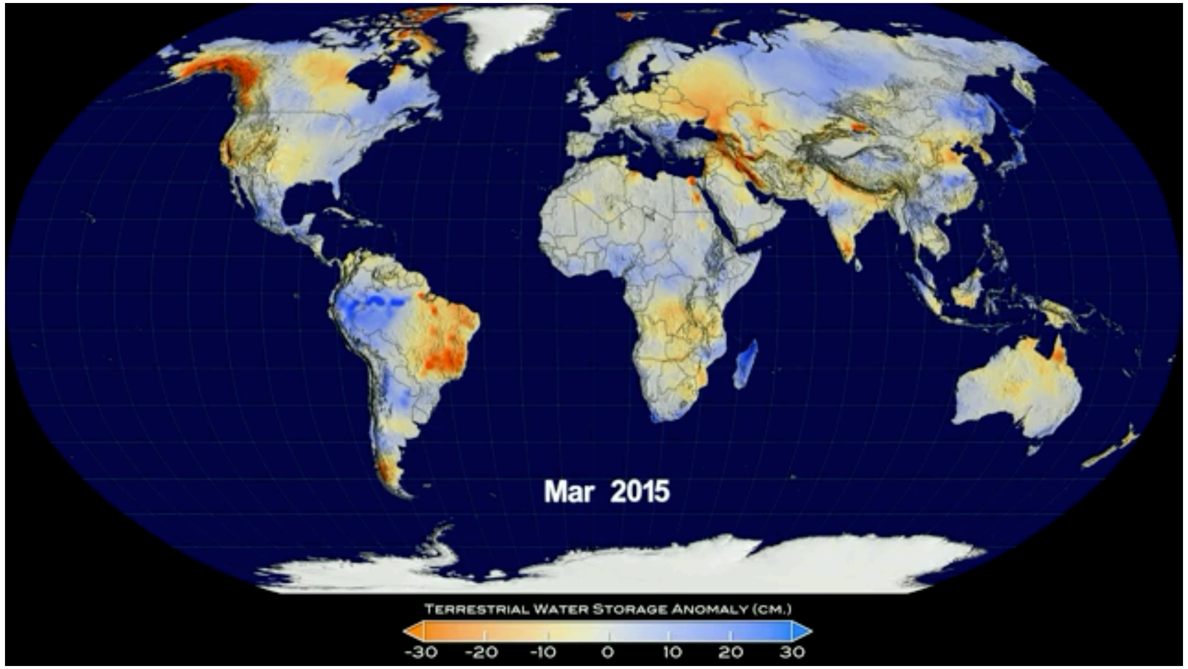
- https://earthobservatory.nasa.gov/features/GRACEGroundwater
- Fundamentals of physics are used to translate GRACE measurements (distance between the satellites) to gravity or mass concentration.
- Subtle shifts in Earth's gravity occur, primarily dominated by water movements from one place to another on and under land, in the ocean, and in the atmosphere.
- Variations in gravity observed by GRACE are interpreted as terrestrial water storage (TWS) changes.



# GRACE Terrestrial Water Storage Data

- https://podaac-tools.jpl.nasa.gov/drive/files/allData/grace/docs/ProdSpecDoc_v4.6.pdf
- GRACE collects about 250 gravity profiles per day.
- GRACE Level-2 gravity products are derived by collecting data for several days. Together with other ancillary data, gravity spherical harmonics coefficients are derived.
- Based on the Level-2 data, monthly mass anomalies (departure from mean mass) are derived indicating anomalies in TWS.

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




https://svs.gsfc.nasa.gov/cgi-bin/details.cgi?aid=4476&button=recent

# GRACE Terrestrial Water Storage Data

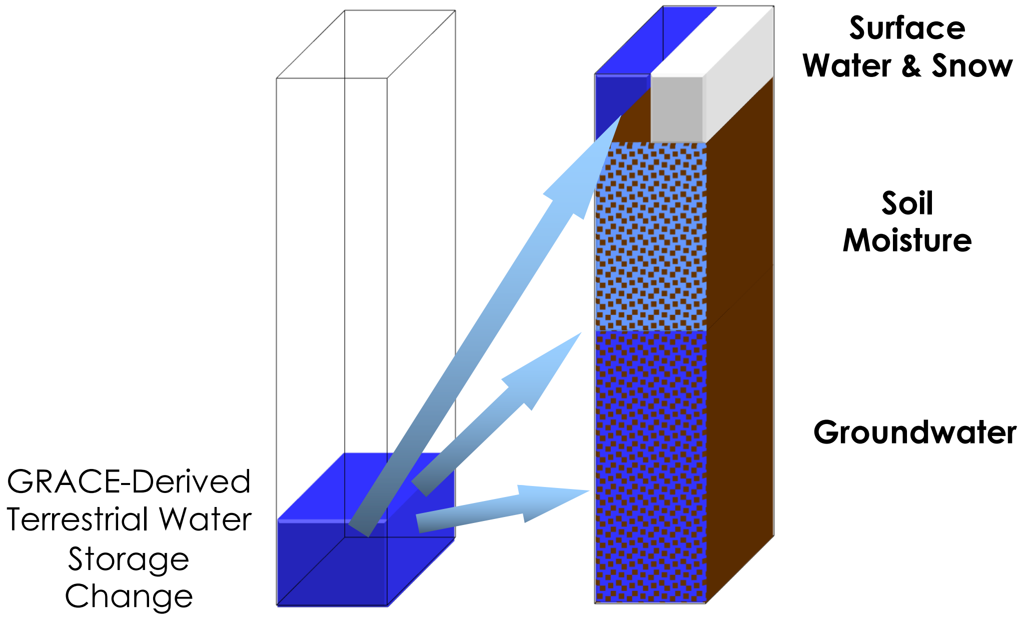
- The TWS data are provided in cm of equivalent water thickness.
- GRACE Level-2 data are available at a spatial resolution of 300-400 km grids (~150,000 km$^2$).
- These data are further gridded at 0.5°x0.5° resolutions (https://grace.jpl.nasa.gov/data/get-data/jpl_global_mascons/).
- Monthly TWS data are available at 1°x1° and 0.5°x0.5° resolutions.
- The resulting errors in monthly TWS anomalies are estimated to be 2-3 cm at the 1°x1° resolution.

**Literature**


1. Landerer and Swenson, 2012: Accuracy of scaled GRACE terrestrial water storage estimates, WATER RESOURCES RESEARCH, VOL. 48, W04531, doi:10.1029/2011WR011453
2. S.C. Swenson. 2012. GRACE monthly land water mass grids NETCDF RELEASE 5.0. Ver. 5.0. PO.DAAC, CA, USA. Dataset accessed [YYYY-MM-DD] at http://dx.doi.org/10.5067/TELND-NC005
3. https://climatedataguide.ucar.edu/climate-data/grace-gravity-recovery-and-climate-experiment-surface-mass-total-water-storage-and

# From Terrestrial Water to Groundwater

- Terrestrial water is a sum of atmospheric water, surface water, and groundwater.
- GRACE measures total column terrestrial water (TWS) and cannot distinguish between water stored as snow, soil moisture, and groundwater.
- Differences between TWS anomalies and changes in water storage determined by land surface models allow for vertical disaggregation of the GRACE measurements.

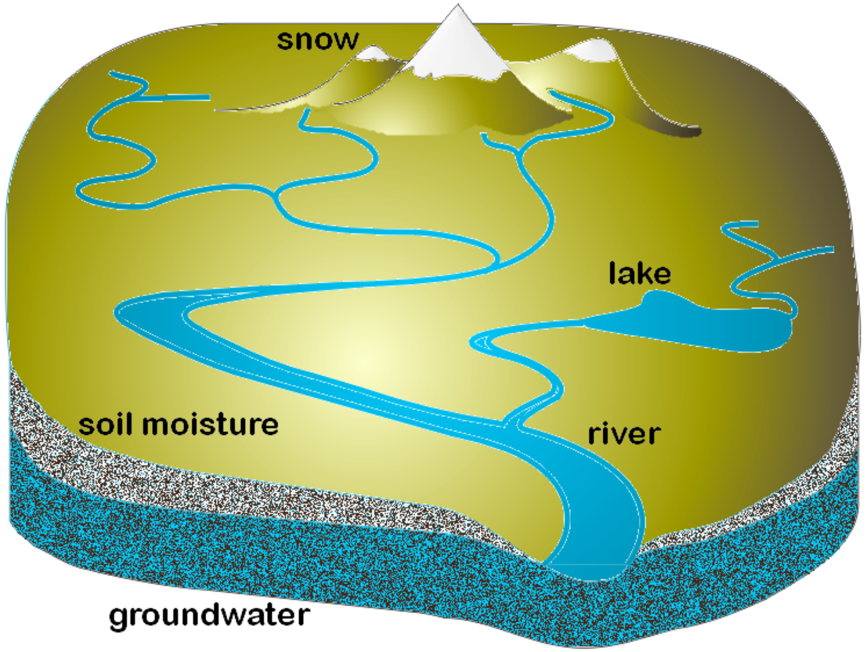


# From Terrestrial Water to Groundwater

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

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

$\mathbf{\Delta GW = \Delta TWS - \Delta SM - \Delta SWE - \Delta SW}$



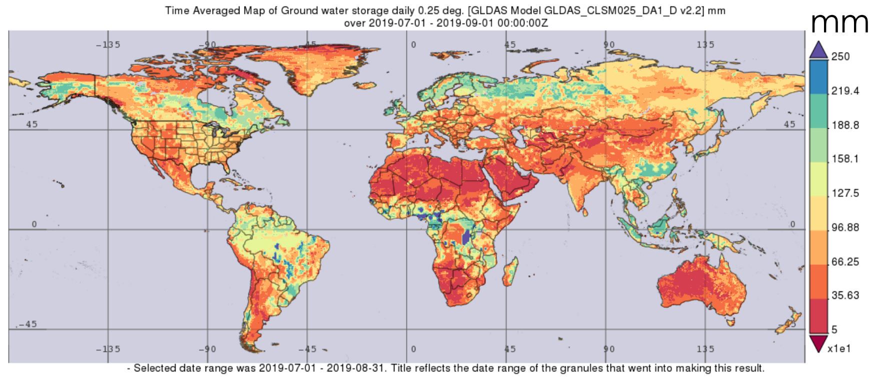

$P$ = precipitation
$ET$ = evapotranspiration
$Q$ = river discharge
**ΔTWS** = **change in terrestrial water storage [from GRACE]**
$\Delta GW$ = change in groundwater storage [unknown]
$\Delta SM$ = change in soil moisture $\Delta SWE$ = change in snow water equivalent
$\Delta SW$ = change in surface water storage
[$\Delta GW$, $\Delta SM$, $\Delta SW$ from Global Land Data Assimilation System (GLDAS) models]

Courtesy: John Bolten, NASA-GSFC

# From Terrestrial Water to Groundwater

- To get groundwater data from GRACE TWS data, soil moisture, surface water, and snow-water equivalent data from Global Land Data Assimilation (GLDAS) are used.
- Details of LDAS models are available from https://arset.gsfc.nasa.gov/sites/default/files/land/20-Ag-Training/Ag_Training_Part2_Consolidated_Final.pdf
- GLDAS Version 2.2 assimilates GRACE TWS data and provides all the water budget components, including groundwater.

GLDAS-v2.2 Groundwater Storage

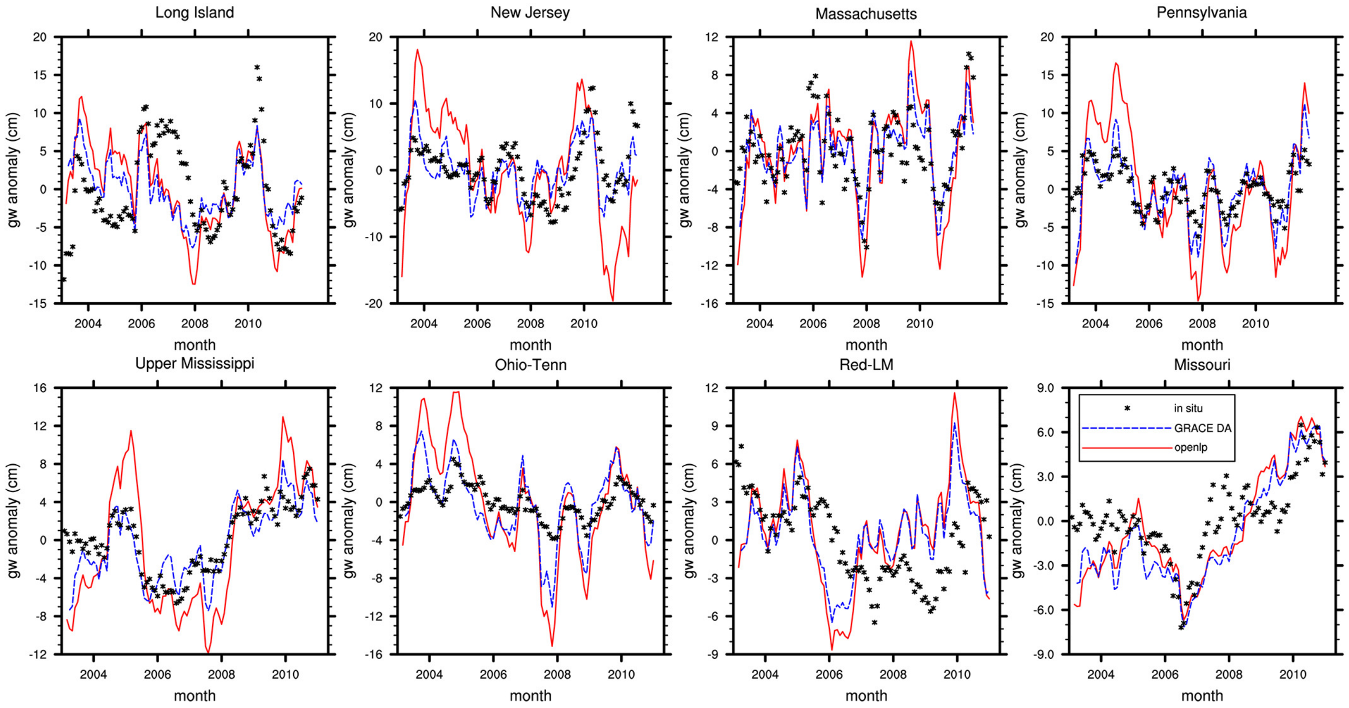



Average of June-July-August 2019

Kumar et al., 2016: Assimilation of gridded GRACE terrestrial water storage estimates in the North American Land Data Assimilation System, DOI: 10.1175/jhm-d-15-0157.1
Li et al., 2019: Global GRACE data assimilation for groundwater and drought monitoring: Advances and challenges, DOI: 10.1029/2018wr024618
Zaitchik et al., 2008: Assimilation of GRACE terrestrial water storage data into a land surface model: results for the Mississippi River Basin, DOI: 10.1175/2007JHM951.1

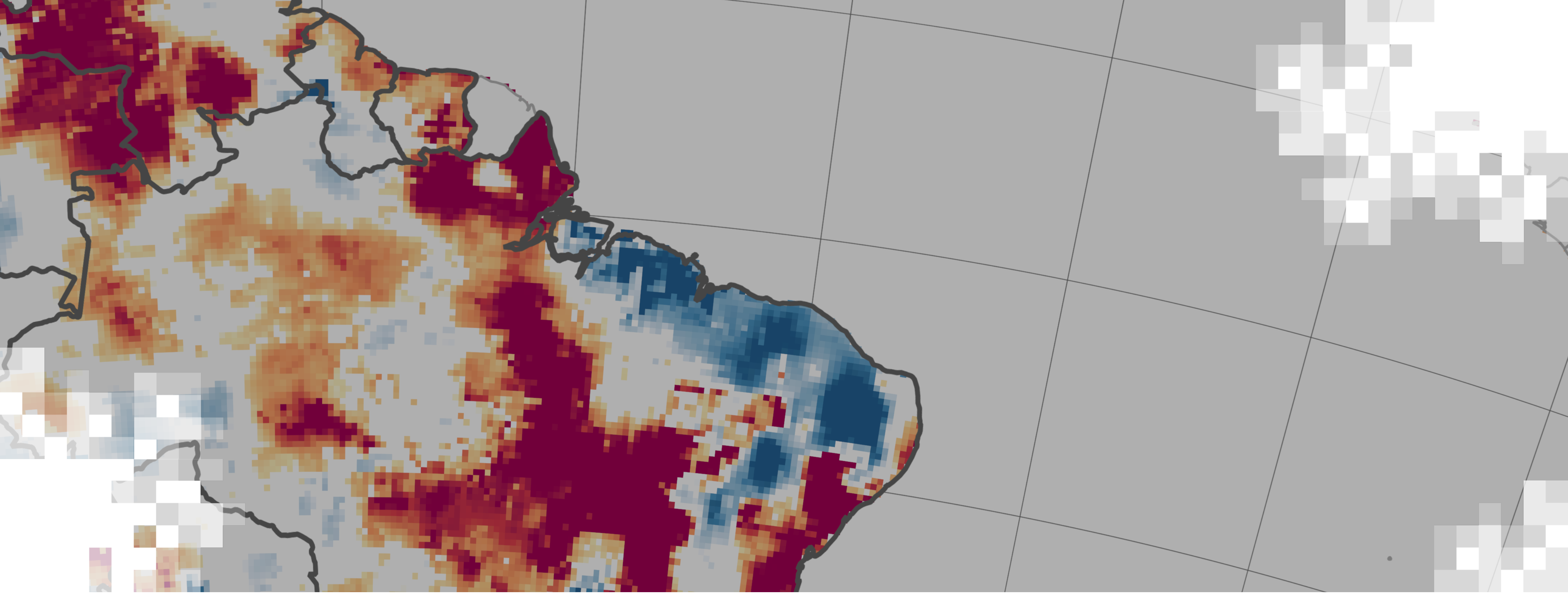
# GLDAS Groundwater

- Validation of groundwater from GLDAS version 2.2 g with 4,000 well measurements shows that GRACE data assimilation improves groundwater estimation by 36% at the regional scale and by10% at point scale compared to groundwater obtained without GRACE data assimilation.




Monthly nonseasonal groundwater storage anomalies from the OL, GRACE DA, and in situ data in the four Mississippi sub-basins and four northeast U.S. regions (Li et al., 2019)

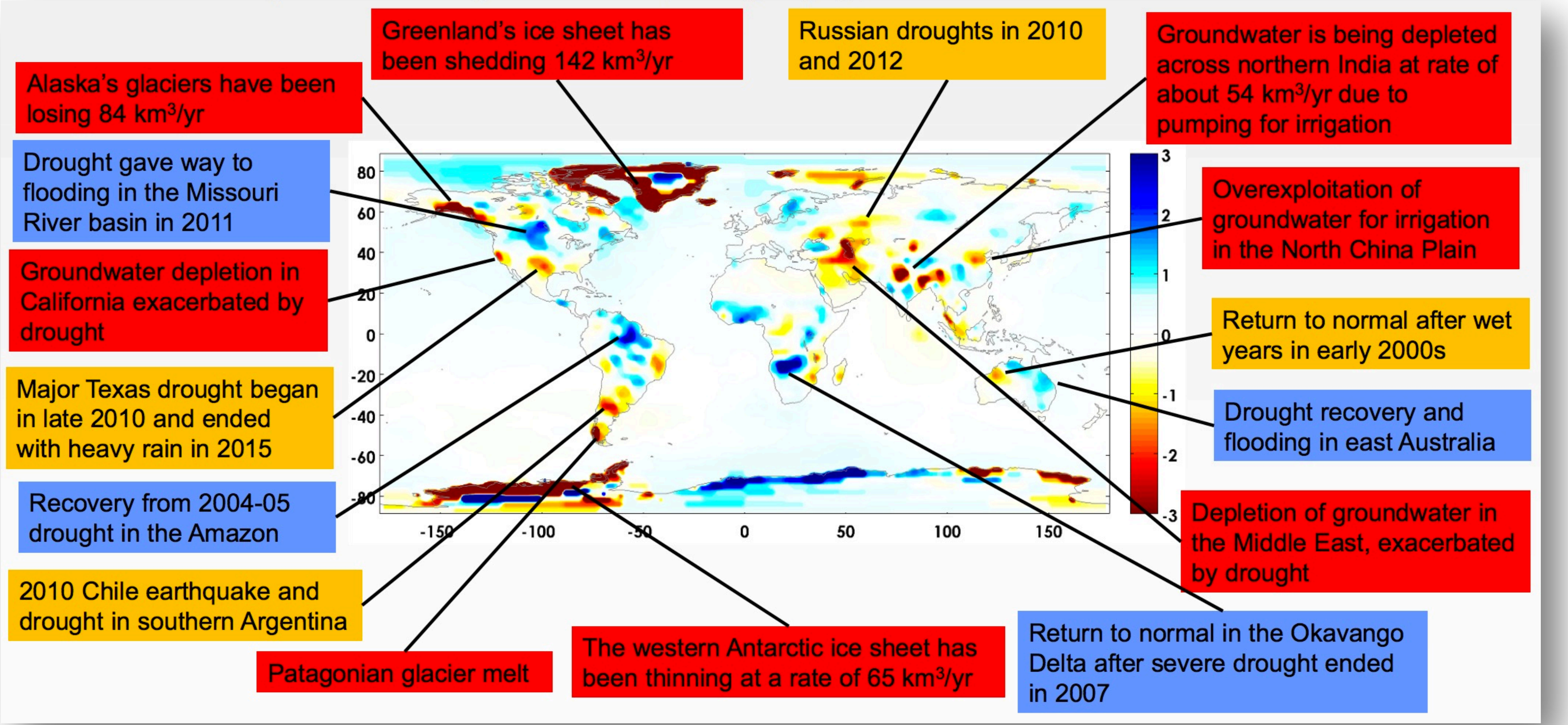
Li et al., 2019: Global GRACE data assimilation for groundwater and drought monitoring: Advances and challenges, DOI: 10.1029/2018wr024618



# Examples of Groundwater Applications

# GRACE Provides Emerging Trends in Freshwater Resources

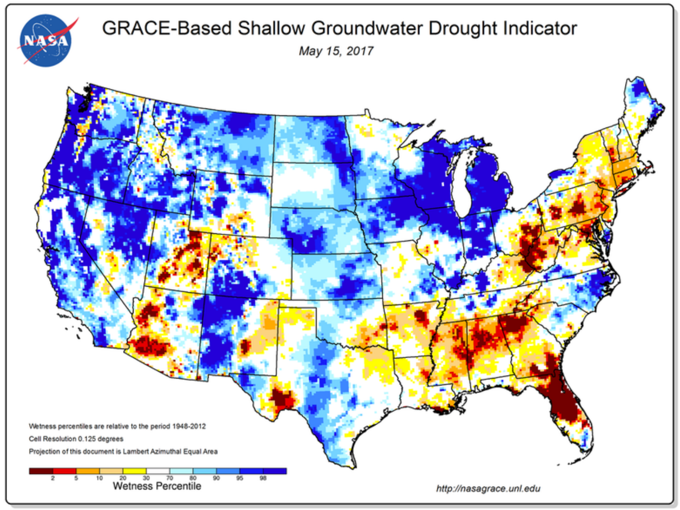
Rate of Change of Terrestrial Water Storage (TWS) as an Equivalent Height of Water (cm/yr) from GRACE, 2002 - 2015



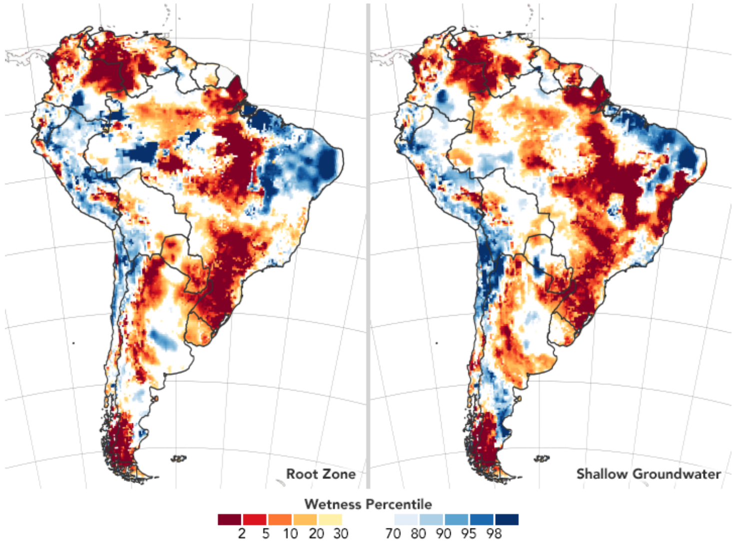

Source: Matt Rodell (NASA-GSFC)

# GRACE and GRACE-FO for Drought Monitoring

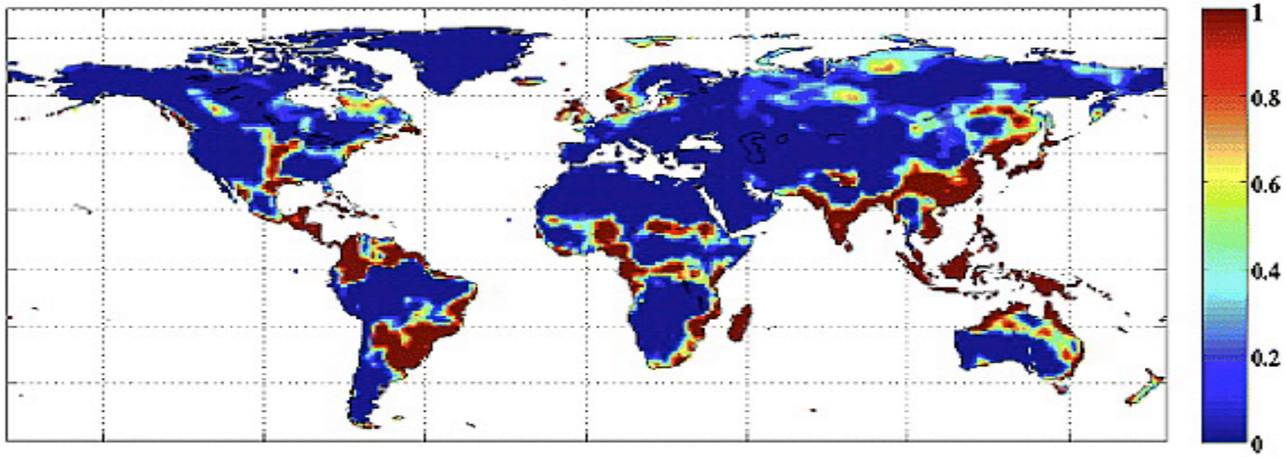
- Weekly dry and wet conditions based on groundwater and soil moisture from GRACE-based TWC and other observations and land surface model
  https://www.drought.gov/drought/data-gallery/groundwater-and-soil-moisture-conditions-grace-data-assimilation



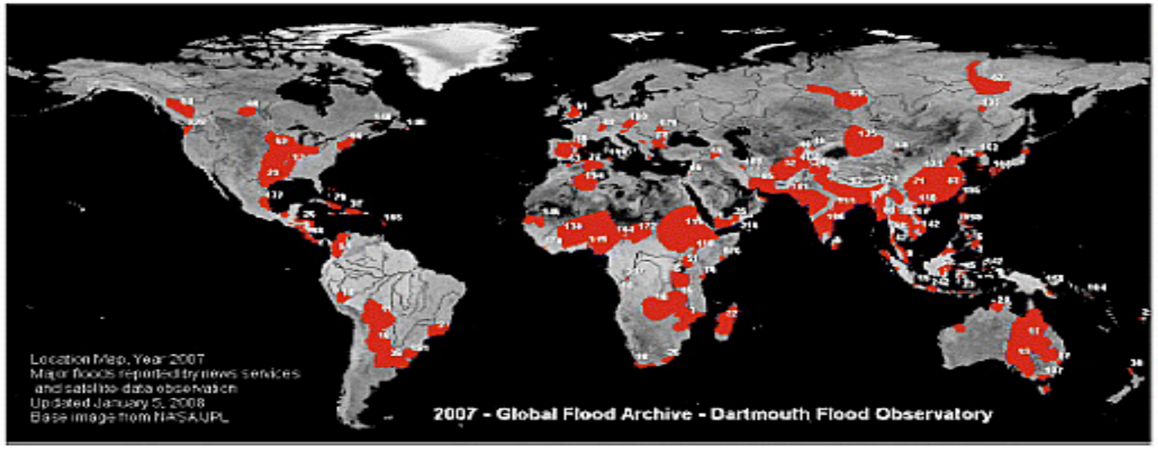

- GRACE-FO observations show root zone soil moisture and shallow groundwater storage in South America showing drought conditions in Brazil’s Mato Grosso do Sul, São Paulo, and Paraná states, according to several news reports. Likewise, drought conditions are shown in northern Argentina, Chile, Colombia, and Venezuela.
  https://earthobservatory.nasa.gov/images/146537/measuring-drought-in-south-america



# GRACE-Based Flood Detection

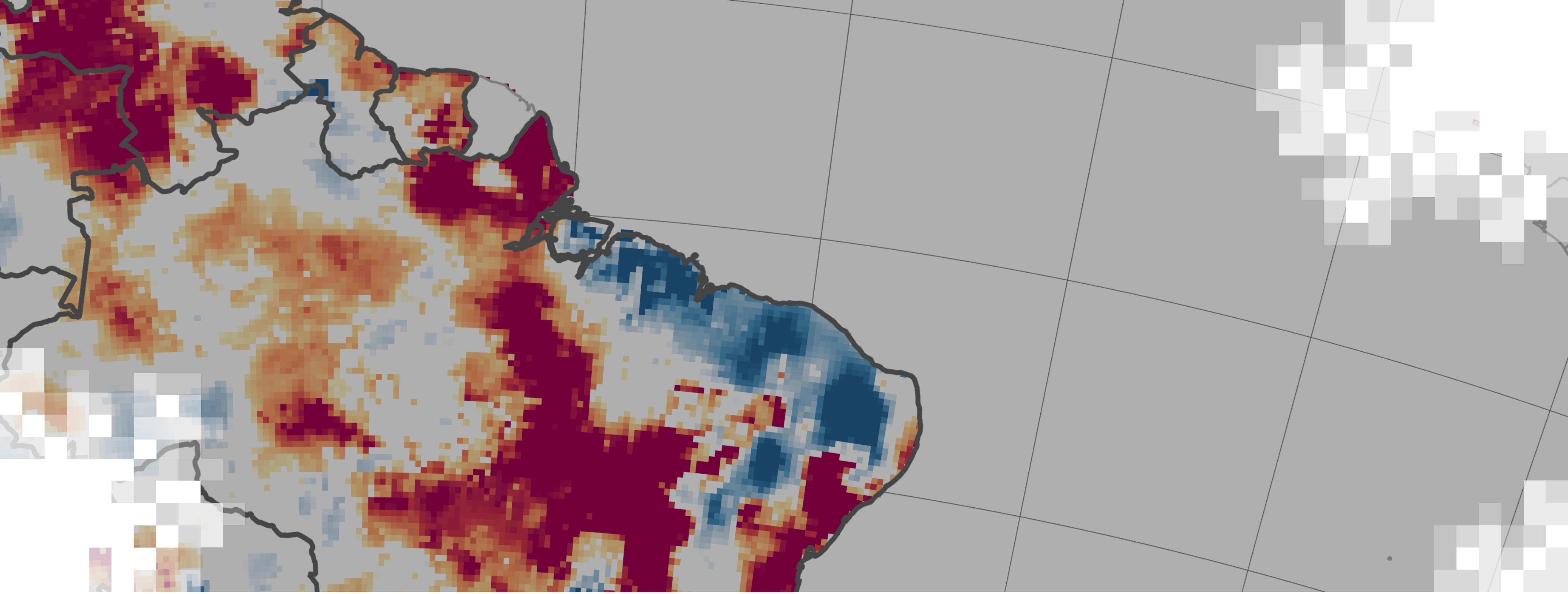



GRACE-Based
Flood Index
Maxima, May 2007




Recorded Floods,
Dartmouth Flood
Observatory, May 2007

Reager J. T. and J. Famiglietti (JPL), 2009: Global terrestrial water storage capacity and flood potential using GRACE, DOI: 10.1029/2009GL040826



# GRACE Data Access and Analysis

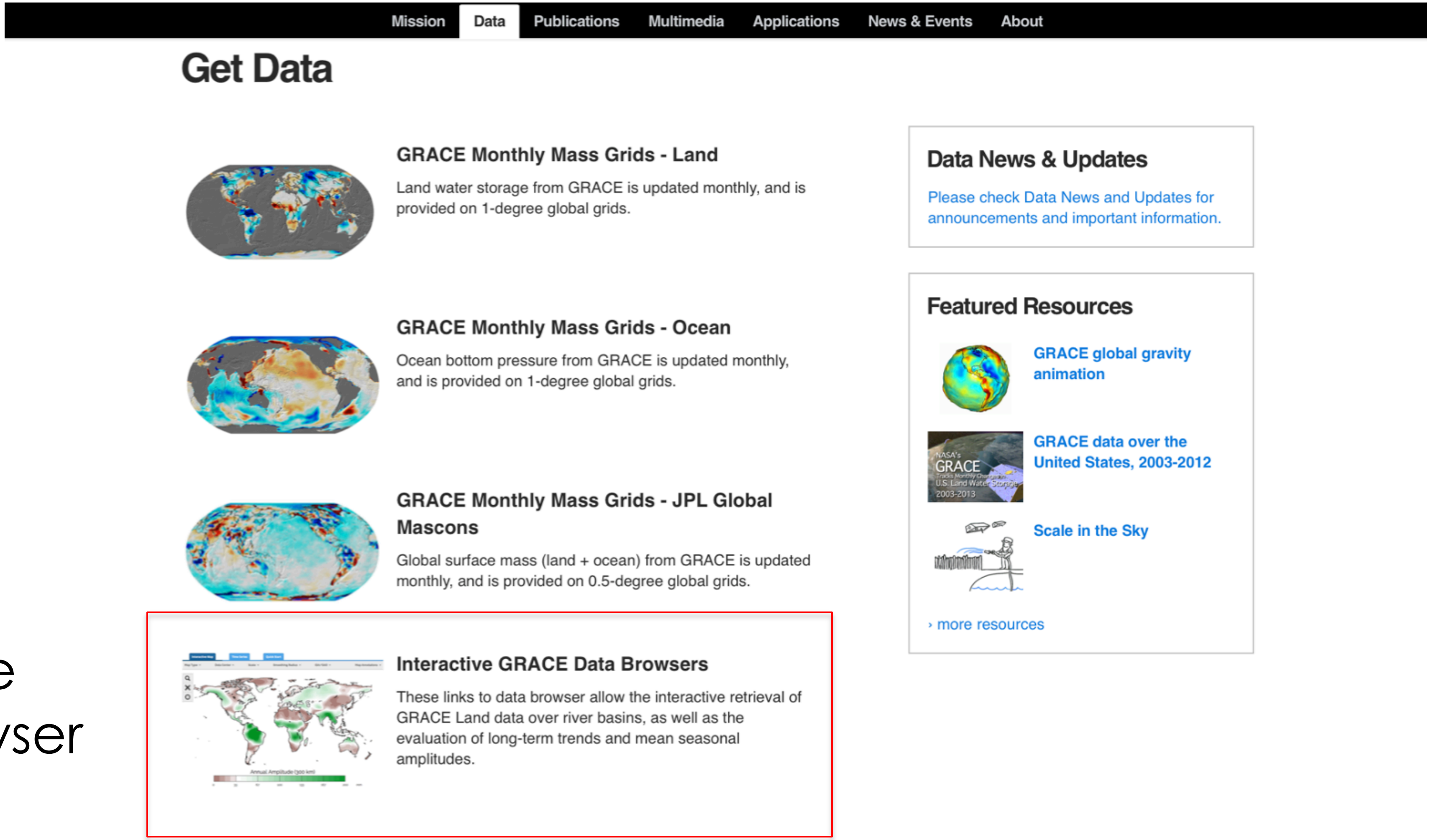
# GRACE and GRACE-FO Data Access

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

- JPL data portal:
  https://podaac.jpl.nasa.gov/grace
- GFZ data portal:
  http://isdc.gfz-potsdam.de
- GRACE website at University of Texas at Austin Center for Space Research (CSR):
  http://www.csr.utexas.edu/grace

# JPL GRACE Data Portal

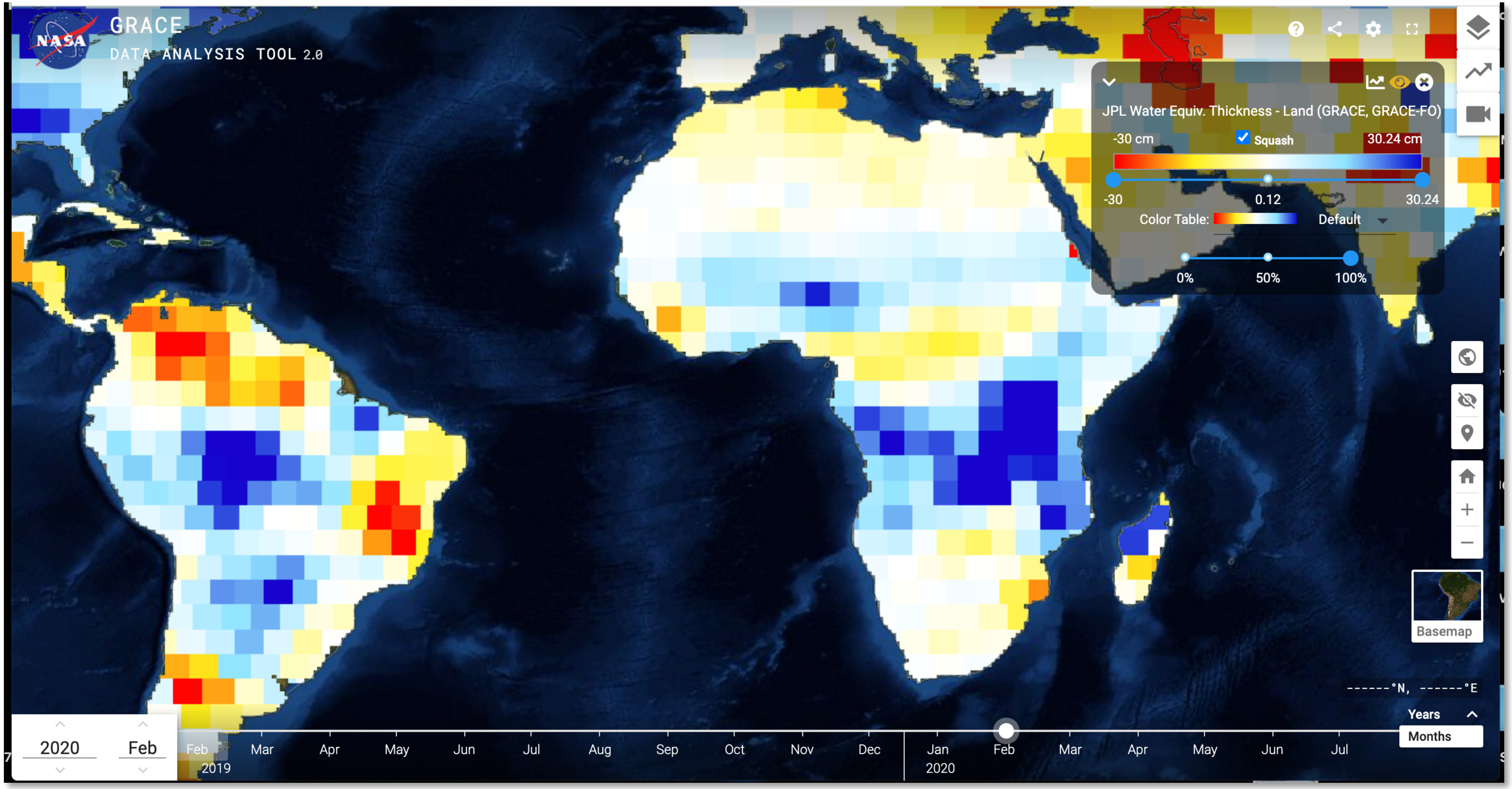
http://grace.jpl.nasa.gov/data/get-data




Interactive Data Browser

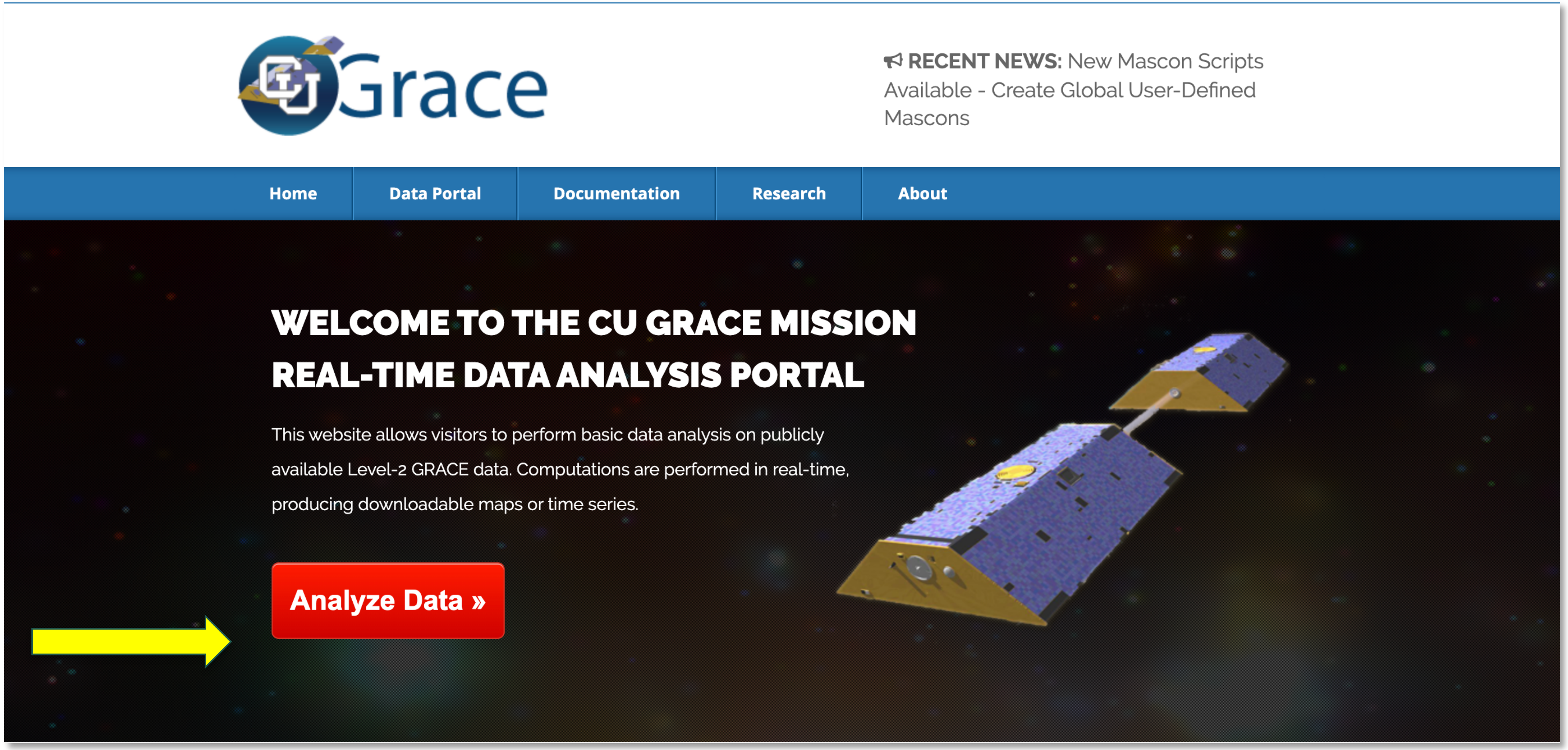
# JPL GRACE Data Analysis Tool

https://grace.jpl.nasa.gov/data/data-analysis-tool/



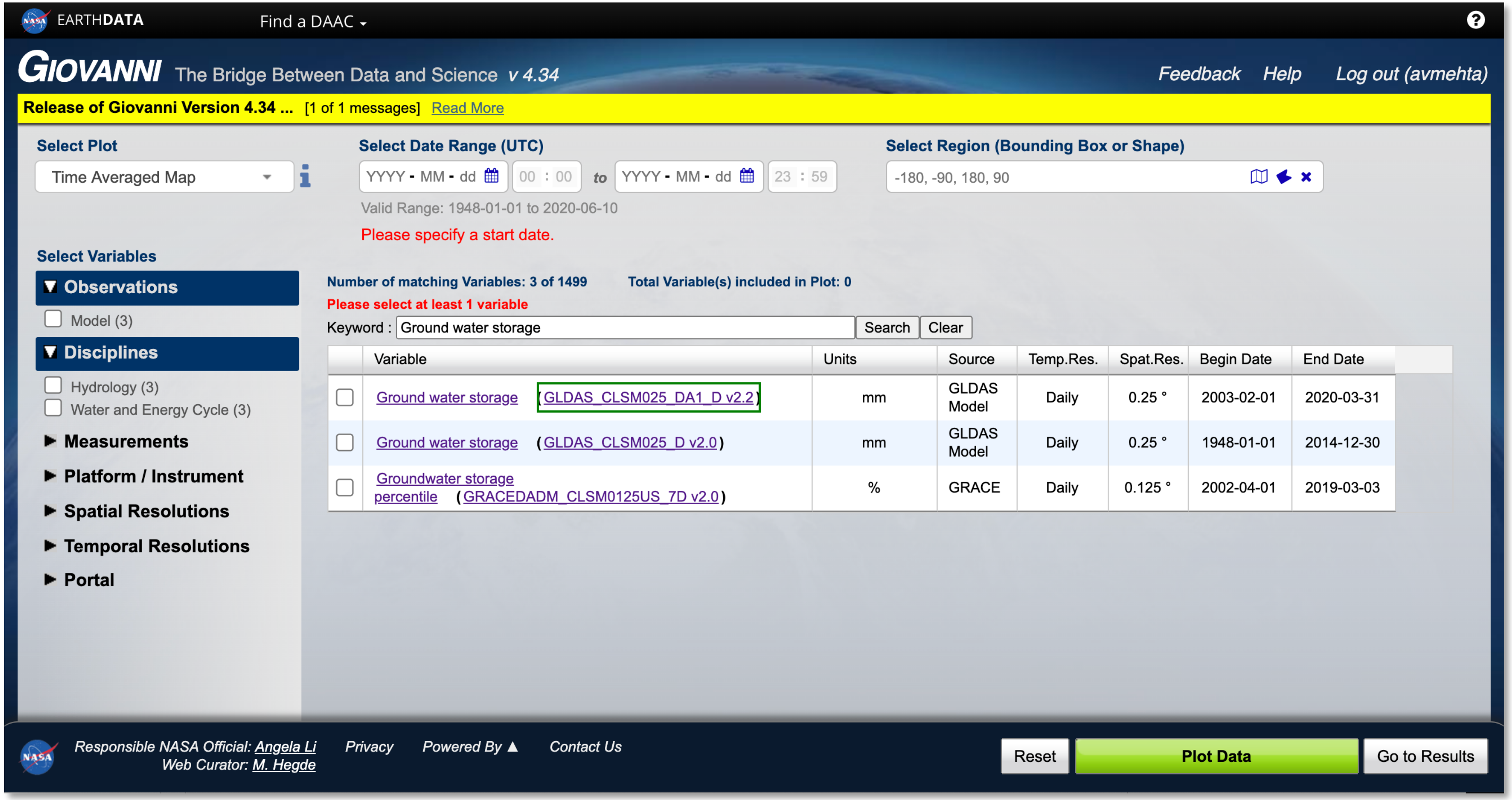
# GRACE Interactive Data Analysis and Download Portal

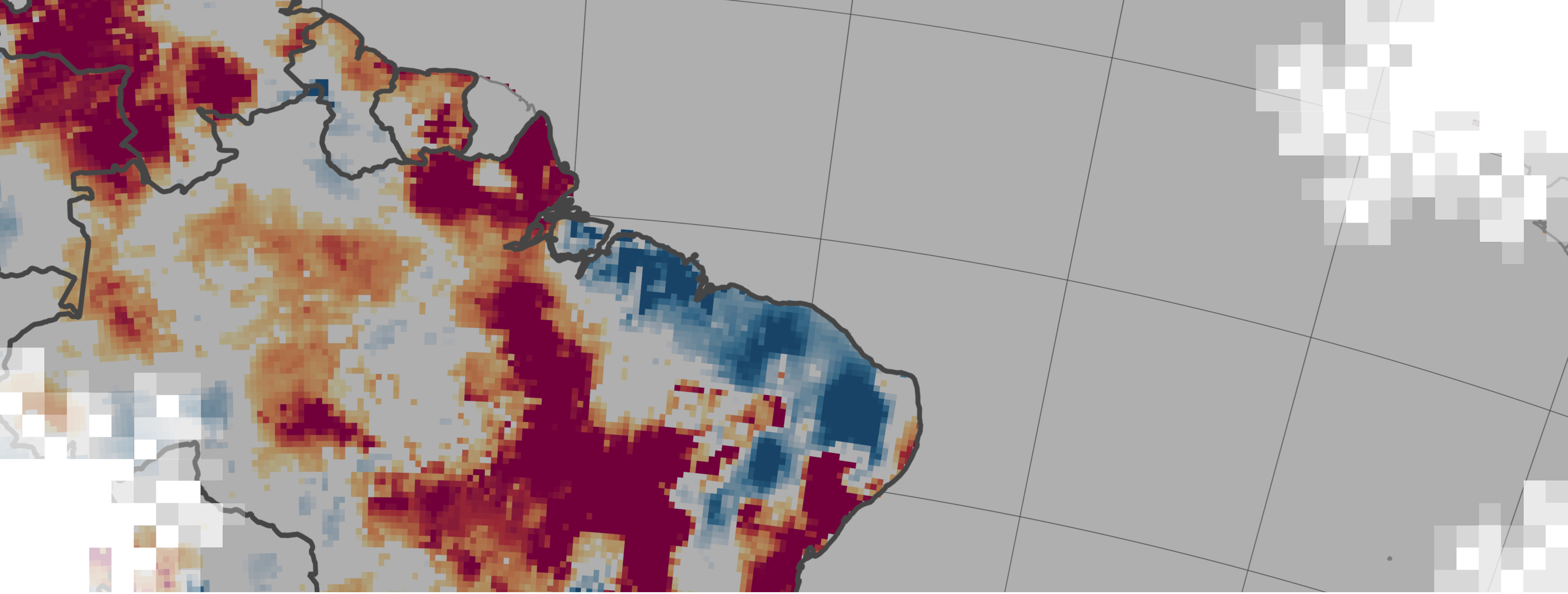
http://geoid.colorado.edu/grace/



# GRACE and GLDAS-Based Groundwater Storage Data Access

https://giovanni.gsfc.nasa.gov/giovanni/





# Demonstration: GRACE Data Access and Analysis

# GRACE and GRACE-FO Data Access

- JPL data portal for TWS data:
  https://podaac.jpl.nasa.gov/grace

- GES DISC, Interactive Online Visualization and Analysis Infrastructure Giovanni:
  https://giovanni.gsfc.nasa.gov/giovanni/

# Summary: Advantages

- 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 ground water depletion.

# Summary: Limitations

- GRACE- and GRACE-FO-based TWS and groundwater are available globally, but the spatial resolution is ~380x380 $km^2$ and can not resolve smaller watersheds.
- The TWS or water equivalent depth are measured in cm, much smaller compared to the Earth's radius (6,378 km), and have estimated errors of 2-3 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.
- GRACE-based TWS data are made available at 1°x1°, and GRACE-assimilated GLDAS ground water data are available at 0.25°x0.25°. However, because of the coarse resolution of GRACE data, two neighboring grids may not include independent estimates.

# GRACE Tracking Groundwater Changes – India

https://svs.gsfc.nasa.gov/3623

# GRACE Tracking Groundwater Changes – Brazil


Courtesy: NASA Goddard Visualization Studio

# Question & Answer Session

- Please enter your questions in the Q&A box.
- We will post the questions and answers to the training website: https://arset.gsfc.nasa.gov/water/webinars/GRACE

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