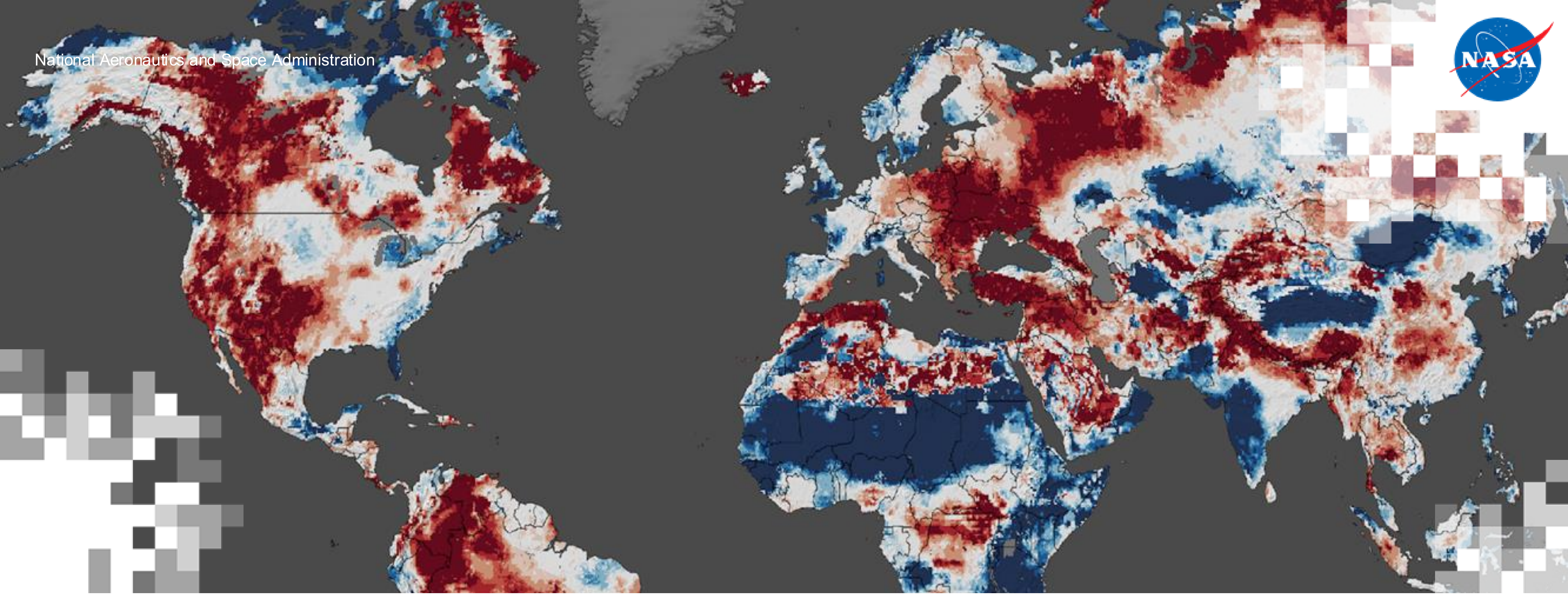

National Aeronautics and Space Administration

Monitoring Groundwater Changes for Water Resources Management

Part 2: Overview and Applications of GLDAS Groundwater Data Products at Regional Scale

ARSET Host: Amita Mehta (612, GESTAR II)
Guest Speaker: Matthew Rodell (610, NASA-GSFC)

April 28, 2026

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

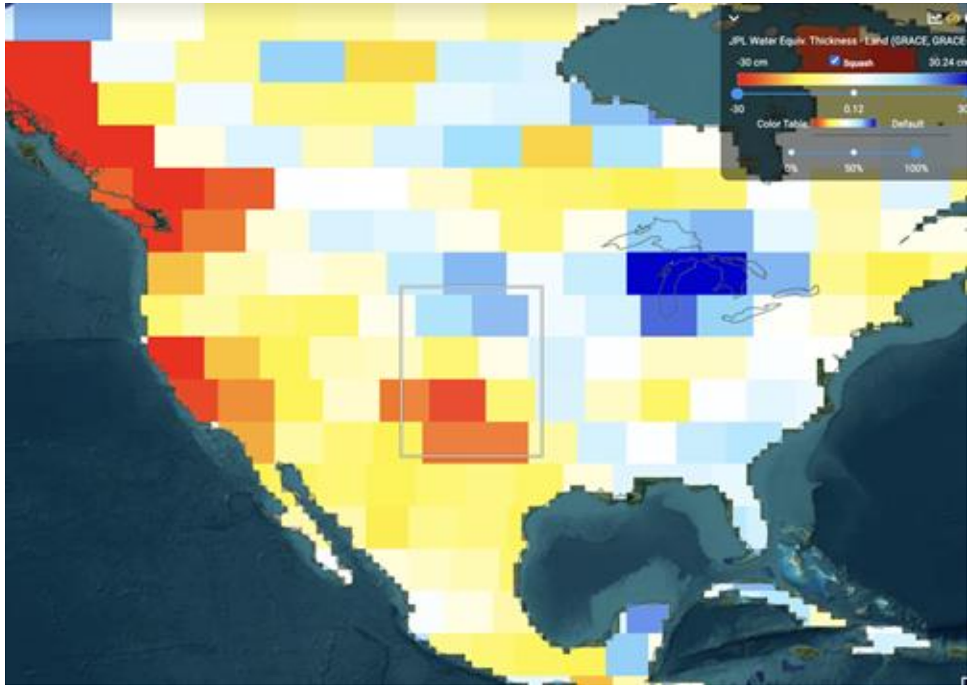
Homework

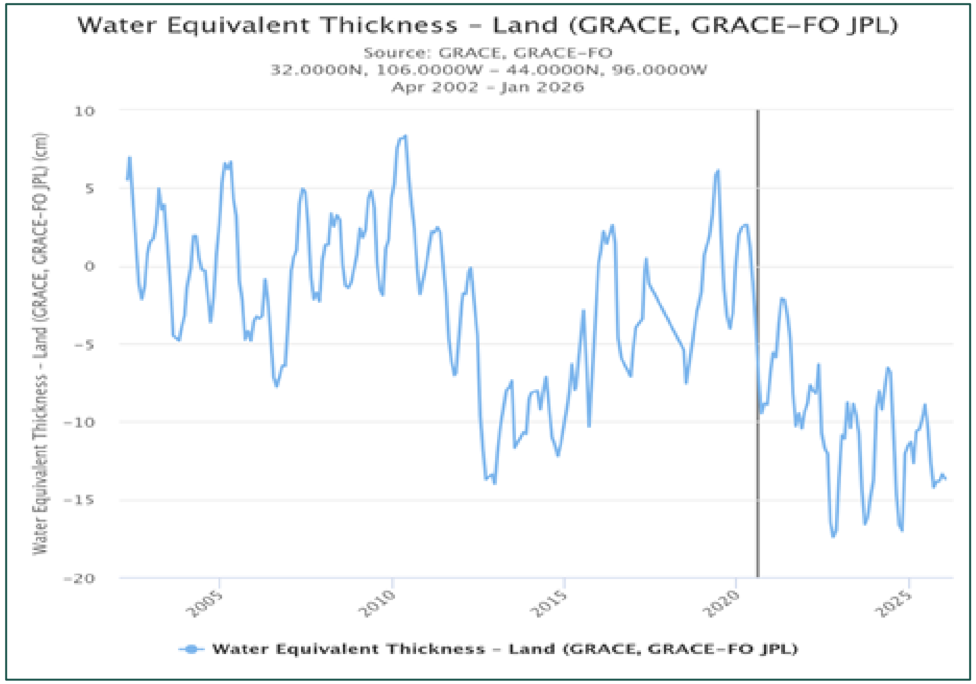
Opens April 30 – Due May 15 – Posted on Training Webpage

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.

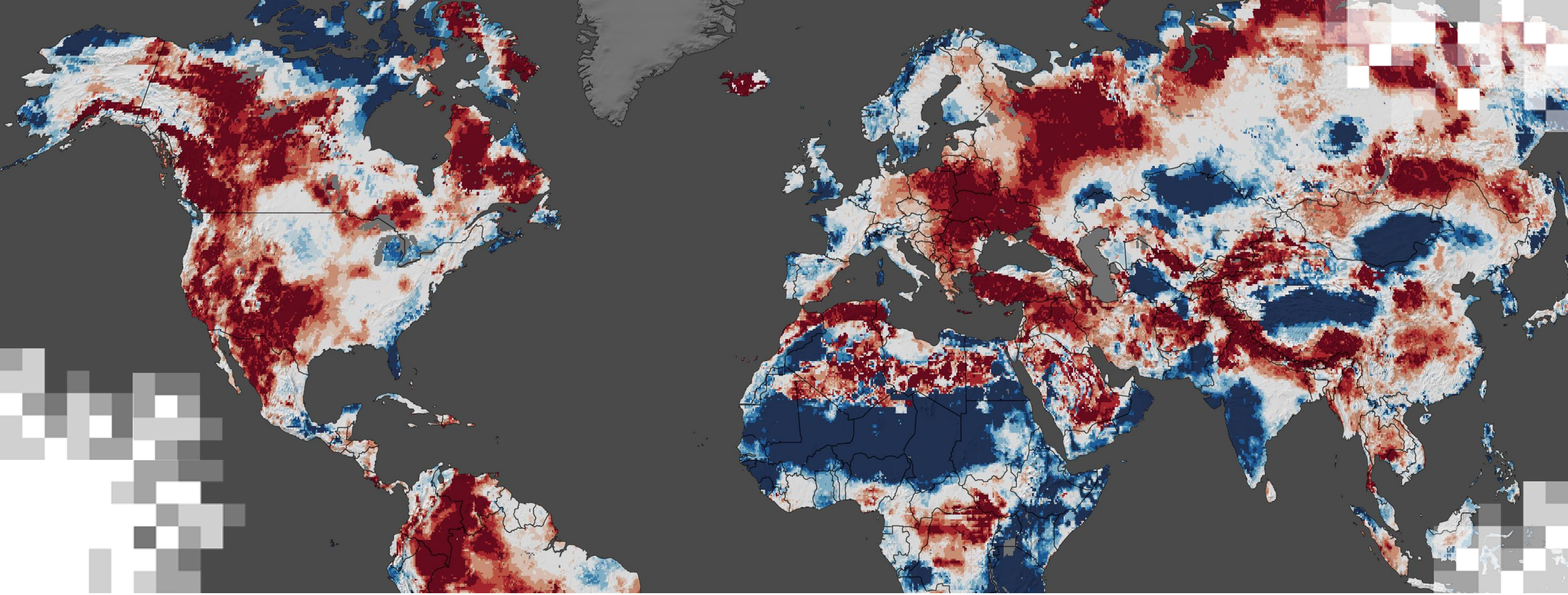
Review: Part 1

- Overview of GRACE(-FO) missions and data products
- GRACE(-FO) data applications: flood, drought
- Terrestrial Water Storage (TWS) data analysis and visualization: GRACE(-FO) Data Analysis Tool





TWS
Ogallala Aquifer



Part 2

Overview and Applications of GLDAS 2.2 Groundwater data products at Regional Scale

Part 2 Objectives

By the end of Part 2, participants will be able to:

- Identify characteristics of groundwater data product from GRACE-assimilated GLDAS
- Monitor interannual to interdecadal changes in groundwater at regional scales using GLDAS data product

Part 2 Outline

- Review: Key aspects of GRACE and GRACE-FO
- Overview of Land Data Assimilation System (LDAS)
- About GRACE/GRACE-FO Data Assimilation in LDAS and groundwater data
- Demonstration:

  - Groundwater data access, analysis, and visualization using Giovanni and QGIS

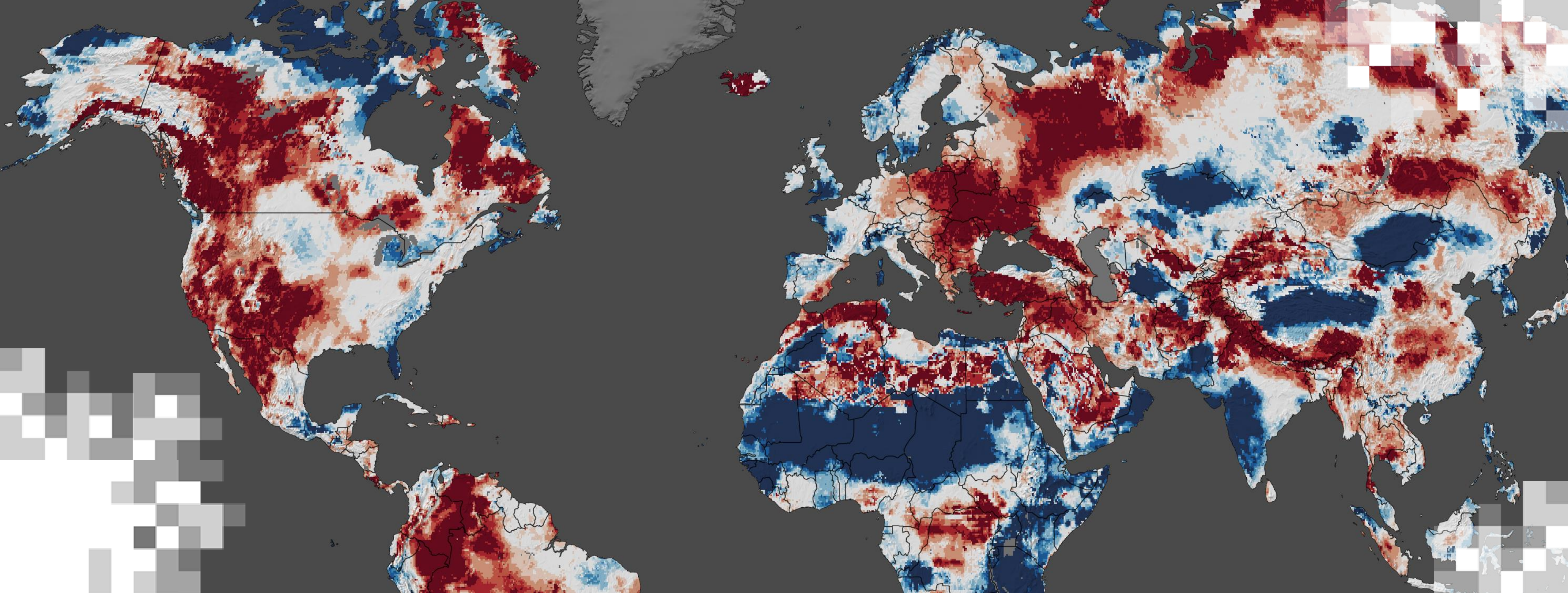
How to Ask Questions

- 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 2 – Trainer

Dr. Matthew Rodell

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

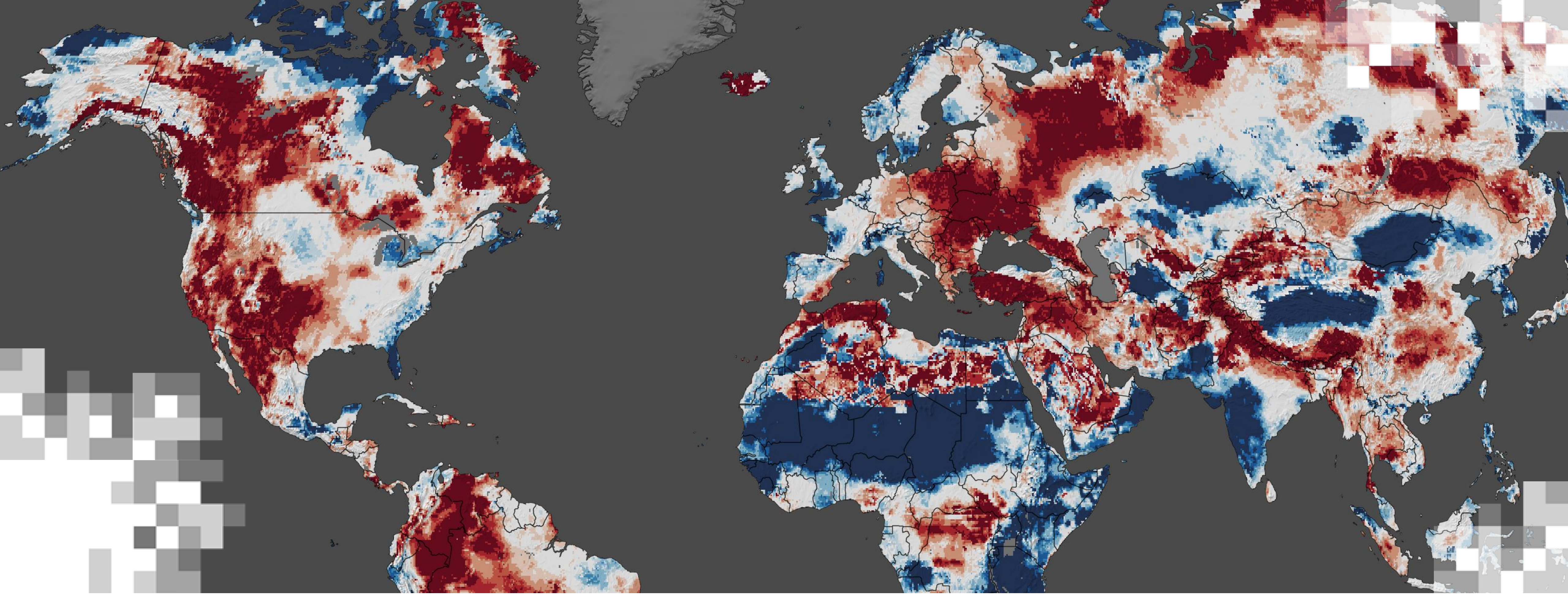


Overview of GLDAS 2.2 GRACE/FO Based Groundwater

Matt Rodell, Ph.D.
Deputy Director of Earth Sciences for Hydrosphere, Biosphere, and Geophysics
NASA Goddard Space Flight Center
Greenbelt, Maryland

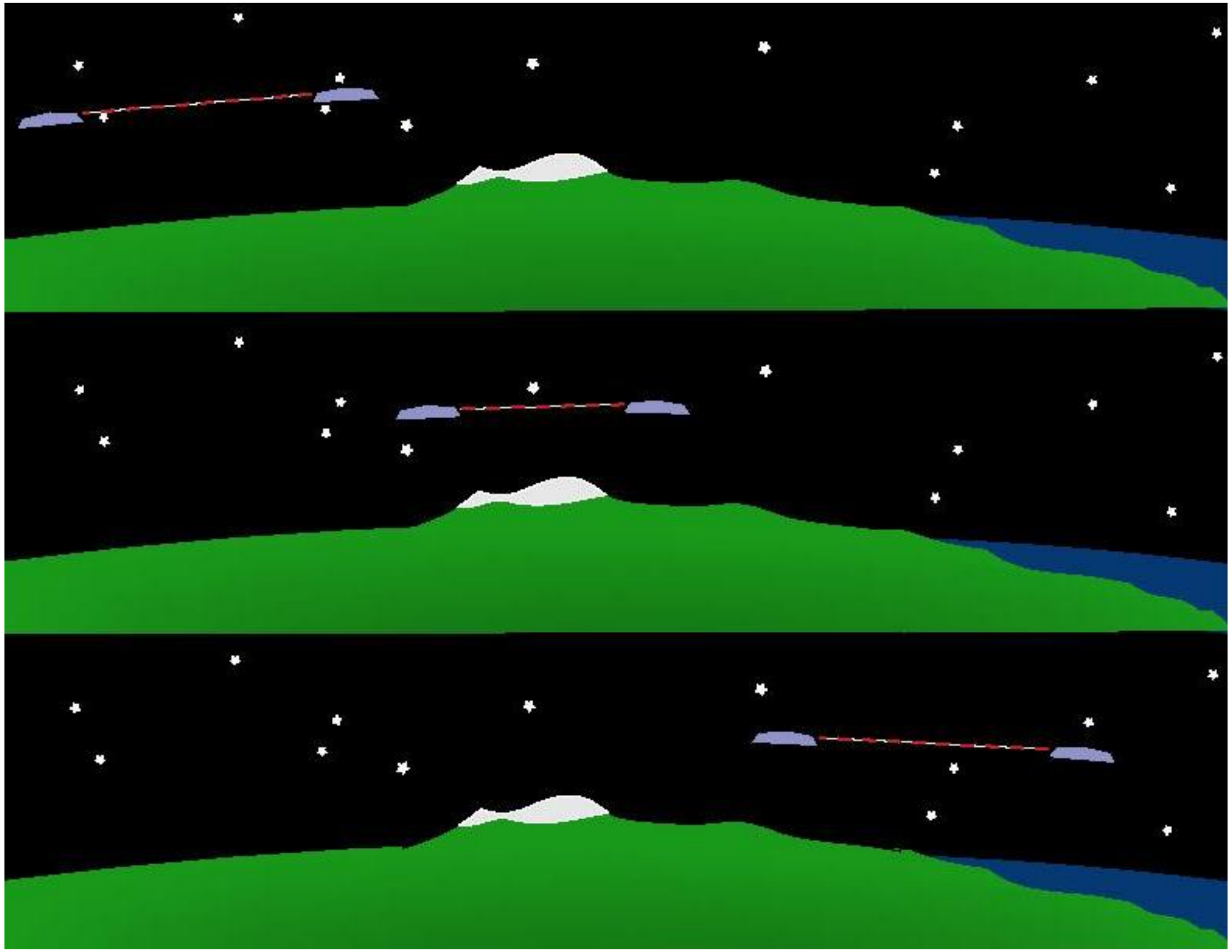
In a Nutshell: What is GLDAS 2.2?

- GLDAS 2.2 is a version of the Global Land Data Assimilation System
  - Numerical model: The Catchment Land Surface Model (CLSM)
  - Spatial extent: Global, excluding Antarctica and Greenland
  - Spatial resolution: 0.25° x 0.25° (~25 km x ~25 km)
  - Time period: 2003-present
  - Input meteorological forcing: European Center for Medium-Range Weather Forecasts (ECMWF) analysis
  - Data assimilation: GRACE and GRACE-FO terrestrial water storage anomalies



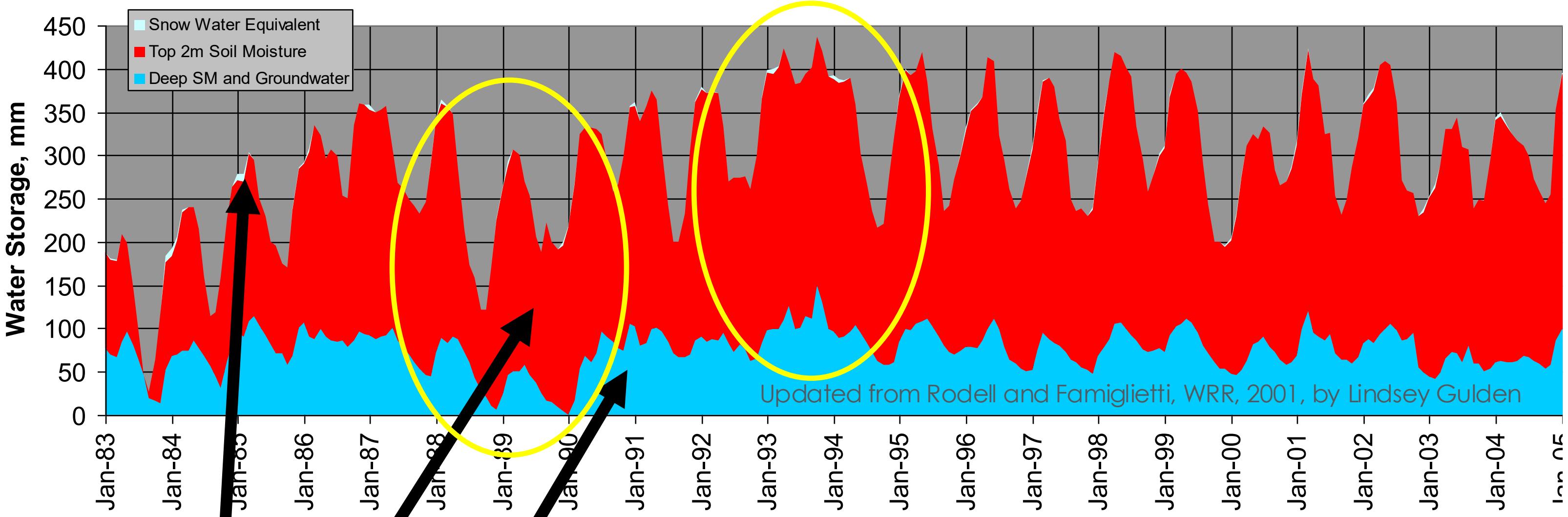
Review of Key Aspects of GRACE & GRACE-FO

The Gravity Recovery and Climate Experiment (GRACE) and GRACE Follow On (GRACE-FO)

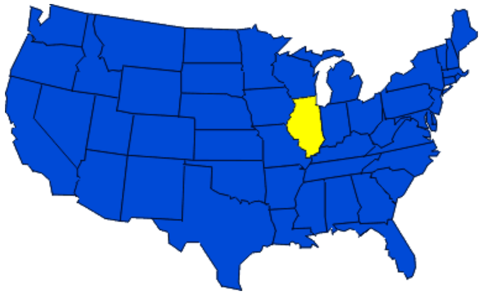


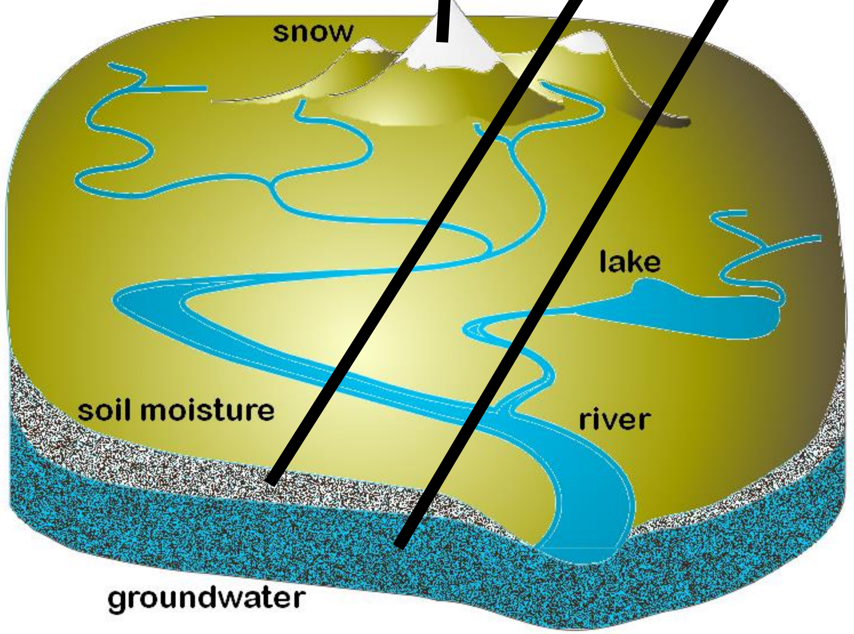
- Two identical satellites flying in tandem, near-polar orbit, ~200 km apart, 500 km initial altitude
- Distance between satellites continuously and precisely tracked by K-band microwave ranging system (and laser for GRACE-FO)
- Gravity (and thus mass) anomalies perturb the orbits of the satellites, and hence the inter-satellite range (distance)
- Not an imager; gravity maps are inferred from the range and positioning data

Terrestrial Water Storage (TWS) Variability



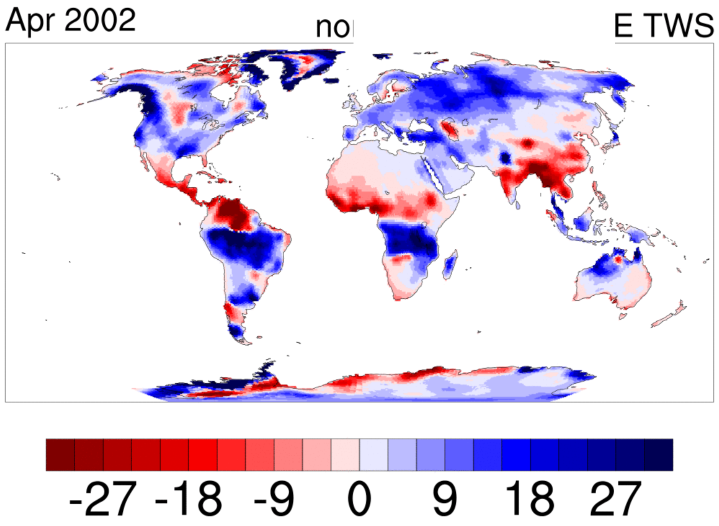
Updated from Rodell and Famiglietti, WRR, 2001, by Lindsey Gulden





Top: 23-year time series of snow, soil moisture, and groundwater storage in Illinois

Right: TWS anomalies (departures from the long term mean at each location), as equivalent heights of water (cm)



GRACE/FO Measures All Terrestrial Water Storage Components

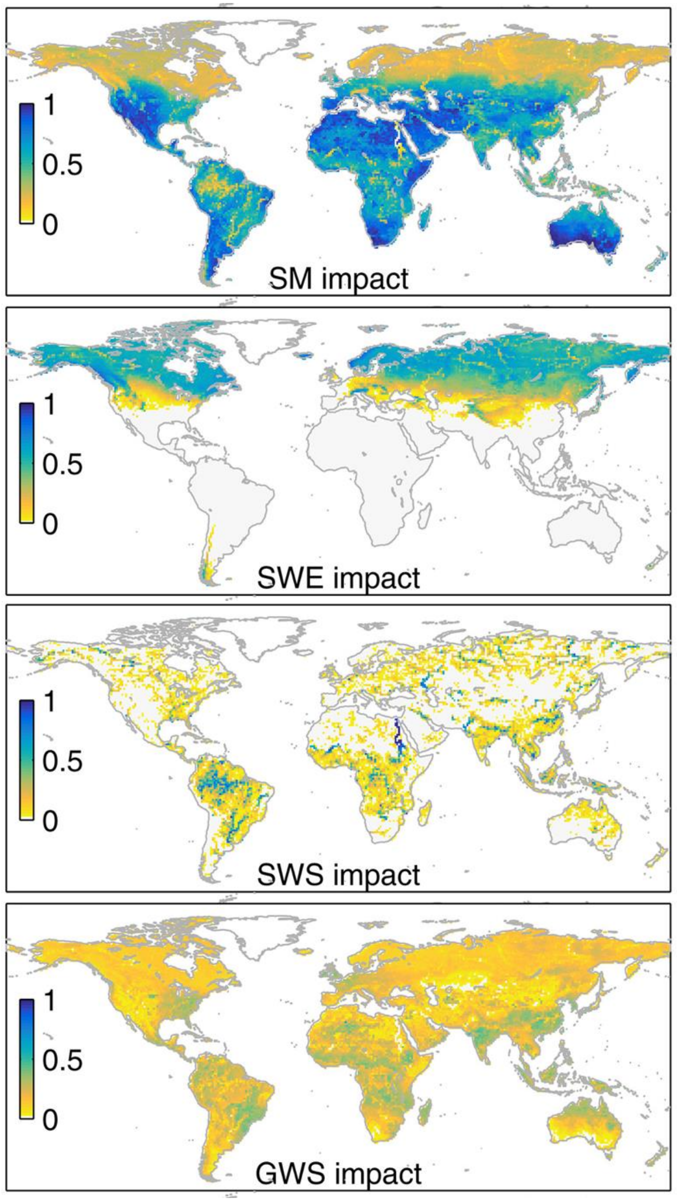
- Visualizations show relative contributions of surface water storage (SWS), groundwater storage (GWS), soil moisture (SM), and snow water equivalent (SWE) on monthly TWS variability during 2003–2014.

- SM - Soil moisture dominates monthly TWS variability in arid and temperate regions

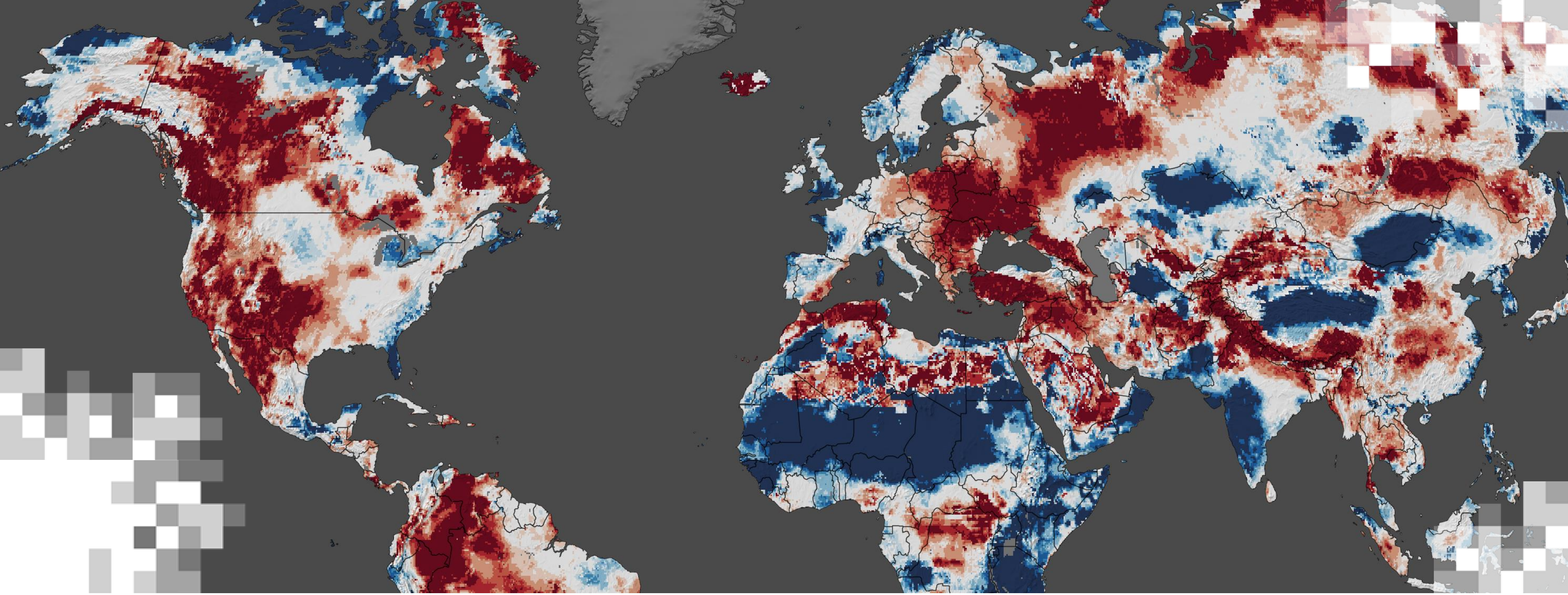
- SWE - Snow dominates TWS variability in boreal and alpine areas

- SWS - Surface water is the dominant contributor to TWS variability in humid tropical regions

- GWS - Groundwater is an important component of TWS variability almost everywhere, and it generally dominates on multi-annual timescales outside of polar regions



Getirana, A., Kumar, S., Girotto, M., & Rodell, M. (2017). Rivers and floodplains as key components of global terrestrial water storage variability. Geophys. Res. Lett., 44(20), 10-359.

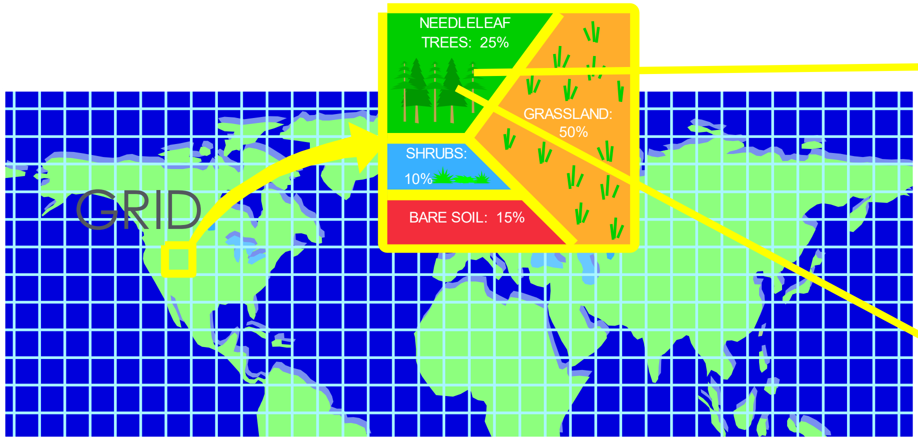


Land Data Assimilation Systems (LDAS)

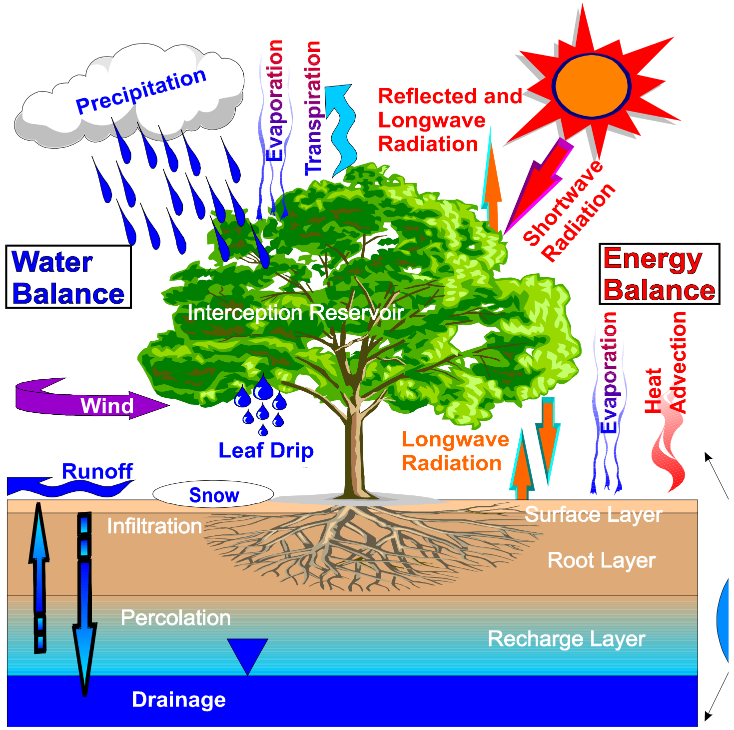
Land Surface Modeling

Land surface models (LSMs) solve for the interaction of energy, momentum, and mass between the surface and the atmosphere in each model element (grid cell) at each discrete time-step (~15 min)

Subgrid Heterogeneity



Surface Vegetation Atmosphere Transfer Scheme



Input - Output = Storage Change

$P + G_{in} - (Q + ET + G_{out}) = \Delta S$

$R_n - G = L_e + H$

System of physical equations:

Surface energy conservation equation

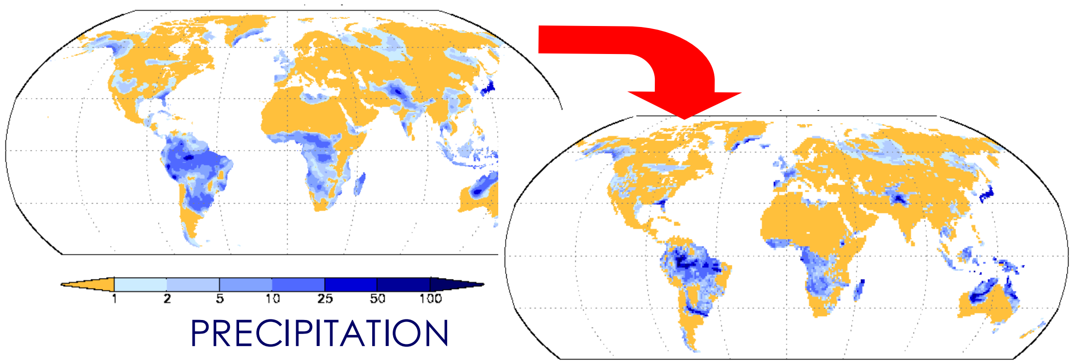
Surface water conservation equation

Soil water flow: Richards equation

Evaporation: Penman-Monteith equation, etc.

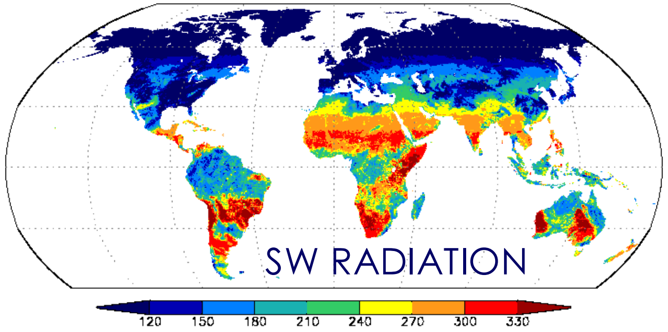
Data Integration within a Land Data Assimilation System (LDAS)

INTERCOMPARISON and OPTIMAL MERGING of global data fields

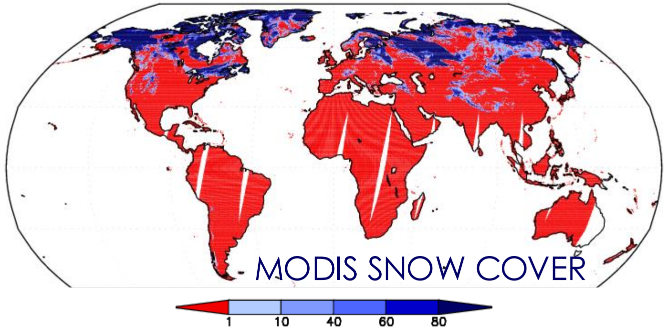


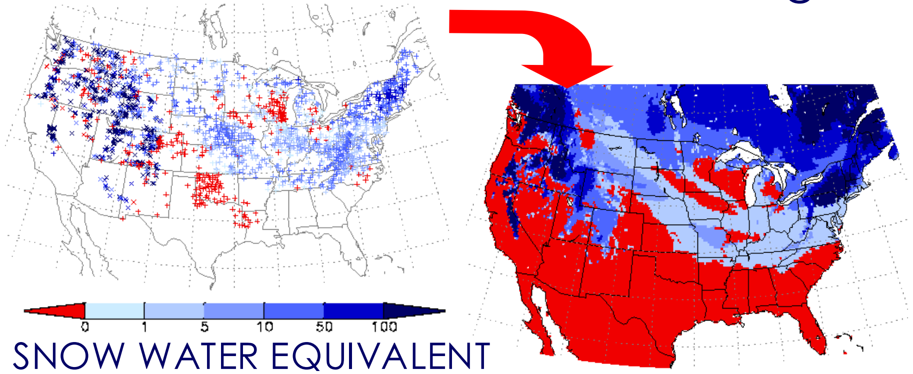
PRECIPITATION

Satellite derived meteorological data used as land surface model FORCING



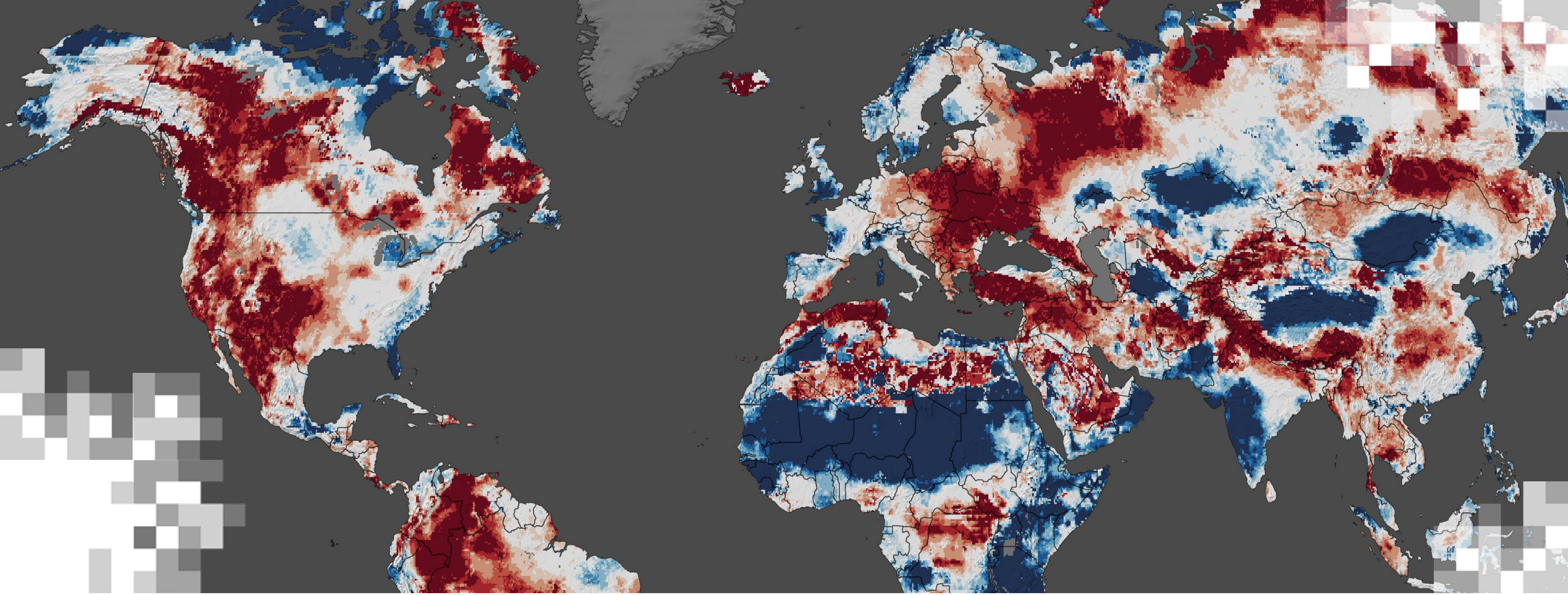
ASSIMILATION of satellite-based land surface state fields (snow, soil moisture, terrestrial water storage, etc.)





SNOW WATER EQUIVALENT

Ground-based observations used to VALIDATE model output



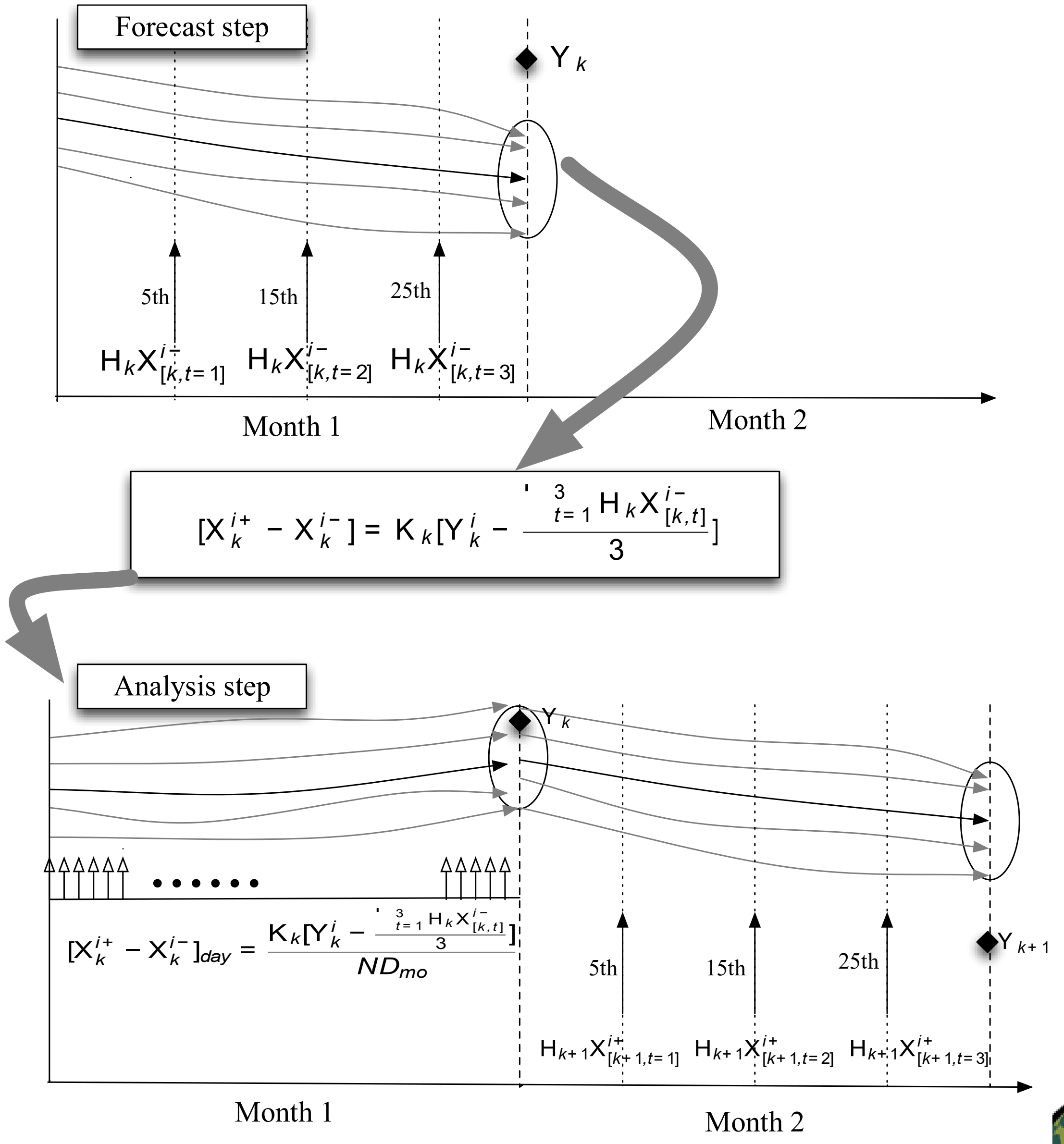
GRACE & GRACE-FO Data Assimilation

Gridded GRACE Data Assimilation within LIS

Configuration

- NASA's Land Information System (LIS) software driving the Catchment land surface model (CLSM) w/ depth to bedrock increased by 3 m
- 3-dimensional Ensemble Kalman Smoother
- 20 ensemble members
- Gridded GRACE TWS anomaly fields from the University of Texas are assimilated
- The assimilation run begins 2/1/2003, initialized by the GLDAS 2.0 CLSM simulation
- The ECMWF operational analysis is the source of the meteorological forcing data

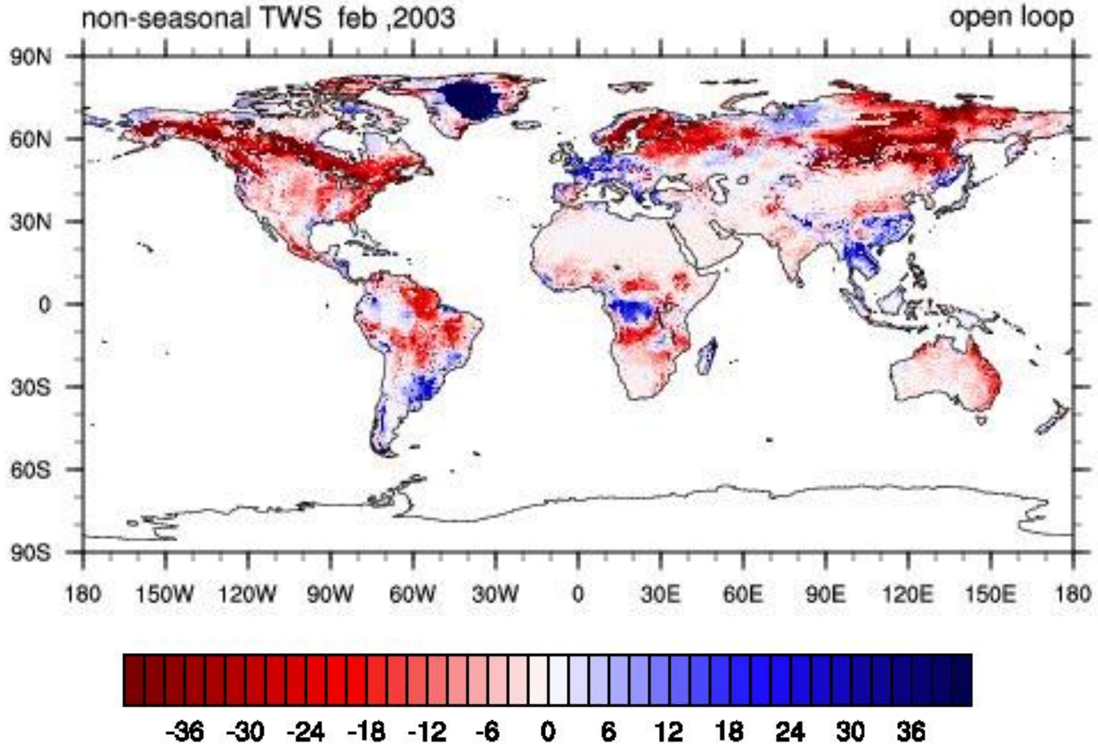
Kumar, S.V., B.F. Zaitchik, C.D. Peters-Lidard, M. Rodell, R. Reichle, B. Li, M. Jasinski, D. Mocko, A. Getirana, G. De Lannoy, M. Cosh, C.R. Hain, and M. Anderson (2016). Assimilation of gridded GRACE terrestrial water storage estimates in the North American Land Data Assimilation System, J. Hydrometeor., 17, 1951-1972.

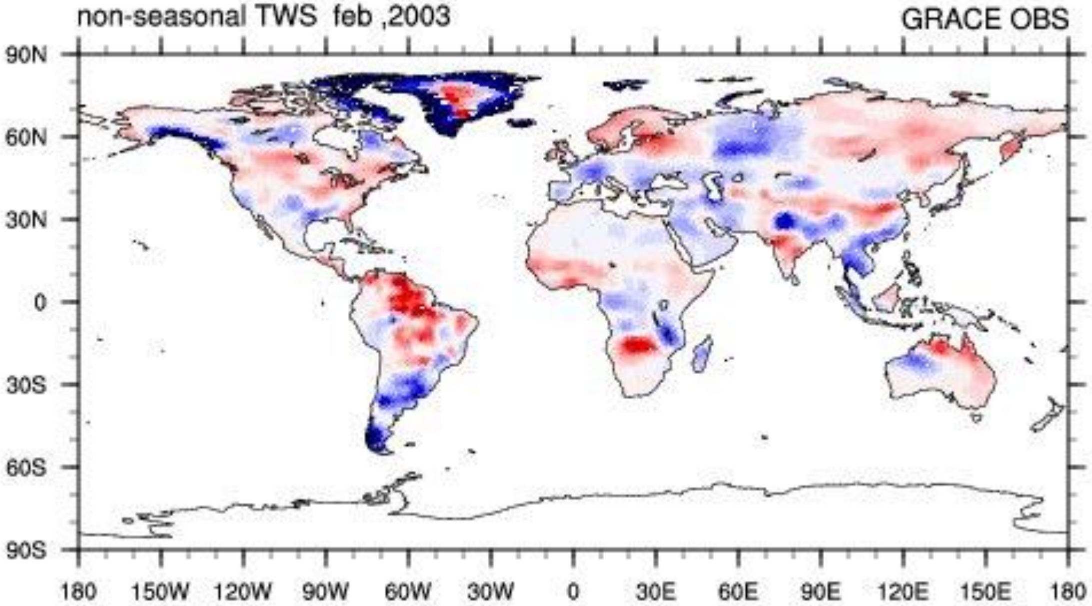


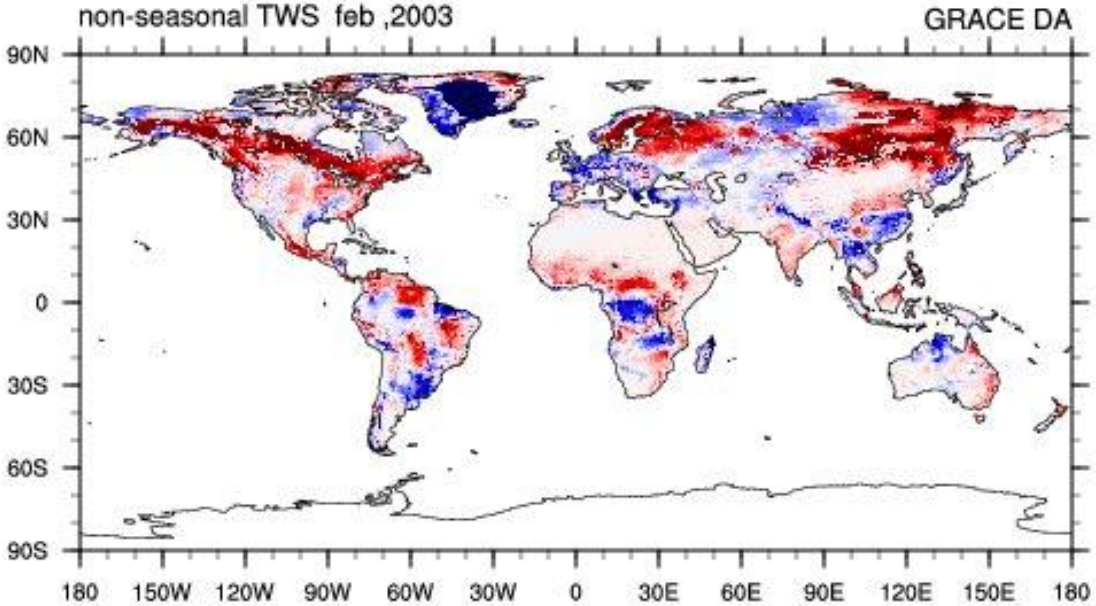
$$[X_k^{i+} - X_k^{i-}] = K_k[Y_k^i - \frac{\sum_{t=1}^{3} H_k X^{i-}_{[k,t]}}{3}]$$

$$[X_k^{i+} - X_k^{i-}]_{day} = \frac{K_k[Y_k^i - \frac{\sum_{t=1}^{3} H_k X^{i-}_{[k,t]}}{3}]}{ND_{mo}}$$

Global GRACE/FO Data Assimilation (GLDAS 2.2)







Non-seasonal TWS anomalies (cm) from:

Top Left: Open loop CLSM

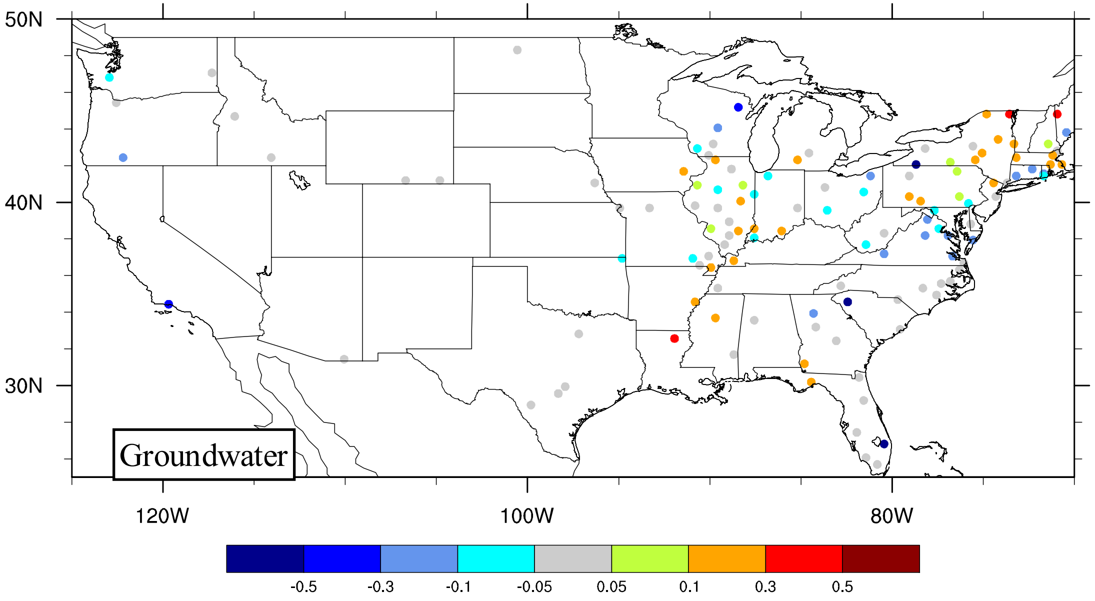
Top Right: GRACE/FO (Save et al., 2016)

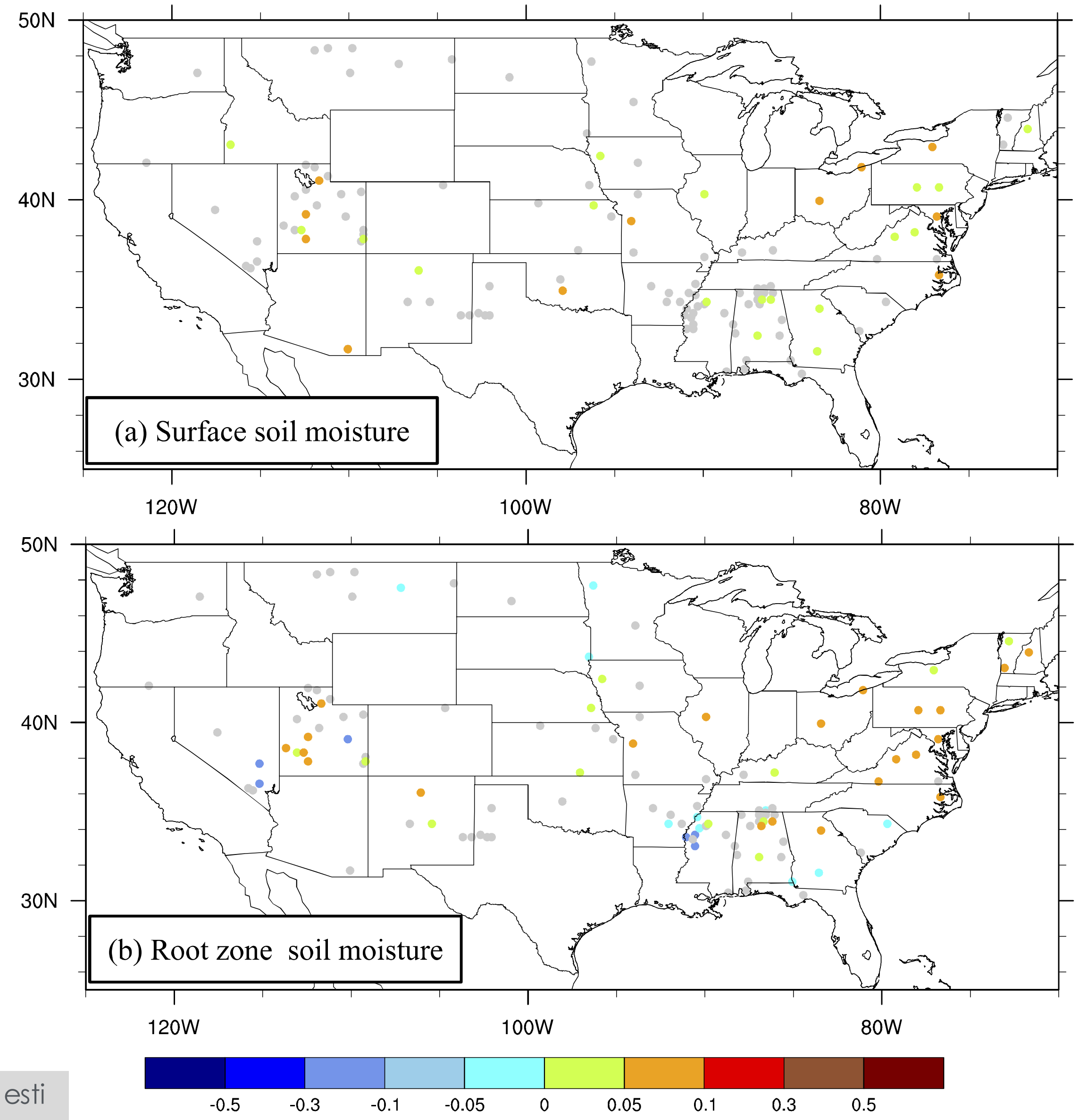
Bottom Right: CLSM GRACE/FO data assimilation

GLDAS 2.2 Data on GES DISC

Li, B., Rodell, M., et al., 2019. Global GRACE data assimilation for groundwater and drought monitoring: Advances and challenges. Wat. Resour. Res., 55(9), pp.7564-7586, doi:10.1029/2018WR024618.

Evaluation of GRACE Data Assimilation Output: Soil Moisture





Anomaly correlation differences (DA - OL); warm colors indicate that the data assimilation performed better than the open loop, relative to in situ observations, cool colors indicate degradation due to DA.

Systematic (but not uniform) improvement in simulated groundwater and soil moisture due to data assimilation.

Kumar et al. (2016), Assimilation of gridded GRACE terrestrial water storage estimates in the NLDAS; J. Hydrometeor., 17(3), 745-759.

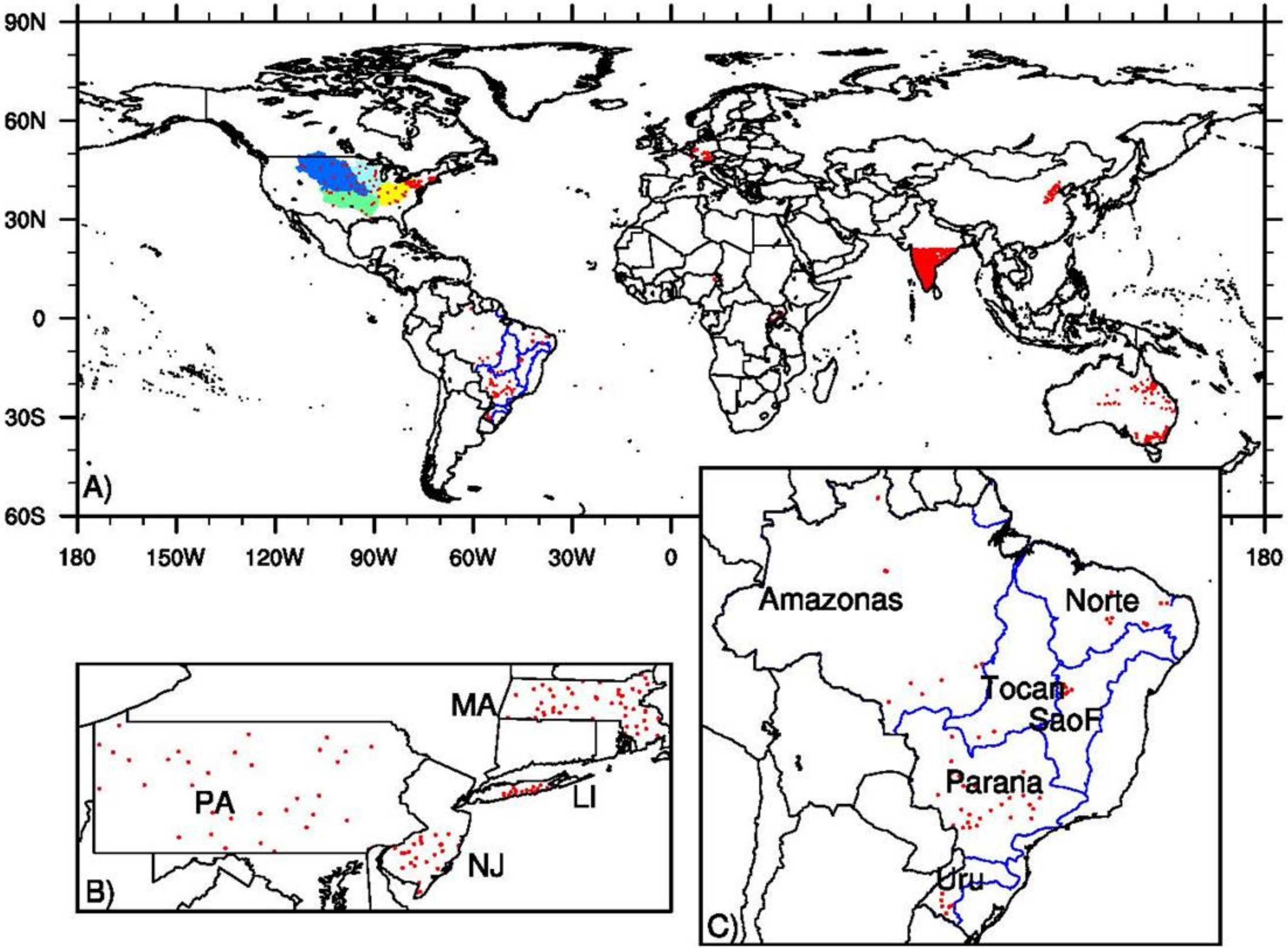
Evaluation of GRACE Data Assimilation Output: Groundwater

Well selection criteria:

1. Unconfined aquifers only (as interpreted from metadata, geological formation, well depth, and seasonal variability)
2. No pumping/injection (unavoidable in North China Plain)
3. Record length ≥ 5 yrs

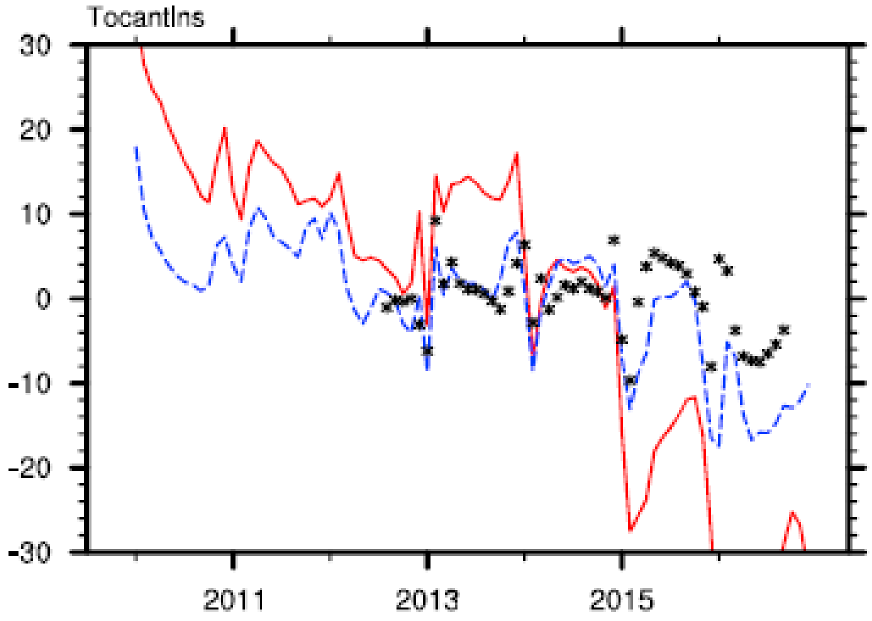
Nearly 4,000 wells in 22 regions or basins: Long Island, NJ, MA, PA, Up-Mis, Ohio-Tn, Red-LM, Missouri; Parana, Sao Francisco, Atlantico Sul, Amazonas, Uruguai, Tocantins, Southern India, North China Plain SW Australia, NE Australia, SE Australia, Rhine, The Netherlands, Uganda

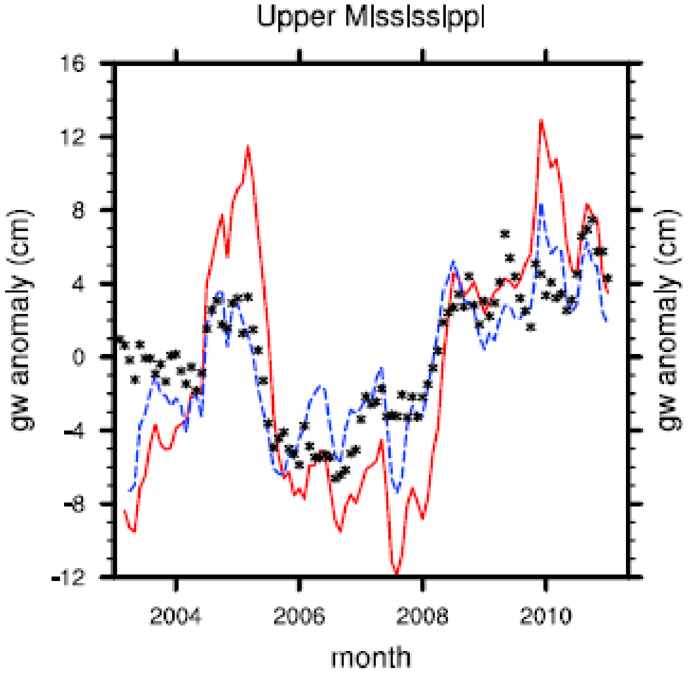
Specific yield individually determined for each well to convert changes in depth-to-water to changes in groundwater storage

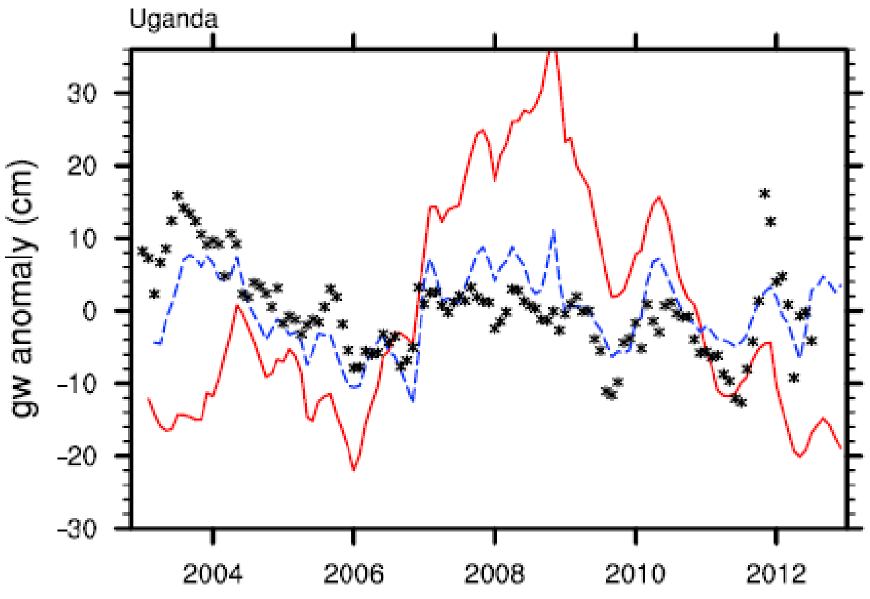


Li, B., M. Rodell, S.V. Kumar, H.K. Beaudoing, et al., 2019: Global GRACE data assimilation for groundwater and drought monitoring: advances and challenges, Water Resour. Res., 55, doi:10.1029/2018WR024618.

Evaluation of GRACE Data Assimilation Output: Groundwater







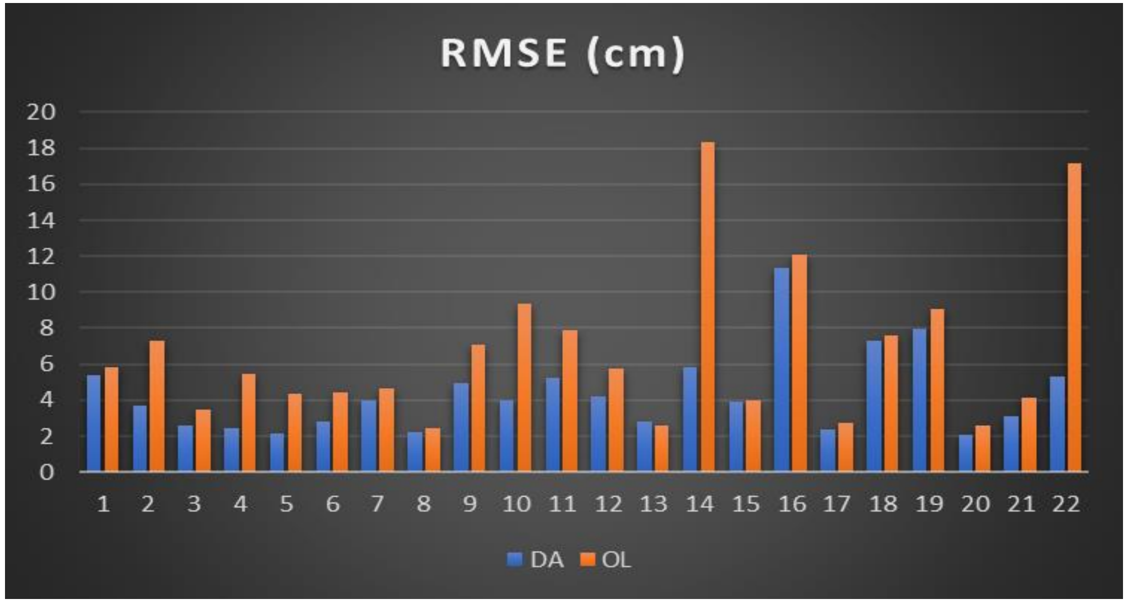
Monthly nonseasonal groundwater storage anomalies from the open loop (no DA) Catchment Land Surface Model (CLSM; red), CLSM with GRACE DA (blue), and in situ observations (black).

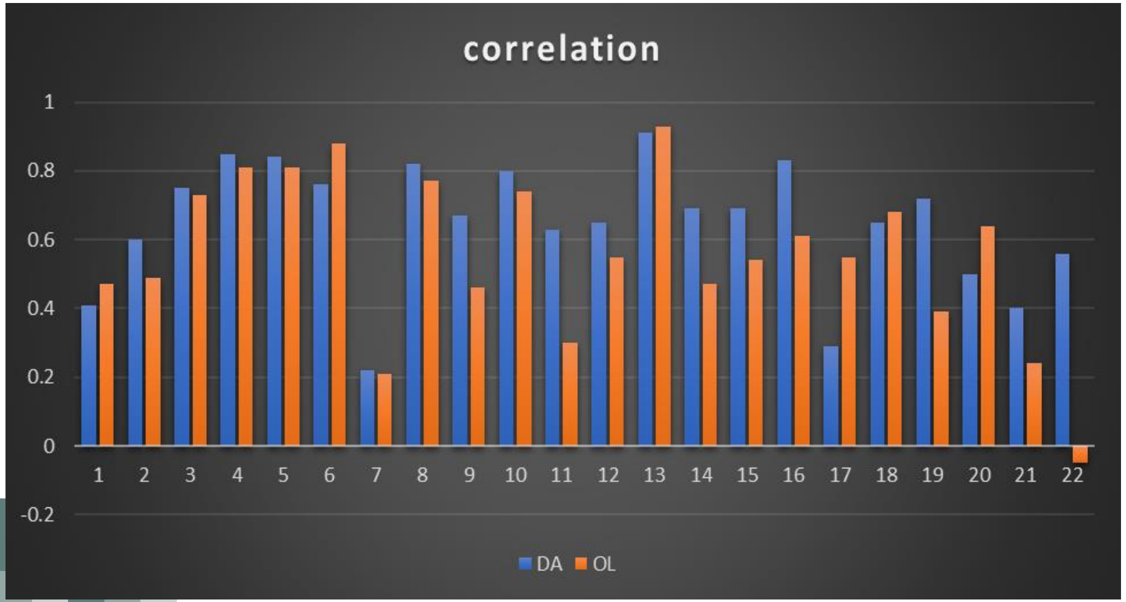
On average, GRACE/FO data assimilation (DA) reduced root mean square error (RMSE) by 36% and increased correlation by 16%.

However, almost all improvements occurred in regions where the open loop overestimated TWS variability so that GRACE/FO DA acted to reduce the amplitude of the variations.

Li, B., Rodell, M., Kumar, S., Beaudoing, H. K., Getirana, A., Zaitchik, B. F., et al (2019). Global GRACE data assimilation for groundwater and drought monitoring: Advances and challenges. Water Resources Research, 55. https://doi.org/10.1029/2018WR024618

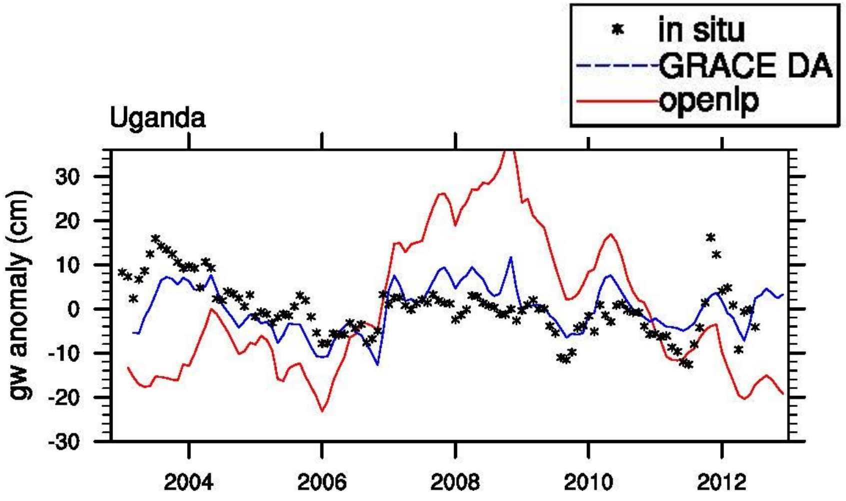
Evaluation of GRACE Data Assimilation Output: Groundwater





#	Region
1	Long Island, New York
2	New Jersey
3	Massachusetts
4	Pennsylvania
5	Upper Mississippi basin
6	Ohio-Tennessee basin
7	Red-Lower Mississippi basin
8	Missouri basin
9	Parana basin
10	Sao Francisco basin
11	Atlantico Norte
12	Amazon basin
13	Uruguai basin
14	Tocantins basin
15	Southern India
16	North China plain
17	Southwestern Australia
18	Northeastern Australia
19	Southeastern Australia
20	Rhine basin
21	The Netherlands
22	Uganda

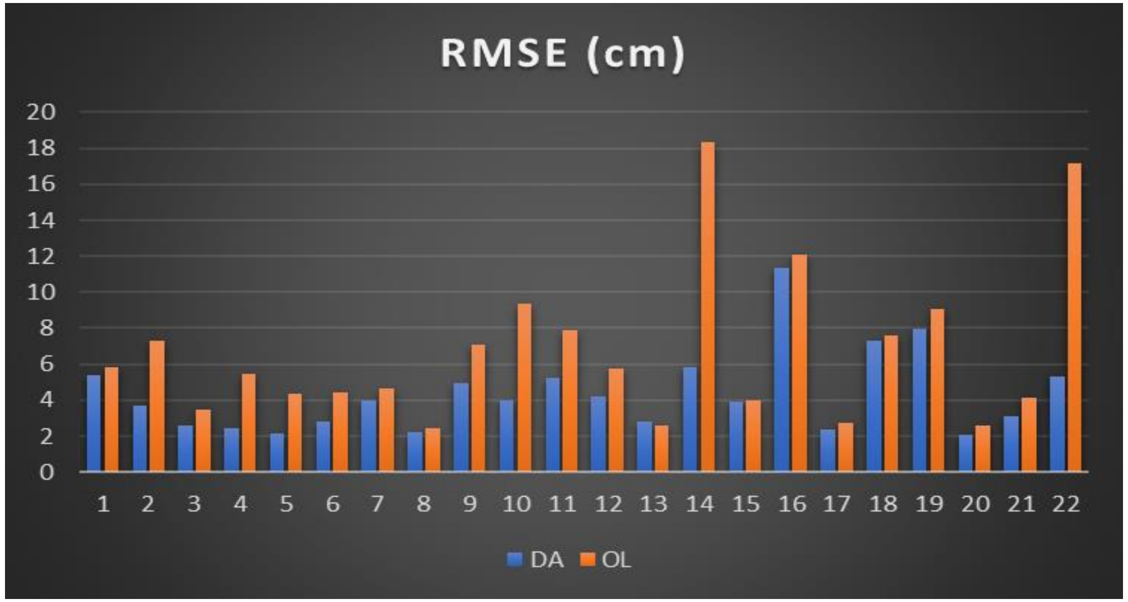
Left: GRACE data assimilation (blue) reduced RMSE by 36% and increased correlation by 16% on average over 22 regions, compared with the open loop simulation (red)

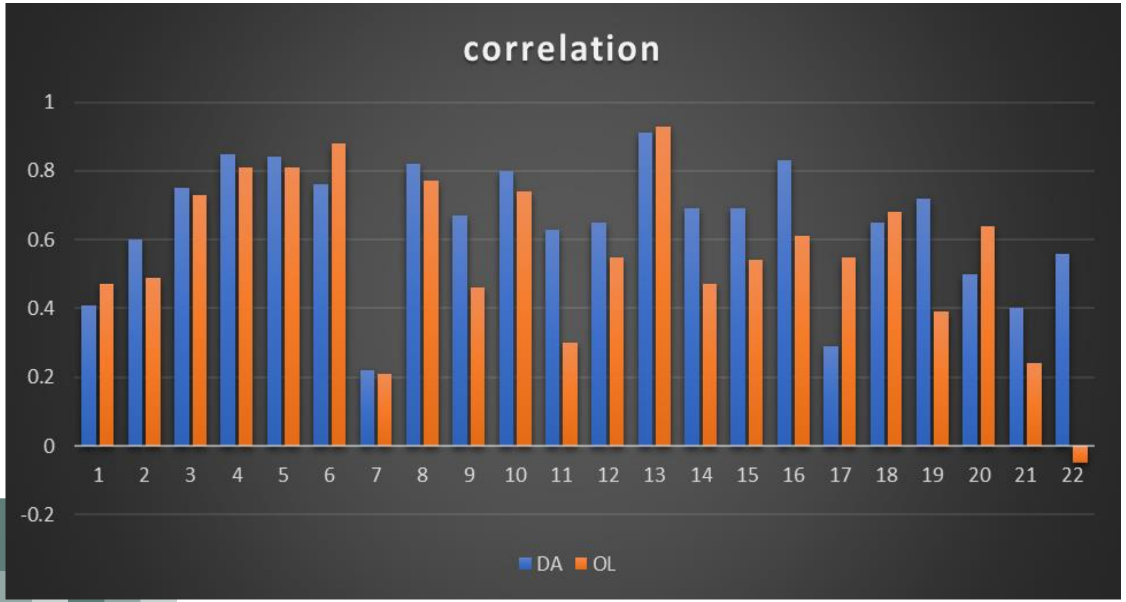


Above: In situ (black dots), open loop (red line), and data assimilation (blue line) groundwater storage anomalies (cm) in Uganda

Li, B., M. Rodell, S.V. Kumar, H.K. Beaudoing, et al., 2019: Global GRACE data assimilation for groundwater and drought monitoring: advances and challenges, Water Resour. Res., 55, doi:10.1029/2018WR024618.

Evaluation of GRACE Data Assimilation Output: Groundwater





Left and Below: Root mean square error (RMSE) and coefficient of correlation between simulated and observed groundwater storage changes in 22 regions around the world. OL = open loop; DA = GRACE data assimilation

Regional Scale Means

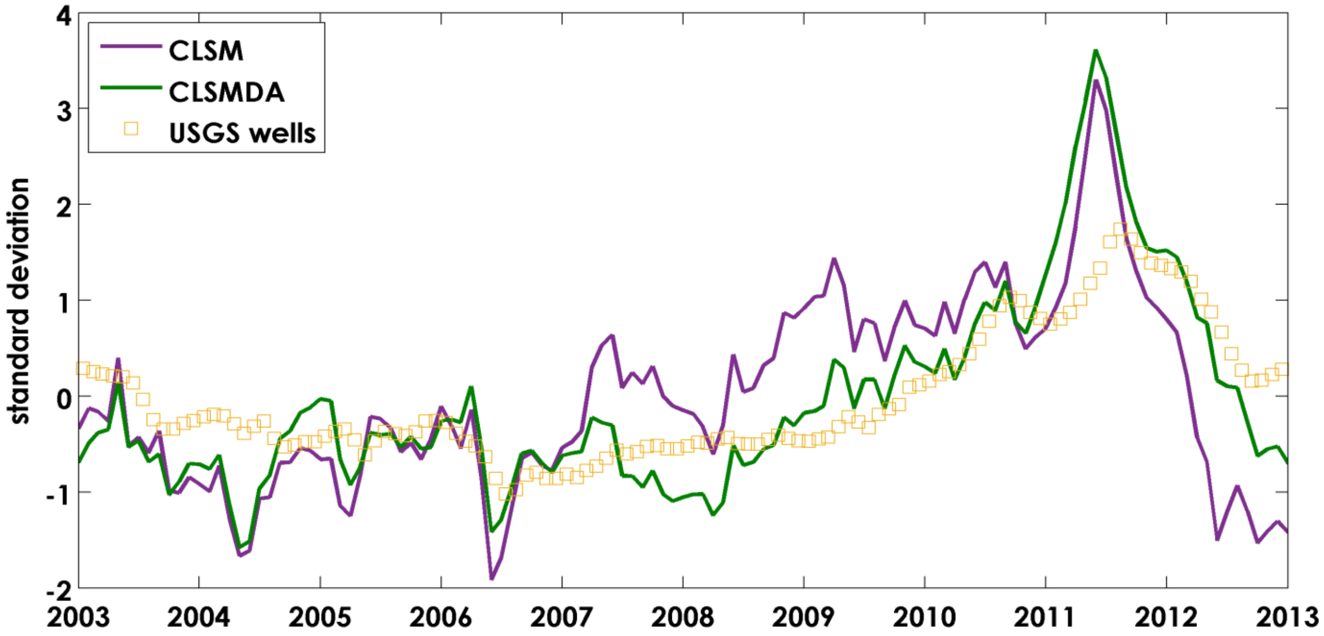
	DA	OL	Change
RMSE (cm)	4.3	6.7	down 36%
Correlation	0.65	0.56	up 16%

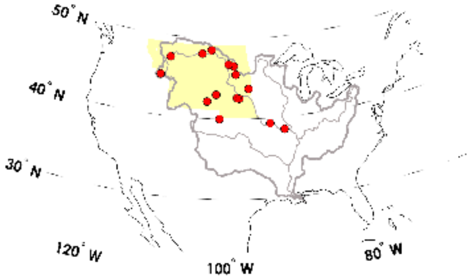
Point Scale Means

	DA	OL	Change
RMSE(cm)	7.6	8.4	down 10%
Correlation	0.33	0.27	up 22%

Li, B., M. Rodell, S.V. Kumar, H.K. Beaudoing, et al., 2019: Global GRACE data assimilation for groundwater and drought monitoring: advances and challenges, Water Resour. Res., 55, doi:10.1029/2018WR024618.

Evaluation of GRACE Data Assimilation Output: Groundwater





USGS observation well locations

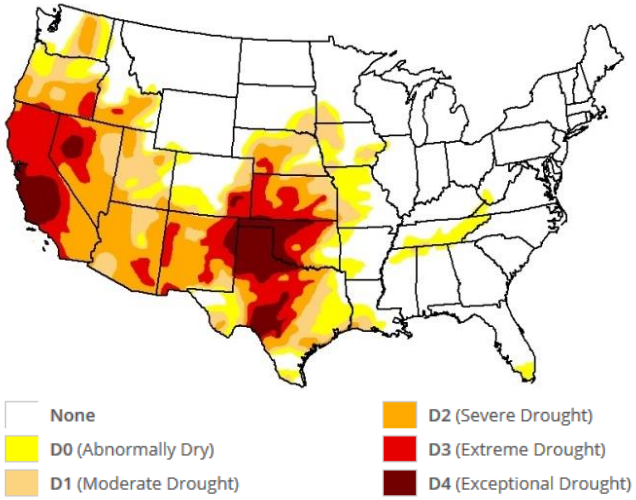
GRACE data assimilation improved simulation of groundwater storage anomalies leading up to and during the 2011 flood event in the Missouri River basin.

Model	Metric	GRACE TWS Anomaly	USGS Groundwater Anomaly
CLSM Open Loop	Correlation coefficient	0.88	0.58
	RMSE	33 cm	2.32 (normalized)
CLSM GRACE Data Assimilation	Correlation coefficient	0.95	0.86
	RMSE	25 cm	1.81 (normalized)

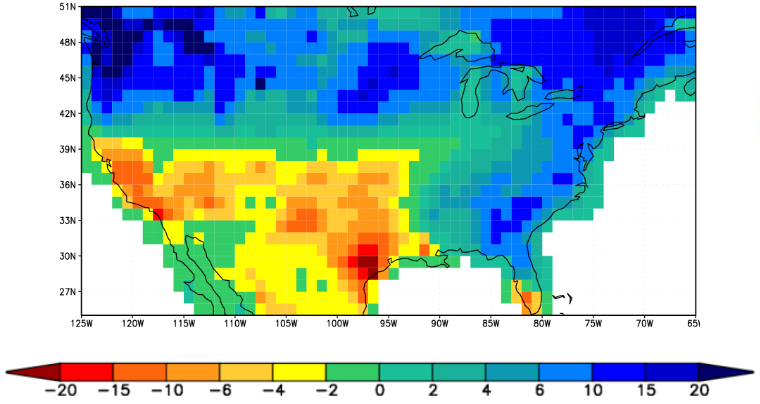
Reager, J.T., A.C. Thomas, E.A. Sproles, M. Rodell, H.K. Beaudoing, B. Li, and J.S Famiglietti (2015). Assimilation of GRACE terrestrial water storage observations into a land surface model for the assessment of regional flood potential, Remote Sensing, 7(11), 14663-14679.

GRACE/FO Data Assimilation Based Wetness/Drought Indicators

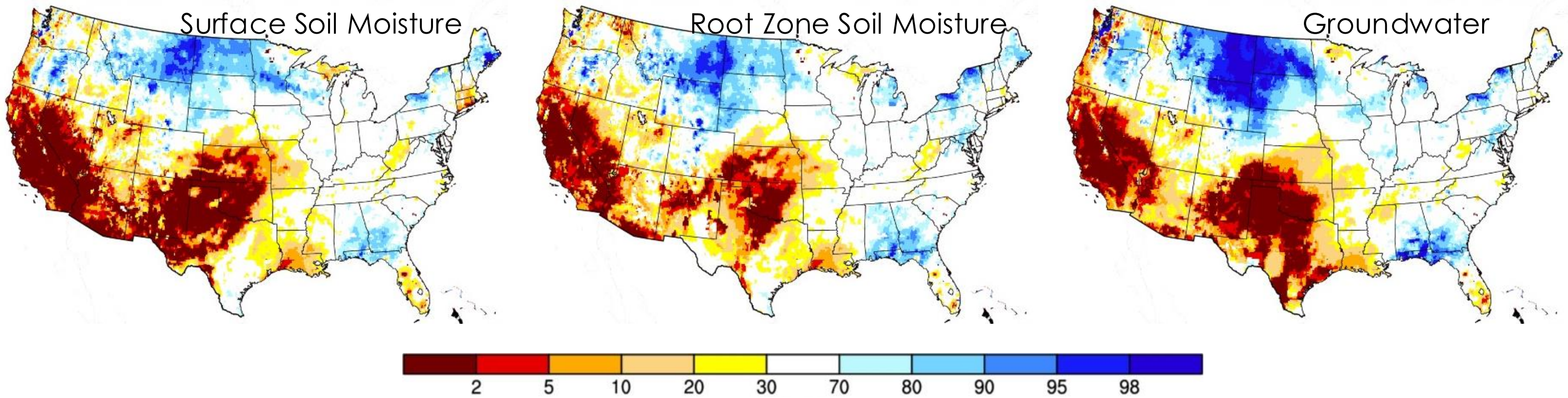
- 1948 to 2014 “open loop” (no data assimilation) Catchment LSM simulation provides background climatology
- 2002 to present Catchment LSM simulation with GRACE DA adjusted to be consistent with the long-term climatology using the overlapping period
- NLDAS2 observation-based meteorological forcing (precipitation, solar radiation, etc.) enables extrapolation of TWS information to near-real time
- Groundwater and root zone & surface soil moisture outputs are converted to percentiles based on the long-term climatology
- Since 2011, weekly maps (below right) and data have been available to authors of the U.S. Drought Monitor (top right) and by the National Drought Mitigation Center



U.S. Drought Monitor for 20 May 2014.



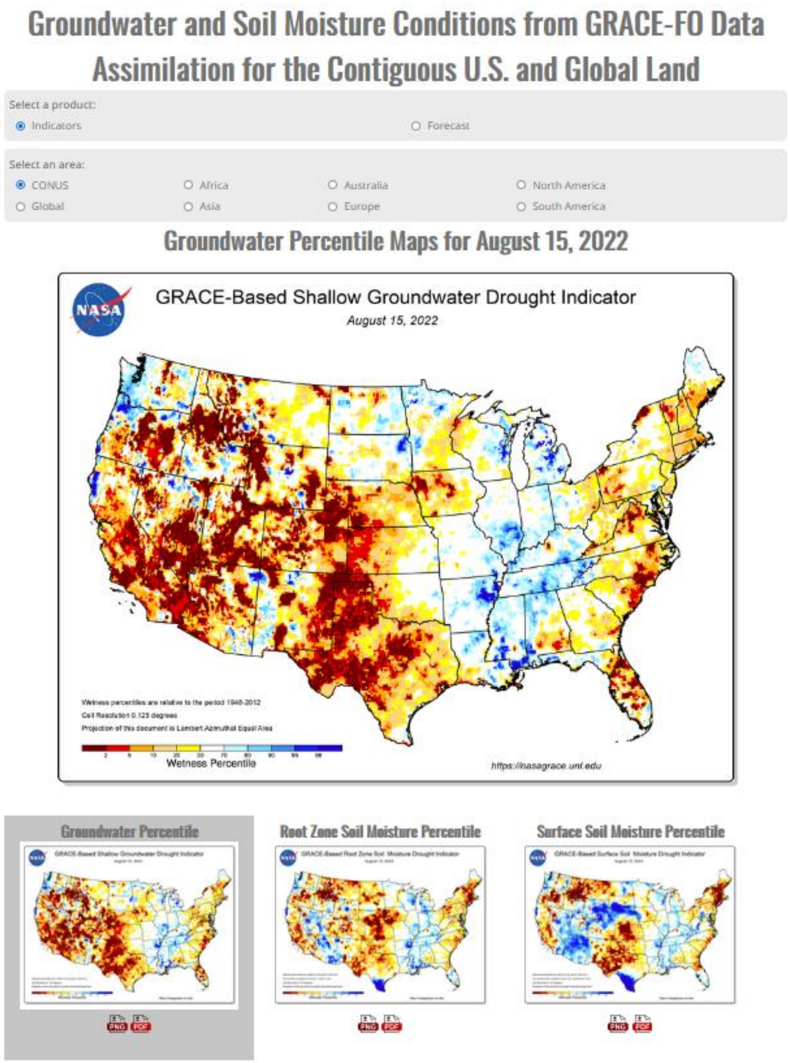
GRACE terrestrial water storage anomalies (cm equivalent height of water) for May 2014 (Tellus CSR RL05 scaled).



Drought indicators from GRACE data assimilation (wetness percentiles relative to the period 1948-2012) for 19 May 2014.

Houborg, R., M. Rodell, et al., 2012: Drought indicators based on model assimilated GRACE terrestrial water storage observations, Wat. Resour. Res, 48, W07525, doi:10.1029/2011WR011291

GRACE-FO Data Assimilation Wetness/Drought Indicators



Groundwater and Soil Moisture Conditions from GRACE-FO Data Assimilation for the Contiguous U.S. and Global Land

Select a product:
● Indicators ○ Forecast

Select an area:
● CONUS ○ Africa ○ Australia ○ North America
○ Global ○ Asia ○ Europe ○ South America

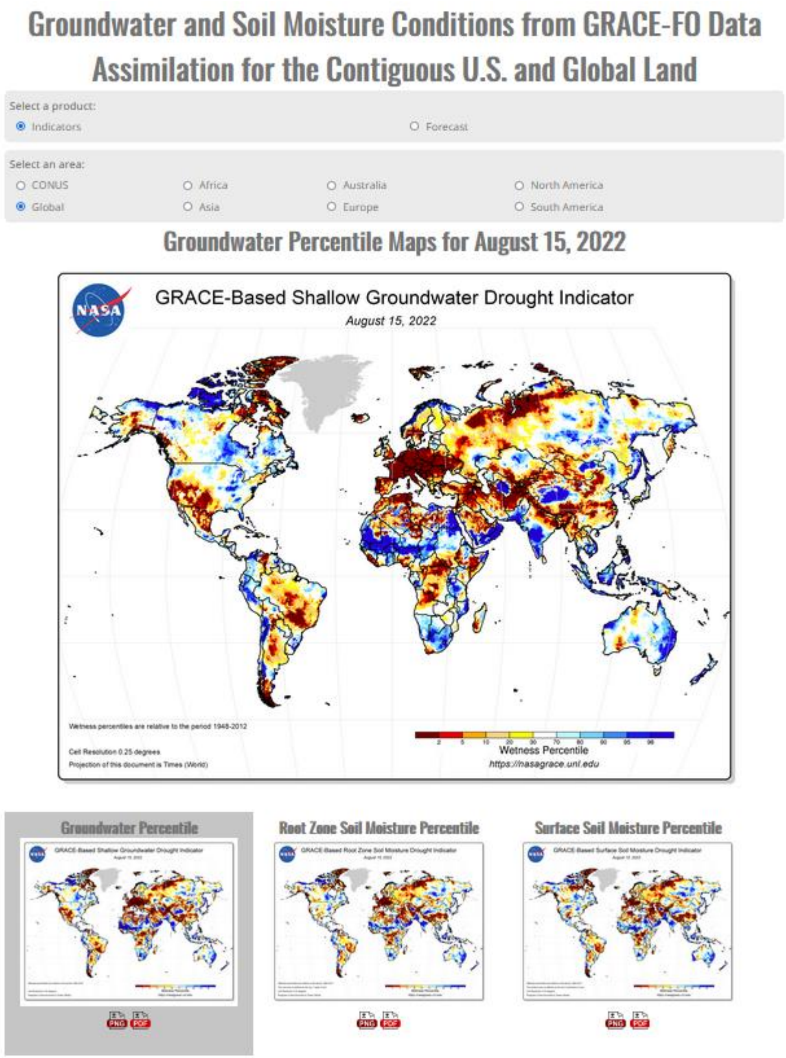
Groundwater Percentile Maps for August 15, 2022

GRACE-Based Shallow Groundwater Drought Indicator
August 15, 2022

Wetness percentiles are relative to the period 1948-2012
Cell Resolution 0.125 degrees
Projection of this document is Lambert Azimuthal Equal Area

https://nasagrace.unl.edu

Groundwater Percentile
Root Zone Soil Moisture Percentile
Surface Soil Moisture Percentile



Groundwater and Soil Moisture Conditions from GRACE-FO Data Assimilation for the Contiguous U.S. and Global Land

Select a product:
● Indicators ○ Forecast

Select an area:
○ CONUS ○ Africa ○ Australia ○ North America
● Global ○ Asia ○ Europe ○ South America

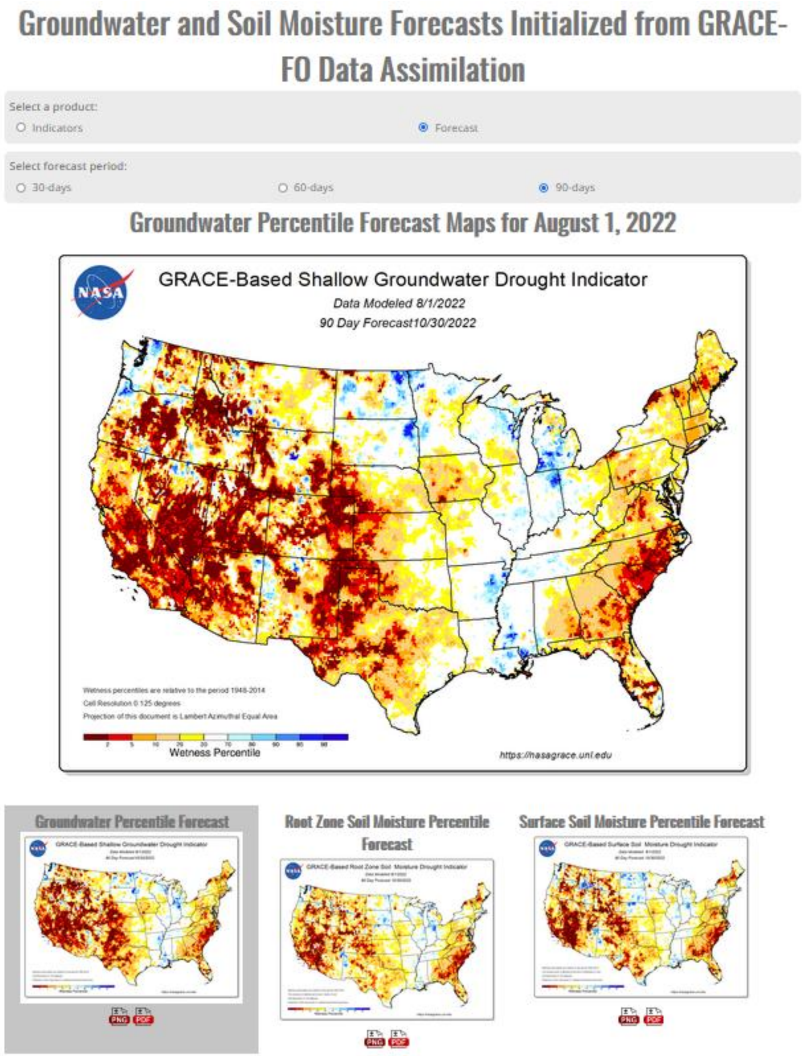
Groundwater Percentile Maps for August 15, 2022

GRACE-Based Shallow Groundwater Drought Indicator
August 15, 2022

Wetness percentiles are relative to the period 1948-2012
Cell Resolution 0.25 degrees
Projection of this document is Times (World)

https://nasagrace.unl.edu

Groundwater Percentile
Root Zone Soil Moisture Percentile
Surface Soil Moisture Percentile



Groundwater and Soil Moisture Forecasts Initialized from GRACE-FO Data Assimilation

Select a product:
○ Indicators ● Forecast

Select forecast period:
○ 30-days ○ 60-days ● 90-days

Groundwater Percentile Forecast Maps for August 1, 2022

GRACE-Based Shallow Groundwater Drought Indicator
Data Modeled 8/1/2022
90 Day Forecast10/30/2022

Wetness percentiles are relative to the period 1948-2014
Cell Resolution 0.125 degrees
Projection of this document is Lambert Azimuthal Equal Area

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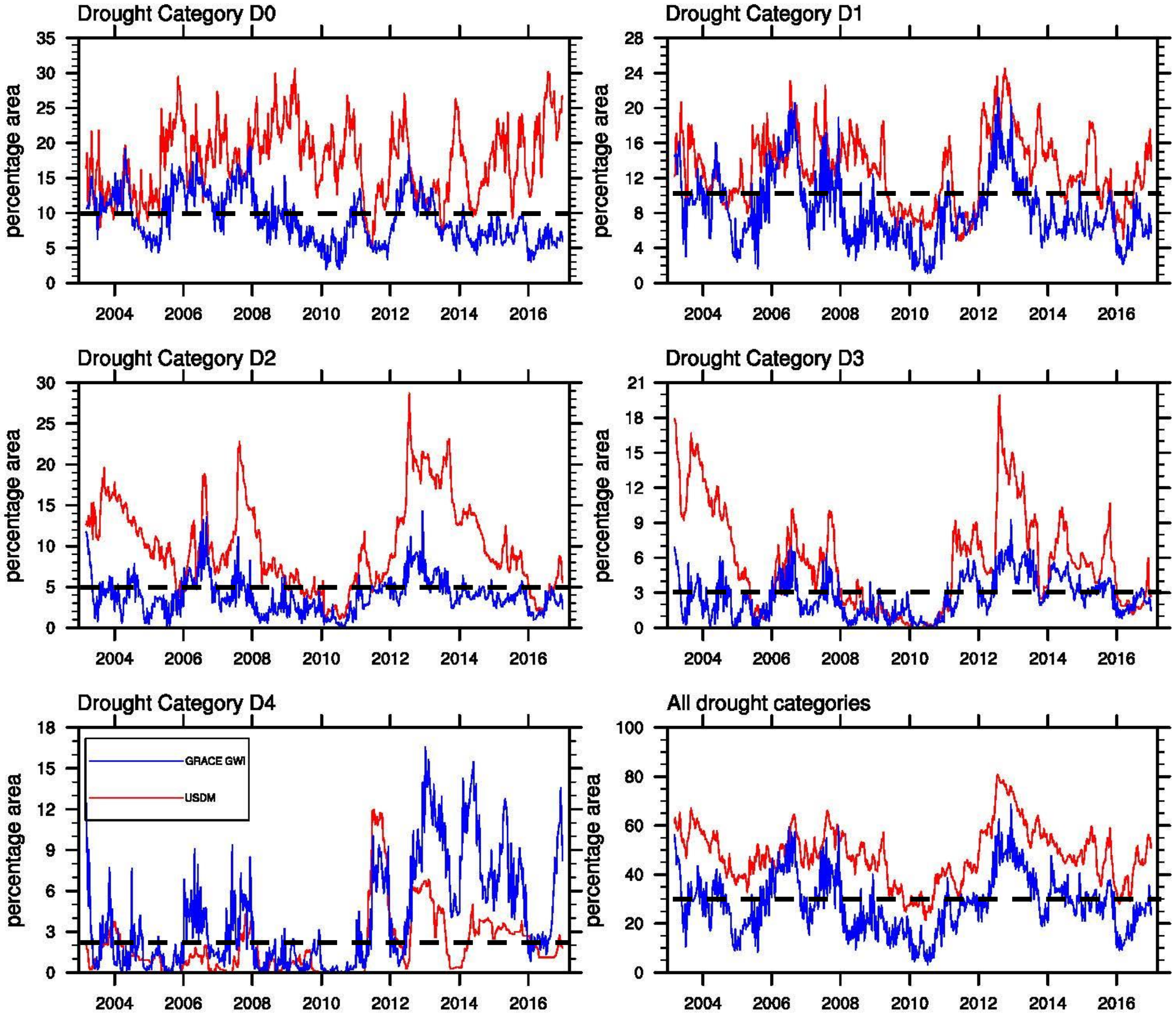
Groundwater Percentile Forecast
Root Zone Soil Moisture Percentile Forecast
Surface Soil Moisture Percentile Forecast

Distributed by the National Drought Mitigation Center

Comparison of GRACE DA and USDM Drought Extent

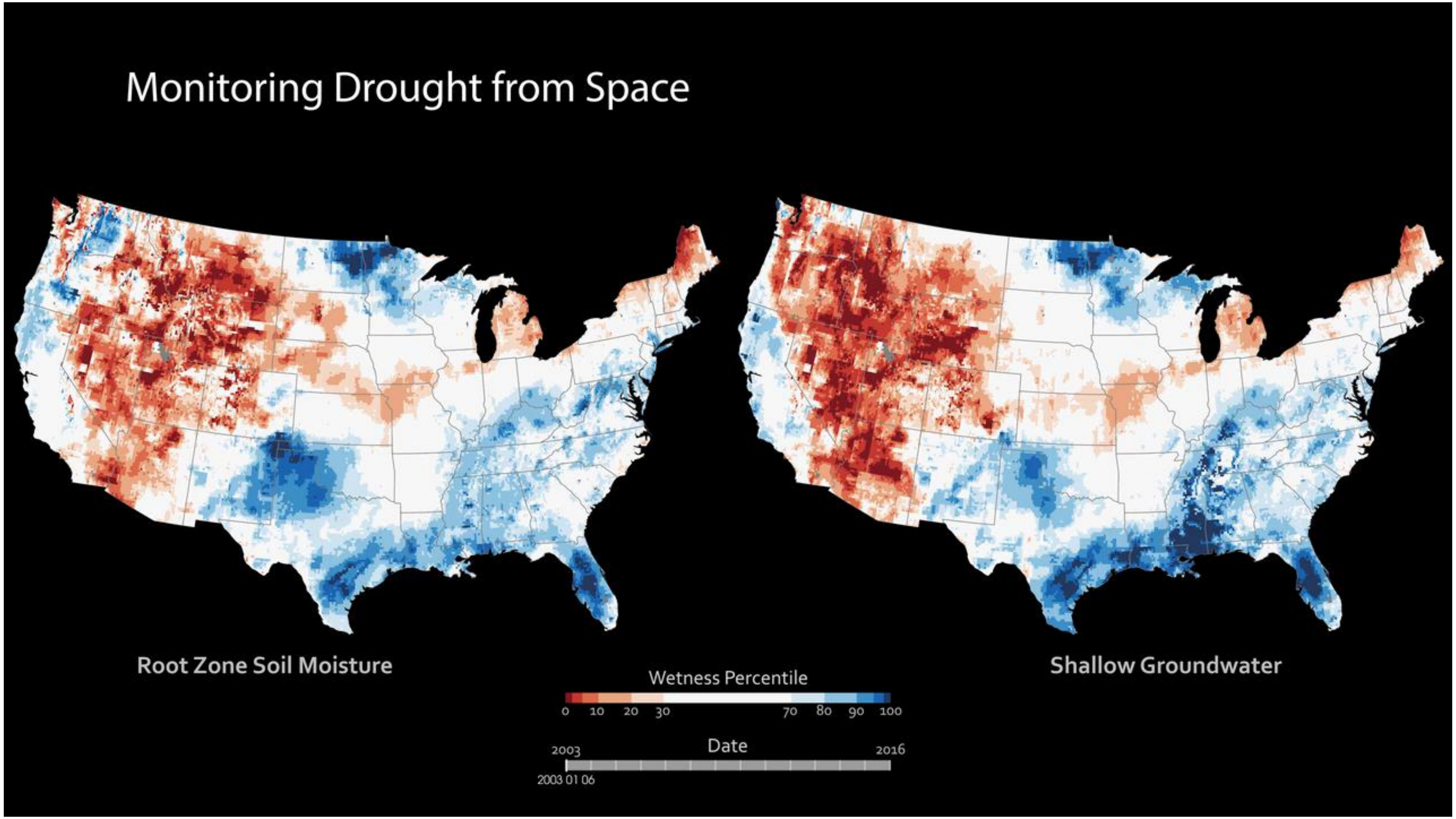


- Very good correlation between total U.S. drought area indicated by GRACE DA based groundwater drought indicators and U.S. Drought Monitor (bottom right)
- Discrepancies among drought categories
- On average, the U.S. Drought Monitor overestimates the area experiencing drought in all but Category D4 (exceptional drought)

Left: Time series of the percentage area of the U.S. in each drought category as indicated by the GRACE data assimilation-based shallow groundwater wetness/drought indicators (blue) and the U.S. Drought Monitor (USDM; red). The dashed black lines show the targeted long-term averages, based on the category definitions (below).

Wetness percentile ranges for each drought category: D0 [21-30%], D1 [11-20%], D2 [6-10%], D3 [3-5%], D4 [1-2%]

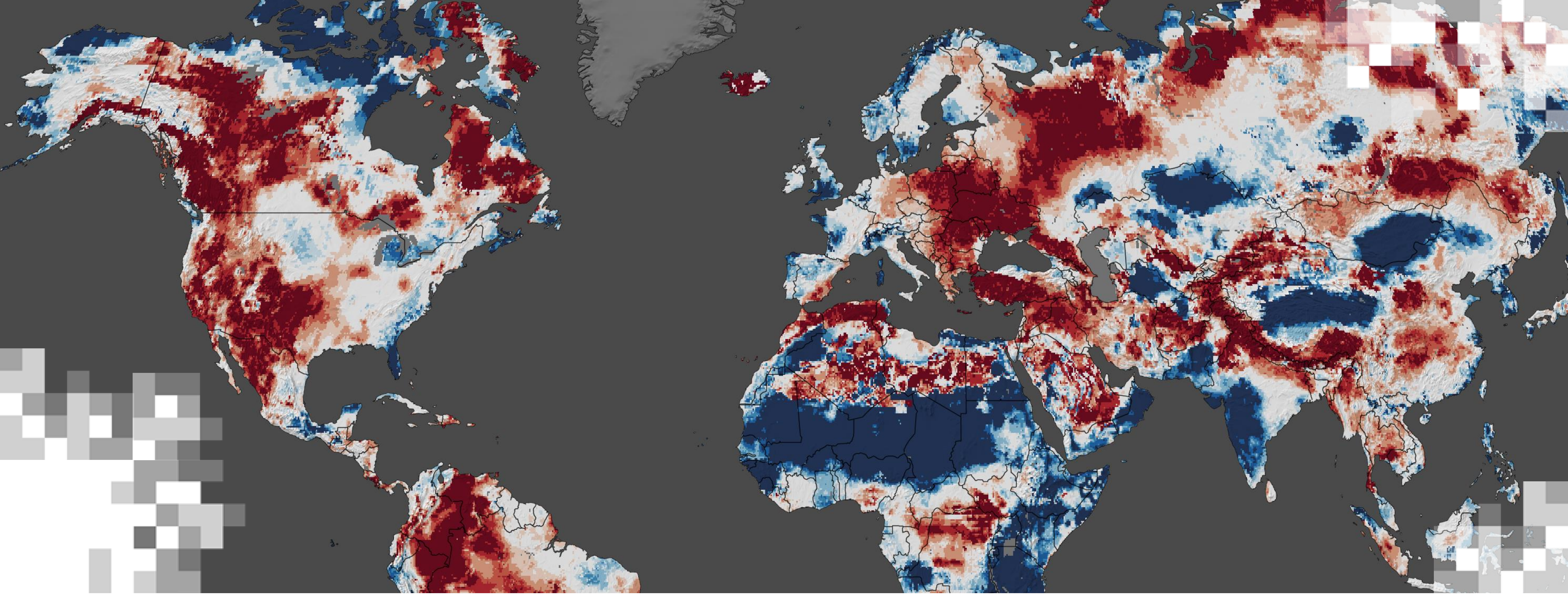
GRACE-FO Drought/Wetness Indicators



Visualization prepared by Marit Jentoft-Nilsen, NASA/GSFC

Summary & Considerations

- GRACE and GRACE-FO observe integrated changes in all forms of water, including groundwater, by measuring gravitational effects on the satellite orbits
- Land data assimilation systems (LDAS) integrate data from disparate sources, using algorithms that represent our knowledge of physical processes to fill spatial and temporal gaps
- GLDAS 2.2 integrates GRACE/FO observations of terrestrial water storage with other information using data assimilation, enabling spatial and temporal downscaling and vertical disaggregation
- GLDAS 2.2 soil moisture and groundwater output has been evaluated extensively using ground-based observations
- Key Limitations
    1. The model does not simulate water management (e.g., groundwater pumping), so it cannot effectively downscale GRACE/FO observations where direct human impacts are significant
    2. The model does not simulate confined aquifer storage changes, which may be an important component of TWS changes observed by GRACE/FO in certain regions
- GLDAS 2.2 output are updated monthly on GES DISC; associated wetness/drought indicator maps and monthly forecasts are updated weekly on the National Drought Mitigation Center website



Demonstration:
Groundwater Data Access, Analysis, and Visualization using Giovanni and QGIS

Demonstration: Using Giovanni for GLDAS Groundwater Data Analysis

- Purpose: Create maps and timeseries of groundwater data
- Region of Interest: Klamath River Basin
- Timeframe: Interannual to Interdecadal groundwater changes

Looking Ahead to Part 3

- Overview of Observational Products for End-Users from Remote Sensing Analysis (OPERA), surface displacement products (DISP).

Homework and Certificates

- **Homework:**
  - One homework assignment
  - Opens on 30/04/2026
  - Access from the training webpage
  - Answers must be submitted via Google Forms
  - **Due by 5/15/2026**

- **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 Affiliation)

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- ARSET YouTube

For questions, comments, or to share how you have applied our trainings to your work or studies, email nasa.arset@gmail.com.

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Thank You!