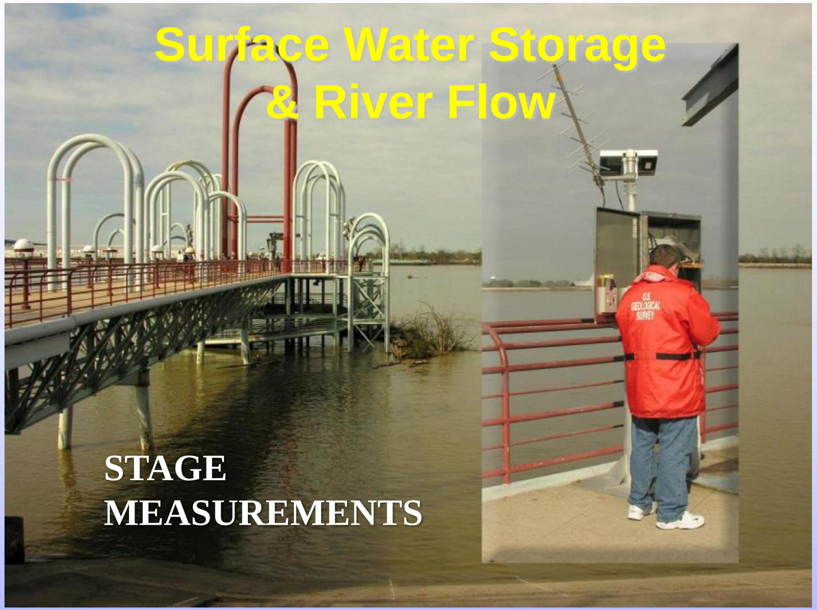
Application of Satellite Gravimetry for Water Resources Monitoring

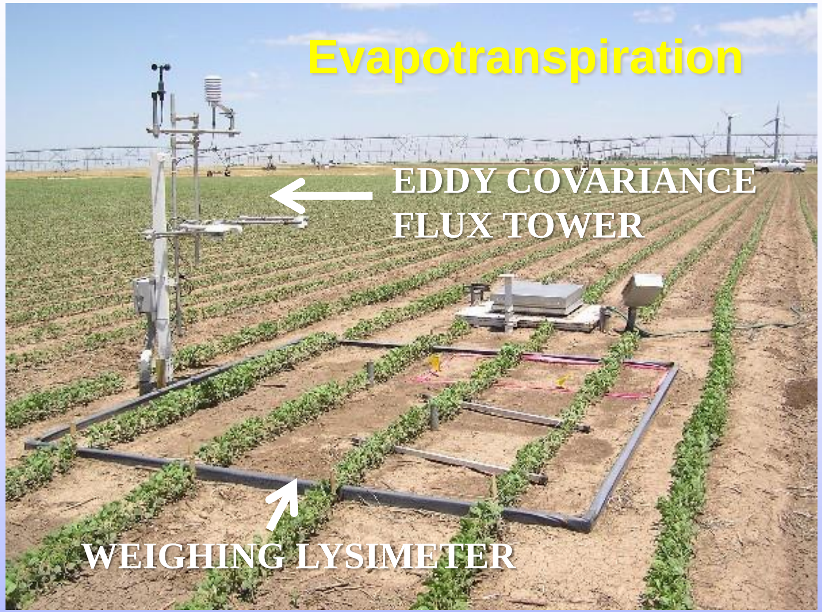
Matt Rodell, Ph.D.

Acting Deputy Director of Earth Sciences for Hydrosphere, Biosphere, and Geophysics
NASA Goddard Space Flight Center

Matthew.Rodell@nasa.gov

In Situ Observation of Water Cycle Variables





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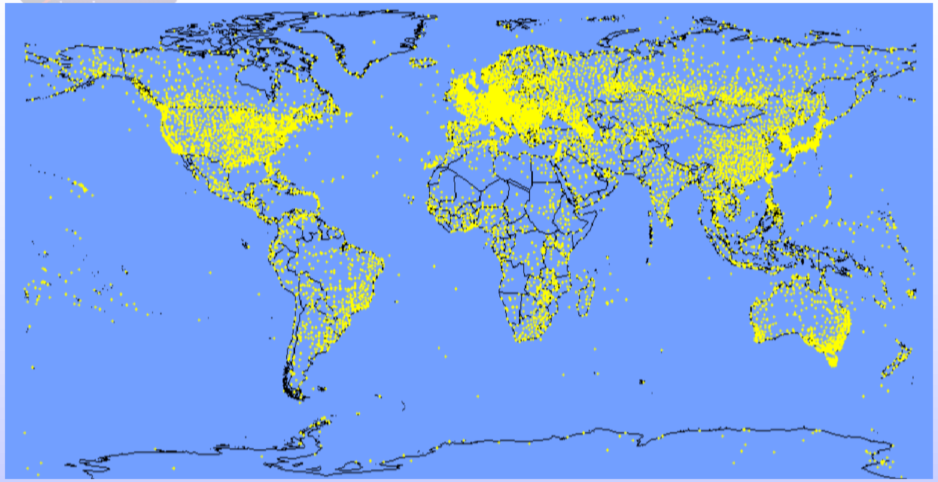
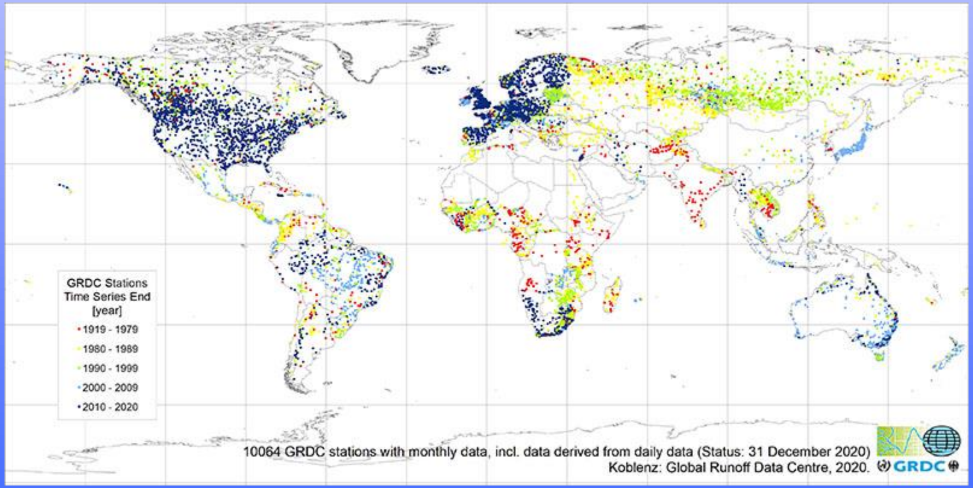
Inadequacy of *In Situ* Observations

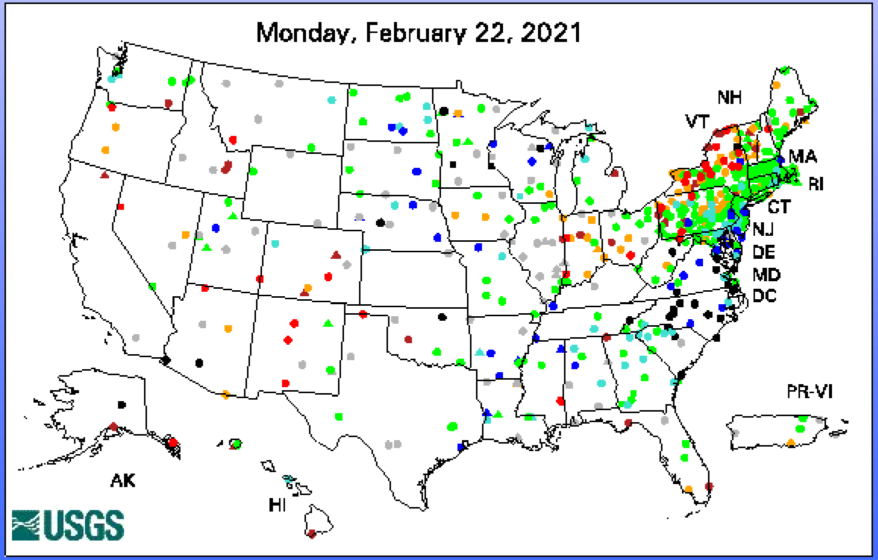


Global Telecommunication System meteorological stations. Air temperature, precipitation, solar radiation, wind speed, and humidity only.

Global Groundwater Monitoring Network. Raw data are not freely available to use.



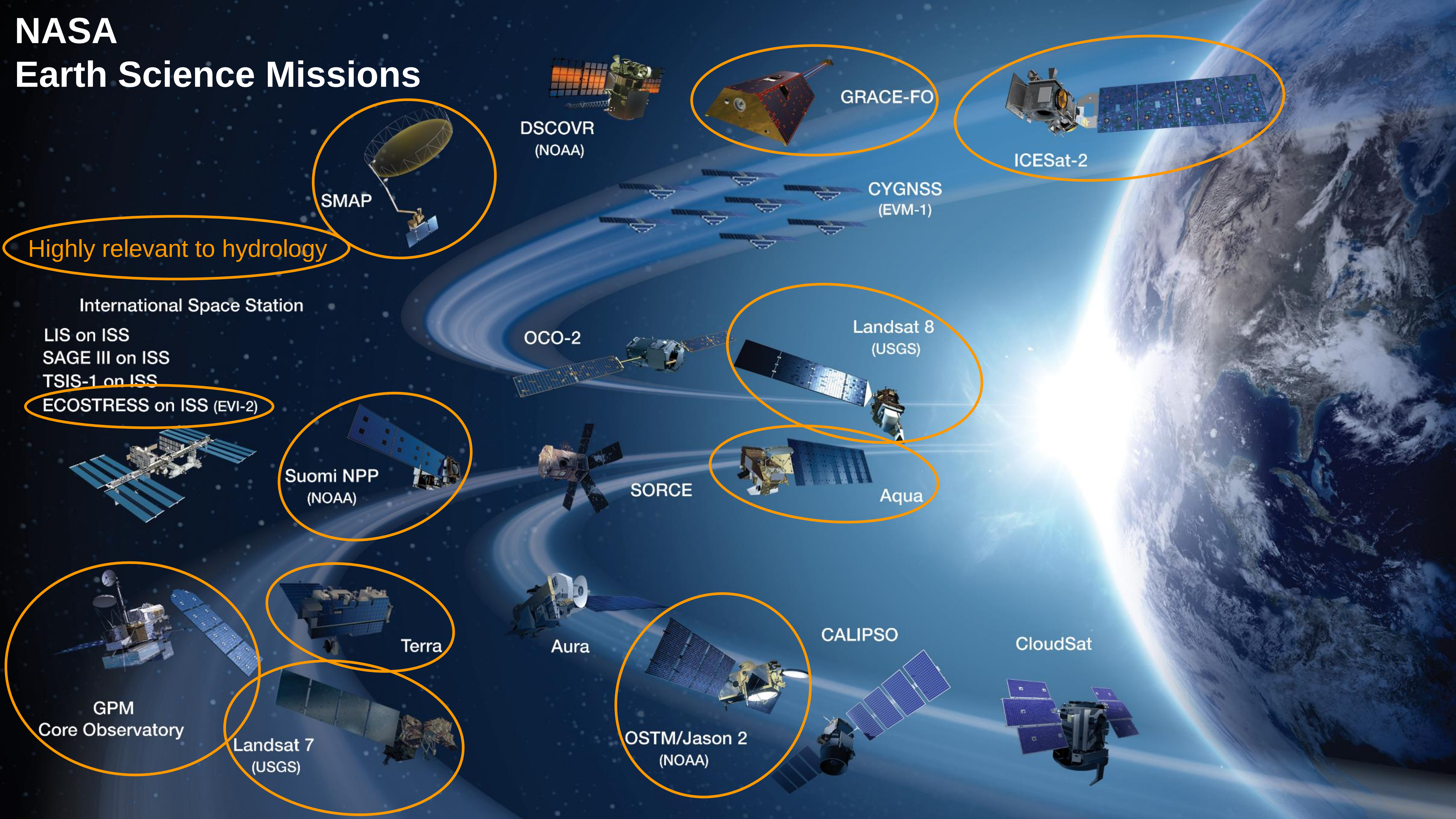
River flow observations from the Global Runoff Data Centre. Warmer colors indicate greater latency in the data record.



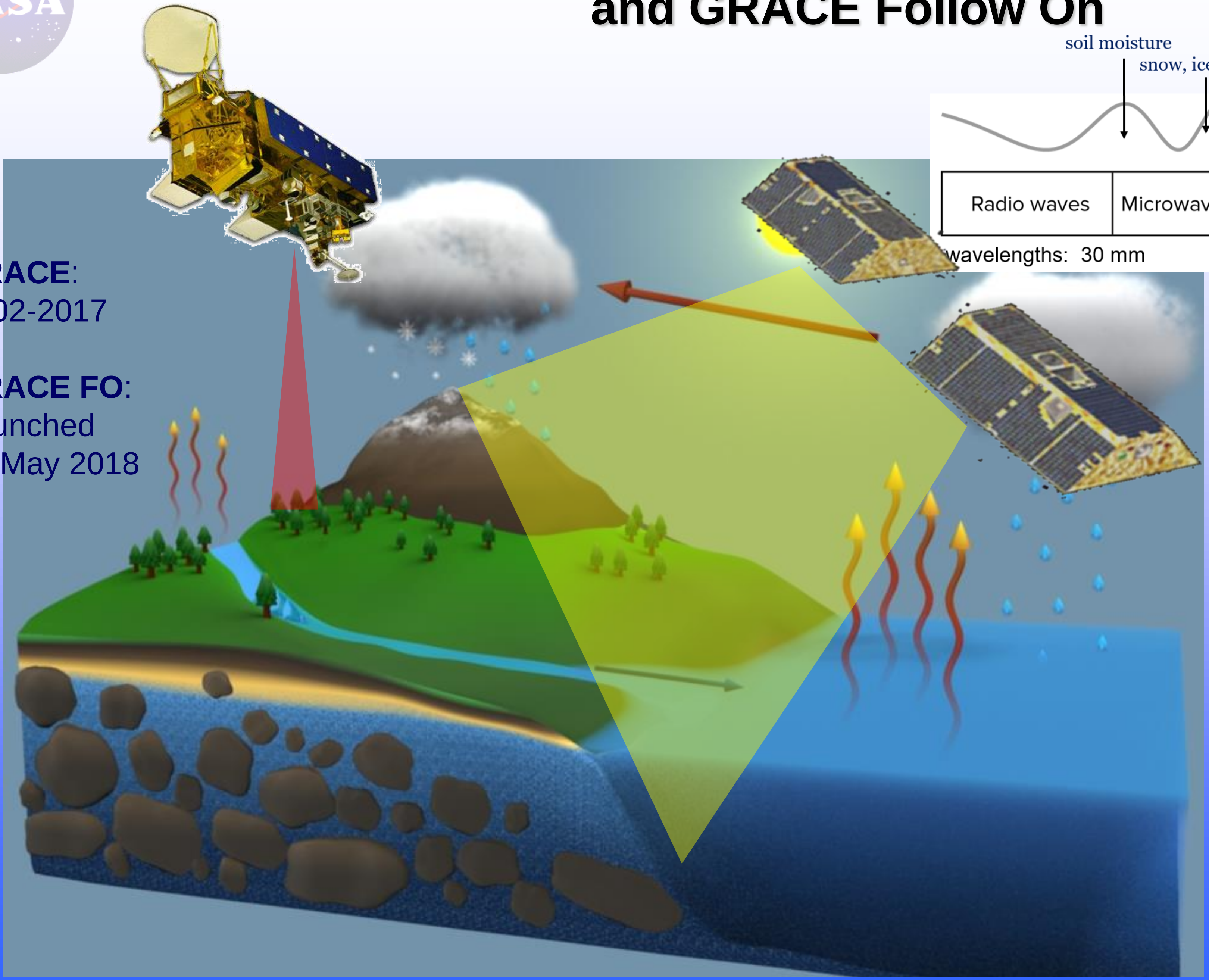
USGS Groundwater Climate Response Network.

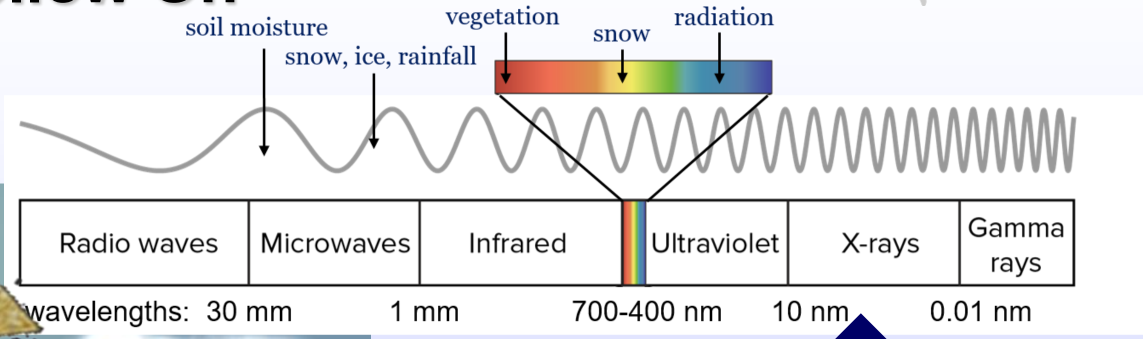
Issues include coverage gaps, delays, measurement continuity and consistency, data format and quality control, political restrictions

Matthew.Rodell@nasa.gov


NASA
Earth Science Missions
SMAP
DSCOVR
(NOAA)
GRACE-FO
ICESat-2
CYGNSS
(EVM-1)
Highly relevant to hydrology
International Space Station
LIS on ISS
SAGE III on ISS
TSIS-1 on ISS
ECOSTRESS on ISS (EVI-2)
OCO-2
Landsat 8
(USGS)
Suomi NPP
(NOAA)
SORCE
Aqua
GPM
Core Observatory
Terra
Aura
CALIPSO
CloudSat
Landsat 7
(USGS)
OSTM/Jason 2
(NOAA)

Gravity Recovery and Climate Experiment (GRACE) and GRACE Follow On





GRACE:
2002-2017

GRACE FO:
Launched
22 May 2018

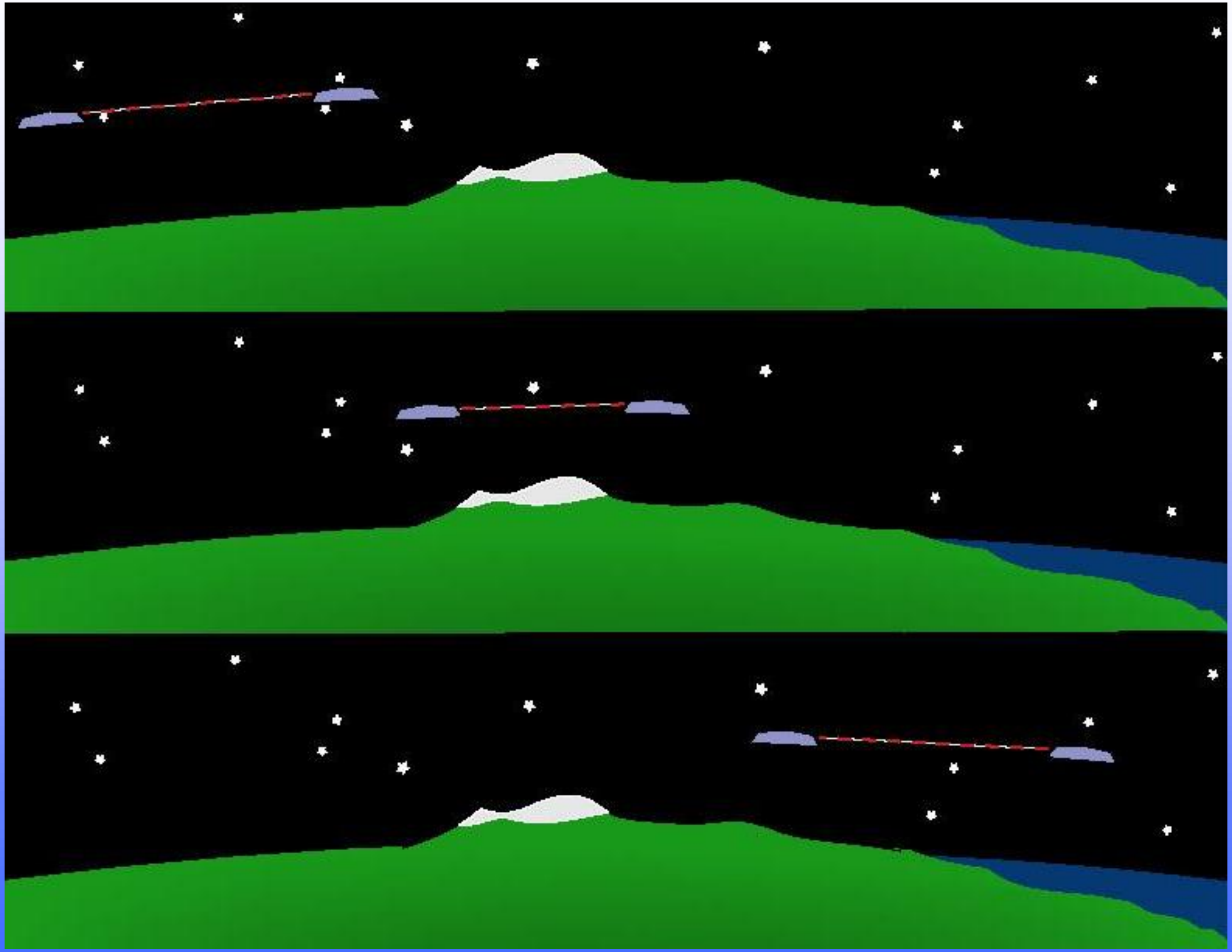
Conventional radiation-based remote sensing technologies cannot sense water below the first few centimeters of the snow-canopy-soil column

GRACE FO.

GRACE and GRACE Follow On are unique in their ability to monitor water at all levels, down to the deepest aquifer

Matthew.Rodell@nasa.gov

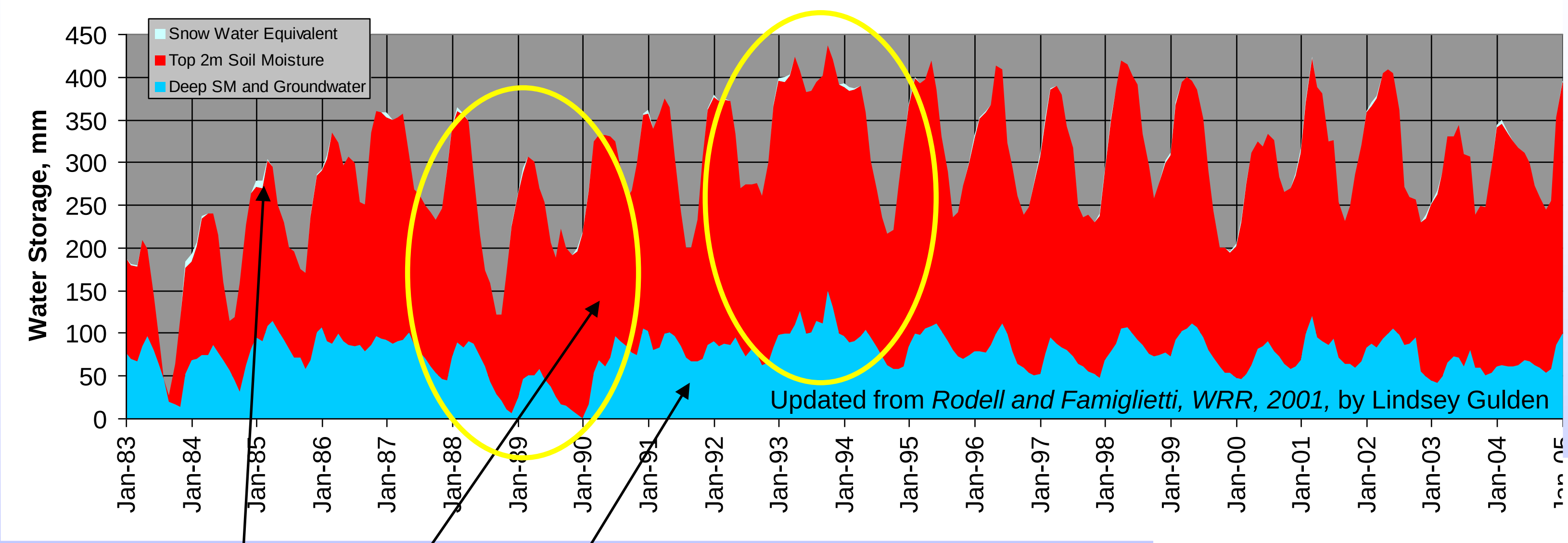
Gravity Recovery and Climate Experiment (GRACE) and GRACE Follow On

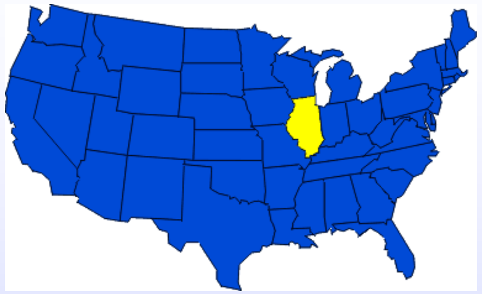


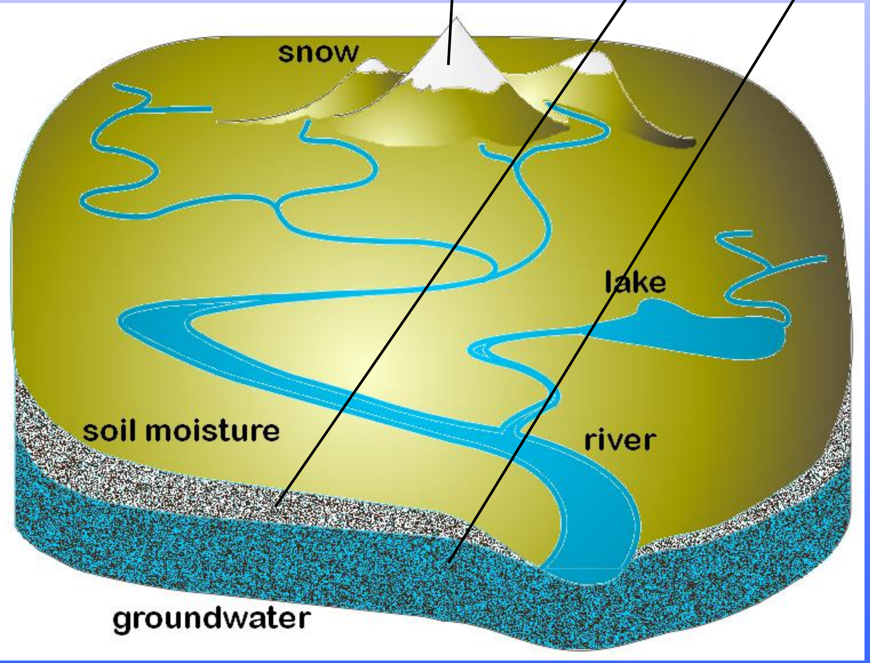
- Two identical satellites flying in tandem, near-polar orbit, ~200 km apart, 485 km initial altitude
- Distance between satellites continuously and precisely tracked by K-band microwave ranging system (and laser for GRACE-FO)
- Mass anomalies perturb the orbits of the satellites, and hence the inter-satellite range (distance)

Matthew.Rodell@nasa.gov

Terrestrial Water Storage Variability

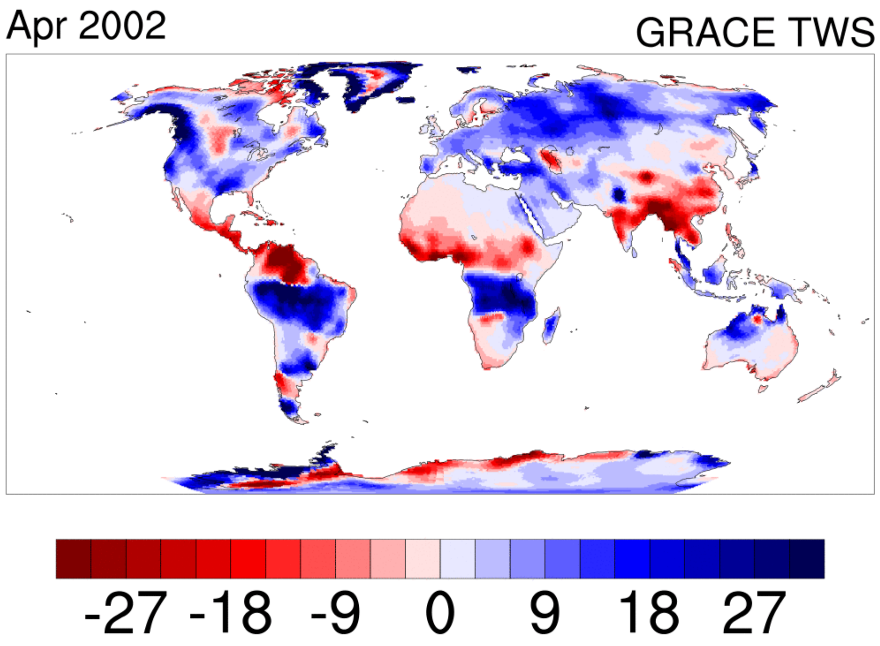




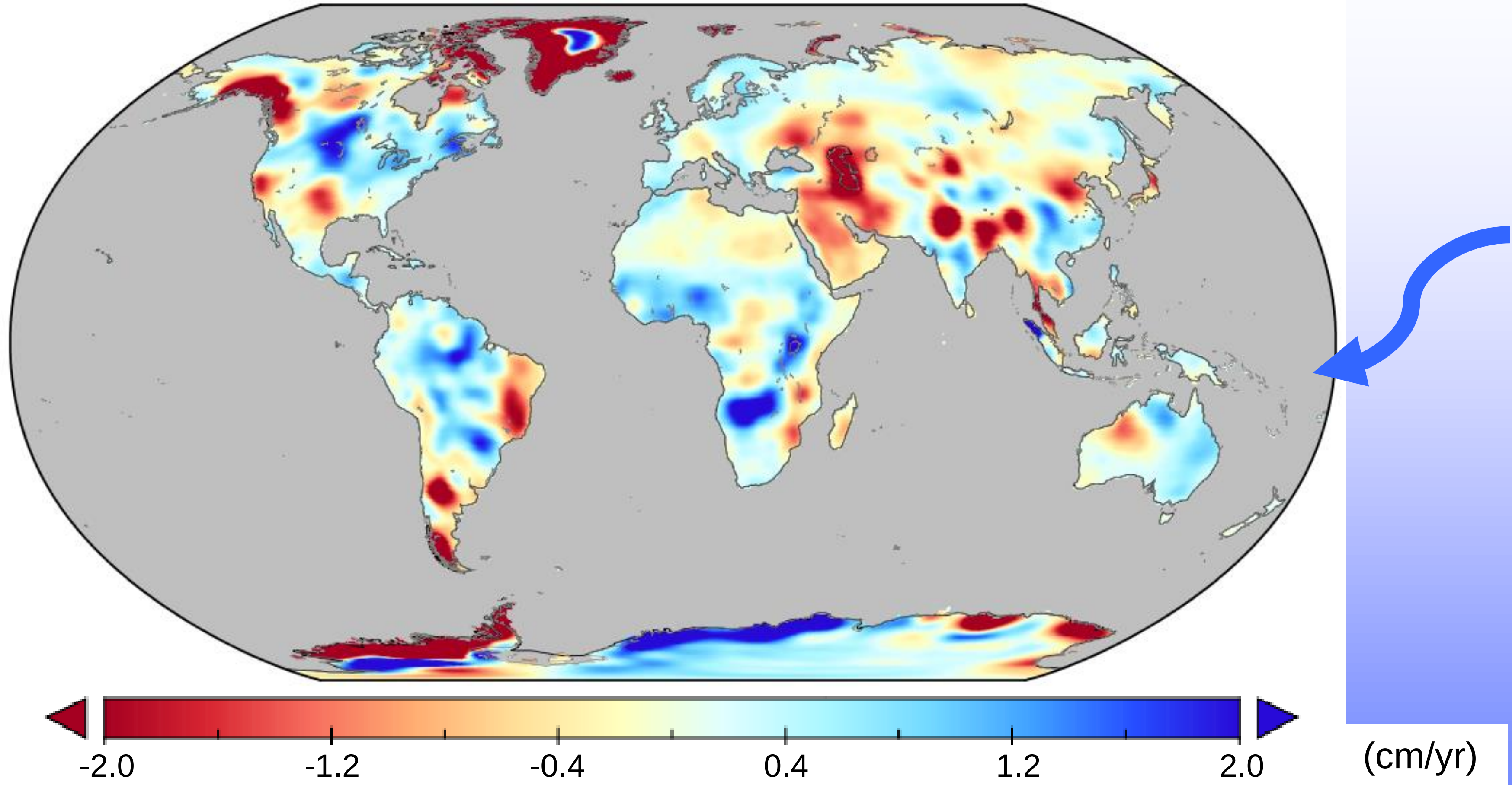


Top: 23-year time series of snow, soil moisture, and groundwater storage in Illinois

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



Terrestrial Water Storage "Trends", 2002-2016



Linear rate of change of TWS* (cm/yr) after first removing the seasonal cycle.

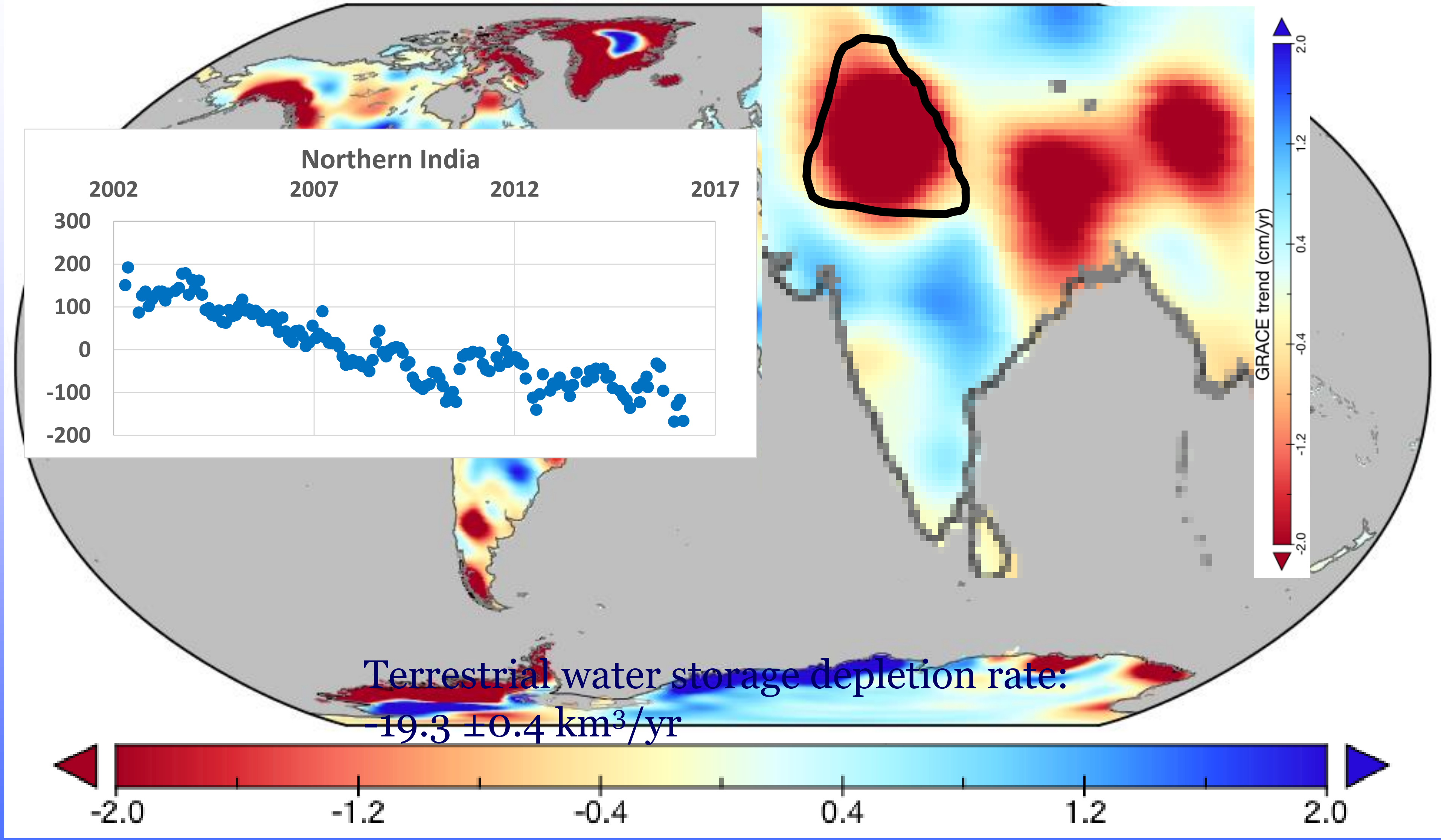
Which apparent trends are caused by
1. Natural interannual variability
2. Water (mis)management
3. Climate change

?

*Watkins, M. M., Wiese, D. N., Yuan, D. N., Boening, C. & Landerer, F. W., 2015: Improved methods for observing Earth's time variable mass distribution with GRACE using spherical cap mascons. J. Geophys. Res. Solid Earth 120, 2648-2671.

Matthew.Rodell@nasa.gov

Emerging Trends in Global Freshwater Storage
Groundwater Depletion in Northern India



Terrestrial water storage depletion rate:
-19.3 ±0.4 km³/yr

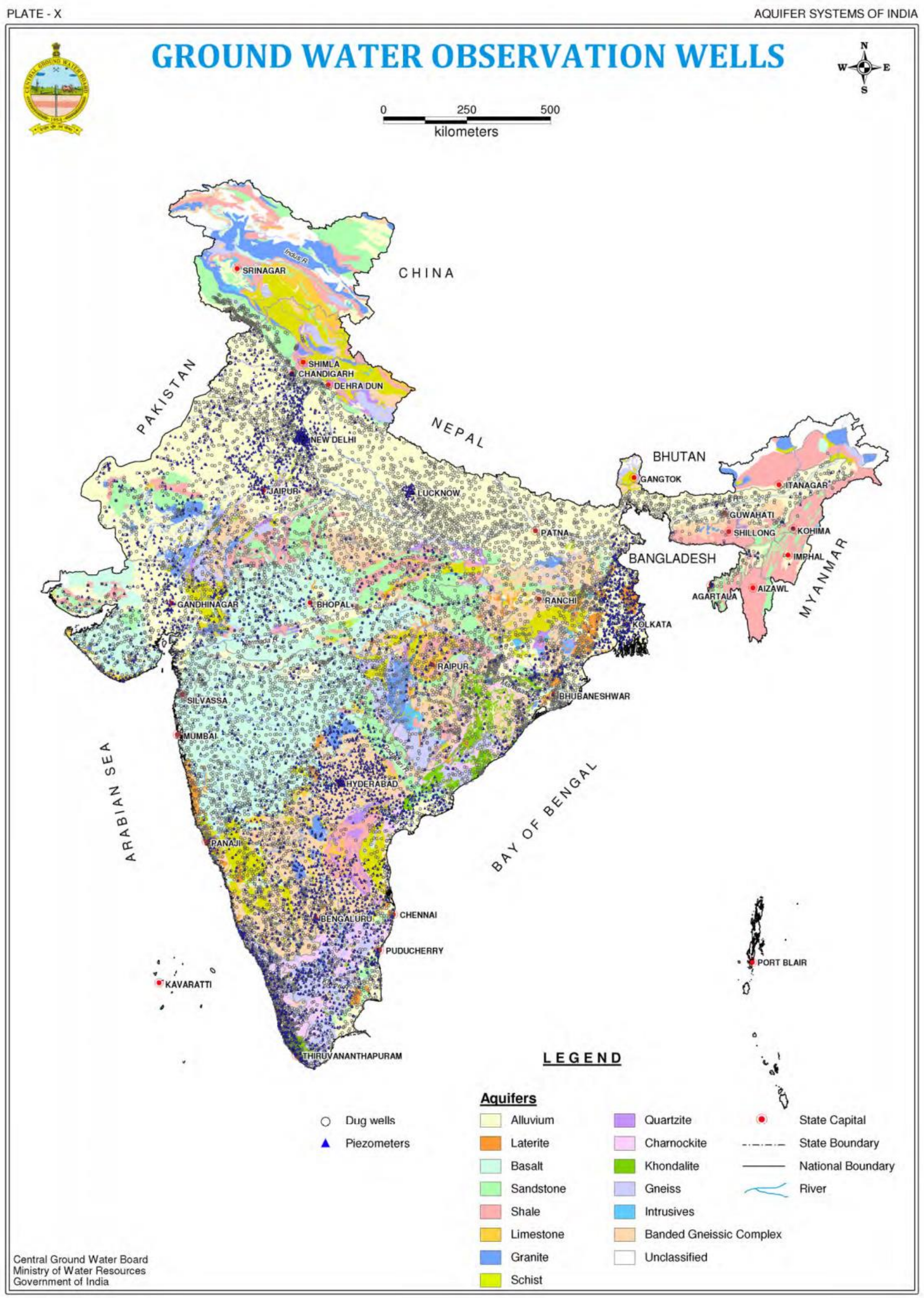
Trends in terrestrial water storage (cm/yr), including groundwater, soil water, lakes, snow, and ice, as observed by GRACE during 2002-16

Matthew.Rodell@nasa.gov

India

Data scarcity is not the issue.

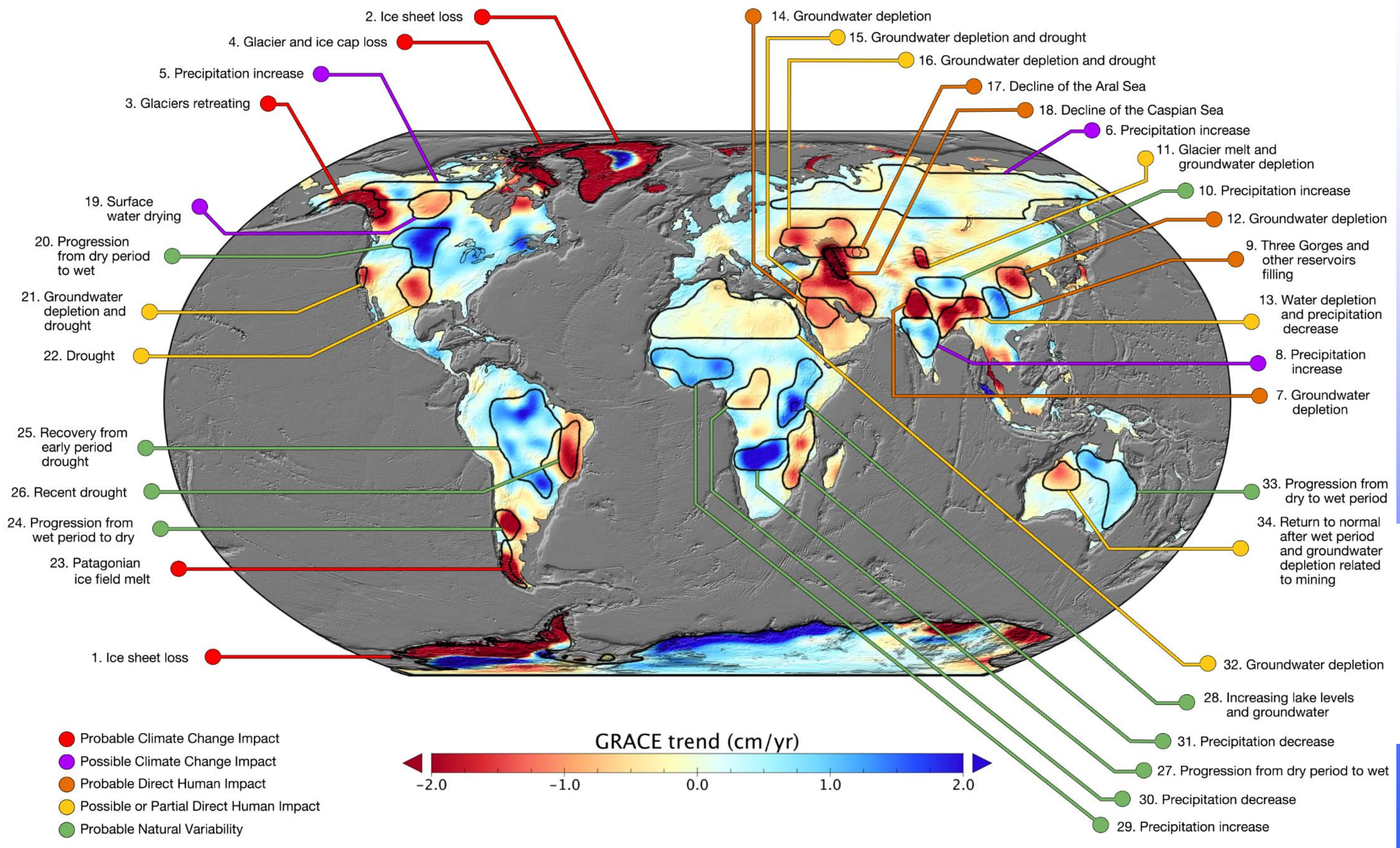
Many wells are monitored but the data are not publicly available.



From the Central Ground Water Board of India, courtesy of Virendra Tiwari

Matthew.Rodell@nasa.gov

Emerging Trends in Global Freshwater Availability

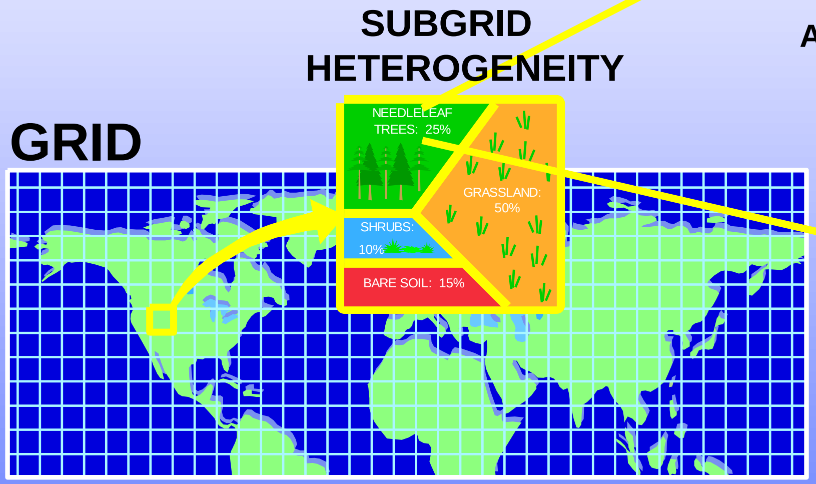


Rodell, M., J.S. Famiglietti, D.N. Wiese, J.T. Reager, H.K. Beaudoing, F.W. Landerer, and M.-H. Lo, 2018: Emerging trends in global freshwater availability, *Nature,* **557**, 651-659.

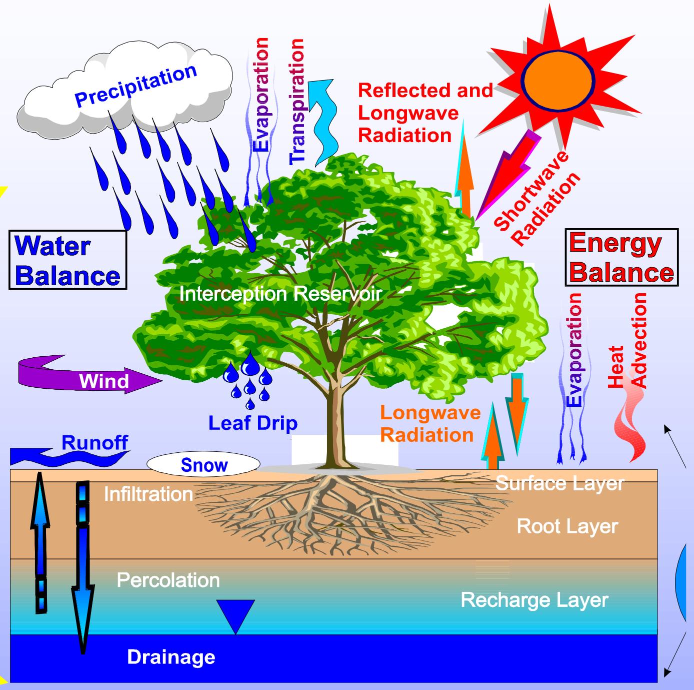
Matthew.Rodell@nasa.gov

Land Surface Model Structure

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)



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

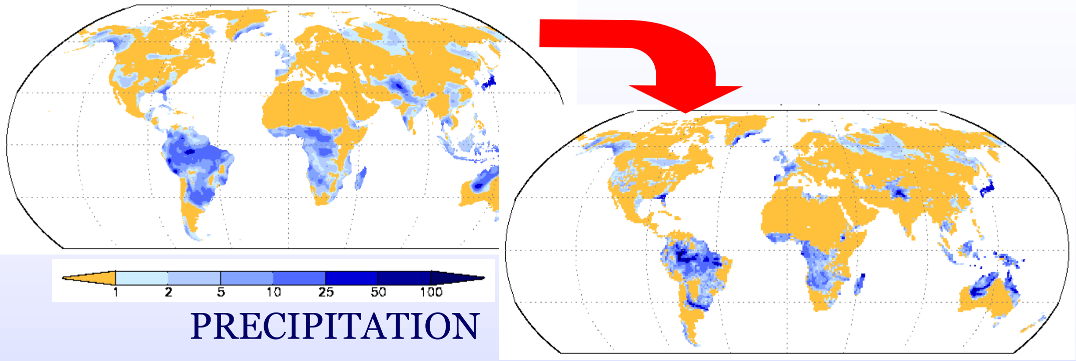
Evaporation: Penman-Monteith equation

etc.

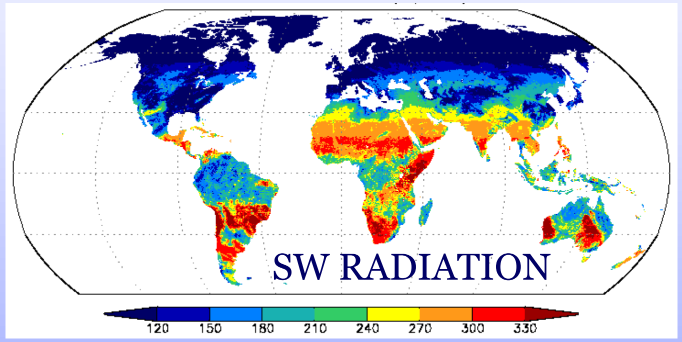
Matthew.Rodell@nasa.gov

Data Integration Within a Land Data Assimilation System (LDAS)

INTERCOMPARISON and OPTIMAL MERGING of global data fields

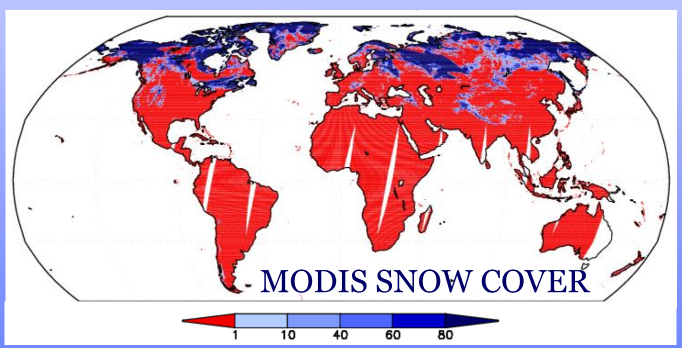


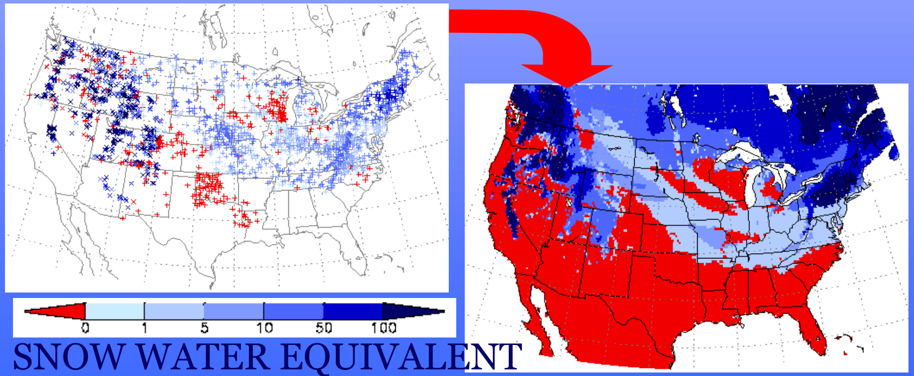
PRECIPITATION



Satellite derived meteorological data used as land surface model FORCING

ASSIMILATION of satellite based land surface state fields (snow, soil moisture, surface temp, etc.)





SNOW WATER EQUIVALENT

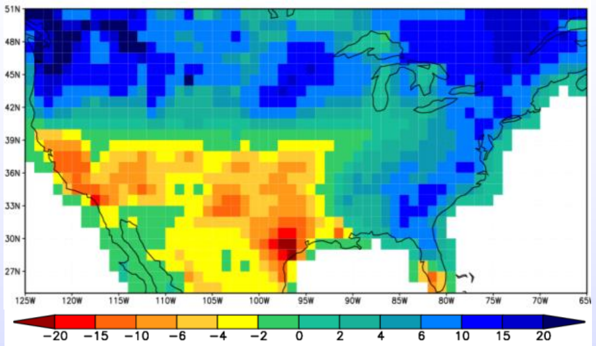
Ground-based observations used to VALIDATE model output

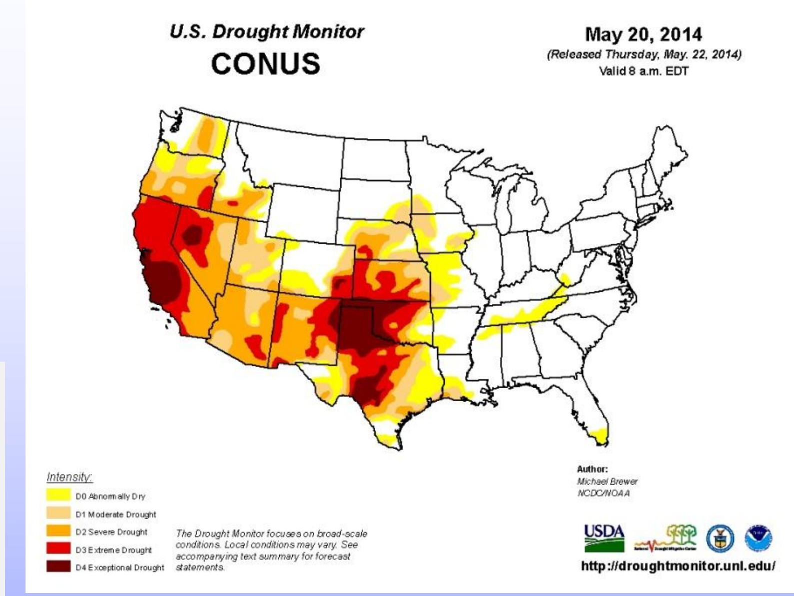
Examples from NASA's GLDAS; http://ldas.gsfc.nasa.gov/

Matthew.Rodell@nasa.gov

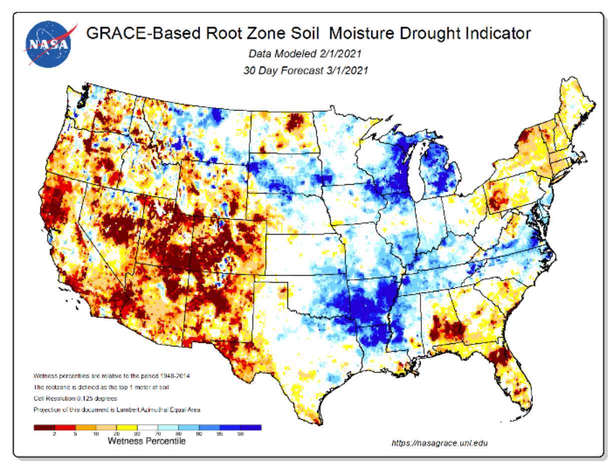
GRACE Data Assimilation for Drought Monitoring & Forecasting

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



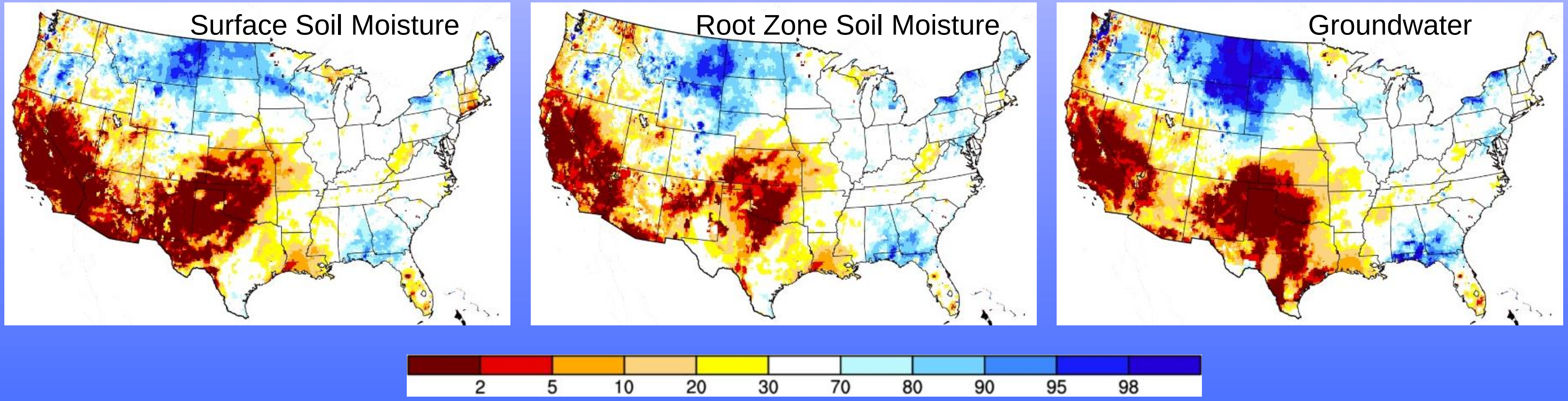


U.S. Drought Monitor product for 20 May 2014.

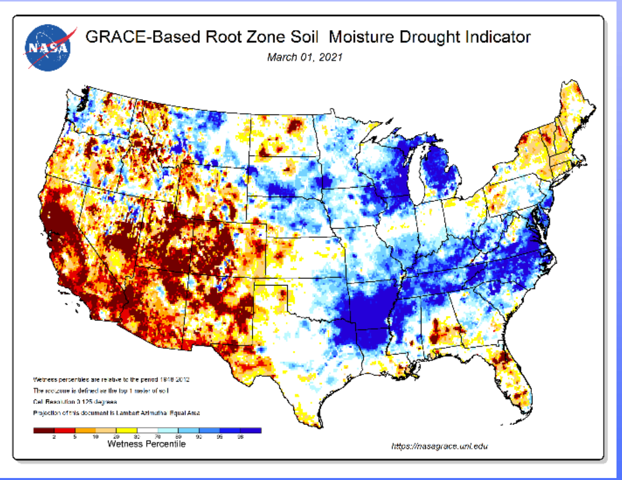


Forecast Root Zone Soil Moisture for 1 March 2021, initialized on 1 February 2021

Data from GRACE and other satellites are integrated within a land surface model to produce timely information on wetness conditions at all levels in the soil column, including groundwater. For current maps and more info, see http://nasagrace.unl.edu/



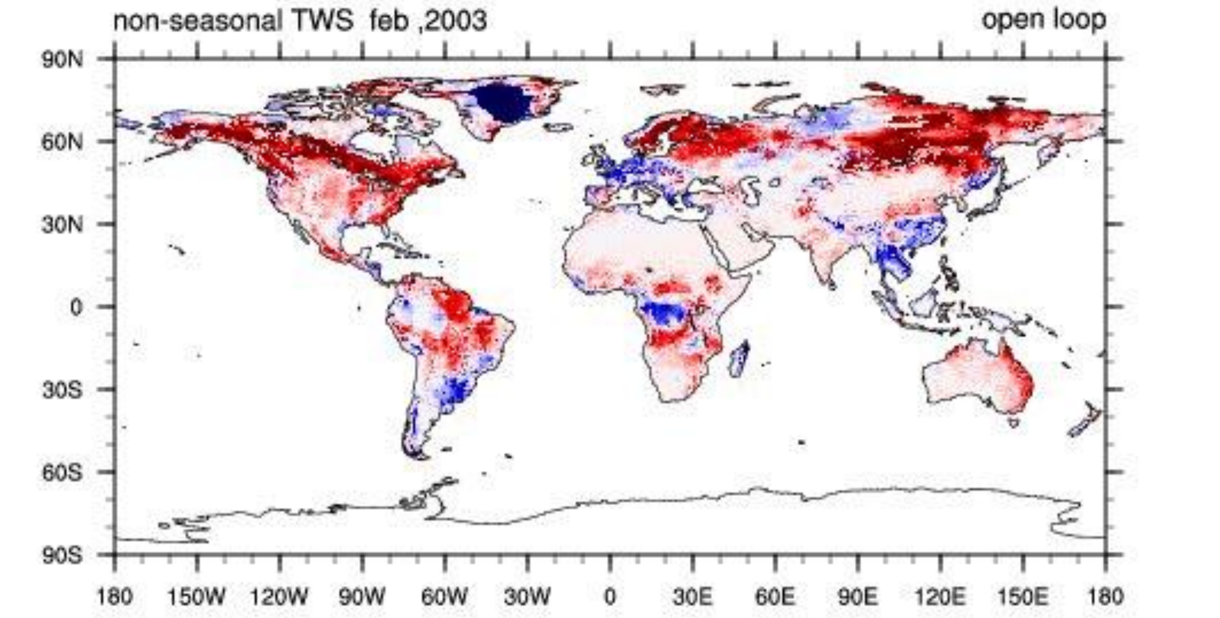
Drought indicators from GRACE data assimilation (wetness percentiles relative to the period 1948-present) for 19 May 2014.

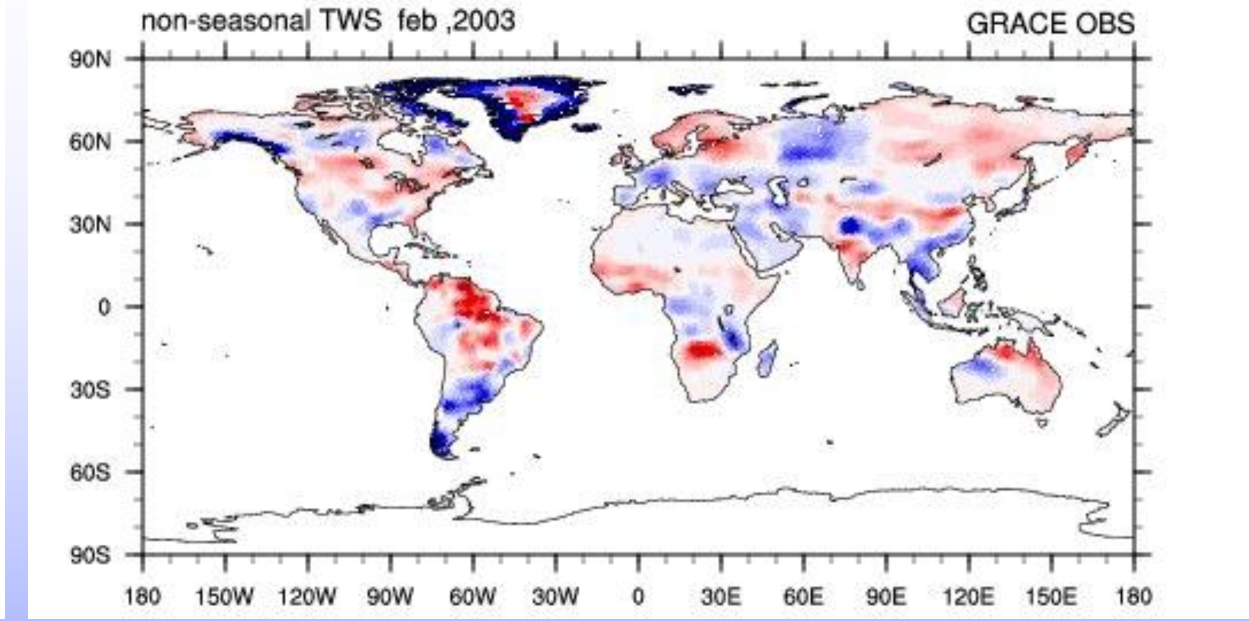


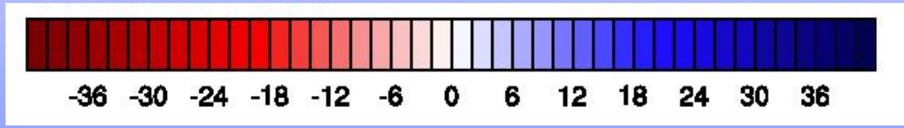
Actual Root Zone Soil Moisture for 1 March 2021

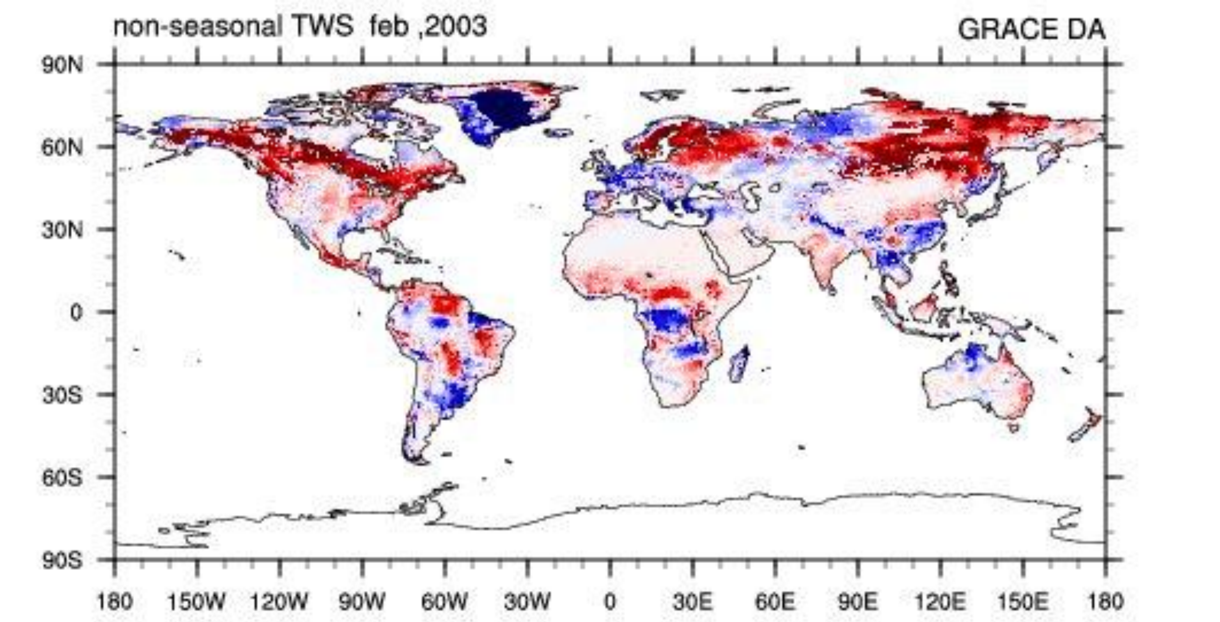
Matthew.Rodell@nasa.gov

Global GRACE & GRACE-FO Data Assimilation









Non-seasonal TWS anomalies (cm) from the Catchment Land Surface Model (CLSM; top left), UT/CSR GRACE & GRACE-FO (*Save et al., 2016*; top right), and CLSM GRACE & GRACE-FO data assimilation (*Li et al., WRR, 2019*; bottom right).

https://disc.gsfc.nasa.gov/

Search “GLDAS 2.2”

dell@nasa.gov

Summary

- Due to the expense, labor, and incompleteness of ground-based observations, space-based observation of the water cycle is critical
- GRACE and GRACE-FO have provided unique, global observations of terrestrial water storage variability since 2002
- These TWS observations have been used to identify areas of increasing and decreasing freshwater availability, which can be attributed to natural variability, direct human impacts, or climate change
- Land surface models integrate various types of observational datasets in order to produce timely, spatially and temporally continuous maps of water cycle variables
- Assimilation of GRACE and GRACE-FO data enables mapping and forecasting of wetness/drought conditions
- NASA and other space agencies are now studying architectures for future satellite gravimetry missions, including a Mass Change mission recommended by the 2017 NASEM Decadal Survey in Earth Sciences

Matthew.Rodell@nasa.gov