# Detection of Extreme Events with GRACE and Data Assimilation

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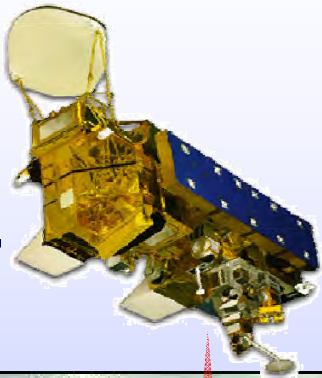
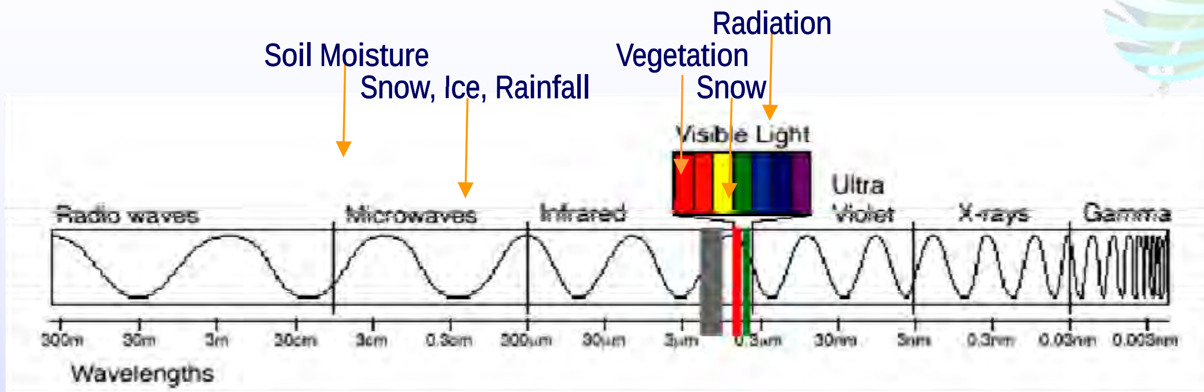
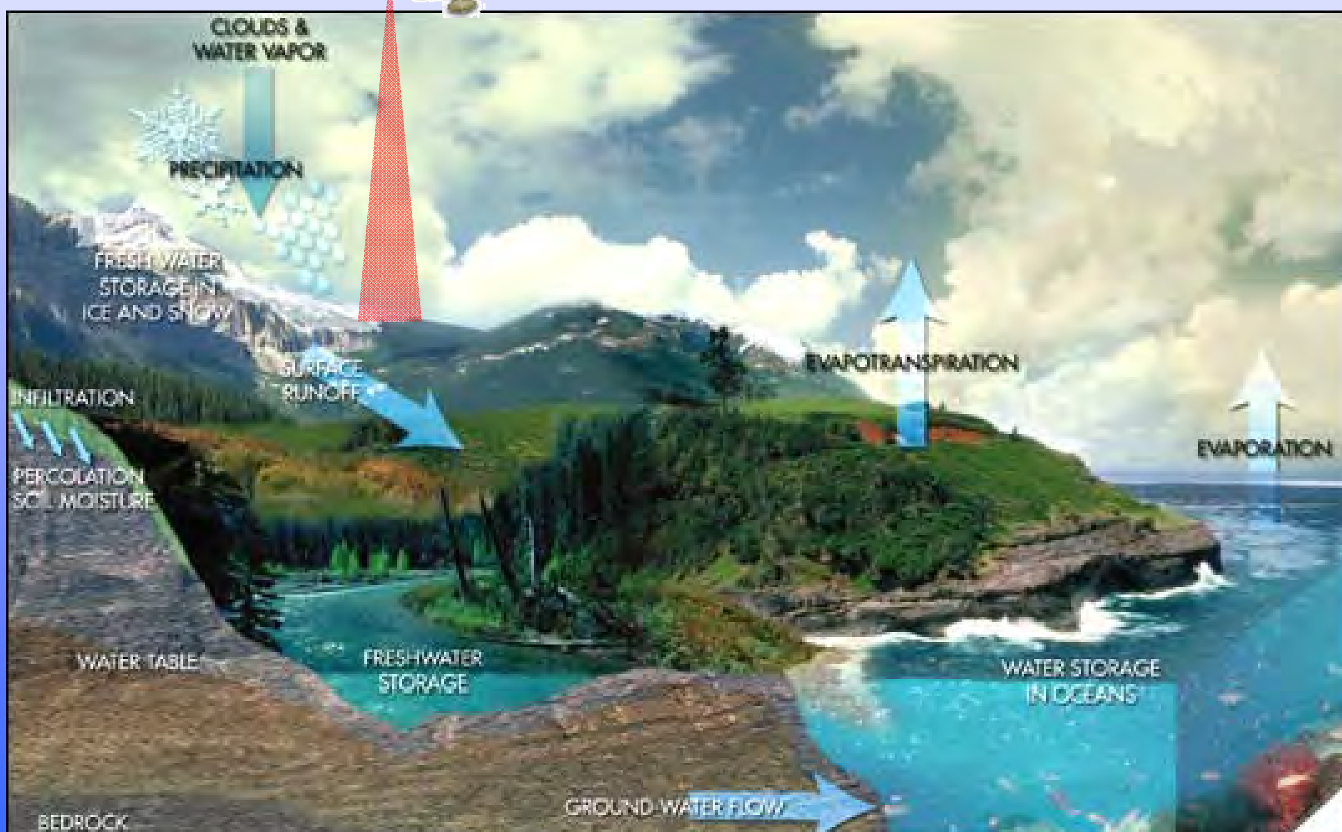
**Chief, Hydrological Sciences Laboratory**
**NASA Goddard Space Flight Center**

# Gravity Recovery and Climate Experiment (GRACE)

**Aqua:**
MODIS,
AMSR-E,
etc.






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

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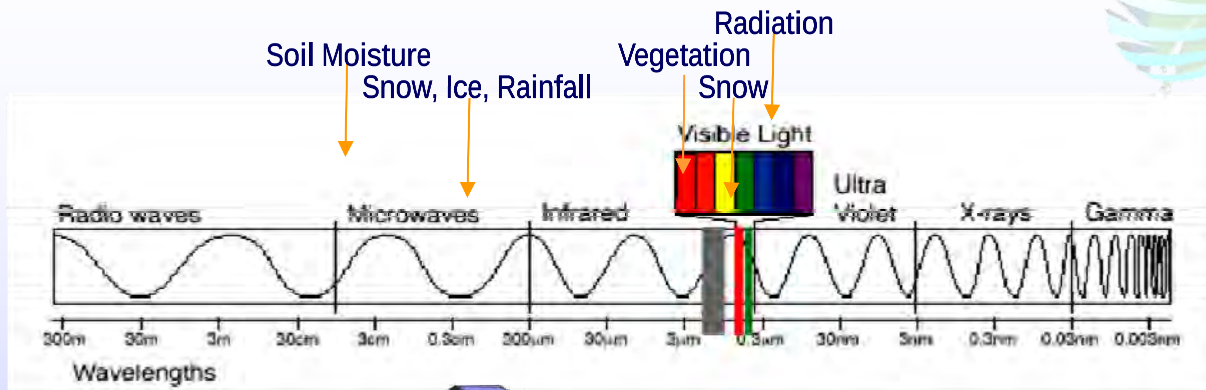
# Gravity Recovery and Climate Experiment (GRACE)




**Aqua:**
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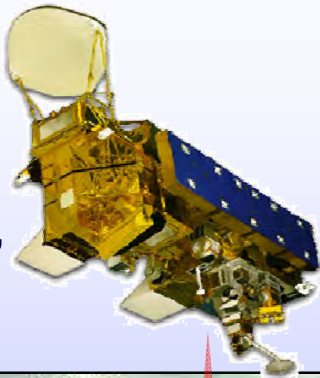


**GRACE**

GRACE is unique in its ability to monitor water at all levels, down to the deepest aquifer

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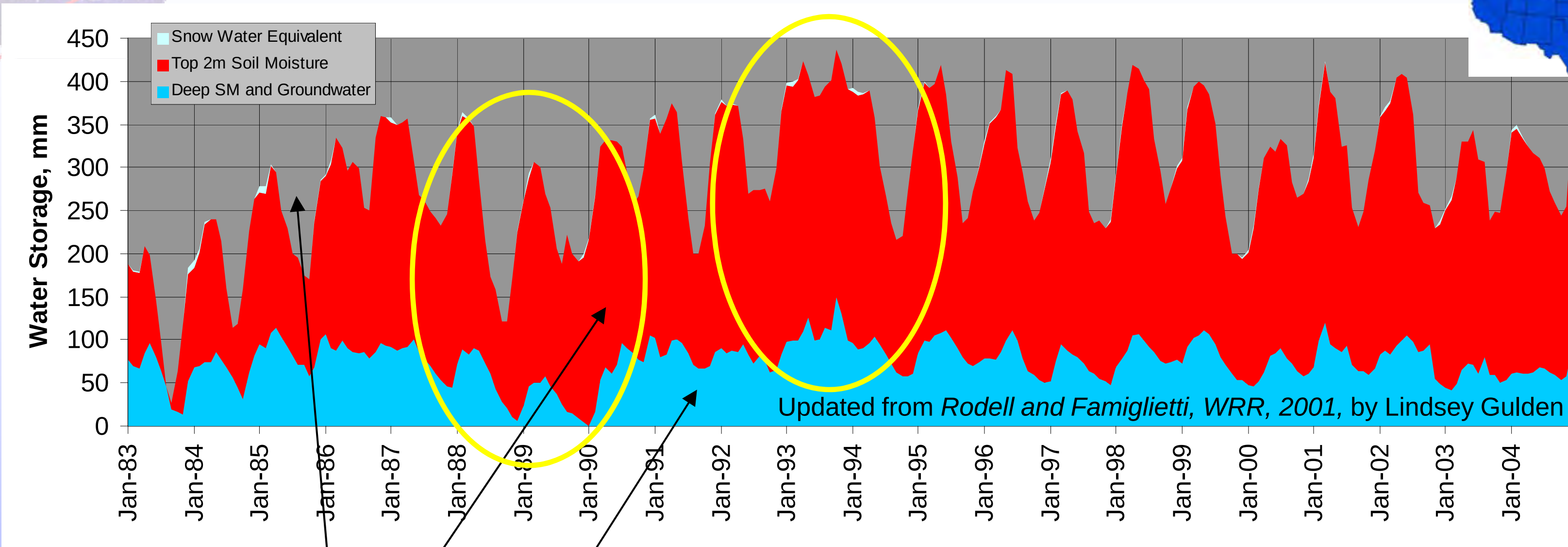
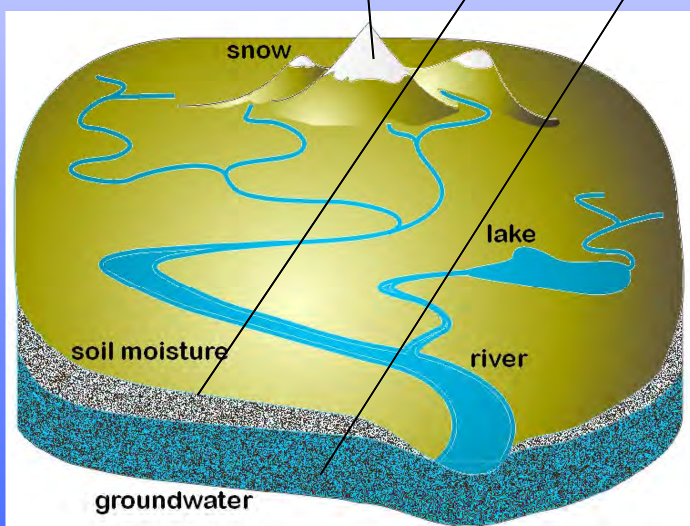
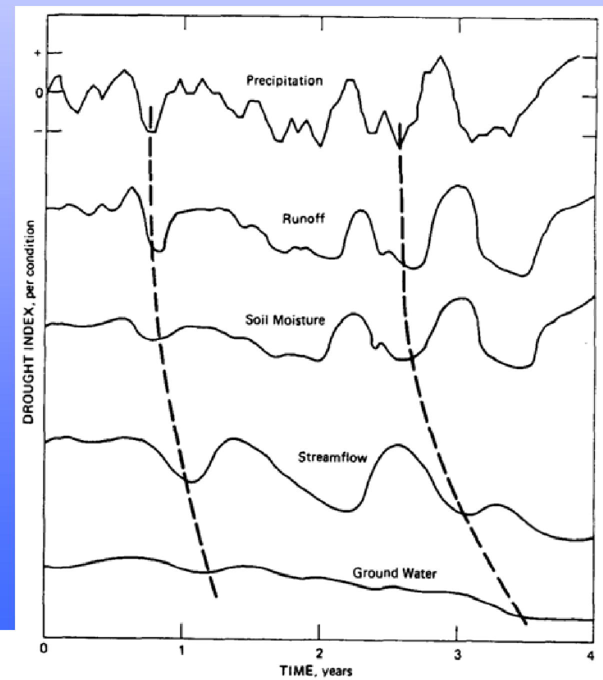
# Terrestrial Water Storage Variability




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

Right: Schematic of drought progression in Illinois




*Changnon, 1987*

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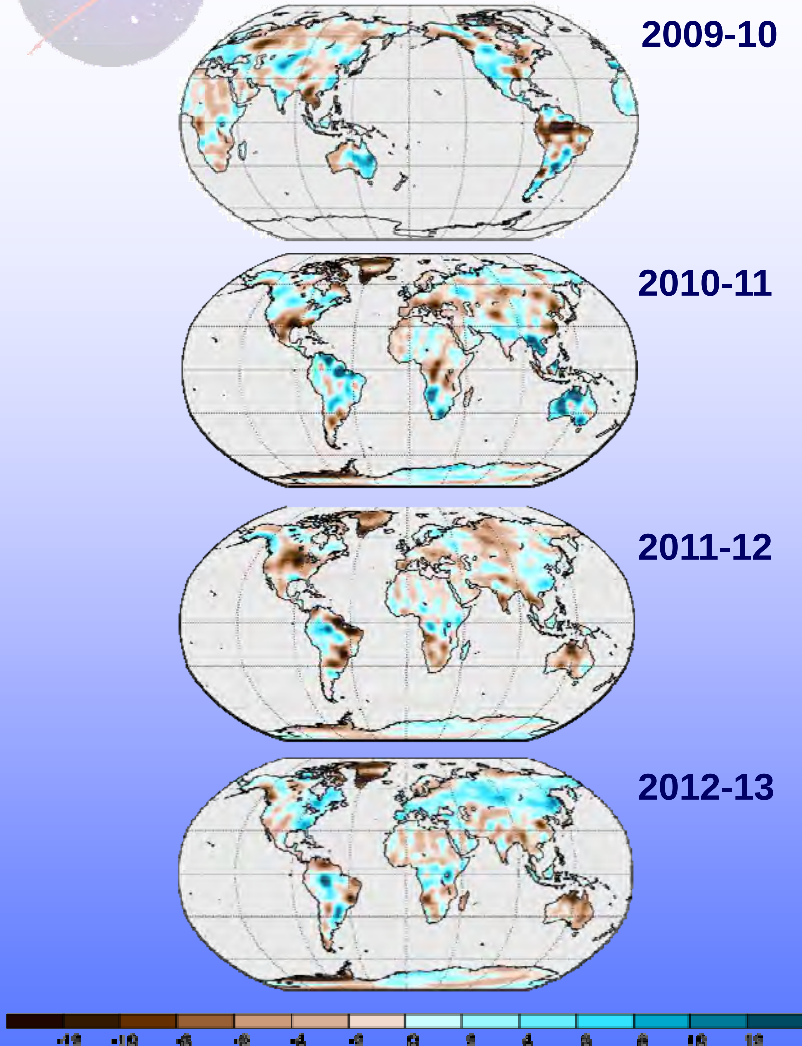
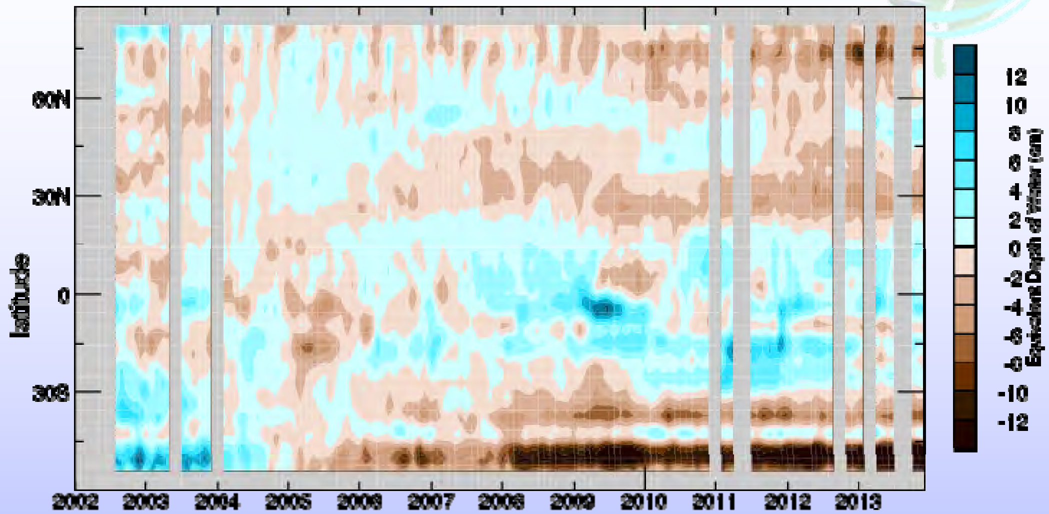
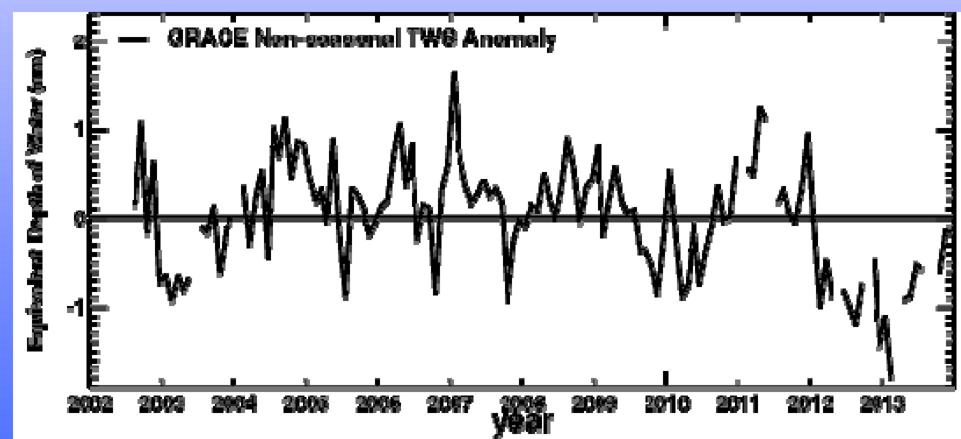
# GRACE in BAMS Annual State of the Climate Issue




Changes in annual-mean terrestrial water storage (cm), based on GRACE satellite observations.




Zonal mean terrestrial water storage anomalies in cm equivalent height of water (reference period 2003-2007).




Global mean terrestrial water storage anomalies (cm), excluding Greenland and Antarctic.

*Rodell, Chambers, and Famiglietti, Bull. Amer. Meteor. Soc., 2013*

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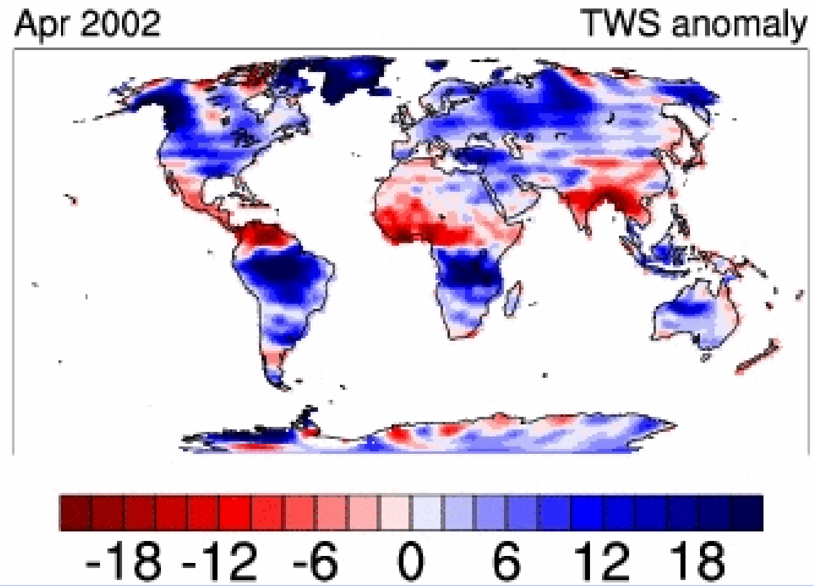
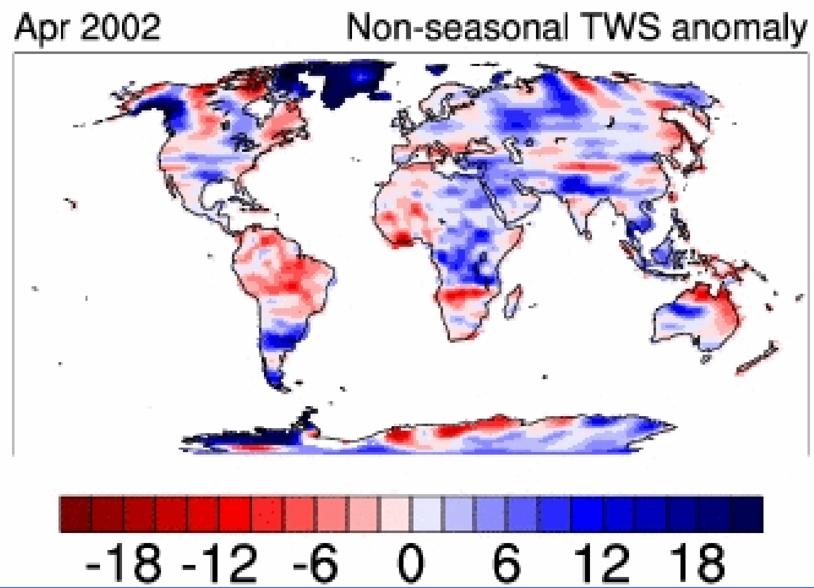
# GRACE Terrestrial Water Storage Anomalies, 2003-2013

Top: Monthly terrestrial water storage anomalies (equivalent height of water in cm), derived from GRACE CSR RL05 data with 300 km smoothing (unscaled), available from http://grace.jpl.nasa.gov (Landerer and Swenson, *Wat. Resour. Res.*, 2012).

Bottom: Same as top, with seasonal cycle removed.





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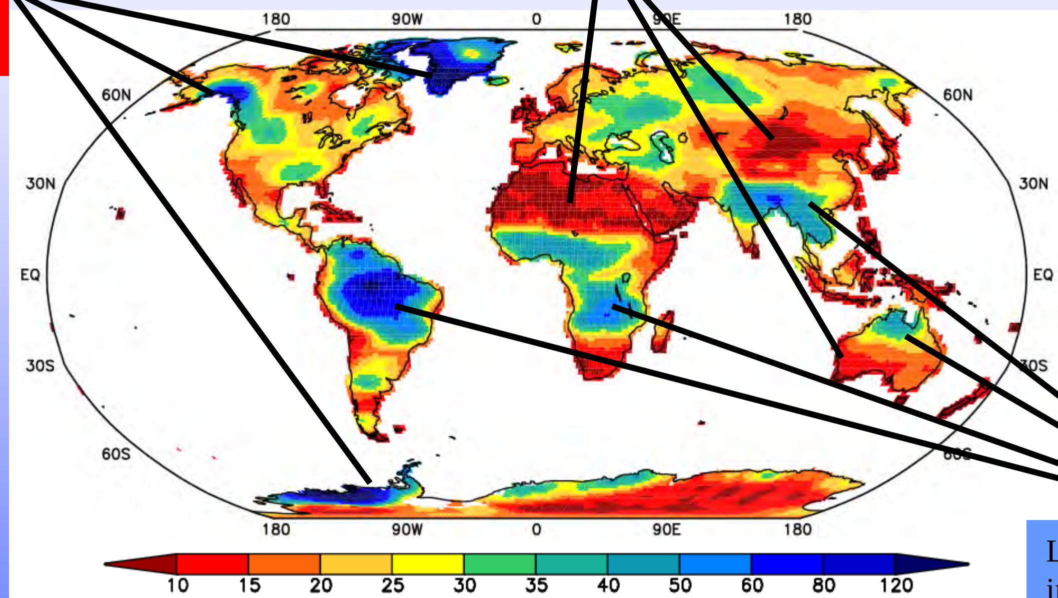
# Range of Terrestrial Water Storage, 2002-2014

Period maximum minus period minimum TWS observed by GRACE, in cm

Large interannual TWS variability where ice sheets and glaciers are diminishing

Minimal TWS variability in dry regions




Large seasonal and interannual TWS variability in the wet tropics

***Extremes of terrestrial water storage should be measured against the normal range and seasonality at each location***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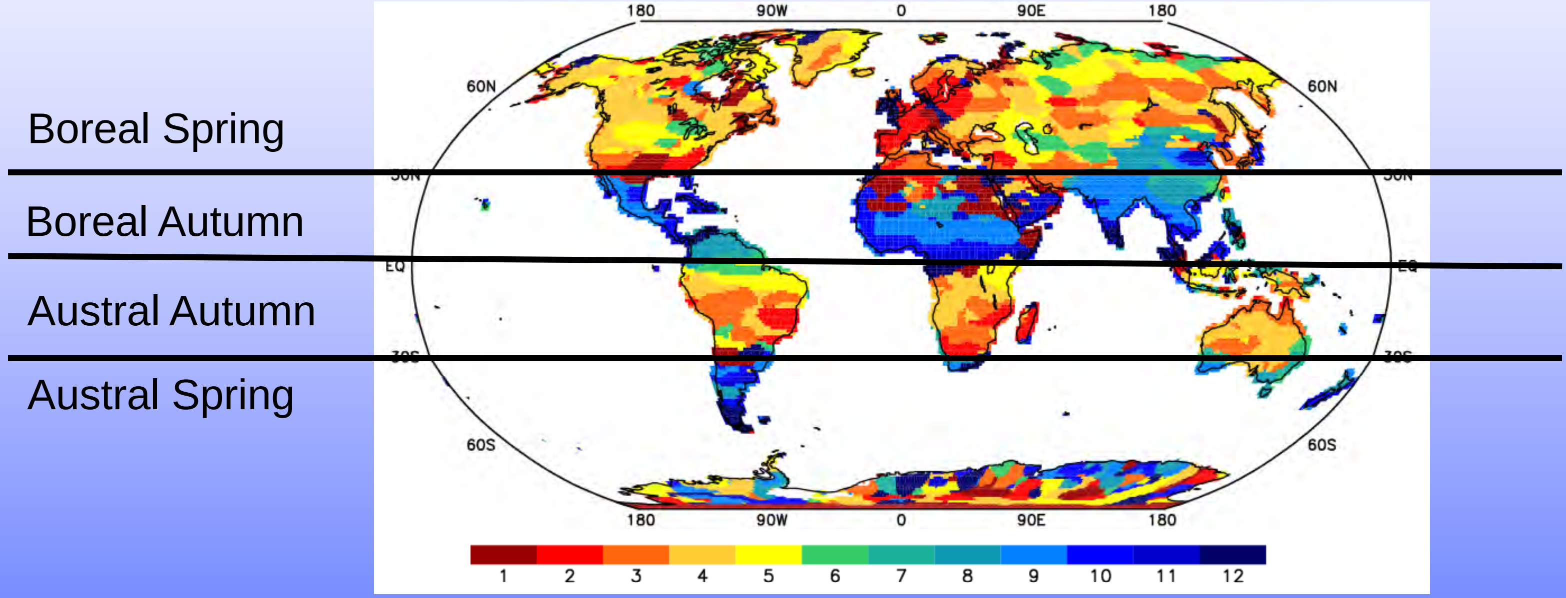
# Month of Maximum Terrestrial Water Storage

Month of maximum TWS observed by GRACE during 2002-14




***Maximum TWS occurs in spring in mid to high latitudes and in autumn in the tropics***

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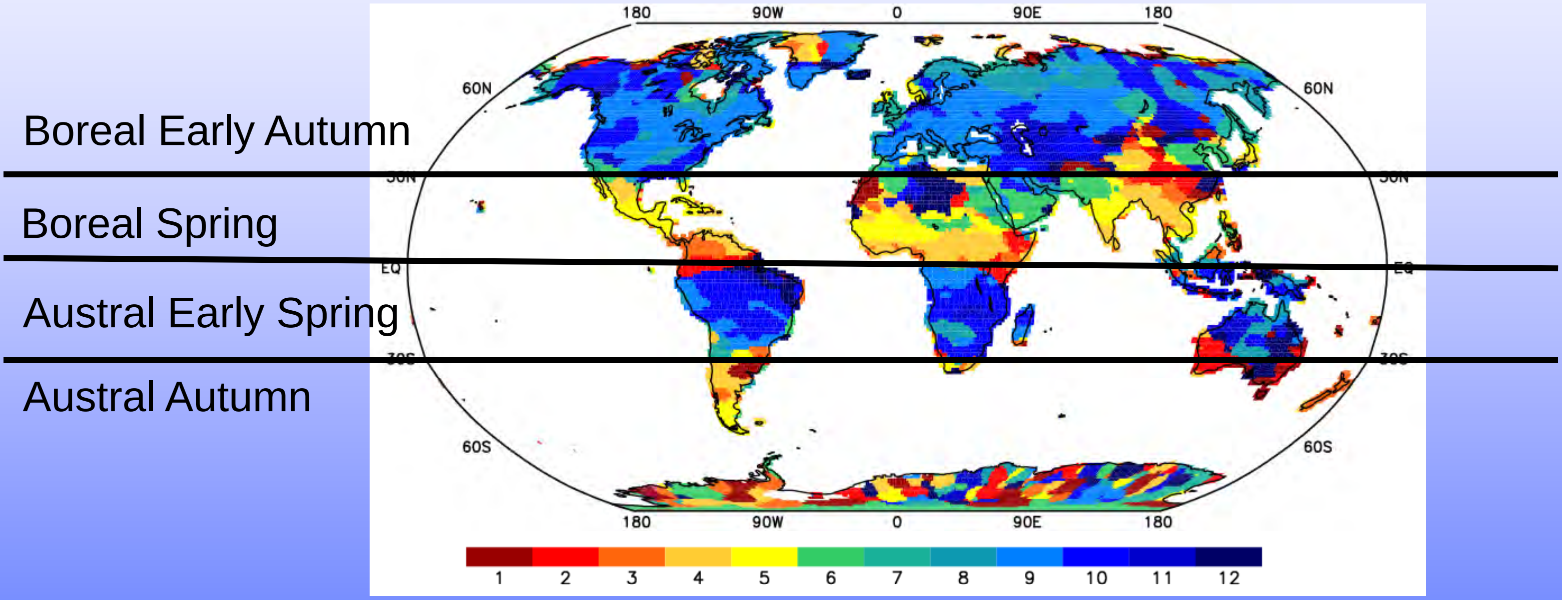
# Month of Minimum Terrestrial Water Storage

Month of minimum TWS observed by GRACE during 2002-14




***Minimum TWS occurs in autumn in mid to high latitudes and in spring in the tropics***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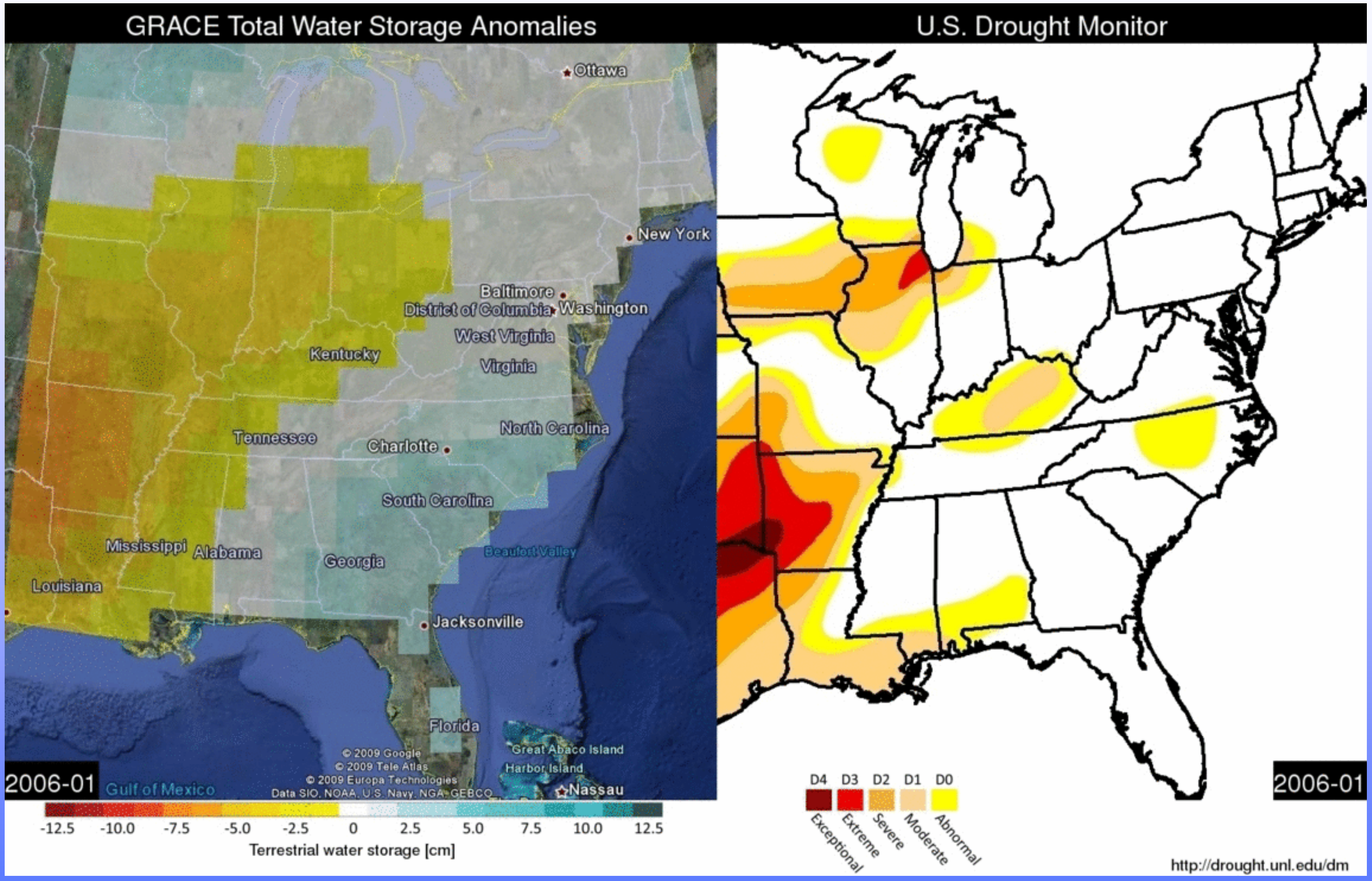
# GRACE Provides a Unique Perspective on Drought

GRACE observes groundwater and deep soil moisture, key indicators of drought




***GRACE captured the evolution of the 2007-08 drought in the southeastern U.S., and is now helping to improve drought monitoring and prediction***

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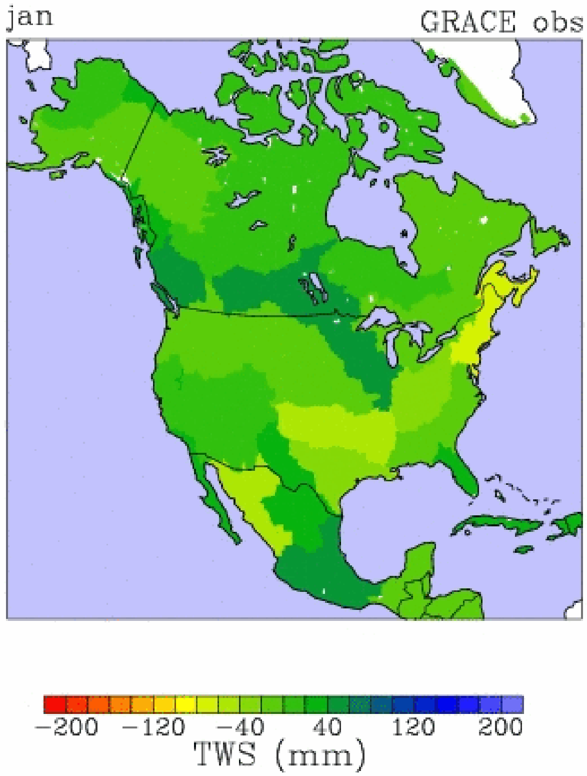
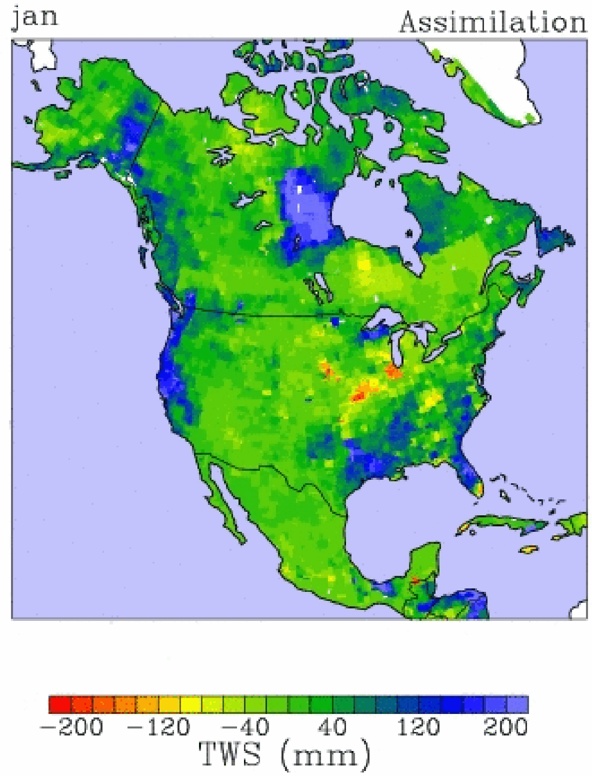
# GRACE Data Assimilation

GRACE water storage, mm
January-December 2003 loop




Model assimilated water storage, mm
January-December 2003 loop




Monthly anomalies (deviations from the 2003 mean) of terrestrial water storage (sum of groundwater, soil moisture, snow, and surface water) as an equivalent layer of water. Updated from *Zaitchik, Rodell, and Reichle, J. Hydromet., 2008*.

- Data assimilation combines modeled and observed estimates and error info to compute optimal estimate
- Catchment land surface model; 20 member ensemble
- Ensemble smoother data assimilation (*Zaitchik et al., J. Hydromet., 2008*)
- Output has improved spatial, temporal, and vertical information

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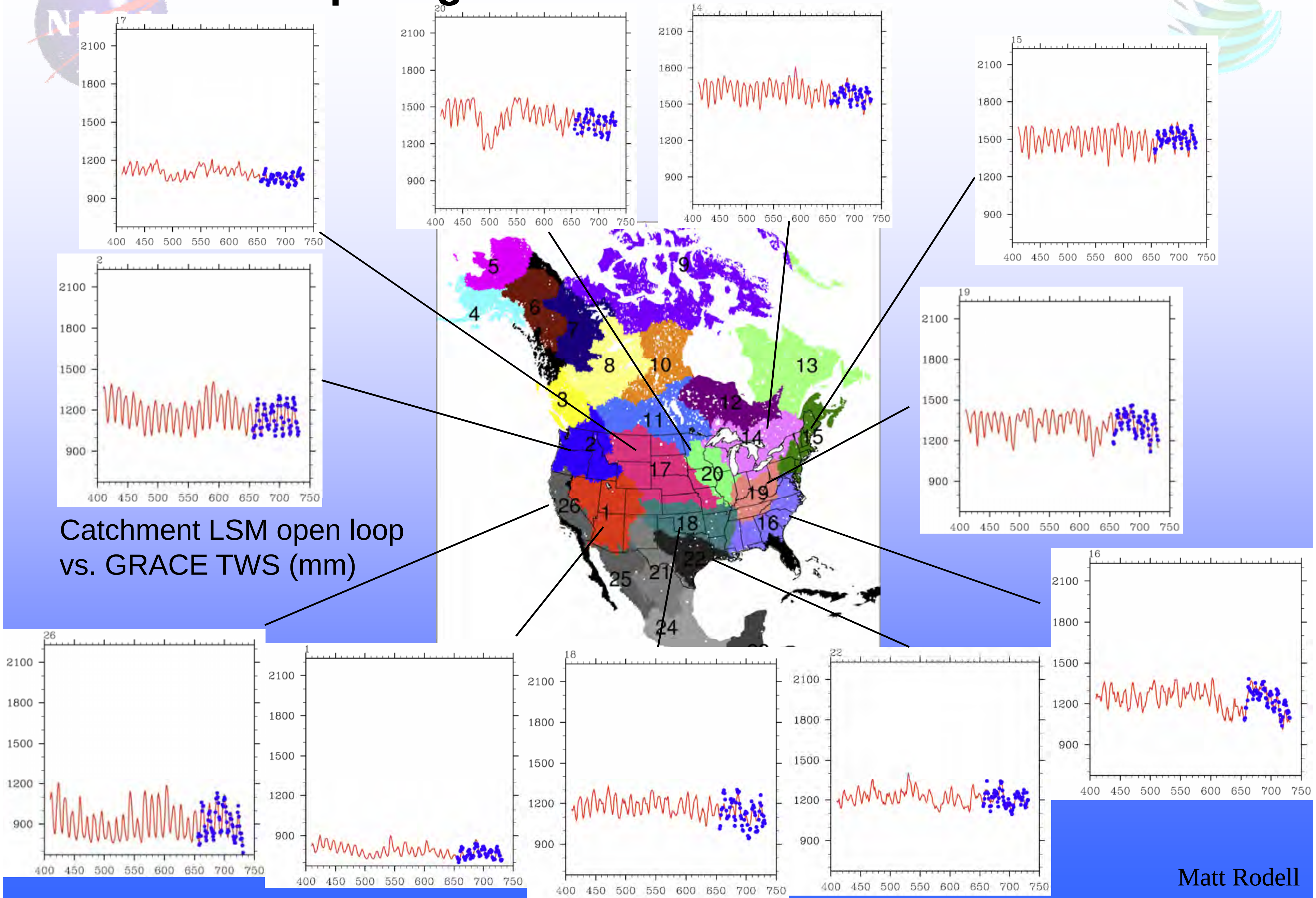
# Preparing for GRACE Data Assimilation




Catchment LSM open loop vs. GRACE TWS (mm)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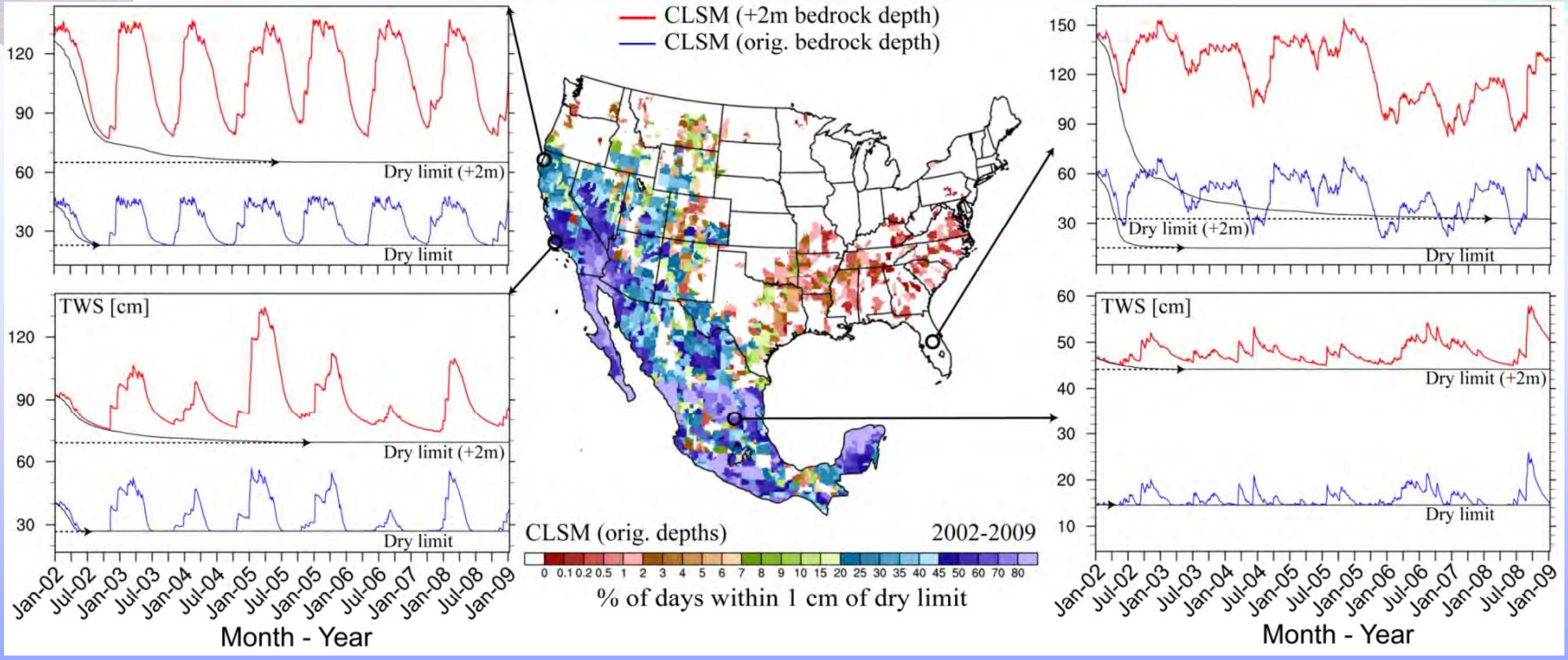
# Preparing for GRACE Data Assimilation




*Houborg et al., WRR, 2012*

- In some cases Catchment model TWS approached a "dry limit", preventing full impact of GRACE data assimilation
- Dry limit quantified (above) by open loop run with no precipitation
- Particularly important for drought monitoring, but also for climatology
- Problem addressed by increasing the depth to bedrock by 2 m
- Unintended consequences for fluxes (e.g., runoff) determined to be minimal, but in some areas the mode of interannual GW variability increased to 20+ years

→ Mask recently developed to prescribe +2m bedrock depth only as needed

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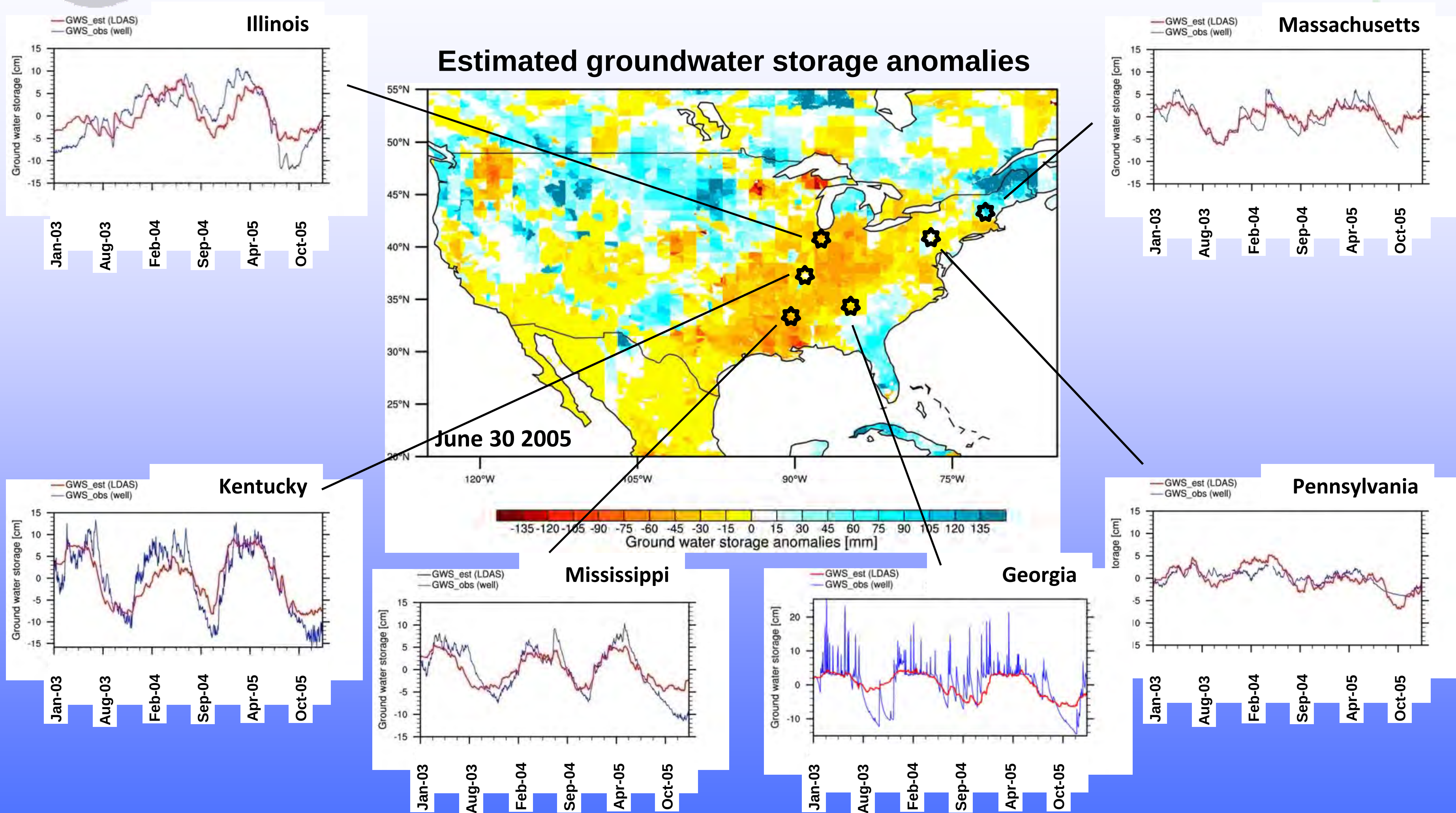
# GRACE Assimilated vs. in situ Groundwater




Modeled (red) vs. observed (blue) groundwater storage (cm eq. h2o)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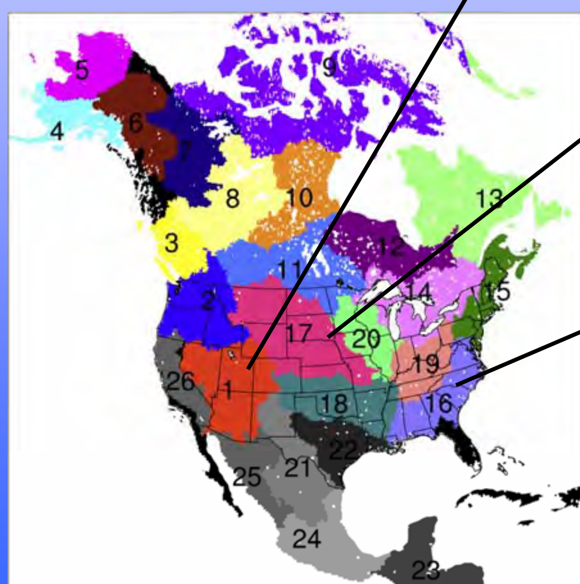
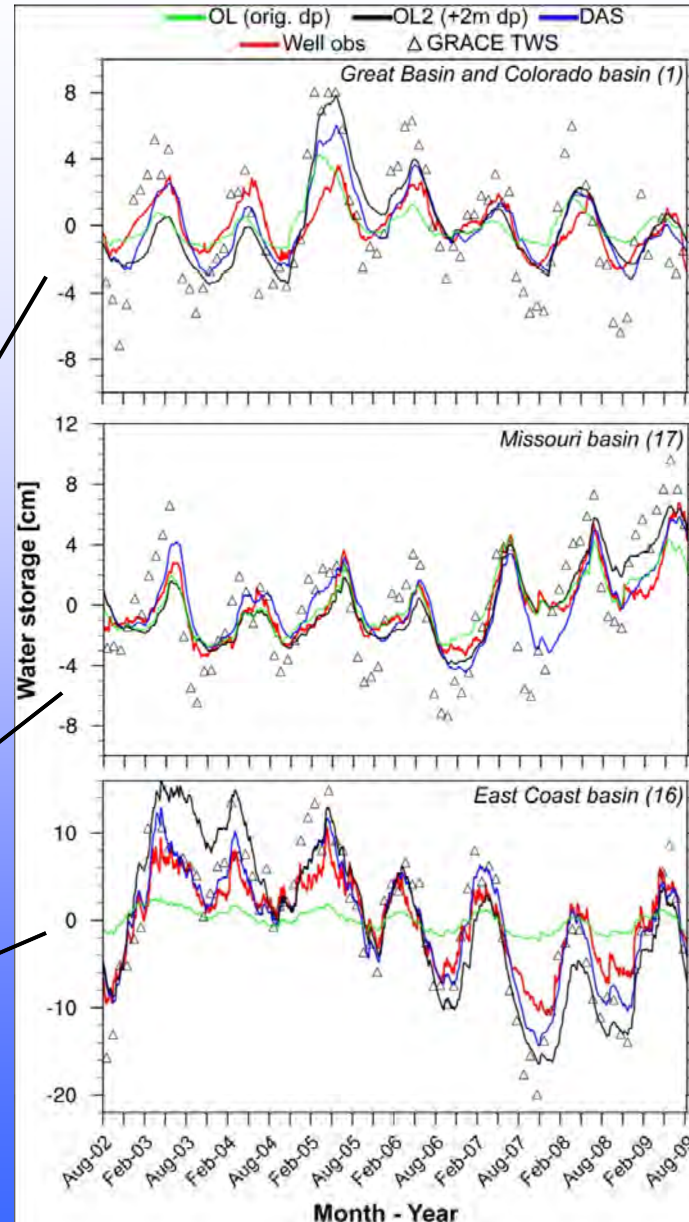
# Evaluating GRACE Data Assimilation

• Simulated groundwater storage anomalies evaluated using GW well observations averaged over major river basins in the U.S.

• Increase in bedrock depth enables more realistic range of groundwater storage anomalies

• GRACE data assimilation generally reduces RMSE, but not in all cases




*Houborg et al., WRR, 2012*

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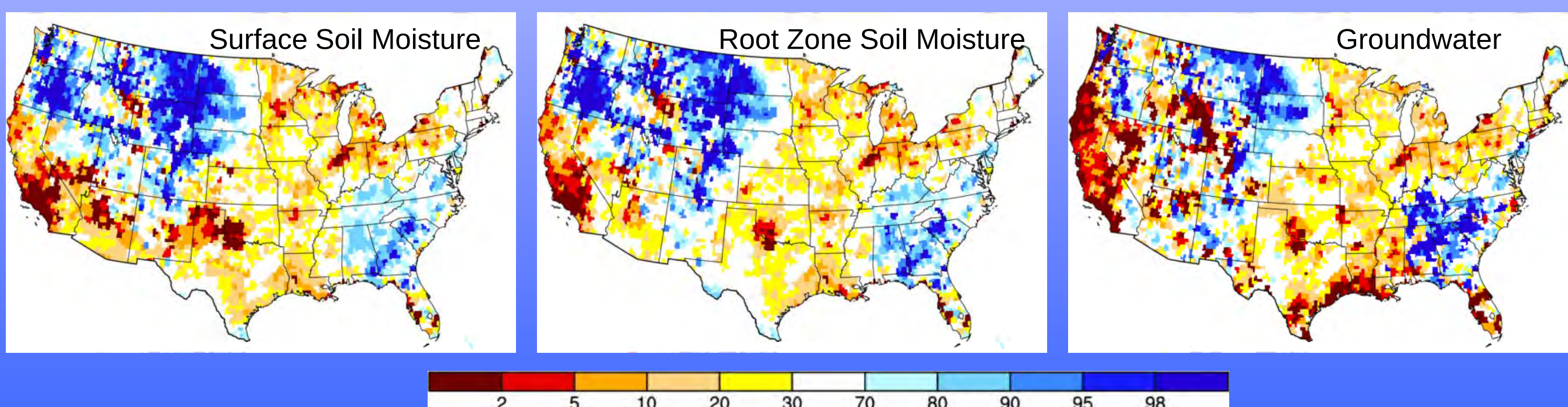
# GRACE Based Drought Indicators

- 1948 to 2010 open loop Catchment land surface model simulation (Princeton forcing) provides background climatology (CDF).
- 2002 to present GRACE data assimilating Catchment LSM simulation (NLDAS-2 forcing).
- Observation-based meteorological forcing inputs (precipitation, solar radiation, etc.) enable GRACE data to be extended to near-real time.
- Long term climatology adjusted to be consistent with the 2002-present simulation using the overlapping period (2002-10).
- Groundwater and root zone and surface soil moisture assimilated outputs are converted to percentiles based on CDF of the long term climatology.
- Data and maps are used by USDM authors and posted on a weekly basis at http://drought.unl.edu/MonitoringTools.aspx




Drought indicators from GRACE data assimilation (wetness percentiles relative to the period 1948-present) for 17 February 2014.

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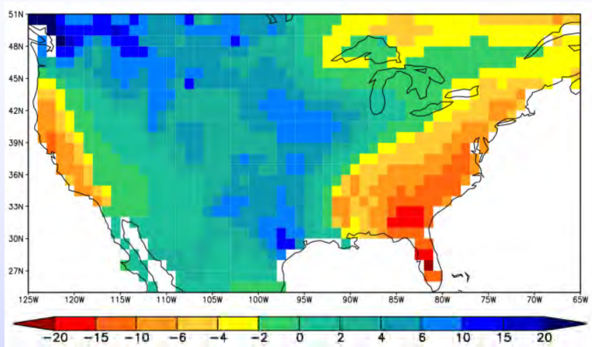
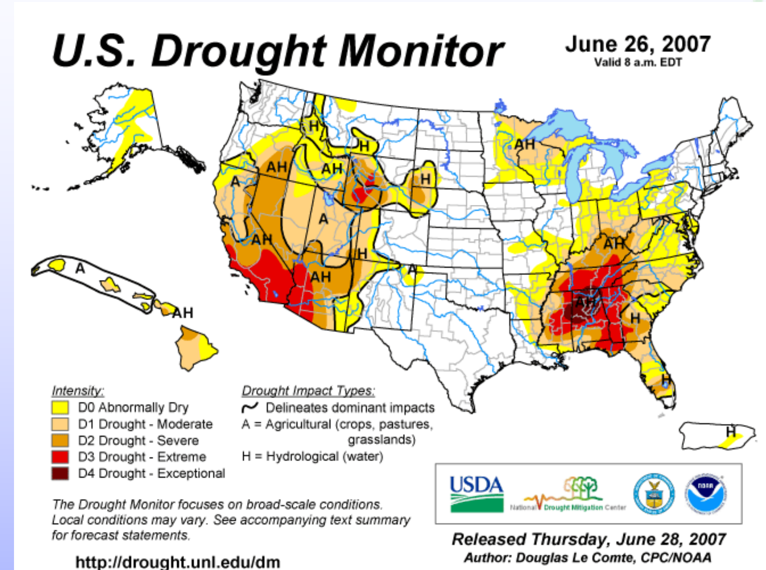
# GRACE Data Assimilation for Drought Monitoring

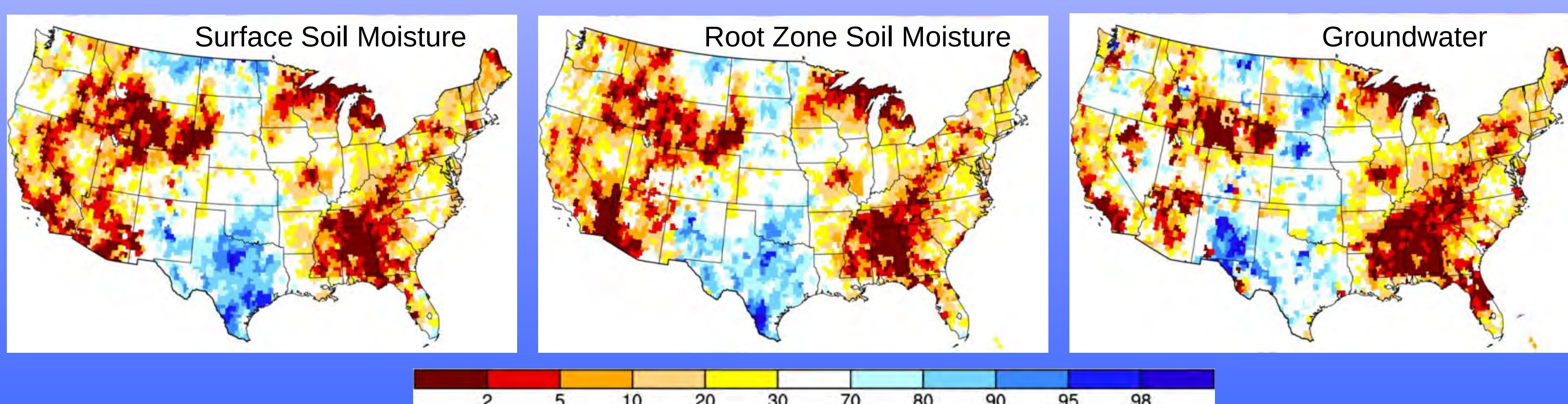



GRACE terrestrial water storage anomalies (cm equivalent height of water) for June 2007 (Tellus CSR RL05 scaled).




U.S. Drought Monitor product for 26 June 2007.

New process integrates data from GRACE and other satellites to produce timely information on wetness conditions at all levels in the soil column, including groundwater. For current maps and more info, see http://www.drought.unl.edu/MonitoringTools.aspx




Drought indicators from GRACE data assimilation (wetness percentiles relative to the period 1948-present) for 25 June 2007.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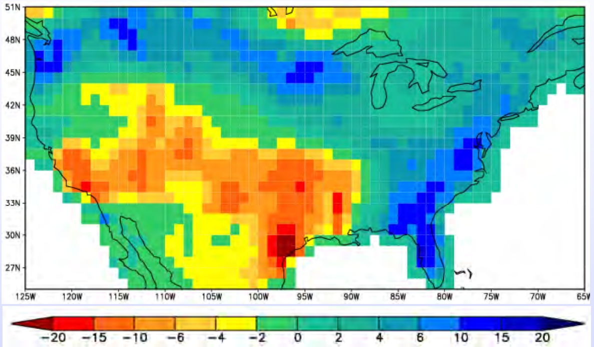
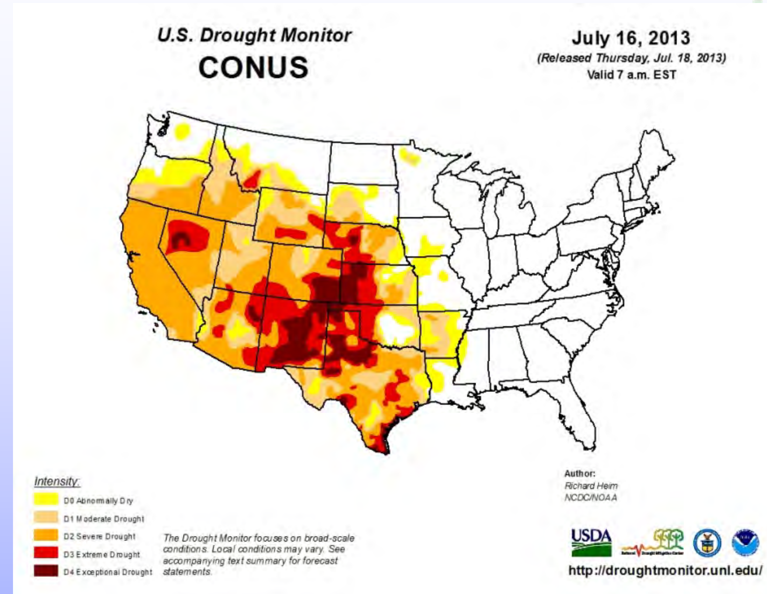
# GRACE Data Assimilation for Drought Monitoring

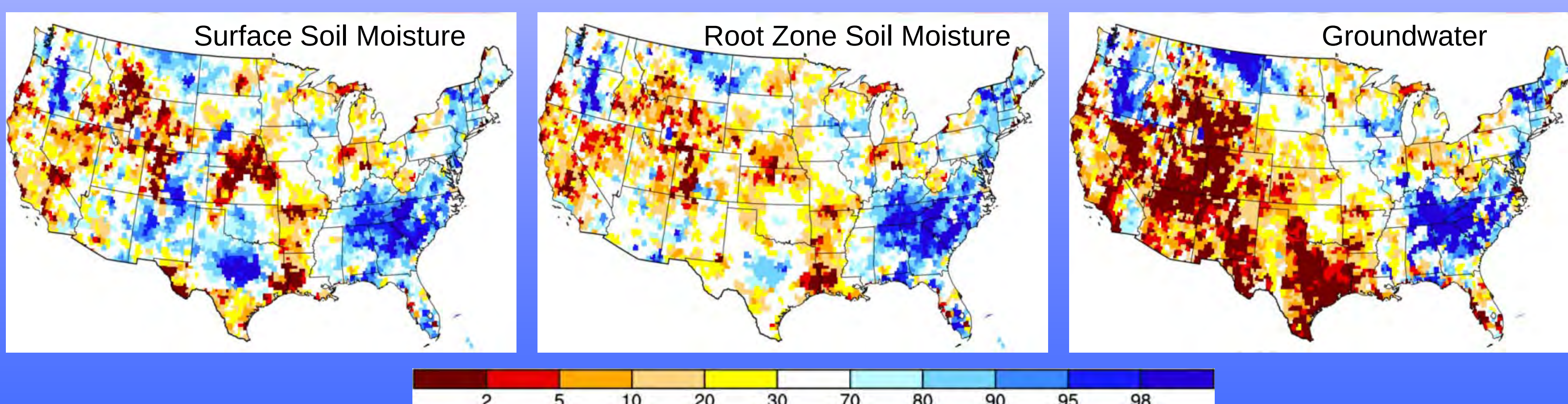
GRACE terrestrial water storage anomalies (cm equivalent height of water) for July 2013 (Tellus CSR RL05 scaled).




U.S. Drought Monitor product for 16 July 2013.

New process integrates data from GRACE and other satellites to produce timely information on wetness conditions at all levels in the soil column, including groundwater. For current maps and more info, see http://www.drought.unl.edu/MonitoringTools.aspx




Drought indicators from GRACE data assimilation (wetness percentiles relative to the period 1948-present) for 15 July 2013.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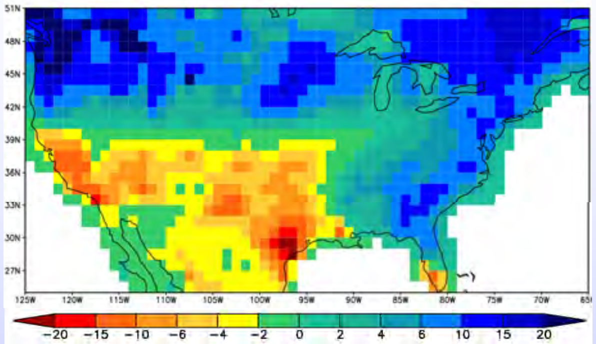
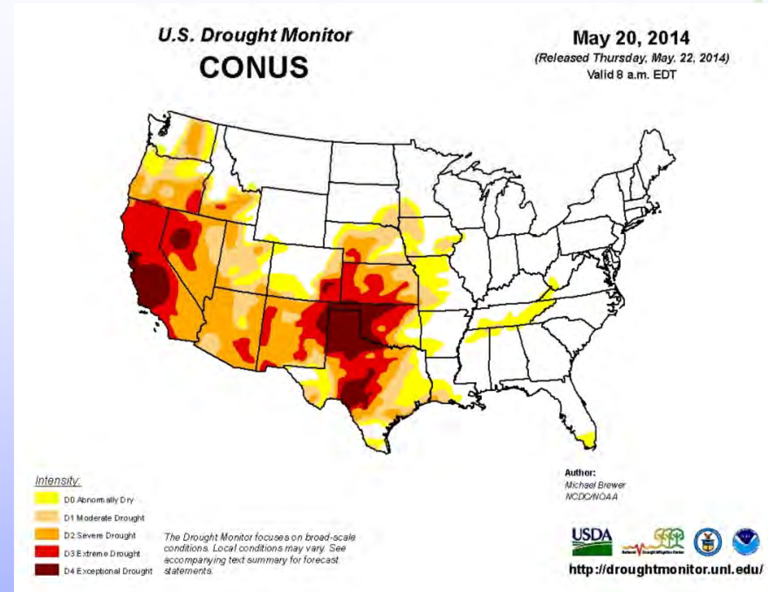
# GRACE Data Assimilation for Drought Monitoring

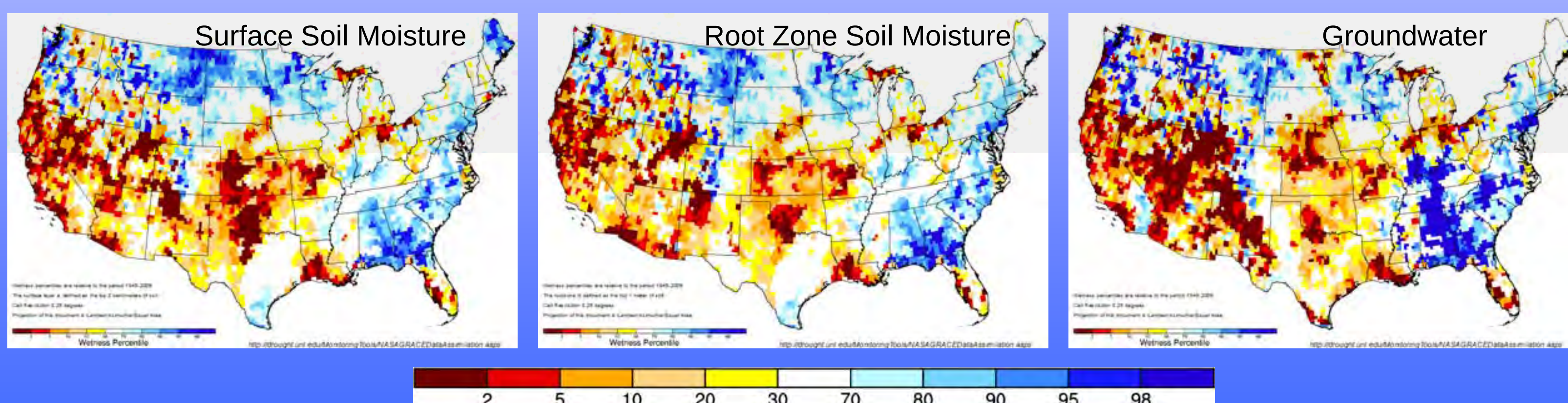
GRACE terrestrial water storage anomalies (cm equivalent height of water) for May 2014 (Tellus CSR RL05 scaled).




New process integrates data from GRACE and other satellites to produce timely information on wetness conditions at all levels in the soil column, including groundwater. For current maps and more info, see http://www.drought.unl.edu/MonitoringTools.aspx




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




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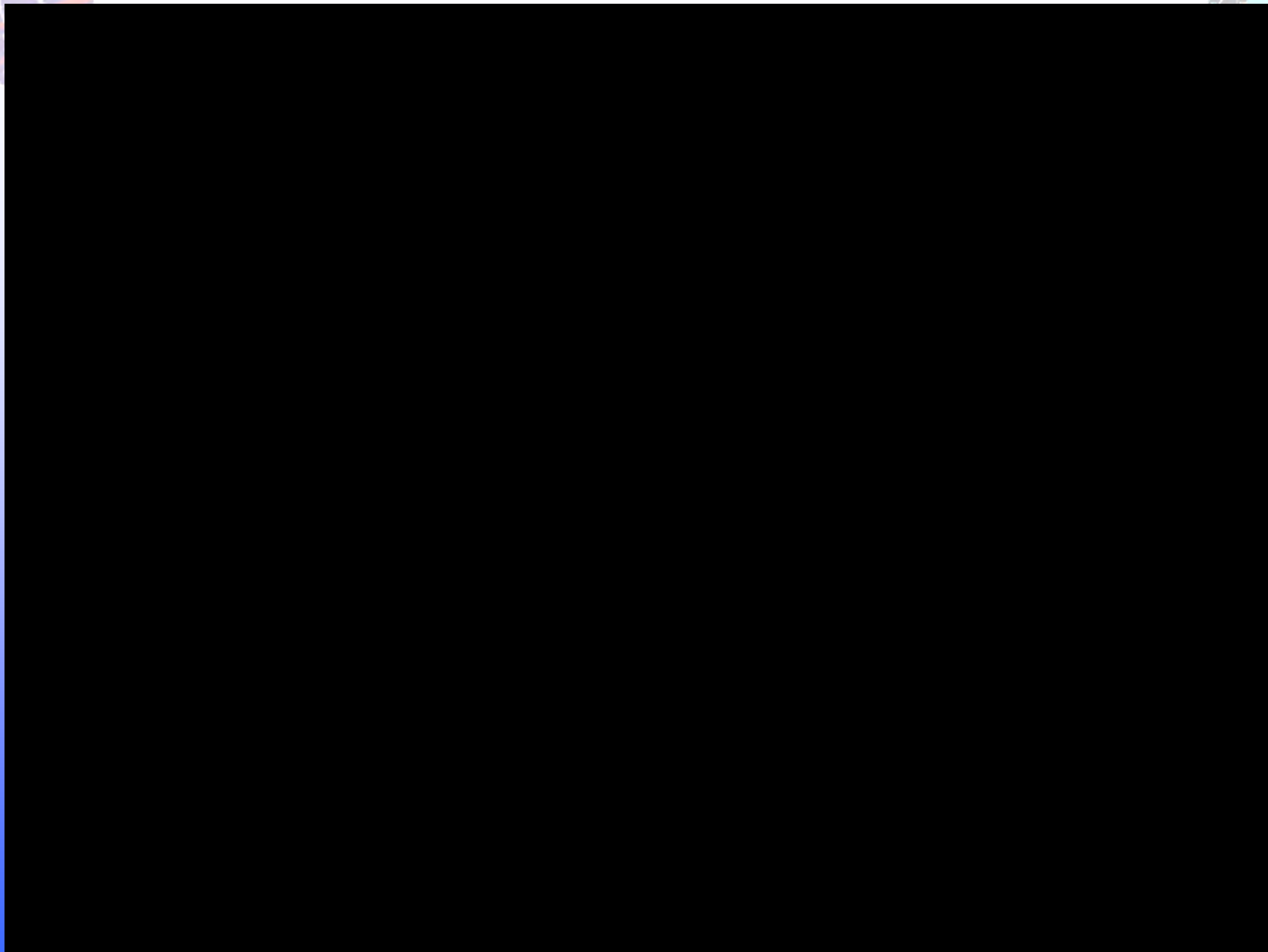
# GRACE Data Assimilation Groundwater Drought Indicator



Visualization prepared by Robert Simmon, NASA/GSFC

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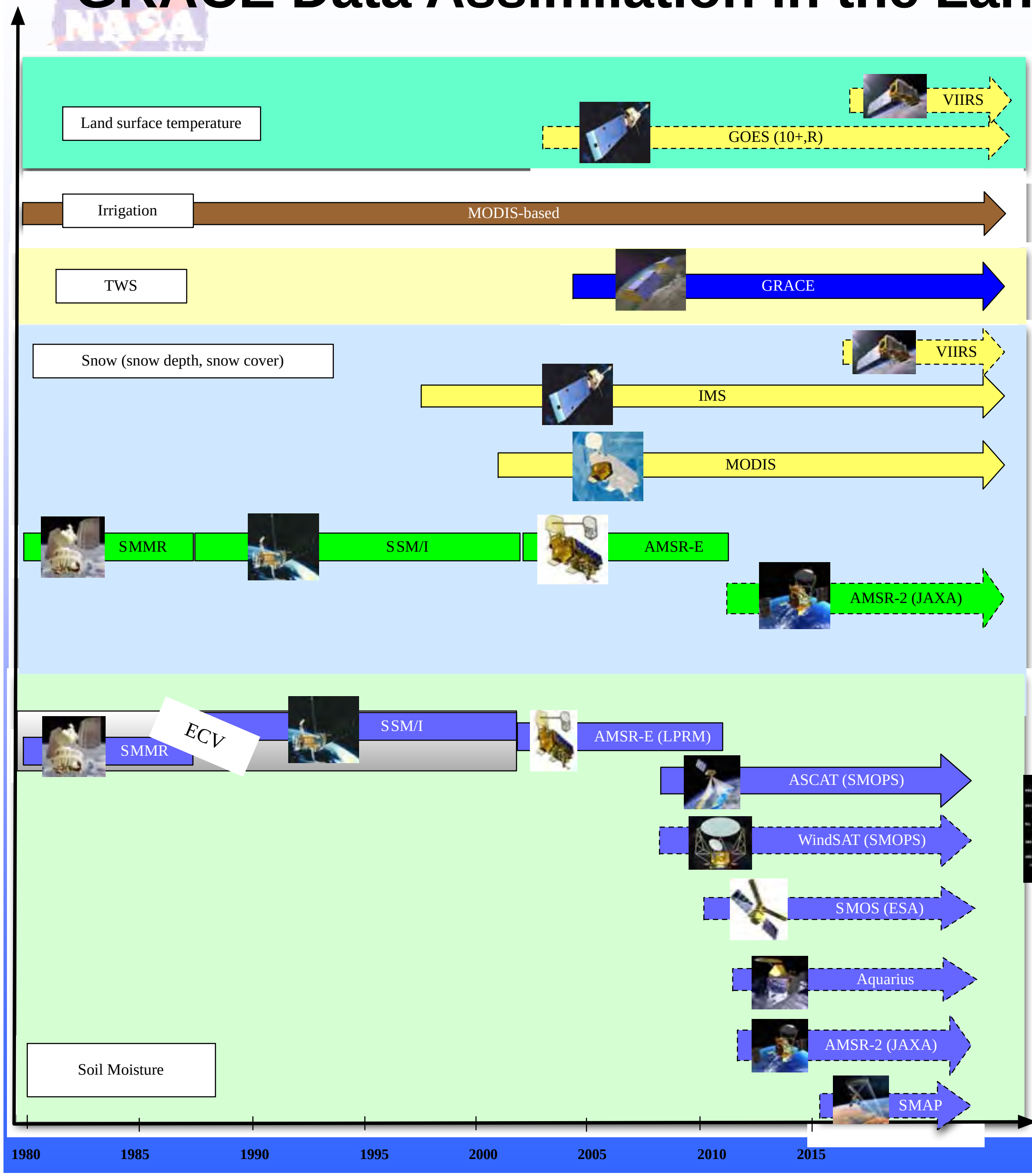
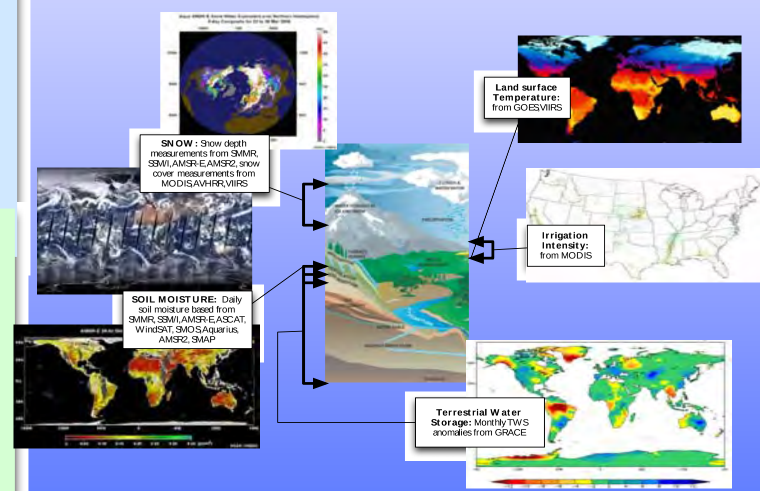
# GRACE Data Assimilation in the Land Information System




Vision: to develop an environment for that enables the simultaneous use of terrestrial hydrological remote sensing datasets.




*Courtesy of Sujay Kumar, NASA/GSFC & SAIC*

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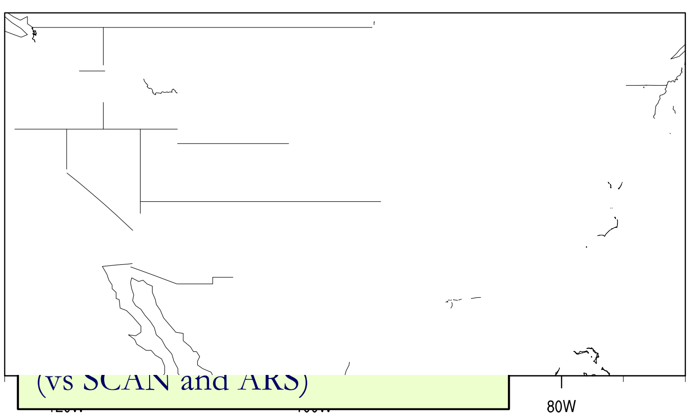
NASA GSFC

# Data Assimilation in the Land Information System

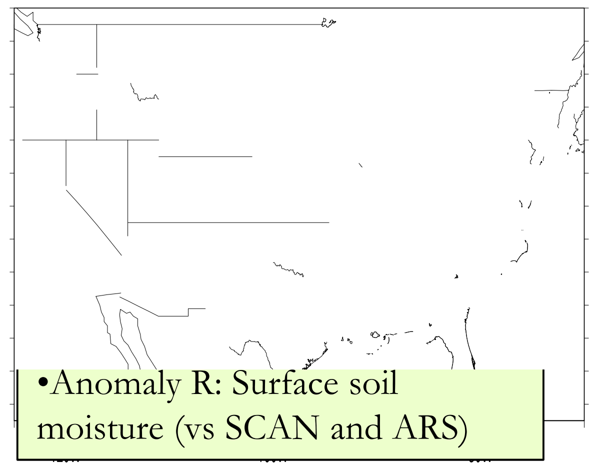
## Assimilation of GRACE data in LIS/Catchment LSM

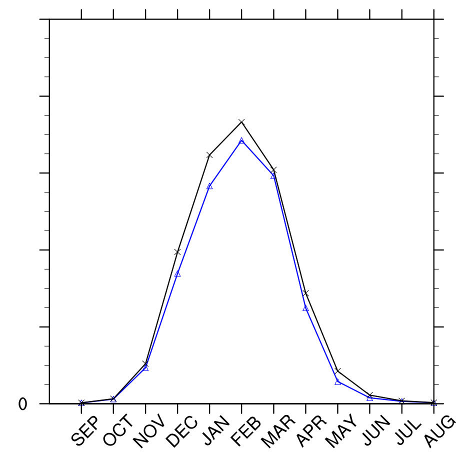
Maps show metric differences –(e.g. Anomaly R(DA) – Anomaly R (OL)); In all panels, warm colors indicate improvements

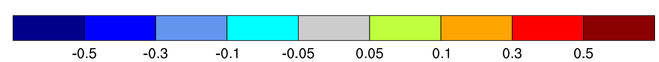



*Courtesy of Sujay Kumar, NASA/GSFC & SAIC*

## Multivariate assimilation in LIS/Noah (soil moisture, snow depth, irrigation; 1979-2013)




**Significant improvements in soil moisture fields from GRACE assimilation**

**Small improvements in various water budget components through multivariate assimilation**

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# Summary and Future Prospects

• GRACE is unique in its ability to monitor all forms of water stored on and in the land, including groundwater, globally.

• By studying the highs and lows of terrestrial water storage in the GRACE record, we gain a new understanding of the dynamics of moisture extremes, and potentially reveal hydrological events that were not previously recognized due to the remoteness of a region or under-appreciation for the role of groundwater storage.

• Assimilating GRACE data into a land surface model enhances their value for extreme event monitoring by improving spatial and temporal resolution and extending the data to near-real time.

• GRACE data assimilation based drought products have been distributed since 2011.

• Gridded GRACE data assimilation has recently been installed in LIS.

• Ongoing activities include global GRACE data assimilation and wetness/drought indicator production, and development of a forecasting capability.

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