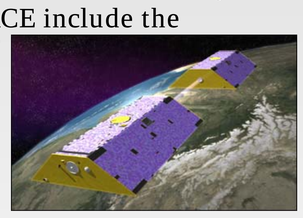
Integrating Data from GRACE and Other Observing Systems for Hydrological Research and Applications

Matt Rodell[1], Jay Famiglietti[2], Eric McWilliams[3], Hiroko Beaudoing[1,4], Bailing Li[1,4], Ben Zaitchik[5], Rolf Reichle[6], and John Bolten[1]

[1]Hydrological Sciences Branch, NASA Goddard Space Flight Center, Greenbelt, Maryland, USA
[2]The University of California, Irvine
[3]Department of Atmospheric and Oceanic Science, University of Maryland
[4]Earth Systems Science Interdisciplinary Center, University of Maryland
[5]Johns Hopkins University, Baltimore, Maryland
[6]Global Modeling and Assimilation Office, NASA Goddard Space Flight Center

Summary

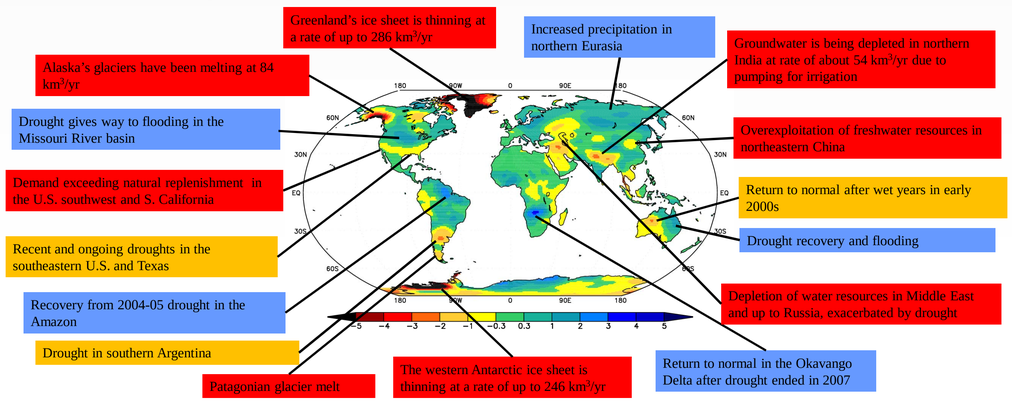
The Gravity Recovery and Climate Experiment (GRACE) satellite mission provides the only space based observations of water on and beneath the land surface that are not limited by depth. GRACE data are immediately useful for large scale applications such as ice sheet ablation monitoring, but they are even more valuable when combined with other types of observations, either directly or within a data assimilation system. Recent hydrological research and applications enabled by GRACE include the following: 1) global monitoring of interannual variability of terrestrial water storage and groundwater; 2) water balance estimates of evapotranspiration over seven large river basins; 3) GRACE data assimilation over several regions; 4) drought indicator products now being incorporated into the U.S. Drought Monitor; 5) NASA's Energy and Water Cycle Study (NEWS) state of the global water budget analysis.



Artist's rendering of the twin GRACE satellites (credit: NASA).

Emerging Trends in Freshwater Resources

Due to the incomplete spatial and temporal coverage of ground-based measurements and the reluctance of many nations to share data, space-based observation provides the best opportunity to keep track of global freshwater resources. With nearly ten years of data from GRACE, we can begin to assess interannual rates of change in terrestrial water storage and infer their origins. We categorize these emerging trends as (1) natural variations that are unlikely to persist in the long term, (2) climate change impacts, or (3) consequences of human activities, in particular consumption of water exceeding natural replenishment.



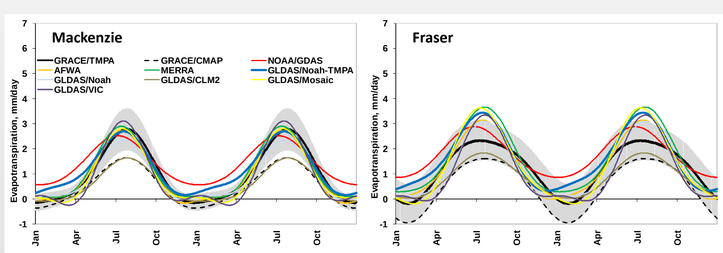
Rate of change of terrestrial water storage as an equivalent height of water (cm/yr) from GRACE, April 2002 to August 2011.

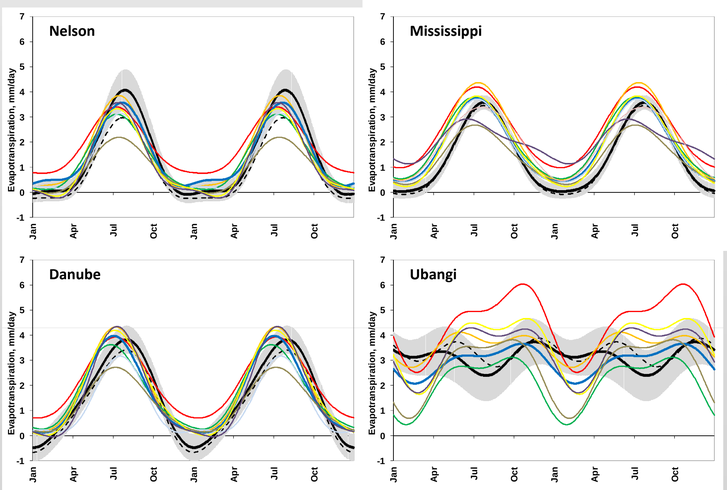
Water Balance Estimates of Evapotranspiration

Properly characterizing evapotranspiration (ET) is essential for water cycle monitoring, weather forecasting, and climate prediction. However, ET is difficult to measure, and different estimation techniques often produce divergent results. One option is to estimate ET as the residual of a terrestrial water budget over a river basin, with observation based precipitation, gauged runoff, and terrestrial water storage changes from GRACE as inputs. While uncertainty in monthly water balance estimates of ET are often too large for those estimates to be useful, uncertainty in the mean annual cycle is small enough that it is practical for evaluating other ET products. Here we compare water balance estimates of ET with those from computer models of land and atmospheric processes over seven major river basins (Mackenzie, Fraser, Nelson, Mississippi, Tocantins, Danube, and Ubangi). An important outcome is that the water budget based ET time series in two tropical river basins, one in Brazil and the other in central Africa, exhibit a weak annual cycle, which may help to resolve debate about the strength of the annual cycle of ET in such regions and how ET is constrained throughout the year.

$$ET = P - Q - \Delta S$$

Observation based precipitation product — River runoff observations — **From GRACE**



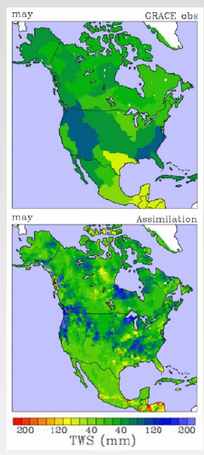


Mean annual cycles (plotted over two years) of evapotranspiration (mm/day) from the terrestrial water budget approach (separately for CMAP and TMPA precipitation), two atmospheric analyses (NOAA/GDAS and AFWA), a reanalysis (MERRA), and five GLDAS land surface model simulations, averaged over seven river basins. The gray area represents uncertainty in the GRACE/TMPA water budget estimates. (Rodell et al., 2011)

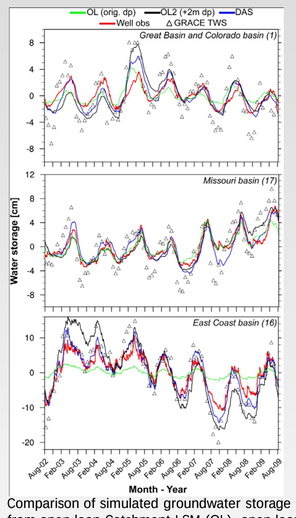
Acronyms
AFWA = Air Force Weather Agency
CLM2 = Community Land Model version 2
CMAP = NOAA Climate Prediction Center's Merged Analysis of Precipitation
GLDAS = NASA's Global Land Data Assimilation System
MERRA = Modern Era Retrospective-analysis for Research and Applications
NOAA/GDAS = NOAA's Global Data Assimilation System
TMPA = Tropical Rainfall Measurement Mission (TRMM) Multisatellite Precipitation Analysis
VIC = Variable Infiltration Capacity model

GRACE Data Assimilation

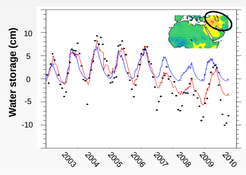
GRACE is unique in its ability to observe changes in total terrestrial water storage (TWS; the sum of groundwater, soil moisture, snow & ice, and surface waters) thus it holds great potential for water resources applications. However, the spatial and temporal resolutions of GRACE data are low, and it provides no indication of the vertical distribution of the observed mass changes. Assimilation of GRACE into a land surface model enables horizontal, vertical, and temporal disaggregation of the GRACE data, and extrapolation to near-real time, by integrating data from GRACE and other sources (Zaitchik et al., 2008), thus generating high resolution fields that are useful for water resources applications. This approach has now been implemented and evaluated over North America, western Europe, and the Middle East North African region.



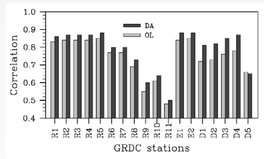
Top: Basin scale TWS anomalies (deviations from the mean, in mm) based on GRACE observations. Bottom: Assimilated terrestrial water storage anomalies have much higher spatial resolution.



Comparison of simulated groundwater storage from open loop Catchment LSM (OL), open loop with increased depth to bedrock (OL2), GRACE data assimilation (DAS), and groundwater well observations, with GRACE TWS observations, over three regions of the U.S.



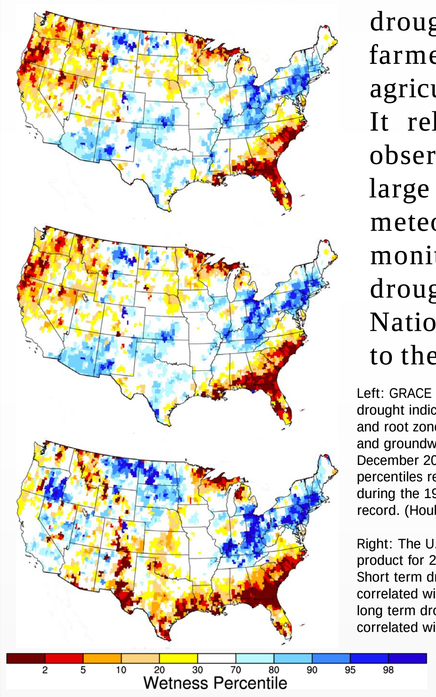
GRACE data assimilation in a drying area of the Middle East including parts of Iraq and Iran. Dots: GRACE TWS anomalies; Blue line: Open loop Catchment land surface model; Red line: GRACE data assimilation.



Improvement in correlation with observed river runoff due to GRACE data assimilation (DA) relative to the open loop (OL) model simulation, at gauging stations in the Rhine (R), Elbe (E), and Danube (D) River basins. (Li et al., 2012)

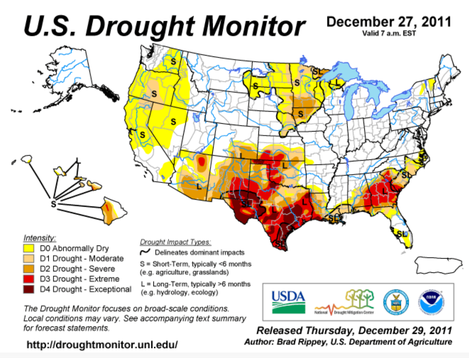
Drought Monitoring

The U.S. Drought Monitor (USDM) is the premier drought monitoring product for the country, used by farmers, state and federal disaster aid officials, agricultural commodities traders, and even USA Today. It relies heavily on precipitation indices and surface observations. Because unconfined aquifer storage has a large dynamic range and responds slowly to meteorological conditions, it is well suited for drought monitoring. New GRACE data assimilation based drought indicators are now being distributed through the National Drought Mitigation Center and used as inputs to the USDM.



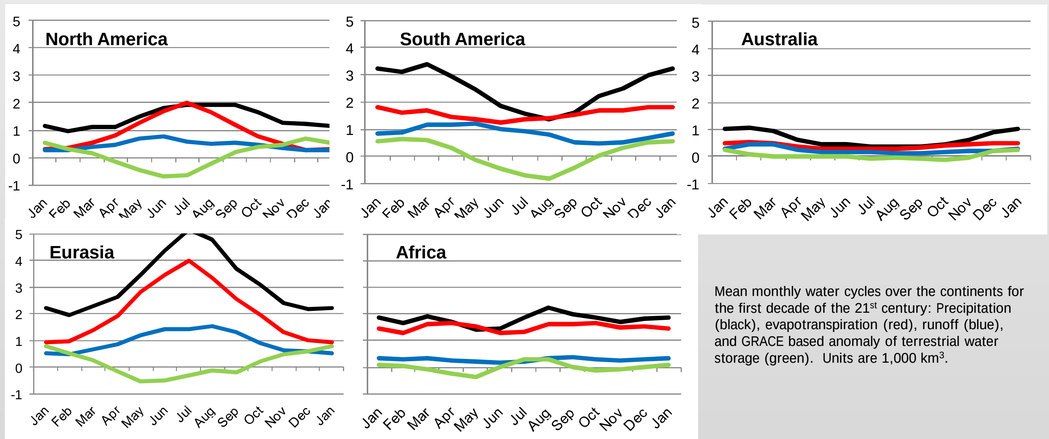
Left: GRACE data assimilation based drought indicators for surface (top) and root zone (middle) soil moisture and groundwater (bottom) for 26 December 2011, expressed as percentiles relative to conditions during the 1948-2011 simulated record. (Houborg et al., 2012)

Right: The U.S. Drought Monitor product for 27 December 2011. Short term drought (S) is well correlated with soil moisture, while long term drought (L) is well correlated with groundwater.



NEWS Water Cycle Climatology

NASA's Energy and Water Cycle Study (NEWS) Climatology working group, which has more than 20 collaborators from multiple institutions, has developed a "state of the global water cycle" assessment based on data from modern ground and satellite observing systems and data integrating models. It is focused on the first decade of the 21st century, with mean fluxes and water storage changes over continents, ocean basins, and at the global scale, on a monthly and annual basis. One unique aspect of this global water cycle assessment is that it is the first to incorporate GRACE derived changes in terrestrial water storage, which balance the fluxes of the monthly terrestrial water budget.



Mean monthly water cycles over the continents for the first decade of the 21st century: Precipitation (black), evapotranspiration (red), runoff (blue), and GRACE based anomaly of terrestrial water storage (green). Units are 1,000 km³.

References

Houborg, R., M. Rodell, B. Li, R. Reichle, and B. Zaitchik (2012), Drought indicators based on model assimilated GRACE terrestrial water storage observations, *Wat. Resour. Res.*, in review.

Li, B., M. Rodell, B.F. Zaitchik, R.H. Reichle, R.D. Koster, and T.M. van Dam (2012), Assimilation of GRACE terrestrial water storage into a land surface model: evaluation and potential value for drought monitoring in western and central Europe, *J. Hydrol.*, in review.

Rodell, M., E.B. McWilliams, J.S. Famiglietti, H.K. Beaudoing, and J. Nigro (2011), Estimating evapotranspiration using an observation based terrestrial water budget, *Hydrol. Proc.*, 25, 4082-4092.

Zaitchik, B.F., M. Rodell, and R.H. Reichle (2008), Assimilation of GRACE terrestrial water storage data into a land surface model: results for the Mississippi River Basin, *J. Hydrometeor.*, 9 (3), 535-548, doi:10.1175/2007JHM951.1.