

New Data Sets to Estimate Terrestrial Water Storage Change

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The total amount of water stored in a river basin affects streamflow at various timescales and defines the river basin's response to atmospheric forcing. For example, spring runoff in mountainous midlatitude catchments depends on winter snowpack, and groundwater storage sustains flow during dry periods. An accurate estimation of terrestrial water storage (TWS) is thus paramount for improved water management. Direct determination of TWS is difficult due to insufficient in situ data on space-time variability of hydrologic stores (snow, soil moisture, groundwater) and fluxes (precipitation, evapotranspiration). However, alternative methods using new data sets show great potential to improve the estimation of intra-annual and interannual TWS dynamics.

Here we provide an overview of four alternative methods and data sets and apply them to the Colorado River basin (Figure 1). The Colorado is crucial to water supply and hydropower of the U.S. Southwest, and the river is currently in the grip of a multiyear drought, a situation that will happen more frequently if climate projections for the region are correct [Seager *et al.*, 2007]. Understanding the relation between climate variability and TWS dynamics is important for sustainable development in the region.

Estimating Water Storage Change

The first method, the basin-scale water balance (BSWB) method (http://www.iac.ethz.ch/data/water_balance/), is based on the coupled atmospheric and terrestrial water balance applied to large river basins [e.g., Seneviratne *et al.*, 2004]. The method relates TWS changes to measured streamflow and atmospheric moisture convergence and to changes in atmospheric moisture content (total atmospheric water vapor contained in a vertical column) derived from reanalysis data sets.

The first BSWB estimates used here are based on the ERA-40 reanalysis (European

Reanalysis 1958–2002; 125-kilometer resolution) and the operational forecast analysis (from 2001 on; 40-kilometer resolution) from the European Centre for Medium-Range Weather Forecasts (ECMWF). Atmospheric state variables are available at four synoptic hours. The second BSWB estimates used here are based on the North American Regional Reanalysis (NARR) produced by the National Centers for Environmental Prediction. These reanalysis data span a period of 28 years (1979–2006) and have a 32-kilometer resolution and a temporal resolution of 3 hours [Mesinger *et al.*, 2006]. Streamflow data were obtained from U.S. Geological Survey gauging stations at Lees Ferry and Imperial Dam.

The second method is based on hydrological modeling. We used the variable infiltration capacity (VIC) model, a land surface model that solves the water and energy balance equations at a user-specified spatial resolution (here one-quarter degree) [Liang *et al.*, 1994]. The meteorological data set of Maurer *et al.* [2002] available for the conterminous United States at 3-hour time steps is used as model input (precipitation, surface temperature, vapor pressure, air pressure, downward shortwave radiation, downward longwave radiation, and wind speed). VIC was calibrated to natural flows [Prairie and Callejo, 2005] at Lees Ferry and Imperial Dam, with modeling efficiencies of 0.88 and 0.85, respectively (an efficiency of 1 indicates a perfect match). In addition, we analyzed the multi-model data from the Global Soil Wetness Project 2 (GSWP-2 [Dirmeyer *et al.*, 2006]) for the period 1986–1995 (1-degree resolution).

The detectability of TWS changes at river basin scales from the Gravity Recovery and Climate Experiment (GRACE) data has been investigated in several recent studies [see, e.g., Tapley *et al.*, 2004]. GRACE seems capable of estimating monthly TWS changes at the size of the Colorado River basin to accuracies better than 1 centimeter. Validated GRACE data are available at <http://geoid.colorado.edu/grace/grace.php>. We obtained estimates of TWS changes for the period January 2003 to October 2006 based on the

processing by GeoForschungsZentrum Potsdam, the Jet Propulsion Laboratory, and the Center for Space Research at the University of Texas. Time differencing was used to convert GRACE TWS anomalies into TWS changes.

The following in situ data were acquired to verify the above three methods. NASA's Southwest Earth Science Applications Center developed a cloud-masked fractional snow-covered area product from advanced very high resolution radiometer (AVHRR) data (1-kilometer resolution) for the Colorado River basin for 1995–2002 and merged the product with interpolated ground-based snow water equivalent (SWE) from Natural Resources Conservation Service SNOTEL (Snowpack Telemetry) sites. We obtained this SWE time series to estimate monthly snowpack water storage changes. Information about reservoir operations from 1979 to 2006 was gathered from the U.S. Bureau of Reclamation and converted into monthly reservoir storage changes. Because of the lack of ground-based soil moisture and groundwater information in the basin, we miss a large component of the terrestrial water storage in this in situ data set, illustrating the difficulties with direct determination of TWS.

Application to the Colorado River Basin

In general, there is good agreement between average monthly storage changes derived from the coupled atmospheric-terrestrial water balance (BSWB-NARR and BSWB-ECMWF) and hydrologic modeling (VIC) methods (Figure 2a). However, it is clear that the dynamic range for VIC is less than for the other estimates, due possibly to its limited storage capacity. Maximum storage changes occur, as expected, in January (+20 millimeters per month) and June (-40 millimeters per month, just before the start of the North American Monsoon). There is a significant difference in amplitude (30%) of the average yearly TWS change cycle between the more mountainous Upper Colorado and the part of the river that is upstream of Imperial Dam. SWE changes for the period 1995–2002 account for most of the overall TWS changes, although the rapid snowmelt in spring is not reflected in the overall storage changes, suggesting that most of the water is stored first. Changes in water storage at



Fig. 1. The Colorado River basin is currently in the grip of a multiyear drought, and water shortages are possible as early as 2010, according to a U.S. Bureau of Reclamation environmental impact statement. The Colorado River basin has a surface storage capacity of almost 60 million acre-feet, or 74 cubic kilometers, in more than 90 reservoirs. The two major reservoirs are Lake Powell (42% of total surface storage capacity in Colorado) and Lake Mead (45% of total capacity). The observed 2006 water year inflow to Lake Powell is 71% of average, and prospects for the 2007 water year also indicate below-average streamflow (69%). As reservoir inflow strongly depends on surface and subsurface water storage, water resources management would greatly benefit from a better assessment of terrestrial water storage (TWS) variability at seasonal timescales.

Lake Powell and Lake Mead peak after the snowmelt and form a small but significant contribution to the overall storage changes.

We also investigated interannual TWS changes. In Figure 2b, smoothed 12-month TWS changes from BSWB-NARR are shown. The period between 1988 and 1992 is characterized by mainly negative values, corresponding to the (modest) 5-year drought in the basin. Similarly, between 2001 and 2006, large negative values are apparent from the data, indicating the current (severe) drought in the basin, even though 2005 appeared to be somewhat wetter (also in agreement with

observations). Further, we can distinguish the wet years between 1983 and 1987 (when Lake Mead was in flood control mode) and the wet years from 1996 to 2000, when reservoir levels in Lake Powell and Lake Mead recovered from the 1988–1992 drought.

The general trend of BSWB-NARR is confirmed by the reservoir data that show storage and release in agreement with wet and dry years, with some time lag. There is good agreement between BSWB-NARR and GSWP-2, although some discrepancies occur in 1992, when NARR predicts a dry year whereas GSWP-2 predicts a wet year. GSWP-2 results

reveal considerable intermodel variability (not shown), which possibly explains this discrepancy. The different GRACE results agree with BSWB-NARR that winter 2005 was generally wet, but the GRACE results disagree with BSWB-NARR about the exact timing of this event. With respect to BSWB-NARR, GRACE underestimates the severity of the subsequent dry period.

Real-Time Monitoring of TWS

Recent technological advances producing geophysical, atmospheric, and hydrologic

data sets offer great potential to diagnose the TWS in hydrologic systems in near real-time. Combined with improved understanding of the causes of regional climate variability (e.g., El Niño–Southern Oscillation), the methods and data sets discussed here will help to improve water management in drought-sensitive areas such as the U.S. Southwest.

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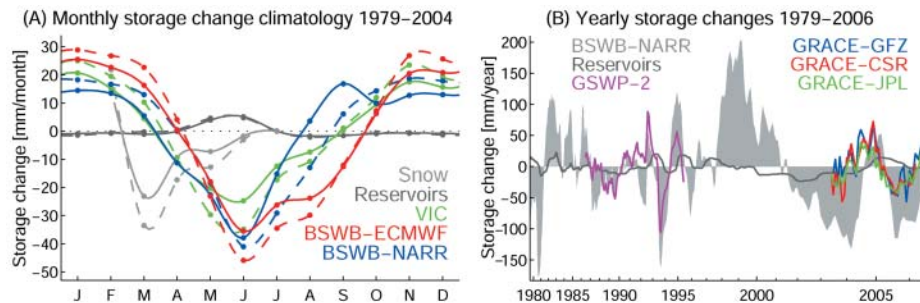


Fig. 2. (a) Terrestrial water storage change climatology in the Colorado River basin for the period 1979–2004. Also shown are average snow water equivalent (1995–2002) and reservoir storage changes (dashed lines, Upper Colorado River at Lees Ferry; solid lines, Colorado River upstream of Imperial Dam). (b) Smoothed 12-month TWS change from BSWB-NARR for the Colorado River upstream of Imperial Dam between 1979 and 2006, reservoirs, GSWP-2 (Global Soil Wetness Project, second phase) based estimates between 1986 and 1995, and different GRACE (Gravity Recovery and Climate Experiment twin satellites) estimates between 2003 and 2006 (note the logarithmic time axis for better comparison).

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NEWS

In Brief

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Profiling floats fully deployed The Argo network of sensor-bearing profiling floats, which allows scientists to observe the basic physical state of the world's oceans, reached its full deployment of 3000 units on 1 November, according to the Argo steering committee. With the full deployment of these floats—which measure ocean water temperature, salinity, and velocity—data from every ocean region are available with an average coverage of one sensor per 3 degrees of latitude and longitude. The floats drift on ocean currents for 10 days, descend to up to 2000 meters in depth, and return to the surface to beam results to passing satellites. “The climate science objectives that drive the Argo array require that we observe the global oceans indefinitely, so achieving the global array is merely the beginning of the observation period,” said Dean Roemmich, cochairman of the Argo program steering

committee and a physical oceanographer at the Scripps Institution of Oceanography.

NASA's lunar planning NASA announced plans on 30 October to establish the NASA Lunar Science Institute (NLSI). To be managed from the Ames Research Center, the institute is expected to begin operations on 1 March 2008 and will augment other agency-funded lunar science investigations by encouraging the formation of interdisciplinary research teams. “NLSI will help us coordinate and expand a number of in-depth research efforts in lunar science and other fields that can benefit from human and robotic missions that are part of NASA's exploration plans,” said Alan Stern, associate administrator for NASA's Science Mission Directorate. The agency also announced which agency centers will take responsibility for specific work to enable astronauts to explore the Moon. The new assignments, which cover elements of the lunar lander and lunar surface operations, among other projects, are listed at the Web site: <http://www.nasa.gov/constellation>.

Quake shakes San Francisco Bay area

A magnitude 5.6 earthquake that shook the San Francisco, Calif., Bay area at 0304:54 UTC on 30 October was the largest temblor in that region since the deadly magnitude 6.9 Loma Prieta earthquake along the San Andreas Fault on 17 October 1989. The recent moderate quake was along the Calaveras Fault 15 kilometers northeast of San Jose, Calif., and was at a depth of 9.2 kilometers, according to the U.S. Geological Survey.

Europe's freshwater fish threatened

Two hundred of Europe's 522 freshwater fish species are threatened with extinction and 12 are already extinct, according to the *Handbook of European Freshwater Fishes*, published in collaboration with the World Conservation Union (IUCN) and released on 1 November 2007. IUCN notes that the main threats to fish species stem from development and population growth and include water withdrawals, large dams, and inappropriate fisheries management that has led to overfishing and the introduction of alien species. Authors Maurice Kottelat, former president of the European Ichthyological Society, and Jörg Freyhof, scientist from Leibniz Institute of Freshwater Ecology, noted that fish conservation should be managed by agencies in charge of conservation, and not as a crop by