5.4 TOWARD INTEGRATING ENHANCED GRACE TERRESTRIAL WATER STORAGE DATA INTO THE U.S. AND NORTH AMERICAN DROUGHT MONITORS

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ABSTRACT

NASA's Gravity Recovery and Climate Experiment (GRACE) satellites measure time variations of the Earth's gravity field enabling reliable detection of spatio-temporal variations in total terrestrial water storage (TWS), including groundwater. The U.S. and North American Drought Monitors are two of the premier drought monitoring products available to decision-makers for assessing and minimizing drought impacts, but they rely heavily on precipitation indices and do not currently incorporate systematic observations of deep soil moisture and groundwater storage conditions. Thus GRACE has great potential to improve the Drought Monitors by filling this observational gap. Horizontal, vertical and temporal disaggregation of the coarse-resolution GRACE TWS data has been accomplished by assimilating GRACE TWS anomalies into the Catchment Land Surface Model using an ensemble Kalman smoother. The Drought Monitors combine several short-term and long-term drought indices and indicators expressed in percentiles as a reference to their historical frequency of occurrence for the location and time of year in question. To be consistent, we are in the process of generating a climatology of estimated soil moisture and ground water based on a 60-year Catchment model simulation which will subsequently be used to convert seven years of GRACE assimilated fields into soil moisture and groundwater percentiles, for systematic incorporation into the objective blends that constitute Drought Monitor baselines. At this stage we provide a preliminary evaluation of GRACE assimilated Catchment model output against independent datasets including soil moisture observations from Aqua AMSR-E and groundwater level observations from the U.S. Geological Survey's Groundwater Climate Response Network.

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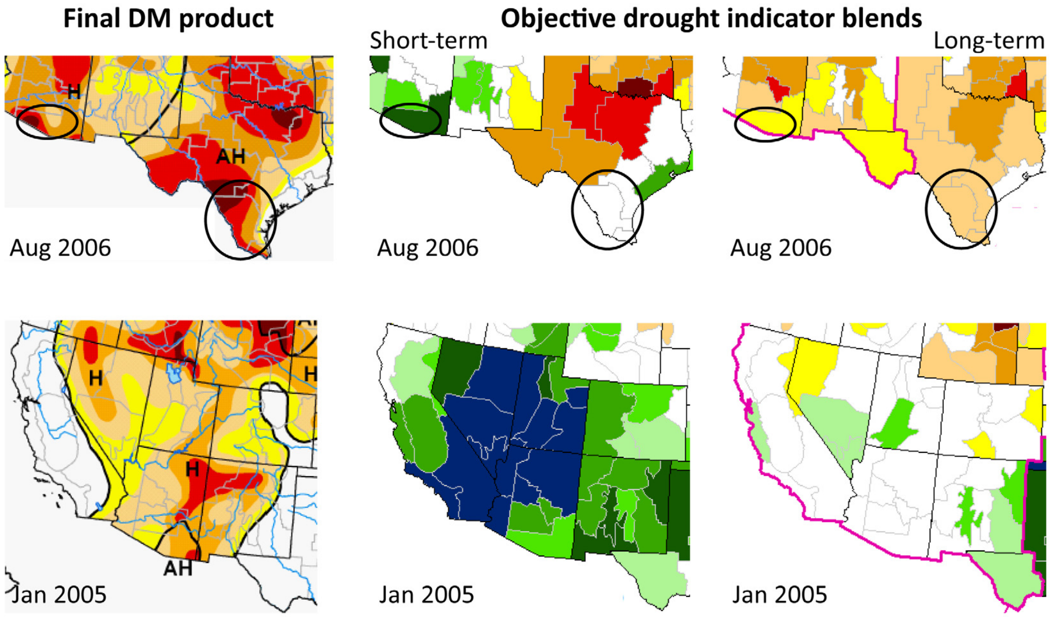
1. INTRODUCTION

Mapping the onset and severity of drought is of critical national importance (WGA, 2004) and improvements in drought monitoring will be of benefit for end users in the Water resources, Agricultural Efficiency, and Energy Management application areas. The goal of this project is to integrate terrestrial water storage (TWS) data derived from NASA's Gravity Recovery and Climate Experiment (GRACE) satellites (Tapley et al. 2004) into the U.S. and North American Drought Monitors (Svoboda et al. 2002; Lawrimore et al. 2002), two of the premier drought products used by governments and stakeholders as decision-support tools to assess and minimize drought impacts. GRACE twin satellites, launched 17 March 2002, use GPS and a microwave ranging system to accurately measure the distance between the two satellites to make unprecedented inferences of monthly changes in the distribution of water on land with sufficient precision (Wahr et al. 2006). While GRACE has a low spatial (no better than ~400 km) and temporal (ten day to monthly) resolution in comparison with other Earth Observation satellites, GRACE is unique in its ability to sense water stored at all levels systematically on a continuous basis. Thus GRACE TWS inferences represent a vertically integrated measure that includes groundwater, soil moisture, surface water, snow and ice, and biomass. The usefulness of GRACE for hydrological applications has been demonstrated in a number of recent studies (Rodell et al. 2009; Yeh et al. 2006; Yirdaw et al. 2008) but the full potential of GRACE estimates of TWS variability still remains to be unraveled.

The value of GRACE TWS data for hydrological applications can be further advanced through data assimilation, which synthesizes the advantages of observations and numerical land surface models, enabling spatial and temporal downscaling and vertical decomposition of the TWS component into groundwater, soil moisture and snow. The U.S. and North American Drought Monitor concept is a process that synthesizes multiple objective drought indices, outlooks and local impacts, into an assessment that best represents current drought conditions



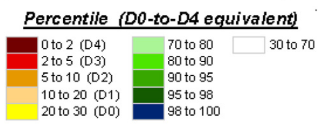


Fig. 1. *The short- and long-term objective blends fail at detecting the severity of actual drought conditions as depicted by the U.S. Drought Monitor. The final Drought Monitor products are the result of an intensive analysis process that incorporates supplemental subjective input to overcome deficiencies in the objective blends.*

(Svoboda et al. 2002). However, the analysis relies heavily on precipitation indices and subjective reports, and lack objective information on soil moisture and groundwater storage conditions. A key objective of this study is to demonstrate that drought conditions can be identified more accurately and objectively through the incorporation of spatially, temporally and vertically enhanced GRACE data. Daily estimates of groundwater, soil moisture, and snow conditions were produced by assimilating monthly column-integrated GRACE TWS anomalies into the Catchment Land Surface Model using an ensemble Kalman smoother (Zaitchik et al. 2008). The integration of the GRACE data into the U.S. and North American Drought Monitors is being accomplished by generating supplemental GRACE-based drought indicators of groundwater and soil moisture consistent with the suite of short-term and long-term indicator blends which currently serve as baselines for the Drought Monitors. We expect that the integration of the enhanced GRACE data into the operational production of objective drought indicator blends will lead to more accurate depictions of short and long-term drought conditions, ultimately benefitting the many stakeholders who depend on these products.

Table 1. The categories of drought magnitude used in the Drought Monitor. Each category is associated with its percentile chance of happening in any given year out of 100 yr.

Category	Drought condition	Percentile chance
D0	Abnormally dry	20 to ≤30
D1	Drought—moderate	10 to ≤20
D2	Drought—severe	5 to ≤10
D3	Drought—extreme	2 to ≤5
D4	Drought—exceptional	≤ 2

2. DROUGHT MONITORS

The U.S. Drought Monitor started operations in 1999 as a cooperation between the Department of Agriculture (USDA) and the National Drought Mitigation Center (NDMC) to centralize the drought monitoring activities conducted by federal, state and academic entities in the U.S. (Svoboda et al. 2002). Maps are produced weekly by a rotating group of drought monitor authors from USDA, NOAA and NDMC. The drought monitor authors take advantage of a suite of short- and long-term objective indicators blended with subjective input from a network of water and climate experts at the local and regional level. The North American Drought Monitor has been providing integrated assessments of drought throughout most of Canada, Mexico and the U.S. on a monthly basis since 2003. A key objective of the Drought Monitors is to provide timely and understandable scientific

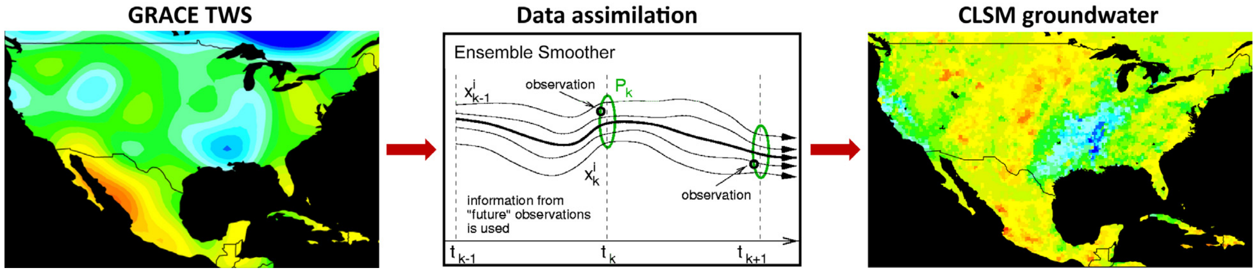


Fig. 2. *Coarse spatial and temporal resolution GRACE terrestrial water storage (TWS) were assimilated into the Catchment land surface model (CLSM) using an ensemble Kalman Smoother. The data assimilation enables spatial and temporal downscaling (to the resolution of CLSM) and vertical decomposition of the integrated GRACE TWS signal into groundwater, soil moisture and snow components.*

information on water supply and drought for decision makes, stakeholders and the general public. Both classify drought severity into four major categories with a fifth category depicting "abnormally dry" conditions (Table 1). Each category is associated with its percentile chance of happening in any given year at a given location. For instance, D3 (extreme) drought conditions would be expected to occur 2 - 5 % of the time.

The current short- and long-term objective drought indicators are all primarily based on precipitation. Important indices include the Palmer drought indices such as the Z-index and Hydrological Index and various standardized precipitation indices to access moisture anomalies on a time-scale of one month to time-scales greater than a year. None of the indicators incorporate systematic observations of deep soil moisture and groundwater storage conditions. The objective blends serve as a starting point in the development of the Drought Monitor and they do not depict drought conditions as accurately as the final Drought Monitor product, which incorporates a variety of subjective input in the form of e.g. opinions from local experts and field reports on how drought is affecting crops.

Fig. 1 reveal deficiencies in the current suite of objective short- and long-term objective blends; In August 2006 the objective blends fail at detecting the severity of the drought in Southern Texas and Arizona and in January 2005 the blends provide no indication of the quite severe drought conditions prevailing in the Western U.S. This may suggest that the objective blends lack other critical indicators of drought such as groundwater storage and accurate soil moisture observations.

3. GRACE TERRESTRIAL WATER STORAGE

The GRACE data used here were acquired from the Tellus website (http://grace.jpl.nasa.gov/index.cfm). The data are based on gravity field solutions provided on a near-monthly basis by the University of Texas Center for Space Research (CSR), the GeoForschungsZentrum Potsdam (GFZ), and NASA's Jet Propulsikon Laboratory (JPL). Each gravity field solution is comprised by a set of spherical harmonic coefficients that describe the Earth's gravity field after the effect of mass distributions resulting from atmospheric and oceanic circulations have been removed. Additional post-processing steps are required to convert the coefficients into maps of terrestrial water storage anomalies (Chambers 2006), which include smoothing to reduce errors associated with the short wavelength harmonic coefficients and destriping according to Swenson and Wahr (2006). A

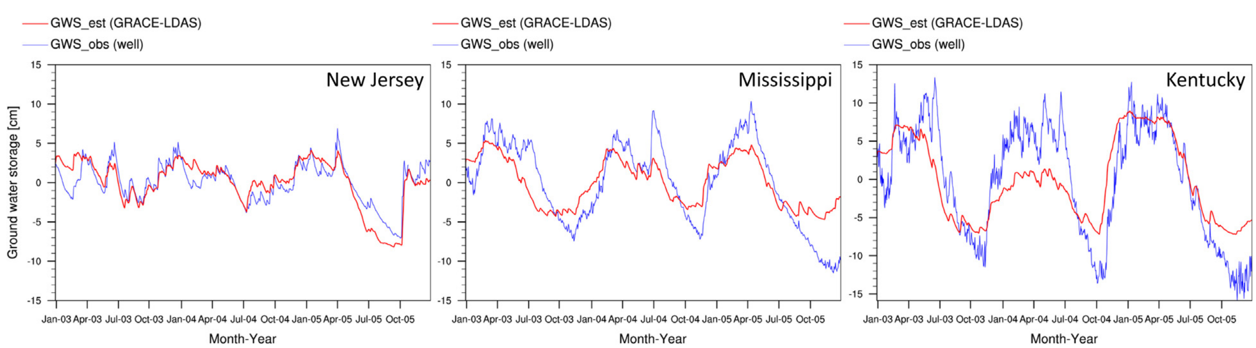


Fig. 3. *Daily average ground water storage anomalies (cm) for Jan. 2003 - Dec. 2006, from GRACE-LDAS simulations (red) and water level records (blue) at USGS Groundwater Climate Response Network well sites in New Jersey, Mississippi and Kentucky.*

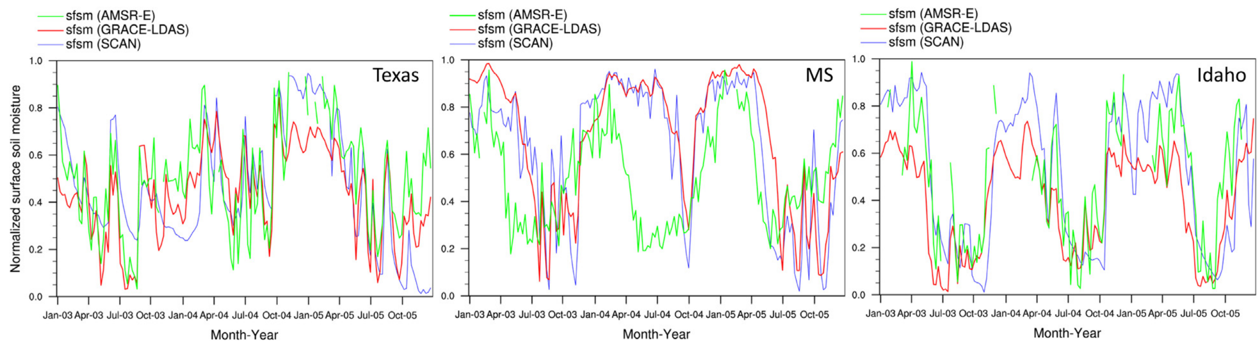


Fig. 4. *Weekly averaged normalized surface soil moisture for Jan. 2003 - Dec. 2006, from VUA-NASA AMSR-E (green), GRACE-LDAS simulations (red) and in-situ observations (blue) at Soil Climate Analysis Network (SCAN) sites in Texas, Mississippi and Idaho.*

correction for glacial isostatic adjustment has also been applied to the data. The uncertainty of these GRACE grids is on the order of 1.7 cm equivalent water thickness for a 500 km Gaussian smoothing radius. We used the Tellus dataset out of convenience for preliminary testing. However, this product is not optimized for terrestrial hydrology, thus we will soon switch to one that is.

Data assimilation is a process that synthesizes the advantages of observations and numerical models. The value of the GRACE coarse resolution column integrated water storage information can be significantly enhanced through data assimilation that enables spatial and temporal downscaling and vertical decomposition into groundwater, soil moisture and snow anomalies. The GRACE Data Assimilation System (GRACE-LDAS) (Zaitchik et al. 2008) merges the basin-scale, monthly, GRACE TWS anomalies into the Catchment land surface model (CLSM) (Koster et al. 2000) by means of the ensemble Kalman smoother (EnKS). The modeled moisture fields are corrected toward the observational GRACE estimate, with the degree of correction determined by the levels of error associated with each. The EnKS uses information from "future" observations to update model fields over a window of time which is preferable in reanalysis or retrospective analysis. The result is new estimates of groundwater and soil moisture anomalies, informed by GRACE TWS but with the high spatial and temporal resolutions of the model (Fig. 2).

4. EVALUATING GRACE ASSIMILATED MOISTURE FIELDS

The GRACE assimilated CLSM groundwater and soil moisture output were evaluated against various independent datasets to assess the value of incorporating the moisture anomalies into the Drought Monitor process. Fig. 3 showcases timeseries validation plots of groundwater storage for a few well sites affiliated with the U.S. Geological Survey's Groundwater Climate Response Network. The observed groundwater storage anomalies were derived based on water level records from wells open to an unconfined or semi-confined aquifer and representative of the local water table. The specific yields, used to convert water level measurements to equivalent heights of water, were provided by Rodell et al. (2006). The GRACE assimilated groundwater anomalies are generally successful in tracking the observed variability at these sites (Fig. 3). While the amplitude is being somewhat underestimated the predicted seasonal cycle of groundwater is generally in phase with the observations.

Fig. 4 compares GRACE assimilated surface soil moisture output against observations from Aqua AMSR-E and in-situ observations from selected Soil Climate Analysis Network (SCAN) sites across the U.S. We used the VUA-NASA AMSR-E surface soil moisture retrieval product which is derived according to the Land Surface Parameter Model (Owe et al. 2008). Generally, there's a good correspondence between the three independent estimates of surface soil moisture when expressed in normalized units (i.e. $[SM_{abs}-SM_{min}]/[SM_{max}-SM_{min}]$). As expected, the AMSR-E retrievals experience issues due vegetation which is particularly evident for the Mississippi SCAN site during the 2004 growing season (Fig. 4).

5. INTEGRATION INTO THE DROUGHT MONITORS

The integration of the GRACE assimilated soil moisture and groundwater fields into the Drought Monitors requires conversion to percentiles to be consistent with the drought monitor products. The percentiles are derived by historic ranking, by creating location and time-specific cumulative probability distribution functions from a historic record of soil moisture and groundwater data. The U.S. Drought Monitor percentiles are based on a record that extents back to 1932. We are in the process of generating a climatology soil moisture and groundwater based on a 60-year Catchment model simulation extending back to 1948 which will subsequently be used to convert seven years of GRACE assimilated fields into soil moisture and groundwater percentiles. Fig. 5 exemplifies the three GRACE-based Drought Indicators (surface soil moisture, root-zone soil

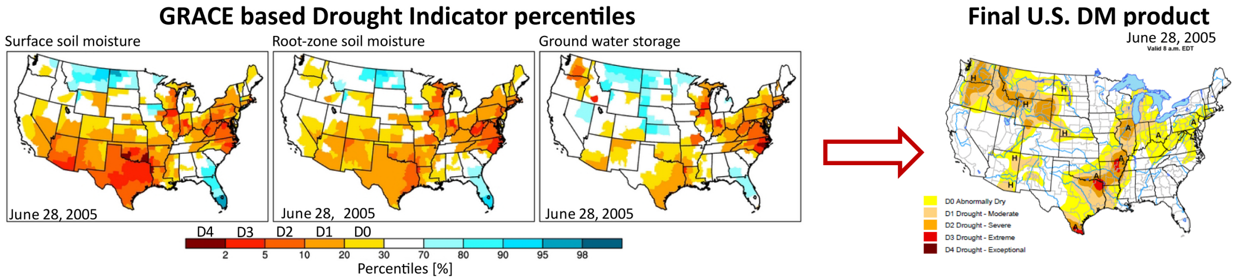


Fig. 5. *Sample GRACE-based Drought Indicators expressed in percentiles relative to their historical frequency of occurrence. Our partners at NOAA and NCDM will be testing the incorporation of these new indicators into the "objective blends" that serve as baselines for the Drought Monitor products.*

moisture and groundwater) that will be incorporated into the short- and long-term objective blends. Based on a short 3-year climatology, the percentiles still capture many of the prevailing drought conditions evident in the final U.S. Drought Monitor product for this period.

6. CONCLUSION

GRACE is unique in its ability to sense water stored at all levels and data assimilation can be used to spatially and temporally disaggregate and vertically decompose coarse resolution GRACE terrestrial water storage into components of groundwater, soil moisture and snow. We expect that drought conditions can be identified more accurately and objectively by incorporating GRACE-based drought indicators into the short- and long-term objective blends, which currently rely heavily on precipitation accumulations and thus lack a proper depiction of land surface moisture conditions. Once the full 60+ year climatology has been used for converting the GRACE assimilated fields into soil moisture and groundwater percentiles, they will be delivered to our partners at NOAA and NCDM for experimentation within the objective blends. At the same time, the added benefit of incorporating the GRACE-based drought indicators will be analyzed through comparison with the current suite of short- and long-term objective indicators and by correlating detectable differences at the regional and local scale to the final U.S. Drought Monitor products.

7. REFERENCES

Chambers, D. P, 2006: Evaluation of new GRACE time-variable gravity data over the ocean. *Geophys. Res. Ltrs*, *33*, L17603, doi:10.1029/2006GL027296.

Koster, R.D., Suarez, M.J., Ducharne, A/, Stieglitz, M., and Kumar, P., 2000: A catchment-based approach to modeling land surface processes in a general circulation model 1.Model structure. *J. Geophys. Res.*, 105 (D20), 24,809-24,822.

Lawrimore, J., Heim, R.R., Svoboda, M., Swail, V., and Englehart, P.J., 2002: Beginning a New Era of Drought Monitoring Across North America. *Bull. Amer. Meteor. Soc.,* 83 (8), 1191–1192.

Owe M., De Jeu, R. and Holmes, T., 2008: Multi-Sensor Historical Climatology of Satellite-Derived Global Land Surface Moisture. *J. Geophys. Res.*, 113, F01002, doi:1029/2007JF000769.

Rodell, M., Velicogna, I., and Famiglietti, J.S., 2009: Satellite-based estimates of groundwater depletion in India. *Nature*, doi:10.1038/nature08238.

Rodell, M., Chen, J., Kato, H., Famiglietti, J.S., Nigro, J., and Wilson, C.R., 2006: Estimating groundwater storage changes in the Mississippi River basin (USA) using GRACE. *Hydrogeology J.*, doi:10.1007/s10040-006-0103-7.

Svoboda, M., LeComte, D., Hayes, M., Heim, R., Gleason, K., Angel, J., Rippey, B., Tinker, R., Palecki, M., Stooksbury, D. , Miskus, D., and Stephens, S.,2002: The Drought Monitor. *Bull. Amer. Meteor. Soc,*. 83(8), 1181-1190.

Tapley, B.D., Bettadpur, S., Ries, J.C., Thompson, P.F., and Watkins, M.M., 2004: GRACE measurements of mass variability in the Earth system. *Science,* 305, 503–505.

Wahr, J., Swenson, S., and Velicogna, I., 2006: The accuracy of GRACE mass estimates. *Geophys. Res. Lett,*. 33, doi:1029/2005GL025305.

Western Governor's Association, 2004: Creating a Drought Early Warning System for the 21st Century: The National Integrated Drought Information System, pp. 13 (http://www.westgov.org/).

Yeh, P.J.-F., Swenson, S.C., Famiglietti, J.S., and Rodell, M., 2006: Remote sensing of groundwater storage changes in Illinois using the Gravity Recovery and Climate Experiment (GRACE). *Wat. Resour. Res,.* 42, doi:10.1029/2006WR005374.

Yirdaw, S.Z., Snelgrove, K.R., Agboma, C.O., 2008: GRACE satellite observations of terrestrial moisture changes for drought characterization in the Canadian Prairie. *Journal of Hydrology,* 356, 84-92.

Zaitchik, B.F., Rodell, M., and Reichle, R.H., 2008: Assimilation of GRACE Terrestrial Water Storage into a Land Surface Model: Results for the Mississippi River Basin. *Journal of Hydrometeorology,* 9, 535-548.