Groundwater Storage Estimates and Variability at the Sub-Region Level using NASA GRACE, C2VSim, and a Statistical Downscaling Approach

California's groundwater is an important resource for domestic, industrial, and agricultural uses. To supplement current groundwater management techniques, satellites have been used to indirectly estimate changes in groundwater storage. The Gravity Recovery and Climate Experiment (GRACE) is a satellite that uses anomalies in the Earth's gravitational field to detect changes in total water storage (TWS) throughout the world. Previous studies have shown comparable results for total groundwater change for the Central Valley Aquifer (CVA) from the DWR hydrologic model C2VSim and GRACE with similar seasonal, annual, and long-term trends. However, this data is not useful to local water managers who work on much finer scales. Thus, a statistical downscaling technique was developed to produce GRACE derived estimates on C2VSim's sub-region level. Additionally, current groundwater estimates do not consider the influence of climatic variability. Therefore, the El Nino Southern Oscillation and the Pacific Decadal Oscillation were compared to GRACE total water storage and ground water storage estimates. This work has the potential to improve California's groundwater management and use of existing hydrologic models for the CVA.

Satellites Detect Total Water Changes

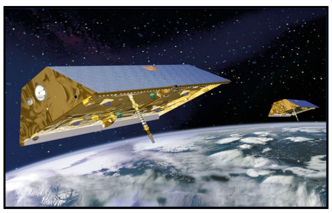

Figure 1: The GRACE satellite orbiting Earth (NASA, 2011).

The GRACE sensor is a pair of twin satellites that fly in tandem orbits approximately 220 km apart (Figure 1). Based on changes in the distance between the two satellites to a precision of 1 μm, GRACE measures monthly gravitational anomalies (deviations from a 10-year average) of the Earth. Gravitational anomalies are attributed to changes in the Earth's hydrologic cycle which are used to calculate total water storage (TWS) anomalies of the Earth[1]. TWS anomalies represent the sum of all hydrologic components including changes in snow, ice, reservoirs, soil moisture, and groundwater. Data obtained from GRACE are processed at the Jet Propulsion Laboratory (JPL) processing center to generate measurements of TWS anomalies. Numerous satellites, models, and ground data are used to generate values for the other hydrologic components which are subtracted from the TWS values to calculate groundwater storage changes. Understanding groundwater storage changes from the GRACE satellite may help determine changes induced from pumping, or drought as a function of natural climate variability.

Previous studies from all over the world demonstrate the use of this satellite for groundwater storage assessment[2,3,4,5,6,7]. GRACE Release 5 data were provided by Dr. Felix Landerer, a GRACE expert at JPL. The GRACE data was processed and clipped to the Central Valley Hydrologic Region (Figure 2). To calculate changes in groundwater storage, changes surface water storage from CDEC (SW)[8], soil moisture from GLDAS NOAH (SM)[9], and snowpack from SNODAS (SP)[10] must be subtracted from TWS.

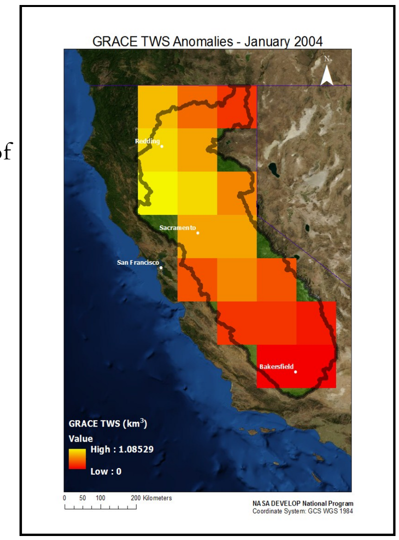

Figure 2: Area of the modeled GRACE dataset compared to the outline of the Sacramento and San Joaquin hydrologic regions.

An Introduction to California's Groundwater

The California Central Valley aquifer (CVA) system [52,000 km^2] is one of the world's most productive agricultural regions and is the second most heavily pumped in the U.S. [11]. It also supplies nearly 20% of the nation's groundwater (GW) demand and provides nearly 7% of the United States (U.S.) food supply, with an estimated annual value of $21 billion [12,13]. Although this is an important resource, the CVA is susceptible to population demands, extended periods of drought, and groundwater pumping. To improve estimates of groundwater change in the CVA, this study used the GRACE satellite along with the C2VSim hydrological model[14,15]. Although GRACE is a useful tool for large regions, the data are coarse, and cannot be used for regional groundwater management (Figure 3). Therefore, the purpose of this study was twofold: first we statistically downscaled GRACE groundwater estimates to the sub-region scale. These estimates were compared with the DWR's hydrological model C2VSim. Secondly, we correlated the downscaled GRACE data to climate cycles such as the El Niño Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO). This will provide a better understanding about how climate variability may affect

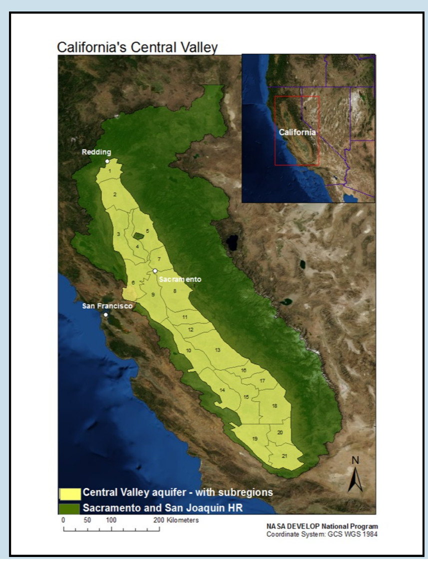

Figure 3: The study area, highlighting the Central Valley aquifer (yellow) and the hydrologic basins of California (green). All changes in the hydrologic basins are assumed to be represented in the Central Valley aquifer.

Downscaling GRACE-derived Groundwater Storage Estimates

For the study period, GRACE calculated a total loss of groundwater storage of –20.6± 7.57 km^3 and C2VSIM a total loss of –20.7± 3.01 km^3

Statistical downscaling is a method of acquiring information known at large spatial scales and using ancillary information to make predictions at local scales [16]. Downscaling methods are often used in climate studies, and have also been used in GRACE GW studies [17]. To begin the process, GW storage anomalies were calculated by subtracting SM, SP, and SW from TWS. We followed a method developed by Hoar and Nychka [2008][16] and implemented three important steps: 1) develop a statistical relationship between the prediction data (data from the hydrological model C2VSim) and a spline of the same data for every location and for every month; 2) obtain an initial estimate of the data from the data to be downscaled (GRACE); and 3) apply the linear model from step 1 to the initial value in step 2 to produce the final downscaled estimate [16].

Calculated total GW storages estimates (not yet downscaled) for the CVA from both GRACE and C2VSim were similar with a total change in GW storage of -20.6 ± 3.01 km^3 and -20.7 ± 7.57 km^3, for GRACE and C2VSim, respectively from October 2004-September 2009 (Figure 4). Downscaled GRACE results compared to C2VSim by region (Figure 5) show a similar spatial trend and when comparing total changes for every sub-region, show strong agreement (Figure 6) ($R^2 = 0.63$, $p < 0.01$ and RMSE = 0.61 km^3).

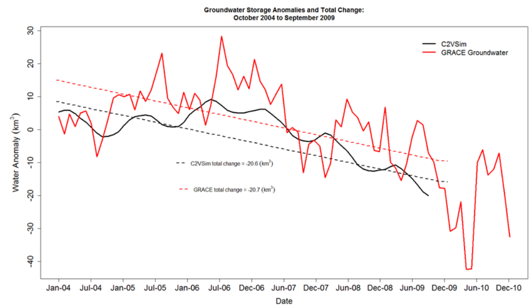

Figure 4: Total change in groundwater storage for the CVA calculated by C2VSim and GRACE (non-downscaled).

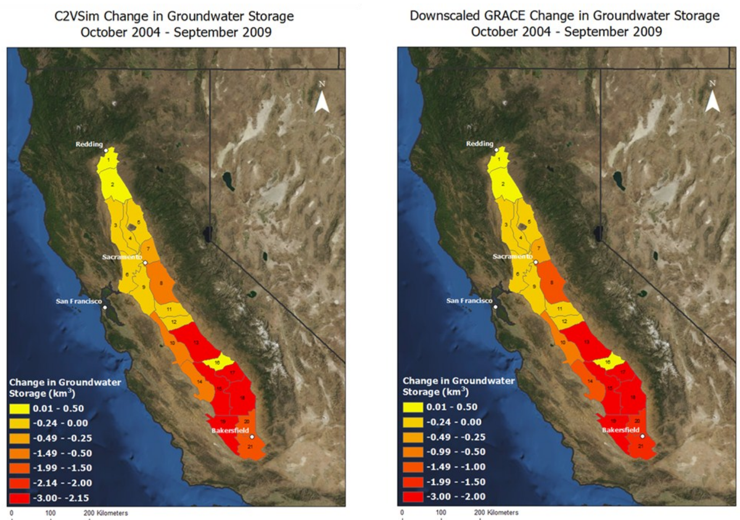

Figure 5: Total change in GW storage calculated by C2VSim and the downscaled GRACE estimates from October 2004-September 2009.

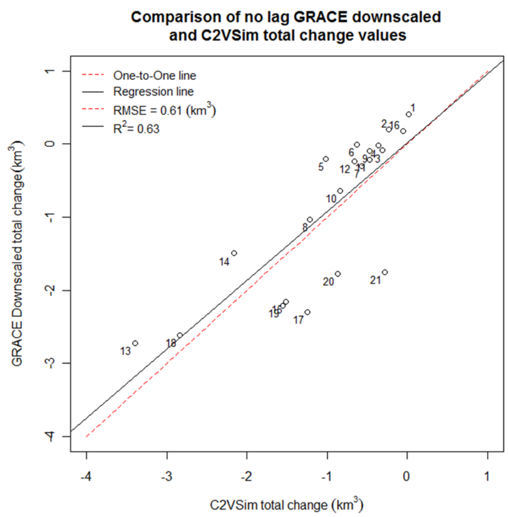

Figure 6: Comparison of total change in downscaled GRACE GW storage and C2VSim for each sub-region.

Climate Variability Analysis

Natural climate variability is associated with changes in precipitation distribution (in space and time), temperature fluctuations, drought occurrence and severity, and streamflow[18,19,20,21]. The El Niño Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) affects precipitation distribution and subsequently GW availability. ENSO has a 2–7 year periodicity and the PDO has a 10–25 year periodicity. In general, California receives more precipitation during the positive phase and less precipitation during the negative phase[18,20,21]. To address how groundwater changes during these natural cycles, we used singular spectral analysis to identify whether patterns in downscaled GRACE GW estimates were similar to natural climate variability. Each of the 21 sub-region GW estimates were time-lagged correlated to ENSO and PDO time-series to determine which climate cycle influenced GW at the statistically significant level.

GRACE TWS estimates for the entire Central Valley are moderately correlated with both ENSO (average of 0.16) and PDO (average of 0.42), with stronger correlations observed in the southern regions compared to the northern regions and slightly higher correlations to the PDO (Figure 7). Additionally time-lagged correlations of downscaled GRACE GW estimates are moderately correlated with both ENSO (range of 0.14–0.41) and PDO (range of 0.12–0.57), with similar spatial and correlation patterns. These results show how GW may be affected by variations in climate and how those effects may vary throughout the Central Valley and can be useful for future water resource management.

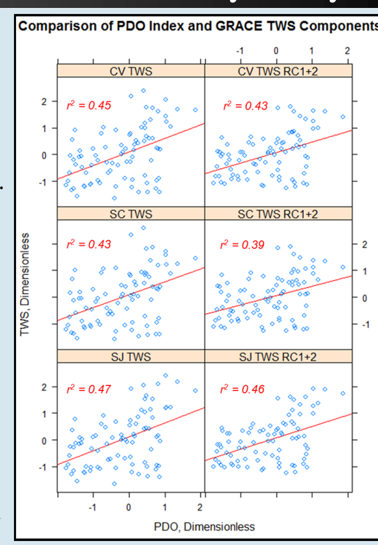

Figure 7: Representation of the GRACE calculation of groundwater storage.

Conclusions

This study successfully created a prototype application for downscaling GRACE GW anomalies to the sub-region scale that may be useful for DWR and regional water agencies. However, improvements to this methodology may be necessary, such as developing a better estimate of splined C2VSim data and conducting an error analysis for each of the 21 sub-regions. With these improvements, the use of downscaled GRACE data could provide water management agencies with more up-to-date estimates of GW storage than currently used techniques. This study also successfully addressed the influence of climate variability on GW storage within the CVA using multiple GRACE TWS and GW datasets. We observed moderate correlations to both the ENSO and PDO, with stronger correlations in the southern portions of the CVA. To more confidently determine the effects of long-term climate cycles on water availability, a longer time series of TWS and GW storage must be used. Finally, forecasting may be used to estimate long-term trends related to climate variability in California. Improvements in estimating GW storage availability within the CVA will better prepare agencies such as the DWR with useful information for water resource management in California.

Figure 8: The Pine Flat Dam on the Kings River.

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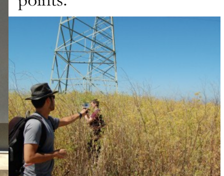
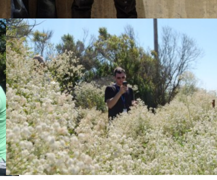
Left: The NASA Ames DEVELOP Team.

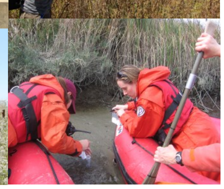
Below: Andrew Nguyen collecting Pepperweed presence and absence data points.



Amber Kuss and Abdelwahab Bourai of the GRACE team measure groundwater levels in the Central Valley, California.



Glade Dlott examines his GPS tool while plotting Pepperweed presence and absence points.



Michelle Newcomer and Amber Kuss collect samples for their Biofilm project in the San Francisco Bay.

The NASA Applied Sciences' DEVELOP Program sponsors paid internships located at Ames Research Center for students to extend science research to local communities. DEVELOP is a NASA Science Mission Directorate Applied Sciences Program training and development internship. Students work on Earth science research projects, mentored by science advisors from NASA and partner agencies and extend research results to local communities. Located in the heart of the Silicon Valley, Ames plays a critical role in virtually all NASA missions in support of America's space and aeronautics programs. As a leader in information technology research with a focus on supercomputing, networking and intelligent systems, Ames conducts the critical R&D and develops the enabling technologies that make NASA missions possible. Ames also is a leader in nanotechnology, fundamental space biology, biotechnology, aerospace and thermal protection systems, and human factors research.

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