Weighing Earth, Tracking Water: Hydrological Applications of data from GRACE satellites

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Abstract

GRACE is a pair of satellites that fly 220 kilometers apart in a near-polar orbit, mapping Earth's gravity field by accurately measuring changes in distance between the two satellites. With a 15 year continuous data record and improving data processing techniques, measurements from GRACE has contributed to many scientific findings in the fields of hydrology and geology. Several of the applications of GRACE data include mapping groundwater storage changes, ice mass changes, sea level rise, isostatic rebound from glaciers, and crustal deformation. Many applications of GRACE data have profound implications for society; some further our understanding of climate change and its effects on the water cycle, others are furthering our understanding of earthquake mechanisms. This paper reviews the GRACE mission and applications of GRACE data with a focus on groundwater hydrology. GRACE has contributed to the field of groundwater hydrology by allowing researchers to calculate changes in total water storage over regions, which in turn, paired with other datasets, has allowed researchers to isolate mass changes in specific components of the terrestrial water system. Combined with data from traditional remote sensing tools and other field measurements, GRACE data is changing the way we understand groundwater fluctuations, and potentially impacting the policies and procedures used to manage groundwater resources. The launch date for GRACE-Follow On is set for May 2018, and assures that this important mission will continue to collect measurements for the next 5 to 15 years.

Section 1: GRACE mission

A. Introduction

GRACE (Gravity Recovery And Climate Experiment) is a set of twin satellites originally launched by Jet Propulsion Labs (JPL) NASA and GFZ, Germany's Geoscience research center and space agency, in March 2002. The GRACE satellites measure Earth's gravitational anomalies through a microwave ranging interferometer system which tracks changes in speed and distance between the two satellites in orbit. The satellites are able to provide detailed data on Earth's mass redistributions over time, with applications in oceanography, hydrology, in understanding crustal deformations in Earth's interior, and more.

Data from GRACE has provided for many novel research projects which have investigated rates of groundwater depletion, rates of sea level rise and different contributing factors, and the mechanisms of earthquakes and tsunamis. There are now 15 years of continuous data on the spatial and temporal variations of Earth's mass distributions. Many of the applications of GRACE data have profound implications for human society; research projects are helping to contextualize climate change as it impacts the water cycle in groundwater, ice mass, sea level, and weather. Other research projects using GRACE data are furthering our understanding of earthquake mechanisms and natural disasters, with the potential to change the way we prepare for or respond to such natural disasters.

The first part of this paper will explore GRACE as a project: I will address how GRACE has been funded, the characteristics of the satellite and its instrumentation, and how the satellites take such precise measurements of gravitational anomalies. In the second part of this paper I will track the applications of GRACE data and the novel findings that scientists have been making with GRACE data. I will place particular focus on applications of GRACE data to groundwater hydrology, and consider what other tools gravitational anomaly data is paired with to give a greater understanding of groundwater reservoirs and the changes taking place in them. By researching and analyzing published literature on the topic, I aim to consolidate recent scientific findings, but more importantly to merge information about remote sensing tools available to researchers, and how they have been used in combination with other data sources to answer important questions in hydrology.

B. Background

GRACE is the first Earth-sensing mission in the history of space flight not to use electromagnetic waves as the method of collecting data (National Aeronautics And Space Administration, 2002). This novel technique makes tracking water as it cycles between land, ocean and atmosphere possible; water is very difficult to track using traditional remote sensing tools and is much easier to track through changes in mass. This is because it is difficult to leverage the spectral characteristics of water in a way that can be measured with traditional remote sensing electromagnetic waves. GRACE data has proven to be a powerful tool when paired with other observations for climate modelling and hydrological applications, and this literature review will help to catalogue the data and methods used.

While it uses a novel measurement technique, the GRACE mission is part of a long line of missions designed to explore Earth's gravity field from space. Since 1964, with the launch of satellite Beacon-B, we have been measuring the long and medium range components of Earth's gravity field (Botai et al, 2012). Scientists have been noting the orbital accelerations and decelerations of traditional remote sensing satellites and using that data to infer temporal gravitational anomalies since then. However, recently, gravitational models of the Earth have been refined resulting in today's significantly more accurate gravitational models with improved spatial and temporal resolution. The GRACE mission actually began as a project to measure more accurately Earth's gravity field which does not change on human timescales. However, as the project progressed, scientists realized the same satellites might be able to measure short temporal variations in Earth's gravity field, which are mostly due to the movement of water. GRACE, along with CHAMP (launched in 2000) and GOCE (launched in 2009), are all designed to measure the long-wavelength part of the gravity field (Botai et al, 2012).

The GRACE mission consists of a pair of satellites launched into a near-polar orbit, with both satellites following the same orbital path with a distance of about 220 kilometers, plus or minus 30 kilometers, between the two (Wahr et al, 1998). When a satellite passes over an area with slightly stronger or weaker gravity, its orbit is perturbed; the satellite doesn't move up or down, but the orbital velocity will change. For example, when passing over an area of stronger gravity, the lead satellite will accelerate and pull ahead of the trailing satellite. When the trailing satellite approaches that same spot, it too will accelerate, and then decelerate after it passes. This set of accelerations and decelerations produces a clear signal, seen through the changes in distance between the two satellites, as shown below in Figure 1. In this figure, the blue line is the path of the satellite, and the graph on the left shows what the signal looks like for changes in distance between the two satellites.

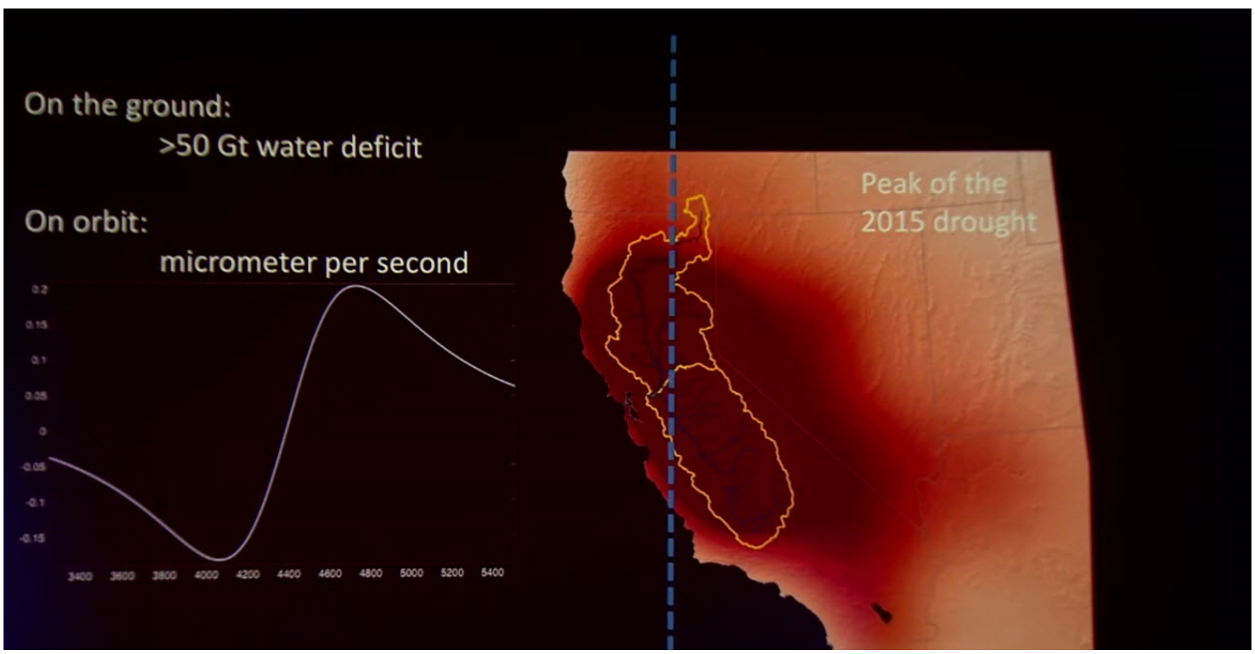

FIGURE 1 Shows the signal from GRACE (changes in distance between the two satellites, in micrometers/second) resulting from a change in mass on the ground. Reprinted from Weight Watching from Space: Tracking Earth's water cycle, by F.M. Landerer, 2017, retrieved from https://www.jpl.nasa.gov/events/lectures_archive.php?year=2017&month=12

These range variations between the two satellites are usually just a few micrometers in length. For example, a loss of 50 gigatons of water on the ground would result in a range variation of about 0.5 micrometers (Argus et al, 2014). They are measured by a microwave ranging interferometer system which sends a continuous signal between the two satellites to measure distance apart. The GRACE-Follow on mission, with a launch date set for May 19th, 2018, will be measured using laser ranging interferometer as well. The temporal gravitational variations resolved by GRACE, such as the example above, are generally on the order of 10^{-6} N/Kg, expressed as variation from the mean (Botai et al, 2012).

The applications of GRACE data can be broken down into four main categories, as follows: tracking water movement both on the surface and underground; tracking changes in ice sheet mass and sea level; tracking ocean currents; and tracking changes in the structure of the Solid Earth. Some of the applications with the most practical day-to-day uses for communities include mapping flood potential, mapping groundwater storage and monitoring drought conditions. One reason GRACE satellites are so useful in taking these measurements is because GRACE data can be used to measure total water storage over an area.

C. Technical Overview

The satellites are also equipped with other instrumentation: most importantly, these include a very sensitive accelerometer, which is used to subtract out any accelerations not due to gravity from the data (see Figure 2 below). These other accelerations and decelerations are mostly due to atmospheric drag, or solar pressure (Reigber et al, 2005). The satellites are also equipped with star cameras, which along with other instruments help to give the satellites' orientation in space. Important instrumentation also includes a GPS zenith antenna for navigation and an atmospheric occultation antenna, which measures temperature and integrates the impact of weather changes into the recorded data (Reigber et al, 2005). The K-band ranging system measures the changes in distance between the two satellites.

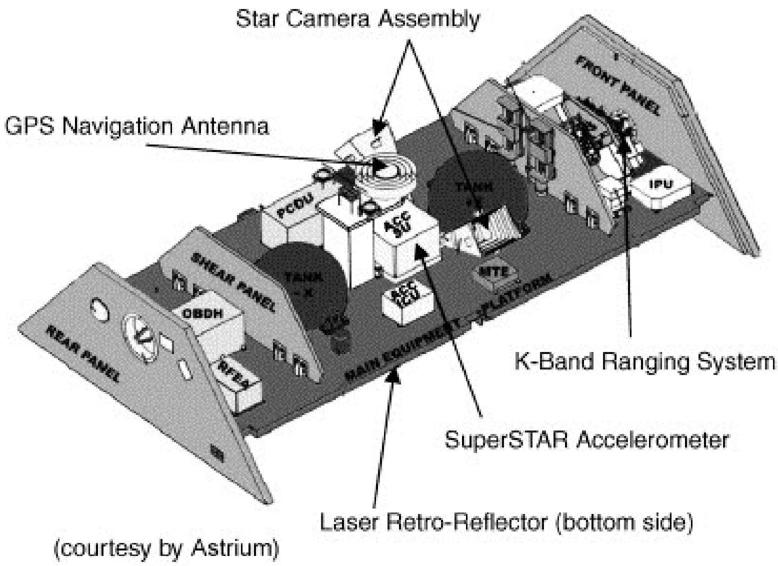

FIGURE 2 GRACE satellite instrumentation. Reprinted from C. Reigber et al, 2005.

The GRACE satellites are in a near-polar orbit and travel at around 7.5 kilometers per second, travelling around the Earth 15 times in a day. It takes 30 days to get coverage of the entire Earth, and so 30 days to produce a gravity field map of the Earth. The satellites were effective for over 15 years after their launch, and so there is data for almost each month between March 2002 and October 2017; GRACE Follow-On mission is expected to resume data collection beginning in July or August 2018. The GRACE satellites were launched into orbit at an original altitude of 500 kilometers; the orbit altitude decreases naturally at a rate of about 1.1 km/month (Reigber et al, 2005). While this is quite low for a satellite, it allows for measurable changes in distance between the satellites as the force of gravity has an inverse relationship to radius, and so the greater the altitude of the satellite, the weaker gravity's influence. The satellites are positioned to be low enough to measure Earth's gravitational signal with accuracy, but high enough for a good signal with less noise. If the altitude were to be reduced, the satellites would feel significant atmospheric drag, which would both reduce the mission lifetime and introduce noise to the system (Landerer 2017).

D. GRACE data

As mentioned previously, data is processed and released as monthly grids because it takes 30 days to get full coverage of the Earth. On the ground, the satellites have a resolution of about 400 kilometers, but within that swathe the satellites can resolve a redistribution of mass due to water of about ½ inch layer (Wahr et al, 1998). Mass changes due to water can be thought of as a thin layer of water near Earth's surface. GRACE has also been able to detect mass redistribution due to displacement of lithosphere, caused by earthquakes, and mass redistributions due to glacial isostatic adjustment. While mantle convection and other Earth processes also change gravity fields, these processes occur over very long time periods, so can be thought of as static; GRACE measures changes in the gravity field that occur more rapidly, which are mostly caused by the movement of water throughout the water cycle. Land and ocean grids are processed differently and released separately, in order to best subtract the effects of clouds, weather, and high-frequency ocean topography changes (Wahr et al, 1998).

While the mechanism through which GRACE collects data is simple, using the data to quantify gravitational anomalies, and calibrating the data, is not as simple. Successive releases of GRACE data sets have seen significant improvement upon each other, and as of October 2017 JPL, CSR and GFZ (who coordinate to process the data) are at Release-06. RL-06 is a reprocessing of the entire dataset from April 2002 to June 2017, integrating updated tide force and weather models, and new data parameterization (Dobslaw et al, 2017).

E. Funding GRACE

GRACE is the first mission to be approved and launched through NASA's Earth System Science Pathfinder program, which funds small-to-medium sized missions " intended to address unique, specific, highly focused scientific issues" (National Aeronautics And Space Administration, 2002) which will provide data to further scientific objectives related to Earth Science. The GRACE mission is a partnership between NASA and DLR; in total the project cost $127,000,000. The NASA portion was approximately $97,000,000 and they were responsible for developing the instrumentation and integration of the systems (National Aeronautics And Space Administration, 2002). Since GRACE was decommissioned in October 2017, JPL has been readying the next mission, GRACE-Follow-on (abbreviated as GRACE-FO), to continue collecting data as soon as summer 2018. As of December 2017 the GRACE-FO satellites have arrived at California's Vandenberg Air Force Base. The launch date for GRACE-FO is set for May 19th, 2018, no sooner than 1:03 PM Pacific Time.

F. GRACE in scientific literature

Over 3700 papers on GRACE or GRACE data have been published and catalogued by JPL librarians since 2001, with an average of 208 publications per year. Figure 3 illustrates the number of GRACE publications by year for each year the mission has been in operation. The number of publications has declined slightly in 2017 and the beginning of 2018, likely because of the decommissioning of GRACE and the lack of data beginning in June 2017. GRACE-FO mission is expected to start collecting data again in late summer 2018. Taking into consideration the year 2012, which had the highest number of publications on record with 288, most papers were published on the satellites' design, instrumentation, or how calibrate and analyze the data (see Figure 4 below). The next most frequent topic of published papers in that year is on glacier mass, ice melt, and isostatic adjustment, followed by papers on groundwater storage, and then papers on earthquakes or crustal deformation. There were also significant numbers of

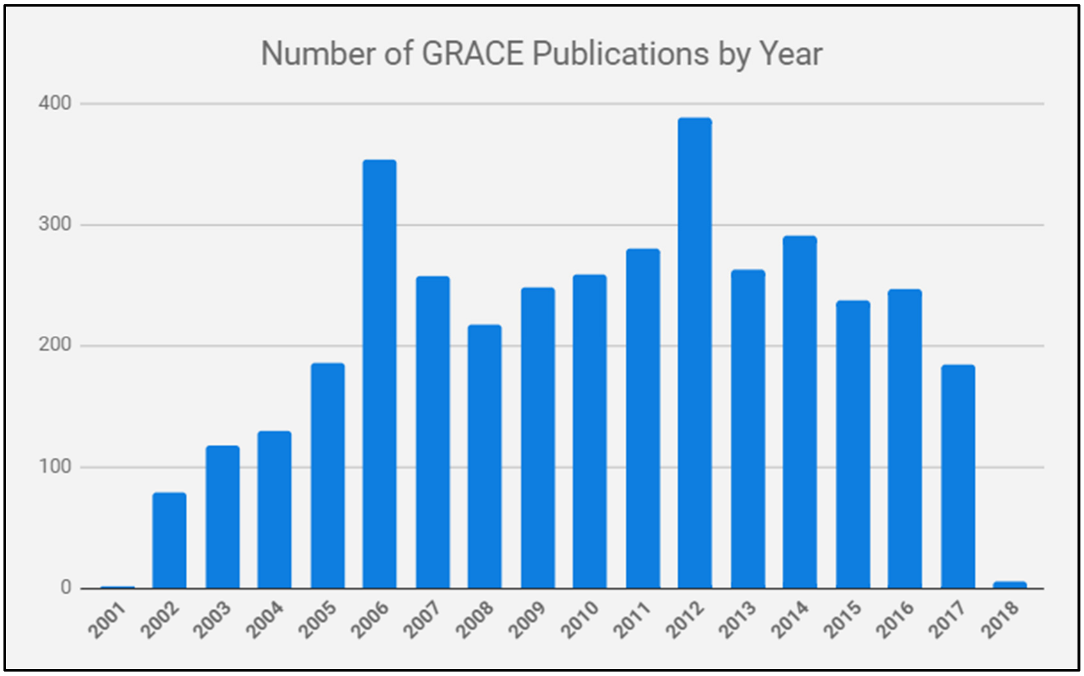

FIGURE 3 (Above) Number of publications using GRACE per year, as catalogued by JPL

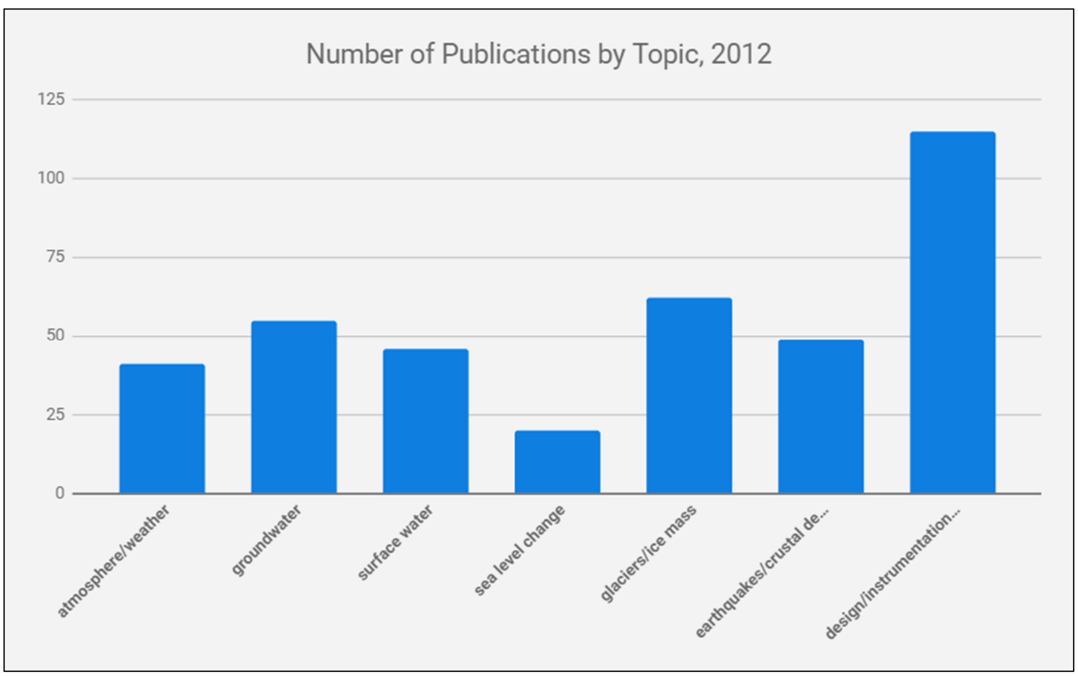

Figure 4 Number of publications on GRACE by topic in the year 2012, as catalogued by JPL. 2012 was the year with the most publications published, as catalogued by JPL, this chart was made by reviewing the titles (and abstracts, as necessary) of those 288 papers.

papers on ocean currents, atmosphere, weather, and surface water storage. Figure 4 shows the distribution of papers across the main toppics in the literature. As GRACE data has been used to see inter-annual variability and decadal trends, it is likely that when data collection continues, the number of publications on GRACE data on all topics will rise again.

Section 2: Hydrological Applications of GRACE data

A. Overview

In this section I have reviewed papers considering how GRACE data can be applied to research questions in groundwater hydrology. I have paid particular attention to the various methods that have been used to bring GRACE data to bear on questions within groundwater hydrology, and what additional tools and datasets are necessary. Findings in hydrology and in groundwater studies have direct, short and long term consequences for the human populations dependent on the water sources in question. Most of the papers on the subject could serve as important sources of data to inform policy changes and planning for future water resource management. In the second half of this literature review I have included several papers on the Colorado River Basin. The streamflow from the Colorado River Basin, an important water resource in the region, is one of the most over-allocated in the world (Castle et al, 2014).

As some of the following papers will show, it is important to be able to distinguish between changes in groundwater (water stored underground in soils, in the pores of rocks or in aquifers) and changes in land surface water. GRACE is a particularly efficient tool for quantifying changes in total water storage; it expands upon the previous abilities of remote sensing tools to observe changes in surface water. This makes GRACE data a particularly apt tool to monitor drought. Drought can be defined as terrestrial water storage changes in excess of the usual. Drought analysis solely using surface indicators such as precipitation, NDVI (Normalized Difference Vegetation Index) or CWSI (Crop Water Stress Index) are insufficient (Jiang et al, 2014). In addition, GRACE data has been shown to be more sensitive to drought than climate and land surface models such as NECEP and GLDAS (Jiang et al, 2014). However, traditional remote sensing tools which use EM waves to measure signals (such as changes in surface water) are still important for helping scientists distinguish between changes happening with surface water and groundwater sources. Seeing changes in surface water can also corroborate findings happening with groundwater. In order to explore these relationships, I will also examine MODIS products which show NDVI and LST (Land Surface Temperature) to consider the groundwater-related findings of the papers on the Colorado River Basin.

The paper published by Jiang et al. in 2014, “The Review of GRACE data applications in Terrestrial Hydrology Monitoring”, can serve to help review applications of GRACE data to groundwater hydrology: first of all, several reasons are presented as to why GRACE is a useful tool. Prior to tools such as GRACE, hydrology studies were dependent upon site measurements that were generally used to extrapolate trends for a larger region. This methodology introduces error, and is costly and time consuming as well (Jiang et al, 2014). Currently, GRACE-based total water storage changes are often used with GPS network observation data, and a combination of hydrological and land surface models. GRACE data has been used to both verify and improve GLDAS (Global Land Data Assimilation System) and climate models with respect to total water storage (Jiang et al, 2014).

This paper also pointed out several limitations of GRACE. For one, while GRACE data is very useful for resolving drought conditions on land, the water storages that GRACE measures through mass changes are less responsive to extreme flooding events, making it less apt for use in floods analysis (Jiang et al, 2014). Secondly, the spatial resolution of GRACE currently only allows for analysis of areas that are 200,000 km2 or larger (Castle et al, 2014). The spatial resolution for total water storage change is 400 km and the data accuracy is 1.5 cm (Jiang et al, 2014). A 2012 study (Wiese et al.) found that a slight change in architecture could result in a substantial increase in the spatial resolution of GRACE data products. The study recommended a pair of satellites inclined at 72 degrees, both in 13-day orbits for satellites intending to determine timevariable hydrology, ice mass variation and ocean bottom pressure signals (Wiese et al, 2012). The laser ranging interferometer, which is a new feature on GRACE-FO, is designed to provide information on the angle between the two spacecraft, as well as to back up the microwave interferometers to measure the distance between the two spacecraft (Sheard et al, 2012). This instrument will be tested as proof-of-concept on GRACE-FO and then if all goes as planned, will be used in the next generation of similar satellites, allowing for measurements of mass changes on Earth's surface at significantly higher resolutions (Sheard et al, 2012).

B. Novel Applications of GRACE in Groundwater Hydrology

The next few papers under consideration all highlight different methods that can be used with GRACE total water storage data in order to answer questions in hydrology. These are a few of many examples of the way GRACE data is being combined with other data ways that have advanced our understanding of the water cycle as it is playing out across Earth today. One study (Nanteza et al, 2012) uses GRACE combined with altimetry or elevation data to consider the link between surface water and groundwater variations in East Africa. The observation of the trend of declining water in several lakes and rivers was a signal which implied a declining water table in the region; using GRACE they were able to quantify the changes in groundwater. To get groundwater from GRACE data, one must first subtract out all other signals. This study used soil moisture, surface water, and snow water equivalents from GLDAS. In order to produce a contour map of water table elevation, Nanteza et al. used data from regularly monitored wells across the region and a DEM (Digital Elevation Model). Comparing changes in groundwater (isolated through subtracting out the above mentioned other factors) and lake surface height data from the altimetry record allowed for observation of causal relationships between surface water and groundwater variations (Nanteza et al, 2012).

Another paper by Joodaki et al. (2014) expands on the methods used to isolate groundwater storage from GRACE's signal to estimate the anthropological contribution (those changes arising directly from human activity) to groundwater depletion in the Middle East. This study used GRACE data, land surface models, and well observations. Again, it is noted that large scale values for total water storage change before products like GRACE were rarely reliable, as they had to extrapolate regional variability from several scattered points (usually from monitored wells). However, well-based trends can generally be used to find an upper bound on groundwater loss as they generally show the greatest amount of lowering in the water table (Joodaki et al, 2014). To find anthropogenic contributions to groundwater change, first groundwater changes must be isolated from GRACE total water storage data. Contributions from soil moisture, snow, canopy storage, river storage, The Caspian Sea and two large lakes were subtracted out, using a gridded land surface model, CLM4.5 (Community Land Model 4.5) (Joodaki et al, 2014). Then, anthropogenic contributions to groundwater storage change were estimated by removing climate-driven contributors from the groundwater change (Joodaki et al, 2014). Lake storage contributions were removed using altimetry data.

Joodaki et al. point out several limitations to GRACE data as well. First of all, using GRACE cannot determine where the mass change within a given region is coming from, at least not very precisely (Joodaki et al, 2014). Further, GRACE has no vertical resolution; using GRACE data alone cannot determine if the mass variability comes from snow and surface water, or soil moisture. Lastly, GRACE can only quantify changes in water storage, not total water storage in itself (Joodaki et al, 2014). Still, using GRACE data along with land surface models and well data allowed for find anthropological trends in groundwater loss, which can serve to show how and at what rate human water consumption is affecting important aquifers. This is of particular relevance in the Middle East, where water is scarce and often a source of multinational conflict, though increasingly this is a concern in all dry regions.

GRACE has also proven useful when combined with InSAR (Interferometric Synthetic Aperture) data. InSAR generates data on surface elevation and surface deformation and can be used to track land subsidence at a millimeter scale. Land subsidence is the reduction of land surface elevation due to removal of subsurface support, often groundwater. As groundwater is depleted in any given region, and removed from rock pores and crevices, the land will eventually subside in response. Land subsistence is a costly threat to property and infrastructure.

In the last decade, InSAR has been valuable in quantifying the response of aquifer systems to groundwater loss (Katzenstein et al, 2012). In a 2018 paper, Castellazzi et al. shows how InSAR can be used to constrain and spatially focus GRACE groundwater mass loss data, allowing GRACE data to be useful for areas smaller than 200,000 km2; as most aquifers are smaller than 200,000 km2, these techniques can make GRACE data more applicable for aquifer water management (Castellazzi et al, 2018). In their method, high resolution InSAR data was fused with GRACE mass data. InSAR data alone is useful only for the most compressible aquifer systems, and not all depleting aquifers subside enough to be detected by InSAR (at rates of 3 to 10 mm/yr.) (Castellazzi et al, 2018). From this process of combining the data and using InSAR to help interpret GRACE data at a higher resolution, the team was able to focus GRACE groundwater mass fluctuations to a scale more useful for water management using a case study in Mexico (Castellazzi et al, 2018). Castellazzi et al. additionally point out the need for guidelines on which GRACE data solutions to use for any given area or application, which can make the data more reliable and even in some cases (such as their methods) improve the resolution of the data.

Section 3: GRACE data and the Colorado River Basin

A. Water situation in the Colorado River Basin

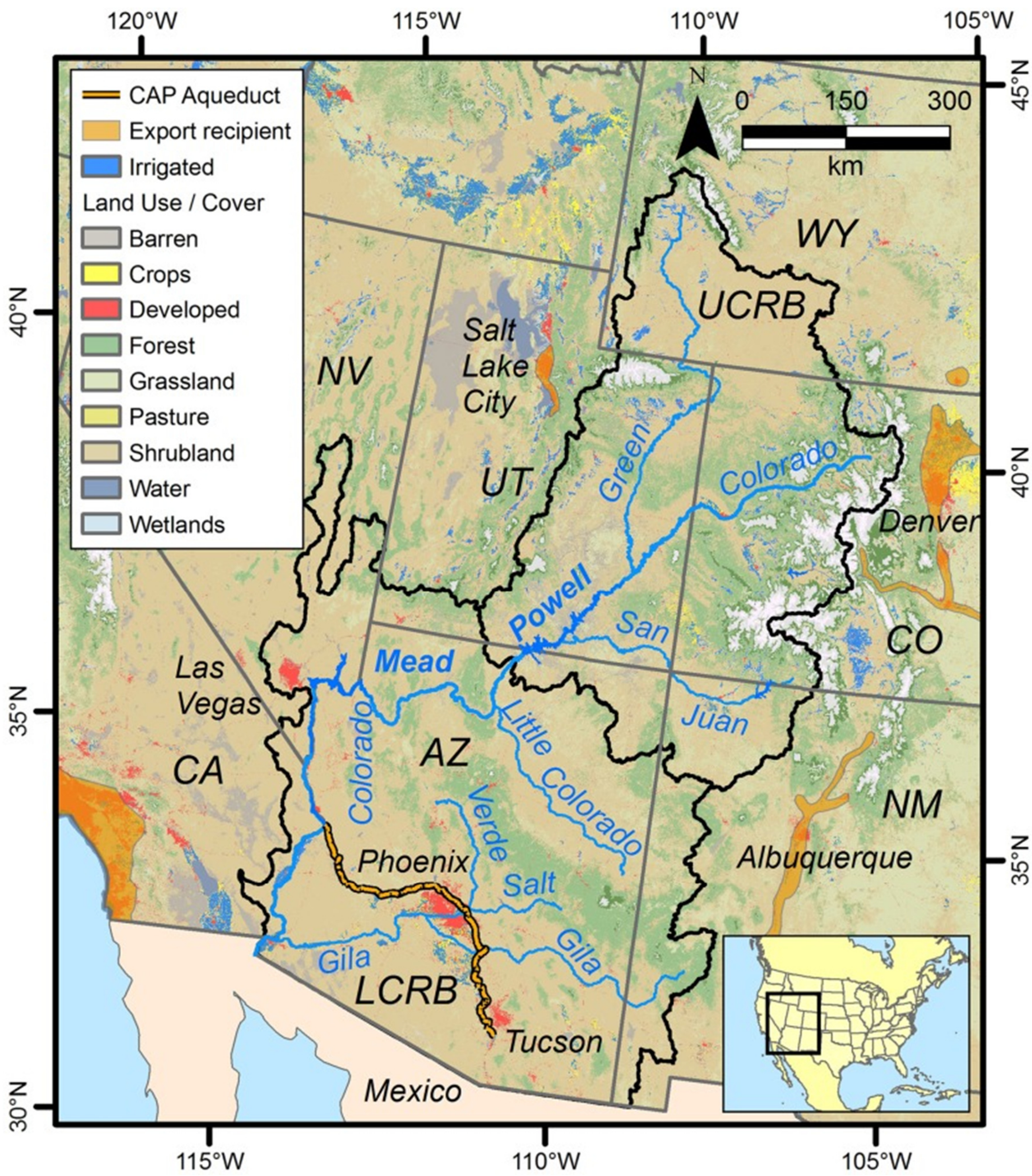

Figure 5 Map of the Colorado River Basin, showing the Upper and Lower basins, based on National Land Cover Data (2006).The two main basins are Lake Powell and Lake Mead. Reprinted from B. Scanlon et al, 2015

In this next section, the papers are focused on using GRACE data to explore groundwater loss in the Colorado River Basin. The Colorado River Basin (see Figure 5, above) is a very important source of water and storage basin, providing water to over 40 million people across 7 states in the U.S. Southwest (Scanlon et al, 2015). Further, during the period from 2004 to 2013, groundwater accounted for over 70% of freshwater loss, indicating that depletion of groundwater storage is an issue that needs to be addressed in order to plan for meeting future water needs in the U.S. Southwest (Castle et al, 2014).

Castle et al. (2014) quantify groundwater depletion in the Colorado River Basin and call attention to how groundwater compromises a greater fraction of river basin use than previously considered. Scanlon et al. (2015) use the Colorado River Basin as a case study to reconstruct long-term total water storage changes using GRACE and datasets that extend past 2002.

The methods both of the above papers use to isolate changes in groundwater storage from GRACE data is very similar. In Castle et al., from total water storage, soil moisture, snow water equivalent, and surface water are subtracted. Scanlon et al. subtract out reservoir storage, soil moisture storage, precipitation, runoff, and snow water storage from total water storage, as shown in Figure 6. Figure 6 shows a time series of each contributing component to total water storage. General trends on total water storage can be derived from this figurethis figure helps illustrate the process by which total water storage, or any component of it, can be derived in km^3. There are sufficient data sets on each of these components in the terrestrial water balance that it is possible to isolate any component, such as groundwater, from the GRACE data. This methodology of using mass balance to isolate certain contributing factors has been demonstrated to quantify changes in groundwater storage with sufficient accuracy, in Rodell et al, 2009

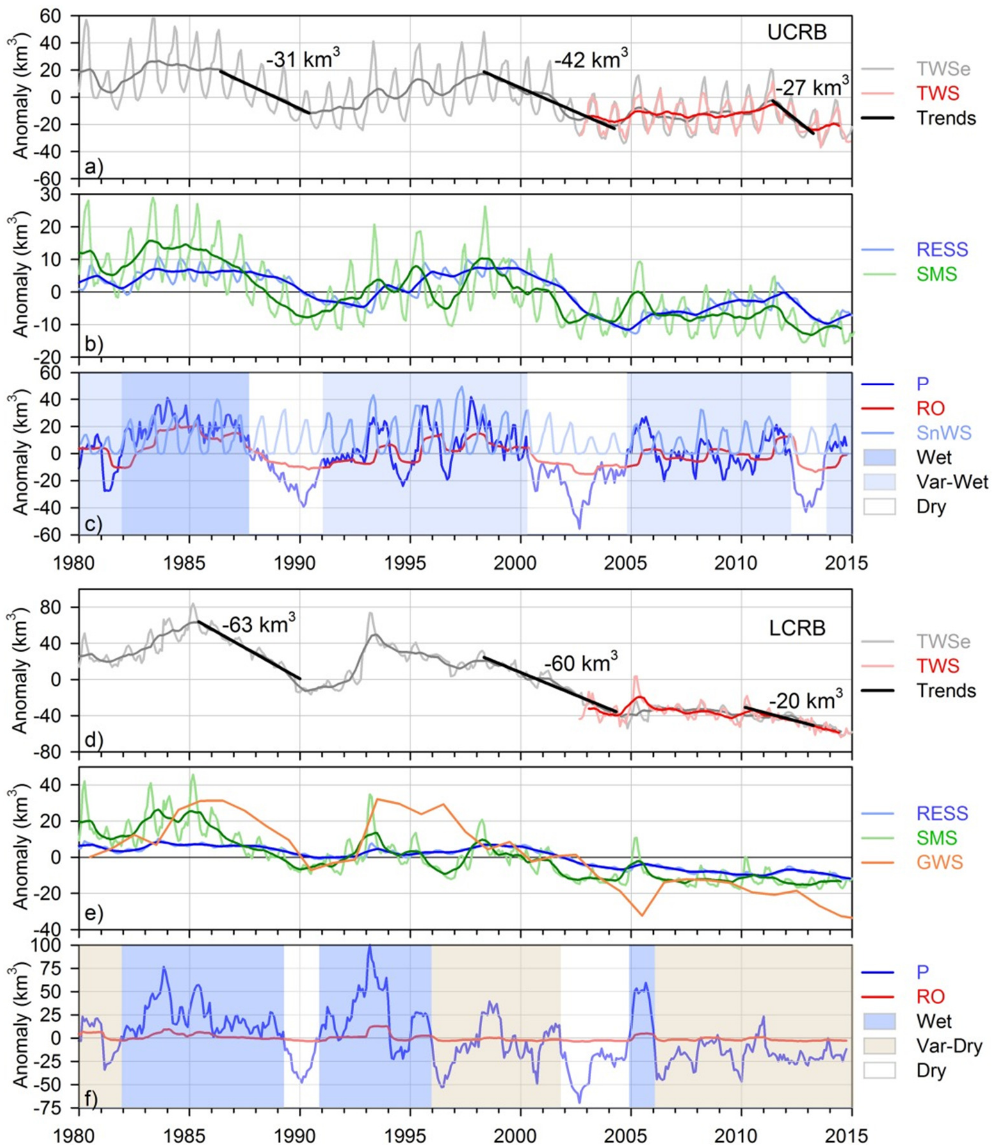

Figure 6 These time series show the components that make up total water storage. Represented here is estimated total water storage (TWSe), GRACE total water storage (TWS), reservoir storage (RESS), soil moisture storage, (SMS from GLDAS), precipitation (P), runoff (RO), snow water storage (SnWS), and groundwater storage (GWS) in the (a–c) Upper (UCRB) and (d–f) Lower (LCRB) Colorado River Basin. Values represent anomalies relative to the 1980–2014 water year means. Reprinted from B. Scanlon et al, 2015.

and Famiglietti et al, 2011. Castle et al. used this method to isolate the changes in groundwater mass in the Colorado River Basin from December 2004 to November 2013. They further processed the GRACE data by filtering it to reduce noise and then later correctively scaling data to restore lost signals over specific regions (Castle et al, 2014). They compared their final estimates of groundwater mass change with changes observed in 74 monitoring wells located throughout the Colorado River Basin.

Castle et al. (2014) found that groundwater compromised a larger percentage of basin water use than previously estimated, and that groundwater withdrawals were not balanced by recharge (Castle et al, 2014). They further found evidence to conclude that the basin's water supply was over-allocated by at least 30% during the nine years covered by the study, and concluded that the Colorado River Basin reserve is already largely unrecoverable by natural means (Castle et al, 2014). This study highlights the importance of enacting a groundwater management plan for the Colorado River Basin now, given that it may not be able to meet the allocation needs of the populations living in the seven states the basin serves in the long term. As this study was done over a period of sustained drought, it also informed my decision of where to look for drought signals that can be picked up by traditional remote sensing tools, such as NDVI and LST, in order to examine the relationship between drought signals in GRACE data products and in traditional remote sensing data products.

Using similar methods to the Castle et al. paper to isolate groundwater mass changes from GRACE data, Scanlon et al (2015) did a study to show how short-term GRACE total water storage data can be extended to help reconstruct long-term total water storage changes. Scanlon et al. compare two data processing approaches for GRACE, one using a new gridded GRACE product with total water storage at a 1 x 1 degree resolution, and secondly the Mascons approach, which was then still being developed by several different groups including JPL and The Goddard Space Flight Center. Scanlon et al. conclude that the Mascons approach has a higher signal to noise ratio and that the solutions have fewer errors; in addition to using the Mascons approach they cite the need to evaluate GRACE data within longer-term hydroclimatic records (Scanlon et al, 2015). The paper focuses mostly on ways of processing GRACE data and situating it within longer historical records, and notes that as GRACE is a young mission, data processing is continuously being improved.

B. Comparing GRACE to Traditional Remote Sensing Data in Colorado River Basin groundwater hydrology

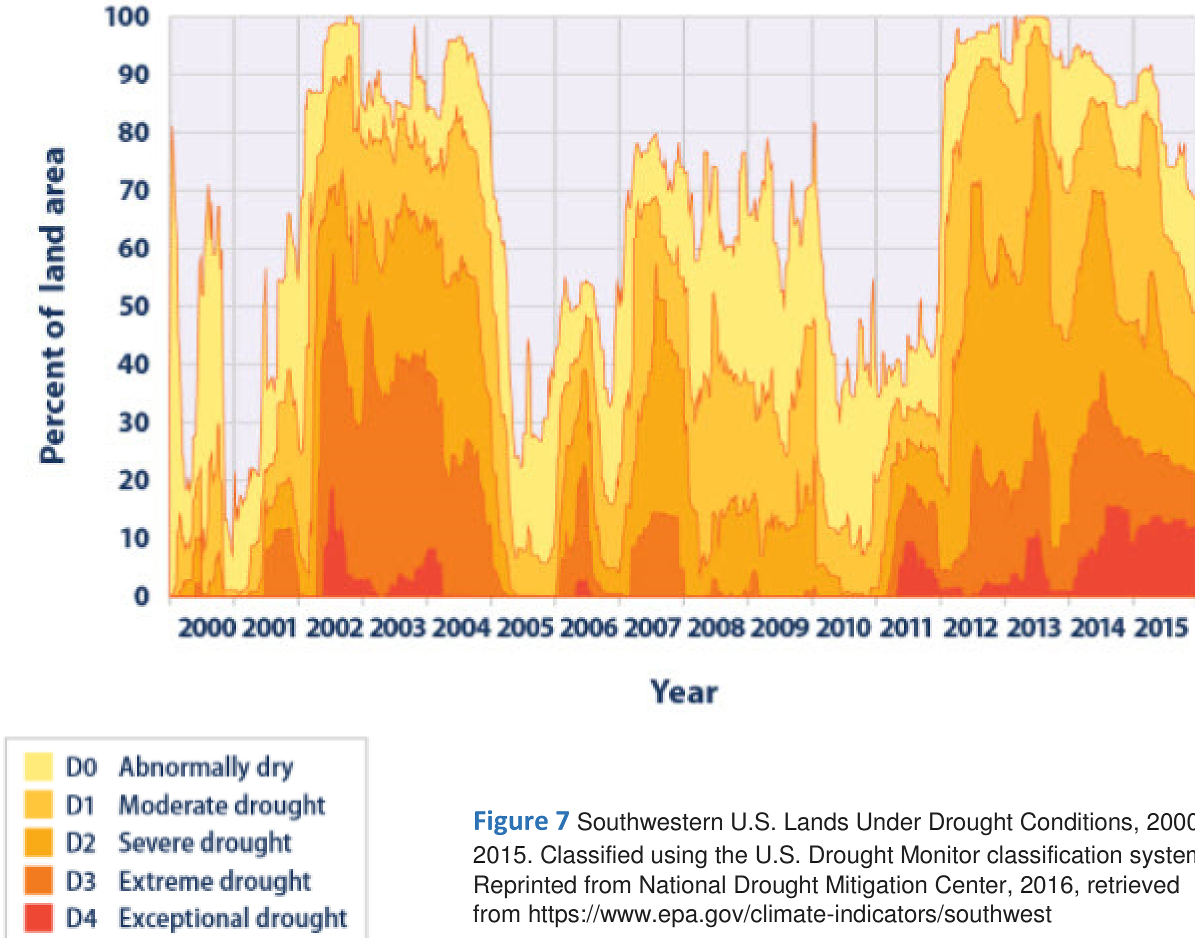

Figure 7 Southwestern U.S. Lands Under Drought Conditions, 2000–2015. Classified using the U.S. Drought Monitor classification system. Reprinted from National Drought Mitigation Center, 2016, retrieved from https://www.epa.gov/climate-indicators/southwest

In order to compare GRACE signals to signals in traditional remote sensing, I looked at GRACE total water storage data and MODIS NVDI and LST data for coordinates in the Colorado River Basin. The Colorado River Basin includes the states of Colorado, Utah, Wyoming, Nevada, New Mexico, Arizona and California, and is part of the hottest and driest region in the U.S. The land is classified as arid and semiarid. Precipitation on the Colorado Plateau is bi-seasonal and occurs mostly during winter and summer months. The bi-seasonal precipitation trend is reflected in GRACE total water storage (shown in Figure 10). The largest source of moisture comes from frontal systems in the winter and spring, and is mostly stored as snow packs which melt and run off in the late spring and summer (Hereford et al, 2002). I chose to examine indicators of drought, because of the relevance of this issue to the region, as well as because drought is something that traditional remote sensing tools such as MODIS can be used to detect through data products such as NDVI and LST. There is also a connection between groundwater loss and drought, and we would expect to see some sort of change in total water storage during times of drought. I chose coordinates in Northwestern Arizona for the data collection. The primary concerns were to locate an area in the Colorado River Basin that was not developed or used for agriculture, during a time where the region experienced drought. The U.S. Southwest experienced extensive drought from 2002-2005 and from 2012-2015, as shown in Figure 7 above. Percent of land area in drought in Figure 7 was

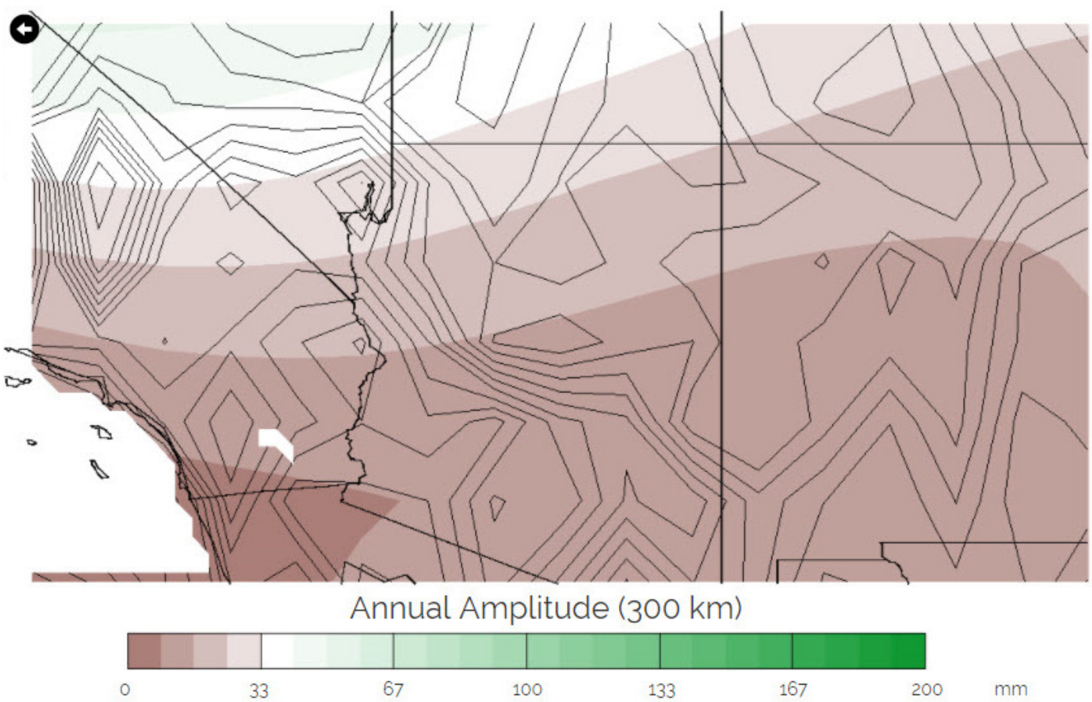

Figure 8 GRACE total water storage, expressed as a layer of water in mm. Resolution is 300 km. Data obtained from the University of Colorado GRACE Data Analysis Website. Retrieved from http://geoid.colorado.edu/grace/

classified using the U.S. Drought Monitor classification system, which integrates many different drought indicators assessed via remote sensing and field measurements.

GRACE total water storage data was obtained from University of Colorado-Boulder's GRACE data portal, which allows site users to do basic data analysis on publicly available level 2 GRACE data. The portal can compile maps and time series in real time. Figure 8 shows the Four Corners region of the Colorado River Basin mapped using GRACE total water storage data, expressed as a layer of water on the surface and measured in millimeters for annual amplitude. A time series of this same data for the years 2002 to 2017 is presented in Figure 10. The data used in the following figures is CSR RL05 DS (Release 05). The coordinates are approximately the same as those used for the MODIS product data, but the portal does not allow for entering latitude and longitude coordinates and instead users must click on a map. However, since there is just one dataset for a large region (due to GRACE data resolution) this is less important. Figure 9 shows the extent of the region my coordinates are located in and gives an idea of the current spatial resolution of GRACE data. Coordinates selected anywhere in the red-colored region would result in the same data for the years 2002-2017, so this is spatially averaged data. In contrast, data products taken from AppEARS (NDVI and LST) have a different resolution and are specific to the coordinates chosen.

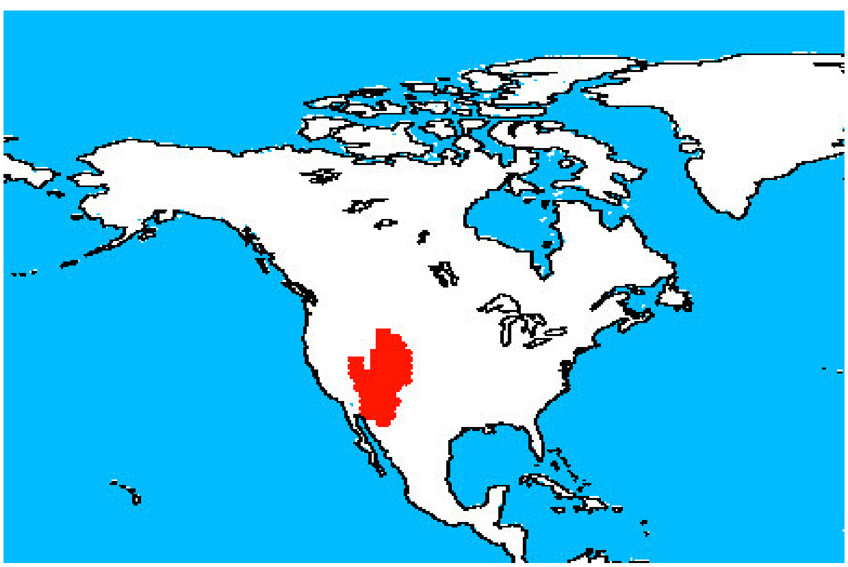

Figure 9 Map of the region for GRACE time series data from the CU Boulder portal. Any point sampled within this area will yield the same time series, because GRACE currently has a resolution on the order of 300 km. Retrieved from http://geoid.colorado.edu/grace/

NDVI and LST were obtained from NASA's Earthdata AppEEARS tool. These data products are produced with measurements from the Terra satellite in MODIS images. I considered the same coordinates in northwestern Arizona during the same time period, from 2002-2017, which includes the range of two significant droughts in the region, from 2002 to 2005 and from 2012 to 2015. Figure 10 shows GRACE total water storage data. Many years have two peaks, which is related to the region's bi-seasonal precipitation. Figure 11 shows NDVI for the same time period. NDVI measures changes in vegetation which reflect patterns in precipitation, such as those brought about by the North American Monsoon. Figure 12 shows LST data during the same time period.

In all of these figures, the two drought periods have been highlighted. There is clearly a downwards trend for total water storage in the GRACE data for the region. The drought signal (lower NDVI, higher LST) is harder to see, but the data is for one particular point (so comes from one pixel), and resolves a much smaller area than GRACE data. The NDVI is lower from 2002-2005, and less definite during the second drought period. LST does also seem to have higher peaks during both drought periods.

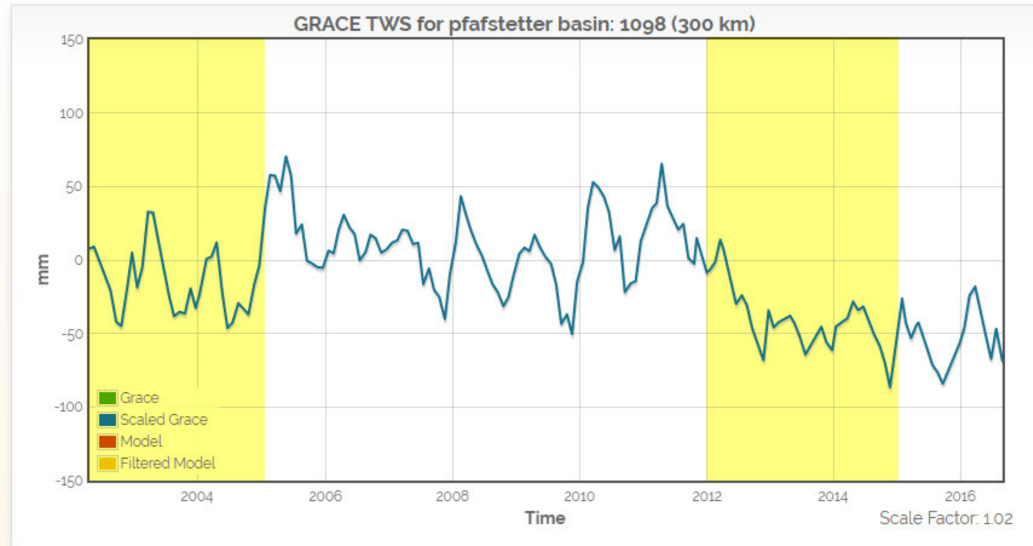

FIGURE 10 GRACE Total Water Storage from 2002 -2017, measured in mm and expressed as anomalies to the mean. Data retrieved from http://geoid.colorado.edu/grace/

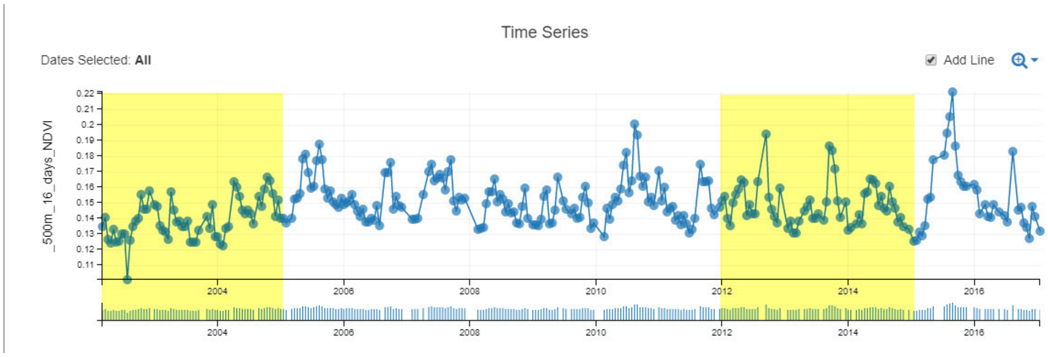

FIGURE 11 NDVI from 01 March 2002 to 01 March 2017 for 36.657860, -110.132556 Navajo County, Arizona. Data retrieved from https://lpdaacsvc.cr.usgs.gov/appeears/

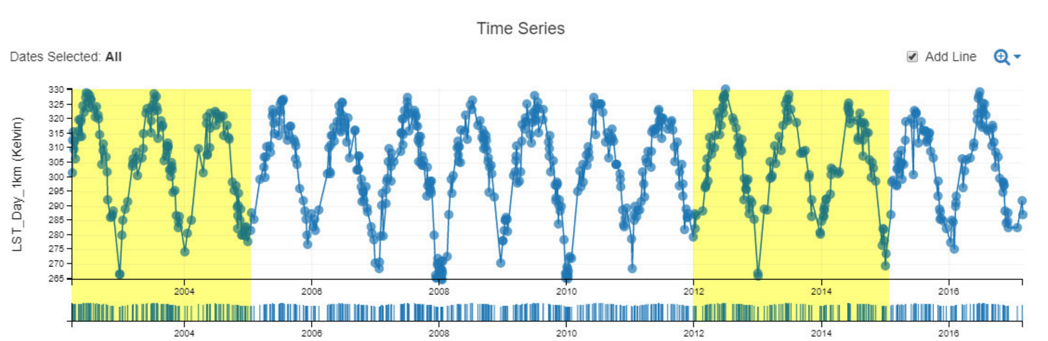

FIGURE 12 LST from 01 March 2002 to 01 March 2017 for 36.657860, -110.132556 Navajo County, Arizona. Data retrieved from https://lpdaacsvc.cr.usgs.gov/appeears/

Conclusion

Data from the GRACE missions are expanding our ability to see and analyze changes in mass distribution on Earth. GRACE data presents particularly many possibilities in the realm of hydrological science and groundwater hydrology; the findings from GRACE data will continue to add to our understanding of the water cycle on Earth and how it is being affected by climate change. GRACE data is useful when combined with other remote sensing and site measurement tools. This data has been used to make advances in our understanding of sea level rise, earthquake mechanisms, and groundwater hydrology. These advances are likely to continue as collection of GRACE data resumes with GRACE-FO in the summer of 2018.

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