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Long-term groundwater storage change in Victoria, Australia from satellite gravity and *in situ* observations

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Abstract

Analysis based on satellite gravity measurements from the Gravity Recovery and Climate Experiment (GRACE) and land surface models indicates that groundwater storage in Victoria, Australia had been declining steadily, until a trend reversal around early 2010, attributed to two wetter seasons in 2010 and 2011. *In situ* groundwater level measurements (from a network of 1395 bores in Victoria) also indicate a steady groundwater depletion since the early 1990's, and show remarkable agreement with GRACE estimates for the 10-year period (2003-2012) in common with the GRACE mission. Groundwater depletion rates for 2005 to 2009 are relatively large as indicated by both GRACE estimates (8.0 ± 1.7 km^3/yr) and *in situ* measurements (8.3 ± 3.4 km^3/yr). Over the same period (2005-2009), GRACE measurements capture significant groundwater depletion in a wider region covering much of the southern Murray-Darling Basin, and the total groundwater depletion rate in this region is about 17.2 ± 4.7 km^3/yr. Annual groundwater storage changes are strongly correlated with precipitation anomalies, but only about one-fifth of anomalous precipitation contributes to groundwater recharge. The strong correlation suggests that this groundwater depletion is primarily related to drought with related groundwater pumping for agricultural and domestic consumption. The remarkable agreement between GRACE estimates and *in situ* measurements demonstrates the great potential of satellite gravity observations in combination with land surface model estimates to quantify changes in regional groundwater resources, especially when *in situ* measurements are limited or unavailable. This study shows the importance of reducing leakage bias in GRACE observations and the effectiveness of the forward modeling iterative method used.

Keywords: Satellite Gravity, GRACE, Groundwater Depletion, Victoria, Murray-Darling Basin, Bore

1. Introduction

Groundwater is a vital resource for agricultural, industrial, and domestic use, both in populous countries such as China and India, and in arid regions lacking adequate alternative water resources. Monitoring groundwater storage changes is a key aspect of understanding the global hydrological cycle and changes related to climate and anthropogenic forcing, and is important in economic development and resource management. Despite this, quantifying groundwater storage change has been challenging. Major difficulties include lack of adequate *in situ* groundwater observations, and complexity of both aquifer geology and groundwater recharge processes. Accurate quantification of groundwater storage change normally relies on both a continuous record of *in situ* groundwater level measurements from a dense well bore network and a good understanding of subsurface soil and rock properties. Unfortunately, *in situ* measurements from large well networks are only available in certain regions, mostly in well-developed countries.

The Murray-Darling basin (MDB) is a large drainage basin (area ~ 1.06 million km^2) in the interior of southeastern Australia (see Fig. 1), covering about one-seventh of the continent. It is Australia's most significant agricultural area, with almost three-quarters of the country's irrigated land, and it generates about 30 percent of national income derived from agriculture (Van Dijk et al., 2007). Australia is the second driest continent after Antarctica, with a mean annual precipitation of ~ 450 mm (Lavery et al., 1997). As the largest drainage system (in terms of water flow) in Australia, the mean discharge rate of the MDB is only ~ 24 km^3/yr, compared to ~ 6900 km^3/yr for the Amazon basin, the world's largest (http://en.wikipedia.org/wiki/Murray-Darling_basin). Many parts of Australia have suffered from an extended drought during the last decade (Leblanc et al., 2009), except for tropical northern and northeastern regions.

Chronic drought conditions and consequent increased groundwater extraction for agricultural, industrial, and domestic consumption contribute to depletion of groundwater storage in regions such as the MDB (Tularam and Krishna, 2009). Assessment of long-term groundwater storage change is essential for effective water resource management and sustainable water use. Available water level measurements from bores have shown an alarming decline in groundwater storage in Victoria, Australia, which covers part of the southern MDB and adjacent coastal regions (Monthly Water Report Victoria State Office of Water http://www.water.vic.gov.au/monitoring/monthly/archive).

Gravity measurements from the Gravity Recovery and Climate Experiment (GRACE) satellites provide an alternative and complementary method for estimating groundwater storage changes (Tapley et al., 2004). Since its launch in March 2002, GRACE has measured changes in Earth's gravity on a monthly basis for over 12 years, with unprecedented accuracy. GRACE time-variable gravity data can be used to quantify total water storage (TWS) change, providing that other geophysical causes of gravity change can be removed from the signal (e.g., Wahr et al., 2004). The record of GRACE data now exceeds 12 years and enables the study of TWS change at intraseasonal, seasonal, and longer- time scales. Regional groundwater storage change can be estimated by subtracting surface water storage. For simplicity, surface water storage is defined here to include snow, surface reservoirs, and soil moisture (the root layer, although soil is typically considered as subsurface). Surface water change estimates are derived from independent sources (hydrological models).

GRACE has proven effective for estimating long-term groundwater storage changes. For example, in two studies of the Indian subcontinent (Rodell et al., 2009; Tiwari et al., 2009), GRACE TWS changes show a significant decline in the Ganges-Brahmaputra river basins (Northwest and North India) from August 2002 to October 2008 whereas simulated soil water storage changes from the Global Land Data Assimilation System (GLDAS) Land Surface Models (Rodell et al., 2004), did not show a similar trend. The absence of a precipitation deficit in this period suggested that losses were due to anthropogenic effects, mainly water extraction for agricultural irrigation and domestic consumption. Depletion was estimated at 17.7 ± 4.5 km^3/yr (Rodell et al., 2009). In a study of California's Central Valley, Famiglietti et al. (2011) estimated a groundwater loss rate of 4.8 ± 0.4 km^3/yr) from October 2003 to March 2010, attributed mainly to pumping for irrigation. GRACE measurements have also revealed significant groundwater depletion in many other regions over the world, including the Middle East (e.g., Voss et al., 2013; Joodaki et al., 2014), North China Plain (e.g., Feng et al., 2013), and High Plains Aquifer in the U.S. (e.g., Scanlon et al., 2012).

Although Australia is generally arid with relatively small hydrologic variations (Awange et al., 2011), GRACE has have proven useful for measuring basin or regional scale TWS and groundwater storage changes in Australia (e.g., Leblanc et al., 2009; Rieser et al., 2010; Awange et al., 2009, 2011; Munier et al., 2012; Forootan et al., 2012; Tregoning et al., 2012). The MDB has experienced one of the most severe droughts globally, termed the Millennium Drought (1997 – 2010) (Leblanc et al., 2012; van Dijk et al., 2013). Both *in situ* bore measurements and GRACE estimates indicate persistent reduction in groundwater storage in the southern MDB region, and the total groundwater loss (based on *in situ* bore groundwater level data) over the entire MDB region between 2001 and 2007 was estimated to be 104 ± 40 km^3 (or 17 ± 7 km^3/yr) (Leblanc et al., 2009). However, accurate quantification of groundwater storage change from *in situ* bore measurements and GRACE are both challenging. Bore measurements are subject to biases due to inadequate spatial coverage and uncertainty of specific yield (needed to convert water level change into storage change). GRACE estimates are affected by biases in GRACE mass estimates and hydrologic model predictions of surface storage. The main motivation in the present study is to analyze *in situ* bore measurements over a time span sufficient to observe decadal scale climate change in the region which, and compare with GRACE estimates derived from improved data processing methods.

This study quantifies long-term groundwater storage changes in the southern MDB vicinity, in the State of Victoria (except its most eastern part), comprising part of the southern MDB and adjacent coastal regions. We use the abbreviation VCT to describe the entire region, covered by the blue boxes in Fig. 2. This area is chosen because of good spatial coverage of *in situ* bore measurements. The study builds on previous analyses of water storage in the MDB using GRACE by extending the study period from ~ 7 to a full 10 years (2003-2012), and by extensive use of *in situ* groundwater level observations from a network of 1395 bores. The extended study period enables us to investigate large interannual variability since 2010. GRACE-*in situ* comparisons serve not only to validate GRACE results, but also to understand limitations of both data types.

A known limitation of GRACE data is spatial leakage related to limited spatial resolution associated with a finite range of spherical harmonics (SH) in the gravity field representation. Leakage introduces biases in GRACE TWS estimates, but can be overcome by a forward modeling method, which has proven effective in previous studies (e.g., Chen et al., 2013, 2014, 2015). Forward modeling as used in this study not only improves the accuracy of GRACE estimates of groundwater storage change, but also better defines their spatial distribution. Other approaches to the spatial leakage problem have been employed, including basin kernel and scaling factor methods (Rodell et al., 2009; Tiwari et al., 2009; Famiglietti et al., 2011) While helpful in reducing biases, these approaches do not improve understanding of spatial distribution. Additionally, leakage biases cannot be satisfactorily removed by these methods without very good *a priori* knowledge of mass changes in the both the studied region and in surrounding areas.

2. Data Processing

2.1 GRACE Data

GRACE data used in this analysis include 115 monthly Release 5 (RL05) gravity fields from January 2003 to December 2012, provided by the Center for Space Research (CSR) at the University of Texas of Austin. Each monthly field consists of fully normalized SH coefficients to degree and order 60. Very low degree SH coefficients, especially degree-2 zonal harmonic coefficients (C_{20}) are known to have relatively large errors, and are replaced by satellite laser ranging (SLR) estimates provided by CSR (Cheng and Ries, 2012). GRACE solutions lack degree-1 coefficients (C_{10}, C_{11}, S_{11}), corresponding to geocenter variations. Seasonal geocenter variations are adopted from estimates of Swenson et al. (2008), but reliable long-term geocenter variations are not available at present. Atmospheric, oceanic, and tidal effects have been removed during GRACE processing models for climate and ocean circulation effects (Bettadpur, 2012).

GRACE SH coefficients are contaminated by noise, especially at high degrees and orders, which cause longitudinal stripes, and other errors. A decorrelation filter (Swenson and

Wahr, 2006) was used to suppress stripe noise, and smoothing with both 300 km and 500 km Gaussian filters (Jekeli, 1981) are applied to suppress noise at higher degrees and orders. Earth deformation due to post-glacial rebound (PGR) was removed using a PGR model (A et al., 2013), although effects within Australia are small. Globally gridded (1° x 1°) fields of surface mass variations (in units of equivalent water height) were calculated from each of the GRACE monthly solutions, following the equations of Wahr et al. (1998).

2.2 Soil, Snow and Surface Reservoir Water Storage Estimates

GRACE gravity variations over Australia should mainly reflect contributions from TWS change, the sum of surface water storage (snow, rivers and lakes, soil moisture) and groundwater storage. However, residual atmospheric mass or tidal effects may remain if models of these contributions used in GRACE processing are imperfect. Surface barometric pressure estimates used to remove atmospheric mass are taken from an atmospheric model (European Centre for Medium-Range Weather Forecasts, ECMWF) are thought to be reasonably accurate over Australia, due to the good quantity of meteorological observations in the region. Tidal signals are periodic, at short periods, but sampling properties of the GRACE mission cause tide model errors to alias into low frequencies in GRACE time series (Ray and Luthcke, 2006).

Model estimates of surface water storage change are taken from the WaterGAP Global Hydrology Model (WGHM Version 2.2) (Döll et al., 2003; Güntner et al., 2007). An alternative surface water estimate using GLDAS is also examined for comparison. WGHM estimates storage variations in canopy, snow, surface water bodies (natural and man-made lakes and reservoirs, wetlands and rivers), soil and groundwater. Precipitation over each WGHM grid cell is transported through various storage compartments, allowing for evapotranspiration. Groundwater storage is effected by a diffuse groundwater recharge model dependent on total runoff, surface conditions (relief, soil texture, glaciers, permafrost) and hydrogeology. The precipitation data set used as model input to WGHM was the Monitoring Product Version 4.0 of the Global Precipitation Climatology Center (GPCC) (Schneider et al. 2011). Other climate forcing data such as air temperature, cloudiness, and number of rainy days per month were taken from ECMWF operational forecast or analysis data.

WGHM data for January 2002 to December 2012 are available at monthly intervals on 0.5°x0.5° grids (with oceans, Antarctica and Greenland excluded). The data were first re-sampled to 1°x1° grids to match GRACE fields used in this study, and then surface storage change was computed for each grid cell as the sum of snow, canopy, surface water body and soil moisture contributions. Snow is expected to be a minor, probably negligible, component. To match the spatial resolution of GRACE data, WGHM 1°x1° grid values were represented in a SH expansion to degree and order 60, and three versions were produced, one without smoothing, and the other two with 300 km and 500 km Gaussian smoothing. These three SH versions of WGHM were then sampled on a 1°x1° grid, and subtracted from GRACE gridded values, to produce a grid of groundwater storage change estimates.

2.3 Leakage Correction of GRACE Estimates

GRACE estimates of water storage change are biased (attenuated in amplitude) due to spatial leakage associated with the finite SH range. Leakage of signals to adjacent regions is a particular problem in coastal basins where signals are spread to the oceans. As noted above, various methods (scale factor and basin kernel) have been employed to mitigate this bias, but are dependent on prior knowledge of water storage magnitudes both within the basin and surrounding regions. This knowledge can be very limited, especially at multi-year time scales. In this study we corrected leakage and bias problems using a forward modeling method (Chen et al. 2014), which does not require such knowledge. The method estimates water storage changes by constraining them to be located mainly on land. Forward modeling is used to estimate water storage changes for each GRACE monthly solution. The forward modeling method is iterative and proceeds as follows:

1) At each 1°x1° grid point, a trial mass field is assigned equal to the uncorrected GRACE value resulting from GRACE data processing as described in Section 2.2.

2) Then the 1º x 1º gridded mass field is once more converted to a SH expansion truncated at degree and order 60. A 500 km Gaussian smoother is applied and the result is evaluated at all 1º x 1º grid points.

3) At each grid point, the difference between the current value of the mass field from Step 2 is added to the field of Step 1 after scaling by a factor of 1.2 (to speed up

convergence). Then the calculation in Step 2 and adjustment in Step 3 is repeated using the updated mass field. Successive iterations are found to converge as differences between the forward modeled mass field and GRACE observations diminish with each iteration. There are no constraints, and adjustments are made at all grid points over the globe, hence the designation as ‘fully unconstrained global forward modeling’.

4) Iteration ceases when residual difference between modeled and GRACE apparent fields falls below a specified value, or after a certain number of iterations. In the present study, we stop after 60, although convergence is largely complete after 50 in most cases.

2.4 *In Situ* Groundwater Level Observations

In situ groundwater level time series from 1395 well bore stations in Victoria State are available from the Victoria Department of Environment and Primary Industries (DEPI)’s network (http://data.water.vic.gov.au/monitoring.htm). These stations (marked by magenta dots in Fig. 2) were selected to provide nearly continuous measurements from 1993 to 2012 with only a few gaps and outliers. Gaps were corrected using linear interpolation, and outliers were identified when values exceeded 3 standard deviations of a residual time series after a degree 5 polynomial and annual and semiannual variations had been removed via least squares. The original groundwater level time series have varied temporal sampling intervals (days to months) and were interpolated to monthly values.

Regional groundwater storage change (ΔGW in equivalent water height) can be estimated from groundwater level observations (Leblanc et al., 2009) by the equation,

$$\Delta GW = S_y \cdot \Delta H \tag{1}$$

in which ΔH is observed groundwater level change, and S_y is specific yield (drainable porosity), the volumetric water fraction a bulk aquifer volume will yield when all water is allowed to drain under the force of gravity. Spatially averaged specific yields in the MDB region are estimated to range from 0.06 to 0.14 with a mean value of ~ 0.1 (Leblanc et al., 2009). We used this mean value in computations.

The spatial distribution of the 1395 stations is very uneven (Fig. 2), with the majority in the north central area. To obtain a representative average, we divided the SMDB region into 29 1°x1° grid cells, and computed an average time series for each cell from all bore level variations within that cell. A mean groundwater level time series for the entire region was then estimated from the average of the 29 grid cells. Most of the 29 individual series show a negative trend, although some variability among the time series is evident (Fig. 3). Groundwater storage variations in the VCT region (in cm of equivalent water height) were computed using eq. (1) and the mean series in Fig. 3 with a specific yield of 0.1, and the result is shown in Figure 4 (blue curve).

3. Results

3.1 Groundwater Storage Change from GRACE

Figure 4 shows GRACE groundwater storage estimates for VCT (integrated over exactly the same region as the *in situ* bore data) after forward modeling. Bore estimates from Figure 3 are shown with a small vertical offset. Low frequency variations in the two time series agree remarkably well over the entire period 2003-2012, both showing declines from 2003 to 2009 with some acceleration from 2005-2009, and reversal of the trend in 2010 and 2011. The GRACE minus GLDAS surface water (soil + snow water) series is also shown in Figure 4. Both GRACE–WGHM and GRACE–GLDAS estimates agree well with *in situ* bore estimates for the period 2003 to 2010. However, since mid-2010, GRACE–WGHM results are more similar to *in situ* data than GRACE–GLDAS.

Figure 5 compares interannual groundwater storage changes from 2003 to 2012 from *in situ* bore data with GRACE (forward model corrected) minus WGHM. In addition Figure 5 shows two GRACE minus WGHM estimates without forward modeling correction (with 300 and 500 km Gaussian smoothing). A one-year moving average smoothing filter was applied to all time series in Figure 5. As in Figure 4, GRACE and bore estimates are in excellent agreement, while GRACE estimates uncorrected for spatial leakage are biased, greatly under-estimating long term variations in groundwater storage.

Without the forward modeling leakage correction, GRACE peak rates in the lower MDB region for the 5 year period from January 2005 – January 2010 would be estimated at ~ –1.5 cm/yr (equivalent water height change), spread over a fairly broad region and extending into the ocean (Fig. 6a). With the forward modeling correction, peak rates are nearly twice as large, about –3 cm/yr, and are concentrated in a much smaller region, almost entirely over land (Fig. 6b).

Using Fig. 6b with integration over the VCT region (blue boxes in Fig. 2), the GRACE minus WGHM estimated loss rate (January 2005-January 2010) is 7.0 ± 1.2 km^3/yr, compared with 8.3 ± 3.4 km^3/yr from *in situ* bore data. Figure 6b shows that small residual variations persist in ocean areas even after 60 iterations of forward modeling. If the region of integration is extended about 100 km into the oceans to include these remnant leakage signals, beyond the blue boxes in Fig. 2, the GRACE minus WGHM estimated groundwater depletion rate is greater, about 8.0 ± 1.3 km^3/yr, and in better agreement with the bore estimate. The GRACE minus WGHM estimate with a negative storage trend extends over an area about twice that sampled by the bore data, including the lower MDB (in excess of half the MDB). For this larger region and the period January 2005-January 2010, the GRACE mass loss rate is 17 ± 3.6 km^3/yr.

3.2 Uncertainty of GRACE Estimates

It is challenging to assess uncertainty in GRACE TWS change estimates, mainly due to lack of adequate in situ measurements to validate GRACE observations. An additional complication relates to removal of surface water storage using WGHM, which has unknown uncertainty. Uncertainties given in the above GRACE estimates only include estimated error in the linear trend fit. This is a 95% confidence interval for the least squares fit slope, derived using a Monte Carlo method to account for non-white power spectrum characteristics of the time series (Chen et al., 2013).

One measure of GRACE uncertainty is Root Mean Square (RMS) variation over the oceans, where true long term mass storage changes are expected to be a few mm/yr, associated with global sea level change. An oceanic region near Australia ([51S-40S, 110E-155E]) was selected for this purpose. It is far enough from land to avoid leakage of variance from the terrestrial water cycle in Australia and elsewhere. RMS variations in this region (0.3 mm/yr) are relatively large compared with other oceanic regions at similar latitudes. We combined this value with the least square fitting error, taking the square root of the sum of squares as an estimated standard deviation. The resulting one standard deviation confidence intervals of loss rates from January 2005 to January 2010 of 8.0 ± 1.7 km^3/yr for VCT and 17 ± 4.7 km^3/yr for the lower MDB.

3.3 *In Situ* Groundwater Level Observations and Precipitation Anomalies

From 1993 to 2012 average storage in the VCT region shows a steady decline with superimposed seasonal variability, until the trend reverses around 2010 to 2011 (Fig. 7), a result of increased precipitation. Least square fit linear trends for 1993-2012 and for 1993-2009 are shown in red and green. Average annual precipitation in the studied region for 2010 and 2011 was about 86 cm, compared with an average of 60 cm for the period 1993 to 2009 (Fig. 8). The precipitation data are from the Global Precipitation Climatology Project (GPCP). The GPCP monthly precipitation analysis (Adler et al., 2003; Huffman, et al., 2009) is a globally complete, monthly estimate of surface precipitation from combined satellite estimates and rain-gauge measurements (over land).

Figure 9 shows residual groundwater storage variations after annual and semiannual variations have been removed via unweighted least square sinusoidal fits. End of year values are marked by red stars, representing an average of adjacent December and January values except at the two endpoints. Year-to-year storage changes are taken as the differences between end-of-year values. Yearly groundwater storage changes are strongly correlated with yearly precipitation anomalies (Fig. 9b), although magnitudes differ by a scale factor of ~ 5. The estimated correlation coefficient is 0.86, well above a 99% confidence level of 0.39 for null correlation (Zhou and Zheng, 1999). A comparably strong correlation was found between groundwater and precipitation anomalies in Northwest India (NWI) (see Fig. 7 in Chen et al., 2014), although in that case the scale factor between groundwater anomalies and precipitation anomalies was ~2, and the analysis covers a shorter period (2003-2012). Here, the analysis covers a 20-year period (1993-2012), and the correlations appear more convincing. The larger scale factor (~5) suggests a great fraction (about 80%) of anomalous precipitation goes to evapotranspiration, runoff, and storage in soil moisture or surface reservoirs.

To compare the spatial distribution of *in situ* groundwater rates with GRACE estimates (for the period 2005.01-2010.01), we compute least square fit linear trends of groundwater storage change for the 29 1x1 degree boxes using a mean specific yield of 0.1. Figure 10 shows trends consistent with GRACE rates (Fig. 6b). The average of the 29 boxes is -2.9 ± 1.2 cm/yr, very close to the GRACE value of -2.8 ± 0.6 cm/yr.

To summarize, bore level data indicate that from 1993-2012 VCT groundwater storage decreased at an average rate of 1.2 ± 0.5 cm/yr equivalent water height, corresponding to a regional loss rate of 3.4 ± 1.4 km^3/yr, and a total loss of about 68 ± 28 km^3 over 20 years. The average loss rate is relatively higher from 1993 to 2009 (1.4 ± 0.6 cm/yr or ~ 4.0 ± 1.7 km^3/yr). Over the 10-year GRACE time span (2003-2012), in situ measurements and GRACE estimates agree well with each other in trends and interannual variability. Estimates of uncertainty are based upon assumed uncertainty in specific yield (~ ± 40%) (Leblanc et al., 2009), and 95% bounds on least squares slope uncertainty (blue dotted curve in Fig. 7). The assumption that uncertainty in specific yield is ~ ± 40% of the mean value (0.1) is largely guesswork, and probably overestimates it. A more accurate estimate would require good knowledge of specific yields in different locations in the region.

4. Summary

Groundwater storage changes were estimated from a 10-year record of GRACE data (2003 to 2012) by subtracting WGHM estimates of surface water storage (snow, reservoirs and soil moisture). GRACE groundwater storage estimates are in excellent agreement with *in situ* bore data in the VCT region (a network of 1395 bores). Both show significant depletion from 2005 to 2009, and reversal of this trend in 2010 and 2011. From 2005.01 to 2010.01, the GRACE minus WGHM loss rate is 8.0 ± 1.7 km^3/yr (or 2.8 ± 0.6 cm/yr of equivalent water height over the region), similar to bore data estimate of 8.3 ± 3.4 km^3yr (2.9 ± 1.2 cm/yr equivalent water height). GRACE data show groundwater loss extending over an area about twice as large as that monitored by the bores, including much of the lower MDB. A groundwater loss rate for this larger region is 17.2 ± 4.7 km^3/yr, in general agreement with a previous estimate (from bore data) of 17 ± 7 km^3/yr for the period 2001-2007 (Leblanc et al., 2009). GRACE estimates, in map form, provide a clear picture of the distribution of loss that is independent of spatial coverage of available bore data. GRACE groundwater change rates from 2005.01 to 2010.01 also agree well with *in situ* measurements (Figs. 6b and 10). An imbalance between depletion and recharge in lower MDB groundwater storage is expected to continue, so GRACE observations will continue to be of value in quantifying regional water storage change.

In situ water level measurements from 1993 to 2012 show that groundwater storage in the VCT region declined steadily from the mid 90's through 2009 followed by a reversal in trend around 2010, due to increased precipitation in 2010 and 2011. From bore data, groundwater storage loss rates were estimated to be 3.4 ± 1.4 km^3/yr for the 20-year period (1993-2012) and 4.0 ± 1.7 km^3/yr for 1993 to 2009. Groundwater storage anomalies are highly correlated with precipitation anomalies but are about one-fifth their magnitude, suggesting that the majority of anomalous precipitation contributes to storage changes in surface reservoirs and soil moisture or to evapotranspiration and runoff.

Bias in GRACE estimates due to a limited SH range and smoothing to suppress noise, can be largely corrected by the unconstrained global forward modeling method. Additional errors in GRACE measurements have been estimated from variations in a nearby oceanic area where the true signal should be near zero. Other major errors may arise in WGHM estimates of surface water storage, from omission of geocenter variations in GRACE solutions, and from imperfect leakage correction during forward modeling. Among these, the WGHM model error is the most difficult to quantify. Additional analysis (not shown here) indicates that WGHM estimates of surface storage changes in major reservoirs of the southern MDB agree reasonably well with *in situ* measurements. However, data for many secondary small reservoirs are simply unavailable, so we must rely on the WGHM estimates. WGHM is not in operational mode, so calculations for the most recent period of GRACE data were not available for this study.

Although WGHM includes a groundwater component, and thus predictions of groundwater storage changes, these predictions in the VIC region are significantly smaller than *in situ* measurements and GRACE estimates obtained in this study (see the comparisons shown in Fig. 11). WGHM values match neither seasonal nor long-term variability estimated in this study and suggest the model is generally deficient in modeling groundwater storage change. Another contribution of this and similar studies is that *in situ* bore data and GRACE estimates can be used to assess and improve future generations of hydrological models.

Estimates from *in situ* bore data are also subject to errors from a number of sources, including inadequate spatial coverage, uncertain specific yield, measurement error, and inadequate spatial sampling. Sub-regional time series groups were averaged to deal with spatial non-uniformity. Although there is a good amount of *in situ* groundwater level data from the well bore network, lack of sufficient geologic data makes it necessary to adopt a mean specific yield (0.1) with a large (40%) uncertainty (Leblanc et al., 2009). The adoption of a single mean value (0.1) may be the largest error source in estimates from *in situ* data. Excellent agreement between GRACE and *in situ* storage estimates suggests that another contribution of studies such as this would allow GRACE and model data to constrain specific yield once other problems (leakage and other biases in GRACE estimates, and spatial coverage of *in situ* data) are addressed.

The strong correlation between yearly precipitation and groundwater anomalies suggests that significant groundwater depletion in the VCT region is primarily related to drought and related groundwater pumping for agricultural and domestic consumption. Groundwater extraction by pumping cannot be balanced by infiltration recharge from soil or seepage from surface water bodies due to drought conditions at the surface. The GRACE mission has entered its 14th year, well beyond its 5-year design-life, and may continue with some operational limitations for a year or more. A GRACE Follow-On mission is planned to be launched in 2017. The remarkable agreement between GRACE estimates and *in situ* measurements (in the VCT region) demonstrates the value of continuing the GRACE time series with GRACE Follow-On and later missions as quantitative tools for monitoring groundwater storage changes even when (or especially when) *in situ* measurements are limited or unavailable.

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Figure 1. Map of the Murray-Darling Basin (MDB, outlined by red line) in Australia. The MDB covers parts of four states (including the Queensland, New South Wales, Victoria, and South Australia), with an area of ~ 1,061,469 km^2.

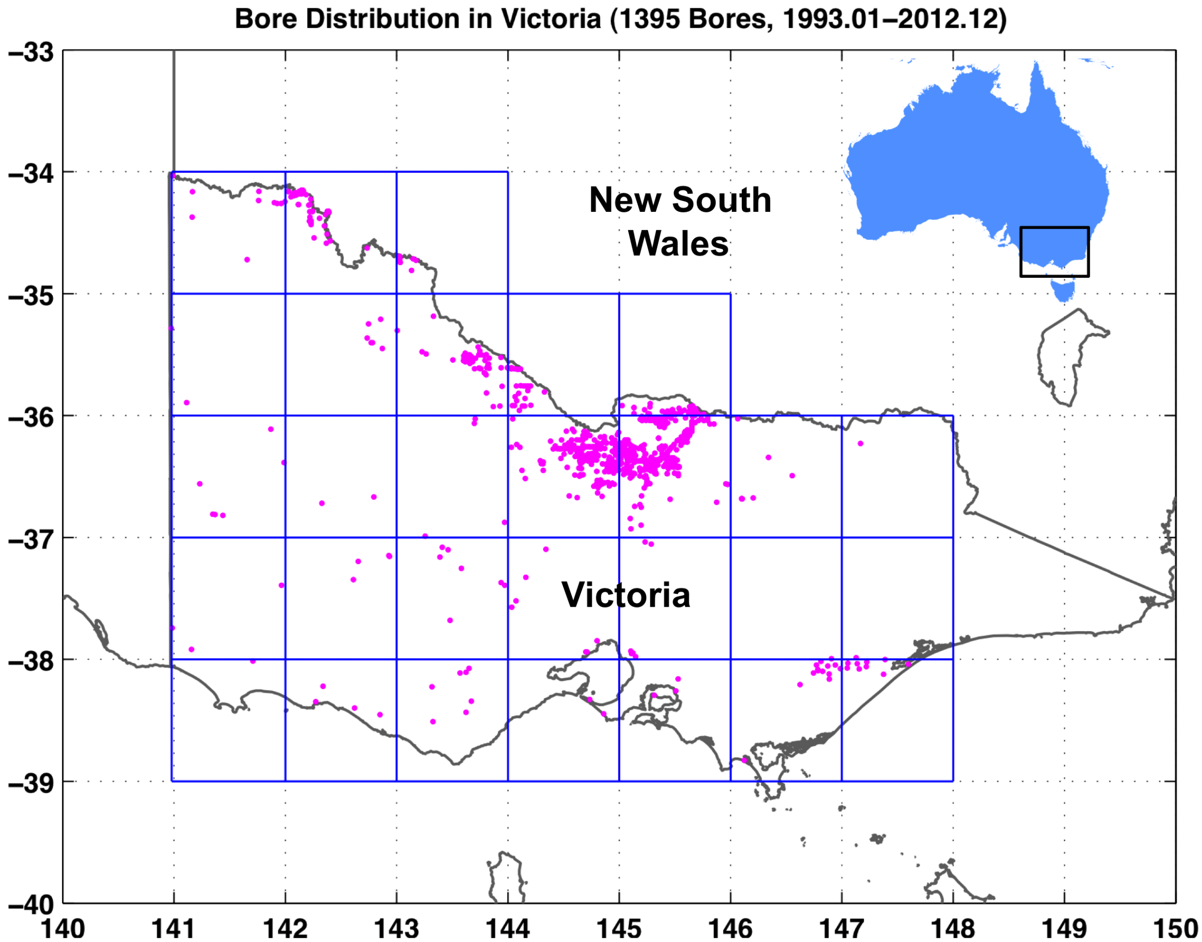

Figure 2. Distribution of 1395 bores (magenta dots) in Victoria State, which covers part of the lower MDB (Fig. 1). Bores are selected from the Victoria Department of Environment and Primary Industries (DEPI)'s network (http://data.water.vic.gov.au/monitoring.htm), and provide nearly continuous groundwater level measurements from January 1993 to December 2012. The blue boxes represent the 1x1 degree grid used for spatial averaging of groundwater storage change estimates and for comparison with GRACE.

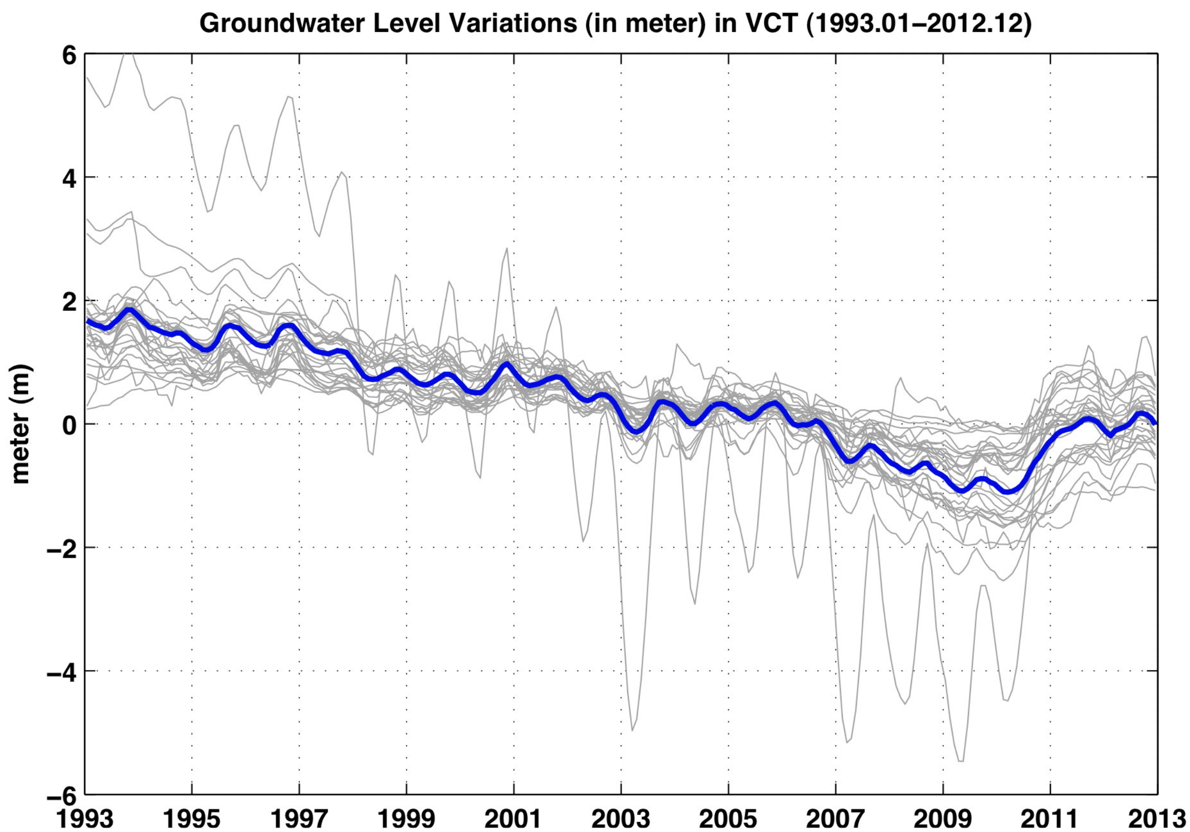

Figure 3. Mean groundwater level variations/anomalies (in meter) in VCT (area covered by the blue boxes in Fig. 2), relative to the mean of the study period. Each gray curve shows mean groundwater level variations in one of 29 1x1 degree boxes in Fig. 2, computed from averaging all bore measurements located within that box. The blue curve is the mean of all 29 time series.

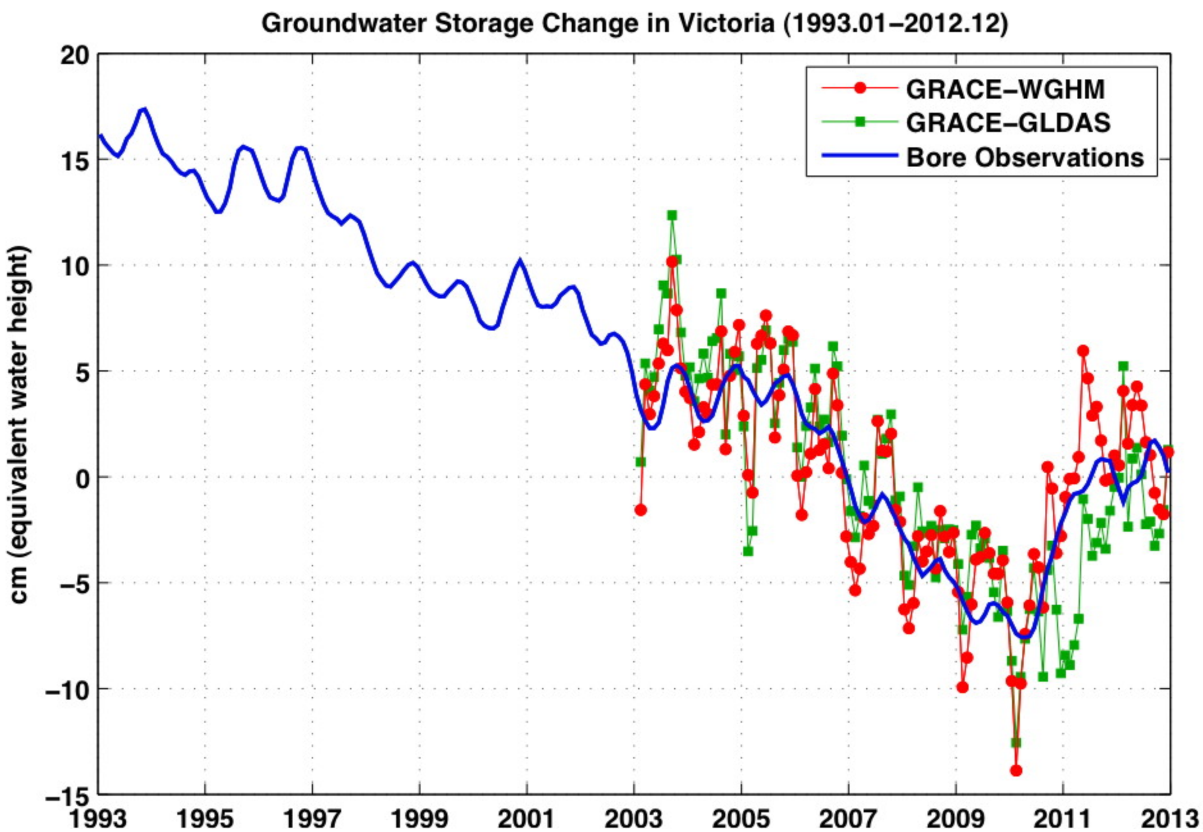

Figure 4. Groundwater storage variations (cm of equivalent water height) in VCT from *in situ* bore measurements (blue curve) and GRACE (red curve with dot markers). Bore results are from Fig. 3, with a mean specific yield of 0.1 is applied. An offset is added to the bore time series, in order to compare with GRACE estimates. GRACE estimates are GRACE total water storage change minus WGHM surface water (soil + snow + surface water bodies), with leakage correction via unconstrained forward modeling (after 60 iterations). A similar GRACE estimate (green curve with square markers) from GRACE minus GLDAS surface water (soil + snow water) is included for comparison.

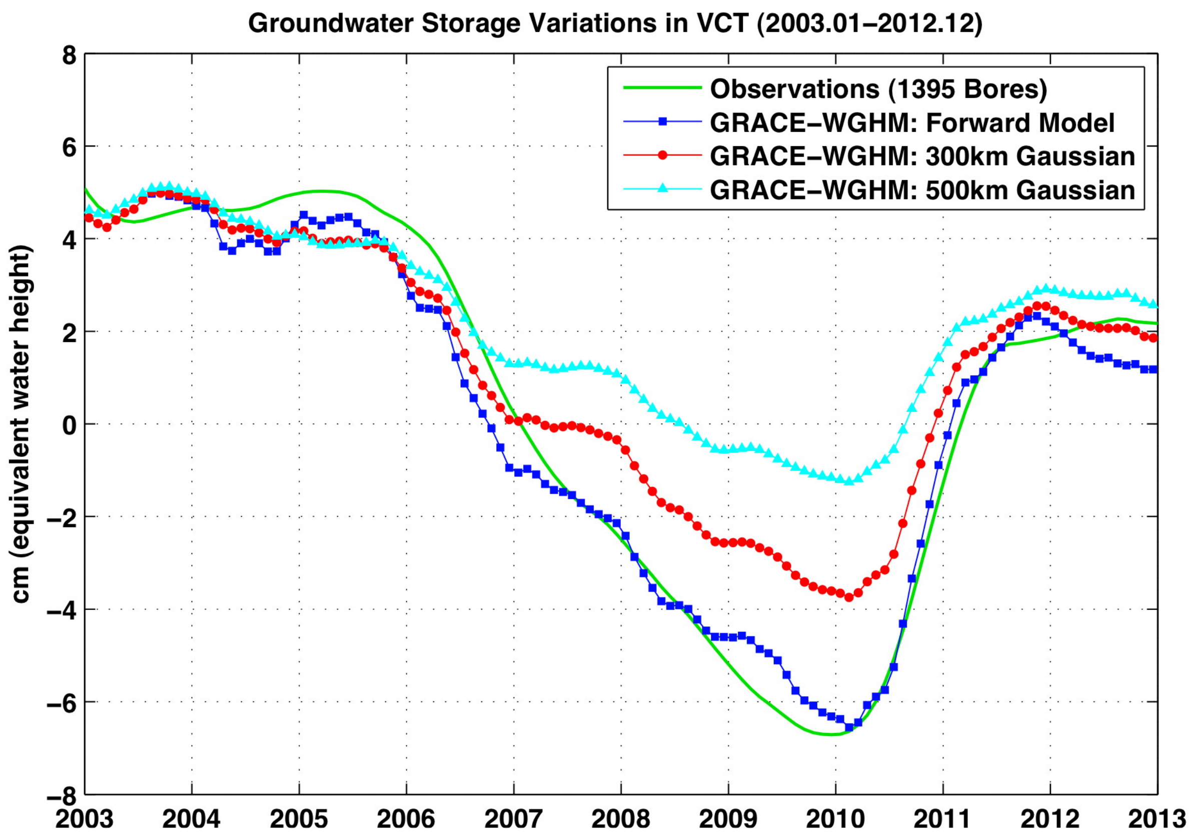

Figure 5. Groundwater storage variations (cm of equivalent water height) in VCT over the GRACE period (2003 through 2012). The *in situ* bore estimates are shown with three GRACE-WGHM estimates. Without leakage correction (red and cyan lines), GRACE estimates show considerably less long-term variability than bore estimates. With leakage correction (blue line) GRACE and bore estimates are in excellent agreement.

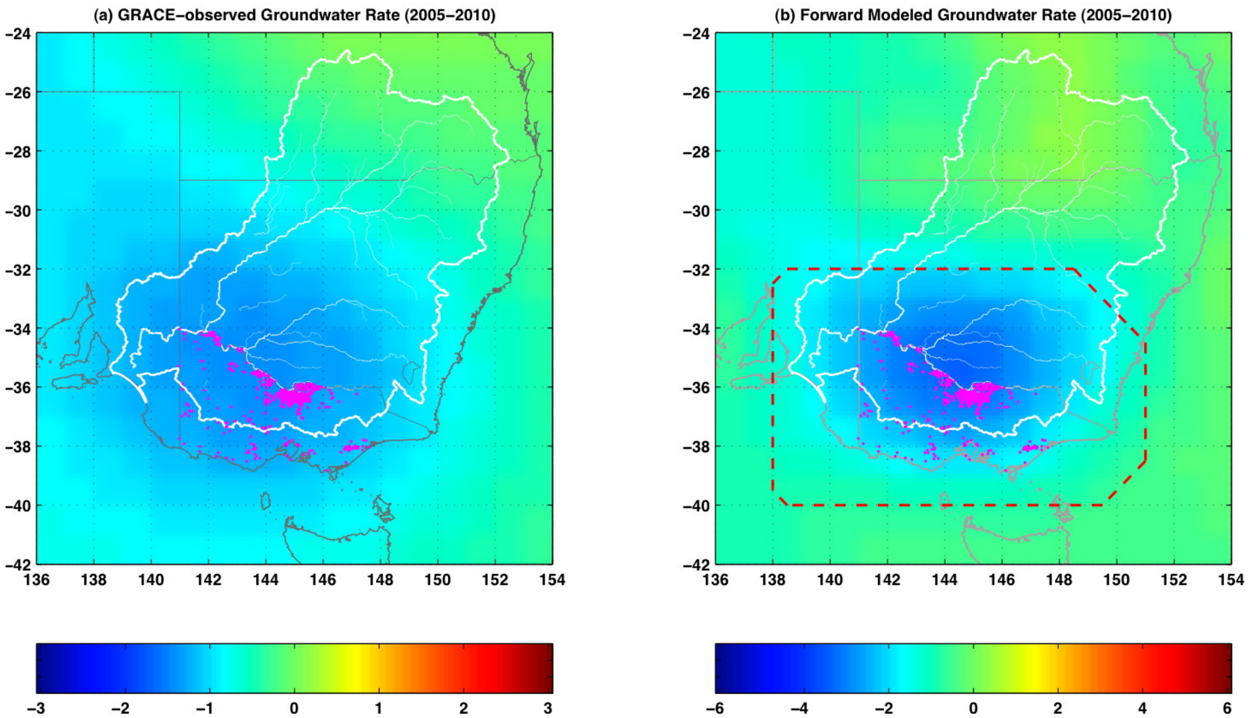

Figure 6. (a) GRACE groundwater depletion rate map (in cm/yr of equivalent water height change) in the lower MDB over the period 01/2005 – 01/2010 without leakage correction (b) After leakage correction with forward modeling, the GRACE rate map shows changes to be spatially concentrated with maximum rates nearly twice as those given in Fig. 6a. Note the different color scales of Figs. 6a and 6b. The 1395 bores are marked by magenta dots.

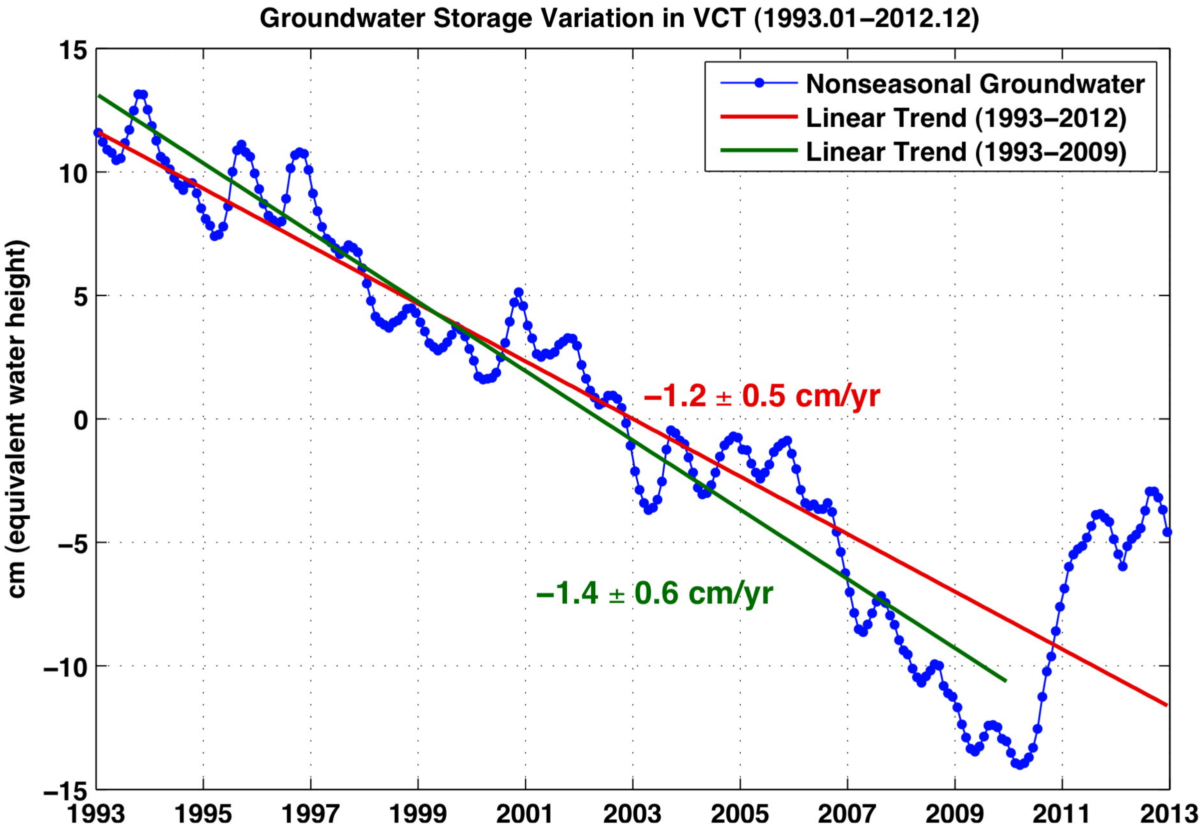

Figure 7. Groundwater storage variations (in cm of equivalent water height) in VCT from *in situ* bore measurements (blue dotted curve). Bore estimates are computed from the mean time series of Fig. 3 using average specific yield of 0.1. Linear trends for two separate periods 1993-2012 and 1993-2009 are shown as red and green straight lines. Uncertainty levels are estimated as the combination of the least squares fitting error and an assumed specific yield error.

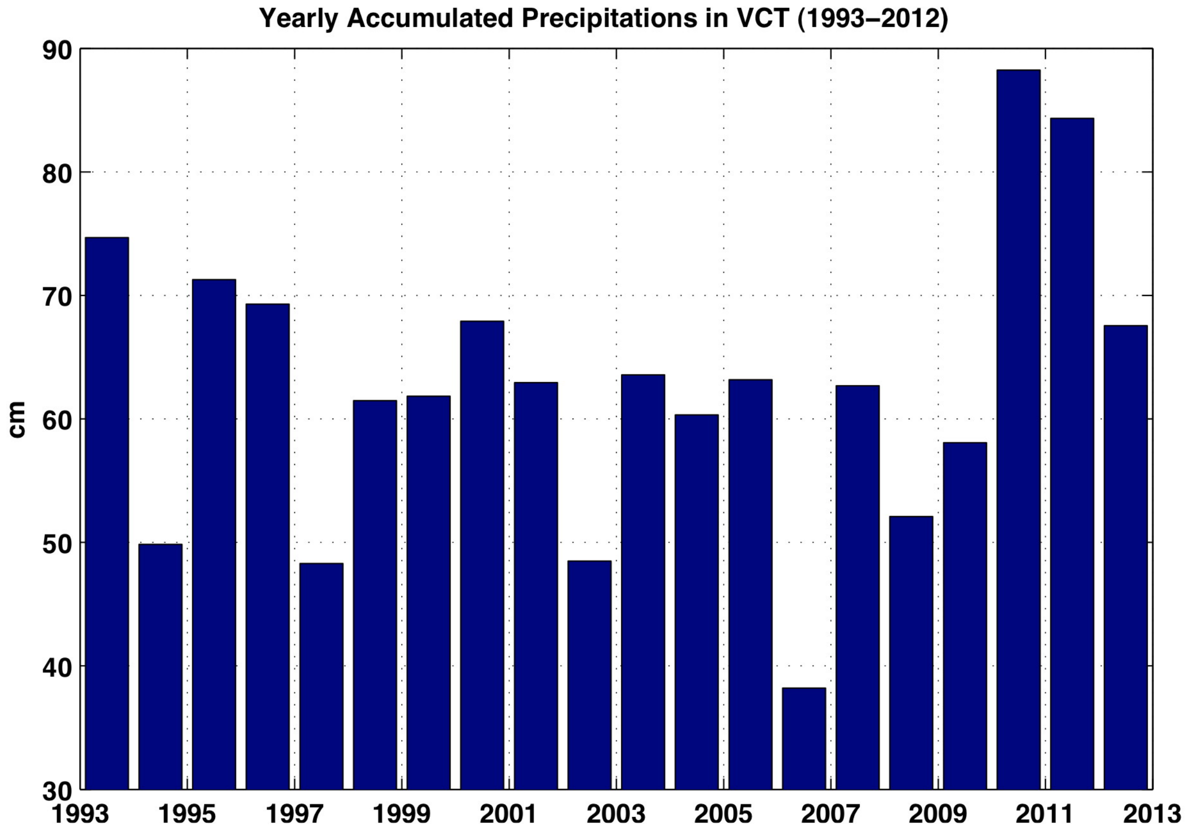

Figure 8. Yearly accumulated precipitation (cm) in VCT, computed from the GPCP precipitation data.

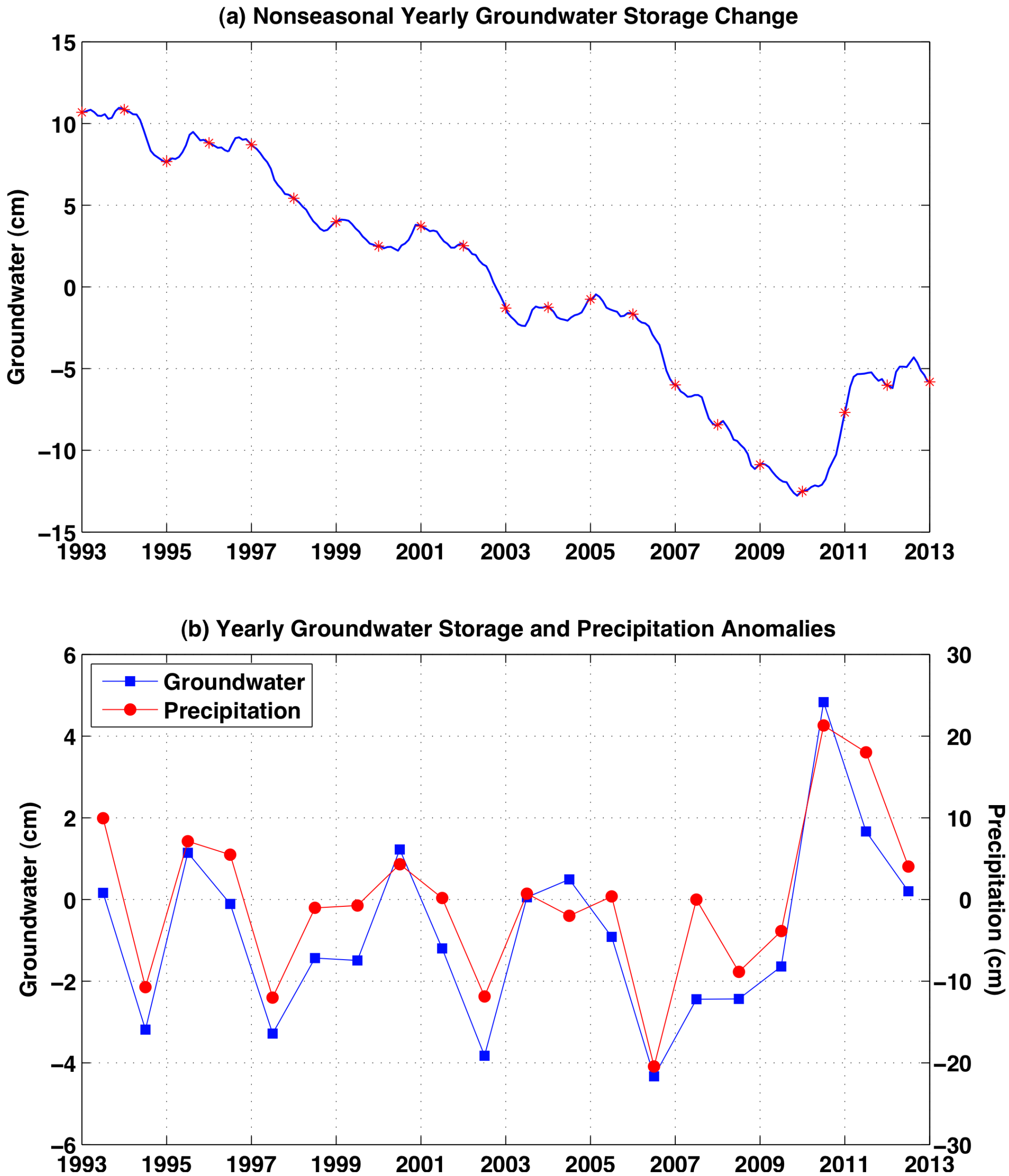

Figure 9. (a) Non-seasonal groundwater storage variations from bore data in VCT, with year-end groundwater storage marked by red stars (equivalent water height change in cm). (b) year to year groundwater storage changes (left y-axis) and precipitation anomalies in VCT (right y-axis). Year to year changes are differences of adjacent red dots in Fig. 9a. Precipitation anomalies are from Fig. 8 with mean removed, and units are equivalent water height in cm. Scales for groundwater (left) and precipitation (right) differ by a factor of about 5, implying that only about one-fifth of anomalous precipitation contributes to groundwater recharge.

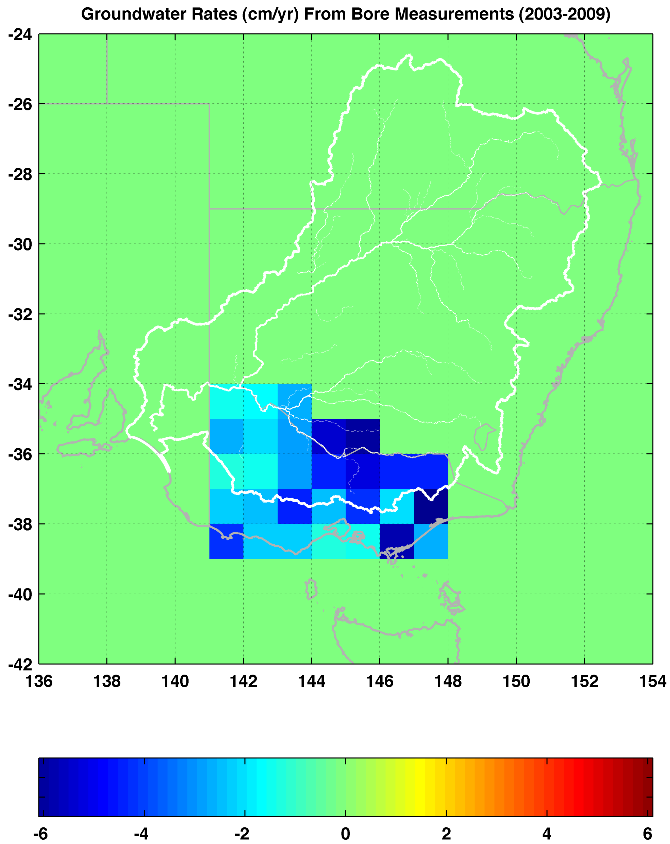

Figure 10. Groundwater rates map from *in situ* bore measurements (in cm/yr of equivalent water height change) in the VCT region over the period 01/2005 – 01/2010. A mean specific yield of 0.1 is applied to the 29 groundwater level time series shown in Fig. 3. Groundwater rates are computed from unweighted least squares fit of each of the groundwater time series.

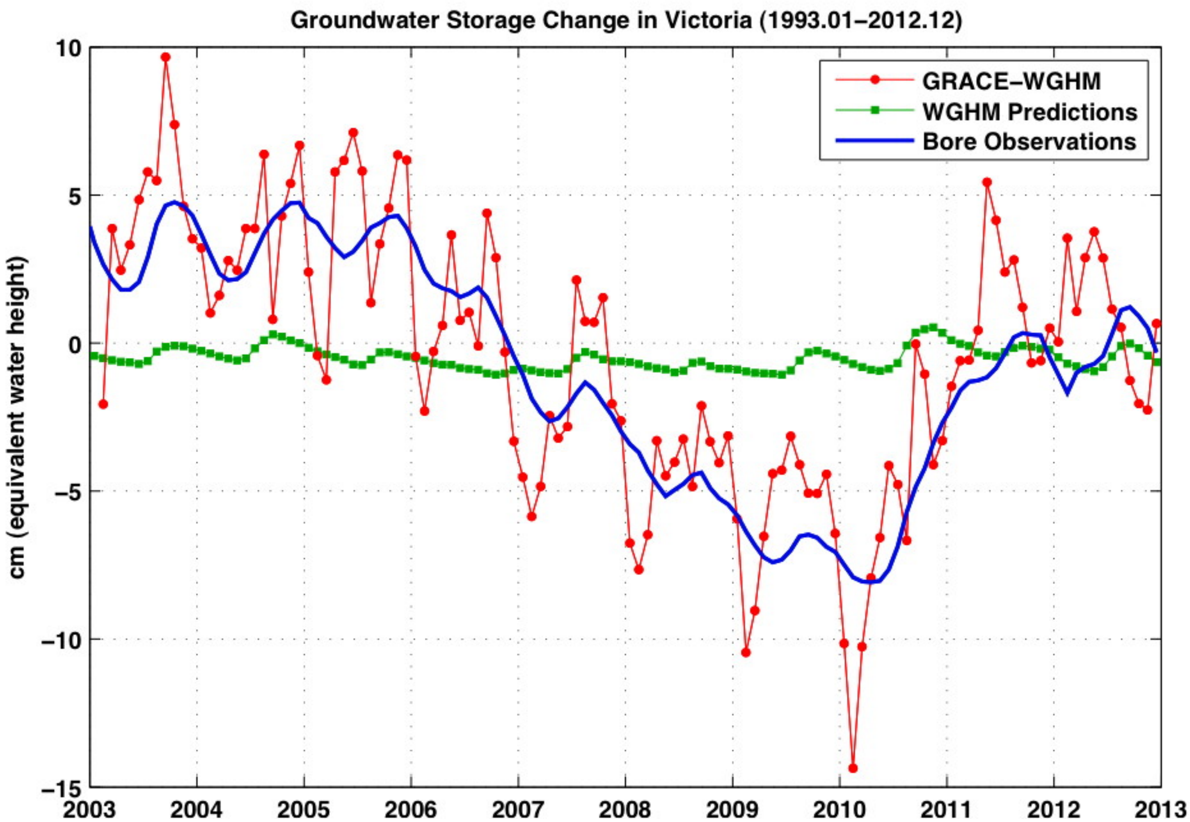

Figure 11. Comparisons of groundwater storage variations (cm of equivalent water height) in VCT from *in situ* bore measurements (blue curve), GRACE minus WGHM surface water (red curve with dot markers), and WGHM model predictions (green curve with square markers).