USING GRACE TO DETECT GROUNDWATER STORAGE VARIATIONS: THE CASES OF CANNING BASIN AND GUARANI AQUIFER SYSTEM

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ABSTRACT

Monitoring groundwater resource is today challenging because of very scarce in situ measurement networks. Here we combine 7 years (2003-2009) of data from the Gravity Recovery and Climate Experiment (GRACE) satellite mission with outputs of four Land Surface Models to detect Groundwater Storage (GWS, water stored below the 1-10 m upper layers) variations. The method is applied on two great aquifers with different climatic regime and anthropogenic forcing: the Guarani Aquifer System (South America) and the Canning Aquifer (Australia). For the former, we find groundwater depletion at a rate of 8 km^3/year in the southern part. At the aquifer scale, this depletion is compensated by a GWS increase at a similar rate in the northern part. At this scale, despite increasing development in groundwater use, GWS variations during the studied time span may be considered as negligible compared to the hydrological variability. The negative trend seen by GRACE over the Guarani Aquifer can be mainly explained by change in water storage of the upper soil layers. On the contrary, in the Canning Basin, results show an important groundwater depletion (after accounting for the upper soil layer component) corresponding to a water volume loss of almost 80 km3 for the whole study period. Since groundwater pumping is little developed in this arid region, the depletion rather reflects climate-related variability in deep water storage due to a return to normal or even dry conditions in recent years after a particularly wet period, as confirmed by precipitation, evapotranspiration and Normalized Difference Vegetation Index (NDVI) data analysis.

Keywords: Groundwater, GRACE, Land Surface Model, Hydrology, Canning Basin, Guarani Aquifer

1. INTRODUCTION

Aquifers are permeable geologic formations that can store and transmit water. In arid or semi-arid regions where little surface water is available or in regions where intensive agriculture is practised, groundwater stored in aquifers is often seen as a crucial and unlimited resource. In the context of climate change and increasing anthropogenic stress, identifying the causes of hydrological variations for managing water resource becomes vital to ensure water sustainability and avoid groundwater depletion. Unfortunately, monitoring groundwater resources is today challenging, essentially because of very scarce measurement networks and uncertainties associated with geological complexity of aquifer systems, abstraction amounts, soil characteristics, etc. Since a few years, Gravity Recovery and Climate Experiment (GRACE) (Tapley et al., 2004; Wahr et al., 2004) observations have been combined with Land Surface Models (LSMs) or in situ measurements to provide estimations of groundwater storage (GWS) variations in a few selected regions: Mississippi River basin (USA) (Rodell et al., 2007; Zaitchik et al., 2008), Murray-Darling Basin (Australia) (Leblanc et al., 2009), Ganges Basin (India) (Rodell et al., 2009; Tiwari et al., 2009), East African Lake region (Becker et al., 2010), La Plata Basin (Chen et al., 2010) and California's Central Valley (USA) (Famiglietti et al., 2011). In these studies, the use of GRACE space gravimetry data was justified because most LSMs do not account for the groundwater component, thus ignore deep aquifer dynamics and, where appropriate, human-related water extraction.

Here we combine GRACE data over a 7 years time span (January 2003 to December 2009) with four LSMs outputs over two great aquifers with different climate regimes and groundwater extraction practises (see contours in Fig. 1). The first one is the Guarani Aquifer System (GAS, 1,200,000 km^2). It is located in South America and is characterised by a humid sub-tropical climate. In this aquifer, groundwater extraction is estimated at a rate of about 1 km^3/year, essentially for public water supply and industrial use (Foster et al., 2009). The second studied aquifer is underlying the Canning Basin (430,000 km^2), located North-West of Australia in a semi-arid region with a climate dominated by the monsoon. The basin is sparsely populated and groundwater extraction is very low (less than 0.1 km^3/year), essentially for pastoral purposes [http://www.water.gov.au]. The choice of these two aquifers was essentially motivated by the great negative trends observed by GRACE in the recent years (see thereafter), and the fact that they are known to have a significant development potential for future domestic and irrigation use. In these regions, models and remote sensing data are of particular interest since no in situ groundwater data are available. As in the previous GRACE-based studies mentioned above, we investigate the hydrological variability of the two regions using in synergy GRACE and LSM outputs and try to attribute observed variations either to the upper layers or to the groundwater component. We also investigate whether the observed groundwater trends can be explained by hydrometeorology only or if an anthropogenic component needs to be invoked. For the GAS, our study is an extension of the study from Chen et al. (2010) in which GRACE data over the La Plata basin is used to quantify the consequences of recent drought conditions. Although the authors used a similar methodology as in the present study, they did not specifically consider the Guarani aquifer but the whole La Plata basin. Their GWS estimate mostly concerned a region where groundwater data was available but this region is located outside the aquifer, with only a small overlap in the southern part of the aquifer with our studied region.

Section 2 presents the data sets used in this study (LSMs, meteorological data and GRACE data). Section 3 compares GRACE-based and LSM water storage in terms of trends and spatial mean. Validation of the results is presented in section 4 by solving the water balance equation using different data sets than in the LSMs in the studied regions. An analysis of the Normalized Difference Vegetation Index (NDVI) and a brief discussion are provided in section 5.

2. DATA AND MODELS

2.1 GRACE

The GRACE space gravimetry mission provides observations of Total Water Storage (TWS) which can be interpreted as the vertically integrated water storage. Here, we use GRACE products (release 2) for the period 2003-2009 (with missing data for June 2003), computed by the Groupe de Recherche de Geodesie Spatiale (GRGS) (Bruinsma et al., 2010). It consists of monthly 1°x1° gridded time series of TWS, expressed in terms of Equivalent Water Height (EWH). At each grid mesh, the TWS anomalies are obtained by removing the temporal mean. The GRGS data are of particular interest since they have been stabilised during the generation process so that no smoothing or filtering is necessary. For comparison, we also use the CSR RL4.0 GRACE products computed by the Center for Space Research and available at [http://grace.jpl.nasa.gov] (Swenson & Wahr, 2006).

TWS derived from GRGS data is obtained from the spherical harmonic (SH) expansion of the gravity field truncated at degree and order 50, corresponding to a spatial resolution of about 400 km on the surface of the Earth. Note that such a spatial resolution allows to consider only basins with an area higher than 1.6 10^5 km^2, which is 3 and 8 times lower than the Canning Basin and GAS areas, respectively.

We corrected the GRACE EWH for the so-called leakage effects due to leaking signal from outside the studied region (a consequence of the low GRACE spatial resolution). For that purpose, we used the approach developed by Longuevergne et al. (2010) and Becker et al. (2011). Outputs from the Global Land Data Assimilation System (GLDAS-NOAH, Rodell et al.,
2004) has been considered as an a priori information to compute the leakage error over the period 2003-2009. We found that in the two studied regions, the leakage error does not exceed 5 % on interannual time scale. As proposed by Chen et al. (2009), errors in GRACE-based TWS may be estimated from the Root Mean Square (RMS) of the GRACE signal over a portion of ocean at a similar latitude. In this study, we prefer to estimate this error by measuring RMS over the Sahara desert since less TWS variability is observed in this region. The temporal mean of RMS over the Sahara desert is of the same order as over ocean (about 2 cmEWH).

Note that we applied the same SH truncation to LSM outputs for a relevant comparison (as suggested by many authors, e.g. Longuevergne et al., 2010).

2.2 Land Surface Models

LSMs use solar radiation and meteorological forcing to compute energy and mass exchange between the lower atmosphere and the land surface as well as water storage change in soil reservoirs and vertical and horizontal water fluxes (for a comparison of different commonly used LSMs, see Dirmeyer et al., 2006). Depending on the model, different layers are represented, such as surface water, soil moisture, snow, vegetation or groundwater. Nevertheless, in most LSMs, only the soil layers that determine the exchange with atmosphere are considered (i.e. 1 m to 10 m depending on the model). For this reason, the total water storage computed by LSMs at each grid cell (sum of water stored in the different layers) is called Top-Layers Storage (TLS) in the following. TLS can be interpreted as TWS minus GWS.

Here we use monthly gridded outputs of three different LSMs: (1) the NOAH model included in the NASA Global Land Data Assimilation System (GLDAS, Rodell et al., 2004); (2) the WaterGAP Global Hydrology Model (WGHM, Doll et al., 2003); (3) the Interactions between Soil, Biosphere and Atmosphere - Total Runoff Integrating Pathways model (ISBA-TRIP, Alkama et al., 2010; Decharme et al., 2010). For the Canning Basin, a fourth model implemented over Australia is considered: the WaterDyn model used as a reference in the Australian Water Availability Project (AWAP, Raupach et al., 2009). GLDAS and AWAP models are available for the period 2003-2009 whereas WGHM and ISBA time series end in 2008. Discrepancies between TLS derived from the different LSMs may come from differences of the numerical schemes and meteorological forcing. As proposed by Syed et al. (2008), discrepancies between models outputs provide an estimation of the model uncertainties.

2.3 Hydrometeorological data

For validation purposes, we used precipitation, evapotranspiration and NDVI data. Precipitations were obtained from multiple climate data sets at a monthly time scale: Global Precipitation Climatology Project (GPCP, Adler et al., 2003), Global Preciptiation Climatology Centre (GPCC, Schneider et al., 2008), Climatic Research Unit (CRU, available online at [http://badc.nerc.ac.uk/data/cru/]) and Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP, Xie & Arkin, 1997). GPCP and CMAP are both given at a 2.5° resolution for the period 1979-2009 from merged satellites and gauges products. GPCC and CRU are obtained only from gauge stations at a spatial resolution of 1° and 0.5°, respectively. The available period is 1951-2009 for GPCC and 1950-2006 for CRU.

At the global scale, evapotranspiration cannot be directly measured and is generally computed from meteorological and radiative forcing. The data used in this study were derived from the Surface Radiation Budget (SRB) and the International Satellite Cloud Climatology Project (ISCCP) forcing. Moreover, three different algorithms were used: the Surface Energy Balance System (SEBS) model, the Penman-Monteith approach and the Priestley-Taylor approach. This evaporation data set was kindly provided to us by E. Wood (personal communication) as monthly 1°x1° gridded time series for the period 2003-2007.

Finally, we used monthly gridded NDVI time series derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) space sensor (NASA's Earth Observatory Team and MODIS Land Science Team; [http://neo.sci.gsfc.nasa.gov]). NDVI informs on the "greenness" of Earth's landscapes and, as shown by many authors (see e.g. Chen et al., 2010; Jin et al., 2011, and references therein), it may provide qualitative information about dry/wet conditions and thus may be related to evapotranspiration.

3. RESULTS

3.1. GRACE trends

Fig. 1 shows GRACE-based TWS spatial trends for the period 2003-2009 over South America (a) and Australia (b). The boundaries of the GAS and Canning Basin are also represented (red lines). Fig. 1 reveals large negative trends localised in the South-West part of the GAS and in the centre of the Canning Basin. Since the spatial structure of these trends are confined into the limits of the two aquifers, the observed negative trends seem to be related to the hydrological behaviour of the basins or the aquifers.

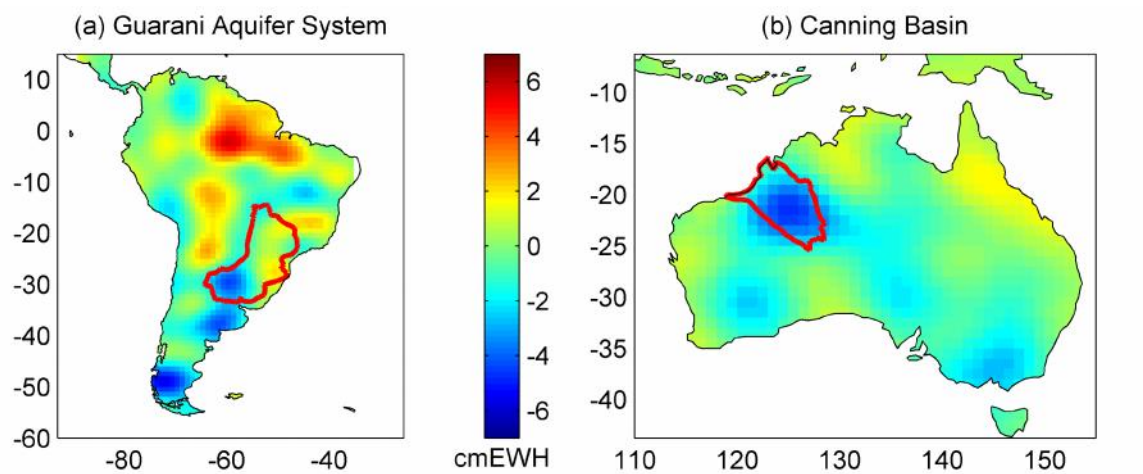

Figure 1: GRACE trends over the period 2003-2009 for South America (a) and Australia (b). Red lines represent the boundaries of the Guarani Aquifer System and the Canning Basin.

3.2. Comparison of GRACE and LSMs

For the two studied regions, the spatial mean of GRACE derived TWS time series is compared to the spatial mean of TLS times series computed with the different LSMs (GLDAS, WGHM, ISBA and AWAP) in Fig. 2 and Fig. 3. The blue shading represents the GRACE error. For each climate data set, the annual precipitation is computed by summing the precipitation over each hydrological year (from July to June). The bars in Fig. 2(a) and 3(a) show the mean of the annual precipitation from the different climate data sets (the error bars represent the discrepancy between the data sets). The seasonal signal of GRACE TWS and models TLS is computed by fitting sinusoidal signals with 1-year and half-year periods on the detrended signals. Fig. 2(b) and Fig. 3(b) represent the detrended non-seasonal GRACE TWS and models TLS, obtained by subtracting the seasonal signal and a fitted linear trend from the complete signals. Tab. 1 shows the RMS between GRACE TWS and models TLS for the complete signal and the detrended seasonal and interannual components over the time span of analysis.

Fig. 2 shows that the hydrological cycle of the GAS presents a strong interannual component with particularly wet years in 2003 and 2007. Despite an overestimation of the seasonal component for ISBA, Fig. 2 and Tab. 1 show a very good correlation between GRACE TWS and models TLS in terms of seasonal and interannual variability. Moreover, trends over the studied time span from LSMs and GRACE are also in good agreement: -12.3 +/- 3.3 km^3/year for GRACE (which represents a water loss of 84 km^3 for the whole period) and -14.0, -5.1 and -9.5 km^3/year for GLDAS, WGHM and ISBA, respectively. In terms of both interannual variability and trend, the good agreement between the three LSMs (mean standard deviation of 10.5 km^3) and their high correlation with GRACE suggests that models are able to reproduce the hydrological dynamics of the region and that, at the aquifer scale, the TWS variations observed by GRACE mainly occur in the top layers. Hence, despite important groundwater extraction in the GAS, GWS variations seem to be negligible compared to TLS variations at the aquifer scale.

Concerning the Canning Basin, the seasonal cycle is more important than for the GAS, but with a non-sinusoidal shape (Fig. 3(a)). Precipitation is decreasing over the study time span, with a particularly dry year in 2005. Since LSMs use precipitation as a climate forcing, this decrease can be directly related to the negative trends in TLS (-3.0, -1.1, -1.2 and -3.8 km^3/year for GLDAS, WGHM, ISBA and AWAP, respectively). Yet, the graph on Fig. 3(a) clearly shows a much larger negative trend in TWS observed by GRACE (see also Fig. 1). The latter reaches -14.1 +/- 1.2 km^3/year and represents a water loss of 99 km^3 for the whole period. Despite this major difference, Fig. 3(b) and Tab. 1 show a high correlation between GRACE TWS and LSMs TLS in terms of the seasonal and interannual variability. Moreover, LSMs are in very good agreement over the whole time span (mean standard deviation of 4 km^3).

Several factors may explain the difference between GRACE and LSMs trends over the Canning Basin. (1) Errors in GRACE data may lead to a bias in the time derivative of TWS. (2) Models may fail to capture the hydrological dynamics over this semi-arid basin. (3) There may be a water loss in the groundwater compartment (the aquifer) which is not accounted for by LSMs. To discriminate from these assumptions, it would have been convenient to investigate in situ groundwater data. Yet, in spite of an active search, no such data have been found over the Canning Basin. Thus we proposed to assess the accuracy of GRACE TWS using a water balance approach (section 4) and to investigate the spatiotemporal patterns of GRACE and one particular model, GLDAS, through an EOF decomposition (section 5). GLDAS was chosen because it presents the lowest RMS (see Tab. 1), all the more so as WGHM and ISBA outputs were not available for the year 2009.

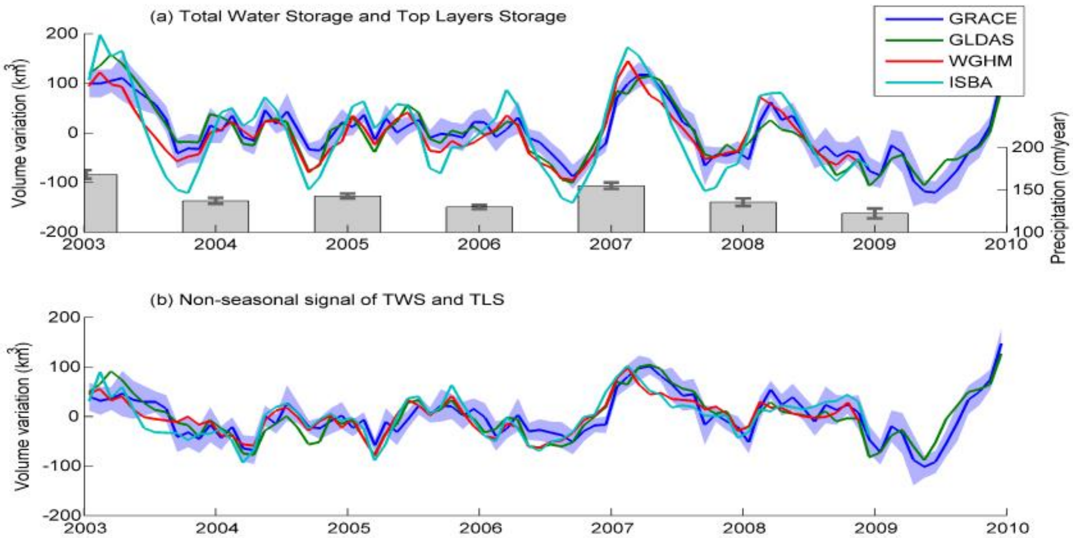

Figure 2: Comparison of TWS from GRACE and TLS from LSMs for the Guarani Aquifer System. (a) Complete signal (the blue shading represents the GRACE error) and precipitation obtained from multiple data sets is also shown (the error bars represent the discrepancy between the data sets). (b) Detrended non seasonal signal.

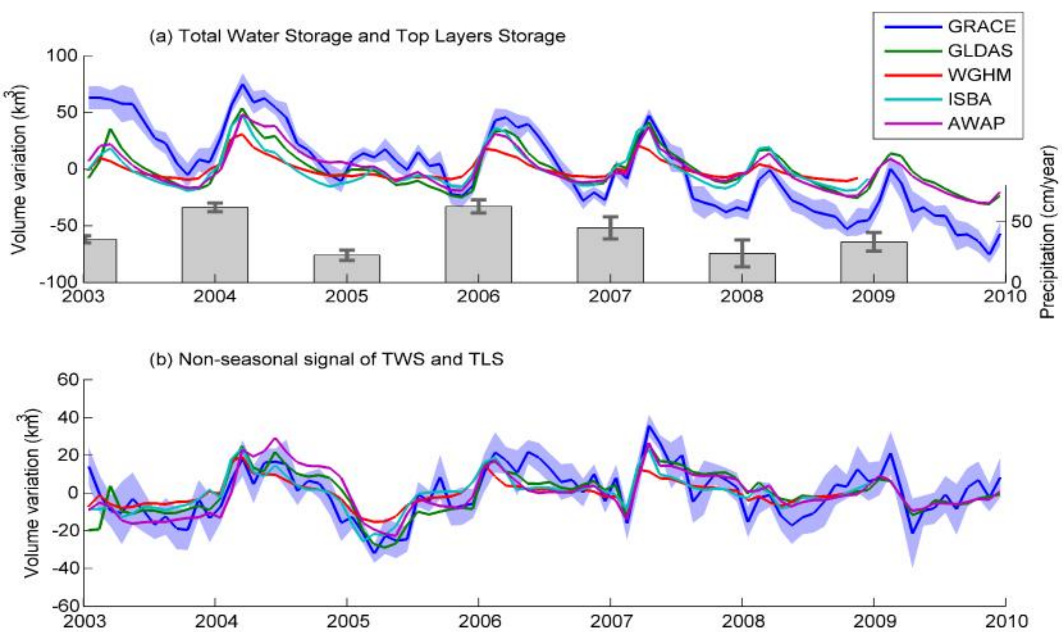

Figure 3: Same as Fig. 2 for the Canning Basin.

	Guarani Aquifer System			Canning Basin		
	Complete	Seasonal	Interannual	Complete	Seasonal	Interannual
GLDAS	22.4	6.2	21.6	10.0	5.0	8.7
WGHM	25.5	17.5	23.2	16.1	12.1	9.7
ISBA	48.0	46.3	27.3	11.6	6.9	8.5
AWAP				11.7	7.5	9.0

Table 1: Root Mean Square Error between detrended GRACE derived TWS and models derived TLS (in km3).

4. VALIDATION OF THE GRACE-BASED TWS VARIATIONS OVER THE CANNING BASIN

As done by Famiglietti et al. (2011), we validated the GRACE results by computing the water budget given by Eq. (1) using essentially independent observations:

$$\frac{d\text{TWS}}{dt} = P - E - R \qquad (1)$$

where P is the precipitation, E the evapotranspiration and R the runoff. Since the Canning Basin is located in a semi-arid region, the mean annual runoff may be neglected [http://www.anra.gov.au/topics/water/overview/wa/basin-sandy-desert.html] and the water budget is essentially driven by P and E. We computed dTWS/dt for the GRGS and the CSR GRACE solutions and P-E using the independent climate data sets presented in section 2.3. For the latter we computed independently the means of P and E before calculating the difference P-E. Besides, we associated an error from the dispersion of individual values around the mean. The mean uncertainty of P-E equals 3.0 km^3/month.

Fig. 4 compares dTWS/dt with P-E. The blue and green shaded zones represent GRACE errors, while the red shaded zone represents the uncertainties in P and E. First, the comparison between the GRGS and the CSR solutions shows that both solutions agree well within their respective error bars. The second graph also shows a good agreement between dTWS/dt and P-E. Namely, the temporal means over the common time period (2003-2007) are -1.7 and -2.0 km^3/month for dTWS/dt and P-E, respectively (thus inside the P-E uncertainty), which gives confidence in the TWS trend observed by GRACE over the region. The good agreement between the different curves leads to the following conclusions: (1) the GRACE data processing has a little effect on TWS in this region, and (2) GRACE well captures the hydrological dynamics over the basin.

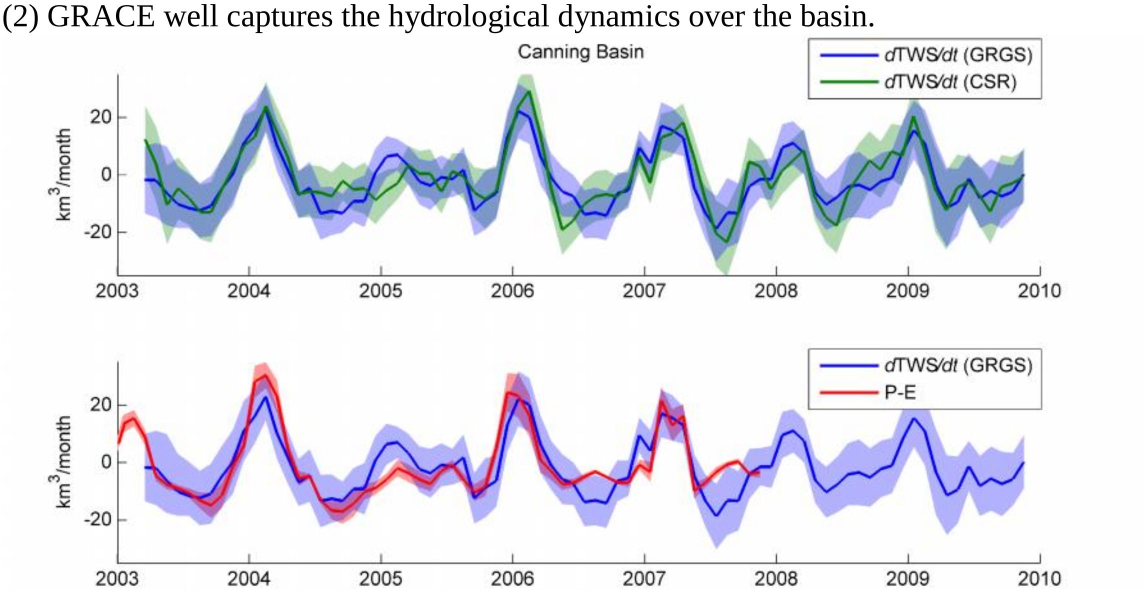

Figure 4: Comparison of the time derivative of GRACE TWS from GRGS with the one from CSR (a) and with the water budget estimate (b) for the Canning Basin. Blue and green shading represent the GRACE error while red shading represents the water budget uncertainties.

5. SPATIAL AND TEMPORAL PATTERNS

In the previous section, we showed that the great difference between TWS and TLS trends for the Canning Basin may not likely be due to GRACE errors or biases. In spite of the good agreement between LSMs, another assumption that could explain this difference is the inability of models to describe the hydrological dynamics. Namely, an underestimation of LSM evapotranspiration would lead to an overestimation of the TLS trend. In order to validate (or invalidate) this hypothesis, we computed the Empirical Orthogonal Functions (EOF) decomposition (Preisendorfer, 1988) to extract the principal spatial and temporal patterns of TWS and TLS from GLDAS. Computations have been done after removing a seasonal cycle component in each grid cell. For comparison purposes, the EOF decomposition has been computed for both aquifers.

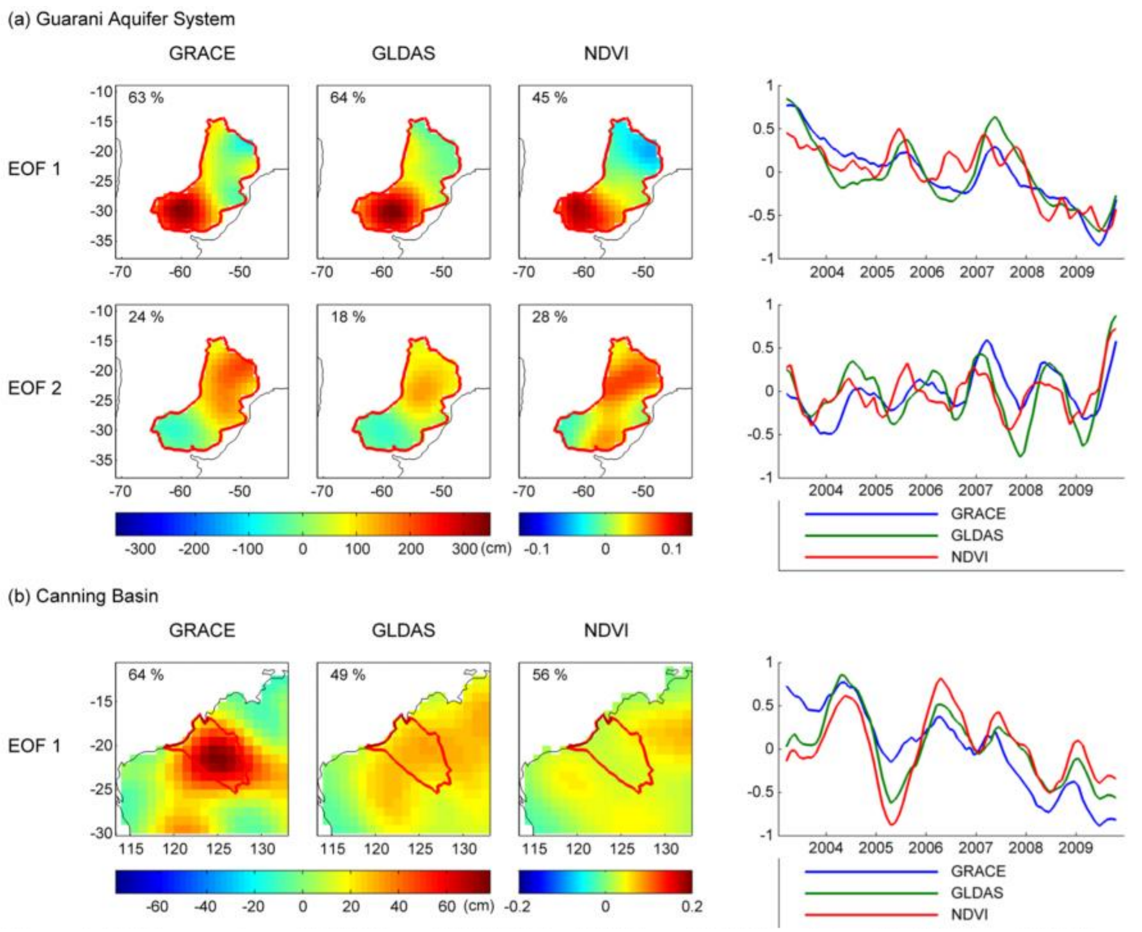

Figure 5: EOF comparison of TWS from GRACE data, TLS from GLDAS model and NDVI from MODIS over the Guarani Aquifer System (a) and the Canning Basin (b). For each mode, the number given in the upper-left corner represents the percentage of the total variability that is explained by this mode.

The first two modes of the EOF decomposition over the GAS are presented in Fig. 5(a). The first mode is clearly related to the depletion localised South-West, as observed in Fig. 1, and represents more than 60 % of the total variability for both TWS and TLS. The second mode corresponds to the interannual variability in the complementary part of the aquifer (North-East). Despite a good correlation between the spatiotemporal patterns of

GRACE TWS and GLDAS TLS for both modes, the graphs suggest a small difference in the long-term trends of TWS and TLS: the GRACE trend seems to be lower (higher) than the GLDAS trend for the first (second) mode. Since the first (second) mode is related to the southern (northern) part of the aquifer, we computed the TWS and TLS trends for these two parts separately. In the northern part, TWS is increasing at a rate of 2.0 km^3/year whereas TLS is decreasing at a rate of 5.9 km^3/year. In the southern part, TWS and TLS are decreasing at a rate of 36.2 and 27.9 km^3/year, respectively. This results suggest that GWS is increasing in the northern part at a rate of 7.9 km^3/year and decreasing in the southern part at a rate of 8.3 km^3/year. The groundwater depletion in the southern La Plata basin shown by Chen et al. (2010) with a similar methodology was confirmed by in situ data. Although these data concerned a region outside of the aquifer, their conclusion is in agreement with ours. Nevertheless, we showed in this study that this depletion is compensated, at the aquifer scale, by an increase in the northern part. Hence, at the aquifer scale, the main TWS variability corresponds to the top layers hydrological variability.

Fig. 5(b) shows the first mode of the EOF decomposition over the region surrounding the Canning Basin. For GRACE TWS, a strong signal is centred over the basin (64 % of the signal) and GLDAS TLS presents a quite similar but more diffuse spatial pattern (49 % of the signal). Both signals have a similar temporal evolution corresponding to negative trends as shown in Fig. 3. The second mode presents a spatial pattern localised outside the basin, over the Kimberley Basin (North-East), and is therefore not presented here.

As written previously, NDVI informs on the "greenness" of Earth's landscapes. High values represent lands covered by green, leafy vegetation and low values show lands with little or no vegetation. Since the vegetation development is directly related to the evapotranspiration, NDVI should be helpful to infer the ability of LSMs to well estimate evapotranspiration, especially during particularly dry of wet seasons when the vegetation development largely differs from normal conditions. Contrarily to Chen et al. (2010), who used this index for January 2009 as another proof of dry conditions in the lower La Plata basin in early 2009, we used gridded time series of NDVI for a spatiotemporal patterns comparison with GLDAS. To that purpose, we performed an EOF decomposition of NDVI anomalies over the two regions. Corresponding leading modes are shown in Fig. 5.

The very good correlation between spatial and temporal patterns of the different signals over the GAS (Fig. 5(a)) shows the relevance of the comparison with NDVI. In particular, NDVI very well captured the drought shown by GRACE and GLDAS in the southern part (likely responsible for a decrease in the vegetation development), as well as the interannual hydrological variability of the northern part. For the Canning Basin (Fig. 5(b)), NDVI presents a temporal pattern highly correlated to GLDAS TLS and to the detrended GRACE TWS. Concerning the spatial pattern, NDVI is quite similar to GLDAS, with no strong signal centred over the basin. This suggests that the vegetation development decreased over the time span in the surrounding region (see the negative trend on the temporal pattern), but not specifically over the Canning Basin, which is in agreement with the GLDAS analysis. Hence, the great negative trend of GRACE TWS seems to be more likely due to a decreasing GWS at a rate of about 11 km^3/year (difference between GRACE TWS and GLDAS TLS trends), representing a total groundwater loss of almost 80 km^3 for the whole study period.

6. CONCLUSION AND DISCUSSION

In this paper, we used GRACE estimations of the Total Water Storage combined with LSM outputs to detect groundwater storage variations. The method was applied on two great aquifers with different climatic and anthropogenic characteristics, but both known to have a high potential for domestic or irrigation use.

For the Guarani Aquifer System, no significant GWS variations were estimated at the aquifer scale, which means that (1) the main part of the hydrological dynamics (on a few years time scale) seems to occur mainly in the top layers and (2) groundwater extraction is currently negligible compared to the hydrological variability. However, the EOF decomposition showed that a groundwater depletion at a rate of 8 km^3/year may have occurred in the southern part of the aquifer and that this depletion have been compensated at the aquifer scale by a GWS increase at the same rate in the northern part.

On the contrary, the important decrease in TWS (14 km^3/year) observed in the Canning Basin seems to be mainly due to a groundwater depletion at a constant rate of 11 km^3/year (total water loss of almost 80 km^3 for the whole study period). To assess this, the GRACE accuracy over the region has been inferred through a water balance approach and the model ability to well reproduce evapotranspiration has been validated by a spatiotemporal analysis and the comparison with NDVI. Since water use remains very low in this sparsely populated region [http://www.water.gov.au], the observed depletion is certainly due to climate variability, i.e. sustained seasonal rainfall decrease over the last few years. This assertion is supported by Fig. 6 which shows the cumulative annual precipitation in the Canning Basin over a longer time span (since 1950). First, the region experienced particularly wet seasons over the period 1995-2005, providing a large GWS surplus. Then, the graph depicts a steady decrease in precipitation during the last decade, leading to a decrease in the aquifer recharge. This suggests that the decrease in GWS could be explained by a return to normal or even dry conditions. This result is in agreement with the interpretation given by van Dijk et al. (2011) who investigated GRACE TWS retrievals over the whole Australian continent.

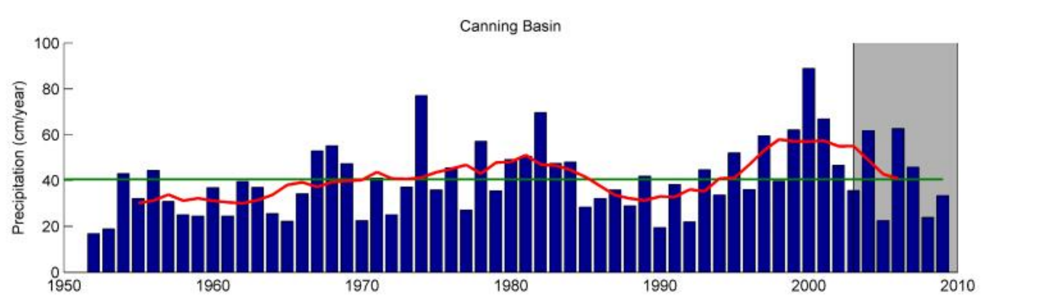

Figure 6: Long term annual precipitation over the Canning since 1950. The red curve shows the 7-years moving average and the green curve shows the temporal mean. The grey zone represents the period 2003-2009 considered in this study.

Despite different climate forcing and modelling schemes used by LSMs, the good correlations between models for the two study cases provides a certain confidence in their ability to represent TLS. Consequently, this kind of study may be used to support groundwater management, especially in poorly monitored regions where no other data is available. As a perspective, GRACE gravity data may be used to improve hydrological models, namely by integrating relevant groundwater reservoirs (Ngo-Duc et al., 2007; Niu et al., 2007) or by assimilating GRACE data into models (Zaitchik et al., 2008).

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