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Hydrology and Earth System Sciences
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Discussions

Interactive comment on "Regional GRACE-based estimates of water mass variations over Australia: validation and interpretation" *by* L. Seoane et al.

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Final Authors Comments.

For other minor corrections please see pdf supplementary documents.

Anonymous Referee 1

Replies to Major comments

(1) The different GRACE products of the study are validated by rainfall observa-

tions. Rainfall is however only one of the input parameters of total water storage changes that are modeled by GRACE products. I would suggest redoing the validation with comparing the GRACE products with terrestrial water storage out puts of AWRA.(e.g., that of van Dijk et al. 2011). Their study clearly shows that AWRA-TWS agrees very well with GRACE and in-situ observations. The resolution of the AWRA model is either 0.25 or 0.5, which is also much better than the computed GRACE solutions.

We understand that precipitation represents only a part of the balance, however, we suspect a logical correlation between the TWS structures and precipitation at the large scale of a continent such as Australia. The study of Rieser et al. (2010) revealed a direct relationship between the precipitation and GRACE surface mass changes over most of Australia.

We have added in the text : Page 8 line 6 Rainfall over Australia, from Bureau of Meteorology (BoM) of the Australian Government, were used for comparison agaisnt GRACE regional solutions following Rieser et al. (2010) who found a direct relationship between rainfall and GRACE surface mass changes.

Unfortunately, it is not allow for us to use the TWS parameter estimated by AWRA model in our paper, but only the soil moisture.

Anyway, comparison between TWS derived from GRACE and AWRA model are large made in previous studies. Van Dijk et al. 2011 show that model is not as optimistic about the so good correlation between the GRACE data and the AWRA outputs over Australia. The discrepances are due to several reason :
1. The quality of input rainfall information because it is poor estimate for some regions.

2. The model appears to drains too fast in some regions and groundwater extraction for irrigation may also have played role especially in Murray Darling Basin.
3. They have partly attributed the divergence in longer term trends to a model deficiency in the description of diffuse discharge.

We have made an analysis of AWRA-derived TWS and we do not find new facts to add. Our main purpose is to validate our GRACE-based regional solutions to indepedent dataset, as the observed data (GW measurements, rainfall and other GRACE solutions) . In order to compare GRACE TWS to the in situ measurements over Murray-Darling Basin, we used soil moisture derived from AWRA model because there are not observations of this parameter and modeled SM is needed to compute TWS.

2) There are some technical issues in the computation that are not well addressed, e.g.,

(a) Solutions are filtered using a combination of ICA and 400km Gaussian filters. Why has 400 km been selected while the new GRACE-level-2 products contain less errors and a filter of 250-300 km might be enough for the Australian case.
(b) For performing a fair comparison between different data sets, all available data should be filtered using a same filter. How have the authors handled this issue?
(c) Some results are derived and left un-interpreted, e.g., page 13, lines 25:28, the authors derive a lag of 4 months and 5 months between GRACE and groundwater observations. Why are the computed lags different? Some previous studies also find a lag of 3 months!

(a) Tests were performed to determine the range of pre-filtering allowing the use of the ICA technique on the GRACE solutions. We pre-processed the Level-2 GRACE solutions using Gaussian filters with different radius from 300 to 900 km. When the GRACE solutions are Gaussian-filtered with averaging radii ranging from 300 to 500 km, the distributions of the observations are sufficiently non-Gaussian to allow the use of the ICA method. For averaging radii lower than 300 km (or greater than 500 km), the signal is dominated by the North South stripes (respectively the smoothing of the GRACE solutions is too important), thus the corresponding histogram is Gaussian. As a consequence, the ICA method is unable to isolate hydrological signal over land and oceans from noise in these cases (Frappart et al., 2010). For a radius of 300 km, the ICA method was not able to separate signal from noise for 6 months in 2004, so we decided to prefilter the GRACE Release 4 solutions with a Gaussian filter of 400 km of radius (Frappart et al., 2011).

We have added : Page 7 line 23: Before applying an ICA method, the Level-2 GRACE solutions need to be somehow low-pass filtered not to have Gaussian distribution. When they are not filtered enough, they are still dominated by striping and their distribution keeps being Gaussian. If they are too filtered, they correspond the long wavelengths of the continental hydrology and they exhibit Gaussianity. Thus, a good compromise of 350 - 400 km to ensure non-Gaussianity has been found by Frappart et al. (2011) after several tests to apply ICA and extract most of the part of the continental hydrology.

(b) Our objective is to compare all the GRACE products over Australia from different sources, taken as they are provided, and then discuss about the differences when confronted to each others.

Analysis centers (CSR, GRGS, GFZ , JPL) have used different stategies to estimate gravity field solutions. GRGS global solutions are computed introducing empirical constraints to obtain the spherical harmonic coefficients in order to reduce leakage and noise problems (Bruinsma et al. 2010) then post-processing filtering is not required. The combination of GFZ, JPL and CSR GRACE solutions using the ICA filter also reduce the noise (Frappart et al. 2011). In our methodology, regional solutions are computed using conservation of energy approach and constraints are introduced to allow the inversion of the linear system (Ramillien et al. 2012). In conclusion, these three solutions are computed or filtered in different ways. Concerning the validation of regional solution, we think that it is interesting to show the perfomance of each technique,i.e, if there is a gain in spatial resolution, a better localization of hydrological structures or leading a too smoother signal.

For comparison to GRACE TWS , the modelled data and grids derived from the in-situ mesurements (groundwater, rainfall), with a better spatial resolution of 0.05 deg, we perfomed a GMT convolution filter Boxcar which consist in a simple averaging of all points inside filter radius of 220 km (or nearly 2 degrees consistent with GRACE resolution).

Page 8 line 4 We have added :

For comparison to GRACE TWS , the model outputs and grids derived from the in-situ measurements (well levels, rainfall), with a better spatial resolution of 0.05 deg, we applied the so-called "boxcar" convolution filter of the Generic Mapping Tools software (Wessel and Smith 1998) which consists in a simple averaging of all points inside filter radius of 220 km (or nearly 2 degrees, consistently with GRACE resolution).

Wessel P. and Smith W.H.F, New improved version of Genereric Mapping Tools released, EOS, Trans. Amer. Geophys. U., vol.79(47), pp. 579, 1998.

(c) Because of the gaps in the starting GW observations inside the Murray-Darling basin, the maximum time resolution of the averaged products is T=6 months, so that it is impossible to "read" time shift lesser than this period of interpolation. (see answer question 10 reviewer 2)

(3) In the entire paper, the authors improperly use some statistical terms. For instance, Abstract Line 17: "ICA solution" is not a valid term. This has been repeated in the entire paper. In page 13, Line 7, even the solutions are called "ICA". I suggest to be more careful on the use of the statistical terms. One can consistently call the products "ICA-filtered solutions".

We have changed in all , the paper ICA or ICA solution by ICA-filtered solutions

4) Some statements that refer to the previous works are not correct. For instance, page 4, lines 14:16 the authors claim that Garcia Garcia et al. 2010 and Forootan and Kusche 2012 propose the using of PCA which is not true. Garcia Garcia et al. 2010 suggest the use of complex PCA instead of PCA to catch the annual component in one mode. Forootan and Kusche compare PCA with VARIMAX and ICA for a global case and prefer ICA to decompose TWS maps. On the other hand, Forootan et al. 2012 propose the use of ICA to reduce the leakage problem. Please revise the manuscript accordingly.
Forootan, E., Awange, J., Kusche, J., Heck, B., Eicker, A. (2012). Independent patterns of water mass anomalies over Australia from satellite data and models. Journal of Remote Sensing of Environment, Vol.124, Page 427-443,dx.doi.org/10.1016/j.rse.2012.05.023

We have changed the text Page 3 line 67: Analysis of GRACE signals over Australia using PCA have already been proposed in previous studies (Rieser et al., 2010; Awange et al., 2011).

We have added reference Forootan et al. 2012 in the introduction also (page 3 line 20)

5) In page 4, Lines 7 to 9, the authors claim that they select Australia since the signal and noise are close. I am not sure if it is true! I agree that the signal over the region is weak, but at the same time atmospheric de-aliasing noise is also weaker over Australia (see e.g. Duan et al. 2012). Wouldn't it be better to test the method over, for instance, middle Asia whose signal is strong and de-aliasing error is also strong?

Even if atmospheric dealising noise is weaker over Australia another source of errors is due to spherical harmonics represention as remarked by referee 2. We have shown that ICA filtered solutions and GRGS solution still have a significant north-south striping ; see for example figure 5 (or figure 6 for the new version of our papier). Other reason is that we have the opportunity to use the the network of ground water and surface water observations in the Murray-Darling basin in the Southeastern part of Australia as well as soil moisture derived from AWRA regional hydrological model for complete the validation. Still, we are agree that the validation over middle Asia would be interesting when the regional solutions over Asia will be computed in the future.

In page 4 line 7: We have added : ... and confront them to a classical global Level-2 GRACE solutions and regional in situ observations in the Murray-Darling drainage basin (Southeast of Australia).

In page 3 Introduction (see pdf suplementary document): We have included the reference :
Duan, J., Shum, C.K., Guo, J., Huang, Z. (2012). Uncovered spurious jumps in the GRACE atmospheric de-aliasing data: potential contamination of GRACE observed

mass change. Geophys. J. Int., 191, 83-87. doi: 10.1111/j.1365-246X.2012.05640.x

6) The manuscript should be rewritten and thoroughly proof read. Some abbreviations are introduced for the first time, e.g. EHW but not written in full.
We have defined all abbreviations (see pdf suplementary document) We changed EHW by EWH

Minor remarks in pdf (Authors comments and answers in pdf suplementary documents)

For other minor corrections please see pdf supplementary documents.

Referee 2 (L. Longuevergne)

1) Authors are comparing GRACE TWS with rainfall or discharge data. Well, these fluxes are only one part of the mass balance equation (d TWS)/dt=P-ET-R, and not directly comparable with TWS.

Soil moisture (SM) from AWRA model is presented and would be more adequate in this duty. Surface water and groundwater data would deserve more space in the article, as it provides a direct comparison with GRACE TWS. Fig 15 is somehow lost at the end of the article and not really interpreted. The comparison of GRACE solutions is not fully fair. On one side, regional solutions provide true inverted mass variations, while the 2 other products (GRGS and ICA) are spatially filtered with leakage remaining and potentially problematic.

We suspect and want to demonstrate by PCA separation in different spatial modes that there is a good correlation between TWS variations and precipitation at large continental scales. The study of Rieser et al. (2010) revealed a direct relationship between the precipitation and GRACE surface mass changes over most of Australia.

We have added in the text :
Page 8 line 6: Rainfall over Australia, from Bureau of Meteorology (BoM) of the Australian Government, were used for comparison agaisnt GRACE regional solutions following Rieser et al. (2010) who found a direct relationship between rainfall and GRACE surface mass changes.

Corncerning ACP analysis of AWRA-L model please see answer question 1 referee 1.

2) Also comparison is mainly based on PCA, i.e. looking at correlation among solutions; this point should be discussed in the paper. In general, the article would benefit from being more focused on the interpretation of the GRACE solutions. Some figures and parts of the article could be sent to supplementary material.

All the figures are important and look meaningful for us, so we do not want to put anyone in supplementary materials.

Page 5356 Line 25 : Authors may also cite the recent article below to support the use of GRACE for groundwater studies. Taylor, R.G., Scanlon, B.R., Doll, P., Rodell, M., van Beek, R., Wada, Y., Longuevergne, L., Leblanc, M., Famiglietti, J.S., Edmunds, M., Konikow, L., Green, T.R., Chen, J., Taniguchi, M., Bierkens, M.F.P., Macdonald, A., Fan, Y., Maxwell, R.M., Yechieli, Y., Gurdak, J.J., Allen, D., Shamsudduha, M., Hiscock, K., Yeh, P.J.F., Holman, I., Treidel,

H. (2013) :Groundwater and climate change, Nature Climate Change, doi : doi:10.1038/nclimate1744

Reference have been added (Page 2 line 26)

3) Page 5357 Line 7 : Aliasing is not the only reason for stripes. They also appear during the the fitting of Stokes coefficients (underdetermined system).

Page 3 line 5 We have added :

Static gravity field and its time-varying variations (i.e., atmospheric and oceans mass changes including the periodic tides) are removed during the GRACE orbits pre-treatment by GINS software that uses a priori models. However, these correcting models remain unperfect by their uncompleteness in the description of natural phenomena by omission and/or by the lack of resolution. As GRACE solutions are averages over constant time intervals, errors in the correcting models with periods from hours to days contaminate 10-day and monthly GRACE solutions by aliasing, and thus degrades their accuracy (Duan et al, 2012). This effect of distorsion deteriorates the detection of true water mass signals into other time frequencies, and makes these signals indistinguishable when they are sampled. Aliasing is complicated in the case of GRACE since mass variations occur both in time and space, but they are sampled mainly along satellite tracks in the nearly latitudinal direction, and represented through global spherical harmonic (SH) functions afterwards. The particuliar distribution of the GRACE tracks due to the single polar orbit plane geometry translates into North-South stripes on the 10-day and monthly gravity field solutions, by the fact that the ability of such an orbit configuration for recovering short-term mass variations is limited. The determination of the GRACE Stokes coefficients leads to underdetermined systems of normal equations to be solved, by creating correlations between SH of high degrees (i.e., $>$ 10-15) (see Swenson and Wahr, 2006), and amplication of the orbit error and the data noise (Himanshu et al., 2012). Another serious drawback of using SH functions for representing the gravity field is "leakage", as energetic signals propagate on the entire terrestrial sphere, since SH are defined as global undulations, and thus come to pollute the water mass estimates in the geographical region of interest. This is particularly the case for a small region (i.e., typically $<$ 1 millions of square km), whereas averaging over a large area such as the Australian continent, surely cancels the spurious short-wavelength SH undulations from outside.

We added the references :

Duan, J., Shum, C.K., Guo, J., Huang, Z. (2012). Uncovered spurious jumps in the GRACE atmospheric de-aliasing data: potential contamination of GRACE observed mass change. Geophys. J. Int., 191, 83-87. doi: 10.1111/j.1365-246X.2012.05640.x

Himanshu; Bettadpur, Srinivas; Tapley, Byron D. (2012). Reducing errors in the GRACE gravity solutions using regularization JOURNAL OF GEODESY Volume: 86 Issue: 9 Pages:695-711 DOI: 10.1007/s00190-012-0548-5.

4) Page 5359 Figure 2 is very difficult to read, but of major interest

We have changed the figure 2.

Line 8 : don't you take into account the static field to correct range rate data?

Yes the static field is take into account to correct range rate data (see answer to question 3). It has been removed to compute the anomalies of TWS as classically done.

line 25: the long-wavelength information from global solutions. This is of major interest when discussing regional solutions. What is exactly done over Australia and how do you come up with degree 6?

As we indicate in the paper, the numerical estimations show us that the predicted regional solutions need to be completed by long wavelength components for comparison with other data sets, when the geographical region is not large enough to contain these long gravity undulations (for more details see Ramillien et 2012). This bias is corrected in the Total Water Storage (TWS) time series, global and regional techniques both yield comparable spatial averages.

To estimate the long wavelength signal loss in the regional solutions, we compute the water mass time series averaged over Australia derived from regional and global GRGS solutions. Then we compute the difference. As observed in Ramillien et al. 2012, this difference is explained by the loss of very long wavelengths (or equivalently, lower harmonic degrees of the observed gravity signals) due to the de-trending of the DPA tracks made over Australia before regional inversion. The numerical verification is presented in Fig. 2 of the paper, where the best agreement between long wavelength loss and long wavelength gravity signals estimated using low degrees spherical harmonic of GRGS is found for degree 6, with a root mean square (RMS) difference of 39 mm of equivalent-water height.

We have added :

page 6 line 5:

In order to reduce unrealistic orbit error at fractions of the satellite revolution period, and thus to avoid instabilities in the inversion of regional solutions, the GRACE-based DPA tracks passing over Australia are linearly de-trended first. The idea for cancelling the lack of long wavelengths in the final 10-day regional solutions is to complete these solutions by adding the large scale undulations of the GRGS solutions to them (Fig.2). For this purpose, we computed the time series of the difference between regional and GRGS solutions, both spatially averaged over Australia. This residual time series represents the large scale undulations that unfortunately are not described by the regional solutions because of the linear de-trending. Several maximum harmonic degrees n=2, 3, 4,..., 12 are then used to make the synthesis of GRGS Stokes coefficients of up to degree n onto smooth 10-day global grids. These latter grids are then spatially averaged over the whole Australia to produce time series per each chosen degree n. These latter profiles are compared to the residual time series. The optimal maximum degree is the one giving the less RMS difference with the residuals. In the particular case of our study, considering GRGS Stokes coefficients of degrees less or equal to n=6 explains the best the residual discrepancy over Australia. This optimal harmonic degree corresponds roughly to the latitudinal dimension of the geographical region considered in the inversion (about 6700 km, here). The long wavelengths from GRGS Stokes coefficients represent about 47% and 45% of the complete hydrological water mass signals over Australia and the Murray-Darling basin, respectively.

5) Page 5360 Line 28 and around. Figure 3 is very difficult to read. Showing maps of trends and amplitude of seasonal cycle would support the interpretation made in this section.

We have added new figures (now figures 4 a and b)

We have added :

Page 6 line 12:

Additionally, we show in Fig. 4 the maps of linear trends and annual amplitudes computed over 2003-2009. Even if the long term variations over Australia are not strictly linear, the trends reveal the regions where the most important mass losses occur for 2003-2009 (period of el Nino influence ; we avoid la Nina influence period 2009-2011), as Murray-Darling basin and the Sandy desert, or mass gain, as around the Canning basin (Northwest of Australia) in the last years. The mean annual amplitudes are maximum at the tropical area.

Similarly, Figure 4 would deserve some improvement.Could you show the"central desert" region on Figure 1. The way Figure 4 (fig 5 in the new version) is plotted may look suspicious. Why don't you show the whole time period? From the rainfall data, 2006.5 to 2006.9 is even dryer than the selected period, and there might be dryer periods throughout the period of interest (2003- 2011). This whole discussion on the Australian climatic settings and how they are captured by GRACE solutions could also be sent to the results and discussion part.

Alternatively, we decide to show the central part of Australia characterized by low precipitation, that we considered for validation (i.e., dry condition test where GRACE signals should be as small as possible, so that observed residuals can be considered as errors and/or noise).

We estimated errors over others driest periods. We changed Fig. 5 (Red histogramms are the driest periods used for error estimation).

Page 4 line 120 we have added :

During the dry periods in the part of the central desert (e.g this region shown in Fig. 1 is estimated in base on the level of rainfall over six consecutive months which remains less than 30mm every month; see Fig. 5a for time periods). As the expected values of mass variations due to hydrology in this area should be small for these periods, then the recovered TWS amplitudes can be also considered as an indicator of the level of uncertainty on our prediction. For GRACE-based solutions, Fig. 5b reveals standard deviation values of 12-19 mm of EWH. Low value of 12 mm for ICA filtered solution are due to resulted smooth signal. Estimated values of regional and global GRGS solutions are close, 19.11 and 16.3 mm respectively.

Line 28:we remember, please update.

We have changed the text :

Page 5 line 140:

We computed the corresponding variation of water volume inside the basin, ... the normalized harmonic coefficients of the considered geographical mask (Wahr et al. 1998; Ramillien et al. 2006b):

6) Page 5361 ICA solution. Why using a 400-km Gaussian smoother, while lighter filters have been shown to be sufficient? Please explain.

As proposed by Frappart et al. (2011), a pre-filtering of 400 km is the compromise for non Gaussianity before applying ICA (see the previous answer to Referee 1).

We have added :

Page 7 line 22 :

Before applying an ICA method, the Level-2 GRACE solutions need to be somehow low-pass filtered not to have Gaussian distribution. When they are not filtered enough, they are still dominated by striping and their distribution keeps being Gaussian. If they are too filtered, they correspond the long wavelengths of the continental hydrology and they exhibit Gaussianity. Thus, a good compromise of 350 - 400 km to ensure non-Gaussianity has been found by Frappart et al. (2011) after several tests to apply ICA and extract most of the part of the continental hydrology.

7) Page 5363-5364 I donť understand how the groundwater data is computed: Why do you need connection between unconfined aquifers to compute distributed GW storage? I don't understand why you are not using borehole with a thick saturated zone? These are as important to determine storage variations (as wells might not penetrate the whole saturated thickness anyway). They may be even more important as connected to large-scale permeable structure. The fact that they contain long-term variations is surely realistic and should be included for a full investigation of GWS. Why not using PCA-derived method (Longuevergne et al., 2007) to extract main regional information content from well data and compare to GRACE? This method is powerful and Beware of modes with similar explained variance. They are not well resolved, and any

linear combination of modes would fit into the PCA determination process (see e.g. Longuevergne et al., 2007). This is why 2 are switched : : : but more could happen.

Longuevergne, L., N. Florsch, and P. Elsass (2007), Extracting coherent regional information from local measurements with Karhunen-Loève transform: Case study of an alluvial aquifer (Rhine valley, France and Germany), Water Resour. Res., 43, W04430, doi:10.1029/2006WR005000.

Longuevergne, L., Scanlon, B., Wilson, C.R. (2010): GRACE hydrological estimates for small basins : evaluating processing approaches on the High Plains Aquifer, USA., Water Res. Res., 46, W11517, doi: 10.1029/2009WR008564

Scanlon, B.R., Longuevergne, L., Long, D. (2012) : Ground Referencing GRACE Satellite Estimates of Groundwater Storage Changes in the California Central Valley, US, Water Res. Res. 48, W04520, doi:10.1029/2011WR011312

Only piezometers (i.e. government monitoring bores) were used in our analysis of in-situ groundwater data (no wells data were used). The lithology of the sedimentary formations that compose the main unconfined aquifers is heterogenous with clay lenses often common at great depth (e.g. Hekmeijer, P., Dawes,W., 2003a). Hence, piezometers screened at the bottom of the unconfined aquifers, representing less than 5% of the piezometers, were excluded.

We thank the reviewer for recommending his method to analyze time series of groundwater hydraulic heads. We found his approach original and very interesting. However, in this case, we are not attempting to decompose the groundwater signals as

in Longuervergne et al. (2007) ; rather we aim to capture the integrated groundwater fluctuations for the whole the region. The Murray Darling Basin spans across several aquifers and climatic zones and the interpretation of the various modes (as was possible in Longuevergne et al., 2007) is not straightforward in this case.

Hekmeijer P., and Dawes W., 2003, Assessment of salinity management options for South Loddon Plains, Victoria: Data analysis and groundwater modelling, CSIRO Land and Water Technical Report 24/03, MDBC Publication No 10/03, Murray–Darling Basin Commission, Canberra ACT

Line 1, Sy has no unit

We have removed the unit.

8) Page 5364 Comparison of GRACE with streamflow data is not really meaningful and may be removed. It is only one flux in the mass balance equation The region of interest is far smaller than the resolution of GRACE Figure 10 does not bring much explanation on processes

Fig 10 b has been removed

We have removed page line (3) streamflow data in the Fitzroy river basin.

We have removed section 2.2.3

9) Page 5365 It would be best to focus this part on the comparison among GRACE solutions. Considering the high correlation between PDO and SOI, the

significance of climatic index within GRACE data cannot be interpreted that straightforward. I would suggest to remove this part as it is anyway out of topic Do you detrend data prior to correlation computation? Line 12 : SOI : same 13 month averaging as ??? rainfall?

Climate index is other independent climate information that allows us to validate regional solutions. Time series have been filtered accordingly (Three month averaging is used as in the case of GRACE-based solutions and rainfall) before the computation of cross correlations.

10) Page 5367 Line 20 : Could you compute correlation between the mode and GW? I have difficulties to see the groundwater contribution in the second mode. Is it here really the point of the article?

It is true there is not significant correlations between mode 2 and GW levels over Murray-Darling Basin. However, we notice a long-term coherency between the multi-year variations shown in the GRACE based temporal mode and the groundwater variations based on the in situ measurements, in particular over Murray basin (see figures 8a and b, or in the new version of the manuscript figures 9a and b). A maximum peak is found around 2006 in both 2-mode PCA and in situ GW signals, but with 6-month lag. The both signals also show a decrease of level or mass until 2008. After 2008 the GW and GRACE based mode 2 signals seem to be constant until 2009.

The key question is where this time shift comes from. There are obvious reasons that can explain the presence of this time lag: (i) the geographical area where the analysis is made is not the same, the comparison is made between GW internannual variations over Murray basin and the temporal mode 2 of GRACE which includes the whole

continent signal, so more signals is spatially averaged in the last case ; (ii) the localized bores distribution is clearly not homogeneous, they do not cover the complete region. The risk is to miss a large portion of signals energy in uncovered area. Whereas he GRACE data have lower spacially resolution but the data coverage made by the satellites along their tracks is more systematic ; (iii) and the sparse TEMPORAL resolution of GW measurements because of gaps in the starting observations before time averaging (6 months for Darling and the whole Murray-Darling basin, 3 months for Murray). We still think it is worth presenting the comparison between 2nd-mode PCA and in situ GW signals as it shows that long-term and large scale climatic oscillation - which reaches its maximum in 2006 over the Australia - has a strong impact on the Murray-Darling region hydrology including the GW. However, we agree with Reviewer 2 that it is difficult to conclude there is a strong and clear correlation between both.

We have added :

Page 13, line 24:

In Figures 9a and b we can notice long-term consistency between the interannual variations observed in the mode 2 and the interannual GW level variations , especially over the Murray Basin : there is a maximum of water mass around 2006 for both, followed by a decrease until 2008 to reach finally a quite constant level. There are simple reasons that can explain the presence of the time shift of the 2006 peak: (1) the geographical area where the analysis is made is not the same, the comparison is made between GW internannual variations over Murray Basin and the temporal mode 2 of GRACE which includes the whole continent signal, so more signals is spatially averaged in the last case ; (2) the localized distribution of bores is clearly not homogeneous since they do not cover the complete region, the shortcoming being to miss a large portion of signals energy in uncovered areas. Whereas the GRACE data have lower spacially resolution but the data coverage made by the satellites along their tracks is surely more systematic ; (3) and the lower time resolution of GW measurements because of gaps in the starting observations before time averaging (6 months the whole Murray-Darling Basin and 3 months for Murray Basin).

For other minor corrections please see pdf supplementary documents.

Please also note the supplement to this comment:
http://www.hydrol-earth-syst-sci-discuss.net/10/C4099/2013/hessd-10-C4099-2013-supplement.pdf

Interactive comment on Hydrol. Earth Syst. Sci. Discuss., 10, 5355, 2013.

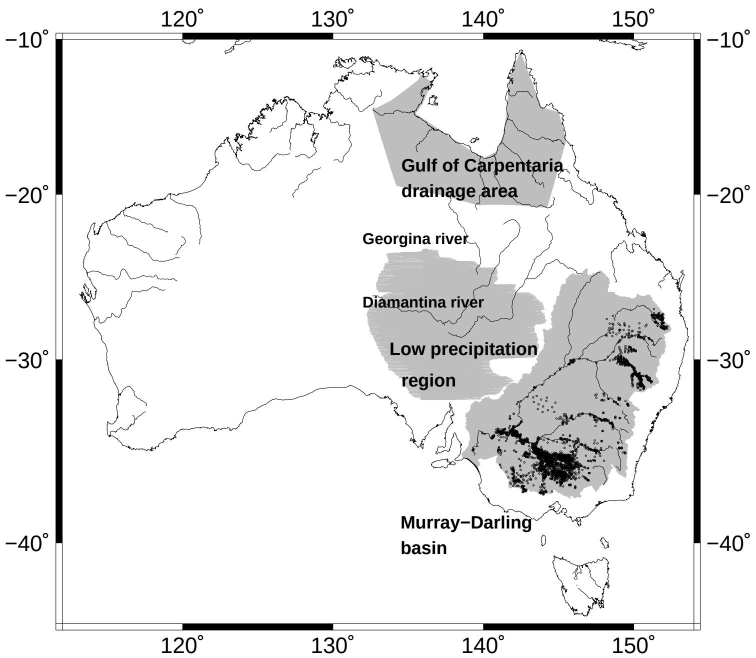

Fig. 1. Australian drainage regions used in our study. Geographical locations of the bores in the Murray–Darling are marked as black cercles.

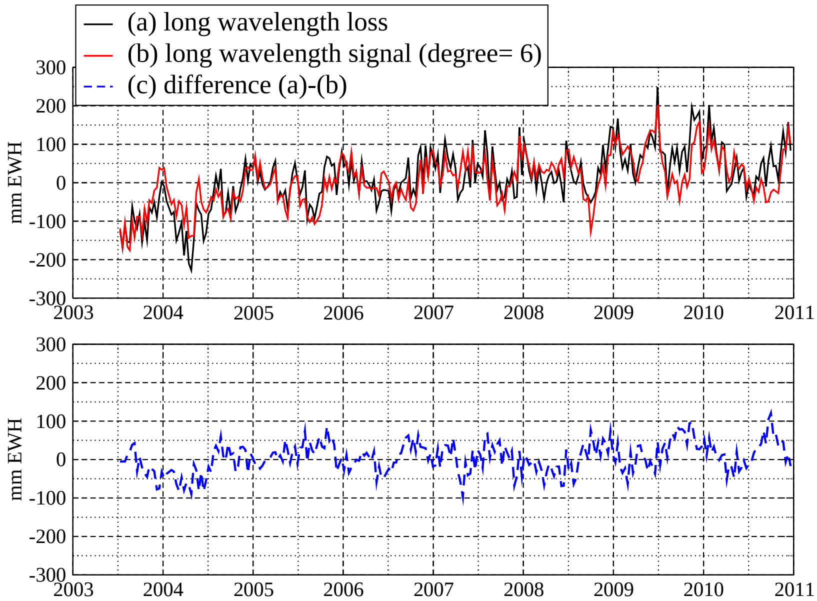

Fig. 2. Water mass time series averaged over Australia: (a) difference between regional and GRGS solutions, (b) GRGS GRACE solutions up to degree 6, and (c) their difference

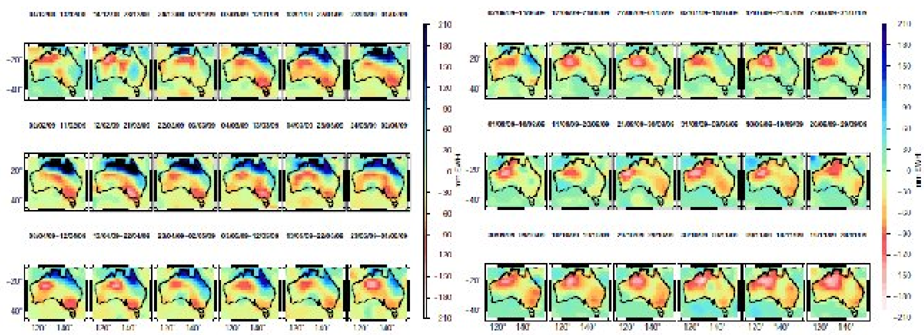

Fig. 3. Time series of regional maps of water mass from December 2008 to November 2009. We can notice the annual signal with amplitude of 250 mm of EWH representing the alternating wet and dry seasons.

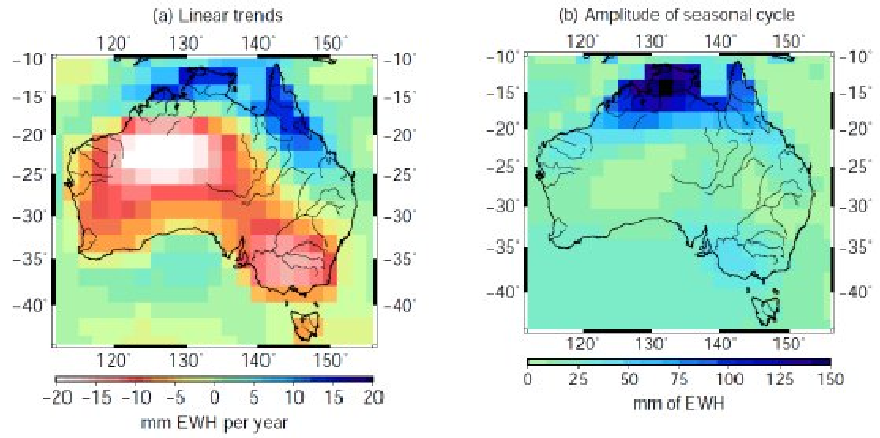

Fig. 4. (a) linear trends and (b) annnual amplitudes derived from GRACE-based regional solutions for 2003-2009.

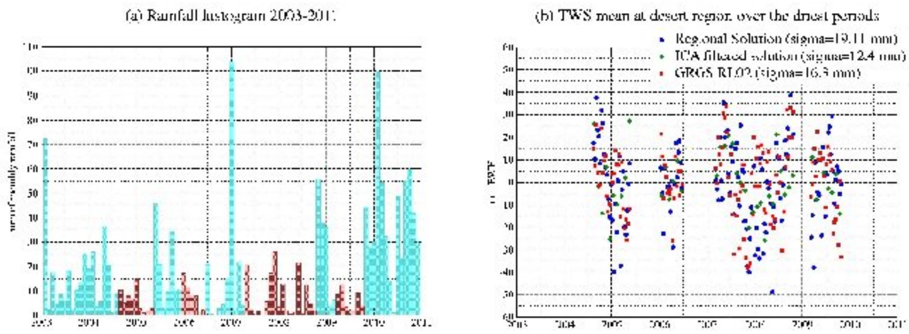

Fig. 5. Time series of TWS means over the estimated desert region (Central Australia) of 18 tiles, the largest signal amplitudes are lesser than 30 mm and the RMS value is of 19 mm.