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Interactive comment on "Reservoir storage and hydrologic responses to droughts in the Paraná River Basin, Southeast Brazil" *by* D. C. D. Melo et al.

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General comments

We would like to thank Dr. Conradt for taking the time to provide such a thorough review of our manuscript.

The general comments are related to the need of providing deeper data analysis with more integration of different datasets, practical application of our findings and more discussions about drought propagation. We fully agree that those ideas should not be ignored and are important for drought preparedness. We recognize that dealing with such a complex system is challenging; therefore, this paper is intended to provide a first cut while acknowledging that further analysis will be required. We plan to conduct additional studies in the future.

Despite the flaws highlighted by the review, we feel that our findings provide a baseline for future research and that our study (especially the revised version) stands on its own and significantly advances our understanding of this region beyond what has been previously reported (Getirana, 2015; Coutinho et al., 2015; Coelho et al., 2015). Our discussion brings new insights to an important issue by assuming that a prerequisite to understanding future droughts is an understanding of past droughts.

We added a "Future Research" section to the manuscript to indicate the recommended improvements that we did not do but that will be addressed in the near future.

A major factor limiting our ability to conduct a more comprehensive assessment, at the present time, is a lack of monitoring data. We recognize that there has been an incredible effort by Brazilian agencies to make hydrometeorological data more accessible. However, a considerable amount of time is required to translate raw data to different parameters relevant to drought assessment, such as calculating SPI, evapotranspiration, etc. For example, the Brazilian Water Agency (ANA - Agência Nacional de Águas) developed an outstanding system called SAR – Sistema de Acompanhamento de Reservatórios (http://sar.ana.gov.br/), where reservoir data (level, % of active volume, inflow, and outflow) from various power plant managing companies are made available for download. However, time series for individual reservoirs must be downloaded separately and intensive processing is usually required. This includes, to name a few, obtaining the level-area-volume relationship for each reservoir (not available at SAR) and converting reservoir levels to volumes.

To our knowledge, data quality screening processes applied by Brazilian data sponsors, such as ANA, are minimal or even absent. In the case of rainfall data, gap filling and data consistency verification methods are relatively simple; however, unreliable data and long gaps in time series of other meteorological variables (air humidity, wind speed, etc) are much more prevalent than one might wish.

The analysis contained in this paper is not intended to be final. Despite the large availability of remote sensing products, we think that ground-based observations are critical and seek to expand the analysis in this study by including groundwater data and ground-based estimates of evapotranspiration.

Coelho, C. A. S., Cardoso, D. H. F., and Firpo, M. A. F.: Precipitation diagnostics of an exceptionally dry event in São Paulo, Brazil, *Theor App Climato*, pp. 1–16, doi:10.1007/s00704-015-1540-9, http://link.springer.com/article/10.1007/s00704-015-1540-9, 2015.

Coutinho, R. M., Kraenkel, R. A., and Prado, P. I.: Catastrophic Regime Shift in Water Reservoirs and São Paulo Water Supply Crisis, *PLoS ONE*, 10, e0138 278, doi:10.1371/journal.pone.0138278, http://dx.doi.org/10.1371/journal.pone.0138278, 2015.

Getirana, A. C. V.: Extreme water deficit in Brazil detected from space, *J Hydrometeor*, doi:10.1175/JHM-D-15-0096.1, http://journals.ametsoc.org/doi/abs/10.1175/JHM-D-15-0096.1, 2015

General Comment 1

Close the hydrological balance. There are data on precipitation, evapotranspiration, and runoff (principal fluxes), and you have soil moisture, reservoir and total water content alterations (principal storages). The only principal storage missing is groundwater, but it should be possible to calculate it as residual difference. The groundwater component could also be approached from the dry weather discharges. And there are other redundances, too, for example two precipitation and two evapotranspiration data sources. Even without modelling, it should be possible to determine whether the numbers are generally “adding up” or where there are larger uncertainties

Response: We agree that it is important to close the water budget; however, current remote sensing data are not sufficiently reliable to close the budget. Previous studies that focused on closing the budget showed that it is infeasible with remote sensing products alone. An example of such a study is: Sheffield, J., C. R. Ferguson, T. J. Troy, E. F. Wood, and M. F. McCabe (2009), Closing the terrestrial water budget from satellite remote sensing, *Geophys Res Lett*, 36.

Basin-wide ET is one of the most difficult variables to be measured or estimated because there is large uncertainty in remote sensing based ET. Long et al. (2015) indicate that remote sensing data are not constrained at all whereas model based estimates of ET are constrained by mass conservation and may be more reliable than remote sensing products. However, previous studies in the Amazon basin (we are unaware of similar studies in the Paraná Basin) show that model-based ET may not be sufficiently reliable either. Fernandes et al. (2007) indicate that ET in reanalysis has 15-30% bias compared to observations in the central and southern Amazon. Current ET products for water budget closure has large uncertainties. Due to the lack of basin-wide ET monitoring, previous studies were unable to balance the water budget in the Amazon basin (Marengo, 2005; Sheffield et al 2009).

Also given that the scope of this paper is to understand extreme events over the Paraná Basin and their impact on reservoir storage, instead of water budget analysis, we did not use water budget terms from different measurements and model results for water budget closure. Extreme events, including droughts, are more relevant to the deviation of certain variables (e.g. rainfall) from its climatological mean, while water budget closure is more relevant for understanding the mean state of each water budget term. Most recent studies on droughts focus primarily on detecting the magnitude of the deviation of hydrological parameters from their mean and understanding drought mechanisms and impacts on water resources (Fu et al., 2013; Salazar, 2007; Malhi, 2009; Lewis et al., 2011; Saatchi et al., 2013; Marengo et al., 2011).

Long, D., L. Longuevergne, and B. R. Scanlon (2014), Uncertainty in evapotranspiration from land surface modeling, remote sensing, and GRACE satellites, *W Resour Res*, 50(2), 1131-1151.

Fu, R., et al. (2013), Increased dry-season length over southern Amazonia in recent decades and its implication for future climate projection, *Proc Natl Acad Sci* USA, 110(45), 18110-18115, doi:10.1073/pnas.1302584110.

Salazar, L. F., C. A. Nobre, and M. D. Oyama (2007), Climate change consequences on the biome distribution in tropical South America, *Geophys Res Lett*, 34(9), L09708, doi:10.1029/2007GL029695.

Malhi, Y., L. E. O. C. Aragão, D. Galbraith, C. Huntingford, R. Fisher, P. Zelazowski, S. Sitch, C. McSweeney, and P. Meir (2009), Exploring the likelihood and mechanism of a climate-change-induced dieback of the Amazon rainforest, *Proc Natl Acad Sci*, 106(49), 20610-20615.

Lewis, S. L., P. M. Brando, O. L. Phillips, G. M. van der Heijden, and D. Nepstad (2011), The 2010 Amazon drought, *Science*, 331(6017), 554.

Marengo, J. A., J. Tomasella, L. M. Alves, W. R. Soares, and D. A. Rodriguez (2011), The drought of 2010 in the context of historical droughts in the Amazon region, *Geophys Res Lett*, 38(12), doi:10.1029/2011gl047436.

Saatchi, S., S. Asefi-Najafabady, Y. Malhi, L. E. Aragao, L. O. Anderson, R. B. Myneni, and R. Nemani (2013), Persistent effects of a severe drought on Amazonian forest canopy, *Proc Natl Acad Sci* USA, 110(2), 565-570, doi:10.1073/pnas.1204651110.

Marengo, J. A. (2005), Characteristics and spatio-temporal variability of the Amazon River Basin Water Budget, *Clim Dyn*, 24(1), 11-22. How well does the ERA40 surface water budget compare to observations in the Amazon River basin? K Fernandes, R Fu, AK Betts - *J Geophys Res: Atmos*, 2008

General Comment 2

There are only a few, general points made on the propagation of the droughts from the meteorological via the natural-hydrological and the water management system into the societal system. This should be much more elaborated and ideally also exemplified. Research questions could be about the different onset times of a drought (meteorological, hydrological etc.), or which information is currently evaluated for the water management (situation in upstream reservoirs? Weather forecasts?) and what your study can do about it. It is not clear to me yet how you "establish a comprehensive understanding of the linkages between meteorological and hydrological droughts for future management" as you advertised in the Abstract.

Response: Indeed, there is a lot more to explore on the topic of drought propagation, perhaps enough to be addressed in a single paper, such as previous studies published in HESS (Van Loon et al., 2012; Iñiguez et al., 2016).

We provide a new figure (Fig 1) to exemplify the propagation of meteorological drought to hydrological drought. We plan to deepen the analysis on this topic in a future project, in which other aspects (drought impacts on groundwater, hydroelectric generation, etc) will be evaluated as well.

The proposed research question on the different onset times of droughts (meteorological, hydrological, etc) was partially addressed in a paper we wrote that was recently accepted for publication in the Brazilian Journal of Water Resources (Melo and Wendland, 2016), which should be available in the near future under the following doi: 10.1590/2318-0331.011616083. In that article we quantified the time lag responses of the hydrological system to meteorological shifts and found a lag time of ≈6 months between significant change in SPI and reservoir storage; and ≈1 month between SPI and Q.

We included these estimates on lag times in the revised version of the manuscript and reference this recent study. Regarding the second point (which information is currently used for water management), we provide a short description of the process adopted by the Electric System National Operator (ONS - Operador Nacional do Sistema Elétrico) in the main text and a detailed description in Supporting Information. Based on the information from ONS, dam operation protocols are related primarily to making the reservoirs function more as flood management systems rather than providing a buffer for drought. The fact that reservoir data are not publicly available prior to 1995 limits our capability to, at this stage, provide all the necessary recommendations of what can be done to optimize water management in this case.

We would like to mention the case of the Murray-Darling basin (Australia) as an example to state that optimal management for a drought may not be the same for a flood. The fact that these two extreme events are widely different in terms of duration and predictability make it even more difficult to achieve such optimized management. We included the following paragraphs to show how our findings can contribute to future management and replaced “comprehensive understanding” with “preliminary understanding”.

“A preliminary understanding of drought propagation, i. e. how meteorological drought culminates in hydrologic drought, was presented here. Our analysis indicates that socio- economic droughts (failure to supply water, electricity, etc) in the PB are subject to a natural cascade of effects (rainfall deficits > soils moisture decrease > run-off reduction > reservoir depletion) that are related to antecedent soil moisture conditions and dam operations.

An important practical measure is to continuously monitor meteorological indices, such as SPI. Based on such indices, it may be possible to anticipate and reduce drought impacts by means of public campaigns to alert the population about the potential drought and to encourage reduction in water and electricity consumption. The lag time between meteorological droughts and hydrologic responses results in time for some actions to be taken to reduce drought impacts, such as modifying dam operations. Given the spatial variability of droughts and the interconnected electric grid in Brazil, another possible measure is to reduce hydroelectric generation in a region potentially affected by an imminent drought and, temporarily, increase electricity generation in other regions.

To manage hydroelectric generation, ONS uses rainfall-runoff models forced with rainfall forecasts from the ETA model (Mesinger et al., 2012); then discharge forecasts are used in stochastic models (in general) to generate scenarios of projected natural discharges at different time scales. Given the uncertainties in the modelling process adopted by ONS to manage hydroelectric generation, dam operators can profit from radar-based real-time rainfall measurements or remotely-sensed near-real-time rainfall estimates. The difficulty of gathering station data for short timescales emphasizes the importance of remote sensing rainfall for reservoir operations. Finally, land surface models can be used in addition to the rainfall-runoff models currently used by ONS, to project hydrologic responses by inputting weather forecast data."

Iñiguez, V., Morales, O., Cisneros, F., Bauwens, W., Wyseure, G., 2016. Analysis of the drought recovery of Andosols on southern Ecuadorian Andean páramos. *Hydrol. Earth Syst. Sci.* 20, 2421–2435. doi:10.5194/hess-20-2421-2016

Mesinger, Fedor, Sin Chan Chou, Jorge L. Gomes, Dusan Jovic, Paulo Bastos, Josiane F. Bustamante, Lazar Lazic, et al. "An Upgraded Version of the Eta Model". *Meteo Atmos Phys* 116, no 3–4: 63–79, 2012. doi:10.1007/s00703-012-0182-z.

ONS - Operador Nacional do Sistema Elétrico. Relatório anual de avaliação das previsões de vazões - 2015 (Annual assessment report of the streamflow forecast). Available at http://www.ons.org.br/download/operacao/hidrologia/pvanual-2015.zip. Last access on 23 Aug 2015.

Van Loon, A.F., Van Huijgevoort, M.H.J., Van Lanen, H.A.J., 2012. Evaluation of drought propagation in an ensemble mean of large-scale hydrological models. *Hydrol. Earth Syst. Sci.*16, 4057–4078. doi:10.5194/hess-16-4057-2012

General Comment 3

The cluster analysis of the reservoir storage dynamics is an interesting view on their operation patterns. But the actual dynamics of single reservoirs over time, ideally with some ideas or information about the decision processes of the dam operators, should also be considered for discussing future management options. One open question to the reader of your current manuscript is: Did the reservoir system sufficiently buffer the drought effects or have there been stress situations (e.g. throttling of power stations) that could have been avoided by better management?

Response: As mentioned in the response to General Comment 2, we provide some information about the decision processes used by the dam operators and how our findings may be useful for future reservoir management.

Regarding the question "Did the reservoir system sufficiently buffer the drought effects or have there been stress situations (e.g. throttling of power stations) that could have been avoided by better management", we partially respond to this question with a new figure (Fig 1). The results shown in Fig 1 suggest that the linkages between meteorological and hydrological droughts changed over time. A short discussion is provided in the revised text on how the ability of the reservoir system to buffer the drought effects improved in 2014 compared to the early 2000s drought.

We mentioned in the introduction that the early 2000s drought led to energy-rationing programs and blackouts but the necessary data on dam operation to answer whether such stress situation could be avoided by better management is not publicly available. Given the fact that in 2000 the electric grid was not fully interconnected and other generation options (thermal power plants, etc) were less available, it is possible that the less critical situations, in term of electric generation, in 2014 were a result of better infrastructure rather than better reservoir management.

Specific comments

Practically all the numbers given are prepended with a math tilde ($\sim$) signalising

uncertainty. The heavy use of this feature clutters up the text and doesn't help much with the interpretation. As hydrologists, we are all aware of the ubiquitous uncertainty in our research field, so I suggest to largely delete these little distractions except in cases where you have only got a really rough guess. (And there,≈, would be the preferable character.

Response: Agreed. Changes made.

According to the Abstract, the Paraná Basin holds 70 million people, on Page 2, Line 15, the same number is given for the whole Southeast Brazil, and on Page 3, Line 26f, 60 million people live in the basin. It would be great to not only have the correct numbers but also their source.

Response: The Southeast Brazil and the Paraná basin have different population. The conflicting numbers were originated from outdated sources. The Southeast region holds 80 million and the Paraná basin holds 60 million. The numbers were revised and corrected; sources were indicated accordingly.

A similar issue exists with the percentage of the basin inhabitants in the Brazilian pop- ulation: 32 % (Page 1, Line 3 and Page 3, Line 27) or 65 % (Supplement Page 3, Line 6f)?

Response: We corrected that issue in the Supplement. It should read "65 million" instead.

Page 1, Line 9: Which one of the (at least two identified) drought events do you mean here?

Response: Soil moisture and runoff decreased during both droughts, resulting in reservoir storage depletion. Hence, this passage refers to both events. We re-wrote that sentence: "... during the droughts, resulting in decreased runoff into reservoirs. As a result, reservoir storage decreased . . . "

Page 1, Line 17: How were the dollar amounts adjusted to 2012 dollars? Did you

use the official Consumer Price Index (CPI)? Please explain.

Response: The dollar amounts were adjusted by the World Meteorological Organization (WMO) and made available in the cited report (http://www.uncclearn.org/sites/default/files/inventory/who002.pdf). We do not know which procedure was adopted by WMO.

Page 1, Line 19: No need to repeat "(adjusted to 2012 $)" here.

Response: We removed that.

Page 3, Line 2: I would rather write "How are different reservoirs operated under drought conditions?", because the reservoirs are not autonomously reacting.

Response: Agreed. This item was rephrased and now reads as suggested.

Page 3, Line 13: I would associate "regional reconnaissance" rather with a spy mission charting an enemy territory than with the blurred Earth view of the GRACE data. Maybe you can find a better term

Response: Agreed. We replaced "regional reconnaissance" with "regional evaluation".

Page 3, Line 22: The research domain area seems only vaguely known to the authors (∼800,000 km^2) although they obviously used a GIS for making the maps. It should be easy to have a more precise figure here.

Response: We replaced $\sim$ 800,000 km^2 with the actual area, 830,000 km^2.

Page 3, Lines 22 and 29ff: First, there seem to be 35 reservoirs in the Paraná Basin, then there are suddenly about 50, of which 37 are considered for the study. Please clarify. (According to what I see from the rest of the material, there are obviously more than 50 reservoirs within the basin, but you acquired the data of 50, including two reservoirs outside the basin. Finally you decided to study only 35 reservoirs within the basin and the two outliers. Is that correct?) The decision process that caused the reduction in the number of investigated reservoirs

should also described in detail here. There are some hints in the Supplement, but your criteria for keeping or dropping single reservoirs remain unclear.

Response: That is correct. There are more than 50 reservoirs in the basin, several of which have negligible volumes to the purposes of this study. We re-wrote those lines to clarify that our selection criteria consisted of (i) filtering the greater than 50 reservoirs to individual reservoir whose areas exceed 1000 ha; (ii) removing reservoirs whose time series contained gaps accounting for more than 50 % of their records.

Page 4, Line 1f: How many reservoirs belong to the Cantareira system and what is their overall storage capacity? How much storage volume is assigned to one inhabitant of São Paulo?

A more detailed description of the Cantareira system is provided in Section 2 as follows:

"The Cantareira system, São Paulo's main water supply system, has an overall storage capacity of 1.45 km^3, including the following reservoirs and respective storage capacities: Jaguari (0.14 km^3), Jacareí (0.89 km^3), Cachoeira (0.11 km^3) and Atibainha (0.3 km^3). Extended dry periods can be critical for the Cantareira and other surface systems. Since the 1960s, five droughts (1977, 1984, 1990, 1992, 2001, 2012 and 2014) reduced reservoir storage supplies for São Paulo (Coelho et al., 2015a). The Cantareira system contribute 47 % (33 m^3/s) of the total water supply to São Paulo's metropolitan region (SPMR) that encompasses 39 municipalities (19.6 million people in 2007) (Whately and Diniz, 2009). Before the water crises caused by the 2014 drought, 8.8 million people were supplied by the Cantareira system with $\approx$ 164 liters per inhabitant per day (SABESP, 2014)."

Page 4, Lines 10ff: The passage from "Standard GRACE spherical harmonic process- ing. . . " to ". . . solutions to match outputs from land surface models spatially" reads as if the respective GRACE data handling had all been your work. Is this true? If not, please make clear which parts of the data preparation were already included in the product you obtained from the University of

Texas CSR

Response: GRACE-based monthly gravity solutions in spherical harmonic format were obtained from the University of Texas Center of Space Research (CSR). We processed these data using standard procedures to reduce noise while minimizing signal loss, including truncation and filtering, then we converted the data to water mass change in terms of equivalent water height. We re-wrote that to make it clear:

"The GRACE-based monthly gravity solutions in spherical harmonic format from Apr 2002 through Apr 2015 were obtained from the University of Texas Center of Space Research (CSR) (Bettadpur, 2012). To reduce noise while minimizing signal loss, **we applied** standard post-processing, including truncation to degree and order 60, de-striping (Swenson and Wahr, 2006), and application of a 250 km Fan filter (Zhang et al., 2015). Then the filtered monthly gravity fields, **after removing the mean**, were converted to total water storage anomalies (TWSA) in gridded 1×1 **degree** solutions to match outputs from land surface models spatially"

Page 4, Lines 21ff: Which precipitation dataset did you use for calculating the SPI, Pobs or PSat ?

Response: We used both observed and satellite datasets to cover the entire studied period: Pobs (1995 - 2013) + Psat (2013-2015). That sentence was rephrased as follows to make it clear:

"Because Pobs is not available throughout the whole analyzed period, remotely sensed rainfall estimates (PSat) were derived from the Tropical Rainfall Measuring Mission (TRMM) Multisatellite Precipitation Analysis (TMPA) 3B43 version 7 product, for the period 2013-2015."

Page 5, Line 1: When applying hierarchical clustering, several decisions have to be taken. For instance, the distance measure or the cutoff height. The result can be quite different when you alter these parameters, so you should explain

explicitely what your choices were and why you made them. Beyond that, it remains absolutely unclear how the locations in the virtual clustering space were derived from the reservoir data. A clear picture about both points is essential for the methods description; this cannot be pushed away into the Supplement.

Response: Our choices were made by means of an interactive process instead of simply defining a value for maximum cluster distance (or cutoff height) and distance function. As you correctly stated, different results can be obtained by altering these parameters; hence, we tested various values, observed the resulting clusters and selected the option that captured, from our perspective, the different responses that exist among the 37 analysed cases. Analogously to project design in Engineering, there is more than one good option here. We do not intend to imply that our choice is the only or best choice, but provides a general overview of the main characteristics of the reservoirs in our sample. Concerning the locations in the virtual clustering space, figure S4 in the Supplement illustrate a simple case where the distance between elements are simply the distance in the Cartesian coordinate system because each element is a set of x,y coordinates. In our analysis, each element can be seen as a function y = f(x) and the distance between elements is measured for each x in the domain ($0 \leq x \leq 246$). The paragraph about this method was re-written to clarify obscure points mentioned above and the adopted value of the cut-off height is now reported in the results.

Page 5, Line 5: I would suggest renaming “Results” to “Results and Discussion”, because this is not clearly separated.

Response: Agreed. Change made.

Page 5, Line 13: Having been introduced to TWS on Page 4, Line 9, we have suddenly TWSA here. And from here on, TWS and TWSA are used interchangeably. As far as I understood the GRACE method, TWS can never be measured in its absolute quantity, only its alterations/anomalies, which is obviously the meaning of TWSA. Please use either TWS or (better) TWSA uniformly in your paper to

avoid confusion.

Response: Agreed. We changed TWS to TWSA throughout the paper.

Page 6, Line 2: This is probably the only place where the repetition of an acronym explantation would make sense: RESS was introduced three pages above and is mentioned here for the first time again.

Response: Agreed. Change made.

Page 6, Line 7f: Why are you so cautious here? The discrepancy is caused by further depletions in deep SMS and groundwater storage! What else could explain it? In the Supplement, you show at least four receding groundwater levels (Figure S7), I think this is more than obvious.

Response: We thank you for acknowledging our effort to support our claim. Perhaps we were too cautious here because we considered the possibility that one might suggest that we only showed a limited number of hydrographs with receding groundwater levels or because of the limitations inherent in SMS simulated by GLDAS.

We rephrased that sentence: "The discrepancy is most likely related to depletion in deep SMS or groundwater storage (GWS). "

Page 6, Line 13: ". . . below the equivalent system maximum capacity" – I am totally in the dark what you mean with the equivalent system. Please explain.

Response: The equivalent system referred to in this study consists of a fictitious reservoir whose storage equals the accumulated storage of the 37 reservoirs. This term is widely used in Brazil as it allows one to easily analyse multiple reservoirs that compose a single system. For instance, the Cantareira is an equivalent system of the reservoirs contained within it. The following sentence was included in Sec. 3.3: "This section presents the results relative to the analysis of the total monthly storage of all 37 reservoirs considered as one equivalent system. "

Page 6, Lines 22ff: Changes in GWS also need to be discussed as link between pre- cipitation and runoff – in drought phases, the remaining runoff is mostly sourced from Groundwater.

Response: Actually, as defined in Page 7, Lines 1-2, runoff in this case is the "infiltration excess (when rainfall exceeds the infiltration rate of the soils) or saturation excess (when soils are close to saturation)" and differs from river discharge (Q), which also includes discharge from the groundwater system during dry periods. We added "and differs from river discharge (Q) " to avoid confusion.

An interesting aspect not addressed here is a possible long-term trend of the GWS over the entire reporting period.

Response: We could not agree more with you about that. The reason we have not addressed long-term trends in groundwater storage in this paper is the limitations related to data access and data processing mentioned in the response to the General comments. In the case of GWS data, there are two portals in Brazil that hold these data. However, the options to search, filter and download these data are rather precarious. The user can either select and download the data for individual wells or perform a complete screening process of which wells are of interest and request the data directly from the data holders. Hence, the effort and time demanded to collect and process the necessary data limited us to include such analysis in the present study and limits us to deliver it in the revised version of our manuscript. However, we plan to examine long-term trends in GWS in a future study.

I also wonder why the role of evapotranspiration in the system is practically neglected here. You have got these data, not a good idea to hide them in the Supplement. This whole paragraph (running onto Page 7) barely scratches the surface and could largely profit by more comprehensive water balance and time series analyses

Response: We do not emphasize the ET data because of the large uncertainties and we do not try to close the water budget as we described in the earlier response to the general comments. We emphasize that this study is a first cut that builds on previous studies, such as the regional analysis of water storage based solely on GRACE and GLDAS (Getirana, 2015), by incorporating both regional water storage data with detailed analysis on individual reservoirs. We recognize that further analysis on the theme is necessary and we plan to conduct such studies in the future, including data on groundwater and ground-based ET. However, we moved some sentences from the Supplement to the main text and included a trend analysis of ET (Fig 2) data as follows:

"Comparison between ET estimates from the global algorithm (ETGlob) by Zhang et al. (2010) and from the MOD16 algorithm (ETMOD) by Mu et al. (2011) indicate a larger inter-annual variation in the latter relative to the former (Fig 2). Given the uncertainty in remotely sensed ET (Long et al., 2014), no attempt was made to identify whether the minima are overestimated by ETGlob or underestimated by ETMOD; rather, we analyse the changes in the ET signal. Although no significant trend in ET in response to the analysed droughts was observed with a $\geq$ 95 % (α=0.05) confidence level, ET decreased by -2.8 cm yr^{-1} between Jan 1998 and Jan 2001, and by -0.3 cm yr^{-1} between Feb 2010 and Feb 2014 (Fig. S8). From Jan 2003 to Jan 2010, a positive trend (α =0.05), shows that ET increased by 3.0 cm yr^{-1}. Such an increase is attributed to hydrologic system recovery as the soil moisture, greatly diminshed due to the drought, recovers to be taken up by the vegetation. In terms of annual ET, the ETMOD signal is practically invariant from 2000 through 2006 but a discrete increase in the moving average suggests that ET rates were higher in the following years (2007–2014). We analysed the change of the mean annual ET between these two periods (2000–2006 and 2007–2014) (Fig. 6). An increase in ET (70 to 200 mm) between these two periods was observed in most of the Paraná basin, especially over the contributing areas in most of the analysed reservoirs (Fig 6). Loarie et al. (2011) showed that replacing pasture by sugarcane in the Cerrado bioma increases ET; and São Paulo (SP) state (30 % of the PB) has been reported as the largest producer of sugar cane (Rudorff et al., 2010). However, the comparison between Fig. 2 and Fig. 6 show larger increases in ET (≥ 120 mm) in the PB occurring mostly in areas with annual crops and pasture, whereas the increase in ET in areas predominantly occupied by sugarcane ranges from 0 to 200 mm. Hence, further investigation would be necessary to precisely identify the causes for that increase"

Page 7, Line 24: Again, the mysterious equivalent system of reservoirs.

Response: This issue was addressed above.

Page 9, Line 1: Delete "reconnaissance", see above

Response: We replaced it by "evaluation".

Page 9, Line 7: "uncertainties in these estimate can be high" – Could you cite some literature or explain otherwise, why it is high and what is "high" in this context? Did you actually do the calculations for the PB and do not dare to publish the (strange?) results?

Response: We did not calculate the uncertainties for the Parana Basin. The uncertainty we refer to was verified by Long et al. (2013), who showed a large range in soil moisture storage estimated by six models. Such uncertainty was also mentioned by Scanlon et al. (2015).

Long, D., L. Longuevergne, and B. R. Scanlon (2014), Uncertainty in evapotranspiration from land surface modeling, remote sensing, and GRACE satellites, *W Resour Res*, 50(2), 1131-1151.
Scanlon, B.R., Zhang, Z., Reedy, R.C., Pool, D.R., Save, H., Long, D., Chen, J., Wolock, D.M., Conway, B.D., Winester, D., 2015. Hydrologic implications of GRACE satellite data in the Colorado River Basin. *Water Resour. Res.* 51, 9891–9903. doi:10.1002/2015WR018090

Pages 9 and 10, Section on implications for water resources: The findings presented here are rather thin. The first two paragraphs are a rug of commonplaces

(e. g. "Op timal management of reservoirs to reduce impacts of future droughts requires an understanding of the controls on reservoir storage", L. 13f) and repetitions ("Monitoring networks of GWS would be extremely beneficial, particularly because GWS can pro- vide information to estimate baseflow to streams", L. 7ff – "Monitoring GWS would also be beneficial for estimating baseflow to streams. . . ", L. 19f). The remaining paragraphs are mainly a wrapup of the results presented in the preceding sections and do not re- ally deliver new insights. Probably the entire section can be deleted without loss of relevant content.

Response: Agreed. We removed the entire section and moved the following part to Summary and Conclusions: "For most reservoirs, including the Cantareira System, meteorological droughts were reflected in the hydrologic system through reduced inflow to the reservoirs. The vulnerability to recent droughts in São Paulo underscores the need for reservoir storage expansion but also reinforces the urgency for diversifying the water sources to enhance drought resilience. In other cases, the upstream reservoirs performed an important role in regulating river discharge and, hence, reducing meteorological drought impacts on inflow to downstream reservoirs. "

Pages 10 and 11, Conclusions: This section should be renamed to "Summary and Conclusions ", because it rehashes again the findings before it states remarkably "This study emphasizes the importance of integrating remote sensing, modelling and monitoring data. . . " (L. 31) – while a real integration of all the data is just what is still missing in this paper

Response: We renamed this section to "Summary " As previously mentioned, the integration of all the data, although desirable, is intended in a future analysis where we plan to include much more detailed evaluation of ground-based data on groundwater storage and ET.

Figure 1: The basin maps are too small. They could be zoomed to equal size with the Brazil overview map as an inset in a corner of the elevation map (which

should be coloured stepwise – the mini scale with minimum and maximum values is of no use). The colour legend of the land use map can be split and also distributed into the northern corners, there is no need to show so much off-basin area in the north.

Response: Agreed (Fig 3)

Figure 1, Caption: What is meant by "(30 x 30 m)"? SRTM data? Then please cite the source properly

Response: 30 x 30 m refers to the approximate horizontal resolution of the elevation map processed from SRTM data by Valeriano and Rosseti (2012). Given that the actual coordinate system of that product is geographic, we rephrased that sentence as follows: The analysed reservoirs are highlighted in dark blue in the digital elevation map (1" horizontal resolution) (Valeriano and Rossetti, 2012)

de Morisson Valeriano, M., de Fátima Rossetti, D., 2012. Topodata: Brazilian full coverage refinement of SRTM data. *Appl Geog* 32, 300–309. doi:10.1016/j.apgeog.2011.05.004

Figure 2: The temperature graph should be replaced by the ET graphs which deserve much more attention.

Response: The temperature graph was replaced by the ET graph (Fig 4).

Figure 3: Should be replaced by the complete picture of the Supplement figure S17. Only three half-subjectively picked extreme years don't give an impression of the general variability

Response: Agreed. Change made.

Figure 7: This looks a bit like a student's pin board; the elements could probably be arranged more neatly in file.

Response: A new figure is provided (Fig 5)

From the Supplement, the following parts should be moved into the main paper: Section S2.4 on topography, climate and land use; Section S5.2 on ET with Figures S8 and S9; and most of Section S5.4 on cluster analysis with the dendrogram shown in Figure S12

Response: Agreed. Changes made.

Technical corrections: Response: We thank you for finding and indicating those errors. They were all corrected.

Supplement: There are also a larger number of typos, missing articles, unnecessary repetitions etc. which I won't list in detail. I would recommend having everything corrected by a native English speaker before re-submission.

Response: Agreed. One of the authors is a native English speaker and has reviewed the revised paper in detail.

Interactive comment on Hydrol. Earth Syst. Sci. Discuss., doi:10.5194/hess-2016-258, 2016.

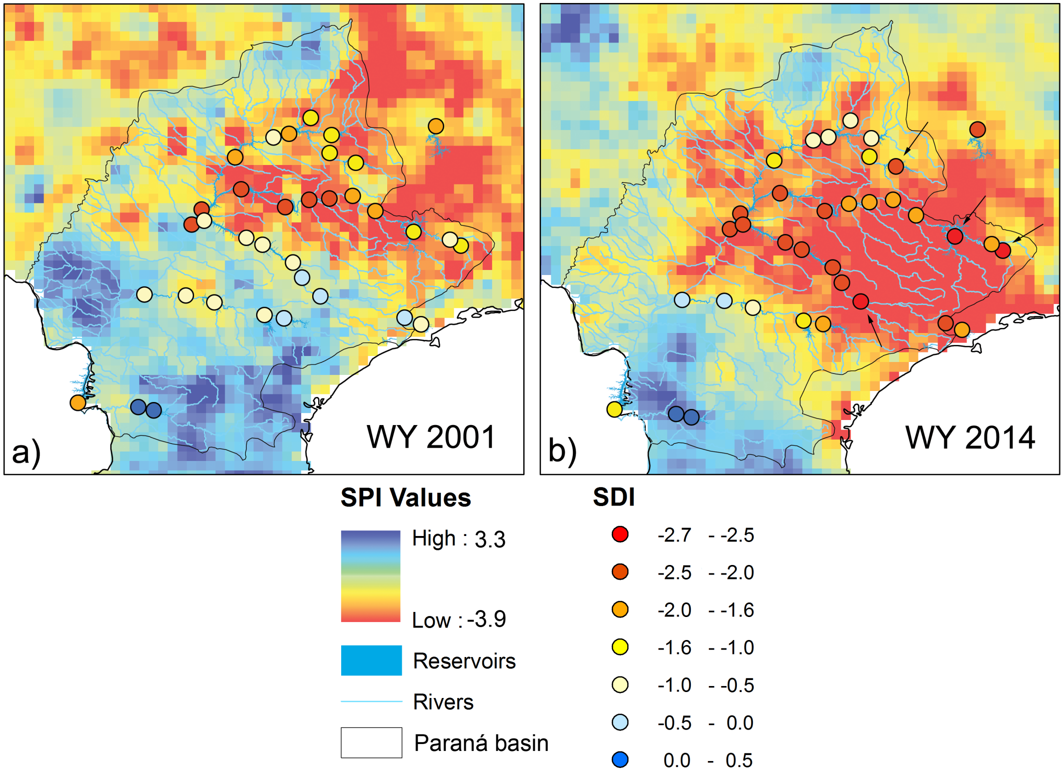

Fig. 1. Spatial variation of the Standardized Precipitation Index (SPI) and Streamflow Index (SDI) in the period of two droughts

Printer-friendly version

Discussion paper

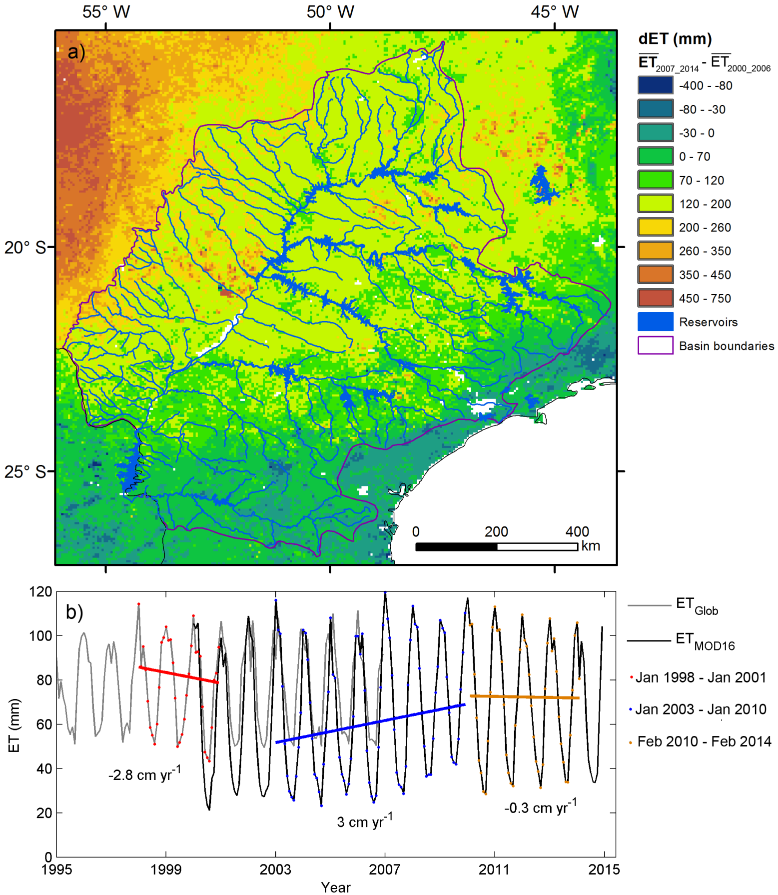

Fig. 2. Changes between the mean annual ET from 2007 to 2014 and 2000 to 2006 (a); short-term trends of ET in the Paraná basin (b)

Interactive comment

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Discussion paper

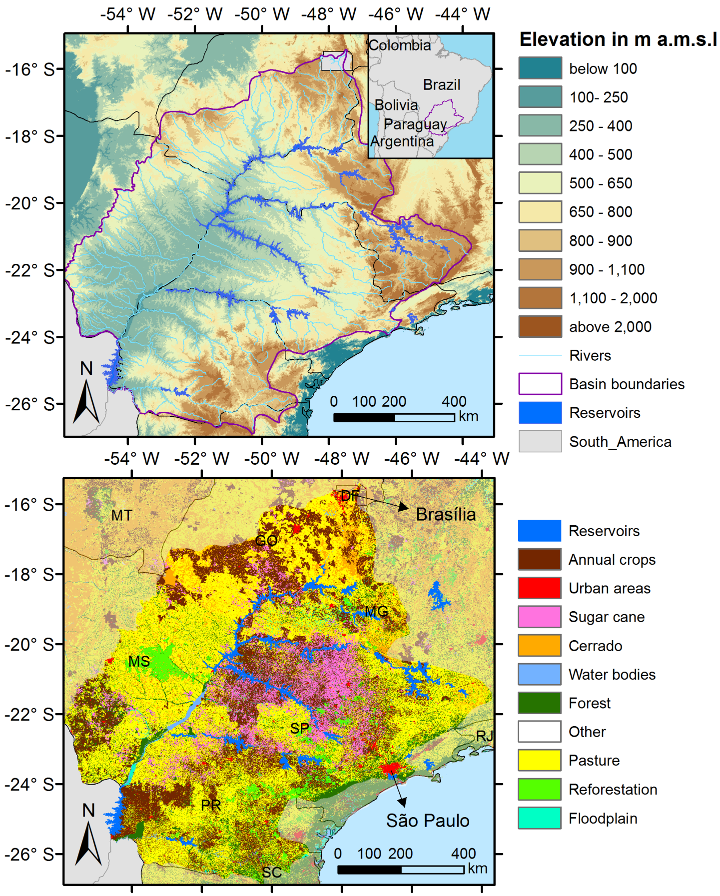

Fig. 3. The Paraná basin in the national context, digital elevation map (1” horizontal resolution) (Valeriano and Rossetti, 2012) and land use map (FEALQ, 2014)

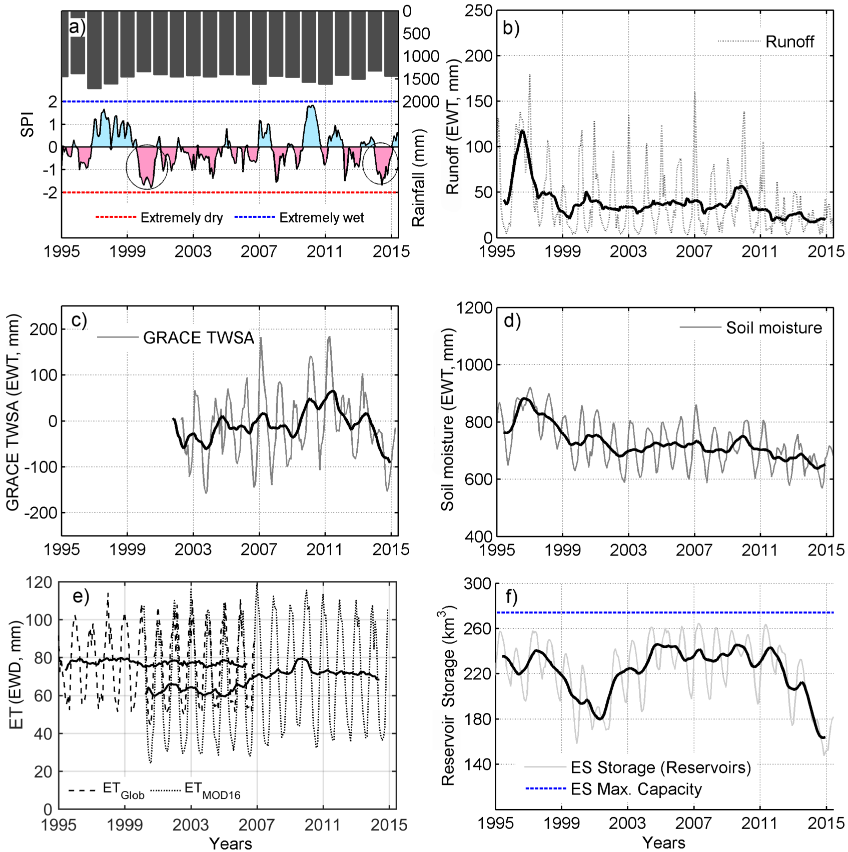

Fig. 4. . Time series of (a) rainfall and SPI, (b) runoff, (c) GRACE total water storage anomaly (TWSA), (d) soil moisture, (e) evapotranspiration (ET) and (f) reservoir storage in the equivalent system (ES)

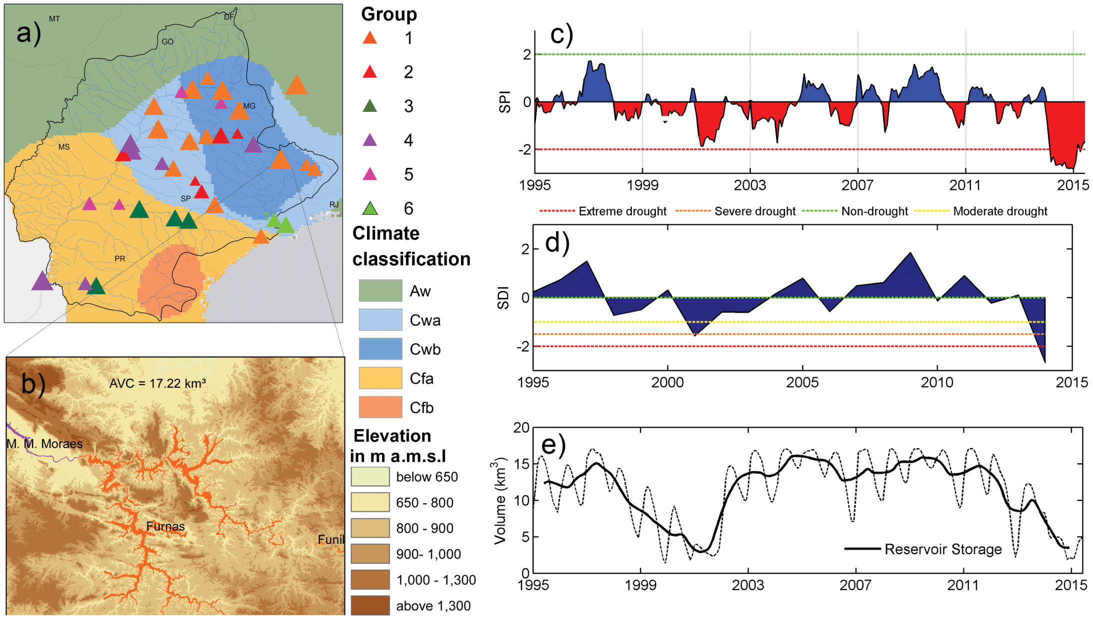

Fig. 5. The 37 analyzed reservoirs in the context of the Paraná Basin clustered in six groups and the number of elements per group. (b) Example of a typical reservoir from group 1: Furnas reservoir