Dear Dr. Weerts,

We are glad to submit a revised version of our manuscript entitled ‘Reservoir storage and hydrologic responses to drought in the Paraná River Basin, Southeast Brazil’, by D. C. D Melo et al.
We thank the reviewers for their valuable comments that helped us to improve the quality of our manuscript.
Please find enclosed the responses to both referees with a point by point explanation of each comment and a marked-up manuscript version.
The original comments by the reviewers are in bold, followed by our responses to them in normal font.
We indicated the Page (P) and Lines (L) where the modifications were made in the revised manuscript. These pages and lines refer to the .pdf version uploaded separately, not the marked-up version in this document.
We considered the evaluation of the suggested ET product from http://landsaf.meteo.pt/. It covers our study area but unfortunately it is available only from 2005 through Nov 2015, corresponding to about half of the analyzed period. For that reason, we did not include it in our analysis.

We hope that the revised manuscript meets the requirements for publication in this journal.
Thank you for your consideration.
On behalf of the co-authors,

Davi de C. D. Melo

Responses to referee #1

General comments

On behalf of the co-authors, I would like to thank Dr. Fernando Fan for the positive feedback and valuable comments. Each comment was addressed and specific responses can be found in the following section. The original referee comments are in bold, followed by our response.

Specific comments

Page 2, lines 5-10: This paragraph is not clear. Why authors just give the name of GRACE satellite and do not talk about the others satellites whose measure precipitation, evapotranspiration and etc..? And after authors are talking about TRMM without presenting it before. I suggest to improve it.

Response: That sentence was modified (P2, L5-8). We include examples of remotely sensed precipitation and evapotranspiration; we also provide the meaning of TRMM before mentioning it in the following paragraph.

Page 3, lines 21-30: I missed the citation from other works that addressed the Parana basin in the literature review. I believe that the authors could include some researches mentioning that this basin is or has been studied by other researchers in other hydrology research. This will give more importance to the work, allowing to understand how this work fits within the existing studies on the basin

Response: Agreed. The revised manuscript includes references to previous studies in the study area (P3, L18-21).

Page 4, line 15: I was not able to identify clearly in which depth was considered for soil moisture using GLDAS, the GLDAS product that the author used contains soil moisture information for various bands (0-10cm, 10-40cm, rootzone, etc). Is it possible to make it more clear in the text?

Response: A more complete description of the GLDAS models is provided in Page 4, Lines 31-34 of the revised manuscript.

Page 4, lines 20-30: If possible I would suggest to transfer more information about SPI/SDI Drought indices from supplementary material to the main text. It would be interesting to give some more detail about the methodology for calculating the SPI/SDI or at least cite the original work that proposed methodology.

Response: We moved the some information related to SPI/SDI from Supplementary Material to the main text (P5, L14-16 and P5, L20-21).

Page 5, lines 5-20: One of the study objectives was to identify the intensity, duration and extent of the droughts at the Parana watershed. It was clear what the periods of 2000 and 2014 had droughts and its duration and intensity (analyzing Figure 2). But for the spatial extent I think it could have been made a simple figure showing the spatial variation of the SDI/ SDI within the period of each drought, showing yet an outline of the area affected by the drought.

Response: To address this comment, we added Fig. R1 and some comments in the revised manuscript (P8, L29-P30, L4).

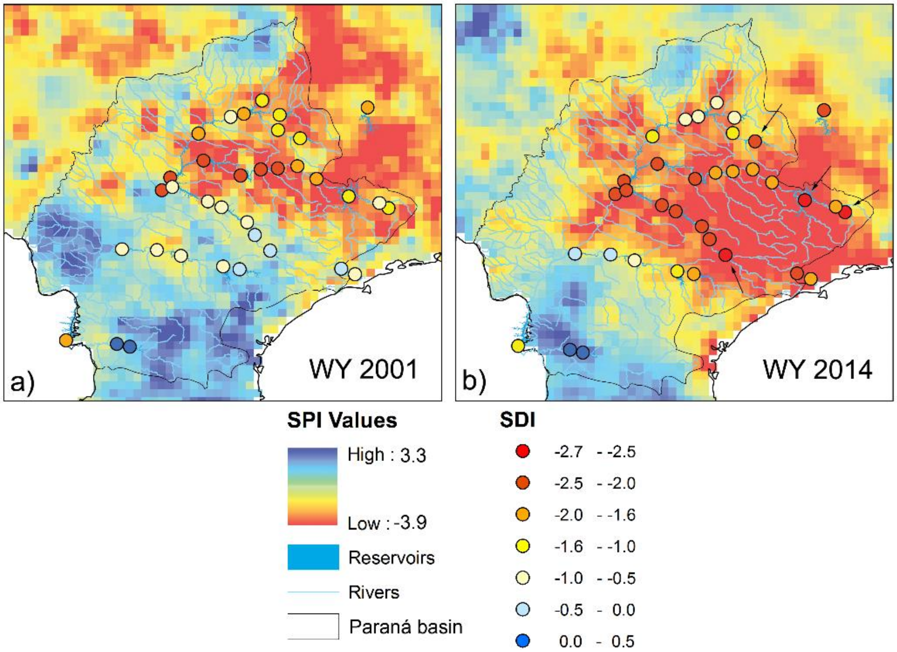

Figure R1 – Spatial variation of the Standardized Precipitation Index (SPI) and Streamflow Drought Index (SDI) in the period of two droughts.

Page 10, lines 25-30: In the conclusions authors shows a summary of results and emphasize as conclusions of the research the importance of integrating remote sensing, modelling and monitoring data and that the analysis highlights the importance of reservoir location. I think those statements are indeed true. But I also think they are kind of trivial, and they are not necessarily innovative conclusions of this single research. I suggest the authors to remove those conclusions (or shorten) and add a conclusion with inverted reasoning: how these results can be useful for the analyzed system? What they mean going for future management of water resources in the basin? How can we evolve with these used techniques for practical or more research purposes?

Response: We agree that they may not sound innovative but they summarize what we did in this study, so we would like to keep it. However, we added a more practical conclusion and replaced the term comprehensive" with "preliminary, as shown in this new paragraph to discuss the proposed question in Pag. 12, Lines 19-34.

Pages 9 and 10: At the discussions or conclusions. I also miss a paragraph, a scheme, a flowchart or something else highlighting the comprehensive understanding of the linkages between meteorological and hydrological droughts for future management proposed in the study objectives. Who are them? Is it possible to make them more clear?

Response: This was addressed in the paragraph in P12, L19-34, inserted in the revised version.

Technical corrections
Page 3, line 7: Please keep verbs tenses consistent. In this case, in the past

Response: Done

Page 5, lines 23-25: I suggest to rewritten this paragraph to avoid the triple "The Grace …"
Response: Agreed. Those sentences were rephrased (P6, L26-29).

Responses to referee #2

General comments by the authors

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 (Page 11) 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, *Theoretical and Applied Climatology*, pp. 1–16, 2015. doi:10.1007/s00704-015-1540-9

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, 2015. doi:10.1371/journal.pone.0138278,

Getirana, A. C. V.: Extreme water deficit in Brazil detected from space, *Journal of Hydrometeorology*, 2015. doi:10.1175/JHM-D-15-0096.1

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, *Geophysical Research Letters*, *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, *Climate Dynamics*, 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 R1) 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 (P3, L22-25).

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 new paragraphs (P12, L19-34) to show how our findings can contribute to future management and replaced "comprehensive understanding" with "preliminary understanding".

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". *Meteorology and Atmospheric Physics* 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 R1). The results shown in Fig R1 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 (P8, L29-P30, L4).
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 (~) 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,$\approx$, made by $\approx$, 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 population: 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 (Supplemente, P1, L48).

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 (P1, L8-9).

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.
We indicate that this adjustment was made by WMO in Page 1, Line 18.

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 (P3, L3).

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 km²) although they obviously used a GIS for making the maps. It should be easy to have a more precise figure here.

Response: We replaced ~800,000 km2 with the actual area, 830,000 km2.

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 (P5, L3-11).

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 Page 4, L10-17.

Page 4, Lines 10ff: The passage from ``Standard GRACE spherical harmonic processing. . . " 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 (P4, L24-29):

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 (P4, L20-23).

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 S5 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 (P5, L31-P6, L7; P9, L9-12).

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. This sentence was rephrased (P7, L9-10).

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 Page 7, Lines 13-14: "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 precipitation 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 (P8, L23).

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 R2) (P7, L32-P8, L15).

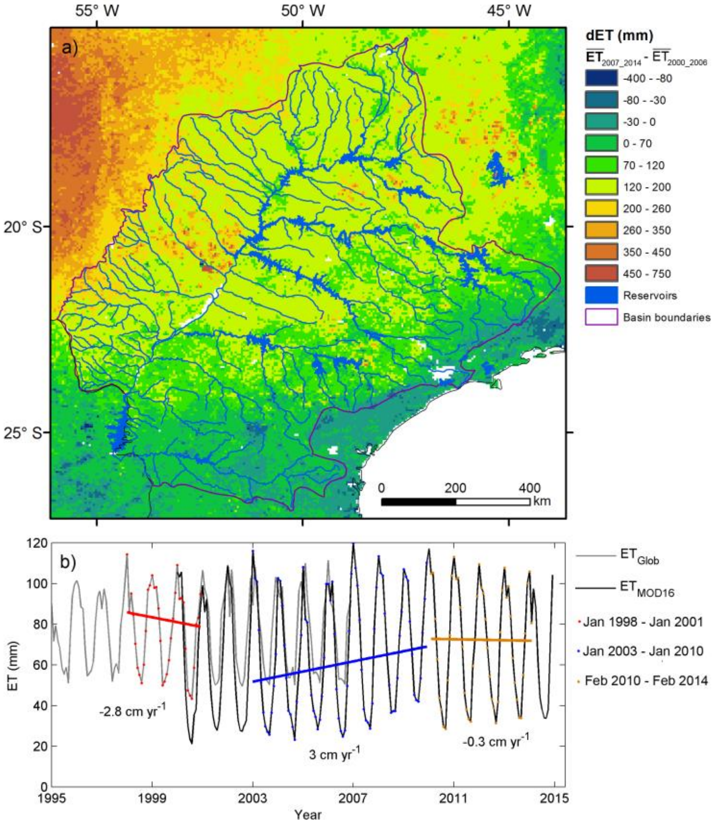

Figure R2 – Changes between the mean annual ET from 2007 to 2014 and 2000 to 2006 (a); short-term trends in ET in the Paraná basin (b)

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: Agreed.

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. "Optimal 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 provide 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 really deliver new insights. Probably the entire section can be deleted without loss of relevant content.

Response: Agreed. We removed the entire section and moved part of it to the Summary (P12, L14-18).

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 R3)

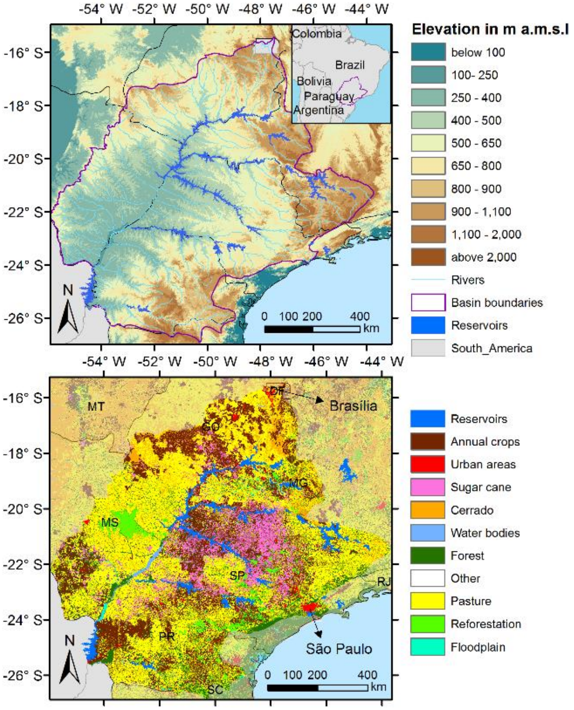

Figure R3 -The Paraná basin in the national context, digital elevation map (1” horizontal resolution) (Valeriano and Rosseti, 2012) and land use map (FEALQ, 2014)

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 shown in Fig. R3.

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 R4).

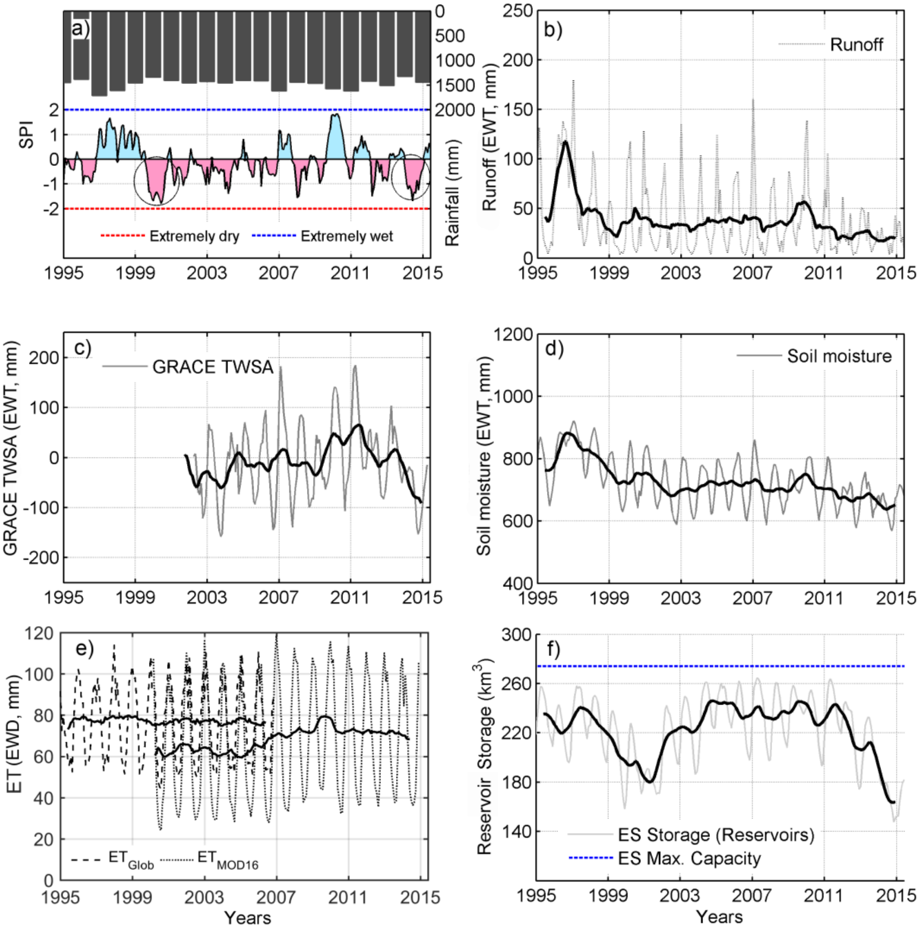

Fig R4 - Time series of (a) rainfall and SPI, (b) runoff, (c) GRACE total water storage anomaly (TWSA), (d) soil moisture, (e) evapotranspiration (ET) and (f) reservoir storage in the equivalent system (ES)

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 R5)

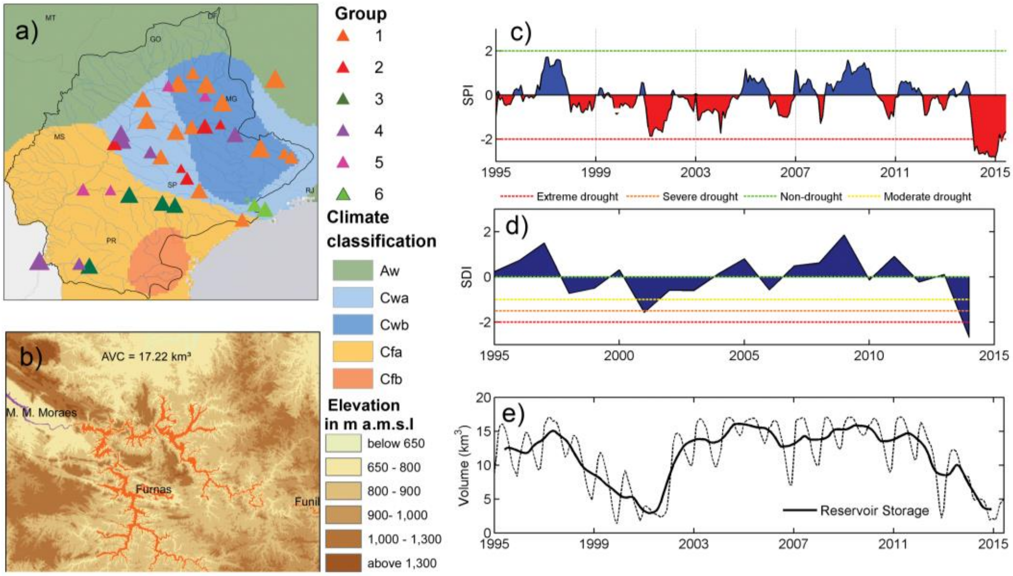

Fig R5 - The 37 analyzed reservoirs in the context of the Paraná Basin clustered in six groups and the number of elements per group. (b) Example of a typical reservoir from group 1: Furnas reservoir

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.

Reservoir storage and hydrologic responses to droughts in the Paraná River Basin, Southeast Brazil

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Abstract. Droughts are particularly critical for Brazil because of impacts on water supply and because most (~~$\sim$~~70 %) of its electricity is derived from hydroelectric generation. The Paraná Basin (PB), a major hydroelectric producing region with ~~$\simeq$~~ 32 % (~~$\sim$ 70~~ 60 million people) of Brazil's population, recently experienced the most severe drought since the 1960s, compromising the water supply for ~~$\sim$~~11 million people in São Paulo city. The objective of this study was to quantify linkages between meteorological and hydrological droughts based on remote sensing, modelling, and monitoring data using the Paraná River Basin in Southeast Brazil as a case study. Two major meteorological droughts were identified in the early 2000s and 2014, with precipitation 20-50 % below the long-term mean. Total water storage estimated from the Gravity Recovery and Climate Experiment (GRACE) satellites declined by ~~$\simeq$~~ $\approxeq$150 km^3 between Apr 2011 and Apr 2015. Simulated soil moisture storage declined during the droughts, resulting in decreased runoff into reservoirs. As a result, ~~R~~reservoir storage decreased $\approxeq$~~$\simeq$~~ 30 % relative to the systems maximum capacity, with negative trends ranging from ~~$\sim$~~17 km^3 yr^{-1} (May 1997 - Apr 2001) to 25 km^3 yr^{-1} (May 2011 - Apr 2015). Storage in upstream reservoirs is mostly controlled by natural climate forcing whereas storage in downstream reservoirs also reflects dam operations. This study emphasizes the importance of integrating remote sensing, modelling, and monitoring data to evaluate droughts and to establish a comprehensive understanding of the linkages between a meteorological and hydrologic drought~~s~~ for future management.

1 Introduction

Droughts have large scale socioeconomic impacts, responsible for ~~$\sim$~~35 % of disaster-related deaths and ~~$\sim$~~200 billion US dollars (US$, adjusted to 2012 by WMO~~$~~) in losses globally between 1970 and 2012 (WMO, 2014). In South America, 48 droughts were responsible for 23 % (US$16.5 billion) of losses caused by disasters (1970 - 2012), including the 1978 Brazilian drought, responsible for a loss of ~~$\sim$~~US$ 8 billion ~~(adjusted to 2012$)~~ (WMO, 2014). There are a variety of different types of droughts, including meteorological, agricultural, hydrologic, and

socioeconomic (Wilhite and Glantz, 1985). Investigating individual types of drought limits understanding of how they are connected, i.e. how meteorological drought (precipitation deficit) propagates through the hydrologic system resulting in socioeconomic drought,
for example. Socioeconomic drought is characterized by the failure to supply economic goods (water, hydroelectric power, etc) as a result of water deficits (Wilhite and Glantz, 1985). Because these drought types are usually related to one another, societal impacts of droughts are often conveyed through linkages between them (Fiorillo and Guadagno, 2009).

Establishing linkages between meteorological and hydrologic droughts is challenging due to the large spatiotemporal variability in water distribution. Increasing availability of remotely sensed ~~(RS)~~ ~~changes~~ anomalies in terrestrial total water storage (TWSA) data from the Gravity Recovery and Climate Experiment (GRACE) satellites, precipitation *estimates from Tropical Rainfall Measuring Mission (TRMM)*, and evapotranspiration (ET) *estimates from Moderate Resolution Imaging Spectroradiometer (MODIS)* greatly enhances our ability to assess linkages between the different types of droughts (Tapley et al., 2004; Huffman et al., 2007; Mu et al., 2007). In addition to remote sensing data, Global Land Data Assimilation Systems (GLDAS) land surface models (LSMs) provide valuable data on water budgets related to droughts (Rodell et al., 2004).

Meteorological drought indicators, such as the standardized precipitation index (SPI), have been used to forecast hydrologic droughts based on a streamflow Drought Index (Tigkas et al., 2012; Fiorillo and Guadagno, 2009). Major hydrologic regimes have been characterized using satellite data (GRACE, TRMM) and GLDAS LSMs (Awange et al., 2014). GRACE satellite data have been used to assess impacts of droughts on TWSA in large basins globally (Long et al., 2013; Leblanc et al., 2009).

In Brazil, drought related studies have focused mostly on the Amazon basin (Frappart et al., 2012; Nepstad et al., 2004; Yin et al., 2014) or semi-arid Northeast Brazil (Marengo et al., 2013). However, Southeast Brazil (~~∼70~~80 million people), accounting for ~~∼~~55 % of national GDP in 2012 (IBGE, 2010; IBGE, 2014), has been subjected to two major droughts since 2000. The early 2000s drought was responsible for a major energy crisis in Brazil, leading to energy-rationing programs and even blackouts, attributed in part to limited transmission and interconnection (Rosa and Lomardo, 2004). The more recent drought (2014) compromised the water supply for ~~∼~~11 million people in Brazil's largest Metropolis: São Paulo.

Reservoir levels in São Paulo's main water supply system (Cantareira System) dropped below 15 % of capacity. The 2014 drought jeopardized potable water supplies of ~~∼~~133 cities (~~∼~~28 million people) in the Southeast region (Lobel et al., 2014), where there are ≈~~∼~~50 reservoirs ~~reservoirs~~ with individual areas exceeding 1000 ha, mostly in the Paraná basin. The 2014 water year (Sep 2013 - Aug 2014) was the driest on record in São Paulo city area since

1962 (Coelho et al., 2015a) with simulated reservoir dynamics changing in response to drought (Coutinho et al., 2015). Analysis of GRACE TWSA ~~anomaly~~ data indicate that between Feb 2012 and Jan 2015, total water storage declined~~e~~ by ~~∼~~6 $\mathrm{cm\,yr^{-1}}$ (56 $\mathrm{km^3\,yr^{-1}}$; totalling 160 $\mathrm{km^3}$) in Southeast Brazil as a result of reduced rainfall (Getirana, 2015).

In this context, it is reasonable to ask whether the meteorological forcing is primarily responsible for the socioeconomic droughts in the region. Would an improved electric distribution system avoid the blackouts that occurred in the early 2000s? Is the water crisis in São Paulo solely linked to meteorological factors? Was 2014 also the driest water year in the entire Southeast region in decades? Were these two droughts similar and, if so, did they result in similar impacts? Finding the linkages between different types of droughts is important to answer these questions. Hence, the objective of this study was to address the following questions related to linking meteorological and hydrologic droughts in the Paraná River Basin in Southeast Brazil:

- What is the intensity, extent, and duration of the recent droughts?
- What are the drought~~s~~ impacts on terrestrial total water storage and reservoir storages?
- How do the droughts propagate through the hydrologic system?
- How are different reservoirs operated under drought conditions?

The Paraná basin (PB) was selected as a case study because of the severity of recent droughts and widespread impacts

on water supply and hydroelectricity generation. To answer these questions, we used remotely-sensed total water storage anomalies from GRACE (Section 2.1, SI Section S3.4), remotely-sensed and ground-based gridded rainfall datasets (Section 2.1, SI Section S3.3), remotely sensed ET (Section 2.1, SI Section S3.3), simulated soil moisture storage and runoff from four LSMs (2.1, SI Section 3.2), and monitoring data from 37 reservoirs (2.1, SI Section 3.1). We used (i) statistical indices to characterize meteorological and hydrologic droughts (Section 2.2, SI Section S4.3), (ii) tests statistics to evaluate the impacts on reservoir storage (Section 2.2, SI Sects. 4.1 and 4.2) and (iii) studied differences and similarities between individual reservoirs (Section 2.2, SI Section S4.4).

Unique aspects of this study include the ~~comprehensive~~ preliminary assessment of droughts using a variety of remote sensing, modelling and monitoring approaches and indicators, comparison of multiple droughts and related hydrologic impacts, and variety of scales of analyses from regional reconnaissance using GRACE satellites to local reservoir responses. This study builds on previous studies, such as the reconnaissance evaluation of drought in Southeast Brazil based on GRACE satellite data by Getirana (2015) by expanding remote sensing, modelling, and monitoring data. The Paraná basin is one of the most studied areas in Brazil, given its relevance in the national context. *Previous hydrologic studies in this area include assessment of climate change impacts on water resources (Adam et al., 2015; Nóbrega et al., 2011), energy and hydrologic modelling (Camilloni et al., 2013; Ruhoff et al., 2013; Getirana et al., 2010), assessment of remotely sensed evapotranspiration (Ruhoff et al., 2013) and energy-based estimation of evapotranspiration (Ruhoff et al., 2012). In terms of drought-related studies,* the area of the Paraná River Basin is much larger~~greater~~ than evaluated in some previous analyses that were restricted to São Paulo city (Coelho et al., 2015b, a; Coutinho et al., 2015). Another recent study brought some insight regarding drought propagation by quantifying the time lag responses of the hydrological system to meteorological shifts; they found a lag of ≈6 months between significant change in SPI and reservoir storage; and ≈1 month between SPI and river discharge (Melo and Wendland, 2016). The large areal extent allows surface reservoir impacts to be assessed at local to system scales, considering upstream-downstream drought impacts based on observed reservoir storage (RESS) data. The results of this study should enhance our understanding of linkages between meteorological and hydrologic droughts to better manage water resources in this region and similar other regions.

2 Study area, data and methods

The study area (~~∼~~ ~~800~~830, 000 km2) comprises the contributing basins to 37~~5~~ reservoirs: 35 within the Paraná basin, and two other nearby reservoirs (Três Marias and Paraibuna) selected because they are in areas affected by the 2014 drought (Fig. 1, Table S2). ~~This~~ The Paraná basin was originally covered by Cerrado and Mata Atlantica biomes which have been replaced by pasture (44 %), annual crops (24 %), sugarcane (9 %) with original Cerrado and forests only occupying 7-9 % each of the land area (FEALQ, 2014). Most of the reservoirs are located near the center of the basin, where the land use consists, basically, of annual crops and sugar cane. Center pivots in the region are mainly located in the northern and southeastern parts of the PB (Fig S2f). Mean rainfall is 1, 500 mm yr−1 and temperature is 23 ◦C (1980-2014) (Xavier et al., 2015).

The topography in the Parana basin (PB) consists, basically, of high plains with maximum altitudes higher than 2,000 m a.m.s.l. (Fig. 1). Most of PB is under temperate highland tropical climate with dry winters (Cwb) and humid subtropical climate with hot summer (Cfa) or with dry winter (Cwa) (Fig. S3b). This basin covers parts of seven Brazilian states (SP, MG, DF, GO, MS, PR and SC) (Fig. 1). Population in the basin (~~∼~~60 million in 2010) represents 32 % of the Brazilian population (SI, section S2.1), including the most populated city in Brazil (São Paulo), with ~~∼~~11 million people in 2015 (ANA, 2010). ~~The reservoirs in São Paulo's main water supply system (Cantareira) have individual storage capacities ranging from 0.1 – 1 km^3~~. The Cantareira system, São Paulo's main water supply system, has an overall storage capacity of 1.45 km³, including the following reservoirs and respective storage capacities: Jaguari (0.14 km³), Jacareí (0.89 km³), Cachoeira (0.11 km³) and Atibainha (0.3 km³). 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 m³/s) of the total water supply to São Paulo's metropolitan region 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 ≈164 liters per inhabitant per day (SABESP, 2014).

2.1 Data sources and processing

This section provides a general overview of the data sets used in this study. Additional details are provided in SI, Section S3.0. Ground-based rainfall data (P_{obs}) from ~~∼~~≈ 1270 gauges (Fig. S3) for the period 1995 - 2013 were interpolated to a $0.25^{\circ} \times 0.25^{\circ}$ grid by Xavier et al. (2015). Because P_{obs} is not available throughout the whole analyzed period, ~~R~~remotely sensed rainfall estimates (P_{Sat}) were derived from the Tropical Rainfall Measuring Mission (TRMM) Multisatellite Precipitation Analysis (TMPA) 3B43 version 7 product, for the period 2013-2015. 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.

The analysis of soil moisture (SM) and runoff (R_{off}) is based on outputs from four Land Surface Models (LSM) from GLDAS 1.0: NOAH, Mosaic, VIC, and CLM (Rodell et al., 2004). *The number of vertical layers (VL) and respective depths (D) vary among LSMs: CLM (10 VL,* $0 \le D \le 3.43\,m$*), Mosaic (3 VL,* $0 \le D \le 3.5\,m$*), NOAH (4 VL,*$0 \le D \le 2.0\,m$*) and VIC (3 VL,* $0 \le D \le 2.0\,m$*). SM is the average layer soil moisture (ALSM) from individual LSMs. ALSM was obtained by depth-averaging the water amounts in specific soil layers*. Descriptions of the LSMs and GLDAS are provided in Section S3.2, SI. The *ET* datasets used were derived from the global ET algorithm (ETGlob) developed by Zhang et al. (2010) and from the MOD16 global evapotranspiration product (Mu et al., 2011) (SI, section S3.3).

There is a large number of reservoirs in the PB, several of which with negligible volumes in the context of this study.

Considering the effort to compile and process the data from individual reservoirs, only reservoirs with individual areas exceeding 1000 ha were selected for analysis (criterion I). The volume of a reservoir with area inferior to 1000 ha ranges around 0.25 km^2, accounting for less than 0.1% of the average storage capacity analyzed in this study.

Approximately 50 reservoirs remained after the application of criteria I. Most of those reservoirs have the primary purpose of generating hydroelectricity. A second criterion was applied, removing cases whose time series contained gaps accounting for more than 50% of their records. Due to data limitations, only 37 of the 50 reservoirs were considered in this study. The maximum storage capacity of the 37 reservoirs is $\approx 250\ km^3$. Daily data on inflow, outflow, water level and storage for 37 reservoirs were downloaded from the Brazilian Water Agency (ANA, Agência Nacional de Águas) web site for the period Jan 1995 - Jun 2015.

2.2 Data analyses

The Standardized Precipitation Index (SPI) was selected as the meteorological drought index because it is probabilistic, its implementation is relatively simple, and its interpretation is spatially invariant (Guttman, 1998). *SPI uses historical rainfall data to determine, at different timescales, the periods of positive and negative anomalies in rainfall based on the cumulative probability of rainfall occurrence over an area or at point (McKee et al., 1993)*. We used the 12 month SPI based on historical monthly rainfall data relative to a 35-year time span (1980-2015) (SI, Section 4.3).

The Streamflow Drought Index (SDI) (Nalbantis and Tsakiris, 2008) was selected as the hydrologic drought index because it is analogous to SPI in that it is computationally inexpensive, easy to implement, and reduces the drought characterization

to a simple severity versus frequency relationship (Nalbantis and Tsakiris, 2008). *For each water year, SDI is obtained for overlapping periods of 3, 6, 9 and 12 months based on cumulative streamflow data*. In addition, it is not data demanding as it requires only streamflow data (SI, Section S4.3). For practical purposes, drought onsets were classified when SPI/SDI were < -1 for at least 6 months. Further details related to calculating SDI are provided in SI, Section 4.3.

The statistical significance of reservoir depletion and trends in monthly reservoir storage were investigated by applying the non-parametric Mann-Whitney U-test (MW U) and a modified version of the rank~~ed~~-based non-parametric Mann-Kendall test (MK) (Kendall, 1975; Mann and Whitney, 1947). The MW U test is a common alternative to the parametric Student`s t-test for testing whether two samples come from the same population (SI, Section 3.1). The MK method is used to avoid making assumptions regarding the distribution of the data and reducing sensitivity to outliers (Hamed, 2008). To overcome possible issues due to positive correlation in the analyzed time series (SI, Section S4.2), we adopted a modified MK trend test for seasonal data with serial correlation (Hirsch and Slack, 1984).

Hierarchical clustering (HC) was used to group the reservoirs and is a commonly adopted approach to identify similar groups

among hydrologic time series (Brito Neto et al., 2015). The similarities among elements and groups of elements are measured by a distance function (Bailey, 1994) which, along with the maximum cluster distance, compose the main parameters to define in a HC method. In this study, we used the Euclidean distance (see Sec. 4.4 in SI for equations) as distance function because it’s been shown to produce good results in past studies (Ramoni et al., 2002) and is available in the Matlab toolbox used here. The maximum cluster distance (MCD) defines the distance below which the objects are considered as part of a single group (see SI, Fig. S12). In this study, we adopted an interactive process to define MCD in which various values were tested, the resulting clusters were observed and a final option was chosen based on its capability to represent the variability existing in the sample. ~~In this study, t~~The ~~objects~~ elements used to generate the clusters are time series of normalized monthly reservoir storage (SI, Section S4.4), that is, we seek to group the reservoirs with similar responses at monthly scale~~.~~ Hence, the clustering analysis performed here does not consider other reservoir characteristics such as storage capacity, location, shape, etc.

3 Results and Discussion

3.1 Meteorological droughts

Two distinct droughts were identified in the Paraná Basin between 1995 and 2015 based on SPI (Fig. 2). The first drought began in Oct 1999 and extended through Aug 2000, during which SPI was ≤ -1.25, characterizing a moderate to severe drought ($-2 \leq \mathrm{SPI} \leq -1$). This drought was followed by a moderate dry year as the average SPI was ~~$\sim$~~≈ -0.6 during the rainy season of 2001 (Dec - Feb). The second driest period occurred between Feb 2014 and Nov 2014, with SPI ≤ -1.20 (Fig. 2). The first drought is hereafter referred to as the early 2000s drought and the second drought~~,~~ as ~~the~~ 2014 drought. The 2014 rainfall deficit was previously identified as part of a prolonged drought (2012 - 2015) by Getirana (2015), who applied break tests to TWSA time series and found a change occurring in Feb 2012. Although our analysis of GRACE-based TWSA also indicates an abrupt change between 2011 and 2012, this change in TWSA reflects a hydrological drought.

The intensity and duration of the drought is spatially variable. Rainfall anomalies in water year (WY) 2001 (Sep 2000-Aug 2001) were~~as~~ more negative over the eastern and northern part of the Paraná Basin whereas the spatial extent of the 2014 drought was greater as most of the PB experienced a reduction of ~~∼~~20 - 40 % in annual rainfall (Fig. 3; SI, section S5.6). Most of the reservoirs are in areas where rainfall deficits ranged from 20 - 50 % of the long-term average (1982-2015). The negative rainfall anomalies decreased towards the southwest portion of the basin which experienced a positive anomaly of up to 20 %. Between 2002 and 2009, two periods of average rainfall with different inter-annual ranges were found followed by an extremely wet year (WY 2010), mainly over the southeastern part of the PB (Fig. 3), after which rainfall systematically decreased.

3.2 GRACE Total Water Storage Anomaly and Component Storages

The GRACE satellite data provide valuable information on regional extent of drought impacts on total water storage anomaly (TWSA), despite its coarse spatial resolution (~~∼~~100 - 200 km^2) (Fig. 4). TWSA data from GRACE does not include the 2001 drought as its monitoring period is from 2002 to present. Analysis of GRACE data indicate greater depletion in TWSA (~~∼~~-60 to ~~∼~~-90 mm yr^{-1} between Apr 2011 and Apr 2015) in Southeastern Brazil, which corresponds to the northeast part of PB. This range encompasses the results reported for the period between Feb 2012 and Jan 2015 by Getirana (2015) whose findings indicate a water depletion rate of -61 mm yr^{-1} in southeastern Brazil (~~∼~~≈920 km^2), corresponding to ≈~~∼~~160 km^3 over three years. The spatial extent of the negative TWSA (Fig. 4) is generally consistent with the spatial distribution in the negative rainfall anomaly in WY 2014 (Fig. 3).

GRACE-TWSA shows large seasonal variability that can be accounted for by seasonal fluctuations in soil moisture storage (SMS) from LSMs and monitored reservoir storage (RESS) (Fig. 5). Interannual variability in GRACE TWSA shows anomalously wet years in 2007 and 2010, related to elevated rainfall. SMS and RESS were also above average in those years. The peak TWSA in Jan 2007 shows the rapid response of the system to the peak in SPI during the same period (Fig 2). Note that SPI was low or close to 1 between 1999 and 2006; therefore, the peak TWSA was not preceded by high rainfall in 2006. There is a long-term decline in TWSA from Apr 2011 to Apr 2015 (≈~~∼~~37 km^3 yr^{-1}, ~~∼~~≈42 mm yr^{-1}), totalling 148 km^3. Depletion in TWSA (~~∼~~≈42 mm yr^{-1}) is greater than that in SMS and RESS combined (~~∼~~≈24 mm yr^{-1}) by ~~∼~~≈40 %. The discrepancy ~~may be~~is most likely related to depletion in deep SMS or groundwater storage (GWS). Simulated SMS from LSMs is restricted to the upper 2 m of the soil profile.

3.3 Analysis of Combined Reservoirs as an Equivalent System

This section presents the results relative to the analysis of the total monthly storage of all 37 reservoirs considered as one equivalent system. According to the MW U test, ~~T~~there is strong evidence (probability $\geq$95%) that the early 2000s (p-value = 0.027) and 2014 (p-value = 0.01) droughts resulted in significant depletion of the total reservoir ~~storage based on the MK U test~~. This depletion corresponds to a reduction of ~~∼~~40 km^3 (~~∼~~−17%) in WY 2001 and ~~∼~~ 34 km^3 (~~∼~~−15%) in WY 2014 of the average storage volume and of ~~∼~~90 km^3 (~~∼~~−33%) and ~~∼~~86 km^3 (~~∼~~−31%) below the equivalent system maximum capacity.

Comparing the negative trends in RESS, the recent drought was more intense than the earlier drought: between 1997 and 2001, the equivalent RESS decreased by 17.1 km^3 yr^{-1} relative to 25.3 km^3 yr^{-1} between 2011 and 2015 (SI, Fig. S10). The reservoir system responded rapidly to the meteorological shifts. RESS was lowest at the beginning of the water year 2001; SPI values indicate the meteorological drought began in Oct 1999, when the SPI was at ~~∼~~−1.3. During the wet period of 2002, the reservoir systems began to recover and by early 2003 the reservoirs were operating at normal capacity, even though the SPI indicated a 30 normal-to-moderately dry condition. Additional information about the recovery/depletion of reservoirs in a spatial context is presented in SI, Section S5.5

3.4 Drought propagation through the system

Variations in precipitation translate to changes in soil moisture storage (SMS) that affect runoff (R_{off}) and ultimately impact RESS. SMS and R_{off} were similarly affected by the early 2000s drought (Fig. 2). After 2001, the almost one decade of relatively normal rainfall was insufficient for SMS and R_{off} to recover from the drought. Not even the extreme wet period in 2010/2011resulted in SMS and R_{off} recovery. Given that rainfall continued to decrease in the following years, the negative trend in SMS and R_{off} persisted.

The average temperature in the Paraná basin decreased by ~~∼~~0.04 °C yr^{-1} within the past 20 years (SI, Fig. S9). However, the analysis of both temperature and ET were inconclusive regarding their impacts on reservoir storage change. ~~Further information about these variables is provided in SI (Section S5.2).~~ Comparison between ET estimates from the global algorithm (ET$_{\text{Glob}}$) by Zhang et al. (2010) and from MOD16 algorithm (ET$_{\text{MOD}}$) by Mu et al. (2011) indicate a larger inter-annual variation of the latter relative to the former (Fig 2). Given the uncertainty involved in remotely sensed ET (Long et al., 2014), no attempt was made to identify whether the minimums are overestimated by ET$_{\text{Glob}}$ or underestimated by ET$_{\text{MOD}}$; rather, we analyze the changes in ET signal. Although no significant trend of ET in response to the analyzed droughts was observed with a confidence level ≥ 95 % (α=0.05), ET decreased -2.8 cm yr^{-1} between Jan 1998 and Jan 2001, and -0.3 cm yr^{-1} between Feb 2010 and Feb 2014 (Fig. S8). From Jan 2003 to Jan 2010, a positive trend, significant at α=0.05, show that ET increased 3 cm yr^{-1}. Such increase reflects the recovery of the hydrologic system as the moisture, absent due to the drought, becomes available again to be consumed by the vegetation.

In terms of annual ET, ET_{MOD} 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 of ET (70 to 200 mm) 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 sugar cane 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 higher increase of ET (≥ 120 mm) in the PB occurring mostly in areas with annual crops and pasture, whereas the increase of ET in areas preponderantly occupied by sugar cane ranged from 0 to 200 mm. Hence, further investigation would be necessary to, precisely, identify the causes for that increase.

The analysis of R_{off}, SMS and TWSA provides insights into the mechanisms that may explain the reservoir responses to droughts. According to SPI, the rainfall regimes during both droughts are similar; however, the greater impacts on reservoir storage in 2014 is likely explained by different antecedent soil moisture conditions. The fact that SMS did not recover after the early 2000s drought implies that higher rainfall amounts would be required for recovery to overcome the cumulative SMS deficit. The extremely wet conditions in 2010/2011 were only sufficient to partially replenish the reduced SMS. Complementary graphs are presented in Supporting Materials, Section S4.2. Runoff can be classified as 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. Therefore, R_{off} is highly sensitive to SMS conditions. If rainfall is insufficient to recover SMS, then R_{off} cannot recover either. After 2010/2011, SMS, R_{off}, and TWSA continued to decline, hence, the main inflow to the reservoirs (river discharge), which depends on runoff and baseflow (groundwater discharge to streams), also decreased. The years preceding the early 2000s drought were wetter than those preceding the 2014 drought: SPI exceeded 1.5 (severely wet) throughout most of the 1997 through 1999 period, and SMS and R_{off} were more than 20 % higher than the following years. Therefore, SMS links meteorological drought to R_{off}, which affects the primary input to RESS: streamflow.

Streamflow data was used to calculate the Streamflow Drought Index and provide insights on linkages between meteorological and hydrologic droughts (Fig. 6) for the water years of 2001 (WY 2001) and 2014 (WY 2014). In general, meteorological droughts resulted in hydrologic droughts, as indicated by the extreme low values of SDI where SPI was negative (Fig. 6). However, some upstream reservoirs (highlighted with arrows) seem to have buffered the effects of the 2014 drought in the downstream reservoirs. Although SPI indicate a severe to extreme dry situation ($SPI < -2$) over those reservoirs, SDI increased from upstream ($SDI < -2.50$) to downstream ($-2.5 < SDI < -2.0$). This means that the river discharge deficit (hydrologic drought) caused by the meteorological drought was (modestly) attenuated by the upstream reservoirs.

Comparison between WY 2001 and 2014 show a larger extend of the most recent drought inside the Paraná basin (PB), which agrees with the rainfall anomaly in Fig. 3. Except for the south and central south of PB, the extent of the hydrologic drought was more critical in WY 2014 than that observed for WY 2001. For instance, the same sub-basin in the center of PB had, in WY 2001, $-0.99 \leq SDI \leq 0$, whereas, in WY 2014, $-2.70 \leq SDI \leq -2.00$.

3.5 Cluster analysis applied to reservoir storage

Changes in RESS reflect the impacts of climate extremes through SMS and R_{off} and also reservoir management for hydroelectricity and water supply. ~~Therefore, reservoir storage reflects a balance between climate forcing and dam operations.~~ Cluster analysis suggested that the reservoirs could be subdivided into six groups (G1, G2, . . . ,G6) based on the time series signal of monthly storage (Figs.7 and 8). The main features intended to be highlighted by creating those clusters in Fig. 7 are: seasonality and changes in time, which will be discussed below. The hierarchical tree of the groups and linkages between them ~~is~~ shown in a dendrogram was obtained by setting the maximum cluster distance (MCD) = 0.6 (Fig. 8). Although the dendrogram in Fig. 8 may suggest higher link consistency for MCD ≈ 0.5, similar characteristics of the seasonal signal would be present in the new groups formed from G1. Hence, the configuration in Fig. 8 was kept. Further details and discussion about such choice is provided in Sec. S5.4 in the Supplementary Material. ~~Although dam are managed primarily by humans, d~~

Dam operations are ~~also~~ constrained by non-human-controlled variables (e.g. natural inflows) and legal obligations to maintain outflows exceeding a minimum value (Q_{min_out}) at all times. The compliance with Q_{min_out} aims to guarantee multiple uses of water resources and is defined by the Electric System National Operator (ONS - Operador Nacional do Sistema Elétrico) for each hydroelectric power plant (HEP). Hence, even though the released outflow from a given reservoir may be reduced to control the decline in storage during a drought, the reservoir will, eventually, experience some depletion given the need to observe Q_{min_out}. 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 to generate scenarios of projected natural discharges at different time scales. Here, we sought to identify how human control and natural forcing dictate the responses in each reservoir.

3.5.1 Natural controls

The reservoirs in group 1 (G1, 15 out of 37) are characterized by well-defined seasonal variations, with good correspondence
between storage change and natural input to the contributing basins (Figs. 7, 8). In general, their storage through time is similar to that described by the equivalent system of reservoirs in terms of depletion during the early 2000s and 2014 droughts. Within G1 reservoirs, the inflows compare well with SPI, indicating a major role of natural forcing on reservoirs responses.

Similarly, comparison between SPI, SDI and RESS in G3 reservoirs also suggests their responses are strongly affected by natural variability (Figs. S37 - S40). Different responses between G1 and G3 reservoirs can be explained by climatological
variations (Fig. 9). The main climatic difference between G1 and G3 reservoirs is the pronounced dry season that occurs in the climate sub-types Cwa (humid subtropical with dry winter), Cwb (temperate highland tropical) and Aw (tropical wet and dry) in G1 reservoirs whereas rainfall is more evenly distributed throughout the year in the sub-type Cfa (humid subtropical) in G3 reservoirs. The occurrence or absence of dry winters affects the seasonal distribution of inflows to reservoirs, hence, impacting the seasonal signal in reservoir storage. Good correspondence between reservoir response and precipitation regime is not restricted to reservoirs in the upper part of the basin, i.e. reservoirs with no upstream reservoir affecting their inflow. What happens in the other cases is that the natural inflow (from undisturbed basins) contributes to the total inflow that explains the reservoir storage change as much as the regulated discharge delivered by the reservoir(s) upstream or the outflow from upstream mimics natural discharge variations (SI, section S5.7).

Although G6 reservoirs are similar to G1 reservoirs in terms of having a well-defined seasonal variations with good correspondence between precipitation variability and reservoir storage change, G6 reservoirs seem to deplete/recover more slowly than those in G1. The reservoirs of the Cantareira System are included within G6 reservoirs (Fig. S53). This system experienced major depletion as result of natural water stress imposed by the recent drought (2014) combined with high demand from São Paulo metropolitan area. The total rainfall in the 2014 water year was 1150 mm, ~25 % lower than the average since 1995, resulting in SPI ≤ -2 (extremely dry). The lowest reservoir levels registered in the storage of the system (early 2015) reached ~ 10 % of the total capacity, making the impacts of the 2014 drought unique.

3.5.2 Anthropogenic controls

Reservoirs in G2 and G5 do not show distinct seasonal variations, indicating that their responses are mainly governed by how they are operated and how the upstream dam is operated, given that all reservoirs in these groups are downstream of other hydroelectric power plants. In addition, the natural component of the total inflow is minimal because the upper undisturbed basin accounts for a small fraction of the total contributing area (Figs. S32 - S36 and S47 - S50). As a result, SPI fluctuations are not always reflected in reservoir storage. In such cases, analysis of SDI is inconclusive as it cannot provide information on natural discharge variability unless the human-controlled component of Q is removed.

For example, storage doubled in the Jaguará reservoir (G2) between 2001 and 2005 (0.04 to ~ 0.08 km^3) even though SPI and SDI indicate the onset of a meteorological and hydrologic drought (Fig. S34). That period was followed by an extremely wet year (2007/2008) but the rainfall increase was not reflected in the inflow (SDI $\approx\sim 0$) or in increased reservoir storage. Finally, no significant depletion was found during the extremely dry period in 2014. The main difference between G2 and G5 reservoirs is the change in average reservoir level (mainly after 2002), positive for G2 and negative to G5, displayed by most of those reservoirs (Fig. 7).

3.5.3 Natural and Anthropogenic controls

Responses in G4 indicate that these reservoirs are equally controlled by natural and operational forcing. The natural component is reflected in the seasonality of storage variation. Their location in the PB, downstream to large reservoirs (Figs. S42-S47), makes them vulnerable to anthropogenic controls. Similar to G2 and G5 reservoirs, storage changes in G4 reservoirs are highly affected by dam operations, which implies that a precipitation deficit can be compensated by reducing outflow and benefiting from regulated discharge from upstream. However, persistence of low inflow may require operation that drastically reduces reservoir storage to maintain Q_{min_out}. That is precisely what happened at the M. M. Moraes Hydroelectric Power Plant (Fig. S43) in 2014 as the Electric System National Operator (ONS - Operador do Sistema Elétrico) decided to reduce the reservoir level by ~8 m.

3.6 ~~Implications for Water Resources~~Future research

The findings presented here and in previous studies related to drought impacts in the Paraná basin are baseline for future analysis. There are a number of gaps that need to be addressed; here we name some. A first prospect to be considered in the future is to quantify drought impacts on the regional water budget. Because remote sensing data sets, especially ET estimates, are not sufficiently reliable to close the budget (Sheffield et al., 2009; Long et al., 2014), future studies should incorporate more ground-based data, such as groundwater level data.

Further analysis on drought propagation features is necessary to better characterize such extreme event in the PB. Van Loon et al. (2012) compiled a number of studies on that topic and identified the following features: pooling (combined meteorological droughts causes a prolonged hydrologic drought); attenuation (terrestrial stores attenuate meteorological drought); lag (between meteorological drought, soil moisture and hydrological drought); and lengthening (longer droughts moving through soil moisture to hydrological droughts). The lag feature was partially addressed by Melo and Wendlad (2016) as lag times between changes in SPI, reservoir storage and river discharge were estimated.

Future researches can profit from more detailed information regarding the decision processes considered for dam operations. Such information is not usually publicly available in Brazil. Hence, this can create a good opportunity to promote more bi-lateral collaboration, especially between hydrology researchers and engineers.

~~GRACE reconnaissance~~ monitoring ~~data provide valuable information for water resources assessment as monthly changes in TWS over large regions can be monitored. Such information can be used to assess the regional responses of the hydrologic system to climate and anthropogenic forcing. Data on the components that make up TWS (SMS and GWS) are generally limited. SMS data are derived primarily from land surface models. Ground-based monitoring of SMS is limited but should be expanded to assess the reliability of SMS estimates from land surface models. GWS can be estimated from GRACE TWS by subtracting the other components of water storage (RESS and SMS); however, uncertainties in these estimates can be high. Monitoring networks of GWS would be extremely beneficial, particularly because GWS can provide information to estimate baseflow to streams.~~

~~This study emphasizes the evolution of drought from meteorological drought through SMS changes to hydrologic drought~~

~~and ultimately impacting RESS. Assessing the relative importance of natural and anthropogenic controls on RESS is critical with natural forcing dominant in upstream and some downstream reservoirs, and anthropogenic controls primarily in down- stream reservoirs. Optimal management of reservoirs to reduce impacts of future droughts requires an understanding of the controls on reservoir storage and relative importance of natural and anthropogenic controls. Relating SPI to SMS, R_{off}, and RESS links meteorological drought to the hydrologic system within a regional context. This study emphasizes the role of antecedent SMS in controlling R_{off} and, ultimately, impacting reservoir responses to drought. Continuous monitoring of SMS would be extremely beneficial in determining when R_{off} might occur in response to precipitation related to drought recovery and would also help with assessing floods because SMS can be used for predicting runoff and streamflow responses to increase/reduced rainfall. Monitoring GWS would also be beneficial for estimating baseflow to streams that provide inflow to reservoirs.~~

~~Because rainfall is spatially variable and dam operation affects downstream reservoirs, distinct impacts on reservoirs were identified depending on their position within the Paraná Basin.~~

~~The group analysis of reservoirs indicates that the responses of individual reservoirs are ultimately controlled by the balance between climatic forcing and reservoir operations. The system response, including upstream-downstream location of reservoirs, needs to be considered when assessing drought impacts. Reservoir operations can benefit from conjunctive optimization in~~

~~which the operation of upstream and downstream reservoirs are accounted for along with weather forecasting and past water storage information.~~

4 Summary

Regional intense droughts in southeast Brazil have caused major depletion in water resources. We analysed remote sensing, monitoring, modelling data to identify linkages between meteorological and hydrologic droughts. Based on SPI, two major meteorological droughts occurred in the Paraná basin between 1995 and 2015. A moderate to severe drought $(-2 \leq \mathrm{SPI} \leq -1)$

occurred in the early 2000s with SPI ≤ -1.25 between Oct 1999 and Aug 2000. The second driest period occurred between Feb and Nov 2014, with SPI ≤ -1.20. Droughts intensity and duration are spatially variable. The 2014 drought was more critical over the northeastern part of the study area, with rainfall anomalies ranging between −20 to −60 %, resulting in SPI values ≤ -2.0 for 6-12 months in some cases (e.g. Furnas reservoir, Fig. 8).

The recent drought monitored by GRACE satellites shows depletion of TWSA of ≈~~∼~~37 km^3 yr^{-1} (42 mm yr^{-1})

over four years from 2011 to 2015 in the Paraná Basin, totaling ≈~~∼~~150 km^3. Simulated SMS and monitored RESS together decreased by 24 mm yr^{-1}, accounting for ≈~~∼~~60 % of TWSA depletion. This recent drought was preceded by an earlier drought (early 2000s) that occurred prior to GRACE monitoring. Reduced rainfall and negative SPI during this drought translated to low SMS and reduced runoff (SDI anomalies) decreasing RESS by~~∼~~30 km^3 in 2001 relative to the average storage volume. Depletion of reservoir storage caused by the early 2000s and 2014 droughts correspond to a~~∼~~31 % reduction relative to the reservoir equivalent system maximum capacity. Two negative short-term trends in RESS were found during the studied period: −17.1 km^3 yr^{-1} (1997-2001) and 25.3 km^3 yr^{-1} (2011-2015), totalling 68 and 101.2 km^3, respectively.

The period between these two droughts is characterized by slightly below average to near normal rainfall; however, rainfall levels were insufficient to overcome the cumulative water deficit that built up during the early drought. Low SMS compromised recovery even after the severely-wet year in 2010. As a result, the system storage reserves were low going into the recent drought and were rapidly depleted during 2014.

While GRACE satellites provide data on regional water storage depletion and recovery related to drought, SMS and R_{off} from LSMs link meteorological drought to hydrologic drought as shown by streamflow anomalies (SDI) that are reflected in inflows anomalies to the reservoirs. However, detailed assessment of drought impacts on reservoir storage requires more thorough analysis of reservoirs at the local scale. Clustering analyses in this study revealed three groups of reservoirs (23 reservoirs) with storage controlled mainly by natural climatic forcing, two groups (9 reservoirs) controlled mainly by reservoir operations and one group (6 reservoirs) controlled by a combination of natural and anthropogenic forcing (dam operations).

The analysis highlights the importance of reservoir location within the system (upstream vs. downstream) in determining the dominant controls on drought impacts on reservoir storage. 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.

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.

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

This study emphasizes the importance of integrating remote sensing, modelling and monitoring data to quantify the duration, extent, and severity of regional droughts and their impacts on water resources, specifically reservoir storage; system evaluation

and detailed analysis of individual reservoirs to determine controls on reservoir response to drought (e.g. natural climate forcing versus dam operations), and the importance of this comprehensive understanding on the linkages between the meteorological and hydrologic droughts for future management.

Author contributions. The first author collected and processed the data from GLDAS, ANA and ONS. ZZ processed and analysed the data from GRACE. LY processed the rainfall data and analysed the results. EW and BS analysed the data and commented on the paper, which was written by DM and BS.

5 Data availability

All the data used in this study is hosted by the Laboratory of Computational Hydraulics of the University of São Paulo and is available at http://albatroz.shs.eesc.usp.br/?q=dados-de-pesquisa.

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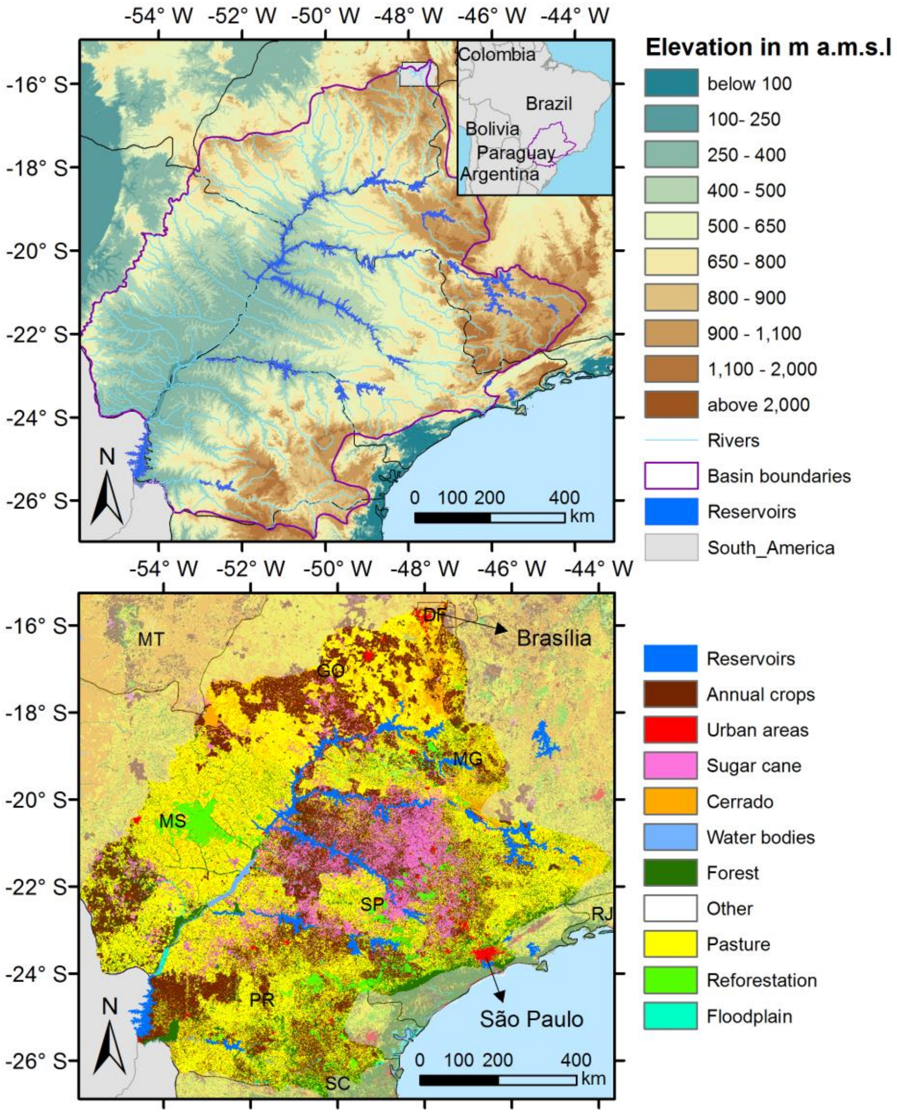

Figure 1. (a) The Paraná River Basin in the national context. (b) The analysed reservoirs are highlighted in dark blue in the digital elevation map (1” horizontal resolution) (Valeriano and Rossetti, 2012) and in (c) the 2012 land use map (FEALQ, 2014). States include: Distrito Federal (DF), Goiás (GO), Minas Gerais (MG), São Paulo (SP), Paraná (PR), Santa Catarina (SC) and Mato Grosso do Sul (MS).

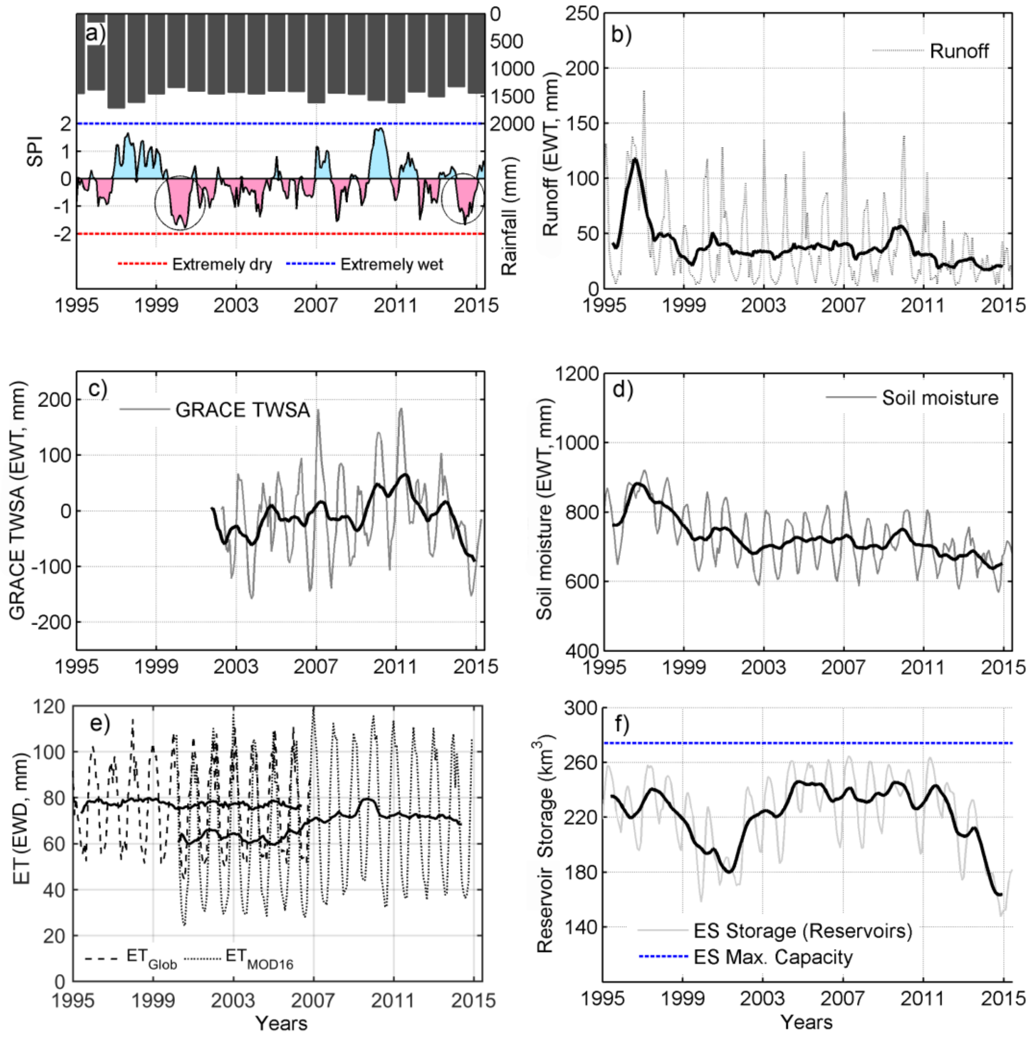

Figure 2. Time series of (a) rainfall and SPI, (b) runoff, (c) GRACE total water storage anomaly (TWSA), (d) soil moisture, (e) evapotranspiration (ET) and (f) reservoir storage in the equivalent system (ES). (a) Standardized Precipitation Index (SPI) categories include: extremely wet (SPI>2); severely wet ($1.5 \leq \mathrm{SPI} < 2$); moderately wet ($1 \leq \mathrm{SPI} < 1.5$); wet ($0.5 \leq \mathrm{SPI} < 1$); normal ($-0.5 \leq \mathrm{SPI} < 0.5$); moderately dry ($-1 < \mathrm{SPI} \leq -0.5$); dry ($-1.5 < \mathrm{SPI} \leq -1$); severely dry ($-2 < \mathrm{SPI} \leq -1.5$); extremely dry (SPI <-2). (b) runoff, (c) GRACE total water storage anomaly (TWSA) and (d) soil moisture are expressed in equivalent water thickness (EWT).

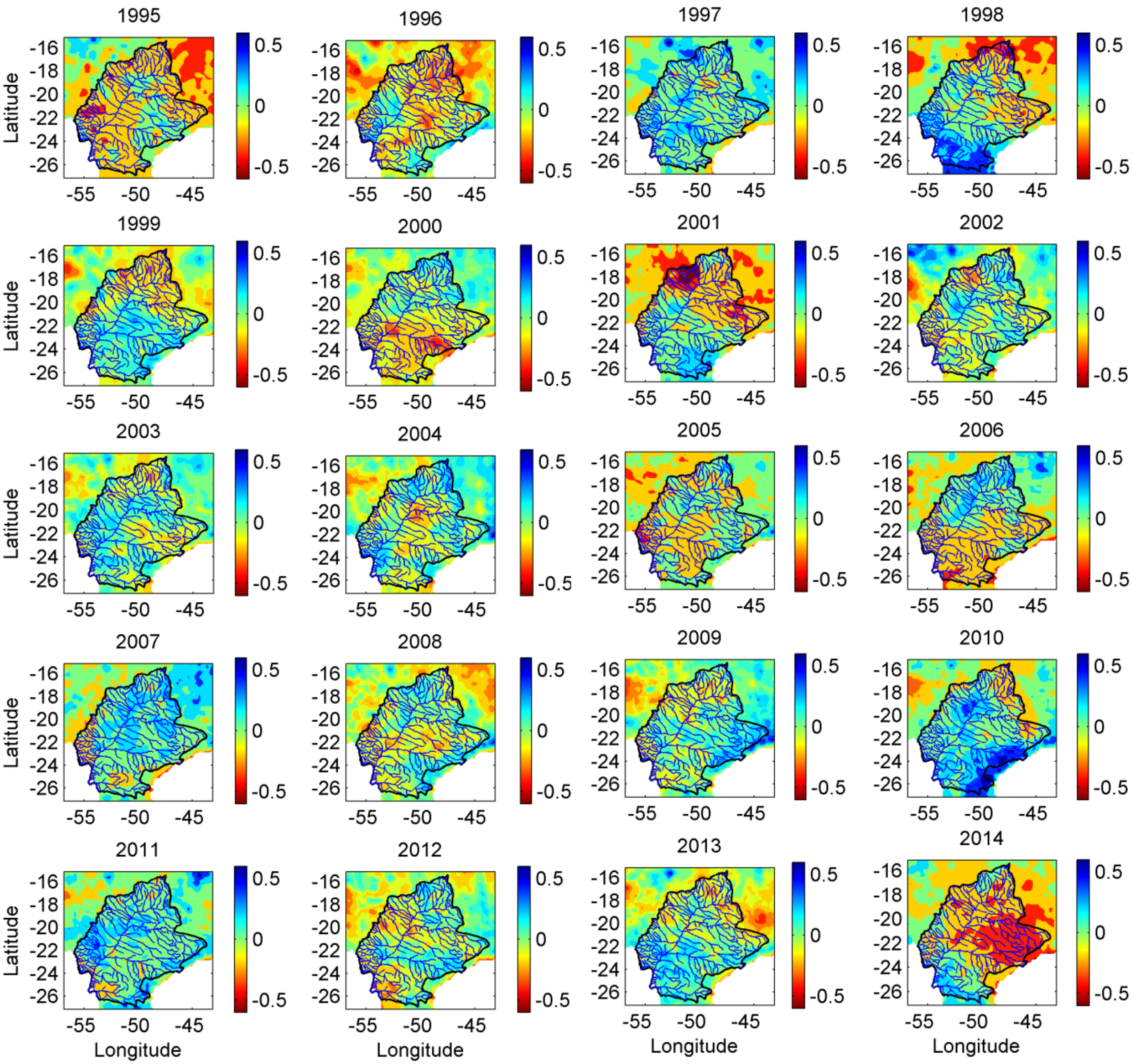

Figure 3. Rainfall anomaly relative to the 1982-2015 mean for 20 analyzed water years (Sep – Aug).

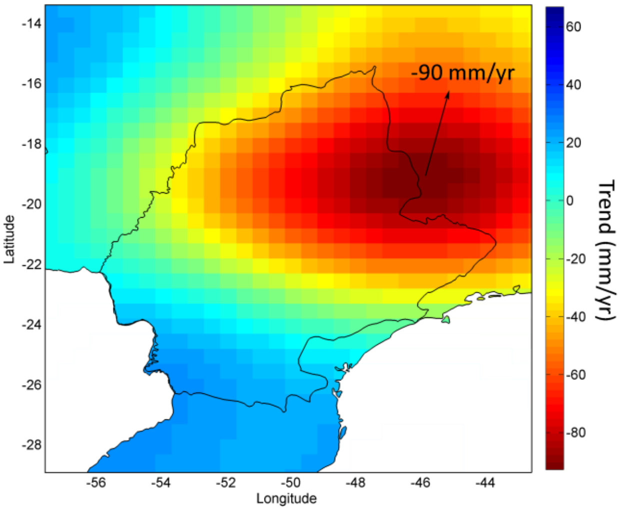

Figure 4. Spatial trends of TWSA between Apr 2011 and Apr 2015

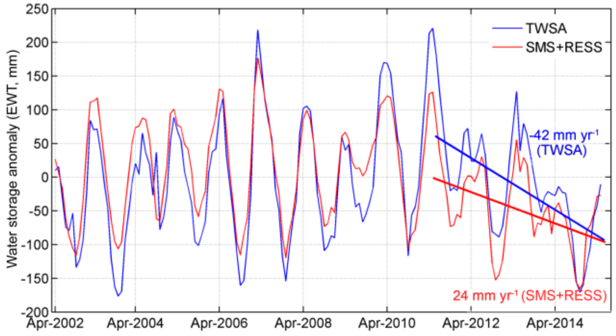

Figure 5. Water Storage Anomalies from GRACE TWS, soil moisture storage (SMS) and reservoir storage (RESS), all expressed as equivalent water thickness.

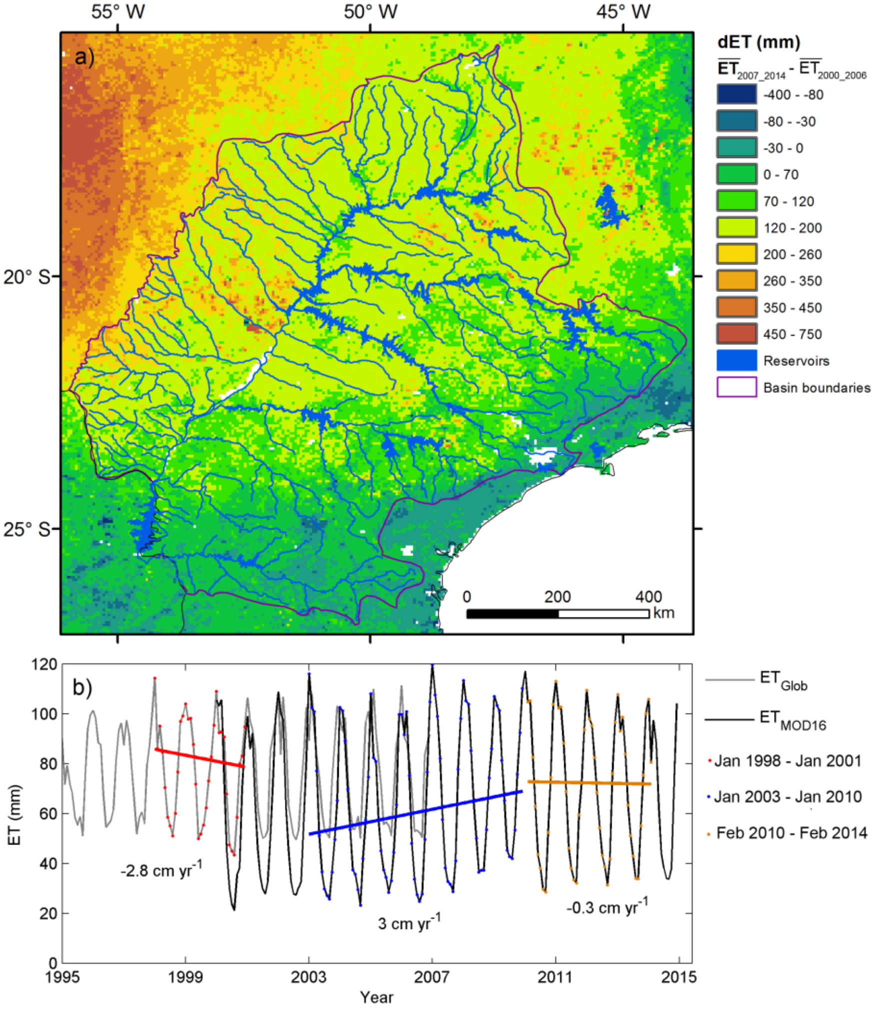

Figure 6. Changes between the mean annual ET from 2007 to 2014 and 2000 to 2006 (a); short-term trends of ET in the Paraná basin (b).

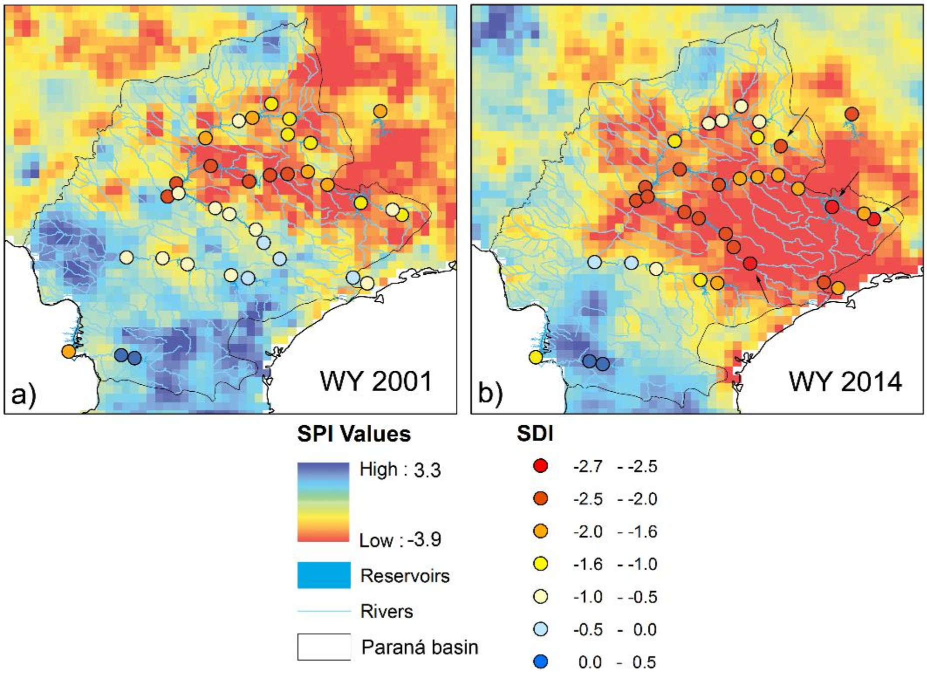

Figure 7. Spatial variation of the Standardized Precipitation Index (SPI) and Streamflow Index (SDI) in the period of two droughts. SPI and SDI are shown for the water years of 2000 (Sep 2000 to Aug 2001) and 2014 (Sep 2013 to Aug 2014).

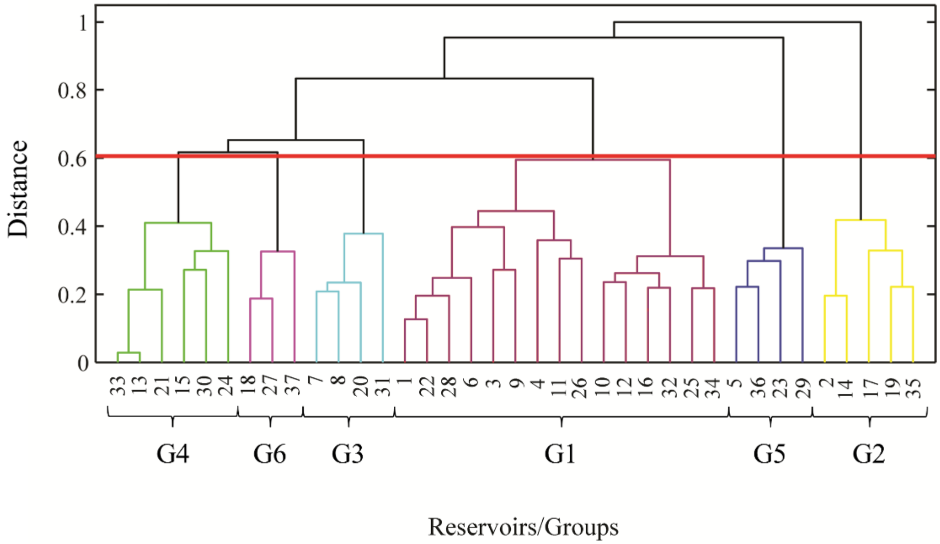

Figure 8. Dendrogram plot showing the hierarchical cluster tree. The distance between individual clusters is given by the height of the links. The red horizontal line indicates the maximum cluster distance (MCD) adopted to determine the clusters.

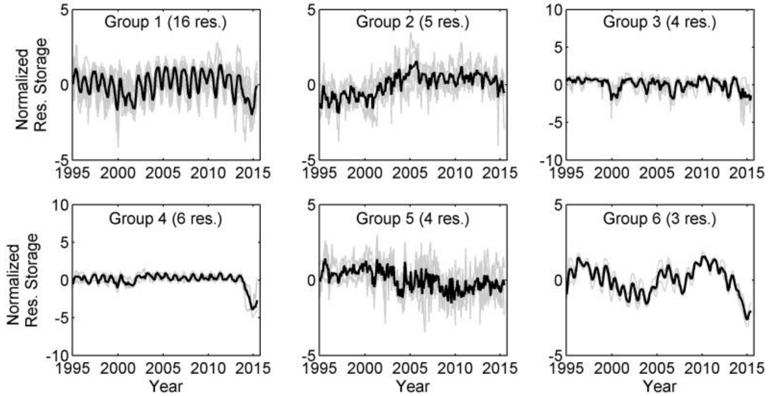

Figure 8. Time series of monthly reservoir storage of the 6 reservoir groups. Individual reservoirs are in light grey. Black lines show the group average.

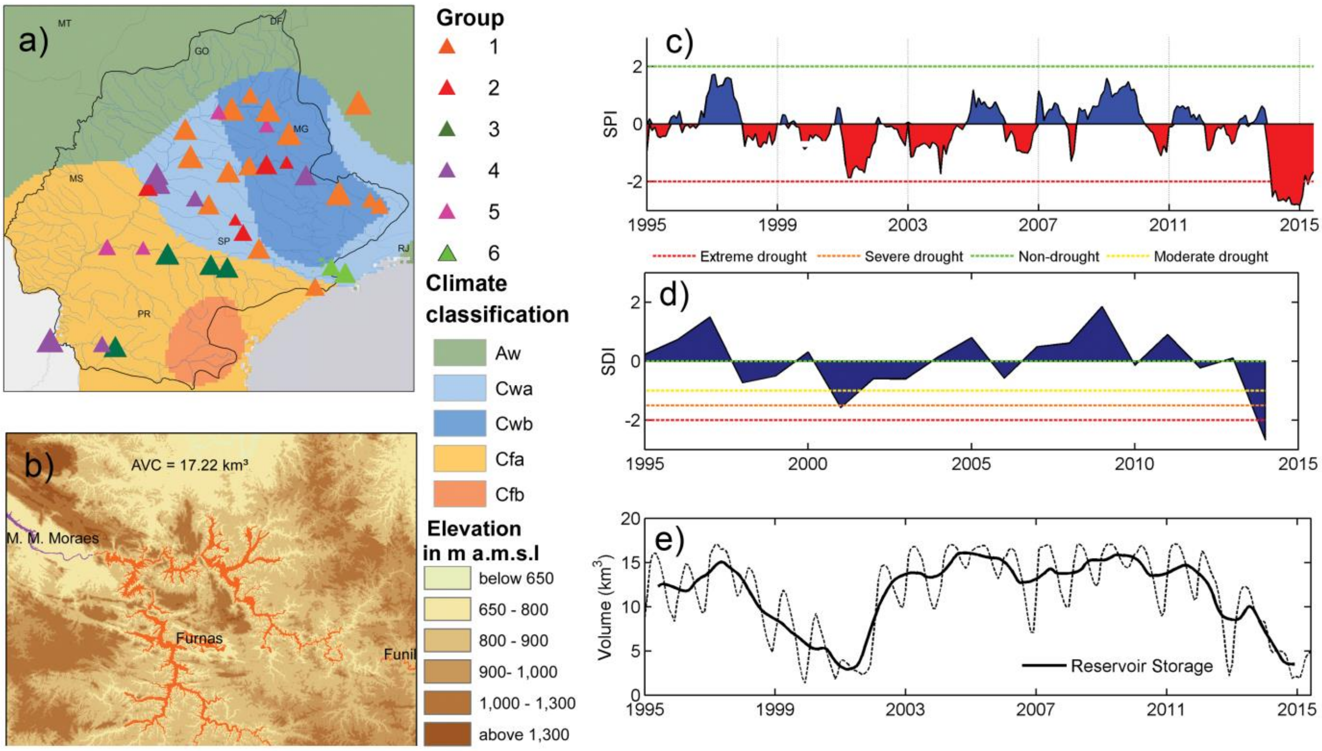

Figure 9. (a) The 37 analyzed reservoirs in the context of the Paraná Basin clustered in six groups and the number of elements per group. (b) Example of a typical reservoir from group 1 (16 reservoirs): Furnas hydroelectric power plant (HEP). Time series of monthly rainfall relative to the contributing area of Furnas HEP and inflow to Furnas reservoir were used to derive the Standardized Precipitation Index (SPI) (c) and Streamflow Drought Index (SDI) (d). Furnas monthly storage is shown in km3 (e). Hydrologic dry conditions are defined by the following states: SDI≥ 0: non-drought, −1 ≤SDI<0: Mild drought, −1.5 ≤SDI<-1: Moderate drought, −2 ≤SDI<-1.5: Severe drought and SDI<-2: extreme drought.