Authors’ response to editor’s and referees’ comments on hess-2019-57

MULTI-DECADAL HYDROLOGIC CHANGE AND VARIABILITY IN THE AMAZON RIVER BASIN: UNDERSTANDING TERRESTRIAL WATER STORAGE VARIATIONS AND DROUGHT CHARACTERISTICS

REVIEWER 1 COMMENTS

Dear authors,

I want to congratulate for a very well written, thought-through, and structured manuscript covering a wide range of topics and providing a very extensive analysis. Applying a continental model to assess water storage variations can be a key contribution for a better understanding of future threads to endangered ecosystems such as the Amazon River basin.

Before acceptance is possible, however, I have a few critical comments which are provided hereafter separated as general and specific comments on the submitted work.

Response: Thank you for your positive evaluation of the manuscript and the constructive comments that helped tremendously in improving the quality of the paper.

We provide a detailed point-by-point response to all comments in the following. We note that we have addressed all your comments and have made necessary changes in the revised manuscript. We have also provided detailed responses to each comment to avoid any confusion along with references directed towards the revised manuscript. Please note that following the other reviewer’s comment, we have made slight changes in the paper outline of the revised manuscript.

General comments

GC1) The work contains a lot of modelling work with subsequent extensive validation and comparison of model results with a range of observations. In this sense, it presents a “classical” technical modelling study with potential to be scaled up to other basins. Since droughts can have pronounced societal impact, I would like to read more about how the presented work can help to not only “anticipate future hydrological conditions” but also how this knowledge could be used as leverage to tackle present and future challenges of water management in the Amazon. Both in the Introduction and in the Conclusion adding the societal dimension and possible added value of your work would be of great benefit to the manuscript.

Response: Thank you for the thoughtful comment. We agree that the outlook based on societal aspects will greatly benefit the manuscript, hence giving a more complete picture of the Amazonian droughts. We have provided additional discussion regarding droughts with respect to the societal dimension both in the Introduction and Conclusion. However, we have attempted to keep the discussion on the societal dimension short as this issue is not completely within the overall scope of the present study. To summarize, we discuss the broad impact of droughts on the livelihood of the local population through the disruption in fish yield, navigation, drinking water supply, etc. We also present an overview of the impact on the financial condition of the riverine population caused by incessant droughts. Further, we have provided a discussion on the application of the results presented in this study towards prediction and mitigation of future drought conditions in the Conclusion section of the revised manuscript.

GC2) Throughout the manuscript, there are quite some adverbs such as “relatively”, “extremely” and so on. Please ensure that you use those words only when absolutely appropriate.

Response: Thank you for the suggestion. We have revised the entire manuscript to avoid the use of adverbs. However, in some locations the adverbs are retained to maintain the statement's inference and to keep them concise, avoiding excessive increase in words because the manuscript is already a little long.

GC3) I found quite some instances where you describe the figures in the actual text (eg. The first seven lines of chapter 4.1). To improve readability and shorten the text, I advise to limit the descriptions to the figure captions and only refer to the figures in the text.

Response: Thank you for the suggestion. We have limited the figure descriptions to figure captions (for example, Figure 1 and 10). General changes to the text are also made to ensure a smooth flow between text and paragraphs.

GC4) You compare interannual and interdecadal results. While I do see the added value of analyzing interannual variation, I am wondering why you decided to compare decades as well? In my opinion this time interval is just not long enough to assess long-term changes. Why not assessing long-term trends over the entire climatology instead?

Response: We agree that the time interval of this study is not long enough for a complete interdecadal analysis. However, given that we simulated the Amazon hydrology for 36 years, it was worthwhile to take a first look at the hydrological changes occurring at a decadal timescale. Realizing the shorter time frame for interdecadal trend analysis, we kept the discussion limited to decadal differences rather than specific trends (section 3.4). Our simulation period also encompasses several ENSO episodes, so it is worthwhile utilizing the simulations to examine how the hydrology is changing decade by decade. Moreover, studies have shown that precipitation exhibit opposite trends over the northern and southern Amazon on interdecadal scales (Lee et al., 2011; Marengo, 2004) making it important to examine how these changes propagate into TWS variations over the region. The long-term trends over the entire climatology have been discussed in the third paragraph of Section 3.4 and in Figure 6.

Specific comments

SC1) Page 2/ line 17: Is it possible to associate the climate and human-induced changes more exactly with the results? What are the driving factors, is it rather the change in climate or the increased human activities that alter the (hydrologic) system in the Amazon?

Response: Hydrological changes in Amazon have been suggested to be a result of a combined impact from climate change and human activities (Cook et al., 2012; Cook and Vizy, 2008; Lee et al., 2011; Malhi et al., 2008; Shukla et al., 1990). Due to the overall scope of the study (focus on droughts) and to keep the manuscript concise, we aimed to keep the Introduction section highly focused on the objective. All the above-mentioned studies, although focus on either climate change or human activities or both, none of them explicitly quantify the causes of the hydrological change, rather it is difficult to do so due to the complex interaction between climate and human activities over a region. Hence, we believe that the overall impact of climate change and human induced changes on the hydrologic system of the Amazon region can be better inferred qualitatively rather than quantitatively. However, we have added the drought related results from these individual studies in the Introduction section.

SC2) Page 2 / lines 23-26: This sentence is in my opinion a repetition of the information presented in the paragraph before (eg. With respect to streamflow reduction). It would be worthwhile considering removing any repetitive statements here and throughout the remaining manuscript.

Response: Thank you for pointing this out. We have removed the sentence and have made some editorial changes on our own for better clarity and flow, ensuring the new paragraphs are logically connected.

SC3) Page 4/ line 6: From the manuscript it does not become clear whether the “opposite trend” between model output and GRACE is only a thing in the Amazon River basin or whether it is issue also on global scale. Please provide this information so readers can get a better idea of the severity of this problem. Also, why is there no explanation available? Maybe provide a brief sentence (based on Scanlon 2018?) since it’s bit unsatisfying to read at the moment.

Response: Thank you for this important comment. Scanlon et al. (2018) has shown that most of the global river basins show a different trend behavior in TWS compared to GRACE. In case of the Amazon River basin, models show an opposite trend behavior in TWS. Scanlon et al., (2018) attributes the discrepancy to model shortcomings, such as poor representation of water stores and some hydrological processes, and uncertainty in forcing datasets. Although, their study quantifies the impact of the above-mentioned causes to some extent, the results vary greatly among models and forcing datasets; hence, giving no clear explanation/quantification of the causes of model-GRACE discrepancy. We have added this information about the “opposite trend” between GRACE and model output in the same line. Further, we have also included a reference directing to section 3.3, where we have a detailed discussion regarding the model-GRACE discrepancy and results from Scanlon et al., (2018).

SC4) Page 5/ line 5 “The LHF model”:

- Even though the paper was already published, adding a flow chart would help the reader to better understand the LHF model and the modelling steps required.
- What is the temporal resolution of model output? Please add.
- Was the model calibrated? If so, how and using which data and parameters? If not, why not? Please add this information.

Response: Thank you for the suggestion. We have added more information about the LHF model and its simulation setup in section 2.8. We have prepared a diagram showing the LHF model setup employed in the study; however, we have included this flow diagram in the revised supplementary information because after adding more information about the LHF model and its setup in Section 2.1 and 2.2, we found this to be less important in the main manuscript. LHF model time steps is of 4 minutes but we save the model output at daily intervals.

Regarding the third question, we have not calibrated the model using any observed datasets as the land surface, hydrologic and groundwater processes in the model framework are physically based. As such, the entire temporal extent of the model is utilized as validation period rather than dividing it into calibration and validation periods. Although, there are some parameters (e.g., manning’s co-efficient) in the physical equations which can be tuned to have a better correlation with observed datasets, we have not performed any tuning as the model represents these processes rather well with the predestined values. We have added this information in Section 2.8 of the revised manuscript.

SC5) Page 5/ line 19: What was the reasoning to use the 2 km version of LHF and not the probably faster 5 km version?

Response: Given the large areas of Amazonian floodplains and its large-scale interaction with the sub-surface water store, it is crucial to simulate these interactions with higher accuracy, to get a relatively complete picture of the hydrology in the region. A finer grid allows the model to retain the spatial details essential for an accurate simulation of floodplain dynamics and the groundwater processes (e.g., convergence along valleys and lateral flow) which are mainly controlled by local topography (Miguez-Macho and Fan, 2012). Moreover, the computational resources which we had at our disposal allowed us to conduct a finer resolution simulation with enough to spare for further analysis. In the past several years, the hydrologic modeling community has put concerted efforts to increase model resolution and move toward hyper-resolution global modeling (grid sizes of 1km or smaller) (Fan et al., 2019; Wood et al., 2011). To contribute to these community efforts LHF has been further refined to 1km grids (Fan et al., 2017). Thus, we feel that going back to a coarse resolution will be unjust as long as computational facilities permit such high-resolution simulations. We have been using LHF at 5km grids for the continental US where computational cost constraints the grid resolution (Shin et al., 2018). In case of our 5km version, the model domain consisted of Continental United States (CONUS), which is ~3.5 times larger than the domain used in this study, hence forcing us to employ a lower resolution (~5km) over CONUS.

SC6) Page 5/ line 26: It is unclear to me why you perform an extensive spin-up of 150 years but then discard the first year of the modelling period too? Were there issues with model stability or initial conditions? Please explain your choices clearly to avoid any misunderstanding.

Response: Thank you for the thoughtful comment. The spin-up was performed for 150 years with the repeated use of forcing from 1979. All the simulations for 1979 were counted towards spin-up and the main simulation was started from 1980-2015. We did not find any issues with model stability or initial conditions, however, as the manuscript intends to mainly focus on the interdecadal changes, the simulation for year 1979 would anyway have to be discarded, as a single year cannot represent a complete decade. Further, discarding the first year of simulation is also a general methodology adopted in other hydrologic modelling studies. We have added this information in Section 2.8 of the revised manuscript to avoid any misinterpretation.

SC7) Page 6/ line 1 “Atmospheric forcing”:

- Why did you decide to use the WATCH data as model forcing? Why not the more recent ERA-5 data?
- The accuracy of forcing plays an important role, also in the Amazon. The work by Towner et al. (2019, HESSD; https://doi.org/10.5194/hess-2019-44) compares several forcing data sets (ERA-I, ERA-5, and re-forecasts) with respect to their relative impact of model accuracy for the Amazon basin. I think that this could provide a good starting point for a brief discussion about the role of forcing in modelling studies and to explain your decision to use WATCH data.

Response: Thank you for pointing this out. We also agree that the accuracy of forcing plays an important role in the simulating Amazonian hydrology. We decided to use WATCH Forcing Data methodology applied to ERA-Interim reanalysis data (WFDEI) because it has been suggested to well represent the observations and is more suitable for hydrological modelling of Brazilian water resources in the past literature (Monteiro et al., 2016) compared to other datasets considered in the studies. Several bias and atmospheric corrections were also applied in deriving the WFDEI dataset (Weedon et al., 2014), hence making it a widely used forcing dataset for regional and global studies. On the contrary, ERA5 dataset is fairly new and limited studies exist in the literature showing its suitability for hydrological modelling over Amazon. We could have used ERA5 in our analysis and checked its effectiveness over Amazon, however this approach would be vastly different than the overall objective of this study. To further explore the model-GRACE discrepancy, one of the main objectives of this study, we are conducting multiple LHF simulation sets with different forcing datasets; this analysis and the model accuracy with ERA5 dataset will be addressed in our forthcoming paper. Moreover, to better explain our decision of using the WFDEI forcing in our analysis, we have provided additional discussion in Section 2.2 which includes your suggested article of Towner et al., (2019).

SC8) Page 6/ line 10: I understand you use annual input for the land cover? Are you confident that this is acceptable given the model runs at a different temporal resolution I assume? Please add a brief statement why you are convinced your choice made is appropriate.

Response: We use the European Space Agency Climate Change Initiative's Land Cover project (ESA-CCI; http://maps.elie.ucl.ac.be/CCI/) land cover maps to represent the land use land cover (LULC) dynamics in our model framework. Land cover dataset from ESA-CCI is the only dataset currently available which satisfies the LHF model requirements in terms of spatial extent, temporal extent and spatial resolution. Although, one can generate land cover maps at higher temporal resolution using Landsat imagery, the resulting process will greatly differ from the overall scope of this study. Moreover, we believe that the impacts of LULC change on the regional hydrology dominate on a longer time scale and its seasonal dynamics are well captured through LAI changes. Both of these dynamics are incorporated in the framework with an annual input of land cover and monthly LAI input. Further, usage of annual LULC input is also the general practice in hydrologic impact studies. To facilitate a better understanding of the model setup, we have added these additional details regarding the use of annual land cover input in Section 2.3 of the revised manuscript.

SC9) Page 6/ line 19: how did you decide to use LAI value 5 as threshold for transitioning into forest? Is this based on expert knowledge, scientific literature or just an arbitrary decision? I can image that in vegetation-rich areas (ie. With generally high LAI values) such as the Amazon this threshold can have a marked influence on the total area eventually specified as forest.

Response: Thank you for pointing out this issue. The threshold of LAI=5 for the forest transition is based on scientific literature. The threshold value was mainly based on the study conducted by Asner et al., (2003) which presents a synthesis of global LAI values for different land cover types. Asner et al., (2003) showed that the evergreen broadleaf and needleleaf forests, which are the major forest types in Amazon, have average LAI values greater than 5 (5.8 and 6.7, respectively). Other studies also classify the evergreen forests in the same LAI range (Myneni et al., 2007; Xu et al., 2018); for example, Myneni et al., (2007) studied the seasonal swings in LAI values and showed that the mean annual LAI is ~5 over the entire Amazonian rainforest (Figure 1A of the citation). Hence, we used the threshold of LAI=5 to get a first-hand approximation of the past forest cover in Amazon. To elaborate a bit more on the method we used to back extrapolate land cover, we have added more information in Section 2.3.

SC10) Page 7/ line 11: did you use monthly averages? Please add this information.

Response: We used the observed monthly averaged streamflow data from Agência Nacional de Águas (ANA) in Brazil for model validation. This additional information about the observed streamflow data is added in Section 2.4.1 of the revised manuscript.

SC11) Page 7/ line 14: Do all stations cover the same period or not? And what about missing values in the time series – are there any and if so how did you treat them?

Response: The streamflow stations were selected based on their data length and data gaps. Data periods varied among streamflow stations, with some spanning over the entire modelling period (i.e. 36 years) and others for more than 30 years. As the observed streamflow values are solely used for model validation, the months with missing data were skipped from the statistical analysis. More information about the observed streamflow data and their usage in the analysis is added in Section 2.4.1 of the revised manuscript.

SC12) Page 9/ line 29: Why is it that GRACE shows little agreement in small basins? Please add a brief explanation. Also, I am wondering whether using GRACE is then the right approach for those basins – would it not be an alternative to skip the GRACE comparison for small basins where it's known a priori that agreement will be small?

Response: GRACE error mentioned in this manuscript refers to bias and leakage correction errors (Landerer and Swenson, 2012; Longuevergne et al., 2010). This type of GRACE error is mainly dependent on the basin size, which increases with a decrease in basin size (Longuevergne et al., 2010). We use the GRACE data to ensure that the simulated TWS variations are within the plausible limits for the Amazon basin and its sub-basins. Also, one of the key discussions made in the manuscript is the discrepancy between model and GRACE, hence skipping GRACE comparison for smaller basins would result into an incomplete analysis. Moreover, to tackle the leakage errors associated with GRACE spherical harmonics products, we also employ the GRACE mascon products in our analysis, which are known to better capture the TWS signal by reducing the error from leakage (Save et al., 2016; Scanlon et al., 2016). Even though, some of the Amazonian sub-basins are fairly small compared to their neighbors, the smallest river basin (i.e. Japura, ~256,000 km^2) under consideration still has a basin area higher than the GRACE footprint (~200,000 km^2) (Longuevergne et al., 2010). Hence, skipping the model-GRACE comparison for these basins will not be wise, as it will not only create a void in the validation but also introduce inconsistency (or even doubt to the reader on why they are excluded) with other analyses done in this study. We have thus decided to include those smaller basins in the analyses.

SC13) Page 11/ line 7: I have my doubts whether the manuscript presents a "state-of-the-art" framework. After all, the model used is already available for quite a while and the main novelty of the presented work is the extensive analysis with GRACE and streamflow data for the Amazon and its sub-basins for a long period of time (which is an important contribution to current process understanding!). Another example would be the WATCH forcing which could be updated with more recent data sets. If you're convince the framework is nevertheless state-of-the-art, I would like to see an elaboration in the model description section why that is the case.

Response: Thank you for pointing this out. We have removed the term "state-of-the-art" from the specified line. We agree that the LHF model has been available for quite a while now, but we cannot stress less on the role of the simulation setup for making the overall framework "state-of-the-art". The version of LHF model we use in this study was last updated in 2012. Novelty of the LHF model lies in that incorporates sophisticated land surface process such as a prognostic groundwater store, dynamic water table and its interaction with surface water stores, lateral groundwater exchange, sea-level influence on coastal drainage and river-floodplain routing by resolving the full momentum equation of open channel flow. In this study, we further incorporated hydrological interactions with human activities, such as LULC change, through dynamic land cover input at annual scale (see response for SC8) and leaf area index input at a monthly scale, hence creating a comprehensive framework for assessing long-term hydrological changes. Although, many other comparable hydrological models also represent some of the above-mentioned hydrological processes in their modelling framework, most of them lack the explicit groundwater scheme (e.g., NOAH, VIC) (Ek et al., 2003; Liang et al., 1994)and the flood dynamics in their framework are fairly simplified, essentially making the surface-subsurface interaction mostly linear reservoir based (e.g., WGHM, PCR-GLOBWB) (Alcamo et al., 2003; van Beek and Bierkens, 2009). Similar level of detail as LHF, is also found in the CaMa-Flood (Yamazaki et al., 2011) model which incorporates a river-floodplain routing system; however, the scheme has not integrated the Saint-Venant equation with other land-surface hydrological processes till date, hence demoting it in the hierarchy.

Therefore, the evident contribution from the long-term simulation setup incorporating the dynamic human role in impacting the hydrological cycle in addition to the original novelty of the LHF model are the key factors behind highlighting our framework as “state-of-the-art”. To demonstrate this to our readers, we have added more information in respective sections of the revised manuscript.

For details regarding the usage of WATCH forcing data in this study, please refer the response for SC7.

SC14) Page 14/ line 3: What was your motivation to employ HydroSHEDS basins for this specific analysis? Do these “sub-catchments” match the geographical extent of the sub-basins you are referring to in the remainder of the manuscript? If not, this choice somehow complicates the analysis by introducing another geographical unit; in this case, I would advise to stick to the sub-basin definition used for the other analyses.

Response: Yes, the “sub-catchments” exactly match the geographical extent of the sub-basins referred in the rest of the manuscript. The LHF model also utilize the topography information from the HydroSHEDS dataset. We decided to use the “sub-catchments”, which are essentially the sub-basins of the Amazonian sub-basins, to study the hydrological drought propagation at higher spatial resolution. This allows us to take advantage of the wide number of the streamflow estimates obtained from the model, to conduct an in-depth analysis of the complex interaction between LULC changes and streamflow. Analyzing the hydrological drought trends at a sub-basin level will constrain the analysis at merely 8 points, further making it difficult to understand while severely underestimating the role of LULC in governing streamflow generated from the region. Therefore, even though we agree with the reviewer that we could use sub-basins for the sake of consistency but going down to smaller catchments would provide finer details of the role of LULC in regional hydrology.

SC15) Page 15/ line 3: You are mentioning “important insights” but I don’t see any further elaboration what those insights could be. Please append this information!

Response: Thank you for the suggestion. We have moved the statement at a location which more appropriately justifies the term “important insights”. The statement now is situated before the start of the discussion in Section 3.6 trailed by the detailed description of individual insight it infers.

SC16) Page 15/ line 4 “Intensification of the Amazonian Dry Season”: This chapter could profit from discussing findings from other literature to put your results into perspective. Please add where applicable!

Response: Thank you for the suggestion. We have added a more exhaustive discussion regarding the “Intensification of Amazonian Dry Season” by combining the results from previous literature and this study in Section 3.7.

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REVIEWER 2 COMMENTS

This study applied a physics-based hydrological model and GRACE product to investigate the hydrological changes in the Amazon basin, especially the water storage and how it related to droughts, for 36 years period. The results of this study are comprehensive and the findings are significant, which improve the understanding of hydrology in Amazon. But there are still some concerns in the manuscript need to be addressed.

Response: Thank you for your positive evaluation of the manuscript. We found significant improvement in the quality of the manuscript following your and the other reviewer's comments. Below we provide detailed responses to your comments along with the references in necessary locations. Please note that following the first reviewer's comment, supplementary figure numbers have changed in the revised manuscript.

GC1) The first two questions regard the modeling approaches. Firstly, it was mentioned that the atmospheric forcing data are spatially interpolated using a bilinear interpolation method to the model grid. The issue is, for example, rainfall events are usually local and spatially discontinuous, whether the bilinear interpolation is appropriate for some of the climatology data.

Response: The Leaf-Hydro-Flood (LHF) model version we used in this study interpolates WFDEI forcing data from 0.5 degrees to the 1 arc minute model grid (~2km) using bilinear interpolation. We agree that more sophisticated interpolation techniques, such as kriging, yield more accurate results compared to the bilinear approach, especially with the rainfall data. However, these sophisticated methods also come at a significant computational cost. Moreover, several previous studies (Fan et al., 2017; Miguez-Macho and Fan, 2012; Pokhrel et al., 2013, 2014) along with this study have shown that even with the bilinear interpolation LHF model yield accurate results. Hence, we firmly believe that implementing a more sophisticated interpolation technique would be unnecessary given the current accuracy achieved from the model. Further it would add significant computational burden as the interpolation is done within the model over a very large domain (~4 million grids).

GC2) Secondly, regarding the LULC change applied to the model, LAI higher than 5 are considered as forest canopy. Then the question is, how does this approach deal with the seasonal variation of LAI as for LULC change?

Response: Thank you for pointing out this issue. The threshold of LAI=5 for the forest transition is the mean annual LAI calculated by aggregating the 8-day composites from GLASS data for every year. We use this mean annual LAI estimates only for deriving the 1980-1991 (years not included in the ESA-CCI data) annual land cover maps. The seasonal variations in LAI are separately incorporated in the model framework at a monthly scale. To elaborate a bit more on the method we used to back extrapolate land cover, we have added more information in Section 2.3 of the revised manuscript.

Further, the threshold value was mainly based on the study conducted by Asner et al., (2003) which presents a synthesis of global LAI values for different land cover types. Asner et al., (2003) showed that the evergreen broadleaf and needleleaf forests, which are the major forest types in Amazon, have average LAI values greater than 5 (5.8 and 6.7, respectively). Other studies also classify the evergreen forests in the same LAI range (Myneni et al., 2007; Xu et al., 2018); for example, Myneni et al., (2007) studied the seasonal swings in LAI values and showed that the mean annual LAI is ~5 over the entire Amazonian rainforest (Figure 1A of the citation). Hence, we used the threshold of LAI=5 to get a first-hand approximation of the past forest cover in Amazon.

GC3) The manuscript consists of 5 parts, but the model descriptions in Section 2 should belong to Section 3, methods. Thus, it would be better to re-organize the contents and the structure of the manuscript.

Response: Thank you for the suggestion. We agree that moving the model descriptions to Section 3, methods, will result into a better structure. We thought of improving it further by combining the current sections 2 and 3 together. In the revised manuscript, we have revised the structure as follows,

2. Model, Data and Methods
2.1 The Leaf-Hydro-Flood (LHF) model
2.2 Atmospheric Forcing
2.3 Land Use Land Cover and Leaf Area Index
2.4 Validation Data
    2.4.1 Observed Streamflow
    2.4.2 GRACE Data
2.5 TWS Drought Severity Index
2.6 Occurrence and Duration of Drought
2.7 Dry Season Total Water Deficit
2.8 Simulation Setup

GC4) In addition, Figures S3, S6, and S8 are not referred nor discussed in the manuscript. Moreover, there are also some specific comments as below.

Response: Thank you for pointing this out. We have added supplementary figure references for the in required locations in the revised manuscript.

SC1. P3L13-15, some of these 'more recent' literature are still more than 10 years old. The author should cite some real more recent papers.

Response: Thank you for the suggestion. We have removed the old citations and have added more recent literature in the revised manuscript. New literature added to the revised manuscript consists of studies conducted in 2010s such as Fan et al., (2019), Shin et al., (2018) and Wang et al., (2019).

SC2. P8L27-29, the description of the symbols in the figure should also be presented in the figure caption.

Response: Thank you for the suggestion. We have added the symbol descriptions in the Figure 1 caption. Also, please note that, according to the other reviewer's comment we have removed the figure description from the main text.

SC3. P9L7, this conclusion is not easy to clarify from the figures. Please describe more clearly and specifically.

Response: Thank you for the suggestion. River basins, such as Japura and Negro, are characterized by high topographic gradients, resulting into an uneven seasonal streamflow pattern. These gradients are not adequately represented in the model framework due to the limitation in model resolution, hence causing higher discrepancies with the observed values. We have added this information in a concise manner in the revised manuscript to have a better understanding of the conclusion inferred from Figure S2.

SC4. P9L14, the discrepancies in some basins cannot be seen from Figure S2, for example, by which metrics?

Response: Thank you for pointing this out. We specifically wanted to point out the discrepancies in the simulated and observed magnitude of peaks in seasonal streamflow cycle. Xingu, Tapajos and Tocantins sub-basins show significant differences between the simulated and observed seasonal peak of streamflow (smaller right panels of each basin, Figure S3 of the revised manuscript) due to the higher hydropower activity compared to the other river basins. We have edited the statement by including additional information to avoid confusion.

SC5. P12L13, the method of t-test should be described in the methodology section unless it is an ordinary t-test.

Response: The t-test methodology we used is the ordinary t-test. We decided to skip its description from the methodology section as the test is very commonly used.

SC6. P14L14, it should be 'Figure 10'.

Response: Thank you for pointing this mistake. We have corrected it to "Figure 10".

SC7. Figure 5, the color change of the rivers is not clear. The line widths of the rivers should be increased.

Response: Figure 5 shows the interdecadal difference in TWS components at the original model resolution (~2km). The data presented in the figure is gridded data, hence we cannot represent the rivers in a polyline format. For better visualization we have removed the inland water and country borders.

SC8. Figure S1 lacks the north arrow and the scale. Moreover, the author should mark all sub-basins and major rivers in this figure.

Response: Thank you for the suggestion. We have marked the sub-basin borders in Figure S2 of the revised manuscript; however, we believe that adding the scale and north arrow to the figure would become redundant due to the presence of the geographical co-ordinates.

SC9. Figure 7, y-axis label is missing.

Response: Thank you for the suggestion. We have added a y-axis label in Figure 5.

SC10. It would be better to include geo-coordinates for all spatial plots, e.g., Figure 3, 4, 5, 6, 8, 9, S4, S5, S7, and S9.

Response: Thank you for the suggestion. We have made the suggested changes in the figures.

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Multi-decadal Hydrologic Change and Variability in the Amazon River Basin: Understanding Terrestrial Water Storage Variations and Drought Characteristics

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Abstract. We investigate the interannual and interdecadal hydrological changes in the Amazon River basin and its sub-basins during 1980-2015 period using GRACE satellite data and a physically-based, 2-km grid continental-scale hydrological model (Leaf-Hydro-Flood) that includes a prognostic groundwater scheme and accounts for the effects of land use land cover (LULC) change. The analyses focus on the dominant mechanisms that modulate terrestrial water storage (TWS) variations and droughts. We find that (1) the model simulates the basin-averaged TWS variations remarkably well, however, disagreements are observed in spatial patterns of temporal trends, especially for the post-2008 period, (2) the 2010s is the driest period since 1980, characterized by a major shift in decadal mean compared to 2000s caused by increased drought frequency, (3) long-term trends in TWS suggests that the Amazon overall is getting wetter (1.13 mm/yr), but its southern and southeastern sub-basins are undergoing significant negative TWS changes, caused primarily by intensified LULC changes, (4) increasing divergence between dry season total water deficit and TWS release suggest a strengthening dry season, especially in the southern and southeastern sub-basins, and (5) the sub-surface storage regulates the propagation of meteorological droughts into hydrological droughts by strongly modulating TWS release with respect to its storage preceding the drought condition. Our simulations provide crucial insight on the importance of sub-surface storage in alleviating surface water deficit across Amazon and open pathways for improving prediction and mitigation of extreme droughts under changing climate and increasing hydrologic alterations due to human activities (e.g., LULC change).

1. Introduction

The Amazon River basin is one of the most hydrologically and ecologically diverse regions in the world (Fan and Miguez-Macho, 2010; Latrubesse et al., 2017; Lenton et al., 2009; Lesack, 1993; Malhi et al., 2008; Moran et al., 2018; Timpe and Kaplan, 2017; Tófoli et al., 2017). It is home to the world's largest tropical rainforest and hosts ~25% of all terrestrial species on Earth (Malhi et al., 2008). Hydrologically, it contributes to 20-30% of the world's total river discharge into the oceans (Clark et al., 2015; Muller-Karger et al., 1988; Nepstad et al., 2008) and accounts for ~15% of global terrestrial

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evapotranspiration (Field et al., 1998; Malhi et al., 2008). Thus, the Amazon is an important component of global terrestrial ecosystems and the hydrologic cycle (Cox et al., 2004; Nobre et al., 1991); it also plays a major role in global atmospheric circulation through precipitation recycling and atmospheric moisture transport (Malhi et al., 2008; Soares-Filho et al., 2010). The hydro-ecological systems of the Amazon are dependent on plentiful rainfall (Cook et al., 2012; Espinoza et al., 2015, 2016; Espinoza Villar et al., 2009; Nepstad et al., 2008) and the vast amount of water that flows down through extensive river networks and massive floodplains (Bonnet et al., 2008; Coe et al., 2002; Frappart et al., 2011; Miguez-Macho and Fan, 2012a; Yamazaki et al., 2011; Zulkafli et al., 2016). The spatiotemporal patterns of precipitation are, however, changing due to climate change and variability (Brando et al., 2014; Cook et al., 2012; Lima et al., 2014; Malhi et al., 2008, 2009; Nepstad et al., 2008), large-scale alterations in land use (e.g., deforestation) (Chen et al., 2015; Coe et al., 2009; Davidson et al., 2012; Kalamandeen et al., 2018; Lima et al., 2014; Panday et al., 2015; Tollefson, 2016), and more recently the construction of mega-dams (Finer and Jenkins, 2012; Latrubesse et al., 2017; Moran et al., 2018; Soito and Freitas, 2011; Timpe and Kaplan, 2017; Winemiller et al., 2016), among others. Such changes in precipitation patterns typically manifest themselves in terms of altered magnitude, duration, and timing of streamflow (Marengo, 2005). A prominent streamflow alteration pattern that has been widely observed across the Amazon is the extended dry-season length (Espinoza et al., 2016; Marengo et al., 2011) and an increase in the number of dry events (i.e., droughts) over the longer term (Malhi et al., 2009; Marengo and Espinoza, 2016), which has been suggested to be a result of ongoing climatic and human-induced changes (Cook et al., 2012; Cook and Vizy, 2008; Lee et al., 2011; Malhi et al., 2008; Shukla et al., 1990). However, the cross-scale interactions and feedbacks in the human-water relationship make it difficult to explicitly quantify the causes. These changes have resulted in decreases in runoff (Espinoza et al., 2009; Haddeland et al., 2014; Lima et al., 2014), and loss of terrestrial biodiversity (Barletta et al., 2010; Newbold et al., 2016; Tófoli et al., 2017; Toomey et al., 2011; Winemiller et al., 2016). Increased variability in streamflow has also resulted in the disruption of the food pulse and fishery yields, which the Amazon region thrives upon (Castello et al., 2013, 2015; Forsberg et al., 2017). Moreover, persistent dry events create social negative externalities, such as deterioration of respiratory health due to drought induced fires (Smith et al., 2014), exhaustion of family savings (Brondizio and Moran, 2008), isolation of communities that are affected by navigation and drinking water scarcity (Sena et al., 2012), hence affecting the overall livelihood of the local communities. Thus, it is critical to understand the characteristics of the historical droughts to better understand the dominant mechanisms that modulate droughts and their evolution over time.

As often is the case, droughts in the Amazon are driven by El Niño events, however, some droughts are suggested to be caused by climate change and variability (Espinoza et al., 2011; Lewis et al., 2011; Marengo et al., 2008; Marengo and Espinoza, 2016; Phillips et al., 2009; Xu et al., 2011; Zeng et al., 2008) and due to accelerating activities causing rapid changes in land use/water cycle (Lima et al., 2014; Malhi et al., 2008). Numerous studies have quantified the impacts and spatial extent of these periodic droughts on the hydrological and ecological systems in the Amazon (Alho et al., 2015; Brando et al., 2014; Castello et al., 2013, 2015, Chen et al., 2009, 2010; da Costa et al., 2010; Davidson et al., 2012; Fernandes et al., 2011; Lewis et al., 2011; Phillips et al., 2009; Saleska et al., 2007, 2016; Satyamurty et al., 2013; Schöngart and Junk, 2007; Xu et al., 2011; Zeng et al., 2008). For example, Lewis et al., (2011) found that the 2010 drought was spatially more extensive than the 2005

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drought; the spatial extent was over 3.0 million km^2 in 2010 and 1.9 million km^2 in 2005. These catastrophic droughts had major implications on the hydrology of the Amazon River basin; for example, the 2005 hydrological drought led to reduction in streamflow by 32% from the long-term mean, as reported in Zeng et al., (2008), and in 2010 moisture stress induced persistent declines in vegetation greenness affecting an area of ~2.4 million km^2 which was 4 times greater than the area impacted in 2005 (Xu et al., 2011). Moreover, these extreme drought events, coupled with forest fragmentation have caused widespread fire-induced tree mortality and forest degradation across Amazonian forests (Aragão et al., 2007; Brando et al., 2014; Davidson et al., 2012; Malhi et al., 2008; Rammig et al., 2010).

Due to the limited availability of observed data (e.g., precipitation, streamflow) for the entire basin, hydrologic characteristics of droughts in the Amazon has been studied primarily by using hydrological models and satellite remote sensing. For example, early studies (Coe et al., 2002; Costa and Foley, 1999; Lesack, 1993; Vorosmarty et al., 1996; Zeng, 1999) examined different components of the Amazon water budget and their trends through relatively simpler models. More recent literature (Dias et al., 2015; Fan et al., 2019; Getirana et al., 2012; Miguez-Macho and Fan, 2012a, 2012b, Paiva et al., 2013b, 2013a, Pokhrel et al., 2012b, 2012a, 2013; Shin et al., 2018; Siqueira et al., 2018; Wang et al., 2019; Yamazaki et al., 2011, 2012) provided further advances in modeling the hydrological dynamics connected with anthropogenic activities in the Amazon and other parts of the world. Methods with varying complexities were used in similar studies, ranging from simple water budget analyses, (Betts et al., 2005; Costa and Foley, 1999; Fernandes et al., 2008; Lesack, 1993; Sahoo et al., 2011; Vorosmarty et al., 1996; Zeng, 1999) to state-of-the-art land surface models (Getirana et al., 2012; Miguez-Macho and Fan, 2012a, 2012b, Paiva et al., 2013a, 2013b; Pokhrel et al., 2013; Siqueira et al., 2018; Wongchuig Correa et al., 2017; Yamazaki et al., 2011, 2012), with some targeting the overall development of parameterization and process representation in the model (Coe et al., 2008, 2009; Dias et al., 2015; Getirana et al., 2010, 2012, Miguez-Macho and Fan, 2012a, 2012b; Paiva et al., 2013b; Pokhrel et al., 2013; Yamazaki et al., 2011), and others on the hydrological changes occurring in the basin due to weather variability (Coe et al., 2002; Lima et al., 2014; Wongchuig Correa et al., 2017).

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The major droughts events in the Amazon, particularly those in recent years, have been detected by satellite remote sensing and their impacts on terrestrial hydrology have been examined (Chen et al., 2010; Filizola et al., 2014; Xu et al., 2011). In particular, the hydrologic impact of droughts have been revealed by examining the anomalies in terrestrial water storage (TWS) inferred from the Gravity Recovery and Climate Experiment (GRACE) satellites. A significant decrease in TWS over Central Amazon in the summer of 2005, relative to the average of the five other summer months during 2003-2007 period, was reported by Chen et al., 2009. However, due to the vast latitudinal extent of the Amazon basin, these severe dry conditions were observed only in some regions of the basin. Xavier et al., (2010) and Frappart et al., (2013) used GRACE TWS estimates to identify the signature of these drought events and suggested that the 2005 drought only affected the western and central parts of the basin, whereas very wet conditions peaking in mid-2006 were observed in the eastern, northern and southern regions of the basin. Although the ramifications of these extreme droughts have been widely studied using remote sensing datasets (e.g., GRACE), the understanding of their time-evolution is limited due to data gaps and short study periods, hence hindering their comprehensive categorization. Further, GRACE provides the changes in vertically integrated TWS variations, thus variations

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in the individual TWS components cannot be estimated solely by GRACE. This shortcoming is overcome by using hydrological models that separate TWS into its individual components and provide simulations for an extended timescale. However, discrepancy between models and GRACE observations has also become a major topic of discussion, as most of the global models show an opposite trend in TWS compared to GRACE in Amazon and other global river basins (Scanlon et al., 2018); yet, no clear explanation or quantification exist in the published literature, apart from the attribution of the discrepancy to model shortcomings (see Section 3.3 for details).

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As referenced above, the changing hydro-climatology of the Amazon basin, along with specific drought related analysis (e.g. 2005, 2010) has been widely reported in a large body of literature published over recent decades. Several studies have used statistical measures to quantify drought severity (Espinoza et al., 2016; Gloor et al., 2013; Joetzjer et al., 2013; Marengo, 2006; Marengo et al., 2008, 2011; Wongchuig Correa et al., 2017; Zeng et al., 2008; Zhao et al., 2017a), concerning common variables, such as streamflow and precipitation, thus limiting the quantification of drought impact on water stores viz. flood, groundwater and TWS. Further, even though these studies encompass different aspects of hydrological and climatic changes, most span over only a few years to a decade, except for some precipitation related studies (Marengo, 2004; Marengo et al., 1998). Other studies have used a relatively longer study period (Costa et al., 2003; Espinoza et al., 2016; Zeng, 1999), but the spatial extent is limited. Thus, a comprehensive understanding of the interdecadal hydrologic change and variability across the entire basin and that of changes in drought characteristics is still lacking. Given the number of droughts that have occurred and their widespread impact in the Amazon, it is imperative to have a better understanding of these past events so as to anticipate future hydrological conditions (Phipps et al., 2013). Many aspects of the droughts are yet to be studied, such as, the inter-dependence between TWS and meteorological (precipitation-related) and hydrological (streamflow-related) droughts. A complete categorization of the drought events with respect to their causes and impacts and the resulting basin response is still coming up short.

In this study, we investigate the interannual and interdecadal variability in TWS and drought events in the Amazon River basin over 1980-2015 period. Our study is driven by the following key science questions: (1) how do interannual and interdecadal changes in drought conditions manifest as long-term variations in TWS at varying spatial and temporal scales in the Amazon River basin? (2) What are the impacts of TWS variations on dry season water deficit and release? Is the Amazonian dry season getting stronger/severe? (3) what are the dominant factors driving the evolution of TWS and drought conditions at varying spatial and temporal scales? And (4) how does the sub-surface water storage regulate the water deficiency caused by the surface drought conditions? These questions are answered by using hydrological simulations from a continental-scale hydrological model and the TWS data from GRACE satellites; the goal is to provide a comprehensive picture of characteristics and evolution of droughts in the Amazon with respect to their types and spatial impact. Specifically, this study aims to: i) examine the impacts of drought conditions on TWS and other hydrological variables; ii) understand the hydrological variability and drought evolution in the Amazon at an annual and decadal scale over the past four decades; iii) quantify the role of sub-surface water storage in alleviating the surface drought conditions; and iv) summarize each drought year by providing a comprehensive characterization for the major drought events in the Amazon and its sub-basins.

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2. Model and Data

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2.1 The Leaf-Hydro-Flood (LHF) Model

The model used in this study is LHF (Fan et al., 2013; Miguez-Macho and Fan, 2012b, 2012a, Pokhrel et al., 2013, 2014), a continental-scale land hydrology model that resolves various land surface hydrologic and groundwater processes on a full physical basis. It is derived from the model Land-Ecosystem-Atmosphere Feedback (LEAF) (Walko et al., 2000), the land surface component of the Regional Atmosphere Modeling System (RAMS) (Pielke et al., 1992). The original LEAF was extensively improved and enhanced to develop LEAF-Hydro for North America (Fan et al., 2007; Miguez-Macho et al., 2007) by adding a prognostic groundwater storage and allowing (1) the water table to rise and fall or the vadose zone to shrink or grow, (2) the water table, recharged by soil drainage, to relax through streamflow into rivers, and lateral groundwater flow, leading to convergence to low valleys, (3) two-way exchange between groundwater and rivers, representing both losing and gaining streams, (4) river routing to the ocean as kinematic waves, and (5) setting sea level as the groundwater head boundary condition. Miguez-Macho and Fan, (2012a) further enhanced the LEAF-Hydro framework by incorporating the river-floodplain routing scheme which solves the full momentum equation of open channel flow, giving more realistic streamflow estimates by considering the prominent backwater effect observed in the Amazon (Bates et al., 2010; Yamazaki et al., 2011). LHF model has been extensively validated in the North and South American continents at 5km and 2km grids, respectively (Fan et al., 2013; Miguez-Macho et al., 2008; Miguez-Macho and Fan, 2012a, 2012b; Pokhrel et al., 2013; Shin et al., 2018) and used to examine the impacts of climate change on groundwater system in the Amazon (Pokhrel et al., 2014). A complete description of LHF can be found in Miguez-Macho and Fan (2012a).

2.2 Atmospheric Forcing

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LHF is setup for the entire Amazon basin including the Tocantins River Basin (~7.1 million km^2). Simulations are conducted for the 1979-2015 period and at the spatial resolution of 1 arc minute (~2 km). Model time step is 4 minutes as in previous studies (Miguez-Macho and Fan, 2012b, 2012a, Pokhrel et al., 2013, 2014). To stabilize water table depth, the model is spun up for ~150 years starting with the equilibrium water table (Fan et al., 2013). Further, the first year is discarded as additional spin-up and results for 1980-2015 period (36 years) are analysed. Dynamic monthly leaf area index (LAI) and annual land use data are used to account for land use and land cover (LULC) changes (see Sections 2.4 and 2.5).¶

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Atmospheric forcing data are taken from WATCH Forcing Data methodology applied to ERA-Interim reanalysis data (WFDEI) (Weedon et al., 2014), available for the 1979-2016 period at 0.5° spatial resolution and 3-hr timesteps. WFDEI dataset is widely used in for both global and regional scales studies (Beck et al., 2016; Felfelani et al., 2017; Hanasaki et al., 2018; Schmied et al., 2014), and has been suggested to well represent the observations in the Amazon region (Monteiro et al., 2016). The original WFDEI data at 0.5° resolution are spatially interpolated using a bilinear interpolation method to model grid resolution (~2km), following our previous studies (Miguez-Macho and Fan, 2012a, 2012b, Pokhrel et al., 2013, 2014; Shin et al., 2018). The more recent European Centre for Medium-Range Weather Forecasts Reanalysis 5th (ERA5) dataset, which provides atmospheric forcing data from 1979 to present day at a spatial resolution of 0.25°, show promise by outperforming its predecessors (Towner et al., 2019). However, as no studies existed in the past literature which comprehensively validated the ERA5 dataset over the Amazon region until recently, WFDEI forcing remains a better alternative as a model input.

2.3 Land Use Land Cover and Leaf Area Index

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The land cover data used in this study are obtained from the European Space Agency Climate Change Initiative's Land Cover project (ESA-CCI; http://maps.elie.ucl.ac.be/CCI/). The data comprise of an annual timeseries of high-resolution land cover maps for 1992-2015 period at a 300m spatial resolution, generated by combining the baseline map from the Medium-spectral Resolution Imaging Spectrometer (MERIS) instrument and the land use land cover (LULC) changes detected from AVHRR (1992 - 1999), SPOT-Vegetation (1999 - 2012) and PROBA-V (2013 - 2015) instruments. The classification follows the LULC classes defined by the UN Land Cover Classification System (LCCS). Spatiotemporal coverage and resolution of these LULC maps are consistent with the specific LHF model requirements; hence we use annual land cover input, spatially aggregated to 2km LHF model grids, following the general practice in hydrologic impact studies (Arantes et al., 2016; Panday et al., 2015). Because the ESA-CCI data did not cover the simulation period prior to year 1992, we derive the time-series products for 1980-1991 period by using the trend in leaf area index (LAI) and the ESA-CCI landcover map for year 1992 as a baseline. A pixel-by-pixel analysis is conducted and the pixels with mean annual LAI higher than 5 are transitioned into forest canopy, whereas for other pixels LULC type is retained from the previous year's LULC map. The threshold of LAI equal to 5 for facilitating the land cover transition into forest is determined based on the LAI classifications provided in past literature (Asner et al., 2003; Myneni et al., 2007; Xu et al., 2018). Reverse prediction of LULC changes was constrained to forest canopy only, as it is difficult to predict the LULC type based on LAI values less than 5. Also, forest cover is known to be the most prominent land cover in the Amazon, hence it is reasonable to assume that most of the LULC changes occurring in the basin are transitioned from forest cover.

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Monthly LAI data are derived by temporally aggregating the 8-day composites from Global Land Surface Satellite (GLASS) LAI product (Liang and Xiao, 2012; Xiao et al., 2014) to monthly values for the entire model domain. GLASS LAI values for the period of 1982-1999 are derived from AVHRR reflectance, whereas MODIS reflectance values are used for period 2000-2012. Because of the data constraint, LAI data for years before 1982 and after 2012 are assumed to be the same as that of years 1982 and 2012, respectively.

2.4 Validation Data

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2.4.1 Observed Streamflow

We use monthly averaged streamflow data obtained from the Agência Nacional de Águas (ANA) in Brazil (http://hidroweb.ana.gov.br). Fifty-five stream gauge stations are selected considering a wide coverage over the Amazonian sub-basins, and a good balance between low and high flow values. The major selection criterion is the data length; i.e., we only include gauges with at least 30 years coverage. In a few cases, such as for Japura sub-basin, the threshold was overlooked because this criterion resulted in a small number of gauging stations. All the selected stations have observational data for varying time frames with minimal data gaps; the months with missing data are skipped in the statistical analysis.

2.4.2 GRACE Data

The TWS products from the GRACE satellite mission are used to validate the TWS simulated by LHF for 2002-2015 period. Equivalent water height from three processing centers, namely: (i) Jet Propulsion Laboratory (JPL) , (ii) the Center for Space Research (CSR), and (iii) the German Research Center for Geoscience (GFZ) (http://grace.jpl.nasa.gov/data/ get-data/) (Landerer and Swenson, 2012) are used along with two mascon products from CSR and JPL; mascon products have been suggested to better capture TWS signals in many regions (Scanlon et al., 2016). Basin-averaged data of variation in TWS anomalies are calculated from GRACE by taking an area-weighted arithmetic mean with varying cell area (Felfelani et al., 2017).

2.5 TWS Drought Severity Index

To examine the occurrence and severity of hydrological droughts over the past decades, we employ the drought severity index derived from time-varying TWS change from GRACE, known as the GRACE Drought Severity Index (GRACE-DSI) (Zhao et al., 2017b). We apply GRACE-DSI framework to the 36-year simulated TWS (referred hereafter to as TWS-DSI) to examine the interannual and interdecadal drought evolution over the entire basin. This index is solely based on the TWS anomalies and has been shown to capture the past droughts with favorable agreement with other drought indices derived from precipitation (e.g., PDSI and SPEI) (Zhao et al., 2017b, 2017a). TWS-DSI is calculated for each grid cell in the model domain as follows,

$$TWS\_DSI_{i,j} = \frac{TWS_{i,j} - \overline{TWS}_j}{\sigma_j}, \qquad (1)$$

where, $TWS_{i,j}$ is the TWS anomaly from LHF for year i and month j; and $\overline{TWS}_j$ and σ_j are the temporal mean and standard deviation of TWS anomalies for month j, respectively.

2.6 Occurrence and Duration of Drought

The characteristics of hydrological droughts are identified from the simulated streamflow using the widely used threshold level approach. Different thresholds have been proposed in previous studies: mean flow, minimum and maximum flows (Marengo and Espinoza, 2016; Wongchuig Correa et al., 2017), 80th percentile (Q_{80}) flow (Van Loon et al., 2012; Van Loon and Laaha, 2015; Wanders and Van Lanen, 2015), and 90th percentile (Q_{90}) flow (Wanders et al., 2015; Wanders and Wada, 2015). In this study, we use Q_{90} which is derived from the flow duration curve where Q_{90} is the streamflow that is equaled or exceeded for 90% of the time. Q_{90} is used to isolate severe drought events over the simulation period. Monthly threshold values are derived using the 36-year simulated streamflow and are smoothed by a 30-day moving average. Drought condition is identified by determining whether the variable is below the threshold, expressed mathematically as,

$$Ds(t,x) = \begin{cases} 1 & for\ Q(t,x) < Q_{90}(t,x) \\ 0 & for\ Q(t,x) \geq Q_{90}(t,x) \end{cases}, \qquad (2)$$

where $Ds(t,x)$ indicates whether the grid (x) is in a drought state at time (t), $Q(t,x)$ is the streamflow and $Q_{90}(t,x)$ is the threshold for grid (x) at time (t). Consecutive drought states are added to get the drought duration. Events with duration less

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We use monthly streamflow data obtained from the Agência Nacional de Águas (ANA) in Brazil (http://hidroweb.ana.gov.br). Fifty-five stream gauge stations are selected considering a wide coverage over the Amazonian sub-basins, and a good balance between low and high flow values. The major criterion is the data length; i.e., we only include gages with at least 30 years coverage. In a few cases, such as for Japura sub-basin, the threshold was overlooked because this criterion resulted in a relatively small number of gauging stations. The station locations are shown in Figure S1; highlighted points are the stations for which monthly time-series is present in Figure S2.¶
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than 3 days are not considered as droughts. The number of drought days per year is calculated by aggregating the duration of all the drought events in a year.

2.7 Dry Season Total Water Deficit

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We define the dry season total water deficit (TWD) as the cumulative difference between monthly potential evapotranspiration (PET) and precipitation (P) for the period during which P<PET. The corresponding drop in the simulated TWS, during the same period as of TWD, is defined as the TWS release (TWS-R). TWD and TWS-R can be conceptualized as the annual water demand and supply as described in Guan et al., (2015). PET estimated at the daily interval using the Penman Monteith approach (Monteith, 1965) as in Pokhrel et al., (2014) is aggregated to the monthly scale to calculate TWD; for consistency, we use the WFDEI forcing data that is used for LHF simulations (section 2.2). TWS anomalies required for the estimation of storage release are obtained from the LHF model.

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2.8 Simulation Setup

LHF is setup for the entire Amazon basin (~7.1 million km^2) including the Tocantins River Basin. Simulations are conducted for the 1979-2015 period at a spatial resolution of 1 arc minute (~2 km). Model time step is 4 minutes as in previous studies (Miguez-Macho and Fan, 2012b, 2012a, Pokhrel et al., 2013, 2014), however, model output is saved at daily timesteps. To stabilize water table depth, the model is spun up for ~150 years starting with the equilibrium water table (Fan et al., 2013) for 1979 and results for 1980-2015 period (36 years) are analyzed. As this study aims to analyze the hydrological changes in Amazon on a decadal scale, simulations for 1979 are considered as additional spin-up and hence not used. Dynamic monthly LAI and annual LULC maps are used to account for LULC changes (see Sections 2.3). Moreover, as the model simulates land surface, hydrologic and groundwater processes on a complete physical basis, no calibration was performed on the model output. Original novelty of the LHF model framework, combined with the incorporated dynamic human role through land cover change creates a "state-of-the-art" framework for assessing long-term hydrological changes. Complete LHF framework along with the input data employed in this study is presented in Figure S1.

3. Results and Discussion

3.1 Evaluation of Simulated Streamflow

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Figure 1 presents the Taylor diagram (Taylor, 2001) illustrating the statistics of the simulated streamflow against observations at 55 gauging locations (see Section 2.4.1 and Figure S2) across the entire Amazon basin. The Taylor diagram provides a synthetic view of error in the simulations in terms of the ratio of standard deviation (SD) of the simulated streamflow to the observed as a radial distance and their correlation as an angle in the polar axis. Most of the stations show a high correlation (> 0.8) and a SD ratio close to unity, indicating a good model performance overall for varying geographical locations and stream sizes over the Amazon. Low correlation (~0.6) is seen for some gauging stations situated on streams with smaller annual mean flow and steep slope profile; for example, the smaller streams across the Andes in Japura and Negro sub-basins, along with the streams in northeastern parts of Amazon. In these streams with high topographic gradients, precipitated water quickly flows away causing slightly erratic patterns of seasonal streamflow, which is apparent in both simulated and observed timeseries (Figures S3 and S4). However, due to the difficulty in resolving hillslopes processes for low-order streams using 2km grids, the model is unable to fully capture the flow seasonality in the streams with high topographic gradient.

The spatial distribution of the simulated streamflow across the entire model domain and the timeseries comparison of simulated vs. observed streamflow at 12 selected stations are presented in the SI (Figures S2 and S3). The simulated seasonal cycle compares well with the observed one for the entire basin (i.e., Obidos station) as well as for most sub-basins; however, discrepancies in the seasonal peaks can be seen in some basins (e.g., Xingu, Tocantins, and Tapajos). Man-made reservoirs generally attenuate streamflow peaks and seasonal variability, reducing the SD, which is reflected in the observed data but not yet accounted for in the model; this could have exaggerated the SD ratio in some cases. For example, the streamflow in the Tocantins River shows higher SD compared to observed streamflow, likely due to the operation of the Tucurui I and II dams. Conversely, the SD ratio is lower than unity at some stations, including those in the Madeira River (Figure 1), due to the dry bias found in the input precipitation (see Figure S5 and Section 3.2). For sub-basins with higher groundwater contribution to streamflow, such as Xingu, Tapajos, Tocantins and Madeira, the dry-season flow is overestimated (Figure S3), which results from possibly exaggerated groundwater buffer in the model for these regions (Miguez-Macho and Fan, 2012a). Given that LHF is a continental-scale model, simulates streamflow on a full physical basis, and is not calibrated with observed streamflow, we consider these results to be satisfactory to study the hydrologic changes and variability.

3.2 Evaluation of Simulated TWS Anomalies with GRACE

Figure 2 presents the comparison of simulated TWS anomalies and GRACE data for the entire Amazon basin and its eight sub-basins; for model results, the individual TWS components are also provided. The model performs very well in simulating the basin averaged TWS anomalies for the entire Amazon basin and most sub-basins. However, some difference between the simulated and GRACE-based TWS anomaly are evident, especially in sub-basins with relatively smaller area and elongated shape (e.g., Purus and Japura). Note that accuracy of GRACE-model agreement is generally low in such small basins due to high bias and leakage correction errors (Chaudhari et al., 2018; Felfelani et al., 2017; Longuevergne et al., 2010), reflected by higher RMSE values in Figure 2. Simulated TWS evidently follows precipitation anomalies (shown in grey bars in Figure 2), implying that any uncertainties in the precipitation forcing could have directly impacted TWS. For example, the simulated TWS peak in 2002 in the Solimoes River basin results from the anomalous high precipitation, however this could not be validated due to a data gap in GRACE. Overall, the model performance is better in the first half of the simulation period (i.e., 2002-2008) compared to the second half, especially in the western sub-basins including the Solimoes and Japura, which could be partially attributed to the decreasing trend in the precipitation forcing noted in Figure S6.

Figure 2 also shows the seasonal cycle including the contribution of different storage components to TWS. In all the basins, simulated seasonal cycle matches extremely well with GRACE, adding more confidence to the model results. TWS signal is

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sturdily modulated by the sub-surface water storage, demonstrating the importance of groundwater in the Amazon, especially in the southwestern sub-basins. The inverse relationship in the seasonal cycle of two sub-surface water stores, viz. soil moisture and groundwater, is readily discernable in Figure 2, which is caused by the competing use of the sub-surface compartment by the two terms (Felfelani et al., 2017; Pokhrel et al., 2013). However, in some sub-basins, such as the Purus, Solimoes and Negro, the low-lying areas with large floodplains causes flood water storage to be equally prominent.

3.3 Trends in Simulated TWS and Comparison with GRACE

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Here, we present a more detailed examination of the simulated TWS by comparing its spatial variability and trend with GRACE data. Because a shift in agreement between model and GRACE was detected in Figure 2 and S7, we conduct a trend analysis for two different time windows: 2002-2008 and 2009-2015 (Figure 3). It is evident from Figure 3 that the model captures the general spatial pattern of TWS trend in GRACE and its north-south and east-west gradients especially for the first half of the analysis period; however, notable differences are evident in the second half (2009-2015), particularly over the Madeira River basin. This is a noteworthy observation given that the basin averaged TWS variability matches extremely well with GRACE data (Figure 2), and thus warrants further investigation. There could be a number of factors contributing to the disagreement, some of which could be model-specific (e.g., wet bias in simulated discharge; Figure S3); however, this is a general pattern observed in many hydrological models as reported in a recent study (Scanlon et al., 2018).

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Scanlon et al., (2018) indicated a low correlation between GRACE and models, which they attributed to the i) lack of surface water and groundwater storage components in most of the models, ii) uncertainty in climate forcing and iii) poor representation of human intervention in the models (Scanlon et al., 2018; Sun et al., 2019). Here, we shed more light on the disagreement issue by investigating the contributions from the explicitly simulated surface and sub-surface storage components and their latitudinal patterns, addressing the first concern noted above which is the most critical among the three in the Amazon because of varying contribution of different stores across scales (Pokhrel et al., 2013). Figure 4 shows trends in TWS anomalies from GRACE products and the LHF simulation for the complete model-GRACE overlap period (i.e., 2002-2015) with climatology and with climatology removed; for LHF results, the surface and sub-surface component contributions to the TWS are shown. Also shown in the figure are the zonal means.

Simulated TWS from LHF model displays a higher correlation with GRACE trends compared to most of the global models discussed in Scanlon et al., (2018). Due to the incorporation of a groundwater scheme and other surface water dynamics, trend in basin-averaged TWS with climatology removed for the Amazon River basin is found to be -1.64 mm/yr, much less negative than most of the simulated TWS trends reported in Scanlon et al., (2018). The difference in the sign of trend can partly be explained by the negative trend observed in the WFDEI precipitation (Figure S6), concentrated over the Andes region which eventually drains into the mainstem of the Amazon through the Solimoes River. Due to steep topography, the impact of decreased precipitation over the Andes range is carried over to its foothills in terms of runoff, hence corresponding well with the negative trends in simulated surface water storage over the Central Amazon (Figure 4). Lower recharge rates in the region with decreasing precipitation trend (Figure S6) are also very likely, which is supported by the negative trend visible in the sub-

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surface water storage in Figure 4, over the northwest region of Amazon. Hence, it can be concluded that, even though the model shows some bias in TWS compared to GRACE data, the model accurately represents the key hydrologic processes in the Amazon basin; yet, these results should be interpreted with some caution while acknowledging the uncertainty in the forcing dataset. We also emphasize that it is important to evaluate models using spatiotemporal trends, especially with GRACE, instead of just using the basin averaged timeseries, a commonly used approach in most previous studies.

3.4 Interannual and Interdecadal TWS Change and Variability

Figure 5 show the interdecadal shifts in mean simulated TWS (total and its components) for the simulation period. Several observations can be made from this figure. First, the change between 2010s-2000s suggests high negative anomalies in all the water stores especially over Central Amazon. This is likely a result of increasing drought occurrence and severity in the region (e.g., the 2010 (Lewis et al., 2011; Marengo et al., 2011) and 2015 (Jiménez-Muñoz et al., 2016) Amazonian droughts). Second, although, the 2000s encompassed one of the severe Amazonian droughts viz. 2005 (Marengo et al., 2008; Zeng et al., 2008), its impact was not pronounced in terms of the decadal mean, which could be due to the offset caused by anomalous wet years including 2006 and 2009 (Chen et al., 2010; Filizola et al., 2014). Third, we find an increase in river water storage in the northwestern region and decrease in the southwest of the Amazon on a decadal scale (Figure 5, column 1, row 2), which is in line with the findings reported in previous studies based on the observed streamflow in 18 sub-basins for the 1974-2004 period (Espinoza et al., 2009; Wongchuig Correa et al., 2017).

The most remarkable feature we observe in Figure 5 is the exceptional interdecadal shifts between the 2000s and 2010s. Central and northwestern part of the Amazon region, encompassing the Negro and Solimoes, along with some parts of the Madeira in southwest, experienced a major decadal dry spell compared to the previous decades. Although a major part of this decadal dry condition could be attributed to the decreasing trend in input precipitation discussed in section 3.3 (Figure S6), the regional hydrologic changes in terms of TWS are also prominent. Another peculiar phenomenon observed at the decadal scale is the start of the negative anomaly in groundwater storage over the Central Amazon. A small but spatially well distributed below-decadal-average water table (dictated by groundwater storage) is evident in the Central Amazon region and the upper stretches of the Madeira basin during the 2010s (Figure 5, column 3, row 4). Since the water table is shallow and groundwater is the major contributor of streamflow in this region (Miguez-Macho and Fan, 2012a), some part of the negative anomaly in surface water stores can be attributed to the below-decadal-average groundwater table.

Significant long-term trends in simulated TWS and its components are evident in sizeable portions of the basin (Figure 6). While a negative trend is found in the southern and southeastern regions (e.g., Madeira, Tapajos, Xingu and Tocantins), the trend is positive in the northern and western regions (Solimoes and Negro) (see Figure S9 for basin averaged trends). Being the major contributor, sub-surface water storage mimics the trend patterns in TWS (see Section 3.2). On the contrary, surface water storage trends are mainly dominated by floodwater and are concentrated along the main stem of Amazon and the upper reaches of the Negro. The positive trends in floodwater can be explained by the corresponding trends in input precipitation (Figure S5). Excess precipitation in sub-basins, such as the Solimoes and Negro, which are characterized by a high topographic

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gradient, is directly translated in the surface water storage, in this case floodwater. Although a corresponding increment in river water storage is also expected, its smaller storage makes the trend magnitudes negligible. Nominal negative trends, but significant, in floodwater storage are found in the upper reaches of Madeira as well, corresponding to the negative trends in input precipitation over that region.

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To provide an in-depth understanding of the interdecadal changes occurring in the Amazon region and to determine whether the changes observed in Figure 5 are significant, we applied a t-test methodology to the long term TWS anomalies at basin and sub-basin levels. The spatial changes observed in Figure 5 are summarized with their interdecadal significance in Table S1, along with the decadal means and standard deviations. Significant change at 99% level is found in Negro River basin throughout the study period, followed by the Solimoes River basin exhibiting significant change in the last three decades. These changes can be attributed to the corresponding changes in precipitation (Figure S5), which follow a similar change in respective basins. However, the significant hydrologic changes in the Tocantins and Madeira can be primarily attributed to LULC changes, as the corresponding changes in precipitation were relatively negligible. For example, the Tocantins River basin underwent major LULC changes in response to heavy deforestation caused by dam construction and cattle farming (Costa et al., 2003) until policies were imposed in 2004 by the Brazilian government (captured in the ESA dataset, Figure S8). Similarly, the Madeira River basin also endured major LULC changes in the late 1990s which were dominated by agricultural expansion (Dórea and Barbosa, 2007).

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3.5 Interannual and Interdecadal Drought Evolution

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3.5.1 Severity of TWS-Drought

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In this section, we examine the time-evolution of droughts and quantify their impacts on TWS variability by using TWS-DSI. The use of TWS-DSI enables the depiction of a "bigger picture" encompassing all water stores that represent the vertically integrated total water availability during droughts and dictate the streamflow. Figure 7 shows the TWS-DSI for individual Amazonian sub-basins, and the 12-month standard precipitation index (SPI) (Mckee et al., 1993) calculated from the basin-averaged precipitation timeseries. As expected TWS-DSI follows a similar pattern of the SPI but differences in the index peaks can be noted for the drought years. For example, the 2005 drought was prominent in terms of TWS in the southwest region, comprising of Purus and Madeira rivers, with TWS-DSI going as high as -3, whereas the corresponding SPI were -1.78 and -2.2, respectively. Similarly, severe TWS drought (e.g. 2001) is detected in the southeastern basins of Amazon (Madeira, Xingu and Tocantins), however, the corresponding SPIs are negligible; the sub-surface storage (major contributor of TWS in these sub-basins) characteristic can be noted in these cases which has a delayed response from the preceding series of low precipitation events due to slow residence time.

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The impact of drought conditions on TWS is quantified by examining the seasonal dynamics in the simulated sub-surface water storage for the four most extreme historical drought years during the simulation period (Figure 8). Although no clear trend can be seen in terms of the evolution of the drought impact on sub-surface water storage, the spatial variability between different drought years is readily discernible. For example, the 1995 and 2010 droughts more or less had a similar magnitude and spatial impact on the sub-surface storage, however, the 2005 drought was more intense and dramatic in the Solimoes River basin; findings also noted in previous studies (Marengo et al., 2008; Phillips et al., 2009; Zeng et al., 2008). Similarly, the more recent drought in 2015 had a more pronounced impact in the eastern and northeastern region and average impact on the other parts of the basin. Due to the shallow water table in the Amazonian lowlands, sub-surface storage acts as a buffer during the low precipitation events, hence facing higher anomalies during drought conditions compared to the long-term mean. As the Negro river (i.e. Northern region of Amazon) basin experiences an opposite seasonal phase compared to rest of the Amazon region, the drought conditions in this basin are observed during the period of December to March. The opposite seasonal cycle of precipitation and flooding in the north and south banks of the Amazon mitigates the amount of flood and droughts in the basin as a whole, while resulting in more dramatic flood or drought in particular sub-basins (e.g. Tocantins, Tapajos and Madeira).

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3.5.2 Time Evolution of Dry Season Total Deficit and TWS Release

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The dry season TWS variability is examined by using the cumulative difference between PET and P, termed as the TWD (see Section 2.7). Further, to examine the response from TWS against TWD, we quantify the TWS-R, hence creating a supply-demand relationship between them. Figure S10 shows TWD, the corresponding TWS-R, and the total contribution of the surface water storage to TWS-R for the extreme drought years during 1980-2015 compared to their respective long-term means. Spatial patterns in TWD and TWS-R are analogous to the patterns in the simulated sub-surface storage during the months of September to November (SON) as seen in Figure 8. We find that TWS-R receives a fairly equal contribution from surface (along the rivers) and sub-surface (soil moisture and groundwater) water stores (rest of the region); however, the latter is more dominant during drought years. A clear positive trend in drought years is visible in Figure S10, indicating an increase in TWS-R, with significant sub-surface contribution, especially in the southeastern part of Amazon. This change can be directly attributed to the major LULC changes occurring in the basin, causing loss of TWS to evapotranspiration through agricultural expansion, especially in the Tocantins, Xingu, Tapajos and Madeira river basins (Chen et al., 2015; Costa et al., 2003; Dórea and Barbosa, 2007).

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3.5.3 Hydrological drought trends in Amazonian sub-catchments

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The hydrological drought behavior of each sub-basin is characterized by quantifying the drought days per year at the Level-5 Hydro-Basins scale (Lehner and Grill, 2013), referred here to as 'sub-catchments'. Based on the streamflow simulated at the most downstream grid in the sub-catchments, temporal trends for the 1980-2015 period are calculated and presented in Figure 9. Significant trends in drought durations are discernible in the Tapajos and Madeira sub-basin along with the southeastern portions of the Amazon, congruent to the heavy deforestation activities found in these sub-basins (Chen et al., 2015; Costa et al., 2003; Dórea and Barbosa, 2007). Although, LULC changes, such as deforestation activities, generally increase streamflow and are also known to offset the impact on streamflow caused by decrease in precipitation over the Amazon (Panday et al.,

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2015), this mechanism is dominant mostly during the wet season. In the dry season, however, the streams in the Amazon are fed primarily by the sub-surface water storage (see Section 3.2), which is negatively impacted by deforestation activities (e.g., increased regional evapotranspiration).

3.6 Comprehensive Characterization of Amazonian Droughts

As a first attempt to comprehensively characterize the Amazonian droughts, we present a summary of all the drought characteristics discussed in the previous sections on a spider plot (Figure 10). Each spider plot is a representation of a drought year with respect to the i) causes of drought and their type in terms of common indices, ii) response of different water stores, such as TWS, to the drought event, iii) role of groundwater storage in alleviating the dry conditions on surface, and iv) the spatial impact of the drought in different sub-basins of the Amazon. Although no significant trend in the combined drought characteristic is apparent, figure 10 provides important insights on the variability of Amazon droughts. It is evident from the figure that the drought variability over the years was significant in terms of both magnitude and spatial impact. The most notable feature in Figure 10 is the distinct relationship between SPI and drought duration. For example, during the 1995 drought, most of the river basins (e.g., Tocantins, Tapajos, Xingu, and Negro) experienced significant meteorological and TWS droughts, however, the severity of hydrological droughts was relatively negligible in those basins. Groundwater-surface water exchange is the key mechanism behind this unique behavior, causing groundwater to fulfill the drought deficit in streamflow over the basin. Due to shallow water tables at the downstream end of these basins, significant quantity of groundwater is fed to the rivers, which manifests as high peaks in total groundwater release evident in Figure 10. Similarly, high number of drought days are found corresponding to less groundwater release, such as during the 1995 drought in Madeira. On the contrary, TWS-DSI, generally follows the same pattern as that of SPI but with a lesser magnitude, which can be attributed to the delayed response from groundwater.

Further, the behavior of the Amazonian sub-basins can be characterized by the shape of the polygon formed by the comparison of different aspects of past droughts. The convex and concave characteristic in the plots mainly depends on the interrelation between meteorological and hydrological drought indices, which is further controlled by the sub-surface water storage. A convex polygon indicates lower groundwater contribution to streamflow in the sub-basin, such as in Purus during 1995 and 2005, whereas a concave polygon suggests higher groundwater release to streamflow in that particular year.

3.7 Intensification of the Amazonian Dry Season

Results suggest an increasing trend in TWD with significant decadal variability over the Amazon and its sub-basins, indicating an increase in dry season length over the past 36 years (Figure 11). Further, the increasing gap between TWD and TWS-R suggest an intensified terrestrial hydrologic system over the dry season during the study period. As the LULC impact is partly accounted for in the PET calculations (i.e., through changing surface albedo), the river basins with substantial LULC change, such as Madeira, Tapajos, Tocantins and Xingu, portray higher TWD trend magnitudes (significance > 95%). The peaks in the TWD corresponds well with drought years, for example, the peaks in the TWD for Madeira are analogous to the drought years

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Moved up [1]: On the contrary, TWS-DSI, generally follows the same pattern as of SPI but, with a lesser magnitude, which can be attributed to the delayed response from groundwater.

Moved up [2]: Although no significant trend in the combined drought characteristic is visible, Figure 10 provides important insights on the variability of Amazon droughts.

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Deleted: in river basins with substantial LULC change such as in the Madeira, Tapajos, Tocantins and Xingu River basins (e.g., 1988, 1995, 2005 and 2010). Due to this definitive response to drought conditions, TWD is also used to characterize historical drought events in the earlier sections. We note that the trends in the total deficit should be interpreted with caution as the uncertainty in the forcing could have affected TWD and TWS-R trend estimates.

We find that the river basins housing high altitudinal areas (Purus, Solimoes and Negro) have a fairly balanced relationship between TWD and TWS-R, but southern and southeastern sub-basins exhibit a higher water deficiency (Figure S11) with approximately 2 to 3-fold differences between TWD and TWS-R during regular years. For drought years, however, the difference between TWD and TWS-R is even higher, creating highly anomalous dry conditions in the sub-basins. Consistent higher values of TWD in southern and southeastern sub-basins of Amazon further highlights the intensification of the dry season with increasing water deficiency corresponding to an almost constant water supply from TWS-R. This phenomenon is also highlighted in Espinoza et al., (2016), which showed an significant increase in dry day frequency in the central and southern parts of Amazon. Results from this study combined with the reported increasing trend in wet season (Gloor et al., 2013), implies an overall intensification of the Amazonian hydrological cycle.

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4. Conclusion

In this study, we examine the interannual and interdecadal trends and variability in the terrestrial hydrological system in the Amazon basin and its sub-basins, with a focus on droughts and their time evolution during the 1980-2015 period by using a continental-scale hydrological model Leaf-Hydro-Flood (LHF) and terrestrial water storage (TWS) data from GRACE satellite mission. For the first time, we provide a comprehensive characterization of extreme drought events in the Amazon basin during the past four decades, while categorizing them with respect to their i) cause, ii) type, iii) spatial extent, and, iv) impacts on different water stores. We also provide an in-depth understanding of the interrelation between different drought types and the corresponding response of the sub-surface storage to surface drought conditions. Our key findings are summarized below.

First, the LHF model simulates the basin averaged TWS variations and seasonal cycle remarkably well for most of the sub-basins compared to GRACE data, however, some differences are observed in the spatial distribution of temporal trends for post-2008 period. We find that this discrepancy is caused primarily by the uncertainty in surface water storage simulations along the mainstem of the Negro and Amazon, whereas uncertainty in sub-surface storage prevails over the Andes. Second, the 2010-2015 period was found to be the driest in the past four decades due to an increase in frequency and severity of droughts. A t-test conducted on the TWS timeseries also indicated significant changes at the 99% level in the decadal mean TWS in the Negro and Solimoes sub-basins. Third, high negative long-term trends in TWS and increasing divergence between dry season total water deficit (TWD) and corresponding TWS release (TWS-R) indicate significant drying in sub-basins such as Madeira, Tapajos, Xingu, and Tocantins. Basin-averaged trends indicate that the Amazon is getting wetter (1.13 mm/yr), however, its southern and southeastern portions are getting drier. TWD is also found to be higher than TWS-R in these sub-basins, with approximately a three-fold difference between the two during some drought years, indicating a strengthening dry season in the region. Fourth, most of the extreme meteorological droughts do not propagate to hydrological droughts

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significantly, as the deficit is absorbed by the subsurface water storage and further reducing TWS drought severity compared to that of a meteorological drought in the Amazonian sub-basins.

Altogether, these results provide important insights on the interannual and interdecadal hydrological changes and the key mechanisms that govern drought events in the Amazon, along with a novel way of categorizing basin behavior during drought occurrence (Figure 10). This framework can be applied to better predict the future hydrological conditions and their corresponding socio-economic impacts toward taking measures to mitigate the drought impacts and facilitate a relatively facile transition of the local population through a future drought event. Basin drying trends reported in this study can also provide key leverage by applying them toward anticipation of the future hydrological conditions for sustainable management of water resources. We also highlight the importance of using spatiotemporal trend estimates for model validation, especially with GRACE, instead of the commonly employed approach of timeseries comparison. Improvement in the correlation between the temporal trends in simulated TWS and GRACE anomaly through the inclusion of a prognostic groundwater scheme which allows dynamic groundwater-surface water interactions in the model framework is also highlighted. Further, the need to investigate the effects of uncertainties in model forcing to TWS simulations is noted because we find that the trends in precipitation are strongly propagated to TWS simulations.

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A limitation of the present study is that the effects of irrigation and manmade reservoirs are not yet incorporated in the model. The basin-wide effects of the existing dams in the Amazon are small (Pokhrel et al., 2012a); however, as more dams are added across the basin, it will become critical to account for such effects. Model improvement is underway (Pokhrel et al., 2018; Shin et al., 2018), and these issues will be addressed in our forthcoming publications. Despite some limitations, this study significantly advances the understanding of changing Amazonian hydrology, and our results have important implications for predicting and monitoring extreme droughts in the region; the research framework can also be applied to other global regions undergoing similar hydrological changes.

Author Contribution

SC, YP, EM designed the research; YP, SC, and GM setup the model; SC performed simulations, analyzed results and prepared the draft; all authors discussed the results and wrote the manuscript.

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Competing interests

The authors declare that they have no conflict of interest.

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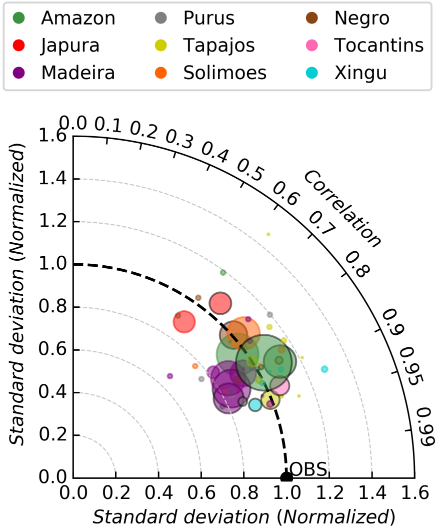
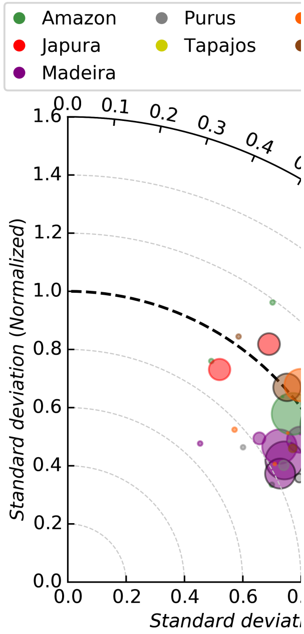


Figure 1 – Taylor diagram showing the correlation and standard deviation ratio between the simulated and observed streamflow at 55-gauge stations across the Amazon. The locations of the 55-gauge stations are shown in Figure S2. Highlighted points with black border are the gauge stations for which timeseries comparisons are shown in Figure S3 and S4. Size of the markers indicates the annual mean simulated streamflow at that station whereas the color indicates the Amazon sub-basin in which the station is located. The linear distance between each marker and the observed data (i.e., OBS; the black dot) is proportional to the root mean square error (RMSE).



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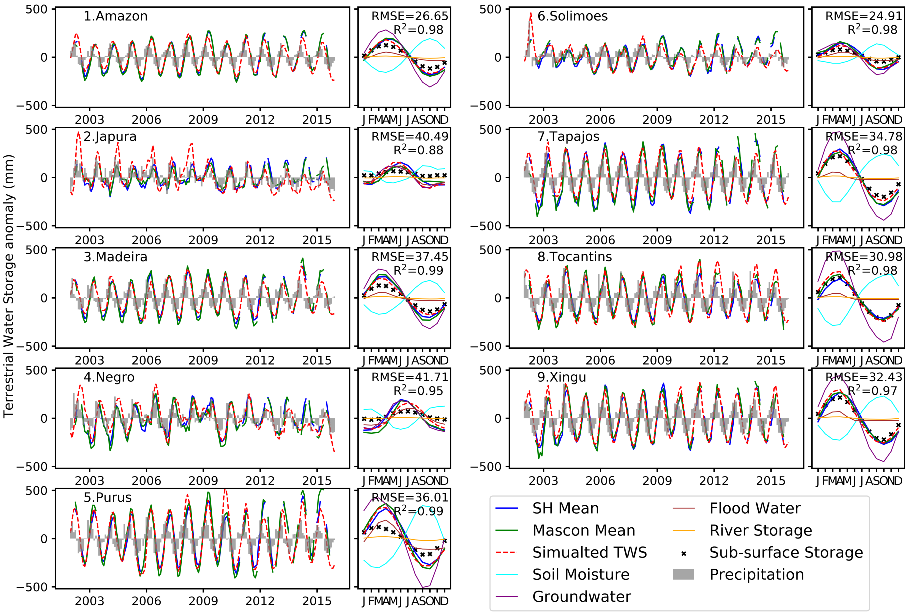

Figure 2 – Comparison of simulated TWS anomalies from LHF and TWS anomalies obtained from GRACE for the entire Amazon and its eight sub-basins for 2002–2015 period. Basin averaged precipitation anomalies obtained from WFDEI forcing dataset are also shown as grey bars. Seasonal cycles of GRACE and simulated TWS are shown in the right panel of each basin along with the simulated individual TWS components. GRACE results are shown as the mean of the spherical harmonics solutions from three different processing centers (i.e., CSR, JPL, and GFZ) and mascon solutions from CSR and JPL. Simulated TWS anomalies are calculated with respect to the GRACE anomaly window of 2004-2009 for consistency.

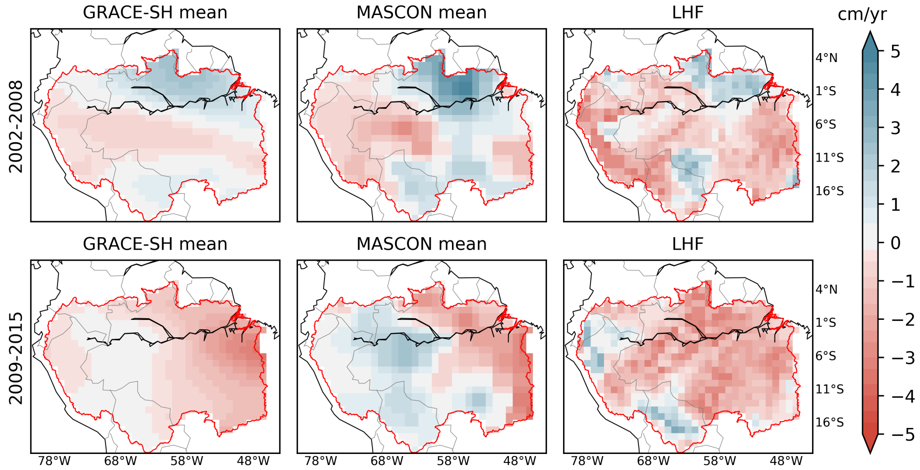

Figure 3 – Temporal trend of GRACE solutions compared to the trend in simulated TWS from LHF for the Amazon River basin for two different time periods. GRACE-SH trend displayed, are mean trends computed from water thickness anomalies obtained from CSR, GFZ and JPL processing centers, whereas the mascon mean trend is computed from anomalies obtained from CSR and JPL centers.

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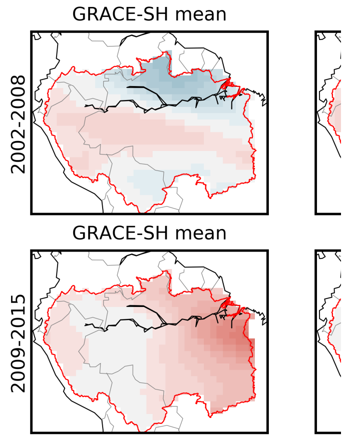

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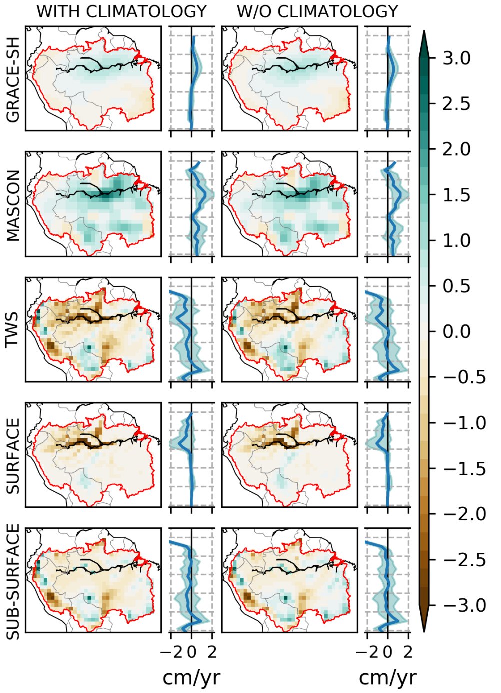
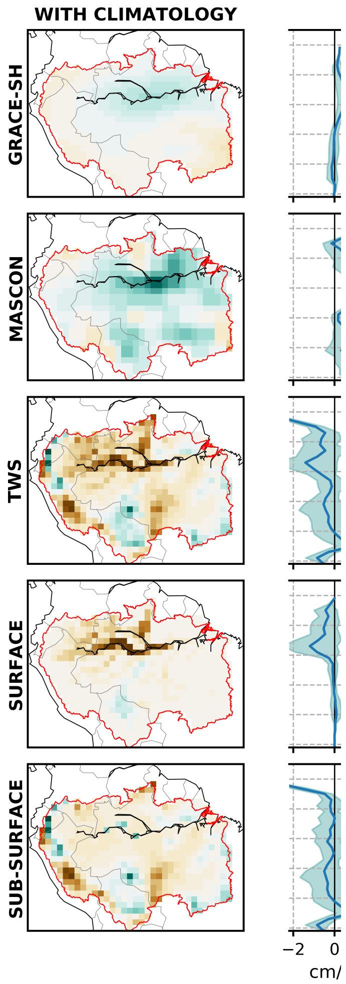


Figure 4 – Same as in Figure 3 but for the complete model-GRACE overlap period (i.e., 2002-2015). The latitudinal mean is shown on the right side of each panel.



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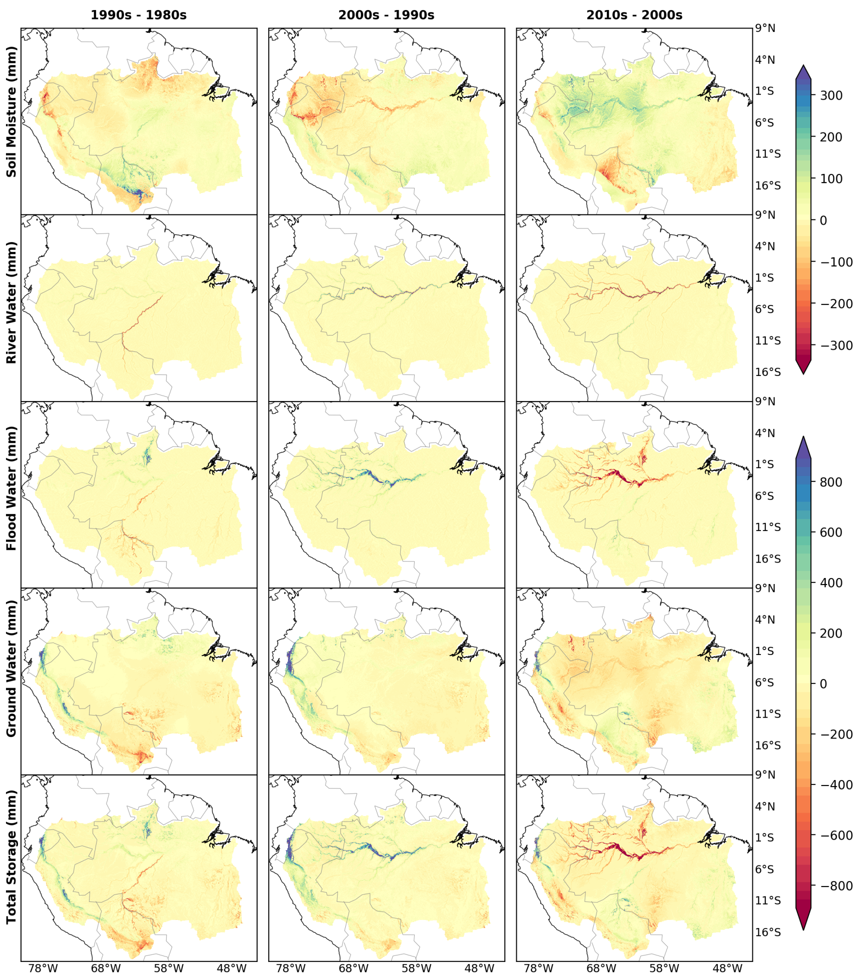
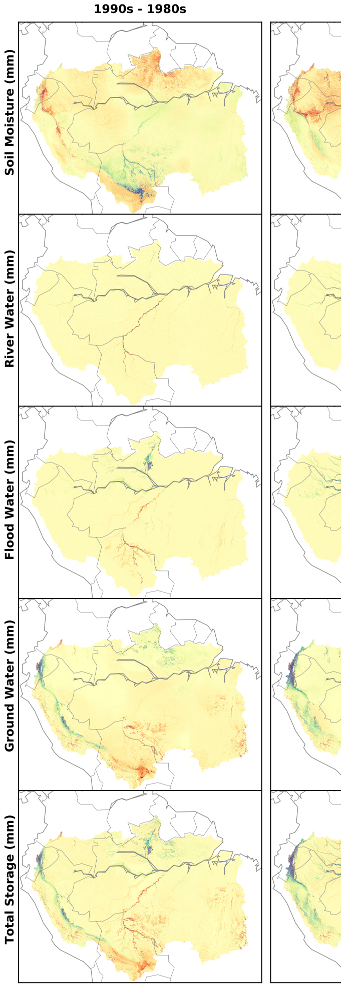


Figure 5 – Interdecadal difference between individual water store and TWS storage for the period of 1980-2015 at the original ~2 km model grids. The changes are displayed as the difference between consecutive decadal means for TWS and its components. Decadal windows are: 1980-1989 as 1980s, 1990-1999 as 1990s, 2000-2009 as 2000s and 2010-2015 as 2010s. Note that the 2010s period consists of only six years and the ranges of color bars differ among the plots.



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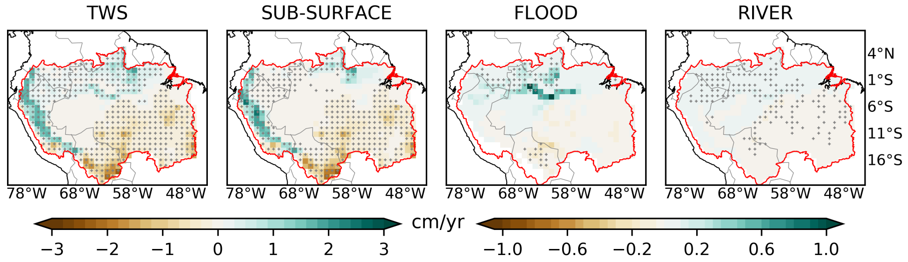

Figure 6 – Temporal trend in simulated TWS and its components (i.e., sub-surface water, flood water, and river water stores) for the period of 1980 to 2015 expressed in cm/yr. Markers indicate significant trends at 99% level. Note that the ranges of color bars differ among the plots.

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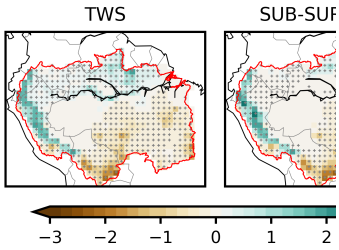

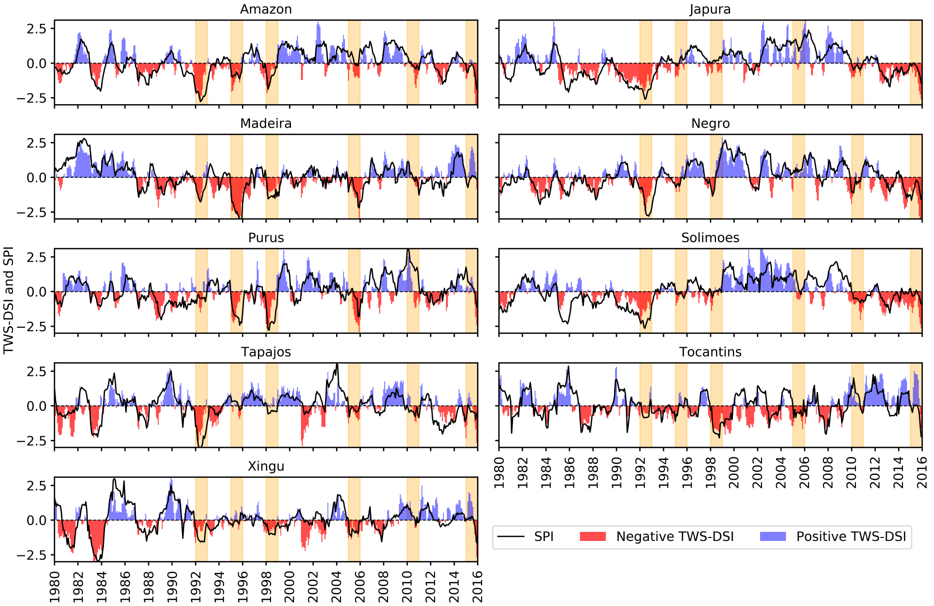

Figure 7 – TWS drought severity index (TWS-DSI) calculated using the simulated TWS from LHF for Amazon and its sub-basins. TWS-DSI are calculated using basin averaged TWS anomalies on a monthly scale. Shaded areas indicate the severe drought years reported in the past literature. Black line is the 12-month standardized precipitation index (SPI) calculated by using basin-averaged precipitation data from WFDEI forcing dataset.

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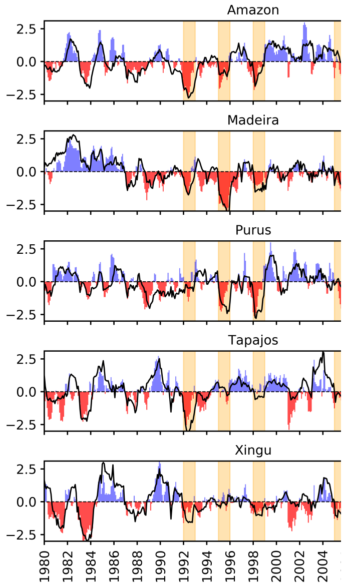

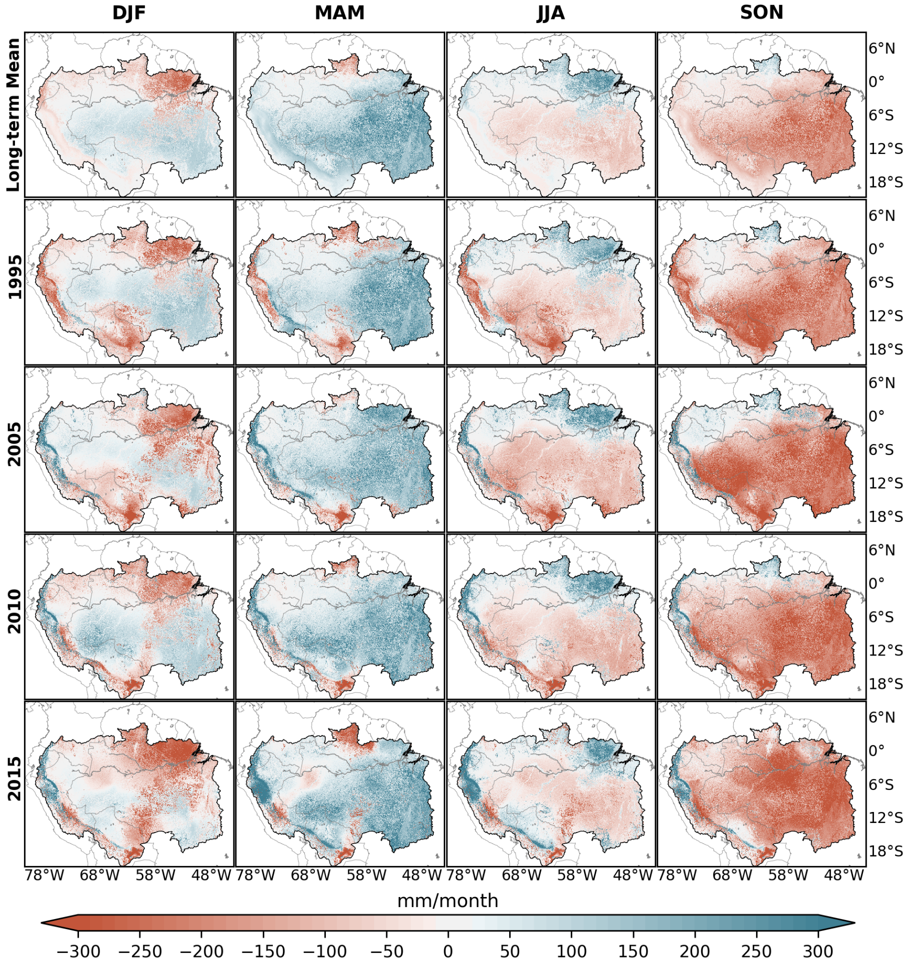

Figure 8 – Seasonal dynamics of simulated subsurface water storage from LHF in the Amazon River basin for extreme droughts during the simulation period. Long term mean is the mean seasonal anomaly for the 1980-2015 period, where DJF is December to February, MAM is March to May, JJA is June to August, and SON is September to November.

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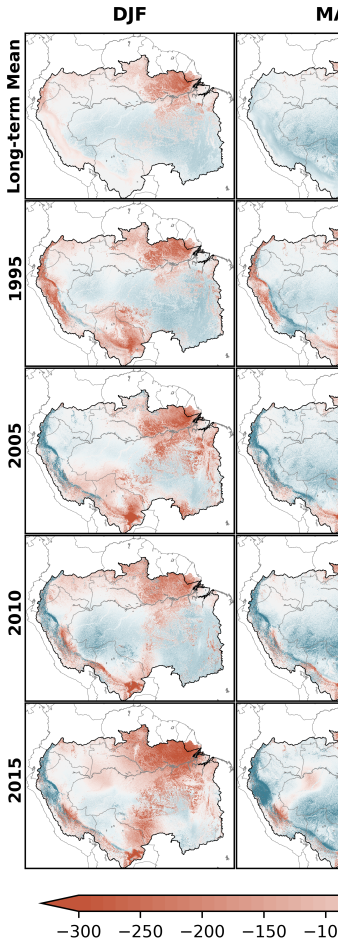

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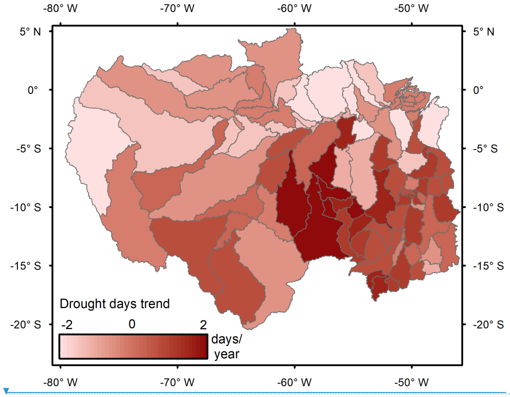

Figure 9 – Trends in drought duration per year in the Amazon at a Level-5 Hydro-Basins scale as defined in Lehner and Grill, (2013), derived by using the Q_{90} threshold from the simulated streamflow by the LHF model. Darker colors indicate the higher positive trend magnitudes.

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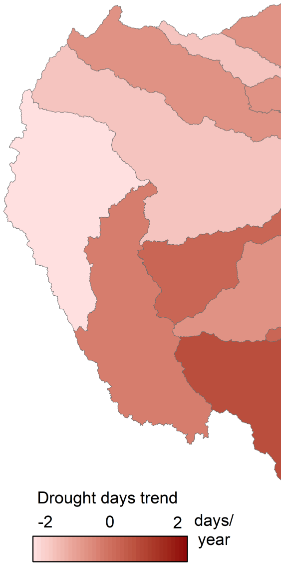


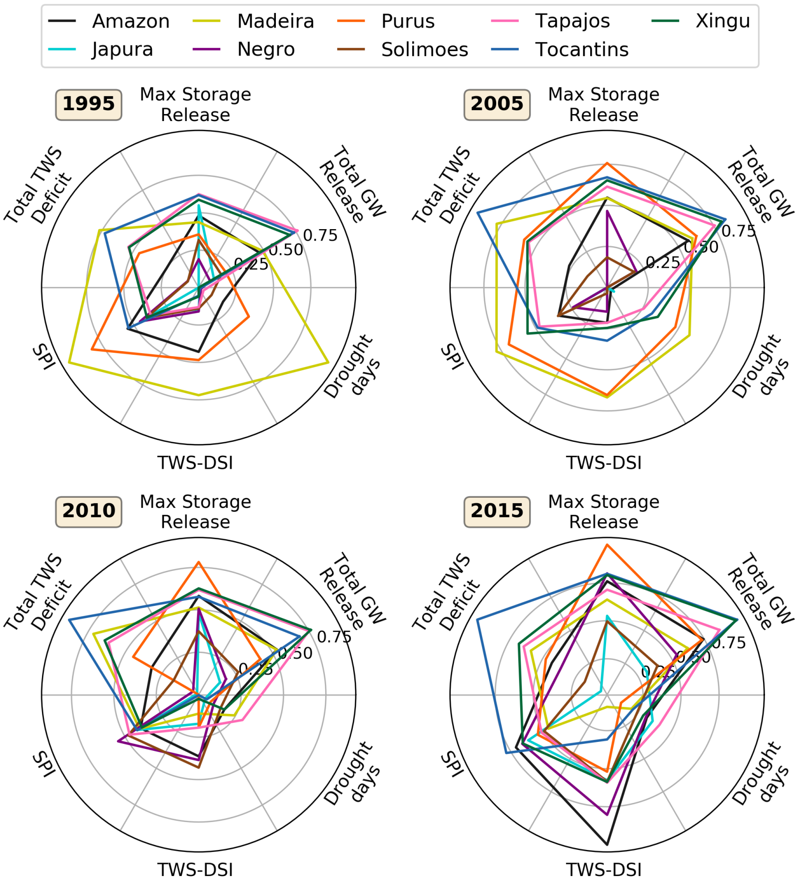
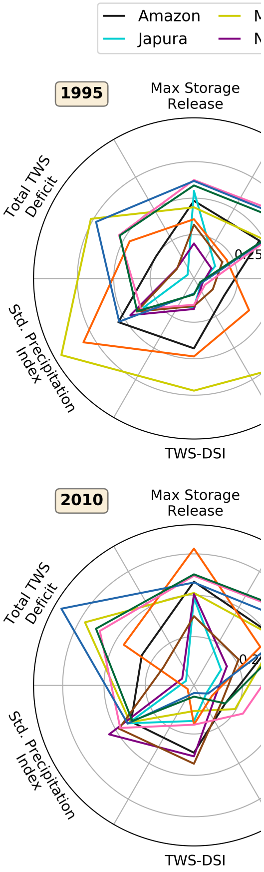


Figure 10 – Inter-comparison and comprehensive characterization of the severe drought events during the modelling period in the Amazon River basin and its sub-basins. Color coding in each subplot represents individual river basin. Note that all variables are basin averages normalized (0-1) for each variable over all drought years. Bottom half of the variables in the figure are drought indices representing different types of droughts: TWS-DSI denotes TWS-drought severity index (Section 2.7), SPI (Standard Precipitation Index) represents meteorological drought severity, and "drought days" represents hydrological drought severity in the basin (Section 2.6). Top half of the variables quantify the water deficit in terms of total TWS deficit (cumulative PET-P), water supply as the TWS release (Max storage release) and the groundwater contribution of TWS release (Total GW Release).



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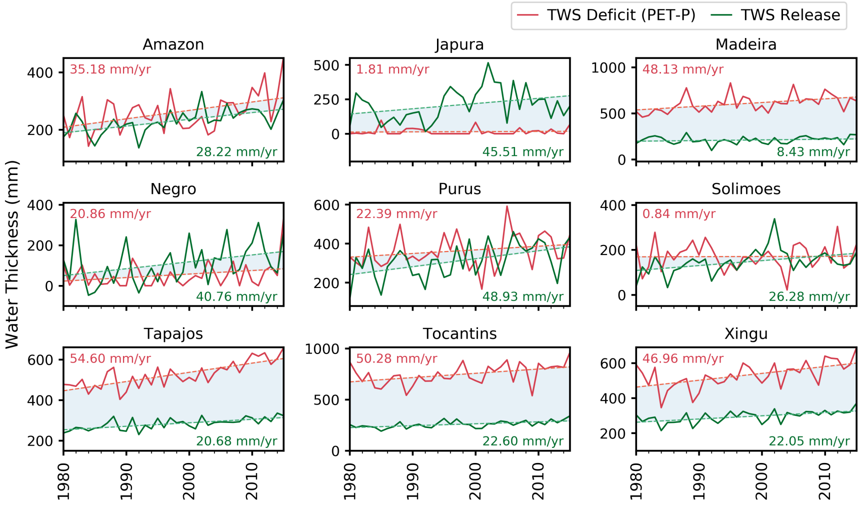

Figure 11 – Trends in dry season total deficit (TWD) quantified as the cumulative difference between potential evapotranspiration and precipitation (PET-P) and corresponding simulated TWS release (TWS-R) from LHF for Amazon and its sub-basins.

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