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Discussions

Interactive comment on "Forecasting terrestrial water storage changes in the Amazon Basin using Atlantic and Pacific sea surface temperatures" *by* C. de Linage et al.

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This document is a point-by-point response to Referee #1.

General Comments: The authors relate remotely sensed terrestrial water storage (TWS) anomalies (TWSA) in several regions of the Amazon Basin to oceanic SST indices to develop empirical modeling frameworks for seasonal prediction of future anomalies. There is a growing body of evidence that droughts, in particular, have large-scale precursors with some predictability. Even though the purpose of this paper is to describe the model development, the authors could do a better job linking their

findings such as recession times to dynamical processes in the region. The references are light on ocean or atmospheric dynamics papers for such critical features as the South Atlantic Convergence Zone (SACZ) and the South American monsoon. While SSTs are the fundamental drivers of the system, the proximate causes of water storage anomalies are the regional to local circulation systems governing local P-E. It is the blizzard of non-linear interactions in the land-atmosphere system at convective to regional scales that introduce the noise into the SST-TWSA relationships in this region. In summary, this paper has the potential to contribute to our understanding of and ability to use predictability in the Amazon Basin but needs more physical connections to the ocean-atmosphere dynamics. Creating a robust empirical modeling system depends on a firm understanding of the potential sources and sinks of predictability.

We understand that our initial explanation of the physics underlying the observed teleconnections was not as comprehensive as it could have been. Because it is impossible to deal with all aspects of such a complex problem in one single paper, we decided to focus on providing context for the reader to understand the specific advances in our paper that are relevant to this field of research, i.e. the analysis of the large-scale features of terrestrial water storage interannual variations from the GRACE satellites and the study of their predictability using remote SSTs. Even if the mechanisms are not yet fully understood, we believe our study contributes in an important way to our understanding of these systems by showing it's possible to explain a considerable amount of variance of the terrestrial water storage anomalies using SSTs one- or even two-seasons ahead. Because seasonal prediction of precipitation sometimes performs poorly, our results may allow a partial bypass of this limitation by using SSTs as predictors for seasonal forecasting of large-scale droughts and floods. That is why we believe this work may have important implications in the field of risk management, even if we do not yet understand all of the underlying mechanisms.

To address Referee #1's concerns, we will dedicate a new subsection of the discussion to link our results with others' papers and review possible physical mechanisms (large-scale as well as more regional and local ones) explaining the observed/unobserved teleconnections between SSTs and TWSAs. We think that such additional elements of discussion will also make the discussion more focused and less general, and as such also will therefore address Referee #2's concerns. We plan to integrate some of the references suggested by Reviewer 1 into this section. We also will introduce in the introduction and section 2.2 some missing important concepts and references related to the South Atlantic Convergence Zone modulation by ENSO, including works by Nogués-Paegle and Mo (1997) and Carvalho et al. (2004).

Specific Comments: This research appears to have been carried out with care and competence. The authors use methods pioneered in previous work and take a step by step approach to isolate spatial variability and forecast lead times. Given they are using linear regression with particular oceanic indices, it does not appear that they can much improve their R2 with additional tinkering with these inputs unless they test new inputs. What can be improved is the understanding of sinks and sources of predictability so that the forces behind the unexplained variance can be identified. Although there is not space for detailed discussion, I point out a number of areas in the paper that need physical context or at the least, better referencing to proximate causes to achieve better understanding of the results. While South America is a rather understudied continent compared to Africa or North America, the authors will find papers by Brant Liebmann, Tsing-Chang Chen, Leila Carvalho, Charles Jones, Kerry Cook, Rene Garreaud, Josefina Arraut, Julia Nogués-Paegle, Marcelo Seluchi, and Mattias Vuille useful for understanding South American land-ocean-atmosphere dynamics. More fundamental work on tropical dynamics by Paul Roundy, George Kiladis, A.J. Matthews, Brant Liebmann, Charles Jones, and K.M. Lau is also essential reading for understanding the time and space scales of SST forcing on the land-atmosphere system.

We plan to integrate many of the references suggested by Referee #1 into a subsection of the discussion. As said above in our reply to Referee #1's main comments, we also will introduce in the introduction and section 2.2 some missing important concepts and references related to the South Atlantic Convergence Zone modulation by ENSO, including work by Nogués-Paegle and Mo (1997), Carvalho et al. (2004) and Grimm et

al. (2003).

12455, Lines 1-18: Droughts tend to affect a much larger spatial scale than floods. The scales of the disasters mentioned in the opening paragraph should be quantified so that this difference may be appreciated.

We agree that the spatial scales of droughts and floods are likely different. We will add a sentence in the introduction to mention this difference of spatial scales. However, we want to emphasize that, due to the GRACE coarse spatial resolution (about 160,000 km^2 at the equator), we can only detect (hence forecast) large-scale droughts and floods.

12455-12456, Line 26- : The discussion of Atlantic links is superficial. Because the Atlantic, unlike the Pacific, is a more direct driver of the South American seasonal cycle, this paragraph should offer a more nuanced and holistic view of links to Atlantic rather than focusing on a single circulation feature and its role in particular droughts. The critical role of the SACZ, in South American monsoon dynamics is not mentioned. Interannual variability in rainfall and the role of the SACZ are well documented, starting with Nogués-Paegle and Mo (1997).

We will modify the revised version (introduction and discussion sections) of our manuscript to introduce and discuss the role of the South Atlantic convergence zone in regulating the South American monsoon and how it is modulated by ENSO. We will also more clearly delineate our study area (e.g. on line 24, p.12456) as a section of northwestern and central tropical South America within 22.5°S-13.5°N and 46.5°W-82.5°W. We mainly focused on the influence of the Inter-Tropical Convergence Zone (ITCZ) in the North Atlantic, because it controls the northern/tropical branch of summer rainfall in South America, rather than on the SACZ that controls the southern/subtropical branch of the South American monsoon. Indeed, it appears from the works by Nogués-Paegle and Mo (1997) and Carvalho et al. (2004), that the regions that are mostly affected by the SACZ are not included in our study area (spanning 22.5°S-13.5°N 46.5°W-82.5°W): Brazil eastern regions in the Tropics, and Brazil southern regions, Uruguay, Paraguay and Argentina northern regions in the subtropics. Even though we show the results for parts of eastern Brazil (i.e. in the Tocantins basin), we chose to focus on the Amazon basin because of the potentially important ecological impact of drought and fires on the tropical forest. The SACZ seems to be somehow connected to Tropical South Atlantic (TSA) SST anomalies, which are positively correlated with rainfall in Brazil Nordeste and negatively correlated in Brazil southern coastal regions (Yoon and Zeng, 1999; Grimm et al., 2003), consistently with the 'seesaw' pattern highlighted by Nogués-Paegle and Mo (1997). However, Yoon and Zeng (1999) show that TSA SSTs are not significantly correlated to rainfall in our study area, except in the Amazon Delta region, explaining only 1.4% of the Amazon rainfall total variance (Zeng et al., 2008). Finally, although the SACZ might not directly influence TWS in our study area (focused on the Amazon basin), there may be some regional, tropical-subtropical interactions between the two systems of the South American monsoon, as highlighted for example by the strong low-level jet advecting moisture from the Amazon basin southward to the north of the La Plata basin during El-Niño events (Grimm et al. 2003).

The study areas cannot be easily deduced from the very busy Figure 1. I suggest a separate panel just showing elevation (shaded) and the outlines of the subregions.
We will add another panel to Figure 1 and split the information into two maps.

12458, Lines 17-21: The regional variations in rainfall anomalies with respect to ENSO phase are considerable. Areas of the basin experience anomalies of the opposite sign during the same phase of ENSO. Here, only one relationship is mentioned. This opening should provide a better perspective on these regional variations or provide references that do explore these variations.
In Tropical South America, the strongest correlations between hydroclimatic variables and Pacific SSTs are negative and are found in South America's northeastern regions (Ropelewski and Halpert, 1987; Enfield 1996; Zeng, 1999; Dettinger et al., 2000; Yoon and Zeng, 2010; this study). According to the same studies, significant anti-correlations are found in the sub-tropics, e.g. in Paraguay, Uruguay, and Argentina northern re-

gions. To broaden the scope of our study, we will mention these regional variations along with the corresponding studies, even though they are found beyond the limits of our study area, i.e. the tropical regions of South America within 22.5°S-13.5°N 46.5°W-82.5°W.

12459, Lines 5-6: It is stated that the AMO is related to North Atlantic SST variability and implicated in US drought. Instead of commenting on the Northern Hemisphere, can the authors substitute comments and references that show that this index and dataset have been shown to be relevant to the Southern Hemisphere, affecting South American monsoon system?
We will replace this comment by a sentence summarizing the impact of anomalous Tropical North Atlantic SST on the atmospheric circulation over the northeastern regions of South America, citing the works by Enfield (1996) and Zeng et al. (2008).

12459, Line 11: "Atlantic Meridional Model" should be "Atlantic Meridional Mode".
This typo will be corrected.

12462, Lines 1-15: This brief physical explanation would benefit from considering previous studies of interannual variability of precipitation and/or streamflow (e.g., Carvalho et al. 2004) and commenting on how these results are more or less consistent with previous work. The position and intensity of features such as the SACZ and the seasonal cycle of the monsoon are the proximate causes of TWSA. For these significant droughts, how did the SSTs impact the progression and intensity of the monsoon? This paragraph also offers the opportunity to explain or at least propose a hypothesis why region C's explained variance (12461, Line 21) is so much lower than the other regions. This needs more follow-up.
At this point of the paper, we would like to keep the result focused on our new findings and avoid citing other works. We will discuss in an additional subsection of the discussion the proximate causes that are responsible for such a low performance of our model in region A (we guess Referee #1 means region A instead of C).

Section 4.2: When there is little context and no proximate causes offered, the relaxation times are just numbers that change from place to place. While there may not be room to go into detail, references relevant to understanding these relaxation times could be provided.
We already provide some information about possible physical interpretations of the relaxation times at several locations in the paper: on lines 27-28 of page 12462 ('A shorter relaxation time τ indicates more sensitivity of the system to SST forcing and thus a shorter memory.'), on lines 7-10 of page 12463 ('Large τ values (6/12 months) were found in the downstream parts of the main rivers, floodplains and wetlands, where the land surface memory increases due to longer residence times of surface water storage and time delays associated with stream and river transport.') and on lines 10-14 of page 12466 ('Use of a spatially varying relaxation term also was justified because some regions have a longer memory, for example in the Amazon downstream regions where the surface water storage component adds memory to the system, because it integrates the runoff from all the upstream regions with various delays with respect to forcing from SST anomalies.'). On lines 7-10 of page 12463, we will provide two additional references for the mentioned residence time in floodplains, which was found to equal 3 months in a floodplain lake (Bonnet et al., 2008), and for the delay associated with river transport and floodplain storage, which amounts about one month every 900 km assuming an effective velocity of 0.35 $\mathrm{m\,s^{-1}}$, used currently used in continental-scale runoff routing modeling (e.g. Miller et al., 1994).

12464, Lines 13-21: The report of differences in the timing of influence of TNAI vs. Niño 4 is interesting but again, suffers from a lack of context here or later in the paper. Do the authors have any comments or can provide any references be made that can shed light on why these results were obtained?
At this point of the paper, the point is not to speculate on the physical mechanisms that lead to such results. However, we will refer to this result in section 5.1, on lines 11-14 of page 12465, when we mention the study by Ham et al. (2003) showing that SST anomalies in the Tropical North Atlantic lead to opposite SST anomalies in the Central

Equatorial Pacific with a lag of three seasons, which may explain the different timing of influence of the two indices over South America northern regions.

12465, Lines 17-19: The authors appear to assume that they can isolate the signals from the two oceans. Before making such an assertion, they should dig into the literature on tropical-extratropical interactions (Paul Roundy's work for a start) to make a more informed judgment on the separability of these signals.
We will reformulate this sentence to make it less confusing. We do not mean the signals from the two oceans are independent because clearly they are not due to complex teleconnections (as shown by the studies cited in this subsection). Our suggestion is simply to transform a set of correlated predictors into a set of independent predictors, so that each part of the observed variance may be attributed unequivocally to one single predictor. This will be useful when we will add other oceanic sources in the model forcing, as for example ENSO is correlated with many other oceanic pools worldwide. Forecasting using empirical models based on a set of various predictors has proven useful, for example in hurricane forecasting at long lead times, when a mechanistic approach fails. The goal of this paper is to show that with a simple model, we are able to explain a relatively large amount of the TWS observed variance, not to explain the complexity of the tropical-extratropical interactions.

12466, Lines 15-20: The discussion of future work is well-conceived. I highly encourage the authors to perform (1) and then report on the results as a follow on to this paper. Too many empirical models, however carefully derived, have fallen down on the job during independent testing using new data.
This may be done with the remaining years of the current GRACE mission, but we will have to wait until the current time series is updated. Moreover, because the current mission is drawing to its end, we may have to wait until the launch of the GRACE follow-on mission scheduled in 2017 before being able to validate our model with another decade-long time series of independent GRACE data.

As for (3), I raise a lot of questions about physical mechanisms in this review that

may require their own paper. However, even with the limited space here, additional comments, hypotheses formulated by the authors, and certainly additional relevant references can be offered to provide a bit more context to the results.
This concern will be addressed in a new subsection of the discussion and by introducing additional hypothesis/references whenever necessary.

12466, Lines 24-25: For future work, I would encourage the authors to adopt a more complete view of the ocean-atmosphere system and look harder at the atmospheric dynamics. The link between the oceans and the local P-E is the non-linear interaction of the atmosphere at multiple spatial scales, from convective to regional. The relaxation time for Region C could relate to the time scale of the Bolivian High-Nordeste Low circulation (e.g., Chen et al. 1999), a circulation system that controls the moisture transports within Region C. This circulation is established by an intercontinental short-wave train wave train resulting from a complex combination of latent heating from deep convection in South America, Africa, and the Western Pacific interacting with the unique topography of South America. This is not going to be fully described by a simple linear combination of SST indices and thus contribute mightily to the unexplained variance in the model.
Thank you for your suggestion and explanation.

Section 6 (conclusions): Although part of the Amazon was quite reducible to SST variations (66% in the northeast), the other sections had far more unexplained variance. More confidence is expressed in this closing than is warranted, particularly since the connections between regional water balances to the relevant ocean-atmosphere-land dynamics are not yet laid out.
We wanted to emphasize the fact that we were able to explain as much variance in the three regions using remote SSTs, rather than focusing on the variance we were not able to predict. It is impressive to be able to predict even as 'little' as 39% of variance in region C 3 months in advance. In the last paragraph of the conclusion, we will add as a future direction of this work the need to investigate the physical processes acting

at the regional scale and being responsible for the small amount of explained variance in region A.

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