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Interactive comment on "A baseline probabilistic drought forecasting framework using Standardized Soil Moisture Index: application to the 2012 United States drought" *by* A. AghaKouchak

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Point-by-Point Response to Review Comments

The author would like to thank the reviewer for the constructive and thoughtful comments and suggestions which led to substantial improvements in the revised version of the manuscript. In the following, the issues raised by the reviewer are addressed point-by-point in the order they are asked. Reviewer's comments are shown in italic; author's reply is shown in regular text.

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Anonymous Referee 3

The article discuss about 'probabilistic drought forecasting framework using SSI and to evaluate the model for 2012 US drought'. During recent years, a large number of articles reported improved drought forecasting techniques using multiple as well as improved drought indices. Based on those previous articles, this article did not seem to be either improving drought indices or forecasting technique, whereas by applying to the continental US, it draws several shortcomings.

Drought indices: There are numerous articles highlighting the application of SPI for quantifying the drought events, which is valid as precipitation is a natural input to water resource system. However, using the concept of SPI, the standardized soil moisture index (SSI) is not useful as it should be, for example, the agricultural water sources is highly variable for USA due to precipitation pattern. The eastern USA is supplemented by rainfall, whereas western USA is irrigated by artificial means (i.e., canal and reservoir operated). Therefore by realizing this fact, the application of SSI for continental USA is a major drawback of the study. The PDSI is a more robust index based on a sceintific reasoning for monitoring agricultural drought in comparison to SSI (which is based on cumulative values). Several articles developed soil moisture deficit index at a shorter temporal scale, which can be more useful for agricultural droughts monitoring and forecasting. The SSI lacks in quantifying soil moisture supply for crop growth, for example, one day extreme precipitation event within a month will provide higher soil moisture, where as it will have negative impact on crop growth.

Response: Please note that the manuscript does not suggest SSI as an alternative to SPI or PDSI (or any other indicator). This issue is highlighted in the revised version of the manuscript. I agree with the Reviewer that the agricultural water sources are highly variable over the USA, and some parts are irrigated. However, the input soil moisture data, used in this study, includes an irrigation scheme, and it is taken into account. It is acknowledged that irrigation schemes have their own limitations [1], and the author does not claim irrigation is fully represented. However, model predictions with respect

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to spatial pattern are consistent with observations which indicate that the observed patterns are reasonably captured.

I agree that there are "soil moisture deficit at shorter temporal scales". However, for persistence-based prediction the memory of the system plays an important role and short-term indices are not appropriate (this is due to the persistence-based nature of the modeling framework). The concept of SSI allows deriving soil moisture information using different time scales.

The Reviewer believes the " SSI lacks in quantifying soil moisture supply for crop growth". I am not sure on what basis the Reviewer believes SSI does not provide information on moisture supply. Similar to other soil moisture indices, SSI provides information on soil moisture anomalies and can be computed for different time scales. Note that monthly drought indicators are not designed to distinguish daily extreme precipitation and resolve their effects on crops. The fact that a daily extreme precipitation will lead to higher soil moisture is not unique to SSI. In fact, monthly soil moisture percentiles and other indicators will show the same signal. However, SSI offers the opportunity to derive soil moisture at longer time scales similar to SPI (e.g., 3-, 6-month). Other than that, it is similar to the other soil moisture-based indices. Having an indicator for longer time scale, the effect of one single extreme wet event may not shift the wet or dry signal. In other words, the nature of SSI allows addressing the problem raised by the Reviewer. The fact that this model is not designed to capture rapid development of extreme events is addressed in the revised version (see Section Conclusions).

Methodology: There is a shortcoming in drought forecasting, when applying a persistence based model to a moving sum drought index (i.e., SSI based on six month accumulated values) for 1 to 2 month lead time. Similar concern was also raised by reviewer 1 (second comment). For example, taking an m period moving sum of the *time-series, it will completely destroy the evidence for an m period periodicity.*

Response: Please note that a persistence-based concept can only be applied to a system with a significant memory. Applying persistence-based prediction to moving sum of time series is very common and has been used in numerous other publications including streamflow and precipitation (e.g., see [2] [3] [4]).

The persistence method works well when weather variables change very little and features on the weather maps move very slowly. However, if weather conditions change significantly from month to month, the persistence method usually breaks down and is not the best forecasting method to use.

Response: We agree and this is exactly the reason, the method is applied to a moving sum. The approach has been used for drought prediction using precipitation in Lyon et al., [2]. Having a moving average of, say 6 months, soil moisture, moving one month a head, soil moisture will not change substantially (because of dominance by 5 month overlap). This is the reason that the method offers some level of drought predictability.

Therefore, the application of proposed methodology has two drawbacks: (a) application of persistence based model to a moving sum time series, (b) the constant selection of 6 month moving sum for all climatic regions of US do not seems to be true as there is a wide variation of climatic patterns across USA, for example variation of precipitation from east to west and temperature north to south, which are major drivers for soil moisture availability.

Response: We acknowledged that this method has drawbacks and discussed the limitation in the manuscript. However, applying the method to a moving sum is not a drawback. In fact, it is necessary. About the constant 6-month moving window; we do not claim that 6 month should be used for everywhere in the United States. The same modeling framework can be used for different temporal accumulations. The purpose of this study is to argue considering soil moisture accumulation alongside other variables provides additional predictive information.

The probability of drought definition (line 18, page 1952) seems to be based on number of events using a threshold level, however more damage will occur at higher severity level. The methodology section is not clearly written, a flow chart might be helpful for linking the components.

Response: Persistence-based prediction relies on historical observations and near past initial conditions. As mentioned in the manuscript, this method cannot be used for prediction of very rare and extreme events that have not been observed in the past (see Section Conclusions). In a 100 year record, a standardized value of -2 (drought severity) is expected to happen between 2-3 times. This means probabilistic analysis of extreme droughts would not be possible because of limited observations in the past. For this reason, a persistence-based method is most suitable for assessing changes in the system relative a moderate drought threshold. We have shown limitations of this method in predicting extreme conditions in Figure 5b to make sure an objective and fair assessment is provided for the readers. In fact, the purpose of showing Figure 5b is that to highlight the limitation of this method in capturing rare events.

In the revised version, we have extended Section Methodology. All the governing equations are provided.

Results: It is highlighted that 'using accumulated soil moisture would significantly improve persistence based forecasting model'. This cannot be a stressed as a major

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findings, as all moving sum time series will have higher persistence level. How do the box plot is created for Texas and California? Is it collection of all the gridded soil moisture ACF values? The higher ACF values of soil moisture with respect to precipitation will not hold true for across USA. This is due to the fact that higher uncertainty involved in soil moisture predictability in comparison to the precipitation as reported by several articles.

Response: It is stressed that the statement was on improvements gained by using soil moisture relative to precipitation (Fig. 1). This was not meant to be a general statement. In the revised version, the above statement has changed to make this clear. I hope that I have adequately addressed the Reviewer's concern.

About ACFs, yes; please note that a similar graph can be generated for different pixels and regions. We agree that the ACFs will be different for various regions and climate. In his classic work, Changnon [5] showed how precipitation deficiencies during a certain period translated, over time, through other components of the hydrologic cycle including soil moisture. Changnon [5] and many others assessed the temporal complexity of drought and its impacts on different variables and showed a delayed and typically smoother response in soil moisture (and groundwater) compared to the original precipitation signal - see Figure 2 in Changnon [5] which indicates higher persistence in soil moisture compared to precipitation. While the ACFs of different variables may be different over different regions, still soil moisture exhibits higher persistence relative to precipitation (e.g., see time series of SPI and SSI in [6]). For this reason, using soil moisture could improve drought prediction.

The author also highlighted similar concerns in page1950, line 5: 'The uncertainty of dynamic soil moisture forecasts is even higher than the climate forcings (precipitation and temperature) because in addition to input uncertainty, model errors: : :.(Wood, 2008). Overrated statements like line 6-10 (page 1956), should be avoided. Use of

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persistence based model on a moving sum time series has several limitations in comparison to the dynamic models.

Response: That is correct; the author stresses that all models and data sets have their own uncertainties and limitations. The author strongly believes in diversity of models, data and indicators for drought prediction. This is the main motivation for this work. Per Reviewer's suggestion, Page 1956 is rewritten. In the revised version, the limitations of the study are highlighted even more. I hope that I have adequately addressed the Reviewer's comment.

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Interactive comment on Hydrol. Earth Syst. Sci. Discuss., 11, 1947, 2014.