Interactive comment on "Identification and simulation of space-time variability of past hydrological drought events in the Limpopo river basin, Southern Africa" by P. Trambauer et al.

Anonymous Referee #1

Received and published: 30 March 2014

Reaction to the interactive comment by Anonymous Referee #1

We would like to thank this referee for his/her interesting comments and suggestions that contributed to improve our paper and to clarify specific points. Hereby we present the authors reply (AC) to the referee's comments (RC).

General Comments:

RC: This manuscript is a very interesting study that analyse the occurrence of severe droughts in the Limpopo river basin using a set of drought indicators as SPI, SPEI, ETDI, RSAI, SRI and GRI. Most of these indicators (except SPI and SPEI) were computed from the output of a finer resolution version of the hydrological model PCR-GLOBWB that was forced with ERA-Interim meteorological data. The authors shows the added value of using hydrological drought indicators jointly with meteorological indicators (SPI, SPEI) to best represent the main drought features in the basin. The objective is straightforward, the paper is well written and follows an adequate methodology. This research is relevant to scientific questions within the scope of HESS. Therefore, my overall recommendation is to publish the paper into the Journal after some minor revisions suggested below.

Specific Comments:

RC: Page 2640, Line 11: what are the other meteorological variables used? In section 2.2 (P 2645, L25) the authors state that all the meteorological variables used were precipitation and 2m maximum and minimum temperature.

> AC: The meteorological input variables are precipitation (P), daily temperature (T), daily minimum temperature (Tmin), and daily maximum temperature (Tmax). We revised the sentences accordingly.
>
> - Page 2640, L11: "PCR-GLOBWB was forced with daily precipitation and temperature obtained from the ERA-Interim global ..."
> - P 2645, L25: "All meteorological forcing data used (precipitation, daily temperature, daily minimum and maximum temperature at 2m) are the same..."

RC: Page 2642, Line 8: Consider adding the word "accepted" or "used" after internationally if this is what you want to mean here.

> AC: No, we did not mean "other indices internationally used", but that this indicator is being replaced by other indicators in other parts of the world, or globally. The statement was modified to clarify: "... but is gradually being substituted by other indicators in other regions".

RC: Page 2642, Line 13: It is not necessary and quite redundant to define again in this line the meaning of SPI-3 as in the previous sentences (lines 10-11) was already defined.

> AC: This definition was deleted.

RC: Page 2644, Line 20: the abbreviations R and P were not defined previously. Either define or expand it.

> AC: This was expanded to RC= Runoff / Precipitation

RC: Page 2644, Line 26: At the beginning of the section the average annual rainfall in the basin was defined as 530 mm/yr and in this sentence the same value is 506 mm/yr. These differences are due to different estimations or datasets used? Please explain or homogenize it.

AC: The differences arise because while the first one refers to general information of the whole basin, the second one refers to the aggregated precipitation for sub-basin #24. To avoid confusion, we changed the sentence at the beginning of the section to: "The average annual rainfall in the basin is approximately 530 mm year^{-1}, ..."

RC: Page 2646, Lines 13-25: Computation of Potential Evapo-Transipiration (PET): The authors state that PET was computed using the Hargreaves formula that is based in temperature alone. Then is stated that the ERAI data was obtained at a resolution of 0.5˚ for the entire continent. Why this data has a different resolution than the temperature dataset depicted before (0.7˚)? are PET data obtained directly from the ERA-I reanalysis or computed using other source of temperature data? Then it was re-interpolated to 0.7˚? Please provide more elements that can help to clarify this points. Moreover, afterward in section 3.2.1 the SPEI computations were performed using the Thornthwaite method. Do the authors think that using different estimations can lead to discrepancies in the derived indicators?

AC: All the meteorological forcing used (from ERAI) has a resolution of approximately 0.7°. This includes also the temperature which was used to compute the potential evaporation. ERAI is archived in an irregular grid (reduced gaussian) over the domain and thus an interpolation was inevitable so that it can be used. The meteorological forcing was applied to the hydrological model with the same spatial resolution as the model (0.5˚), using bilinear interpolation to downscale from the ERAI grid to the model grid. This was added in P2646, L24-25 to clarify.

SPEI is a meteorological drought indicator, computed only from meteorological variables: precipitation and potential evaporation. Therefore, this indicator is not necessarily similar to the agricultural/hydrological droughts indicators derived in this study from hydrological model outputs. Part of the differences between the resulting indicators might be due to the method used for the computation of the potential evaporation, but the differences due to this are probably not significant. Agricultural indicators derived from the hydrological model, for example, make use of actual evaporation or soil moisture. Actual evaporation in the semi-arid Limpopo basin is largely limited by moisture availability and generally less sensitive to the differences in potential evaporation products (Trambauer et al., 2014).

RC: Page 2652, L 16-17: It's not clear how the indicators were "aggregated over several sub-basins". Which sub-basins? The sub-basins are not formally defined in the manuscript. In Figure 5 to 8 the captions are confusing as well; how the time series were aggregated over each station? or each sub-basin was named after the hydrometric station? This points should be clarified, please explain or rephrase.

AC: Yes, each sub-basin referred in this paper is based on the hydrometric station used. This was clarified both in the manuscript and in the figures:

- At the end of Section 2 and in Fig.1 caption the following sentence was added: "The sub-basins draining to each hydrometric station are named after the station number".
- In Figures 5 to 8 we changed "Station" for "Sub-basin"

RC: Section 4.2.1: The results in this section are rather vague and qualitative. Agricultural drought is depicted here with two indicators (RSAI and ETDI). However Agricultural droughts are related with more than only physical aspects as economic factors that are related with impact indicators as well. Here, at least is possible to state that these indicators provides information for the assessment of agricultural drought. Also the statement that the indicators are able to reproduce the dry/wet conditions is at least too qualitative. Please provide more elements that can support this affirmations.

AC: As suggested by the reviewer, the following sentence was added: "These indicators provide information for the assessment of agricultural droughts". To provide more elements that can support the statement that the indicators are able to reproduce the dry/wet conditions, we added the figure shown below. This figure shows for the two indicators presented here, the fraction or percentage of the basin that is under at least moderate drought conditions (Indicator < -1) for the whole period.

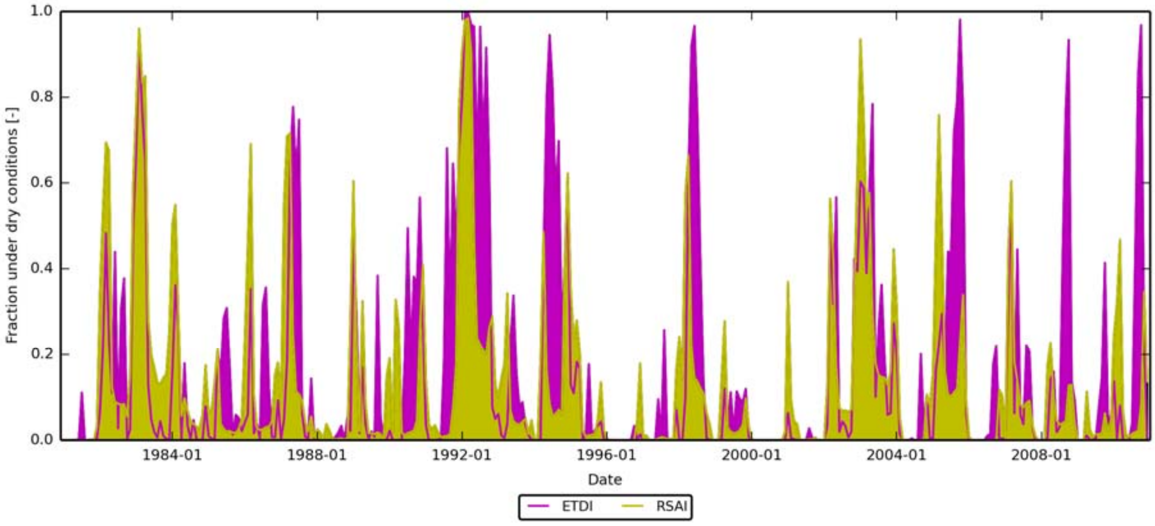

Fig. XX Fraction of the Limpopo basin under moderate to extreme droughts represented by the indicator value (Iv < -1.0).

We added the following text in the manuscript: "This is also supported by Fig XX, which shows the fraction of the Limpopo basin under moderate to severe droughts, i.e. Iv < -1.0. Both indicators illustrate that a large part of the basin was under at least moderate drought conditions for the years with recorded droughts events."

Moreover, we added a complementary figure that shows for the two indicators presented here, the fraction or percentage of the basin that is under at least moderate wet conditions (Indicator >1) for the whole period. This figure (see below) is added as supplementary material.

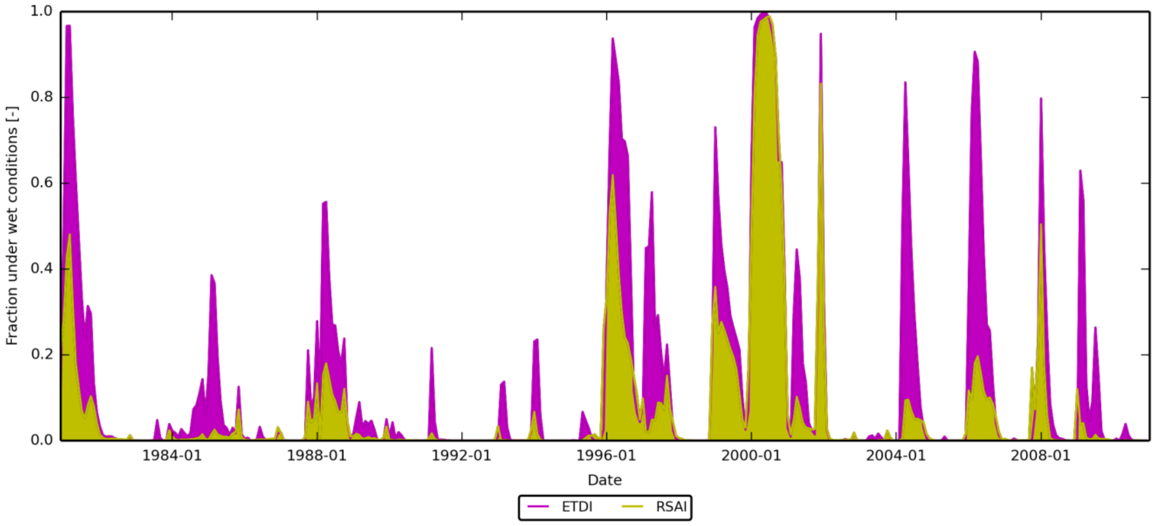

Fig. XXX Fraction of the Limpopo basin under moderately to extreme wet conditions represented by the indicator value (Iv > 1.0).

RC: Section 4.2.3: Again here is not completely clear how the time series were aggregated. This should be clearly stated even if a sub basin is named after the station number. Also, this section could be benefited by a more quantitative analysis. For instance a correlation analysis that includes the different indicators and aggregation periods could help to support the main affirmations in the conclusions section.

AC: Sentence in L4-5 (P2656) was modified to: "Figure 5 presents the time series of aggregated drought indicators for sub-basin #24. Note that the sub-basins are named after the hydrometric station number."

As suggested by the reviewer, to provide a more quantitative analysis we added a correlation table for one of the sub-basins. Similar correlation results were found for the other sub-basins. In the manuscript we added the following text: "Table 5 presents a correlation matrix between all the indicators considered in this study for sub-basin #24. Similar correlation results were found for the other sub-basins. The table shows that the agricultural drought indicators ETDI and RSAI have highest correlations with SPEI-3, SPEI-6, SPI-3, SPI-6 and with SRI with low aggregation periods (1 to 3 months). For every station the correlation between the agricultural indicators and SPEI is slightly higher than with SPI. While the hydrological drought indicators SRI-6 and SRI-12 present highest correlations with the meteorological drought indicators SPI-12 and SPEI-12, the extended hydrological drought indicator SRI-24 is better correlated with the meteorological drought indicators SPI-24 and SPEI-24. GRI shows the highest correlations with SRI-6 and SRI-12."

Table 5: correlation matrix for sub-basin 24

	SPI-3	SPEI-3	ETDI	RSAI	SPI-6	SPEI-6	SRI-1	SRI-2	SRI-3	SRI-6	SPI-12	SPEI-12	SRI-12	SPI-24	SPEI-24	SRI-24	GRI
SPI-3	***1.00***																
SPEI-3	***0.91***	***1.00***															
ETDI	***0.79***	***0.82***	***1.00***														
RSAI	***0.70***	***0.73***	***0.84***	***1.00***													
SPI-6	***0.77***	***0.75***	***0.81***	***0.79***	***1.00***												
SPEI-6	***0.72***	***0.80***	***0.83***	***0.80***	***0.94***	***1.00***											
SRI-1	0.69	***0.71***	***0.84***	***0.84***	***0.74***	***0.75***	***1.00***										
SRI-2	0.67	***0.71***	***0.83***	***0.85***	***0.75***	***0.78***	***0.97***	***1.00***									
SRI-3	0.63	0.68	***0.81***	***0.85***	***0.75***	***0.78***	***0.94***	***0.99***	***1.00***								
SRI-6	0.51	0.58	***0.75***	***0.82***	***0.71***	***0.76***	***0.87***	***0.93***	***0.96***	***1.00***							
SPI-12	0.53	0.56	0.70	***0.74***	***0.73***	***0.75***	***0.72***	***0.75***	***0.78***	***0.82***	***1.00***						
SPEI-12	0.48	0.58	0.68	***0.71***	0.68	***0.77***	0.69	***0.73***	***0.75***	***0.81***	***0.96***	***1.00***					
SRI-12	0.37	0.45	0.61	0.65	0.53	0.61	***0.74***	***0.80***	***0.83***	***0.91***	***0.81***	***0.83***	***1.00***				
SPI-24	0.45	0.48	0.56	0.59	0.60	0.63	0.65	0.68	0.69	***0.72***	***0.79***	***0.80***	***0.76***	***1.00***			
SPEI-24	0.40	0.48	0.52	0.54	0.54	0.62	0.60	0.62	0.64	0.67	***0.71***	***0.79***	***0.73***	***0.96***	***1.00***		
SRI-24	0.30	0.35	0.44	0.46	0.42	0.47	0.60	0.64	0.67	***0.71***	0.57	0.62	***0.80***	***0.83***	***0.84***	***1.00***	
GRI	0.37	0.34	0.48	0.57	0.48	0.42	***0.72***	***0.75***	***0.76***	***0.76***	0.57	0.48	***0.73***	0.60	0.49	0.66	***1.00***

RC: Page 2656, L24: For the spatially aggregated time series the threshold that defines the drought severity changes depending on the size of the sub-basin (number of points to be averaged) but in any case it is not anymore comparable with the thresholds of a single point time series. The authors can still use any threshold but this is not anymore related with a probability of occurrence. This should be clear stated in the description.

AC: This was stated in the description in section 3.3. The sentence in P2652 L20 - L23 starting in "Values lower..." was modified to clarify to: "Based on the SPI values, droughts may be classified into mild (0 > SPI >-1), moderate (-1 ≥ SPI > -1.5), severe (-1.5 ≥ SPI > -2) and extreme (SPI ≤ 2) (Lloyd-Hughes and Saunders, 2002, see Table 3)". After this sentence, the following sentences were added:
"For SPI and SPEI the spatially averaged indicators are not anymore related with a probability of occurrence. However, we still use the same thresholds for the characterization of the sub-basin aggregated droughts, as we understand that the resulting indicators would not be very different from the computation of these indicators with aggregated precipitation and potential evaporation. For agricultural (ETDI and RSAI) and groundwater indicators (GRI) this is not the case as these are not defined based on a probability of occurrence."

RC: Page 2657, L19: The authors states that the 2003-2004 drought was “quite mild when averaged over the whole basin” However I don’t see any Figure or table that can support this affirmation. Then it’s not clear if this affirmation is due to the spatial aggregation over the whole basin. Please either remove this comparison or add any supporting material.

AC: The sentence was changed to: "... quite mild when averaged over the largest selected sub-basin (#24)". A comparison of Figures 5 and 8 then supports this affirmation.

RC: Page 2660, L 3-7: I don't see any quantitative argument or even a discussion in how SPEI-3 can be a good option to replace ETDI and RSAI in absence of evaporation or soil moisture data. Even if it's a reasonably argument it should be evaluated in the manuscript. Section 4.2.1 or 4.2.3 will be benefited with a more quantitative analysis (like correlation analysis) between these indicators and the SPEI/SPI. Without this is hard to agree with this affirmation.

AC: A more qualitative analysis including a correlation matrix was added in sections 4.2.1 and 4.2.3.

RC: Page 2660, L10-12: Again, here I don't see any evidence in the paper that can lead to the conclusion that "GRI generally represents drought periods similar to SPI-24". From Figure 5 to 8 it's clear that the indicator is lower bounded and not reacting to dry conditions as the other indicators including SPI and SPEI-24. Either remove or provide more information that supports this affirmation.

AC: We agree with the reviewer on that this statement was not accurate. The sentence was changed to: "The groundwater indicator GRI mostly remains in near normal conditions". Moreover, we can observe from the correlation tables that GRI shows the highest correlations with SRI-6 and SRI-12. This makes sense given the direct connection between groundwater and runoff, where groundwater (baseflow) contributes to the total runoff.

Technical corrections:

RC: Figure 1: Expand the caption adding a reference of the sub-basins that are used in the analysis.

AC: This was done.

RC: Table 4. Add to the caption the variable evaluated. Runoff?

AC: The caption was modified to: "Model evaluation measures for runoff for selected stations"

RC: Glantz, 1988 (Page 2641) is listed as Glantz 1987 in the reference list. Please check and modify accordingly.

AC: This was revised and corrected.

RC: Consider removing the "a" after Trambauer et al., 2014a as there is only one reference for these authors and year.

AC: This was done.

Interactive comment on "Identification and simulation of space-time variability of past hydrological drought events in the Limpopo river basin, Southern Africa" by P. Trambauer et al.

Anonymous Referee #2

Received and published: 31 March 2014

Reaction to the interactive comment by Anonymous Referee #2

We would like to thank this referee for his/her interesting comments and suggestion that contributed to improve our paper and to clarify specific points. Hereby we present the authors reply (AC) to the referee's comments (RC).

General comments:

RC: The authors present an analysis of droughts in the Limpopo basin over the period 1979-2010. The analysis is based on the results of a global scale hydrological model run with spatial resolution of 0.05°. Model results were used to compute a set of drought indicators and to characterize drought occurrence, duration, intensity and severity in the Limpopo basin. Results show that simulated hydrological drought indicators are able to reconstruct the history of droughts in the basin. I found particularly interesting the graphs showing the compared time evolution of drought indicators for agricultural, hydrological, groundwater and extended groundwater drought in different stations. The topic fits well within the scope of Hydrology and Earth System Science, the objectives are clear and well identified, the methodology for the analysis correctly described and the conclusions are relevant and adequately supported by the results and discussion. The uncalibrated model shows acceptable agreement with observations in downstream stations in the basin and the analysis performed on simulated flows is very interesting for drought characterization. Therefore, I believe the paper deserves publication in Hydrology and Earth System Science.

Specific Comments:

RC: I also think that there are a few points which I believe would improve the paper:

a) On page 5, line 27, the authors state that the Limpopo basin is heavily modified. There are significant differences between naturalised and observed runoff due to reservoir storage and water abstractions. However, while discussing hydrological model performance (page 11, lines 11-25) they do not offer information on how they accounted for water abstractions in their comparison with model results. What runoff data source was used for the comparison? Was runoff directly measured in the stations compared with naturalised runoff generated by the model? The fact that PBIAS was not considered for model evaluation suggest that this is the case. Were results compared on a daily, monthly or annual basis?. I think the methodology applied for model evaluation should be clarified. Perhaps a scatter plot of models results vs. observations in some stations would illustrate the results and help the reader evaluate model performance.

> AC: The model runoff results were compared with runoff data collected from the Global Runoff Data Center (GRDC), the Department of Water Affairs in South Africa, and ARA-Sul (Mozambique) as stated in Section 2.2. In Section 3.1.1 we describe the hydrological model, and indicate that the model accounts for main reservoirs in the basin, which are included in the routing scheme. Moreover, abstractions are considered in the irrigation module. The irrigation requirement for the irrigated crop area within a cell (described in section 2.2) is supplied through the storage of freshwater in the cell or from the nearest stream. The model then represents modified or observed runoff, and not naturalized runoff. Results were compared on a monthly basis.

In section 4.1 we added: "Runoff estimates from the hydrological model were verified with observed runoff on a monthly basis". We believe that scatter plots of model results vs. observations take up a lot of space and does not add much value to the paper. In table 4 we include some performance statistics, including R^2.

b) More information should be provided about hydrometric stations, in addition to Figure 1. Perhaps basin area and mean annual runoff (naturalised and observed) should be added to Table 2. What was the source of information on naturalised runoff coefficient? This would help the reader interpreting model evaluation results presented on Table 3.

AC: Basin area and mean annual runoff for the hydrometric stations were added to Table 2. The naturalized discharge was estimated as observed discharge plus the estimated abstractions. This is explained in Section 2.1.

c) I do not think I understand the symbols used in Figure 9. According to the legend, drought severity is represented twice, on the vertical axis and through bubble size. Perhaps the vertical axis corresponds to drought duration and it is just a typo. I suggest redrawing the figure, trying to make it more clear. In my opinion, there are too many (14) drought indicators and many bubbles overlap. Bubble size prevents a clear identification of delays between successive types of drought (agricultural, hydrological, groundwater, etc.). I suggest selecting one indicator from each of the four groups shown in Figs 5-8, since there is a good overall agreement among indicators in each group. I also suggest using a different symbol for each drought severity (like, dot, triangle and star), but without changing size, to allow a clear visualization of delays from one group to the next.

AC: As suggested, we have redrawn the figure. Only one indicator from each group was selected and the differences in size were not used. Moreover, to clarify, instead of representing only the ending month of the drought, we present the whole duration of the graph by using lines instead of points. In this graph only the 6 major droughts mentioned in section 4.2 are presented to avoid overlaps. In the manuscript we modified the sentence that presents the graph as follows:

"As an example for sub-basin #24, Fig. 9 presents the duration and severity of the six most severe recorded droughts as identified by the meteorological drought indicator SPEI aggregated for different periods to represent agricultural, hydrological and extended hydrological droughts (muli-year droughts). The graph shows that the multi-year droughts resulting from the accumulation of shorter successive droughts are the most severe as a result of its duration. These droughts can be the most hazardous, as a succession of mild droughts that can initially seem non-problematic can result in very severe droughts if they last for a long time. The average intensity of these droughts is generally lower than that of the agricultural droughts, which can be very intense but often with shorter duration.

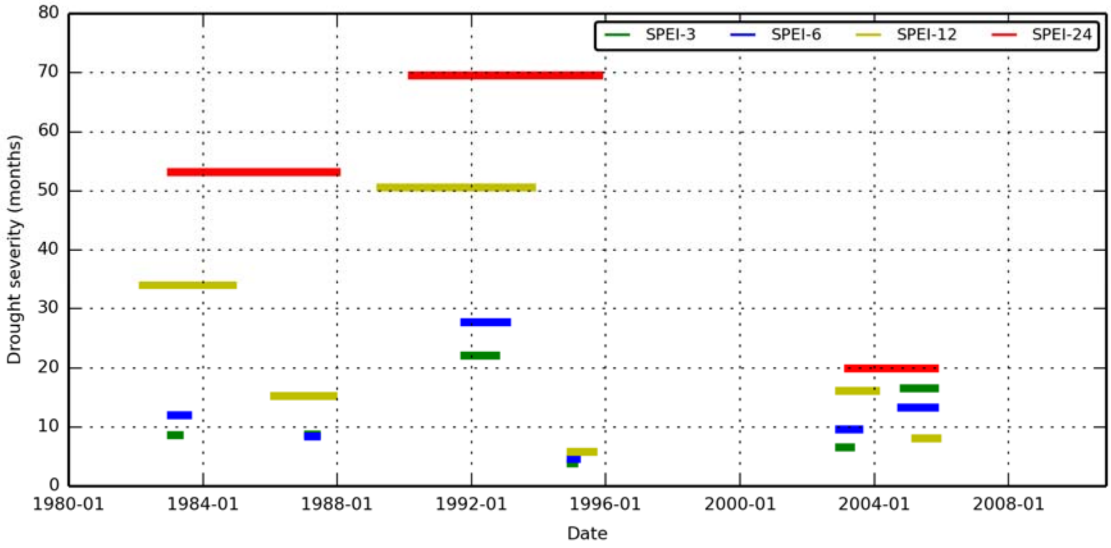

Fig 9. Drought severity and duration for the 6 most severe droughts in the period 1979-2010 for the indicator SPEI with different aggregation periods.

Technical corrections:

RC: From the formal standpoint, the paper is very well written, correctly organized and adequately illustrated with tables and figures. Although I am not a native English speaker, I believe the following expression should be corrected: On page 11, lines 23-24, "we use them as a simply test of concordance"...... (use them simply as a test...? or ..as a simple test of..?).

AC: yes, it was change to "...as a simple test of..."

References:

Khedun, C. P., CHOWDHARY, H., Giardino, J. R., MISHRA, A. K., and Singh, V. P.: Analysis of drought severity and duration based on runoff derived from the Noah land surface model, 2011.
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Trambauer, P., Dutra, E., Maskey, S., Werner, M., Pappenberger, F., van Beek, L. P. H., and Uhlenbrook, S.: Comparison of different evaporation estimates over the African continent, Hydrol. Earth Syst. Sci., 18, 193-212, 10.5194/hess-18-193-2014, 2014.

Interactive comment on "Identification and simulation of space-time variability of past hydrological drought events in the Limpopo river basin, Southern Africa" by P. Trambauer et al.

Anonymous Referee #3

Received and published: 9 April 2014.

Reaction to the interactive comment by Anonymous Referee #3

We would like to thank this referee for his/her interesting comments and suggestion that contributed to improve our paper and to clarify specific points. Hereby we present the authors reply (AC) to the referee's comments (RC).

General comments:

RC: The manuscript addressed relevant scientific content within the scope of HESS and presented an important topic of droughts particularly in the context of climate change and climate variability. This is useful for water resources planning and management. However, some scientific methods or assumptions were not clearly outlined particularly on the use of the PCR-GLOBWB, which was "not calibrated", the discussions on its performance and confidence of its results for use in drought identification. For example, in the conclusion it was mentioned "... carefully setting up model parameters but with no additional calibration", is this not the same as model calibration or manual calibration? Also, was the model tested for its performance on low flows that are associated with hydrological droughts? These issues go together with allowance for traceability of results by other scientists.

> AC: By "…carefully setting up spatially distributed maps of model parameters" we do not mean model calibration or manual calibration. This is a spatially distributed and detailed process based model, which requires spatially distributed maps of parameters (e.g. soil layer depths, soil storage capacity, hydraulic conductivity, etc.), and these maps are estimated from available maps and their derived properties (see explanation in Section 2.2). In this model there are around 17000 grid cells within the Limpopo basin. For this kind of model the usual model calibration is not helpful and very challenging. By "carefully setting up" we are referring to using the most reliable available datasets and their interpolation/aggregation for preparing the spatially distributed parameter maps. This statement was added in the manuscript.
> The model was tested for its performance in general, and in this study we test its performance on simulating hydrological droughts by comparing with reported historic drought events.

RC: The uses of these terms are not clear: identification, simulation and characterisation of droughts. Also, there is need to explain the use of the term "simulation" as used in the title! Moreover, the time variability of hydrological droughts were analysed in detail at the gauging stations. One wonders why observed data at these stations were not used in the droughts identification/characterisation/simulation.

> AC: The term "simulation" as used in the title refers to the representation of the hydrological model to hydrological droughts, which are "characterized" by different drought indicators. By drought characterization we denote its description in terms of severity and duration. By "identification" of the hydrological droughts we mean the correctly detection of droughts by the model when compared to reported historic droughts events.
> In the gauging stations we used the commonly used hydrological drought indicator SRI. It is not possible to include SRI from observed data given that there are gaps in the data and the computation of SRI requires a monthly runoff data set for a continuous period of at least 30 years without missing data.

RC: Please explain if you set for hydrological droughts and use SPI or SPEI for longer timescales such as SPI-6 and SPEI-6 or SPI-12 and SPEI-12 or SPI-24 and SPEI-24, can you still call these as meteorological indicators?

AC: These are still meteorological drought indicators given that they are computed only from meteorological variables: precipitation and potential evaporation. However, when these are aggregated for longer periods, they are commonly used as indicators of hydrological droughts. This is why in this study we compare these with the hydrological drought indicators.

RC: Can you say that SPI or SPEI are robust and adequate for all types droughts identification but what matters is the consideration for the timescale to be used for either meteorological or agricultural or hydrological droughts?

AC: Normally SPI or SPEI with different aggregation periods appear to be generally adequate to represent different types of droughts, and that is why they are commonly used in this way. However, agricultural and hydrological droughts may be triggered by other factors than the meteorology, such as the antecedent conditions. In these cases, SPI and SPEI might not capture the agricultural or hydrological drought.

RC: Further, the word "drought" is confusing as it was used interchangeably to refer to all types of droughts without clear distinction of the type of the drought under discussion!

AC: This was addressed and the different types of drought were distinguished in the manuscript.

RC: The manuscript did not indicate related work on hydrological simulation/modelling for drought assessment especially when considering for example, meteorological to agricultural droughts (e.g. Schulze, 1984; Mulungu et al., 2008; Mulungu et al., 2009) or meteorological to hydrological droughts or agricultural to hydrological droughts in the southern African region.

AC: We cited the related work of Schulze, 1984. We could not find the papers of Mulungu et al., 2008 and 2009. We added in the introduction: "Together with the development of the first drought indicators, hydrological models were also used for agricultural and hydrological drought assessment. Schulze (1984) applied the ACRU hydrological model in Natal, South Africa (southern of the Limpopo basin) to compare the severity of the 1979-1983 drought with previous droughts in the previous 50 years. He identified hydrological modeling as a potential powerful tool in drought assessment and indicated that droughts in terms of water resources and crop yields do not necessarily coincide".

Specific comments

RC: Page 2640, Line 21-22: It was not clear how successfully in "... can successfully identify hydrological droughts ..."?

AC: All major historic droughts events reported in the period 1979-2010 were identified by the hydrological drought indicators resulting from the results of the hydrological model. The word successfully was deleted from the text to avoid confusion.

RC: Page 2640, Line 28: "... to capture the severity of the drought". Which one? is it meteorological, agricultural or hydrological drought?

AC: Hydrological drought. This was added.

RC: Page 2640/41, Line 28-30: How the meteorological indicators failed? Say where SPI-12 was expected to give a hydrological drought? Also, not clear how the combination of indicators (e.g. SPEI-3, SRI-6, SPI-12) was useful measure for identifying hydrological droughts? Is it that all indicators gave the same signal of hydrological droughts or the results of the indicators were equal to the observed situation of hydrological droughts or the indictors have to be used together (in unison or tandem) to identify hydrological droughts?

AC: The statements say "in some cases", and we aim to express that in some particular cases the hydrological drought might have been triggered by, for example, antecedents conditions in the basin while the meteorological conditions are nearly normal, and therefore meteorological drought indicators alone do not capture these events. An example of this is presented in P2657, L28. The statement on the combination of indicators was clarified. By "a combination" we mean that computing these three indicators together is a useful way to identify from agricultural to long-term hydrological droughts. This was clarified in the manuscript.

RC: Page 2641, Line 3-4: "... is possible to make a characterisation of the drought severity, indicated by its duration and intensity". Not clear? Use past tense and reword as drought characteristics include severity, time of occurrence, duration, intensity and extent!

AC: This was clarified as suggested by the reviewer as follows:
"Additionally, it was possible to make a characterisation of the drought severity in the basin, indicated by its time of occurrence, duration and intensity.

RC: Page 2643, Line 8-9: "The model is tested by identifying historical droughts ... with simulated hydrological and agricultural drought indicators". Not clear, reword and use past tense!

AC: This sentence was reworded to clarify as follows:
"The model was tested by comparing the simulated hydrological and agricultural droughts indicators in the period 1979-2010 with reported historic droughts events in the same period."

RC: Page 2643, Line 23-25: What are climate indicators? Also, the focus of the paper on hydrological droughts is missing!

AC: The word "climate" was changed to "meteorological". The focus on the paper is largely on hydrological and agricultural droughts. Both types of drought indicators are computed from the results of a hydrological model. In this paper we do not focus on meteorological droughts but we compute meteorological drought indicators only to compare with the model-computed indicators.

RC: Page 2651, Line 20: Why a gamma distribution function was used for runoff?

AC: A gamma distribution function was used given that the work of Shukla and Wood (2008), which introduced the SRI, indicated that the Gamma distribution may perform better than others for low runoff values. Moreover, the gamma distribution is selected in a wide range of literature on SRI e.g: (Khedun et al., 2011; Madadgar and Moradkhani, 2011).

RC: Page 2652, Line 22-23: "... values lower than -2.0 corresponding to severe droughts (see Table 3)". Make corrections for the threshold for severe droughts as lower than -2.0 is extremely dry!

AC: The word "severe" was changed for "extreme".

RC: Page 2653, Line 23-24: Table 4: Why the PCR-GLOBWB model had satisfactory values for R2 and NSE while RSR was above 0.70 for stations 23 and 15?

AC: For stations 23 and 15 also the R2 and NSE and not satisfactory: ($R2<0.65$, $NSE<0.5$)

RC: Page 2654, Line 2-3: Why the model was not having satisfactory performance in other runoff stations? Also, was the model tested for its performance on low flows that are associated with hydrological droughts?

AC: Smaller basins (e.g. #15) normally perform poorer than larger stations due to a resolution issue. Even though the hydrological model has a resolution of 0.05°, the meteorological input has a resolution of approximately 0.7°. The model was tested for its performance in general, and in this study we test its performance on simulating hydrological droughts by comparing with reported historic drought events.

RC: Page 2655, Line 1-2: Why the SRI values were not calculated from observed data at station 24? Is it possible to have SRI values from observed data in Fig. 3?

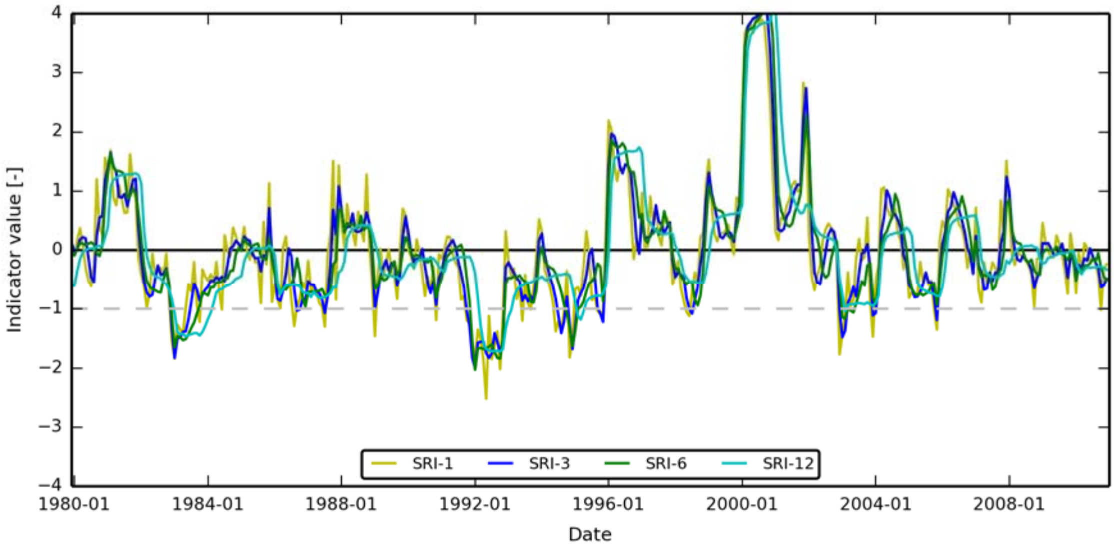
AC: It is not possible to include SRI from observed data given that there are gaps in the data and the computation of SRI requires a monthly runoff data set for a continuous period of at least 30 years without missing data. This was added in the manuscript. There is a similar indicator called Streamflow Drought Index (SDI), proposed by Nalbantis and Tsakiris (2009), which allows the computation even if there are missing values. The years with missing values are not considered in the long term statistics (mean and standard deviation), and the SDI is only computed for the years without missing data in the monthly series. It is possible to compute SDI from observed data but of course it is not directly comparable with SRI.

RC: Page 2656, Line 6-8: How and what was the time step for ETDI and RSAI computation in order to compare with, say SPI-3 or SPEI-3?

AC: The time step of ETDI and RSAI are monthly. The computation of these indicators are explained in section 3.2.2

RC: Page 2656, Line 11-14: Why SPI-6 (as hydrological indicator) was not compared with SRI-1 or SRI-2 (hydrological indicators too)? Why the fluctuations of SRI-6 was lower than that of SPI-6 or SPEI-6?

AC: SRI-1 and SRI-2 were also compared with SRI-6. This is now shown in the correlation table added. We also added SRI-1 in Fig. 3 (see below). SRI-1 and SRI-2 present the highest correlations with ETDI and RSAI.



The fluctuation of SRI-6 was lower than that of SPI-6 probably due to the higher persistence of streamflow when compared to precipitation. This was added in the manuscript. Moreover, from the correlation table we observe that the correlation of SRI-6 is higher with SPI-12 than with SPI-6.

RC: Page 2656, Line 19-20: How and what was the time step for GRI computation in order to compare with, say SPI-12, SPEI-12, SRI-12, etc.?

AC: The time step of the groundwater drought indicator GRI is monthly and its computation is explained in section 3.2.2. GRI is computed differently than SPI and SPEI, and does not need to be accumulated over several months.

RC: Page 2657, Line 26-28: What was the reason for the mismatch between meteorological indicators and hydrological indicators? Also, since you are using the following for reference to hydrological droughts, can you refer to SPI-6, SPEI-6, SPI-12 and SPEI-12 as meteorological indicators?

AC: The mismatch that occurs in some cases is probably because the hydrological drought is triggered by a combination of meteorological conditions and antecedent moisture conditions in the basin. In these cases, the "mismatch" is expected and it is where we can see the added value of computing hydrological drought indicators instead of using meteorological drought indicators with high aggregation periods. As explained before, SPI-6, SPEI-6, SPI-12 and SPEI-12 are still meteorological drought indicators given that they are computed only from meteorological variables: precipitation and potential evaporation. However, when these are aggregated for longer periods they tend to represent hydrological droughts. Still, it is not correct to refer to them as hydrological drought indicators.

RC: Page 2658, Line 14-15: Why the period 2003-2004 is missing as observed in sect. 4.2?

AC: This was a typo; the drought year 2003-04 should have been mentioned in the text.

RC: Page 2658, Line 26-29: "... the bigger the bubble, the more severe the drought". Not clear as the Y-axis shows the direction of increasing severity but bigger bubbles can be found at low levels of Y-axis! Also, Why with exception of the RSAI?

AC: This graph was modified to make it clearer (show in the answer to Reviewer #2).

RC: Page 2659, Line 11-12: "... carefully setting up model parameters but with no additional calibration". Is this not the same as model calibration or manual calibration?

AC: We believe this is not really the same. Please see explanation above.

RC: Page 2659, Line 22-24: Please explain why GRI was an exception in representing the most severe droughts.

AC: This is explained in Section 4.2.2. Results show that the computed GRI mostly remains in near normal conditions. We believe that this might be due to the fact that GRI is not transformed into the normal space. Moreover, the distribution of values is constrained by the capacity of the groundwater reservoir in the hydrological model.

RC: Page 2660, Line 3: Why not SPI-3? SPEI-3 and SPI-3 had more or less same patterns (Figs. 5-8)!

AC: We agree with the reviewer on that SPI-3 and SPEI-3 have more or less the same patters and that SPI-3 is also a useful indicator. If we want to suggest only few indicators to represent from short to long term hydrological droughts we thought that recommending three would be enough. In our opinion, even though SPI-3 and SPEI-3 have similar patterns, SPEI is more complete as it integrates potential evaporation which is an important factor in the development of droughts. Moreover, the correlation between the other agricultural indicators and SPEI is slightly higher than with SPI (see correlation matrix added).

RC: Page 2660, Line 12-13: Why SPI-3 was left out? There was no much difference between SPEI-3 and SPI-3 (Figs. 5-8)! Also, it was not clear what do you mean by "a combination of different indicators (SPEI-3, SRI-6 and SPI-12)" and by "effective way"!

AC: Please see answer to previous comment. By "a combination" we mean that computing these three indicators together is a useful way to identify from agricultural or short-term hydrological to long-term hydrological droughts.

Technical corrections

RC: Page 2641, Line 24: Define the abbreviation SPEI at the first mention.

AC: The abbreviation SPEI is already defined at the first mention in the abstract.

RC: Page 2642, Line 4: Define the abbreviation PHDI at the first mention.

AC: This was done.

RC: Page 2644, Line 20: Define RC, R and P

AC: The runoff coefficient (RC) is defined, and the formula in this sentence was changed to RC= Runoff / Precipitation.

RC: Page 2645, Line 26: Missing Trambauer et al., 2014a

AC: This was corrected, the "a" after "2014" should not be there.

RC: Page 2646, Line 24: Missing Trambauer et al., 2014a

AC: This was corrected, the "a" after "2014" should not be there.

RC: Page 2647, Line 8: Missing Trambauer et al., 2014a

AC: This was corrected, the "a" after "2014" should not be there.

RC: Page 2653, Line 7: "... intensity (value) of -1.0 ..." Not "or"

AC: This was corrected.