List of changes compared to original manuscript

- Big changes in the text (abstract, introduction, methodology, discussion, conclusions)

- Extra references about;
  a) Data limitations
  b) Advances in flood forecasting Africa
  c) Advances on seasonal forecasting

- Changes in the methodology
  a) Changes in weather-scale precipitation section
     - Removal of the precipitation terciles section, since no significant differences were found
     - Standardization and comparison of the maximum 7-day precipitation of No-Floods to the preceding 7-day precipitation of floods (PRE7)
     - Standardization and comparison of the max 7-day precipitation (MAX7) of the flood onset months to the PRE7 and to the maximum 7-day precipitation of No-Floods.

  b) Changes in seasonal-scale section
     - Removal of the FPU section
     - Comparison of flood to no-flood SPEIs
     - Relative odd calculation for SPEI threshold exceedance

  c) Changes in combined weather- and seasonal-scale section
     - Removal of False Alarms graph
     - Relative odds when combining seasonal SPEIs and SPEI0
     - Relative odds when combining seasonal SPEIs and PRE7

Reviewer 1

GENERAL COMMENT: The authors investigate the influence of high-intensity rain events and antecedent moisture conditions on flood probability in a large target area, including almost the entire African continent. Based on a data set of reported floods (provided by Munich RE), the short-term (event-precipitation) and long-term conditions (SPEI) before each event are systematically compared. The results indicate, that most of the reported floods are related to high precipitation events during the last seven days. Further the authors argue, that rather moist conditions on seasonal scale lead to enhanced flood risk, most likely due to filled up storage systems. While the research target is timely and the manuscript is well structured and easy to follow, I have some serious concerns about the statistical methods and the interpretation of the result. Particularly the conclusions remain very vague! Thus I recommend to extend the statistical analysis and to better test, whether the conclusions are robust and really supported by the underlying data sets. In the following I will summarize my major concerns. Since I expect the text to change significantly, I will not go into detail at this stage of the review process.

RESPONSE: We thank the reviewer for his/her comments, and we are pleased that he/she finds the topic timely and the paper easy to follow. Based on the comments and suggestions, we suggest a thorough revision of the original manuscript. Below, we address the comments point-by-point.

COMMENT 1: Introduction and data sets: The presentation of previous research in the field of flood forecasting in Africa is very short. No information is given on the timing of floods in different sub-basins of this vast target area and on the general climatic conditions. This information would be highly valuable in order to interpret (and scrutinize) the results of the statistical analysis. (E.g. It could be interesting to identify some differences between Eastern and Western Africa, which seem to behave differently in terms of the SPEI-flood relationship.) Likewise the introduction of the data sets is insufficient. I would expect a detailed description of the advantages and drawbacks of the data – especially the daily precipitation values on a coarse grid are extremely uncertain, since they do not cover local scale convective events, which frequently trigger high-intensity rain. The Munich Re data are introduced in two sentences only – again I think it would make sense to better discuss its origin and shortcomings!

RESPONSE 1: We would like to thank Reviewer#1 for his/her comments and recommendations. In the revised version, we include the Köppen climatological map (Level 1) to give more information regarding the general climatic conditions of each flooded location. Moreover, we have compared different climatological and geographical areas in terms of their SPEIs. Although some differences in terms of SPEI-flood relationship are observed, these are not statistically significant. Therefore, we have not drawn any conclusions out of that. Furthermore, we do agree that the datasets lack a rigorous description. Therefore, in the revised manuscript we discuss: a) The uncertainty in disaster datasets, and the reasons for the discrepancies between them (e.g. different entry criteria, time period covered) b) An extended description of the sources of NatCatSERVICE database. c) The possible explanations of the upward trend in reported floods over time. d) The difference between the hydrological definition of a flood compared to the definition that it is used by flood loss reporting, and discuss how this difference can be associated with missed events. e) The uncertainty of hydrological variables in the reanalysis dataset due to the lack of ground-based precipitation records in our area of interest. f) The sensitivity of the reanalysis product to the resolution choice. g) The uncertainty in hydrological variables in tropical regions and in southern Africa h) The large uncertainty in of the daily precipitation reanalysis dataset in capturing local-scale high intensity precipitation events.

COMMENT 2: Statistical Methods: The majority of the methods used is purely descriptive and does not allow to draw verified conclusions. One example is Fig. 9., which shows the mean seasonal SPEI values before reported floods. The authors argue, that floods, which are not preceded by high-intensity rains (0-33%-interval) have larger SPEI-values during antecedent seasons. However, all of the lines are very close to each other. A test for statistical significance (t-test or similar) would be necessary to support this statement. Further a presentation with boxplots would be more suitable, since it does not only show the mean, but also the range (and overlap) of the different classes.

RESPONSE 2: We agree with Reviewer #1 that the methods used in the original manuscript are rather descriptive. To accommodate the comments of Reviewer #1, we performed a statistical comparison between Flood and No-Flood events, presented by means of boxplots. For each ‘flooded cell’ the no-flood cases that are taken into account refer to the particular flood onset month of the no-flood years. Due to the very high number of no-flood events, the median value is close to 0 at all time-scales. The SPEI0-SPEI6 values of floods are significantly higher, which is underpinned by the results of a z-test (p=0,05). More specifically, the median value of SPEI0, exhibits a value close to 1. This indicates that, as expected, the wetness in the end of these months was high, demonstrating that SPEI0 could be used as a flood monitoring tool. On the (overlapping) seasonal time scales we see a positive relationship between reported floods and SPEI, which reduces while moving from SPEI1 to SPEI6 (0.5 to 0.1). Regarding the different weather-scale intervals (i.e. 7-day precipitation terciles): their median SPEI values of the different 7-day precipitation terciles do not exhibit any statistical significance differences and therefore in the original manuscript, we used descriptive results. In the revised version, we have removed this part. Instead, we compare the maximum 7-day precipitation during no-flood events in the 31-year record with the 7-day precipitation that preceded the flood events. For each flood, we standardized the 31 values (1 for the Flood (F) and the 30 for No Floods (NF), with a mean of 0 and standard deviation of 1. The results of the z-test showed that preceding PRE7 of floods did not exhibit any significant difference with that of no-floods (p> 0,1). This shows that although PRE7 that preceded the flood is high, it does not fully justify the flood generation: There probably were also similar magnitude events, in the same locations and during the same months that floods were reported, that did not lead to a (reported) flood. Being aware of the dataset limitations (e.g. incapacity of reanalysis datasets to capture convective rainfall events, likely inaccurate onset date, etc.), the message that we want to convey is that since we observe a relation between seasonal SPEI and flooding and that relation does not always need a relation via weather-scale precipitation, implies that there probably is another factor that affects flooding on a seasonal scale prior to flood generation. This factor could be the soil saturation due to limited water storage capacity. These factors have been addressed in the revised version of the paper.

COMMENT 3: Dependency of SPEI and 7-day precipitation. An increased SPEI value before flood events might have different reasons. One would be the limited capacity of the storage. A second one could be the persistence of the climate. That would explain, why the 66-99% interval in Fig. 9 shows the highest SPEI for all seasons. In order to draw robust conclusions, it would be necessary to disengage those processes. In Fig. 10, the frequency of flood under different SPEI combinations is shown. The analysis of further combinations (e.g. SPEI0 - normal and SPEI3 - moist) could support the conclusions of the manuscript. Again, a test of statistical significance is highly recommended. Would it further be possible to show a point-cloud of seasonal SPEI against 7-dayprecipitaion for all flood events? A clear negative relationship (higher SPEI values lead to flooding although 7-day precipitation is not extreme), would also support the conclusion.

RESPONSE 3: As also mentioned in the response of Comment 2, we observed small but non-significant differences of the SPEI values between the precipitation classes. Therefore, we have removed this section from the analysis. In the revised version, we compare the frequency of floods and no-floods under different SPEI combinations. Since our sample size is not large, the combination of different categories of SPEI (e.g. SPEI0-normal & SPEI3-high) gives us a small number of events for each one of them. Therefore, we have used exceedance thresholds (e.g. SPEI0>0 & SPEI3>2). Based on the frequency of flood and no-flood events, we quantify the elevated probability of having a flood event compared to a no-flood under each combination. For example, when SPEI0>0 and SPEI1>1, it is 4 times more likely to have a flood event than can be expected assuming a random flood generation process.

COMMENT 4: The authors highlight, that a forecast based on the findings is possible and that uncertainties could be reduced. I have the feeling that this is very optimistic. Would It be possible to establish a very simple tool for each of the FPU-units (e.g. based on a SPEI threshold value) and quantify the probability of hits and false alarms?

RESPONSE 4: We agree that establishing a forecast-based financing system based on the finding of this research is quite a challenge. We have formulated our recommendations more cautiously. Our conclusions now include a message that forecast based financing could be based on some results of our research, and that there are seasonal flood signals, which might support more effective forecast-based risk mitigation solutions. Regarding the FPU-units, we have decided to leave them out of this paper, as their sample size is small, not allowing us to draw robust conclusions. Regarding the very simple tool that Reviewer #1 mentions, we include graphs that show the elevated probability, which is calculated by the frequency of floods and no-floods that exceed several thresholds (see R.3).

COMMENT 5) Conclusions and discussion: The conclusions and the discussion section include many statements, which are not proven by the data or by literature (E.g. second paragraph, page 15, but also others). I recommend to carefully check, and to focus on findings, which are really supported by the data.

RESPONSE 5: In the revised manuscript, we now make statements that they are based on statistical analysis and have supported our conclusions with extended literature research.

Minor remarks

COMMENT 6: Section 2.1 and 2.2 could have more meaningful subtitles.

RESPONSE.6: We agree and have changed these titles.

COMMENT 7: p.5l.5: “The weather scale and SPEI periods do not overlap and the SPEI period lasts until the date of the weather scale period.” This is not possible, since the SPEI is defined on a monthly time scale? Does the SPEI period end with the month before the flood event?

RESPONSE 7: We understand that in this part clarification is needed. SPEI is indeed defined on a monthly time-scale, but the seasonal SPEI period (SPEI1 , SPEI3, SPEI6) ends on the month before the month that the 7-day period is calculated. For example, if a flood is reported on January 1st, the 7-day period ends on December 23rd and the SPEI periods ends in November. In the revised text we have explained this more clearly.

COMMENT 8: Fig. 2: I am confused about the hydrograph. Is this a schematic figure or is it somehow based on discharge time series? If I understand the figure correctly, discharge already increases seasons in advance. Usually the start of a flood event is defined as the first significant increase of discharge (which would be 5 months in advance in Fig. 2).

RESPONSE 8: Indeed, this graph might be confusing. Its is mainly to provide the reader a better understanding of the different time periods. The continuously increasing high discharge during the antecedent months does not represent reality. We have replaced it with a new one, where the discharge has a significant increase close to flood onset date.

COMMENT 9: p6.l14: Floods are grouped into wet and dry seasons? How exactly is this relevant for the statistical analysis?

RESPONSE 9: We agree with Reviewer #1 that the grouping the floods in wet and dry seasons does not provide any extra data for the statistical analysis. So, it is removed from the revised manuscript.

Reviewer #2

"Approach of potential interest but currently lacking significant statistical evidence"

GENERAL COMMENT: Dear authors and editors, I evaluated this paper exploring the use of SPEI and 7-days antecedent precipitation as indicators of damage triggering floods in the sub-Saharan Africa. If I put the glasses and look at the manuscript in the viewpoint of an NGO looking for an assessment about this topic, then I would be rather satisfied with this report. As contribution for the scientific community this manuscript: - lacks of rigorous description of the data sources and their limitations; - makes in my opinion wrong use of the term "lead time" in many sections; - has a rather small sample; - do not looks at missed events; - presents a very simplistic descriptive statistical evaluation; - poorly acknowledges recent effort in seasonal forecasting (e.g. http://www.hydrol-earth-systsci.net/special_issue824.html). Concerning the missed events, have you tried to obtain information about events not reported in the Münich-RE report, but being taxed as potential flooding in FPU with less than 5 events? I am generally very positive with respect to pragmatic approaches like this, but here I have the feeling that here more efforts are needed in order to better support the statements concerning the potential of this method as a early indicator of floods. Please consider also the comments in the PDF.

RESPONSE: We thank the reviewer for his/her comments, and we are pleased that he/she is very positive about pragmatic approaches like this. Upon his/her comments, we have thoroughly revised the paper. The revised manuscript includes an extended statistical analysis to support our conclusions. We have also addressed the limitations of our study that have been mentioned by the reviewer, and have removed some of our results, which could not be supported by statistical analysis. Below, we address the comments point-by-point.

COMMENT 1: The manuscript lacks of rigorous description of the data sources and their limitations.

RESPONSE 1: We thank Reviewer #2 for his/her comment and after re-reading the manuscript, we agree that the strengths and limitations of the data sources were not presented thoroughly. In the revised version we have addressed the following descriptions; a) The uncertainty in disaster datasets, and the reasons for the discrepancies between them (e.g. different entry criteria, time period covered) b) An extended description of the sources of NatCatSERVICE database. c) The possible explanations of the upward trend in reported floods over time. d) The difference between a hydrological flood event and a reported flood event as listed in the Munich RE database, and how this is associated with missed events. e) The uncertainty of hydrological variables in the reanalysis dataset due to the lack of ground-based precipitation records, especially in developing countries. f) The sensitivity of the reanalysis product in the resolution choice. g) The uncertainty in hydrological variables in tropical regions and in southern Africa h) The large uncertainty of daily precipitation reanalysis due to the incapacity of capturing local-scale high intensity precipitation events.

COMMENT 2: It makes in my opinion wrong use of the term "lead time" in many sections. RESPONSE 2: Yes, that is correct. The term 'lead time' is associated with forecasts, while this paper examines the conditions prior to the flood events. We have replaced 'lead time' with 'antecedent time', throughout the revised paper.

COMMENT 3: It has a rather small sample.
COMMENT 4: It does not look at missed events.
COMMENT 5: Concerning the missed events, have you tried to obtain information about events not reported in the Münich-RE report, but being taxed as potential flooding in FPU with less than 5 events?

RESPONSE 3, 4, 5: We agree that the sample used in our study is rather small to produce statistically robust results. However, to our knowledge, this study is unique cause it has taken into account a considerable number of real floods, trying to link reality to physical parameters, while most studies stay in the model world. To increase the sample size, we also included flood events reported in the earlier years of the dataset (i.e. from the 1980s onwards). Regarding the missed events, we would like to emphasize that NatCatSERVICE database does not include a flood based on the hydrological definition (i.e. high water levels, peak discharges). Instead, an event enters the dataset when there is property damage and/or when there are people affected. Hence, the paper focuses only on these damaging events, which are usually the ones that humanitarian organizations are interested in. However, by examining only the grid points where floods were reported and not all the grid points of sub-Saharan Africa, we have decreased the number of missed events. In the revised version, we explicitly mention these assumptions. Finally, when revising our paper, we have omitted analyses based on regional FPUs, since we feel that our dataset is too limited to identify enough data points per FPU.

COMMENT 6: It presents a very simplistic descriptive statistical evaluation.

RESPONSE 6: We agree that the original version of the paper presented a descriptive statistical rather than inferential statistical evaluation. In the revised version, we now perform statistical significance tests, which are carried out for; a) The SPEIs of flood and no-flood events b) The 7-day precipitation of flood and no-flood events, c) the max 7-day precipitation during the flood month and a the 7-day precipitation of no-flood events. The no-flood cases considered refer, for each 'flooded cell', to the particular flood onset month of the no- flood years. Due to the very high number of no-flood events, the median value at all time scales is close to 0. The SPEI0-SPEI6 median values of floods are significantly higher, which is underpinned by the results of the z-test (p=0.05). More specifically, the median value of SPEI0, exhibits a value close to 1. This indicates that, as expected, the wetness in the end of these months was high, demonstrating that SPEI0 could be used as a flood monitoring tool. On the (overlapping) seasonal time scales we see a positive relationship between reported floods and SPEI, which reduces while moving from SPEI1 to SPEI6 (0.5 to 0.1). In addition, we compare the maximum 7-day precipitation of each location during the no-flood years to the 7-day precipitation that preceded the flood events. For each flood, we standardized the 31 values over our 31 year of data (1 for the Flood (F) and the 30 for No Floods (NF), with a mean of 0 and standard deviation of 1. This figure presents in boxplots the standardized 7-day precipitation (PRE7) of Flood (F) and No-Floods (NF) events. The results of the z-test showed that preceding PRE7 of floods did not exhibit any significant difference with that of no-floods (p= 0.1). This shows that although PRE7 that preceded the flood is high, it does not fully explains the flood generation. There were probably also similar magnitude events, in the same locations and during the same months that floods were reported, that did not lead to a (reported) flood. Being aware of the dataset limitations (e.g. incapacity of reanalysis datasets to capture convective rainfall events, likely inaccurate onset date, etc.), the message that we want to convey is that since we observe a relation between seasonal SPEI and flooding and that this relation does not need a relation via weather-scale precipitation, implies that there probably is another factor that affects flooding on a seasonal scale prior to flood generation. One factor might be the soil saturation due to limited water storage capacity. This has been discussed in the revised version of the paper. Finally, we have omitted the original Figure 8 (SPEI per precipitation class) in the revised version, since conclusions based on this figure could not be supported with statistical significant differences.

COMMENT 7: It poorly acknowledges recent effort in seasonal forecasting (e.g. http://www.hydrol-earth-systsci.net/special_issue824.html).

RESPONSE 7: We thank Reviewer #2 for the link. In the revised version, we include some of these references (see 'Additional References').

Comments in the PDF

COMMENT 8: Consequently, they are more reliant on post-disaster response and preparedness activities, often assisted by international donors and humanitarian organizations. Consider here to have a look at Stephens et al. "Floodiness" approach. Stephens, E., J. J. Day, F. Pappenberger, and H. Cloke (2015), Precipitation and floodiness, Geophys. Res. Lett., 42, 10,316–10,323, doi:10.1002/2015GL066779.

RESPONSE 8: In the revised version, we have included this reference.

COMMENT 9: Here you might have a look at a recent HEPEX-HESS special issue on sub-seasonal to seasonal forecasting http://www.hydrol-earth-systsci.net/special_issue824.html

RESPONSE 9: We have read some interesting and relevant papers of the HEPEX-HESS special issue and we have included some of them in the revised version (see 'Additional References').

COMMENT 10: The long-term ('seasonal-scale') wetness reflected in the SPEI for the preceding 1, 3 and 6 months, and (b) the short-term ('weather-scale') cumulative rainfall over the 7 days preceding the event. You could call this also long-memory and short memory disposition.

RESPONSE 10: Thank you for your remark. The text of the revised version has been changed significantly and we have taken this remark into consideration.

COMMENT 11: Figure 1: Schematic overview of the approach followed in this study. %False alarms seems a quite trivial metric for a sound assessment.

RESPONSE 11: We agree.

COMMENT 12: Munich Re NatCatSERVICE disaster database. Is there any cross validation of the accuracy/completeness of this data source?

RESPONSE 12: Unfortunately, we have not conducted any cross-validation of NatCatSERVICE database. The reason is that it is the only dataset at our disposal that provides details of reported flood events, such as coordinates, onset and end dates for the entire sub-Saharan Africa since 1980. We have also looked at other disaster datasets such as EM-DAT and DesInventar, but a systematic cross-validation was not possible as they did not have detailed geographical descriptions, and have only a limited number of reported floods.

COMMENT 13: How you deal with the mismatch between the 0.5◦ and the 2.5◦ resolution? Wouldn't TRMM be an option to evaluate recent years?

RESPONSE 13: We think that the datasets should be consistent in their spatial scale and therefore in the revised version, we have upscaled the 0.5◦ to 2.5◦ resolution, in order to take into account a larger flood affected area. TRMM provides observations only since 2000 and therefore we'd rather not use it for the sake of consistency throughout the paper.

COMMENT 14: A statistical procedure was applied to fit the accumulated records to a log-logistic distribution with a mean of 0 and a standard deviation of 1. This should be shown or referenced

RESPONSE 14: We agree. In the methods sections of the revised manuscript we include the relevant references.

COMMENT 15: Above you speak about 7 days preceding the event, and here you speak about 7 days "lead time". In my understanding lead time is associated to forecasts

RESPONSE 15: That is correct. We agree that the 7 days preceding the event would rather be called "antecedent time" and not "lead time". We now only refer to 'lead time' when we talk about forecasts.

COMMENT 16: Figure 2: In this sketch I have the impression that you are dealing with a rather trivial problem, since 7 days prior to the flood peak you have already about 50% of the flood volume and 90% of the peak level. Please discuss. Minor: Add also SPEI0, Minor: Think about the word "lead time"

RESPONSE 16: We thank reviewer #2 for this remark. We agree that the graph is confusing. The purpose of this graph is mainly to provide the reader a better understanding of the time points of SPEI and 7- day precipitation. The figure doesn't show any real flood event. We agree that usually a flood is defined with a significant discharge increase close the flood onset. In the revised manuscript, we replaced the graph with a more realistic one. Moreover, SPEI0 is shown on the map. Finally, we have substituted 'lead time' with 'antecedent time'.

COMMENT 17: How efficient is the flood reporting for each country?

RESPONSE 17: Unfortunately, to our knowledge, there is not any research that analyzes the efficiency of the flood reporting in each African country.

COMMENT 18: High correlation between flooding and wetter-than-average conditions. (trivial)
RESPONSE 18 Indeed, we agree that this sentence does not give any important information to the results and we have removed it.

COMMENT 19: In how many cases was SPEI1> 1 but no flood was recorded?

RESPONSE 19: Taking into account all the 'flooded cells' and the months that in each one the flood was generated, we get 1731 cases with SPEI1>1 that no flood was recorded. This number accounts for 11.5% of all no-flood cases. In the revised version, we compare the percentages of flood and no-flood events that exceeded different thresholds and we quantify the elevated probability found for flood events.

COMMENT 20: SPEI3 > 0.5 was slightly above average (52%), Is my understanding correct: If SPEI3 is > 0.5 then in about 50% of the cases you might expect a flood. Is this not very close to throwing a coin?

RESPONSE 20: Our dataset consists of 501 floods over 31 years. Every flood is placed on a grid cell and therefore for each grid cell there is 1 flood and 30 no floods in the record. Therefore, there are 15030 cases of no-floods. SPEI0>1 for 1666 no-flood cases (11%), SPEI1>1 for 1731 (11.5%) no- flood cases (11.5%), SPEI3>1 for 1571 no-flood cases (10.5%) and SPEI6>1 for 1454 no-flood cases (9.5%), while the corresponding percentages for floods is 41% (SPEI0), 27% (SPEI1), 21.5% (SPEI3), 16% (SPEI6). In the revised version, we present these increased probabilities. Moreover, in the revised manuscript, we also combine the seasonal SPEIs with SPEI0 and 7-day precipitation. Following the same way of thinking, comparing the percentage of floods and no-floods that exhibited an SPEI3>0.5, we are arguing that it is twice more likely to have a flood in the location, where a flood was reported, when SPEI3> 0.5.

COMMENT 21: Fig.7 Why not showing boxplots here?

RESPONSE 21: We have used boxplots in the revised version of our paper.

COMMENT 22: Limpopo basin - Check the references Seibert, M., Merz, B., and Apel, H.: Seasonal forecasting of hydrological drought in the Limpopo Basin: a comparison of statistical methods, Hydrol. Earth Syst. Sci., 21, 1611-1629, doi:10.5194/hess-21- 1611-2017, 2017. Trambauer, P., Werner, M., Winsemius, H. C., Maskey, S., Dutra, E., and Uhlenbrook, S.: Hydrological drought forecasting and skill assessment for the Limpopo River basin, southern Africa, Hydrol. Earth Syst. Sci., 19, 1695-1711, doi:10.5194/hess-19-1695-2015, 2015. Dutra, E., Di Giuseppe, F., Wetterhall, F., and Pappenberger, F.: Seasonal forecasts of droughts in African basins using the Standardized Precipitation Index, Hydrol. Earth Syst. Sci., 17, 2359-2373, doi:10.5194/hess- 17-2359-2013, 2013.

RESPONSE 22: We thank Reviewer #2 for these relevant and interesting articles. In the revised version, we have included include some of them (see 'Additional References').

COMMENT 23: (> 99th percentile) How many samples are in each 7-day precipitation category for the reported flood events?

RESPONSE 23: The samples in each 7- day category are: 0-33 percentile: 53 cases, 33-66 percentile: 119 cases, 66-100 percentile: 329 cases. However, since we did not find any statistically robust results, we have taken this part out.

COMMENT 24: Fig9. 5-colored boxplots welcome

RESPONSE 24: We have included boxplots in our figures.

COMMENT 25: Fig10 I try to understand, If SPEI1&0 are above 2, then in about 50% of the cases a flood occurred. Correct?

RESPONSE 25: Yes, that is correct. However, as explained in R.12, the no-flood cases are way more than the flood cases. In the revised version, we include figures, in which we show the elevated probability of having a flood when SPEI0 & SPEI1>0.

Additional References

In the revised document, we have included the following references;

Dutra, E., Di Giuseppe, F., Wetterhall, F., and Pappenberger, F.: Seasonal forecasts of droughts in African basins using the Standardized Precipitation Index, Hydrol. Earth Syst. Sci., 17, 2359-2373, doi:10.5194/hess-17-2359-2013, 2013

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Coughlan de Perez, E., Stephens, E., Bischiniotis, K., van Aalst, M., van den Hurk, B., Mason, S., Nissan, H., and Pappenberger, F.: Should seasonal rainfall forecasts be used for flood preparedness?, Hydrol. Earth Syst. Sci. Discuss., doi:10.5194/hess-2017-40, in review, 2017

Seibert, M., Merz, B., and Apel, H.: Seasonal forecasting of hydrological drought in the Limpopo Basin: a comparison of statistical methods, Hydrol. Earth Syst. Sci., 21, 1611-1629, doi:10.5194/hess-21-1611-2017, 2017

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The influence of antecedent conditions on flood risk in sub-Saharan Africa

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Abstract Most flood early warning systems have predominantly focused on forecasting floods with lead times of hours or days. However, physical processes during longer time scales can also contribute to flood generation. In this study, we follow a pragmatic approach to analyse the hydro-meteorological pre-conditions of 501 historical damaging floods over the period 1980 to 2010 in sub-Saharan Africa. These are separated into a) weather time scale (0-6 days) and b) seasonal time scale conditions (up to 6 months) before the event. The 7-day precipitation preceding a flood event (PRE7) and the Standardized Precipitation Evapotranspiration Index (SPEI) are analysed for the two time scale domains, respectively. Results indicate that high PRE7 does not always generate floods by itself. Seasonal SPEIs, which are not directly correlated with PRE7, exhibit positive (wet) values prior to most flood events across different averaging times, indicating a relationship with flooding. The paper provides evidence that bringing together weather and seasonal conditions can lead to improved flood risk preparedness.

1 Introduction

In recent decades, weather-related disasters have accounted for about 90% of all natural disasters (UNISDR, 2015a). There is an upward trend in disaster loss, which is driven by global climate change and the increasing concentration of populations and economic assets in flood-prone areas (Bouwer et al. 2007; Prenger-Berninghoff et al. 2014). Flooding affects millions of people across the globe each year. Between 1980 and 2012 the average annual reported losses and fatalities due to floods exceeded $23 billion and 5,900 people, respectively (EM-DAT, 2012; Jongman et al., 2015).

Flood risk management has traditionally focused on long-term flood protection techniques such as levees and dams (Kellet and Caravani, 2013). Today, people employ complex combinations of flood risk strategies, ranging from technical flood protection measures to financial compensation mechanisms such as insurance, as well as nature-based solutions (Aerts et al., 2014). Lower-income countries often cannot afford and implement preventive measures, mainly due to the high investment costs (e.g. Douben, 2006). Consequently, they are more reliant on post-disaster response and preparedness activities, often assisted by international donors and humanitarian organizations.

The role of science in disaster risk reduction has been globally recognized in the Sendai Framework (UNISDR, 2015b). Preparedness activities and flood forecasting have received increasing attention and have led to new science-based early action systems (Coughlan de Perez et al., 2014). Weather forecasts, with typical lead times of some hours or days, have

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become the basis of such systems (Alfieri et al., 2012), and they have played an important role in reducing flood impacts not only in developed countries (Rogers and Tsirkunov, 2010), but also in several lower-income ones (Golnaraghi, 2010; Webster, 2013). Therefore, research stresses the importance of their improvement. For example, the devastating 2010 Pakistan floods could have been predicted 6-8 days in advance if quantitative precipitation forecasts had been available, providing sufficient time for reaction (Webster et al., 2011).

On longer time scales, seasonal forecasts have been used in early warning and early action systems. A seasonal forecast was used to successfully prepare for floods in West Africa by the International Federation of Red Cross and Red Crescent Societies (IFRC) (Tall et al., 2012; Braman et al., 2013). With regard to floods, seasonal forecasts are used for signaling a likelihood of increased precipitation. Recently, the ECMWF System 4 seasonal precipitation forecast has shown higher predictive skill than climatology for the Niger, Blue Nile and Limpopo basins (Dutra el al., 2013; Seibert et al. 2017), and advances have been achieved in prediction skill and resolution for seasonal precipitation in western Ethiopia (Zhang et al. 2017). However, Stephens et al. (2015) showed that mean monthly precipitation is not well correlated with global floodiness, demonstrating the shortcomings of using seasonal precipitation as a proxy for flood hazard by itself and stressing the importance of modeling the hydrological systems before issuing warnings based on precipitation forecasts.

Depending on the region, factors other than precipitation can also play a role in generating floods. For instance, evapotranspiration and soil saturation are considered important in flood forecasting (Sivapalan et al., 2005; Merz et al., 2006; Parajka et al., 2010; Fundel and Zappa, 2011). Reager et al. (2014) demonstrated that basin-scale estimates of total water storage, including soil moisture, could be used to characterize regional flood potential for the Missouri 2011 floods several months in advance. Floodiness in Southern and Eastern Africa also showed strong correlations with seasonal average soil moisture (Coughlan de Perez, 2017), and the large role of antecedent moisture, rather than high rainfall, was demonstrated by Schröter et al. (2015) on the June 2013 floods in Germany. These physical factors are likely to influence the length of the flood build-up period, which can range from a few days to several months before an event (Nied et al., 2014). So, as forecast skills are inversely proportional to lead time (Molteni et al., 2011), the likelihood of taking action against flood in vain increases with the longer warning lead times. This requires further research on weather and seasonal flooding drivers that may lead to improved flood preparedness.

This study assesses the role of the antecedent conditions on short to long time scales prior to flood generation. We ask what conditions often preceded major flood events, offering insights on how to extend lead times for preparedness by relying on observational systems. For that, we take into account reported damaging flood events from 1980 to 2010 in sub-Saharan Africa. We discuss the potential role of seasonal-scale indicators complementary to the weather-scale phenomena for indicating an increased flooding likelihood. More specifically, we analyse the correlation between floods and hydro-meteorological variables, both on a weather (0-6 days before each flood event), and on a seasonal time scale (up to 6 months before each flood event). Weather scale conditions are evaluated by the 7-day precipitation (PRE7) that preceded the flood event. Seasonal scale conditions were drawn from the Standardized Precipitation Evapotranspiration Index (SPEI). Although SPEI has been applied in studies focusing on seasonal forecasting of droughts (Mossad and Alazba, 2015; Xiao et al., 2016), we argue that it could also be used in flood monitoring and forecasting. The findings of this study contribute to the emerging literature on this topic (Goddard et al., 2014; White et al., 2015) and may be of use to humanitarian organizations and decision-makers for preventive flood risk management planning.

The remainder of this paper is structured as follows. Section 2 outlines the methodological framework and the data used in the analysis, followed in Section 3 by the results. Section 4 discusses the findings and the limitations of the study, including suggestions for further research. Section 5 provides a brief conclusion.

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2 Methodology

Figure 1 shows the different steps in the approach taken by this study. The analysis is based on damaging flood events in sub-Saharan Africa for the period 1980-2010 that are reported in NatCatSERVICE database (Munich Re, 2014).

We assessed the antecedent weather and climate conditions in the locations of reported floods using two indicators: (a) the short-memory anomaly ('weather-scale') evaluated by the cumulative rainfall over the 7 days preceding the event (PRE7), and (b) the long-memory anomaly ('seasonal-scale') reflected in the SPEI for the preceding 1, 3 and 6 months (SPEI1, SPEI3, SPEI6).

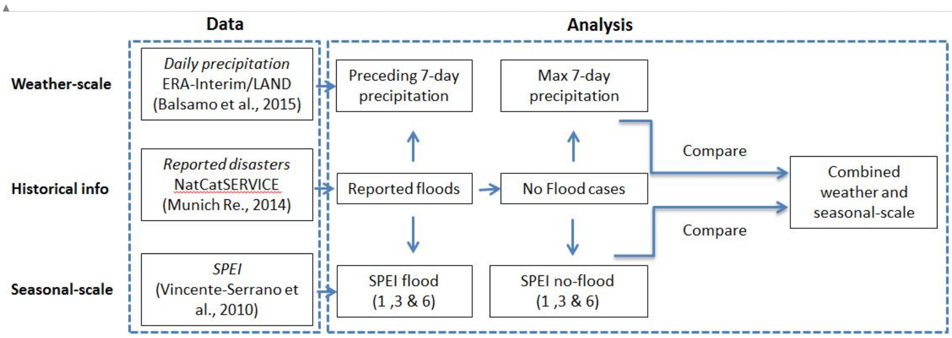

Figure 1: Schematic overview of the approach followed in this study.

2.1 Datasets and their limitations

Study area and reported floods

We used the NatCatSERVICE, a natural disaster database maintained by Munich Reinsurance Company (Munich Re, 2014) to identify the reported flood events in sub-Saharan Africa. This area includes many flood-prone countries (UNISDR, 2015a), which lack hard protective infrastructure against flooding. Hence, early warning and timely preparation play an important role in risk reduction. Events in the database are entered on a country level when there is property damage and/or there are people affected (injured, dead). So, not all the hydrologically defined floods (i.e. unusually high discharges and peak water levels) fulfil the entry criteria in the insurance databases. Hence, many hydrological floods are likely not included in the database as they did not cause any severe damages. By taking into account only the damaging events, we expect the research will be especially useful to the humanitarian sector. Recorded information includes fatalities, affected population, economic losses, onset and end dates and a pair of coordinates of each event. The sources of the database include national insurance

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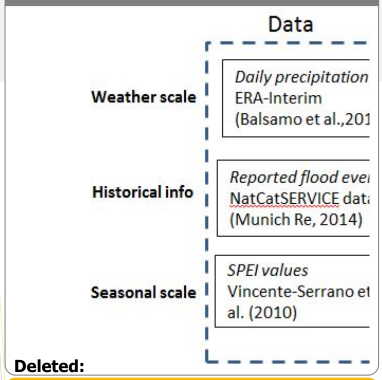

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agencies, online databases from news agencies, governmental and non-governmental organisations, and a worldwide network of scientific and insurance contacts (Tschoegl et al. 2006).

The NatCatSERVICE data includes two categories of inland flooding: a) riverine floods and b) flash floods. This study focused on riverine floods, as flash floods usually have a smaller extent, shorter build-up period and antecedent conditions play a less important role in their generation (Nied et al., 2014). We identified 501 damaging reported riverine flood events in sub-Saharan Africa between 1980 and 2010. Figure 2 shows the number of reported floods per year over the period 1980-2010 and the economic losses per year caused by these floods. The upward trend in flood number over time could be attributed to increased exposure due to population growth and urbanization (Jongman et al., 2012) and underreporting of events in the earlier years due to limited penetration of communication technology (Kron et al., 2012).

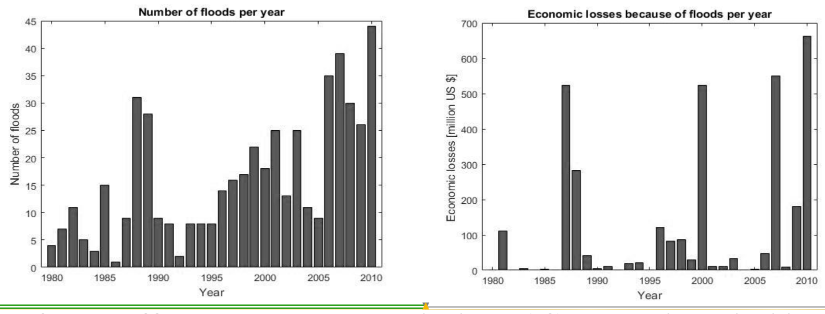

Figure 2: Number of floods per year that are analysed in this study (left) and economic losses in million US $ per year caused by these floods (right) in sub-Saharan Africa between 1980 and 2010 (Munich Re, 2014).

Daily precipitation

Daily precipitation was derived from the European Centre for Medium-Range Weather Forecasts (ECMWF) global reanalysis of land-surface parameters, ERA-Interim/Land, over the period 1980-2010 (Balsamo et al., 2015) (available online at http://apps.ecmwf.int/datasets/). The gridded daily time series were extracted at 2.5° x 2.5° horizontal resolution. This large resolution was chosen a) because it corresponds to the average flooded areas (64,000 km2) (Douben, 2006), and b)to reduce the likelihood of possible errors in the reported coordinates from the NatCatSERVICE database.

Standardized Precipitation Evapotranspiration Index (SPEI)

The SPEI, developed by Vicente-Serrano et al. (2010) was used to evaluate the antecedent soil conditions before the reported flood events. The SPEI is a normalized variable for a long time-series of at least 50 years, comparing monthly net precipitation totals (precipitation minus potential evapotranspiration) with their long-term means over different time scales (1, 3, 6 or 12 months). An x-month SPEI provides a comparison over the same x-month period for all years in the historical record. Shorter accumulation periods (1 month) represent surface soil water content, while longer ones (3, 6, 12 months) indicate the subsurface state (e.g. soil moisture, groundwater discharge) (Du et al., 2013). Unlike the Standardized Precipitation Index (SPI), the SPEI takes potential evapotranspiration into account, which can consume a large portion of total rainfall (Abramopoulos et al., 1988). Precipitation and evapotranspiration together largely determine soil moisture variability, and thus indirectly affect the flood build-up period through links between soil moisture, river discharge, and groundwater storage (Vicente-Serrano et al., 2010). Although some studies have successfully applied SPI as a flood indicator (Seiler et al. 2002; Guerreiro et al. 2008), SPEI has not yet been applied.

In this study SPEI values were first derived at a 0.5° x 0.5° spatial resolution (available online at http://sac.csic.es/spei/index.html), and subsequently they were upscaled to2.5° x 2.5° resolution in order to be

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consistent with the daily precipitation dataset. Mean monthly temperature from the NOAA GHCN_CAMS gridded dataset (Fan and van den Dool, 2008) and mean monthly precipitation from the Global Precipitation Climatology Centre (GPCC) (Schneider et al., 2015) beginning in 1950 were used to estimate the monthly potential evapotranspiration (PET), as in Thornthwaite (1948) (see Vicente-Serrano et al., 2010, for more detail on the processing of the SPEI index). The ECMWF's ERA-Interim reanalysis dataset was not used for this as it is considerably shorter in time. The SPEI values are given for the end of each calendar month. Positive and negative SPEI values indicate wet and dry periods, respectively (Table 1).

SPEI class	Class description
≤-2	Extremely dry
-2 ; -1.5	Severely dry
-1.5 ; -1	Moderately dry
-1 ; -0.5	Mild drought
-0.5; 0	Near normal dry
0; 0.5	Near normal wet
0.5 ;1	Mild wet
1 ; 1.5	Moderately wet
1.5 ;2	Severely wet
>2	Extremely wet

Table 1: Classification of SPEI values (Edossa et al., 2014).

2.2 Analysis

Temporal scale

An illustrative example of discharge in relation to time, before, during, and after a hypothetical flood event is given in Figure 3. The time points of the different flood phases that were used in the analysis are mentioned. The start date of each flood, as reported in the NatCatSERVICE flood dataset (Munich Re, 2014), is the end of the 'flood build-up' period, during which we assumed that the physical processes that led to flooding took place (Nied et al., 2014).

The build-up period was divided into two parts: a preconditioning period at the seasonal scale (up to 6 months before the flood onset), and a flood triggering episode of a 7-day duration at the weather-scale period. In this way, we aimed to distinguish between the antecedent conditions that may have led to an increased flooding likelihood from the intense raifall prior to the event. The build up period ends with the month before the rainfall event so as the two periods do not overlap. The seasonal-scale period was split into 1, 3, and 6 month periods, and the SPEIs (SPEI1, SPEI3, SPEI6) with corresponding accumulation time periods were used. SPEI0, which is independent from the seasonal SPEIs, has 1 month accumulation time period and refers to the flood onset month itself.

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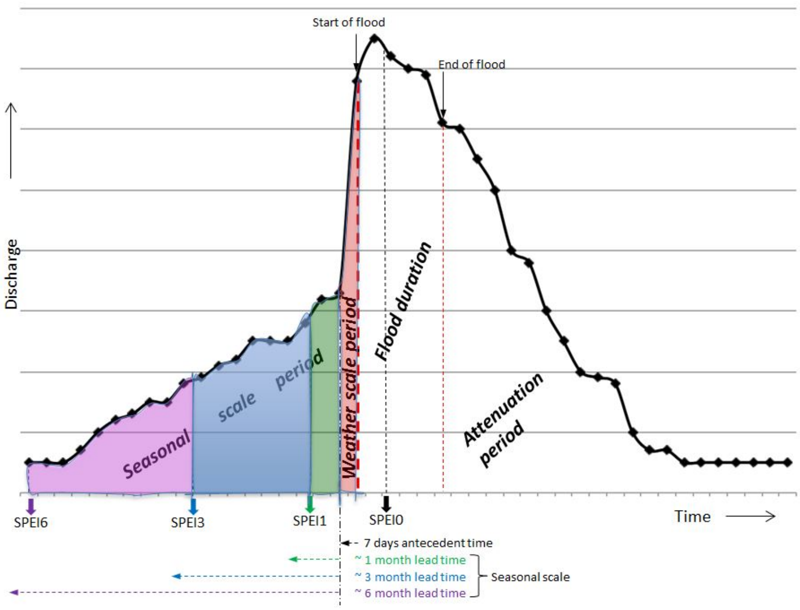

Figure 3: Theoretical discharge before, during and after a hypothetical flood event. Weather scale period starts 7 days before flood onset date, Seasonal scale period is split into 1-, 3- and 6-month accumulation periods. It starts 6 months before flood onset date and continues until the last month before the one that includes the

7-day precipitation. SPEI0 is defined as the SPEI over the calendar month in which the flood onset took place.

7-day precipitation (PRE7)

Using ECMWF's ERA Interim/Land dataset, we calculated the 7-day preceding precipitation (PRE7), having as ending point the reported onset date of each flood and the maximum 7-day precipitation (MAX7) during the month that each flood was reported. The length of the precipitation period leading to a flood depends highly on the local characteristics. For example, a 2-day precipitation sum is best correlated with flood frequency and magnitude in the high ranges of the Swiss Alps, but longer-duration precipitation affects flood occurrence more in the western and eastern Swiss Plateau (Froidevaux et al., 2015). Hence, we expect to be on the safe side by using a relatively long synoptic time window (7 days), similarly to Webster et al. (2011).

Subsequently, for each flood, we used its particular onset month and location to identify the maximum 7-day precipitation within that month of the other dataset years, in which no flood was reported. Using both PRE7 and MAX7 we standardized the 31 values (1 flood and 30 no-floods) over the entire 31 year dataset, with a mean of 0 and standard deviation of 1. The year with the flood event was labelled separately (F) from the remaining 30 no-flood events (NF). We repeated this procedure for all 501 flood events. Then, we compared PRE7 and MAX7 and we performed a two-tailed z-test of unpaired samples to evaluate whether the medians of PRE7and MAX7 in case of a flood differed significantly from that of the NF cases.

Preceding SPEI values and SPEI0

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SPEI values for the months before a flood event are labeleds SPEI1, SPEI3 and SPEI6, indicating accumulation time scales of 1, 3 and 6 months, respectively (Figure 3). These seasonal SPEI values are not independent, as shorter-period SPEIs (e.g. SPEI1, 3) are part of the calculation of longer-period ones (e.g. SPEI6).

SPEI0 has 1 month accumulation period and refers to the end of the month that includes the flood's reported start date. So, it is independent from the other SPEIs. This was used to evaluate the wetness in the end of this month and check whether it could be used as a flood monitoring tool. All month definitions were based on calendar days.

For each flood, we used the same flood onset month and the same location in order to get the SPEIs of all the NF cases. We performed a two-tailed z-test of unpaired samples to compare the median SPEI values of the different time periods of NF events (n=15030) with those of flood events (n=501). Then, after counting the frequency of floods and NFs using several SPEI thresholds (from SPEI>-3 up to SPEI>3), we divided it with the total number of flood and NF respectively, to compare the different flooding probabilities.

Combination of PRE7 and SPEI0 with preceding SPEIs

In a final assessment, we used the preceding seasonal scale SPEIs in combination with SPEI0 and PRE7 to calculate the frequency of floods and NFs under various SPEI thresholds, which range from -1 to +3. In this way, we compared the joint probabilities of flood cases and no-flood cases, bringing together the preceding seasonal-scale conditions with the conditions during the month of the flood for a simple risk assessment.

3 Results

3.1 Floods in sub-Saharan Africa

Figure 4 shows the spatial distribution of the 501 selected flood events over the period from 1980 to 2010 on the Köppen climatological map. The tropical climate areas (in green) experience 43% of all reported floods, the dry climate areas (in yellow) 36% and the oceanic climate areas (brown) 22%. Most floods were reported in continental sub-Saharan countries. South Africa faced the highest number of reported flood events, followed by Kenya, Somalia, Mozambique and Ethiopia. In southern Africa, a considerable number of floods were reported in the areas of the Limpopo and Zambezi river basins and along the coast of South Africa. Eastern Africa also experienced a significant number of flood events, mainly in the southern part of the Nile and near lakes Turkana and Victoria. In West Africa, there is a concentration of floods along the Volta, Niger and Senegal rivers. The pattern shows consistency with the floods reported by Dartmouth Flood Observatory (Global Archive of Large Flood Events, 2010, available at http://floodobservatory.colorado.edu/), which shows that most recent deadly floods happened in places where the population has increased more rapidly in recent years (Di Baldassarre et al., 2010).

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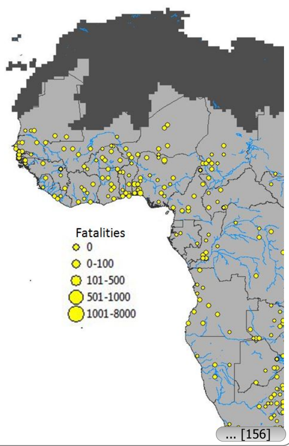

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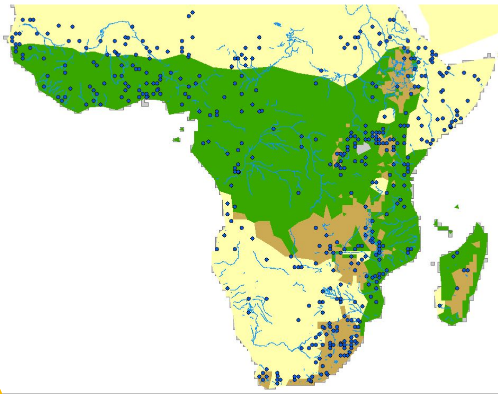

Figure 4 Floods in sub-Saharan Africa from 1980 to 2010on the Köppen climatological map (green: tropical climate, yellow: dry climate, brown: oceanic climate)

3.2 Relation of 7-day precipitation with flooding

Figure 5 (left panel) presents the standardized 7-day precipitation (PRE7) of flood (F) and no-floods (NF) events. On each boxplot, the central red line is the median and the edges of each box are the 25th and 75th percentiles. The whiskers extend to the most extreme data points, covering the 99% of the values and the outliers are plotted individually (+). The results of the z-test showed that the median of the preceding PRE7 of floods did not exhibit any significant difference with that of no-floods (p=0.1). This reveals that although PRE7 is high, it cannot explain by itself the generation of the flood. Similar magnitude events, in the same locations and during the same months that floods were reported occurred without resulting in a (reported) flood.

Figure 5 (right panel) shows that the median of MAX7 was significantly higher than the median of the NF cases (p= 0.05). From the two panels, we can see that the median of MAX7 differs significantly from the PRE7. The difference between them implies that these events occur at different moments within the month of the flood, and that the PRE7 value does not always capture the highest precipitation amount within that month. This may reflect inaccuracies of the reported flood onset date, more precipitation before the 7 days, which created flood favorable conditions, or more precipitation after the flood onset date, which contributed to longer flood duration.

However, from this figure, we see that in many occasions very intense precipitation events did not produce any flood, implying that there should be also other factors other than high precipitation that have contributed to flood generation.

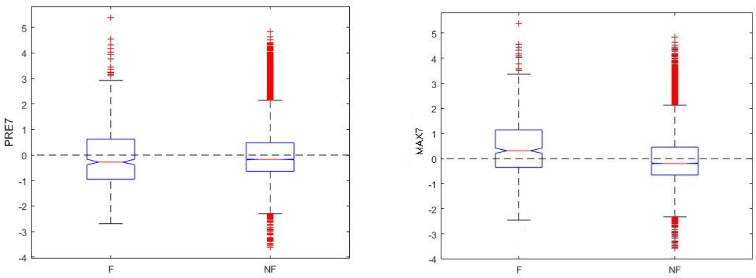

Figure 5 Standardized 7-day preceding precipitation (PRE7; left panel) and maximum 7-day precipitation (MAX7; right panel) of Floods (F; left bars) and No-Flood (NF; right bars) events collected over all 501 reported flood events.

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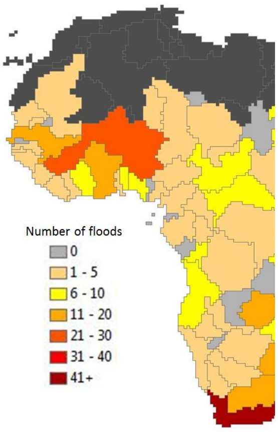

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3.3 Relation between SPEI0 and seasonal-scale SPEIs with flooding

Figure 6 shows the SPEI values of all floods (F) and no-flood (NF) events on different time scales (0, 1, 3 and 6 months prior to the flood onset month). The no-flood cases that are taken into account refer to the particular flood onset month of the no-flood years. For no-flood events, the median value of SPEI is slightly below zero for all time scales. The median SPEI0-SPEI6 values representing the flood cases are significantly higher, which is underpinned by the results of the z-tests (p values < 0.05). More specifically, the median value of SPEI0 for flood events exhibits a value close to 1, which indicates that the wetness in the end of these months was high. The high SPEI0 values demonstrate that it could be used as a flood monitoring tool. The median value of seasonal SPEIs, which are independent from SPEI0, constantly lays in the wet categories (>0), for all the time scales, showing that the wet antecedent conditions have likely played a role in flood generation. The highest median values are found for SPEI1, followed by SPEI3. The median value of SPEI6 is significantly lower than both of them, showing that when the accumulation period is longer, the SPEI tends to climatological conditions and flood signals become more vague. The percentage of floods that exhibit wetter than normal condition (SPEI greater than 0) is 78%, 70%, 65% and 57% for SPEI0, SPEI1, SPEI3 and SPEI6, respectively.

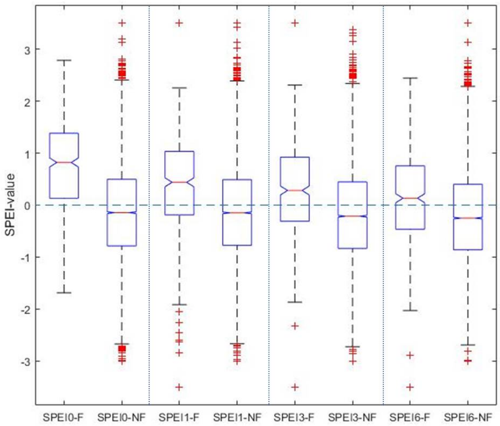

Figure 6 SPEI0 and seasonal-scale SPEIs for Flood (F) and No-Flood (NF) events

Figure 7 shows the relative odds ratio using several exceedance thresholds for the SPEIs, which range from -3 to +3 (horizontal axis). Basically, this ratio shows how much more likely it is that a flood event may happen given a specific SPEI value compared to a no-flood (with a value 1 denoting no elevated probability). Each line represents SPEI values for the different lead times (SPEI0-purple, SPEI1-blue, SPEI3-red and SPEI6-green). For SPEI values below -1, the probability of having a flood and a no-flood is the same for all SPEIs (ratio is 1). After that, a slight increase in flooding frequency is observed for the seasonal SPEIs. When looking at SPEI values over 1.5, it becomes approximately 2.5 times more likely to have a flood when SPEI1 and SPEI3 exceed this threshold. While the SPEI1 and SPEI3 exhibit similar values, the SPEI6 shows considerably lower ratios, indicating that the flood events, which were preceded by such a long wet period are few. For the month that the floods were reported (SPEI0), the maximum ratio is reached when looking at SPEI values over +2, when it becomes 6.5 times more likely to have a flood event. The big difference in the increased probability of flooding of SPEI0 and seasonal SPEIs shows the importance of the conditions during the flood onset month. Using thresholds higher than +2 (black dashed line), the SPEIs behave more erratic because they have only very few observations (less than 10 floods). Hence the data-points right of the dashed line should not be considered reliable.

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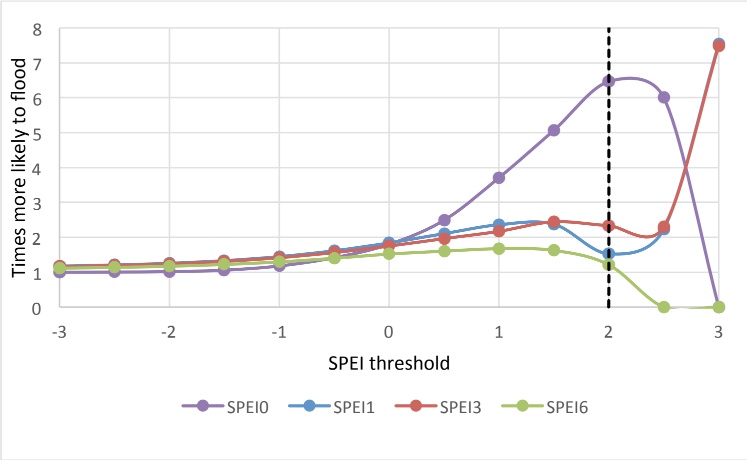

Figure 7: Relative odds between flood and no-flood likelihood as function of the SPEI exceedance value. The black dashed line is used as a boundary, after which there are few flood events (less than 10)

3.4 Combination of seasonal-scale SPEIs with SPEI0 and PRE7

We now discuss the flood probability focusing on the joint occurrence of conditions at the preceding seasonal time scale and conditions during the flood onset month. Figure 8 shows the relative odds of flood and no-flood given SPEI0 threshold values conditional to certain seasonal SPEI values. In the x axis, the thresholds of SPEI0 are given. Each line in the graph represents the combination of SPEI0 with seasonal SPEIs of different thresholds (SPEI1--blue, SPEI1-red, SPEI3-green).

The relative odd of flood versus NF increases when seasonal SPEI thresholds increase (comparing the dashed lines with the solid lines). Compared to Figure 7, the probabilities are higher showing that taking into account both the conditions during the months that preceded the flood and the conditions during the flood onset month results in even higher increased flooding likelihoods. In this case, the maximum values are found when SPEI0 exceeds 2 and the seasonal SPEI thresholds are above 1 (dashed lines). For instance, using SPEI6 > 1, it is 14 times more likely to flood. The combination of SPEI1>1 and SPEI0 exhibits the highest elevated probability up to the SPEI0 threshold of 1.5, where the it becomes 9 times more likely to have a flood event. Although the number of flood events in this case was still not high (i.e. 37 flood events, which corresponds to 7.5% of all reported floods), it should be taken into account that only a very small percentage of no-floods fulfilled this criterion. We discuss results until the black dashed line, as right of it there are fewer than 10 flood events per data point.

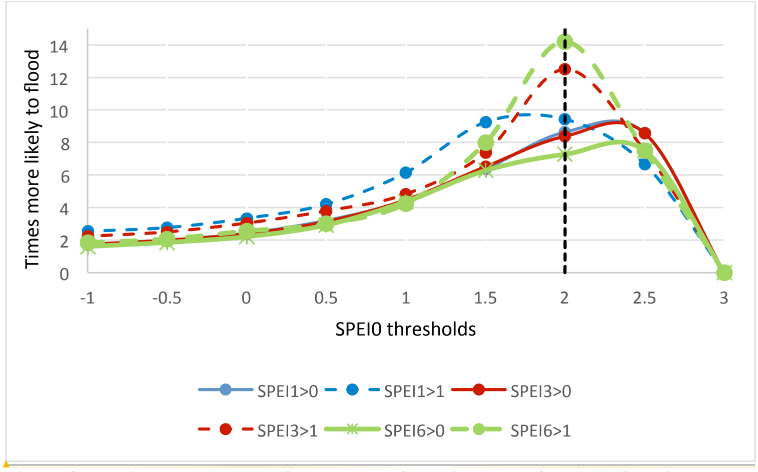

Figure 8 Relative odds between flood and no-flood likelihood for given SPEI0 thresholds conditional to certain seasonal SPEI values (blue: SPEI1, red: SPEI3, green: SPEI6). The black dashed line is used as a boundary, after which there are few flood events (less than 10)

Finally, we present the relative odds between flood and no-flood likelihood for the joint probability of PRE7 and seasonal SPEI thresholds (SPEI1-blue, SPEI3-red, SPEI6-green) (Figure 9). We see that for increasing thresholds, it becomes more likely to have a flood compared to a no-flood. The maximum values observed are 4.8 and 4.3, when PRE7 is higher than 2 and SPEI1 and SPEI3 higher than 1. This figure clearly shows that bringing together PRE7 and seasonal SPEIs leads to increased flooding likelihood.

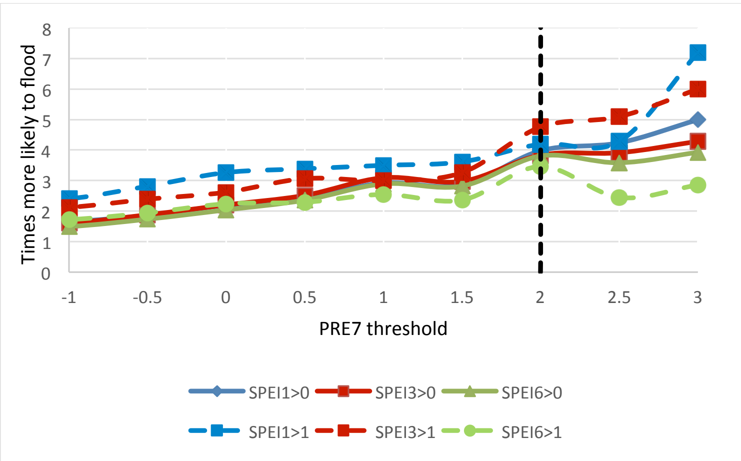

Figure 9 Relative odds between flood and no-flood likelihood for given PRE7 thresholds conditional to certain seasonal SPEI values (blue: SPEI1, red: SPEI3, green: SPEI6). The black dashed line is used as a boundary, after which there are few flood events (less than 10)

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4 Discussion

Role and limitations of the weather-scale conditions

The role of weather-scale meteorological conditions (particularly rainfall) in flood generation is generally accepted (Webster et al., 2011; Jongman et al. 2014; Froidevaux et al., 2015). Our results showed that the flood events were preceded by 7-day precipitation (PRE7), comparable to the maximum observed 7-day precipitation of the flood onset months during the no-flood years. This indicates that although PRE7 was high, it is not able to fully justify the flood generation by itself, leading us to hypothesize that there should be other factors or explanations, other than intense rainfall, that have led to the flood event. These factors can be subject to either poor data (i.e. reanalysis datasets, disaster database) or to the conditions that preceded the PRE7 event.

Despite the absence of high quality daily precipitation datasets in Africa (Lorenz and Kunstmann, 2012; Rogers and Tsirkunov, 2013; Zhang et al. 2013), precipitation reanalysis data offers valuable information over poorly monitored regions such as sub-Saharan Africa (Zhan et al. 2016). However, due to the lack of valuable ground-based precipitation records, especially in developing countries, the reliability of precipitation extremes in reanalysis datasets over land varies in location and time period and it can be very sensitive to reanalysis product and resolution choice (Herold et al. 2017). Particularly, the daily precipitation values on a coarse grid are largely uncertain as they do not capture local scale convective events, which are often responsible for high-intensity precipitation and could significantly affect our results.

The rationale to perform the analysis over a large area around the reported flood coordinates is to deal with the uncertainty in the presented location of the reported flood and to capture the impact of the rainfall in neighboring areas, including some upstream, which may have contributed to the flood generation mechanisms. Due to insufficient information in the disaster dataset, it is difficult to determine the exact delineation of the upstream area. So, we followed this simplified approach. The real world is much more complicated, as the response of hydrological systems to precipitation varies considerably depending on time and place (Eltahir and Yeh, 1999). Further studies should give this serious consideration, carrying out analyses on local spatial scales and using hydrological models to estimate the travel and the concentration time of the upstream rainfall to each flood location.

Finally, in order to gain insights into the uncertainty of the flood onset date, we compared the maximum 7-day precipitation (MAX7) during the onset month of each flood, with a) PRE7 and b) the maximum 7-day precipitation of no-flood events. In both cases, MAX7 was significantly higher. This shows that the 7 days prior to the reported onset date (PRE7) did not exhibit the highest precipitation during the flood month, as one might have expected. This means that either the flood reported date was not accurate or that the MAX7 worked complementary to PRE7 leading to the flood generation. Again, focusing on a local scale, getting accurate information on the onset date, precipitation, discharges, etc. would be an important addition in future research.

Role of seasonal-scale conditions

Our results showed that the most reported floods were preceded by wet seasonal conditions, as all the SPEIs were greater than 0 (SPEI1-70%, SPEI3-65%, SPEI6-57%). Comparing the seasonal SPEI of floods to that of no-floods, we see that the first is significantly higher than the second across the different seasonal timescales, indicating there were several cases that SPEI could have served as an early warning indicator, in case it had been monitored or forecasted. However, the median SPEI of floods goes towards climatological conditions for longer accumulation periods. This should be considered together with the decreasing forecast skill over the lead time (Molteni et al., 2011) in order to identify whether and at which point SPEI could be used as a flood warning indicator.

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In a simple quantification of the flooding probabilities, we found the relative odds of floods and no-floods under various SPEI thresholds. When using a threshold of 1.5 for SPEI1 and SPEI3, we found that it is around 2.5 times more likely for a flood to occur. Although this number is not high, it is still first evidence that seasonal parameters could be used in flood warning systems. Using the same threshold for SPEI0, which refers to the conditions during the flood onset month, we found that it was 6.5 times more likely a flood to have occurred. This shows that SPEI0 has captured in several cases the unusually wet conditions during the flood and it could be used as a flood monitoring tool.

Finally, by bringing together the short- and the long-term conditions, we saw that the different time scales can be used complementary to each other for flood warnings. Using thresholds for both seasonal SPEIs and SPEI0, the likelihood of having a flood compared to a no-flood is considerably increased compared the same likelihood when taking into account only weather or seasonal scale conditions. For instance, when SPEI0 is above 2 and SPEI1, SPEI3 and SPEI6 are above 1, it becomes around 10, 12 and 14 times more likely to have a flood compared to a no-flood. Nevertheless, SPEI0 refers to the entire month, when the flood was reported and not to the conditions that preceded its generation. Therefore, an early warning early action system could monitor rainfall and temperature observations, getting ready when the previous three months have had a high SPEI, and taking further action if the upcoming month is forecasted to also have a high SPEI.

On the other hand, when connecting PRE7 with seasonal SPEIs, the relative odds ratio did not exhibit so high values. However, the resulting increased probabilities (around 4 and 5 times more likely to have a flood when PRE7 is above 2 and SPEI1 and SPEI3 are greater than 1), demonstrate that in several cases the seasonal scale conditions created flood favorable conditions, which turned into flood events by the high PRE7. This result stresses the significance of the joint evaluation of weather and seasonal conditions in flood risk assessment.

Our findings are in line with those of Berthet et al. (2009), who demonstrated that the variety in preceding moisture plays a major role in flood generation in France at similar levels of flood-triggering precipitation, and with Nied et al. (2014), who showed that a small amount of rainfall can result in flood generation when the soil is saturated. The combination of weather- and seasonal-scale condition is also supported by Pathiraja et al. (2012), who showed that there was an underestimation of the magnitude of flood flows in the Murray-Darling Basin in Australia when the joint influence of flood-producing rain events and antecedent wetness was not taken into consideration. Nevertheless, performing a more detailed analysis focusing on a (sub-)catchment area, including ground observations and the use of a hydrological model, could provide more information regarding the antecedent conditions.

Uncertainty in disaster database

In this research we followed a pragmatic analysis using reported damaging flood events in sub-Saharan Africa from NatCatSERVICE database. Natural disaster databases are lacking standardized procedures in monitoring and collection of disaster loss data and therefore, numerous biases and wide disparities in the number and type of disasters is observed among them (Wirtz and Below, 2009; Gall et al., 2009). For this reason, we did not perform any cross-validation and we chose to use events only from one database for the sake of consistency. NatCatSERVICE provided the highest number of reported events and also provided georeferenced data and onset dates, which were necessary for the analysis.
Uncertainties regarding the accuracy of the reported onset date and the exact place of the event exist, as these datasets are often susceptible to human errors and omissions (Jongman et al., 2015). Furthermore, in the dataset used, there is an increasing trend in flood numbers over the years, which may be caused by an upward trend in reporting frequency rather than occurrence frequency. Finally, regarding the no-flood cases that are used in this analysis, we should acknowledge that we cannot declare with certainty that there were no floods in these cases, as it is likely that they were not reported (e.g. omission in the dataset, not significant impact etc.).

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We acknowledge that our sample (501 events) is small, and it was probably one of the reasons that we did not produce statistically significant results in different geographical areas. Nevertheless, to our knowledge, it is the first study that analyses the preconditions of so many historical flood events, trying to link the reality with physical parameters.

Policy Relevance

The approach applied in this study fits well in the global policy on disaster management: the Sendai Framework of Disaster Risk Reduction (SFDRR) (UNISDR, 2015b). The Framework calls for enhanced efforts to reduce risk from natural hazards (including floods), such as protection, financial risk transfer and early warning systems (Mysiak et al., 2016). Seasonal forecasting systems are promising measures that can complement existing warning systems, and support post disaster risk reduction strategies such as relief operations. For this, the SPEI-based approach of using seasonal information to prepare for flood events could be further developed and eventually used to support disaster preparedness activities in the regions at risk. For example, it could be a useful tool in the Forecast-based Financing (FbF) approach, which is currently being developed by the Climate Centre of the Red Cross/Red Crescent (Coughlan De Perez et al., 2015) and aims to disburse humanitarian funding based on forecast information. The idea behind it is to take action based on the progressively increasing flood warning information. This could be implemented by the 'Ready-Set-Go' concept (Goddard et al., 2014), where each of disaster preparedness is activated when the output of different forecast types (e.g. seasonal, weather), exceeds a certain threshold.

So, early warning systems can use the results of this research to set up operational programming to take action before flood events. First, if they are monitoring SPEI6, SPEI3, and SPEI1, people can take general preparation actions when the values increase, knowing that the risk of flooding is slightly elevated for the coming month. Once they see that the observations from the past season show high SPEIs, then they can check forecasts for the SPEI of the coming month, and 7-day rainfall forecasts, to take additional preparedness actions if those also show high values. An action system based on this combination of observations and forecasts could instigate major preparedness. In order to enable such a system, both monitoring and forecasts of SPEI should be made available. Local SPEI-related indicators tailored to specific river basins can also be derived and forecasted.

4 Conclusions

This paper explores the influence of antecedent conditions of reported damaging floods in sub-Saharan Africa for the period 1980-2010. Our analysis follows a pragmatic approach, being based on 501 large-scale reported floods taken from NatCatSERVICE disaster database (Munich Re, 2014). While most studies base their analyses on modeled discharges and floods, this research tries to link a considerable amount of real events to physical parameters that have contributed to their generation. We have examined both separately and together the impact of short- and long-term antecedent conditions prior to each event. To do so, we have clearly distinguished the flood antecedent conditions between weather and seasonal scales based on their reported onset date. The weather scale conditions encompass 0-6 days prior to each flood onset date and are captured by the 7-day accumulated precipitation (PRE7) and the seasonal-scale conditions are reflected in the values of the Standardized Precipitation Evapotranspiration Index (SPEI) 1, 3 and 6 months before each flood.

The results indicate that although 7-day precipitation (PRE7) prior to floods was high, it did not exhibit any statistically significant differences with maximum 7-day precipitation observed on the same locations and during the same onset months that floods were reported. On the other hand, the maximum 7-day precipitation during the flood onset month (MAX7) was significantly higher than both PRE7 and maximum 7-day precipitation of the no-flood cases, which shows that in several cases, an extreme event occurred during the flood onset month. Although the outcomes demonstrate the catalytic role of

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hydro-meteorological phenomena in flood generation during the days close to the flood onset, emphasizing the importance of weather forecasts in flood forecasting, they do not explain the fact that extreme precipitation does not always lead to flood events.

At the seasonal scale, high SPEIs values are associated with flooding, denoting wet conditions across the different time scales before the flood event. Given the long SPEI accumulation periods used (i.e. 1 to 6 months), that Having disengaged seasonal from weather-scale conditions, the relation of seasonal SPEI and flooding does not include weather-scale precipitation, implying that there should be other factors that are related to SPEI. Given the long accumulation periods used (i.e. 1 to 6 months) this factor could be the soil saturation of each place, probably because of limited water storage capacity. Setting a threshold of seasonal SPEI>1.5, we see that it becomes up to 2.5 times more likely to have a flood event (for SPEI1 and SPEI3). Using the same threshold for SPEI0, which represent the conditions during the flood onset month, it is 5 times more likely a flood to have occurred, demonstrating that SPEI0 could be used as a flood monitoring tool.

The combined analysis of weather- and seasonal-scale flood antecedent conditions reveals that their joint influence affects flood generation, exhibiting higher flood elevated probabilities than when taking into account either PRE7 or SPEI. Exploring various combinations of weather and seasonal scale thresholds, the results show that flooding probabilities further increase with increasing thresholds. Translating them into practice, we conclude that seasonal-scale wetness, as defined by SPEI, could be a useful input to the weather-scale flood forecasts based on which disaster actions are to be taken. This information could be related to the ongoing work in the humanitarian sector to better prepare risk mitigation actions, which could be taken progressively when pre-set thresholds are exceeded.

Acknowledgments

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