**Review of Törnros and Menzel**
**Characterizing droughts under current and future climates in the Jordan River region by J.H. Stagge**

## General Comments

**Comment:** The authors calculate the SPI at several time scales using observed data for the Jordan River region and determine that the SPI-6 is most strongly correlated with NVDI, a measure of vegetation cover and vigor. Using three GCM simulations, SPI-6 is then calculated for current (1961-1990) and future conditions (2031-2060), and subsequently used to identify the most extreme drought events during each period. These drought events are used within a hydrological model to compute irrigation water demand for the region. The authors conclude that droughts in the eastern Mediterranean region are projected to be prolonged and more severe over the next century, resulting in an increased total water demand for the region.

The content and conclusions of this paper have merit and deserve publication in HESS, but the paper requires significant rewriting prior to publication.

The primary weakness of this paper stems from lack of detail in explaining the work that was performed, but in the Introduction and Methods sections. Because the Introduction does not clearly explain how the various sections fit together, it is difficult to follow the linkage between (1) SPI/NVDI correlations with observed data, (2) drought durations estimated using GCM simulations, and (3) future estimates of irrigation water demand. This problem is further exacerbated by a lack of specifics in the Methods section. The results appear to be interesting, but without details on precisely how SPI and drought durations were calculated and how these values were aggregated, these results do not have context.

I agree with Reviewer 1 that several statements in this paper are very strong, without significant support from the literature. When SPI is used in arid regions and to model climate change, there should be significant qualifications because this index has poor performance near zero precipitation and does not include the effects of temperature on evapotranspiration.

**Reply:** We would like to thank Dr. James Stagge for reading the manuscript and giving us very useful comments. We are happy to hear that the manuscript has merit and deserve publication in HESS, and we are sorry to hear that it occasionally lacks in detail. We are aware of that we conducted a high number of different analyses and that it is important that they are well explained and that linkage between the sections are clear, therefore we are extra grateful to receive such detailed reviews that can help us to improve the manuscript. In a revised version of the manuscript we will clarify the applied methods and analyses and make sure that the linkages are clear Extra attention will be paid to the introduction and the definition of objectives (see e.g. review#1 for clarified objectives). We will also put effort in improving the method section and include more support from literature.

We would once again like to thank Dr. James Stagge for spending time in reading our manuscript and for providing us with valuable feedback. The general comments that have been raised in this section are also recurring in the specific comments, were they now will be replied to one by one.

## Specific Comments

### Drought indices and their usage

**Comment:** The introduction lists several drought indices. I agree with Reviewer 1 that drought types (meteorological, soil moisture, or agricultural) should be introduced along with types of drought indices. It is important to note that the Palmer Drought Index is based on a soil water balance equation, incorporating an estimate of potential evapotranspiration, while the SPI does not. This has implications when discussing soil moisture/agricultural droughts, particularly when climate change projections show a significant increase in temperature and duration of warm/dry spells. The author may want to mention the SPEI (Vicente-Serrano 2010), which is calculated similarly to SPI, but incorporates evapotranspiration, thereby including the effect of temperature increases.

**Reply:** Thank you for this advice. In a revised version of the manuscript we will introduce different types of drought, as well as some of the most applied drought indices and their advantages and disadvantages. It will be mentioned that the PDSI and Crop Moisture index are based on a soil-water-balance and accounts for the effect of evapotranspiration and that this would be beneficial when addressing a future change in temperature. It will furthermore be mentioned that there also is a need for simpler drought indices, relaying on less data and fewer calculations than the PDSI (Hayes et al., 1999; Smith et al., 1993). Because SPI only recognizes precipitation anomalies, it will also be noted that the SPEI includes evapotranspiration.

### SPI – Definition and Methods

**Comment:** SPI should be better defined within the introduction and significantly more detail should be provided on methodology.

**Reply:** Thank you for this comment, SPI will be clearer defined within the introduction: "Another well-known drought index is the Standardized Precipitation Index (SPI), developed by McKee et al. (1993) and applied worldwide. The index uses long data records on precipitation as the only input and in contrast to other drought indices, the SPI can be applied on different timescales (e.g. 1, 3, or 6 months) in order to address time-lags between precipitation and the water supplies in soil moisture, ground water, snowpack, streamflow and reservoir storage (McKee et al., 1993). The SPI has been recommended by the World Meteorological Organization (WMO, 2011) for characterizing meteorological droughts."

We also agree that more detailed information should be provided within methodology. Therefore, we would like to introduce a new headline under methods (2.2 SPI; see also the two following comments).

**Comment:** Page 5877, Lines 14-15: The definition of SPI is poorly worded. Please use a clearer SPI definition, as in (Guttman 1999, Agnew 2000, Lloyd-Hughes and Saunders 2002, or Tsakiris and Vangelis 2004).

**Reply:** SPI will be defined more clearly: "The SPI uses long-term precipitation series, preferable not shorter than 30 years, as only input (McKee et al., 1993). To begin with, a probability density function is fitted to the long-term precipitation series for a certain time-scale of interest. The fit is conducted separately for each month of the year and the series is a running time series of e.g. 1, 3 or 6 months cumulative precipitation. The probability density function is thereafter transformed to a standard normal distribution with the mean value of 0 and standard deviation of 1".

**Comment:** Page 5877, Lines 19-20: Using SPI < -1 to define drought is an arbitrary definition proposed by McKee et al (1993) because it is convenient and is easily understood statistically. Although this definition has been used regularly in the literature, there is little physical basis and no consensus that this is the only valid definition of drought. Therefore, please soften the language in lines 22 and 23. Also, when citing this SPI<-1 definition, it is useful to explain its statistical meaning – that accumulated precipitation less than this magnitude is expected to occur in 15.9% (1 std dev) of the month in question.

**Reply:** Thank you for this advice. In a revised version of the manuscript we intend to write: "Drought conditions occur when the SPI is negative in an event where the minimum SPI drops below a certain threshold value. McKee et al. (1993) suggested a threshold value of -1 for moderate drought; the SPI value is expected to be below this threshold in 15.9% (1 standard deviation) of the time."

**Comment:** Page 5878, Line 13: The paper claims that a drought index based on precipitation alone is appropriate for the eastern Mediterranean, citing Törnros (2010). Many papers have concluded that SPI is less appropriate in arid or semi-arid regions because of difficulties fitting distributions near zero and the importance of evapotranspiration (Edwards and McKee 1997, Wu 2007, Lloyd-Hughes and Saunders 2002). Tornros (2010) finds a correlation between precipitation and NDVI, but does not compare this with any other indices or climate variables, such as evapotranspiration. So, while precipitation may be correlated with NDVI, this does not imply that a more thorough water balance index is not better suited to describe agricultural droughts in the eastern Mediterranean.

**Reply:** Thank you for pointing this out. This manuscript focuses on SPI and its different time-scales. Less attention is paid to other drought indices, which indeed could perform just as good. It is true that, by conducting correlation analyses between precipitation and NDVI it cannot be concluded that a precipitation based drought index performs better than an index that also incorporates evapotranspiration. Although, we did not intend to claim this we understand that the sentence might be misinterpreted. In a revised version of the manuscript we would like to clarify that also other drought indices can perform well. This will be done in the introduction as well as in the discussion.

**Comment:** Page 5878, Lines 22-24: When trying to quantify the effects of climate change using a drought index, it would be useful to use an index such as the SPEI, which includes increases in evapotranspiration losses due to temperature increases. This is not necessary for this paper, but a note should be made to this effect.

**Reply:** We agree, it would be very interesting to conduct the same analyses by using SPEI. However, this is out of the scope of this study. Nonetheless, in a revised version of the manuscript we will introduce SPEI in the introduction. Furthermore, we would like to add the following in the discussion: "… the applied approach should also be employed to evaluating the performance of other drought indices like the SPEI and PDSI, which incorporates the influence of evapotranspiration."

## Explanation of Methods

**Comment:** SPI methods should be highlighted in greater detail. Page 5881, Line 19-21 makes it seem as though 1961-2001 is used as the reference period (or long-term time series) for calculating SPI using observations. However, within the climate change section, it appears that the entire time series (1961-2060) is used to normalize accumulated precipitation (Page 5882, lines 25-27), making it impossible to compare observed SPI with GCM simulations of current conditions. Is this correct? If you were to select a single reference period (1961-2001), you could verify GCM current condition simulations with observed data, as suggested by Reviewer 1.

**Reply:** This is correct; we have used two different time-periods in order to normalize our data. Indeed, it could be beneficial to normalize also the GCMs according to the period of observed data (1961-2001). Unfortunately this would require major modifications of the applied SPI code (since it automatically normalizes the SPI according to the full length input series). An alternative to use the same period for normalization could be to pay more attention to the uncertainties related to the GCMs (independent of the SPI). As suggested by reviewer#1 we will include information regarding climate extremes in a revised version of the manuscript.

**Comment:** The SPI notoriously has difficulties in fitting precipitation at or close to zero (Wu 2007). For much of the region, the method for handling zero precipitation becomes important at SPI-1 or SPI-2, particularly in April or May. How is this handled in your work? Could this explain the potentially anomalous result (negative correlation) for SPI in Figure 3?

**Reply:** Thank you for this advice. In a revised version of the manuscript we will mention that SPI has problem in fitting a probability density function to precipitation at or close to zero (Wu et al., 2007). At the moment, the months with zero precipitation are not treated differently than the wet months, but indeed it is a disadvantage of the SPI. We will therefore mention the impact this may have on the results during the dry summers, especially when applying short time-scales. We also agree with your last comment, we will mention that this could be one of the reasons why the SPI-1 and SPI-2 show negative correlation at the end of the growing season.

**Comment:** Spatial aggregation methods are not well explained in the Methods section. It is unclear whether SPI is calculated for all 96,000 cells separately and aggregated using the land cover classes or if you average precipitation based on these land cover classes and then calculate SPI. Additionally, the paper highlights the need for climate sub-regions because climate in the region is heterogenous (Page 5880, lines 14-15), but it appears these regions are not used in the correlation analysis (Figure 3). Ji and Peters (2003) do make use of climate regions in their similar work.

**Reply:** SPI was calculated separately for each single grid cell. For the purpose of correlation analyses, the SPI was thereafter aggregated according to land-use. I.e., the correlation analyses were conducted for the mean SPI and mean NDVI of each land-use; this will be clarified in a revised version of the manuscript.
The response to precipitation differs between plant species (Rosenthal et al., 1987), therefore the correlation analyses were conducted separately for each land-use and not according to climate regions which include a mix of land-uses. However, we believe that the results regarding drought characteristics are important for the whole region and should not be limited to specific land-uses. See also a similar comment by reviewer#1.

**Comment:** The method for calculating drought duration and unique drought events should be explained in greater detail. There is a short explanation in the results section (Page 5886, Lines 21-23) which should be moved to the Methods section and expanded upon. Similar to SPI, the paper should be very specific whether (1) mean drought duration was calculated for all cells and averaged, (2) SPI values were averaged by region and drought duration was calculated, or (3) precipitation was averaged by region followed by SPI and drought duration calculations.

**Reply:** Thank you for highlighting this. The SPI was calculated for each grid cell separately, and (1) also the drought statistics were derived individually for each grid cell, thereafter aggregation was taking place. This will be clarified: "the SPI series of every 1 × 1 km pixel was evaluated according to the duration and frequency of droughts. The drought duration is the number of months with continued drought conditions (SPI < 0 in an event where minimum SPI <-1), and the drought frequency is expressed in drought events per decade. It was furthermore distinguished between moderate (minimum SPI < -1.0), severe (minimum SPI < -1.5), and extreme (minimum SPI < -2.0) drought

according to McKee et al. (1993). Once the drought statistics had been calculated for each pixel, the results were aggregated according to three climate regions for visualization purposes."

### Results

**Comment:** Page 5884, Lines 23-25: The paper states "no significant correlation is obtained between NDVI and the 1-month SPI". However, Figure 3 shows p-values of 0.03 (Mosiac/May), 0.06 (Cereals/Apr), and 0.08 (Cereals/May). This statement should be qualified that "little significant correlation is detected …".

**Reply:** The sentence will be rewritten according to the suggestion.

**Comment:** The link between SPI and IWD analysis is a bit unclear. It appears that SPI is used only to identify a single, most extreme drought event from the current and future GCM simulations. Once identified, the full GCM dataset is used to simulate water demand for these two periods using the TRAIN model. If this is true, please provide characteristics of these drought events (duration, mean temperature, precipitation, wind speed, radiation, humidity). This will help the reader understand the projected differences between the current and future conditions.

**Reply:** Thank you for this comment. Your understanding of the approach is correct in the sense that a single, most extreme drought was identified. However, we were unclear in expressing that this was done for all three climate projections; this resulted in six identified droughts (3 for the current period and 3 for the future period). In a revised manuscript, this will be clarified in methods. It would be a challenge to organize all the characteristics of these six events; mean values of e.g. temperature would furthermore not allow a completely fair comparison since the droughts may stretch over different seasons. Therefore, we believe that it is better to not include all the data. Nonetheless, we should at least mention the mean drought lengths of the current and future droughts.

## Technical Corrections

**Comment:** - Page 5879, Lines 13-16 This statement provides good rationale for the research, but seems out of place following your main research statement. Perhaps it can be moved earlier in the Introduction.

**Reply:** The text will be moved to a more appropriate place.

**Comment:** - Spatial interpolation of precipitation is extremely fine for climate variables (1 km2). I assume this level of downscaling is performed because the land use cover database uses this resolution. This should be mentioned during the downscaling discussion (Page 5881, Line 1-2).

**Reply:** Your assumption is corrected. We will mention this in the downscaling section.

**Comment:** - Page 5887,Lines 1-5: I recommend presenting mean drought duration as decimal months (8.95 months rather than 8 months and 29 days) to make it clear that the original data is at the monthly scale. Showing the number of days implies that you are calculating drought duration at the daily scale.

**Reply:** Thank you for pointing this out, the suggestion will be implemented.

**Comment:** - Page 5888, Lines 11-13: Please remove the semicolon and make this sentence into a list: "100-150 mm during the reference drought, between 150-200 mm

during the future drought period, and in excess of 200 mm for some land uses in extreme cases".

**Reply:** The sentence will be changed according to the suggestion.

## References


Agnew, C. T. (2000). Using the SPI to Identify Drought: DigitalCommons@University of Nebraska - Lincoln.

Edwards, D.C. &McKee, T.B. (1997). Characteristics of 20th Century Droughts in the United States at Multiple Scales. Atmospheric Science Paper No. 634, May 1-30.

Guttman, N. B. (1999). Accepting the Standardized Precipitation Index: A Calculation Algorithm. JAWRA Journal of the American Water Resources Association, 35(2), 311-322. doi: 10.1111/j.1752-1688.1999.tb03592.x

Hayes, M. J., Svoboda, M. D., Wilhite, D. A., and Vanyarkho, O. V.: Monitoring the 1996 Drought Using the Standardized Precipitation Index, Bulletin of the American Meteorological Society, 80, 429-438, 10.1175/1520-0477(1999)080<0429:MTDUTS>2.0.CO;2, 1999.Ji, L. & Peters, A.J. (2003) Assessing vegetation response to drought in the northern Great Plains using vegetation and drought indices. Remote Sense. Environ., 87, 85-98.

Lloyd-Hughes, B., & Saunders, M. A. (2002). A drought climatology for Europe. International Journal of Climatology, 22(13), 1571-1592.

McKee, T. B., Doesken, N. J., & Kleist, J. (1993). The relationship of drought frequency and duration to time scales. Paper presented at the Proceedings of the 8th Conference on Applied Climatology.

McKee, T., Nolan, J., and Kleist, J.: The relationship of drought frequency and duration to time scales, In Proceedings of the 8th Conference of Applied Climatology, 17-22 January, Anaheim, CA. American Meteorological Society, Boston, MA, 179-184., 1993.

Rosenthal, W. D., Arkin, G. F., Shouse, P. J., and Jordan, W. R.: Water deficits effects on transpiration and leaf growth, Agron. J, 76, 1019-1026, 1987.

Smith, D. I., Hutchinson, M. F., and McArthur, R. J.: Australian climatic and agricultural drought: Payments and policy. , Drought Network News 5, 11-12, 1993.

Törnros, T. (2010). Precipitation trends and suitable drought index in the arid/semi-arid southeastern Mediterranean region. Global Change: Facing Risks and Threats to Water Resources (Proc. Of the Sixth World FRIEND Conference., 157-163.

Tsakiris, G., & Vangelis, H. (2004). Towards a Drought Watch System based on Spatial SPI. Water Resources Management, 18(1), 1-12. doi: 10.1023/B:WARM.0000015410.47014.a4

Vicente-Serrano, S. M., Beguería, S., & López-Moreno, J. I. (2010). A multi-scalar drought index sensitive to global warming: the standardized precipitation evapotranspiration index – SPEI. Journal of Climate, 23, 1696-1718.

Wu, H., Svoboda, M. D., Hayes, M. J., Wilhite, D. A., & Wen, F. (2007). Appropriate application of the standardized precipitation index in arid locations and dry seasons. International Journal of Climatology, 27(1), 65-79. doi: 10.1002/joc.1371