

Interactive comment on “Increased incidence, duration and intensity of groundwater drought associated with anthropogenic warming” by John P. Bloomfield et al.

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We would like to thank Referee #2 for their review comments on the paper and appreciate the feedback and insights that they have provided.

Response to the Specific comments

Specific comment 1. We entirely agree with Referee #2 that "referring to the country-scale precipitation is not support that there are not any systematic trends in precipitation at two sites". However, we do feel that we have addressed this issue in the paper, although perhaps not sufficiently explicitly.

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As mentioned in the introduction (Lines 42-43), it is notoriously difficult to characterise trends in hydrometric variables, such as precipitation time series, that may contain a range of frequency structures and noise within them. This is one of the reasons (though not the only one) why we have not adopted a formal trend analysis approach to the study and have instead taken the approach of looking for systematic changes between periods in the long records. In this context, at Lines 265 to 272 we describe the results of a test of the probability of the difference in the number of dry months in the periods 1891-1932 and 1974-2015 and show that there is no statistical difference in precipitation between the start and the end of the records at both sites.

To make our approach more explicit, we propose to revise the first para of the Methods section at Line 198 as follows: "Given the aim of the study, one approach would be to undertake formal trend analyses of the standardised groundwater level, air temperature and precipitation data to see how each of these variables change over time at each site, to try and identify break points, and to see if and how any trends or break points are correlated. However, given the difficulties in identifying and quantifying local trends in long hydrological time series (Wilby 2006; Watts et al., 2015) and given that we are not interested in absolute trends or break points but rather in any changes in correlations between standardised variables consistent with our prior knowledge of the effects of climate change (Trenberth et al., 2015), we instead follow the approach of Diffebaugh et al. (2015). They investigated changing frequency of drought, as measured by the Palmer Modified Drought Index (PMDI), with standardised annual average precipitation and temperature anomalies and looked at changes in those variables and their relationships. Diffebaugh et al., (2015) chose to analyse their 100-year-long records in two halves. However, in this study three periods have been used for the analysis, 1891-1932, 1933-1973 and 1974-2015. This means that the last period, 1974-2015, coincides with the period of greatest documented anthropogenic warming over the study area (Karoly and Stott, 2006). In addition, the use of three periods for analysis provides more granularity in the description of changes in the standardised indices with time. One benefit of this approach is that the assumptions

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that there is i.) no change in precipitation between the first and the last periods at the two study sites, and ii.) a systematic, significant increase in temperature (previously attributed to climate change, Sexton et al., 2004; Karoly and Stott, 2006; Jenkins et al., 2008; King et al., 2015) across all three periods can be tested explicitly (see Results, section 3.1)”

Specific comment 2. Referee #2 suggests that, rather than use three equal periods for the analysis of the standardised time series, time series analysis techniques could be used to search for change points in the standardised temperature record and that these change points could then be used to sub-divide the time series prior to the STI-SGI-SPI analysis. There are a number of reasons why we did not follow this approach.

Reiterating our remarks related to Specific Comment 1 (above): formal trend analysis, and in particular identification of meaningful change points in hydrological or climatological time series, is particularly challenging and highly sensitive to noise in the signals and such formal time series methods are not consistent with our stated approach of simply describing changes in frequency and nature of groundwater droughts across a period of known warming. As importantly, there is no evidence of clear change points from previous analyses of anthropogenic warming in the CET. For example, the whole period of investigation is subject to continuous long-term warming with many local periods of superimposed variation in temperature, see for example Figure 1, p.2 of Karoly & Stott (2006) and Figure 1.4, p10 of Jenkins et al (2009).

However, to address the specific comment, we propose to include in the modified introduction to the Methods section (see above) a note to the effect that we have not used change point analysis to sub-divide the analysis periods, rather that we have simply investigated and characterised changes in frequency and nature of groundwater droughts across a period of known long-term warming. Referee #2 also noted that “there is almost no text about the second third period (1933-1973), but it is included in all figures and tables”. This was a conscious decision to reduce the description and discussion of the results in the text. We originally included more description of the ob-

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servations and results for the middle third of the records but it made the paper more wordy without changing or adding to the substance of the findings, discussion or conclusions of the paper. In the light of the Referees comments we have reviewed the text again but propose not to add any extra text as we still think additional text would be superfluous. As the Referee notes, the results for the middle period are all available for the readers in the figures and tables.

Response to the Minor Remarks

1. Line 279, “blue” should be revised to “red”. Agreed. In addition, the figure does not show a running mean, rather the line is the mean of the standardised index for each third of the record. Consequently, the text will be amended to read “The red bold line shows the mean standardised index for each third of each record”.
2. Figure 3, the numbers in the x-axis (1, 2, and 3) needs to be referred to the first (1891-1932), second (1933-1973), and last (1974-2015) third periods in the caption or legend. Agreed. The caption will be revised to read as follows: “Percentage of monthly STI, SGI and SPI as a function of six ranges of standardised values from ≤ -2 to ≥ 2 for the first (1891-1932), middle (1933-1973) and last (1974-2015) thirds of the records from CH and DH, denoted by columns 1, 2 and 3”.
3. Line 379, please remove of “anomalies”. Agreed, the change will be made.
4. Line 403, please remove “the” in “given the that”. Agreed, the change will be made.
5. Line 431, it should be “(Maxwell and Condon, 2016)”. Agreed, the change will be made.
6. Line 454, it should be “(Doble and Crosbie, 2017)”. Agreed, the change will be made.
7. Figure S4 in the supplementary materials, please provide the name of the site to the corresponding plot, in caption or legend. Agreed, the site names will be added to the plots.

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