# Response to reviewer's comments

We would once again like to thank the Referees for their time and their thoughtful comments and insights. We believe that the review process has resulted in significant improvements to the paper.

**General observations**

The Editor has asked for the paper to be revised as follows:

> "The referee's comments were quite relevant, as it was also recognised by the authors in their replies. The answers to all the comments are interesting and deserve to be included somehow in the revised version of the manuscript. I expect that the authors can significantly improve the scientific quality of the paper by revising the text and the figures. In their replies, the authors propose to make no changes to the text in response to some of the referees' comments. I recommend the authors to carefully consider those comments and to evaluate whether rephrasing or reorganization of the text might avoid any possible misunderstanding by the readers".

Based on this feedback from the Editor, we have made modifications to the text and figures in response to **all** the comments from the Referees.

In addition to our responses to each of the referees specific comments (see below), we would like to highlight some changes to the data analysis in the revised version of the paper that have been stimulated by comments from the reviewers:

- Based on our response to Comment #5 from Referee #1 and Technical Comment #2 from referee #3, we present a more explicit description of the accumulation and averaging periods of the SPI and STI data, and in the revised paper we now use an accumulation period of six months, $SPI_6$, for Dalton Holme. This provides a more consistent treatment of the two sites while resulting in no changes to the main findings, inferences or conclusions of the study.
- In response to Comment #1 from Referee #2 and Comment #2 from Referee #3, we have provided more information on the statistical tests for change in the SGI, STI and SPI series, including notes on an additional change point analysis that we have undertaken. In so doing we found a minor error in our initial estimation of the level of significance of the change in STI between the first and last analysis periods (previously estimated to be <0.001 for both sites, and now corrected to read 0.03 for Chilgrove House and 0.005 for Dalton Holme). Again, these additions and changes, while adding more information, do not change the overall findings, inferences or conclusions of the study.
- In response to a number of comments, but particularly Comment #6 from Referee #1, we recognised that the old Figure 6 and the associated analysis in the text inadequately described changes $SGI_e$ characteristics between the analysis periods. Figure 6 in the original draft only described changes in drought duration, the revised new Figure 6 and associated revised text now describe both changes in the number of events, their duration, intensity and magnitude. As with the other changes to the manuscript, this adds more information but the overall findings and conclusions of the study remain unchanged.

Also, please note that we have taken the opportunity of the revision of the paper to simplify and amend text to improve legibility, for example we have simplified the title of the paper to "Changes in groundwater drought associated with anthropogenic warming". We have also corrected a number of typos, formatting errors (section number 3 was repeated in the original manuscript, so we have now re-numbred the sections accordingly), and some minor data transcription errors. Again, these changes do not affect the overall findings, inferences or conclusions of the study.

**Referee-specific responses and changes to the paper**

Note: All references to lines in the Referees Comments are to line numbers in the original paper unless otherwise stated. All references to lines in our Responses are to new line numbers in the revised paper unless otherwise stated.

**Referee #1**

Comment 1. "I found figure 4 (the core business of the work) very interesting. As pointed out by the Authors, SPI<0 appears to be a broad prerequisite for groundwater drought. Moreover, I agree that increasing groundwater drought is associated with increasing temperature. However, there are some anomalies shown in Figure 4, which in my opinion should be furtherly investigated. There is an interesting difference between the second and the third period for the CH dataset: the majority of the most intense groundwater episodes during the second period (SGI < -2) occur for negative or close to zero STI, whereas in the third period positive temperature anomalies seem to play a fundamental role, as almost all of the drought episodes (both for SGI < -2 and -2 < SGI < -1.5) are associated to STI > 0 and SPI < 0. This difference is strange and should be somehow explained: why the aquifer differently reacts to meteorological forcing?"

Response 1. Monthly values of SGI in the second period at CH are as much a response of the groundwater system to natural variability in precipitation deficits as they are to longer-term underlying changes associated with anthropogenic warming. The "most intense groundwater episodes during the second period (SGI < -2) [at CH]" noted by Referee#1 are in fact associated with a single major drought episode in 1933-1934. The effect of warming is better understood by considering the changing location of the centroid of the groundwater drought months (now added in the revised paper) in Figure 4.

To clarify these points we have:

- Added explanatory text at L402-411 to describe the effect of natural variability in precipitation deficits on data presented in Figure 4, including a note on the 1933-34 event.
- Added a new Figure S5 in the Supplementary Information illustrating how the intense groundwater drought months in the middle period at CH are associated with the evolution of the 1933-34 event.
- Added the centroid of the SGI data for each period to Figure 4 to explicitly show that the centroid of the SGI months is associated with an increasing mean STI with time and added new explanatory text at L425-430.

Comment 2. "Addressing the previous point, please consider also the following: the Authors "postulate that increased evapotranspiration associated with anthropogenic warming is a major contributing factor to the observed increasing occurrence of individual months of groundwater drought as well increasing the frequency, duration and intensity of episodes of groundwater drought" (page 15, line 404), despite the phreatic surface is approximately 40 m and 15 m below the topographic surface at CH and DH, respectively. According to the Authors, the fundamental role played by the transpiration is favoured by the significant thickness of the capillary fringe. This could be a possible explanation. However, at DH (where the water table is much higher than at CH, potentially making the aquifer more sensitive to temperature changes), the increase in temperature occurs over the entire period. I would have expected to find also in the second period an increase of the groundwater drought episodes with respect to the first period. In my opinion, an explanation to this anomaly should be given."

Response 2. As with our response to Comment 1 from Referee 1 (above), we feel that we have probably not emphasised sufficiently that groundwater droughts, as expressed in the monthly SGI (Figure 4) and by the episodes of groundwater drought $SGI_e$ (Figures 6 and 7), are primarily controlled by natural variation in precipitation deficits. The effects of anthropogenic warming are secondary and superimposed on the natural variability in precipitation droughts. At DH the second period was on average slightly wetter than the first period, while the last period is slightly drier than the first (mean SPI 0.03, 0.05, and -0.09 for periods 1891-1932, 1933-1973 and 1974-2015 respectively). Consequently, that the middle analysis period at DH has one less episode of groundwater drought than the first period is not surprising. In addition, we note that a year-long episode of groundwater drought started in December 1973 and ended in November 1974 at DH. This has been included in the statistics for the last analysis period. If it had been included in the middle period then the number of droughts at DH would have been 9, 9, and 15 for periods 1891-1932, 1933-1973 and 1974-2015 respectively. This discussion illustrates the naturally 'noisy' nature of the groundwater drought data driven by noisy precipitation data, the difficulty of identifying subtle long-term trends imposed by warming, and emphasises why we have chosen to analyse relatively coarse periods and use averages to characterise change across the record.

As we feel that we did not sufficiently emphasise the role of naturally varying precipitation deficits in controlling the overall pattern of drought episodes at the two sites in the initial draft we have added text to emphasise this point in the Abstract at L10-11, and in the text at L402-405, and L445-447 and at L507-510. In addition, we have added text at L445-458 to reflect Referee's comment and the specific discussion points above.

Comment 3. "One more thing on the capillary fringe. Please, quantify its thickness for both sites".

Response 3. The thickness of the capillary fringe at both sites is unknown and, in addition, there are no direct measurements of matrix water content, matric potential, pore-size or pore-throat size distributions in the matrix of the Chalk for either of the sites. However, it is known that the capillary fringe in the Chalk is primarily controlled by the microporus characteristics of the matrix, which are remarkably uniform across the Chalk of the UK.

We have added text at L552-555 to clarify these points.

Comment 4a. "It is not clear to me the reason for using standardized indexes in the analyses. As Authors know very well, standardized indexes are related to frequency (pdf) analysis. Therefore, doubling one index (i.e. from -1 to -2) does not mean doubling the intensity of the anomaly".

Response 4a. There are two broad approaches to identifying and characterising droughts including groundwater droughts. Namely, standardised indices and threshold level approaches (see Van Loon, 2015 for a recent overview). To clarify why we have used standardise indices in favour of the threshold approach to characterise droughts we have added a new discussion of the pros and cons of each approach and a justification of our choice at L262-279 at the start of the Methods section. In addition, we have added a note at L307-309 to explain the non-linear nature of standardised indices.

Comment 4b. "Temperature and precipitation data come from gridded dataset and, considering the limited surface of the study areas, only one pixel has been considered. Therefore, why not use directly observed data of precipitation and temperature?"

Response 4b. The extent of the groundwater catchments at the two study sites is unknown, though expected to be only a few square kilometres in extent (see Figure 1). There are no rain gauge or temperature records that continuously cover the study period at the sites. This study has been part of a larger study to reconstruct precipitation and hydrological droughts back to 1890 (the Historic Droughts Project, see https://historicdroughts.ceh.ac.uk/ ). As part of that study the Met Office in the UK has reconstructed gridded precipitation and temperature records on a 5km by 5 km grid across the UK back to 1890. We have chosen to use that gridded data product in this study since there is no other consistent dataset to use and we consider that it is at an appropriate resolution given the probably limited nature of the groundwater catchments at the two sites.

We have revised the text at L210-220 to clarify these points.

Comment 5. Page 8, line 241. “The optimal averaging/accumulation period was found to be 6 and 7 months for CH and DH respectively”. If I have understood correctly, Pearson correlation coefficients shown in figure S4 between SGI and SPI have been computed for a range of SPI accumulation periods considering the current month (i.e. $SPI_n$ of March, for n = 1, … 12 is put in relation with SGI computed in March). This means that the percolation time from ground surface to saturated zone is neglected, not considering possible delay time of the impact of precipitation anomaly on groundwater level anomaly. Please, justify this choice”.

Response 5. The optimal accumulation period is based on a phenomenological relationship between two time series, i.e. an accumulated precipitation and a groundwater level time series. It is not based on any consideration of recharge processes. Estimating correlations between a standardised hydrological drought index and varying SPI accumulation periods to characterise the relationship between precipitation deficits and droughts is a well-established approach, see for example a recent paper by Barker et al. (2016) in HESS on streamflow droughts, or various papers on groundwater droughts by the current authors (Bloomfield et al., 2013; 2015; Marchant et al., 2018). However, to address the specific query above, if the optimal accumulation period for precipitation is 6 months, i.e. $SPI_6$, then the March SGI is optimally correlated with all rainfall accumulated over the previous six month period, i.e. from (previous) October to March. From a process perspective, this would mean that March SGI would reflect any recharge that occurred during the six-month period prior to March. So although this is not a process-based relationship we assert that “percolation time from ground surface to saturated zone” is not neglected at all.

The text in the Methods section has been significantly extended at L336-346 to clarify these points. (Please note that in the revised paper we now use $SPI_6$ for both CH and DH. A full explanation is give in our response to Technical Comment #2 from Referee #3 below).

Comment 6. Figure 6: “I would have standardized the cumulative frequency distribution. In this analysis, I’m interested in a possible shift of the duration probability distribution. Probably they are very similar for the two analysed periods.”

Response 6. When considering this comment and reading the interpretative text associated with Figure 6 in Section 3.3 we realised that we had provided only a limited description of changes in drought event characteristics. In addition, when considering the data for the limited number of drought episodes in each analysis period we have subsequently decided that analysis of the distribution of their characteristics may not be appropriate. Consequently, we have drafted a new Figure 6 to show changes in the frequency of episodes and mean drought episode characteristics across the analysis periods. We have also extensively revised the text discussing the new Figure 6 at

L445-471 to describe and discuss the new figure and data. We believe that this new plot and associated text now better describe changes in the characteristics of $SGI_e$ across the three periods.

Comment 7. (Minor remarks). “Please, change the order of the subplots in Figures 2 and 3 putting SPI first, then STI and finally SGI (groundwater drought is a consequence of climate anomalies)”

Response 7. Figures 2 and 3 have been revised as requested.

Comment 8. (Minor remarks). “Figure 5. As in this case SGI refers to the mean over a given drought episode and not to the monthly SGI, please use another notation.”

Response 8. Revisions have been made to Figure 5 (and Figure 7) to include new notation to denote event mean SGI, as $SGI_e$. The Methods section has also been revised to make the distinction between SGI and $SGI_e$ clear at L352-355 and the Results and Discussion text modified appropriately too.

**Referee#2**

Comment 1. “In Line 58-60, the authors mentioned that such analyses requisite needs no systematic changes in precipitation. Did the authors analyze the trends in precipitation at the site studied for different time steps: full length (1891-2015), first third (1891-1932), second third (1933-1973), and last third (1974-2015)? I asked this question because the authors explained about changes in temperature at the sites (that follow the Central England Temperature, Lines 147-152) and provided Figure S2 in supplementary materials (to confirm it). However, there is no such explanation or figure for precipitation referring to the sites studied. The authors only mentioned that annual mean precipitation shows no trends since 1766 and also no attribution of changes in it to anthropogenic factors (Lines 152-156). Referring to the country-scale precipitation is not support that there are not any systematic trends in precipitation at two sites, even considering a 5km * 5km”.

Response 1. We believe that the assertion that precipitation does not show long-term trends at either site is addressed in the paper already. For example, Figure 2 qualitatively shows no long-term variation in monthly SPI with time or in mean monthly SPI over the three analysis periods. Figure 3 also illustrates no long-term variation in SPI. However, more importantly we explicitly test the hypothesis that there is no statistically significant change in SPI across the record. At old L265-272 (new L371-384) we describe the results of a statistical 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.

Given the Referee’s comment, we acknowledge that the above points were probably not articulated clearly enough in the original draft, consequently, we have added text justifying the use of the sites and their associated characteristics at the start of the site description section, section 2, by adding new text at L99-104.

In addition, a new change point analysis added in response to Comment 2 from Referee #2 (see below) indicates that there are no significant change points in the standardised precipitation time series, as described at L233-248.

Comment 2a. “In Lines 175-176, the authors mentioned they considered three periods for their analyses (1891-1932, 1933-1973, and 1974-2015) because each of these periods cover a considerable groundwater drought episode. At first, there is almost no text about the second third period (1933-1973), but it is included in all figures and tables.”

Response 2a. We note the comments regarding the lack of discussion of the middle period in the text and recognise that it would be useful to include some discussion of the middle period where appropriate. However, we also want to make the Results and Discussion sections to be esily digestible and not overwhelm the reader with too much data. So we have where appropriate included additional information and comments regarding the middle period, for example see L428-429, L460-462, L495-497 and L526-531. Of course, data on all three periods is available in the Supplementary Information in Tables S1 to S3.

Comment 2b. “Then, in my opinion, the authors need to do the regime shift analysis for STI to identify the change point of the temperature time series as the authors are primarily looking for anthropogenic warming effects. Finally, based on these changing points, the groundwater droughts and SPI should be investigated.”

Response 2b. We understand the suggestion from Referee 2 that two (or more) periods could be defined by using formal trend analysis methods to identify a change point in the temperature time series and that any differences in groundwater droughts could be analysed between those two periods. However, since we assert that groundwater droughts are primarily driven by precipitation deficits and modified by the effects of anthropogenic warming, and given that anthropogenic warming is not typically characterised by discrete change points, but rather has increasingly effected the climatology of the UK since the late 1800s, we don’t think a change point approach based on the STI record is appropriate to the aim of the study. We are not interested in attribution of groundwater droughts. As we mention in the Introduction, Diffebaugh et al. (2015) have addressed a very similar problem to us and developed the simple but we think elegant solution of dividing the observational record in equal time periods and characterising and exploring change in hydrological drought in terms of concomitant change in SPI and STI between the periods. We have chosen to follow their approach.

However, based on the suggestion of Referee #2, we have investigated the SPI, STI and SGI series for change points to provide an additional insight into the data. We have added significant new text describing the new change point analysis, the results and a justification of why this approach has not been used to define the analysis periods at L233-260

Minor remark 1. “Line 279, ‘blue’ should be revised to ‘red’”

Response Minor remark 1. Change made.

Minor remark 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”.

Response Minor remark 2. Change made to legend.

Minor remark 3. “Line 379, please remove of ‘anomalies’”

Response Minor remark 3. Change made.

Minor remark 4. “Line 403, please remove ‘the’ in ‘given the that’”

Response Minor remark 4. Change made.

Minor remark 5. “Line 431, it should be ‘(Maxwell and Condon, 2016)’”

Response Minor remark 5. Change made.

Minor remark 6. “Line 454, it should be ‘(Doble and Crosbie, 2017)’”

Response Minor remark 6. Change made.

Minor remark 7. “Figure S4 in the supplementary please provide the name of the site to the corresponding plot, in caption or legend”.

Response Minor remark 7. Change made.

**Referee#3**

Comment 1. “Given that temperature rises throughout the three periods, this also means that high temperatures will coincide with groundwater drought more often. That means that over average STI values, e.g. STI > 1 will in this setup automatically be more common during the third period both for drought and flood conditions in groundwater, which can be seen in Fig 2. How much of the increase in temperature-related groundwater droughts does this account for? Groundwater droughts due to temperature could have been just as frequent in the earlier periods, but due to the trend in the STI values, just below the hard detection threshold of STI > 1”.

Response 1. It is explicitly not our aim to attribute groundwater drought episodes to anthropogenic warming. Hence, we are not trying to answer the question: “How much of the increase in temperature-related groundwater droughts does this [anthropogenic warming] account for”? The aim of the paper is to undertake the first empirical analysis to characterise changes in groundwater drought incidence, duration and intensity given known climate warming and the absence of other major change factors (see original L76-84). We have revised the last paragraph of the Introduction at L82-96 to emphasise this point.

In addition, Referee #2 suggests that “Groundwater droughts due to temperature could have been just as frequent in the earlier periods, but due to the trend in the STI values, just below the hard detection threshold of STI > 1”. For clarification, the frequency of occurrence of the observed groundwater droughts is fixed based on our definition of groundwater droughts where for either drought months or episodes of groundwater drought SGI <-1 or $SGI_e$<-1. We are not suggesting that any episodes of groundwater drought are “due to temperature” associated with any given STI threshold. Instead, we identify the groundwater droughts, and asses how their characteristics differ between the three analysis periods in the context of STI and SPI (where STI shows significant changes and SPI does not). We have made some minor revisions to the Introduction at L52-68 to emphasise this point.

Comment 2. “When finding the highest correlating SGI to SPI aggregation periods, you get correlation coefficients between .7 and .8 at 6 and 7 months respectively. Even though these values are considerably high, showing the SPI/SGI on a cross-plot would reveal a considerable number of events where SPI does not predict SGI well. I wonder therefore, whether there is a bias in the aggregation period. The SPI with selected aggregation period (e.g 6 months) over time could become a worse predictor, such that droughts associated with precipitation deficit become rarer (as seen in the third period)? A longer aggregation period would possibly show a smaller change in precipitation-related droughts. When looking at the study by two of the authors (Bloomfield and Marchant, 2013), the same locales were used among others, but DH had a longer aggregation period of 10 months, while using a shorter, more recent time period. Has a shift in the recharge regime occurred, which has been observed in other locations? If this is the case, surely the driver also is due to changes in the hydrological cycle”.

Response 2. There is no evidence for changes in the maximum correlation between SPI and SGI or between STI and SGI across the whole observation period. The correlations for SPI-SGI over accumulation periods up to 12 months are similar between the first third and the last third of the observational record (Figure S4). They are also characterised by an insensitivity to accumulation periods once they reach a maximum at about 6 months, particularly at DH. This explains why for small differences in the observational record analysed maximum accumulation periods of 6 months (this study) and 10 months (Bloomfield and Marchant, 2013) have been observed. We revised the text at L323-334 to reflect these observations.

Comment 3. “It did not become clear to me from the method section of the paper what was done with STI and why. As I understand, at different aggregation periods correlation coefficients between SGI and STI were calculated. These are generally weak 0 - -.2 (Supplement) and have a minimum (absolute maximum) at around 6 months, meaning that generally cold spells lead to more recharge and vice versa. There is quite some uncertainty involved though, at these low correlations, the relationship will be positive almost as often as it is negative. Despite this, I agree that this is the expected general tendency, I wonder though if this 6 month aggregation is still valid in the case of extreme events. My expectation would be that this behaviour changes and that for droughts only relatively short periods of relatively hot weather is needed for severe entailing groundwater droughts. If this is the case/could be shown, the findings would be even more interesting”.

Response 3. Monthly STI is estimated using the same method of standardisation as is used for SGI (and SPI) and STI standardisation (like SPI and SGI standardisation) has been performed across the full record (see L311-313).

In order to investigate relationships between the driving meteorology and hydrological responses, such as changes in monthly groundwater levels, it is common practice to search for a significant accumulation period for precipitation since hydrological response to meteorological anomalies is typically lagged. This approach was established by McKee et al (1993) when they introduced the SPI approach. We have estimated average STI over varying periods and correlated this with monthly SGI and then used this along with the estimates of correlations between SPI and SGI based on various SPI accumulations to find the accumulation / averaging period that gives the highest absolute summed cross-correlation for the entire observational series (see L323-334). We do this because we want to treat both the precipitation and air temperature aspects of the driving meteorology in a consistent manner.

We agree that the correlation between SGI and STI estimated in this manner is relatively week (this is now made explicit at L327-329), and that there is uncertainty in the relationship between SGI and $STI_6$. However, we want to re-emphasise that in the study we are exploring relationships between the standardised variables, we are not ascribing causative or predictive skill to the correlations illustrated in Figure S4. However, we note that the six month optimal accumulation/averaging period that is used provides a good characterisation of hydrological droughts. For example, practice in more process-based studies of the Chalk (e.g. Folland et al., 2015) it is common to consider the previous winter half year climatology as an indicator of subsequent groundwater drought status. New text has been added to L341-346 to reflect this observation.

Finally, we agree that the relationship between intense hot periods and groundwater droughts would be worthy of investigation. However, since the aim of the paper is to look at the relationship between centennial-scale warming and changing drought characteristics, investigation of the effect of extreme heatwave is out of scope of the current study. We have modified the text at L92-93 to this effect.

Comment 4. “30 meters and more of thickness in capillary fringe seems unusually high. In Ireson et al. (2009) data was modelled for two locations different from CH and DH. Are these representative for CD and DH locations?”

Response 4. There is a real paucity of observational data to constrain the height of the capillary fringe in the Chalk. The value of 30 meters for the thickness of the capillary fringe cited in the paper is based on the theory of Price et al. (1993). This value is widely accepted in the absence of systematic observations. For example, while developing their Chalk unsaturated zone model, Ireson et al. (2009) also assumed that “the matrix [in the unsaturated zone of the Chalk] will generally remain saturated by capillary forces” and modelled changes in Chalk unsaturated zone pore pressure and water content as a function of variations in fracture incidence and aperture. Ireson et al. (2009) modelled field data from two sites from the Chalk of the Pang-Lambourn catchment in the Chilterns. Although the site was on the same aquifer formation as CH and DH, i.e. the Chalk, we agree that there is no reason to expect that results from those sites should necessarily be representative of CH and DH since they were primarily considering the effects of fracturing on unsaturated zone drainage and this may vary widely between Chalk sites.

The text in the Discussion has been extensively revised at L539-562 to reflect the discussion above.

Technical comment 1. “L234ff: Clarify that the indices are calculated over the entire period”.

Clarifications at L281-282 and at L311-313.

Technical comment 2. “L240-241: Put maximum correlations into text”

Correlations have now been detailed at L324 and 328. Please note, previously in the first draft of the paper an optimal accumulation and averaging period of 7 months for DH was based on the maximum absolute summed cross-correlation coefficient for SGI-SPI and SGI-STI estimated to greater than two significant figures. However, when estimating the co-efficient to two significant figures the coefficient is the same for 6 months and 7 months. Hence in the revised paper, 6 months has been used optimal accumulation and averaging period for DH and all data and plots have been revised appropriately.

Technical comment 3. “L269-272: Unclear what is meant by "probability of the difference", please specify what has been done here. Statistical significance”?

Additional explanation of the statistical analysis is now at L371-378.

Technical comment 4. “Fig2: Very information-dense. The percentage values mean different things in the different panels, it should be possible to clarify within the figure”.

Figure 2 revised as requested.

Technical comment 5. “Fig 3: Instead of using integers 1-3 for periods, use the interval of years on the y-axis”.

Figure 3 revised as requested.

Technical comment 6. “Fig 4: Add location to the figure (CH, DH) so it becomes clear directly what the reader is looking at. Additionally it would be beneficial to see which of the non-drought months come from the specified period”.

Figure re-drafted as requested.

Technical comment 7. “Fig 6: Why not include the second period? I get the impression from Fig 5 that drought durations are not dissimilar for the second and third period, especially for CH”.

Figure 6 has been re-drafted (see response to Referee#1, comment 6)

Technical comment 8. “L412-416: Difficult sentence to digest, not clearly conveyed what the conclusions of the paper by Maxwell and Condon (2016) are”.

Text simplified significantly at L541-543 to clarify.

Technical comment 9. “Supplement, FigS4: Add locations CH/DH to the figure”.

Locations added.

**References**

Lucy, J., Barker, L. J., Hannaford, J., Chiverton, A., and Svensson C.: From meteorological to hydrological drought using standardised indicators. Hydrol. Earth Syst. Sci., 20, 2483–2505, 2016

Bloomfield, J. P., and Marchant, B. P.: Analysis of groundwater drought building on the standardised precipitation index approach. Hydrol. Earth Syst. Sci., 17, 4769–4787, 2013.

Bloomfield, J. P., Marchant, B. P., Bricker, S. H., and Morgan, R. B.: Regional analysis of groundwater droughts using hydrograph classification. Hydrol. Earth Syst. Sci., 19, 4327–4344, 2015.

Bonferroni, C. E. 1936. Teoria statistica delle classi e calcolo delle probabilità, Pubblicazioni del R Istituto Superiore di Scienze Economiche e Commerciali di Firenze 1936

Chen, J., and Gupta, A. K.: Parametric statistical change point analysis, Pub. Birkhauser. 2000.

Marchant et al., 2018

McKee, T. B., Doesken, N. J., and Kleist, J.: The relationship of drought frequency and duration to timescales. Proc. 8th Conf. App. Clim. 17–22 January 1993, Anaheim, California USA. 1993.

Van Loon, A. F.: Hydrological drought explained. WIREs Water, 2, 359–392, 2015.

World Meteorological Organisation. Standardized Precipitation Index User Guide. M. Svoboda, M. Hayes and D. Wood. WMO-No. 1090. WMO Geneva, Switzerland. 2012.

# ~~Increased incidence, duration and intensity of~~ Changes in groundwater drought associated with anthropogenic warming

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**Abstract.** Here we present the first empirical evidence for changes in groundwater drought~~s~~ associated with anthropogenic warming in the absence of ~~significant~~ long-term ~~long-term trends~~changes in precipitation. Analysing standardised indices of monthly groundwater levels, precipitation and temperature, using two unique groundwater level data sets from the Chalk aquifer, UK, for the period 1891 to 2015, we ~~describe~~ show that precipitation deficits are the main control on groundwater drought formation and propagation. However, long-term changes~~an increase~~ in groundwater drought are shown to be associated with anthropogenic warming over the study period. These include increases in ~~both~~ the frequency and intensity of individual groundwater drought months, and increases ~~an increase~~ in the frequency, ~~duration~~magnitude and intensity of episodes of groundwater drought, as well as an increasing tendency for both longer episodes of groundwater drought and for an increase in droughts of less than one year in duration ~~since 1891 associated with anthropogenic warming~~. We also identify a transition from coincidence of episodes of groundwater drought with precipitation droughts at the end of the 19th century, to an increasing coincidence with both precipitation droughts and with hot periods in the early 21st century. In the absence ~~either~~ of long-term changes in precipitation deficits ~~during episodes of groundwater drought or long-term changes in the occurrence and intensity of consecutive dry winters~~, we infer that the changing nature of groundwater droughts is due to changes in evapotranspiration (ET) associated with anthropogenic warming. We note that although the water tables are relatively deep at the two study sites, a thick capillary fringe of at least 30~~-~~m in the Chalk means that ET should not be limited by precipitation at either site. ~~;~~ ~~that~~ ET may be supported by groundwater through major episodes of groundwater drought~~;~~ and, hence, long-term changes in ET associated with anthropogenic warming may drive long-term changes in groundwater drought phenomena in the Chalk aquifer. Given the extent of shallow groundwater globally, anthropogenic warming may widely effect changes to groundwater drought characteristics~~this phenomenon may be widespread~~ in temperate environments.

## 1 Introduction

Globally groundwater provides of the order of one third of all freshwater supplies (Doll et al, 2012; 2014), 2.5 billion people are estimated to depend solely on groundwater for basic daily water needs (UN, 2015), and it sustains the health of many important groundwater-dependent terrestrial ecosystems (Gleeson et al, 2012). This high level of dependence on groundwater means that communities and ecosystems across the globe are vulnerable to both natural variations in groundwater resources (Wada et al., 2010) and to the impacts of anthropogenic climate change on groundwater (Green et al., 2011; Taylor et al., 2013). Groundwater droughts, taken here to mean periods of below normal groundwater levels (Tallaksen & Van Lanen, 2004; Van Loon, 2015; Van Loon et al., 2016a; 2016b), are a major threat to global water security (Van Lanen et al., 2013) and are potentially susceptible to being modified by climate change. Since drought formation and propagation are driven by precipitation deficits and evapotranspirative losses associated with elevated temperatures, there is an expectation that ~~global~~ anthropogenic climate change, and in particular ~~global~~ anthropogenic warming is already modifying the occurrence and nature of droughts (Dai, 2011; Sheffield et al., 2012; Trenberth et al., 2014; Greve et al., 2014). However, to date there have been no systematic investigations of how warming due to anthropogenic climate change may affect groundwater drought (Green et al., 2011; Taylor et al., 2013; Jackson et al., 2015), and it has even been noted in the IPCC Fifth Annual Assessment of Impacts, Adaptation, and Vulnerability that: 'there is no evidence that … groundwater drought frequency has changed over the last few decades' (Jiménez Cisneros et al., 2014, p.232). This significant gap in our understanding of groundwater drought is not surprising given the limited availability of long groundwater level time series suitable for analysis (Jimenez Cisneros et al., 2014) and the low signal to noise ratios characteristic of many hydrological systems (Wilby 2006; Watts et al., 2015). In addition, the challenges of formal attribution of groundwater droughts due to ~~global (or~~ anthropogenic~~)~~ warming (Trenberth et al., 2015), and the potentially confounding influences of land use change and groundwater abstraction on groundwater drought (Stoll et al., 2011; Jimenez Cisneros et al., 2014; Van Loon et al., 2016a; 2016b) complicate any analysis of such droughts. Here we address some of these challenges and present the first empirical evidence for the effects of anthropogenic warming on the changing nature groundwater droughts.

Groundwater systems have been shown to effect global land-energy budgets and regional climate (Senevirante et al., 2006; Trenberth et al., 2009; Maxwell and Condon, 2016) and can control the generation of large-scale hydrological droughts, particularly in temperate climates (Van Lanen et al., 2013). Although the role of evapotranspiration (ET) in regional- to global-scale drying is still a matter of active debate (Dai, 2011; Sheffield et al., 2012; Greve et al., 2014; Milly and Dunne, 2016), there is an expectation of a general increase in ET, and hence of general drying associated with ~~human-induced global~~ anthropogenic warming (Trenberth et al., 2014). E~~, and e~~ven if ~~heating from~~ anthropogenic warming may not necessarily cause droughts, Trenberth et al. have noted that it is expected that when droughts do occur that they are likely to set in more quickly and to be more intense in a warming world (Trenberth et al., 2014). In order to investigate the evidence for such changes in groundwater droughts it is ~~necessary~~ desirable to identify sites from unconfined aquifers with long, continuous records of groundwater levels where there have been no systematic long-term changes in precipitation or land cover. In addition, the sites ideally should be free from the systematic, long-term influence of groundwater abstraction. In this context, we investigate the empirical evidence for changes in the character of groundwater droughts in the period 1891 to 2015 associated with anthropogenic warming at t~~T~~wo such sites, representative of groundwater systems in temperate climates, ~~have been identified~~ from the Cretaceous Chalk, the major aquifer of the UK. These sites are at Chilgrove House (CH), believed to be the world's longest continuously monitored groundwater level observation borehole, and at Dalton Holme (DH) (Figure 1).

We have adopted an approach similar to that of Diffebaugh et al. (2015) in order to investigate how anthropogenic warming may have effected groundwater droughts at CH and DH. Diffebaugh et al., (2015) demonstrated how anthropogenic warming has increased hydrological drought risk in California over the last approximately 100 years by comparing the changing frequency of drought, as measured by the Palmer Modified Drought Index (PMDI), with standardised annual average precipitation and temperature anomalies. Here, instead of using the PMDI, we use the Standardised Groundwater level Index, SGI (Bloomfield and Marchant, 2013)~~,~~ to characterise the monthly status of groundwater, and compare changes in SGI with changes in standardised monthly air temperature and precipitation. We have chosen not to use the Standardised Precipitation Evapotranspiration Index, SPEI, (Vincente-Serrano SM et al., 2010; Trenberth et al., 2014) in our analysis as we explicitly wish to analyse the correlations between SGI and standardised temperature and between SGI and standardised precipitation independently (Stagge et al., 2017).

We have not attempted to formally attribute any groundwater droughts to climate change. Rather, we follow the approach of Trenberth et al. (2015) and investigate how climate change may modify a particular phenomenon of interest. In our case, given the known centennial-scale anthropogenic warming over the UK described in section 2.2 (Sexton et al., 2004; Karoly and Stott, 2006; Jenkins et al., 2008), using an empirical analysis we address the following question. ~~: h~~How has the occurrence, duration, magnitude and intensity of groundwater drought, as expressed by changes in monthly SGI and in episodes of groundwater drought, changed over the ~~same~~ period 1891 to 2015? Once relationships between naturally varying precipitation anomalies, groundwater droughts and anthropogenic warming are quantified and characterised, subsequent studies may consider attribution of groundwater droughts. Such studies may address questions related to assessing how much of the anomaly in any given groundwater drought can be explained by anthropogenic warming, but attribution-based questions are out of scope of the current empirical study. Note also that investigation of the relationship, if any, between episodes of extreme heat (heatwaves) and groundwater droughts is not in the scope of the present study. Although the analysis is restricted to data from two sites in the UK, the findings have potentially significant implications for changes in groundwater drought driven by anthropogenic warming given the global extent of shallow groundwater systems (Fan et al., 2013) and this is discussed in section 5.

## 2 Site descriptions & drought context

The Chilgrove House (CH) and Dalton Holme (DH) sites meet the requirements of the study in that continuous, long records of groundwater level are available from small rural catchments negligibly impacted by land-use change and abstraction over the period of study (section 2.1). Importantly, both sites are subject to long-term warming associated with anthropogenic climate change (section 2.2). In addition, there are no major long-term changes in mean precipitation at the two sites over the analysis period (demonstrated qualitatively in section 4 and quantitatively through the results of a simple statistical test, section 4.1). The sites, ~~used in this study~~ ~~are~~although unusual due to their length, continuous nature and frequency (monthly or better) of the groundwater level observations,~~.~~ ~~However, they~~ are representative of groundwater systems and hydrological settings that are common throughout large, populous areas of the globe including Europe, Asia, N. and S. America and parts of Australia and southern Africa, in that ~~.e.~~ they represent shallow, unconfined aquifers in temperate regions.

### 2.1 Site descriptions

The ~~Chilgrove House (~~CH~~)~~ and ~~Dalton Holme (~~DH~~)~~ groundwater observation boreholes are located in the Chalk, the principal aquifer in the UK (Downing et al., 1993; Lloyd, 1993). CH is in south-east England and DH in the east of England (Figure 1). The CH and DH hydrographs are the two longest, continuous records in the UK's National Groundwater Level Archive (NGLA) (British Geological Survey, 2017). Hydrographs such as these in the NGLA are taken to be representative of the major UK aquifers, in this case of the Chalk aquifer, and were selected to being in areas least affected by abstraction (Jackson et al., 2015). There are no major groundwater abstractions in the immediate vicinity of the observation boreholes. Both observation boreholes are located in small rural catchments with no major population centres or industrial activities, and there has been no long-term change in land use in the catchments over the study period. The inference of a lack of any systematic impacts from abstraction on groundwater levels at CH and DH is supported by the observed good correlation between precipitation and groundwater levels at the two sites (Bloomfield and Marchant, 2013).

CH is a 62.0 m deep observation borehole in the Seaford Chalk Formation, a white chalk (limestone) of Coniacian to Santonian age. Groundwater levels over the observation record have an absolute range of about 43.7 m, with a maximum groundwater level of about 77.2 meters above sea level (masl) and a minimum level of about 33.5 masl, equivalent to <1 m to about 43 m below ground level at the site (Supplementary Information, Figure S1). The hydrograph generally has an annual sinusoidal response, typical of unconfined Chalk, with an annual groundwater fluctuation of around 25 m, although double and higher multiple recharge peaks and episodes are also relatively frequent due to natural variability in precipitation (recharge can occur in summer as well as winter with appropriate antecedent conditions and precipitation). Variability in winter recharge means that in some winters, such as 1854-5, 1897-8, 1933-4, 1975-6, 1991-2 and 1995-6, minimal recharge occurs. This characteristically results in a nearly continuous decline in groundwater levels throughout the recharge season, and in all cases groundwater droughts occurred during the following summers. There are no clear geological or catchment constraints on either the lowest or highest groundwater levels at CH. However, the River Lavant, approximately 2 km to the south-east of the CH borehole, is a Chalk bourne stream that drains the catchment. The flowing length and discharge of the Lavant reflect the regional groundwater level. Land cover in the Lavant catchment is approximately 35% woodland, 65% arable and grassland with a small number of villages. Comparison of Ordnance Survey land cover mapping from 1898 and 2015 shows that there has been no substantial change in land cover in the vicinity of CH during this period (Ordnance Survey, 1897; 2015).

DH is a 28.5-m-deep observation borehole in the Burnham Chalk Formation, a thinly-bedded white chalk of Turonian to Santonian age. Groundwater levels have a range of 14.8 m, with a maximum groundwater level of about 23.8 masl and a minimum of about 9.6 masl, equivalent to a range from about 10 m to about 25 m below ground level (Supplementary Information, Figure S1). The groundwater level hydrograph has a broadly sinusoidal appearance. Groundwater levels at DH respond more slowly to rainfall than at CH, despite the thinner unsaturated zone. This is probably due to local effects of thin glacial till deposits near DH. Maximum groundwater levels at DH may be controlled by the elevation of springs that feed a small surface drain about 0.75 km to the south. There are no clear geological or catchment constraints on the lowest groundwater levels. DH is located in a flat lying area with no major streams or rivers. Land cover in the immediate vicinity of DH is predominantly arable and grassland with a number of small areas of woodland and villages. Comparison of Ordnance Survey land cover mapping from 1892 and 2015 shows that there has been no substantial change in land cover during this period (Ordnance Survey, 1911; 2015).

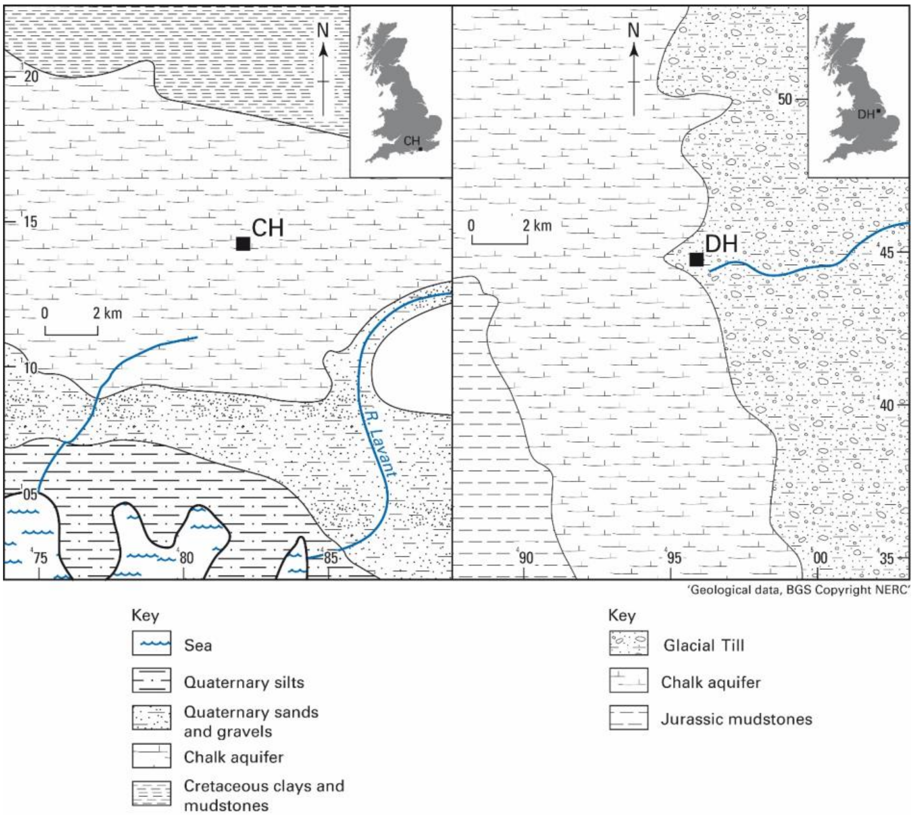

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**Figure 1. Location of the CH and DH observation boreholes, local geological setting, coastline and surface water courses.**

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## 2.2 Climate & drought context

Average monthly air temperature at CH over the observation record from 1891 to 2015 is 9.4°C and at DH it is 9.1°C, with maximum and minimum average monthly temperatures of 19.8°C and 18.8°C and -3°C and -1.6°C at CH and DH respectively (Supplementary Information, Figure S2). In the Köppen–Geiger classification (Peel et al., 2007), the climate at CH and DH can be characterised as temperate and falls in the ocean or maritime climate category, being representative of large parts of north-west Europe. Mean monthly precipitation at CH is 83 mm, slightly higher than at DH where the mean monthly precipitation is 58 mm.

Air temperature across both catchments closely follows the Central England Temperature (CET) monthly series (Parker et al., 1992) (Supplementary Information, Figure S2). Analysis of the CET record shows that near-surface air temperature in England has been rising at a rate of 0.077°C/decade since 1900 (Parker & Horton, 2005) and by about 0.42°C/decade between 1975 and 2005 (Karoly and Stott, 2006). ~~, and~~ ~~t~~The observed recent warming in mean annual CET at least since 1950 has been formally ~~inferred~~ attributed~~to be due~~ to anthropogenic forcing ~~-~~(Sexton et al., 2004; Karoly and Stott, 2006; Jenkins et al., 2008; King et al., 2015). In contrast, annual mean precipitation over England shows no systematic trends since records began in 1766, and there has been no attribution of changes in annual mean precipitation to anthropogenic factors (Jenkins et al., 2008; Watts et al., 2015). In addition, we note that there is no evidence at either of the study sites for a systematic change in long-term monthly precipitation across the observational records (see sections 3.2 and 4.1). Precipitation in the UK is, however, seasonal and highly variable, with a tendency towards dr~~y~~ier summers in the south-east and wetter winters in the north-west (Jenkins et al., 2008; Watts et al., 2015), and ~~.~~

~~T~~the precipitation time series at CH and DH show seasonal and inter-annual variations, including episodes of meteorological drought consistent with the broad drought history of southern and eastern England (Supplementary Information, Figure S3).

~~-~~A number of studies have described major episodes of hydrological drought, including groundwater drought, in the UK since the 19th Century (Marsh et al., 2007; Lloyd-Hughes et al., 2010; Bloomfield & Marchant, 2013; Bloomfield et al., 2015; Folland et al., 2015; Marchant and Bloomfield, 2018) and the societal impacts of those droughts (Taylor et al., 2009; Lange et al., 2017). Marsh et al. (2007) identified seven episodes of major hydrological droughts in England and Wales between 1890 and 2007 using ranked rainfall deficiency time series and analysis of long river flow and groundwater level time series (Marsh et al., 2007, Table 2) as follows: 1890-1910 (known as the ‘Long Drought’); 1921-1922; 1933-34; 1959; 1976; 1990-92; and 1995-1997. Marsh et al. (2007) noted that of these major droughts~~,~~ all but one, the drought of 1959, had sustained and/or severe impacts on groundwater levels. All the major droughts typically had large geographical footprints extending over much of England and Wales as well as over parts of north western Europe (Lloyd-Hughes and Saunders, 2002; Lloyd-Hughes et al., 2010; Fleig et al., 2011; Hannaford et al., 2011). However, regional variations in drought intensities were present within and between the major drought events as function of spatial differences in driving meteorology and catchment and aquifer properties (Marsh et al., 2007; Bloomfield & Marchant, 2013; Bloomfield et al., 2015; Marchant and Bloomfield, 2018).

T~~he t~~hree periods have been used for analysis in this study, namely: 1891-1932, 1933-1973 and 1974-2015 (see section 3.2~~3~~).~~,~~ We note that this means that each analysis period contain ~~notable~~ episodes of previously documented major historic drought. For example, the first analysis period includes the ’Long Drought’ of 1890-1910 (Marsh et al., 2007), the middle period includes the drought of 1933-1934, the most intense groundwater drought on record at CH, and the last period includes the 1975-1976 drought a major groundwater drought at both CH and DH (Bloomfield & Marchant, 2013).

## 3 Data & methods

### 3.1 Data

Groundwater level measurements are available back to 1836 for the observation borehole at CH, while groundwater levels are available for DH back to 1889. We have chosen to analyse the 125-year-long series of observed monthly groundwater levels from 1891 to 2015 common to both sites. The groundwater level data have been taken from the National Groundwater Level Archive, NGLA (National Groundwater Level Archive, 2017). Groundwater level observations are typically at least at monthly intervals. Groundwater levels have been linearly interpolated to the end of the month prior to standardisation, as the SGI requires groundwater level data on a regular time step.

There are no continuous rain gauge or temperature records for either of the sites that cover the entire study period. However, gridded temperature and precipitation data (5 km by 5 km gridded UKCP09 data) are available for the UK for the period 1910 to 2011 (Met. Office, 2017). The work described here is part of a Natural Environment Research Council (NERC) funded Historic Droughts project (see Acknowledgements) that has extend these records back to 1891 using newly recovered, digitised and gridded meteorological records, and extended the gridded data to 2015 using unpublished updates. We have used this extended gridded dataset in the present study. ~~Average monthly air temperature and total monthly precipitation are from the Met. Office UKCP09 gridded (5 km x 5 km) observation dataset (Met. Office, 2017).~~ Although the extent of the groundwater catchments are unknown at both sites they are likely to be restricted to a few square kms given the nature of the local hydrogeology (Figure 1). Consequently, t~~T~~emperature and precipitation data have been extracted for the 5 km by 5 km grid cell in which the CH and DH observation boreholes are located, in a manner analogues to Jackson et al., (2016), rather that averaging the gridded climatological data over a larger area. ~~Published temperature and precipitation data are available for the period 1910 to 2011 (Met. Office, 2017). The work described here is part of a Natural Environment Research Council (NERC) funded Historic Droughts project (see Acknowledgements) that includes work to extend records back to 1891 using newly recovered, digitised and gridded meteorological records, and extended to 2015 using unpublished updates.~~

### 3.2 Methods

As mentioned in the introduction, t~~T~~he empirical analysis described in this paper broadly follows the approach of Diffebaugh et al., (2015), i.e. analys~~e~~is of changes in the frequency and co-occurrence of three standardised indices with time, where one index is a measure of the ~~droughtiness~~ hydrological drought status of the system and the other two indices separately characterise precipitation and air temperature anomalies. Diffebaugh et al., (2015) chose to analyse their 100-year-long records in two halves. However, in this study we have divided the observation record into thirds to give three periods ~~have been used~~ for use in the analysis, namely 1891-1932, 1933-1973 and 1974-2015. This provides some granularity in the description of changes in the standardised indices with time and means that the first period is associated with the least anthropogenic warming while~~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).

An alternative approach to dividing the records for analysis could have been to try and identify one or more significant change points in the temperature record using time series analysis techniques and then to use those periods to characterise any differences in the relationships between hydrological droughts and features of the driving climatology between those periods. Change point analysis (Chen & Gupta, 2000) can lack statistical power because of the temporal correlation amongst the data and the need for a correction to account for the multiple hypotheses that are in effect being considered. So for example, the Bonferroni correction (Bonferroni, 1936) would require that to demonstrate significance at the $p = 0.05$ level that each hypothesise be tested at the $p = 0.05/1499 = 3\times10^{-5}$ level based on the length of the time series in the present study. When a change point analyses was conducted on the monthly standardised groundwater level, precipitation and air temperature time series from each site and the model residuals were assumed to be independent, significant steps were identified in each series. However, when temporal correlation in the time series was accounted for with a first order auto-regressive model, only steps in the air temperature series from both sites and the groundwater level series from DH persisted. The most significant step in the CH air temperature series was in November 1988 ($p = 2\times10^{-7}$). For the DH temperature series the most significant step was also in November 1988 ($p = 2\times10^{-8}$), and for the DH groundwater level series it was in April 1984 ($p = 0.01$). However, after a Bonferroni correction only the steps in the monthly standardised air temperature time series remained significant.

Notwithstanding the results of the change point tests, the change point approach to defining analysis periods has not been adopted in the present study for a couple of reasons. Since the aim of the study is to characterise changes in relationships between groundwater droughts and climatology in the context of previously documented long-term warming we want to make no prior assumptions regarding specific periods with potentially different temperature regimes. In addition, as we know from previous studies that anthropogenic warming will have effected both series since at least the 1950s (Sexton et al., 2004; Karoly and Stott, 2006; Jenkins et al., 2008; King et al., 2015) the meaning of any change points identified post 1950 in the context of anthropogenic warming would be unclear and is an approach towards attribution that we are explicitly trying to avoid in the current study. However, we note that the change point analysis described above is consistent with the findings presented in the Results (section 4), in that the latter part of the observational record at both sites is significantly warmer than the earlier part of the record. ~~In addition, the use of three periods for analysis provides more granularity in the description of changes in the standardised indices with time.~~

A wide range of methods have been used to characterise and investigate hydrological droughts including groundwater droughts. They broadly fall into two classes: standardised indices and threshold level approaches (see Van Loon, 2015 for a detailed recent overview). Threshold level approaches use a pre-defined threshold, which may vary seasonally. When flows or, in the case of groundwater, when levels fall below a given threshold a site is considered to be in drought. Drought characteristics, such as duration, magnitude and frequency can then be estimated. This approach has the benefit of being able to characterise aspects of droughts in absolute terms and hence is particularly useful for water resource management planning or to understand processes at a particular observation borehole. However, it does not lend itself so easily to studies where there is a need to compare multiple sites and multiple indicators of change. For example, in the present study it would be necessary to define and justify six seasonally varying thresholds (two for each site identifying precipitation and groundwater drought thresholds and one for each site identifying hot period thresholds). In contrast, droughts characterised using standardisation approaches enable the comparison of hydrological anomalies between different sites and/or between different components of the terrestrial water cycle using common standardised anomalies from a normal situation (Van Loon, 2015). Given the need in this study to compare relative changes in groundwater droughts at two sites across long observational records and to explore the relationships between groundwater droughts and precipitation deficits and air temperature, we have chosen to use standardised drought indices. This approach has the additional benefit of only needing to estimate a single common, consistent, internationally recognised (WMO, 2012) descriptor of drought based on a standardised drought index.

The Standardised Groundwater level Index, SGI (Bloomfield and Marchant, 2013), has been estimated across the full observational records from 1891 to 2015. It has been ~~is~~ used to characterise monthly status of groundwater, and to compare changes in SGI with changes in standardised monthly air temperature and precipitation over the same period. The SGI builds on the Standardised Precipitation Index (SPI) of McKee et al. (1993) to account for differences in the form and characteristics of groundwater level time series. The SPI was proposed by McKee et al. (1993) as an objective precipitation-based measure of the severity and duration of meteorological droughts. It assumes that drought status is described by a normally distributed index. However, Bloomfield and Marchant (2013) demonstrated that parametric transformations of groundwater levels typically produced poor approximations to normal distributions, and concluded that it is doubtful if the resulting standardised series could be objectively compared. Instead Bloomfield and Marchant (2013) recommended a non–parametric approach to the standardisation of groundwater level hydrographs similar to other non-parametric approaches, for example Osti et al. (2008) who used a plotting position method to estimate a standardised precipitation, and Vidal et al. (2010) who used a non-parametric kernel density fitting routine to estimate a normalised soil moisture index.

SGI has been estimated using the monthly groundwater level time series. The SGI relies on a non–parametric approach to the standardisation of groundwater level hydrographs (Bloomfield and Marchant, 2013). It is estimated using a normal-scores transform (Everitt, 2002) of groundwater level data for each calendar month. This nonparametric normalisation assigns a value to observations, based on their rank within a data set, in this case groundwater levels for a given month from a given hydrograph. The normal scores transform is undertaken by applying the inverse normal cumulative distribution function to $n$ equally spaced $p_i$ values ranging from $1/(2n)$ to $1-1/(2n)$. The values that result are the SGI values for the given month. These are then re-ordered such that the largest SGI value is assigned to the $i$ for which $p_i$ is largest, the second largest SGI value is assigned to the $i$ for which $p_i$ is second largest, and so on. The SGI distribution which results from this transform will always pass the Kolmogorv–Smirnov test for normality. The normalisation is undertaken for each of the 12 calendar months separately and the resulting normalised monthly indices then merged to form a continuous SGI time series. Note that the resulting standardised drought index is not linear and that drought conditions (SGI <-1) will be expected about 16% of the time while extreme drought conditions (SGI <-2) would be expected only about 2% of the time (McKee et al., 1993).

A Standardised Temperature Index (STI) and a Standardised Precipitation Index (SPI) have been calculated by applying the SGI method to the average monthly temperature (STI) and a monthly accumulated rainfall (SPI) time series across the full observational records from 1891 to 2015. Due to the lagged response of groundwater levels to driving meteorology (Bloomfield and Marchant, 2013; Van Loon, 2015), correlations between SGI and

STI$_q$ and between SGI and SPI$_q$ will vary with $q$, where $q$ is the averaging period (for preceding months temperature) or accumulation period (for preceding months precipitation). In order to assess changes in groundwater droughts in the context of the driving climatology in a consistent manner, ~~Here~~ we estimate Pearson cross-correlation coefficients between SGI and STI and between SGI and SPI for periods $q$ = 1 to 12, and then search for the period $q$ with the highest absolute summed cross-correlation (Supplementary Information, Figure S4), i.e. the period that is associated with the highest correlation between groundwater levels and the antecedent driving meteorology (both precipitation and temperature).

The maximum absolute summed cross-correlation for accumulation and averaging periods was found to be six months at both sites, where individual cross-correlations between SGI and SPI$_6$ are 0.76 and 0.75. Note no systematic variation is observed in the correlations between SGI and SPI and between SGI and STI (Figure S4) across the observation record: correlations between SGI and SPI are similar in the first and last third of the observational record. As would be expected, the cross-correlation between SGI and STI is weaker than that of SGI and SPI with correlations between SGI and STI$_6$ of -0.15 and -0.35 for CH and DH respectively (Figure S4). The six month maximum absolute summed cross-correlation period is consistent with previous analyses of SPI accumulation at the two sites. It is the same as the SPI accumulation period identified by Bloomfield and Marchant (2013) for CH and slightly less than that for DH (Bloomfield and Marchant, 2013, Table 2) (note that cross-correlation co-efficients at DH are particularly insensitive to $q$ beyond six months, Figure S4). This is despite the accumulation periods in Bloomfield and Marchant (2013) being based on standardised precipitation alone and being estimated for a shorter observation record than the present study.

Given the above, we have used a six month accumulation for precipitation and a six month average for temperature in the analysis. For simplicity, throughout the following description of the results and discussions, all subsequent references to SPI and STI relate to SPI$_6$ and STI$_6$ unless otherwise stated. Although the correlations between SGI, SPI and STI are based on simple phenomenological correlations between the time series they reflect recharge and discharge processes at the sites and are consistent with accepted conceptualisations of drought generation in the Chalk. For example, at both sites the standardised groundwater level at the end of the winter recharge season, i.e. SGI in March, is correlated with accumulated precipitation for the six months prior to March, i.e. the winter half year from October to March. Previously, Folland et al., (2015) have documented a variety of climate and other drivers of multi-annual hydrological droughts across the English Lowlands, the region within which CH and DH are located, based on precipitation deficits established during winter half-years.

~~The optimal averaging/accumulation period was found to be 6 and 7 months for CH and DH respectively. Consequently, SPI$_6$ and SPI$_7$ have been used in the analysis of data from CH and DH respectively and in the following reporting of results and discussions all references to SPI are for those accumulation periods.~~

There is a plethora of definitions of meteorological drought (Lloyd-Hughes, 2014; Van Loon, 2015). Here we follow the WMO convention for SPI (McKee et al., 1993; World Meteorological Organisation, 2012) where precipitation ~~or meteorological~~ drought is defined as any period of continuously negative SPI that reaches an intensity of -1 or less. By analogy, we define any month with a negative SPI or SGI of -1 or less as a precipitation or groundwater drought month and any month with a positive STI that reaches an intensity of 1 or more as a hot month. ~~a p~~Periods of continuously negative SGI or SPI that reaches a monthly intensity of -1 or less is defined as an episode of groundwater (SGI$_e$) or precipitation (SPI$_e$) drought, and a period of continuously positive STI that reaches a monthly intensity of 1 or more, denoted by STI$_e$, is defined as a hot period.

In addition, we are interested in the degree of co-incidence between episodes of groundwater drought~~s~~, precipitation drought~~s~~, and hot periods. Groundwater droughts have been assessed to be co-incident with precipitation droughts or with hot periods if both the following conditions are met: i.) any part of a groundwater or precipitation drought episode or hot period overlaps, and ii.) within the periods, incidents of monthly SGI ≤ -1 either overlap with or postdate incidents of either monthly SPI is ≤ -1, or monthly STI is ≥ 1.

## ~~3~~4 Results

### 4~~3~~.1 Changes in standardised monthly temperature, groundwater level and precipitation since 1891

SGI time series show that there has been a large increase in the frequency of months of groundwater drought since 1891 at both sites (Figures 2 and 3 and Supplementary Information Table~~s~~ S1~~ and S2~~). The frequency of months of groundwater drought has more than doubled between the first third (1891-1932) and the last third (1974-2015) of the record, i.e. from about 10% of months at both sites in the first third of the record to 21~~.1~~% and 25~~.9~~% at CH and DH respectively in the last third of the record. The increase in frequency of groundwater drought months is associated with a very large increase in the frequency of hot months, from 5~~4.8~~% to 34~~.4~~% of the months at CH and from 2~~1.8~~% to 34~~5.8~~% of the months at DH. In contrast, there has been no systematic change in the frequency of precipitation drought months. The probability of these changes in standardised indices between the first and last thirds of the observational record being significant has been estimated. Given that the standardised monthly indices are normally distributed, a null model can be estimated where each standardised index is assumed to be a realisation of temporally auto-correlated Gaussian random function (with auto-correlation function estimated from the observed data). A~~The~~ 'probability of~~ the~~ difference' for a standardised index between analysis periods can be estimated as follows. If we define D as equal to the number of droughts in the last analysis period minus the number of droughts in the first analysis period (for example) then the probability of difference is the probability, under the null model, that D is greater than the observed value. Estimated in this way, the probability of the difference in the number of hot months in the period 1891-1932 and 1974-2015 being as extreme as the observed is 0.03~~< 0.001~~ for ~~both ~~CH and 0.005 for DH. For groundwater drought months the probabilities are 0.056 for CH and 0.055 for DH, but for precipitation drought months they are 0.70~~6~~ for CH and 0.36~~45~~ for DH. From this it is inferred that the increased incidence of hot months and of groundwater drought months between the start and end of the record is very unlikely to occur by chance at both sites, but that there is no significant difference in the probability of precipitation drought.

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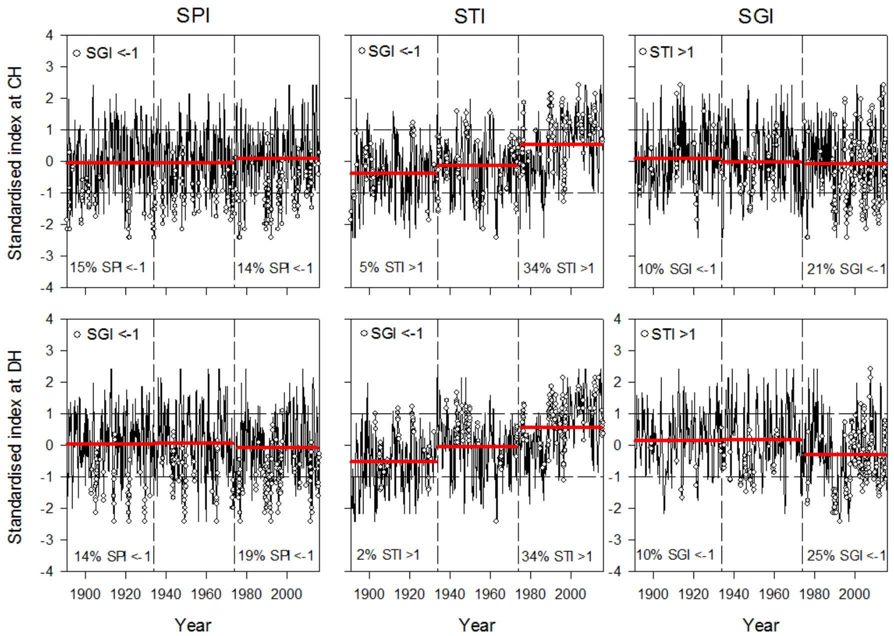


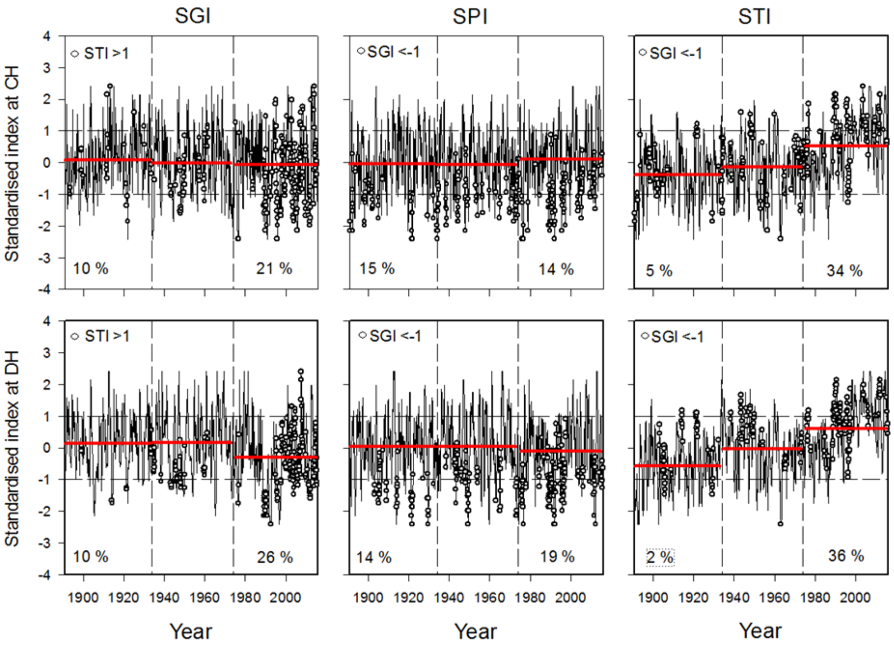
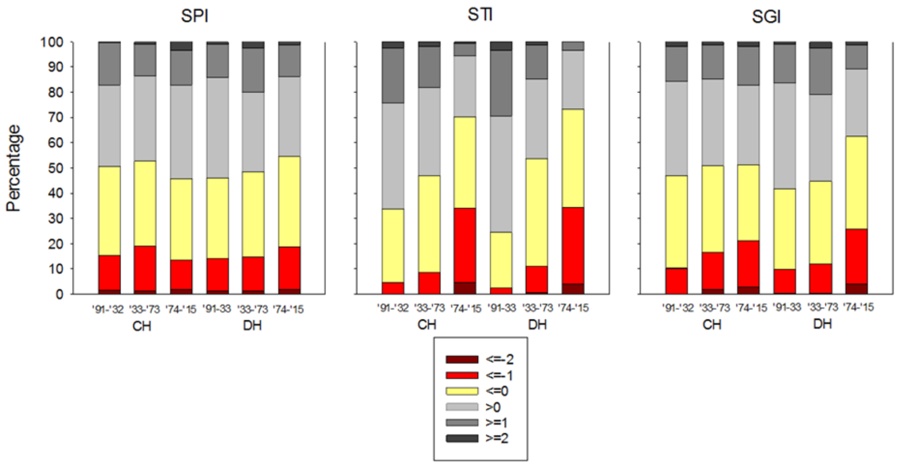


**Figure 2. Changes in standardised indices of ~~groundwater level,~~ precipitation~~, and~~ temperature and groundwater level since 1891. Time series of SP~~G~~I, S~~P~~TI, and S~~T~~GI for CH (upper panels) and DH (lower panels) for the period 1891-2015, with mean values for first, middle and last thirds of the record~~42 year running mean~~ highlighted in red~~blue~~. Open circles in plots of SGI denote months where STI is ≥ 1, and in plots of SPI and STI denote months**

**where SGI is ≤ -1. Percentages ~~(rounded to the nearest integer)~~ are ~~shown of~~for months in the first and last third of the records where SGI and SPI are ≤ -1 and STI is ≥ 1.**



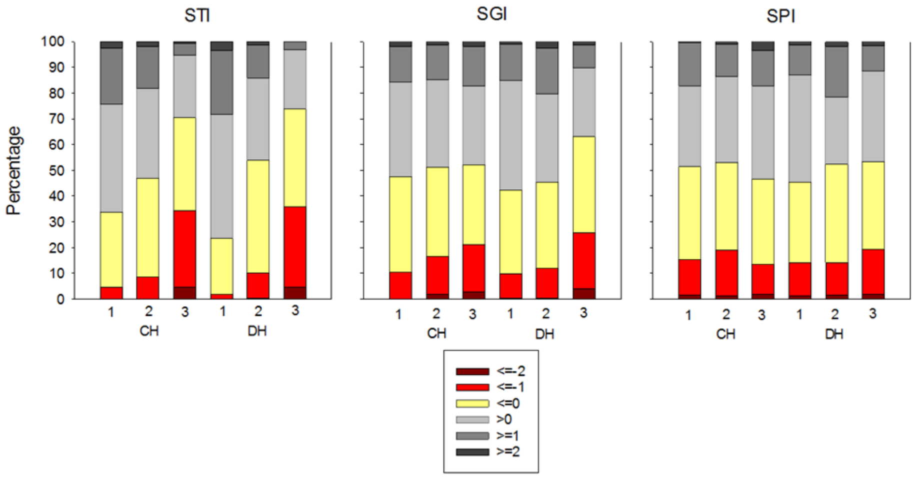


**Figure 3. Percentage of monthly SP~~T~~I, S~~G~~TI and S~~P~~GI as a function of six ranges of standardised values from ≤ -2 to ≥ 2 for each third of the records from CH and DH.**

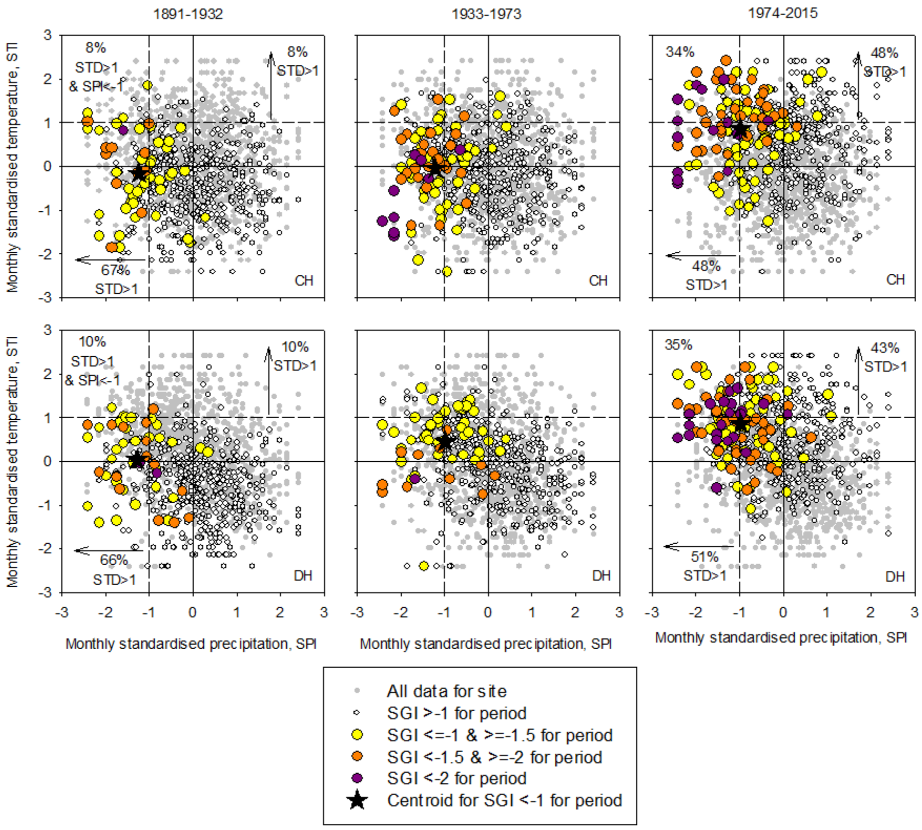
## 4~~3~~.2 Changes in association between monthly groundwater drought, temperature and precipitation

Figure 4 shows the occurrence of groundwater drought months as a function of SPI and STI at CH and DH for the periods 1890-1932, 1933-1973 and 1974-2015. It shows how groundwater drought months reflect both natural variability in the driving drought climatology, specifically in precipitation deficits, but also underlying changes associated with anthropogenic warming.

Dry months (SPI <=0) appear to be a broad prerequisite for groundwater drought months throughout the record at both sites (Figure 4). Natural variation in precipitation deficit is clearly the primary control on groundwater drought months across the whole period at both sites and major groundwater droughts driven by significant precipitation deficits are evident in the data. For example, six of the eight most extreme groundwater drought months in the middle period at CH (where SGI <-2) are all associated with a single episode of major precipitation deficit and drought that lasted from Autumn 1933 to Autumn 1934 (see Supplementary Information Figure S5). The drought of 1933-34 was related to consecutive dry summer and winter half years resulting in effectively no groundwater recharge over a 12 month period (Marsh et al. 2007; Alexander & Jones, 2000). Because that drought occurred at the start of the middle third of the observational record it is associated with a relatively cool period with respect to the full standardised series.

However, number of trends can be seen in addition to the natural variability in precipitation deficits. As a consequence of the increase in frequency of groundwater drought months and of hot months across the observational record, there has been a considerable increase in the number of groundwater drought months that coincide with hot months, particularly in the last third of the record (Supplementary Information Table S2). The percentage of groundwater drought months that coincided with hot months increased from about 8% and 10~~2~~% in the period 1891-1932, to about 48% and 43~~52~~% in the period 1974-2015 for CH and DH respectively~~ (Figure 4)~~. At the same time, there has been a slight reduction in the coincidence of months of groundwater and precipitation drought for these two periods, from ~~about ~~67% to 48~~50~~% and from ~~about ~~66~~71~~% to 51~~67~~% for CH and DH~~ (Figure 4)~~. For the last third of the record, since 1974, this means that groundwater drought months are now almost as likely to coincide with hot months as they are to coincide with months of precipitation drought. So the increase in the percentage of groundwater drought months that coincide with both hot months and precipitation drought months between the first and last periods of the observational record, from about 8% to 34~~23~~% and from about 10% to 35~~30~~% for CH and DH, is almost entirely due to the effect of warming.

~~Although dry months (SPI ≤ 0) appear to be a broad prerequisite for groundwater drought months throughout the record at both sites (Figure 4), an increasing number of wet months are associated with groundwater drought months. For example, in the last third of the record, a total of 10 and 11 groundwater drought months at CH and DH, respectively, were associated with wet months, compared with just one month at both sites during the first third of the record up until 1932. ~~To illustrate and emphasise the combined effects of these changes in the relationship between SPI, STI and SGI across the three periods, Figure 4 shows the centroid for all groundwater drought months (SGI<-1) for each third of the record. At CH and DH there is a strong overall warming trend with mean STI for all groundwater drought months increasing from -0.16 to -0.04 to 0.85 at CH and from 0.03 to 0.44 to 0.98 at DH between 1891-1932, 1933-1973 and 1974-2015. This is consistent with the warming trend across the whole record (Figure 2 and 3).


1891-1932
1933-1973
1974-2015
Monthly standardised temperature, STI
Monthly standardised precipitation, SPI
8%
STD>1
& SPI<-1
8%
STD>1
67%
STD>1
CH
34%
48%
STD>1
48%
STD>1
10%
STD>1
& SPI<-1
10%
STD>1
66%
STD>1
DH
35%
43%
STD>1
51%
STD>1
3
2
1
0
-1
-2
-3
All data for site
SGI >-1 for period
SGI <=-1 & >=-1.5 for period
SGI <-1.5 & >=-2 for period
SGI <-2 for period
Centroid for SGI <-1 for period

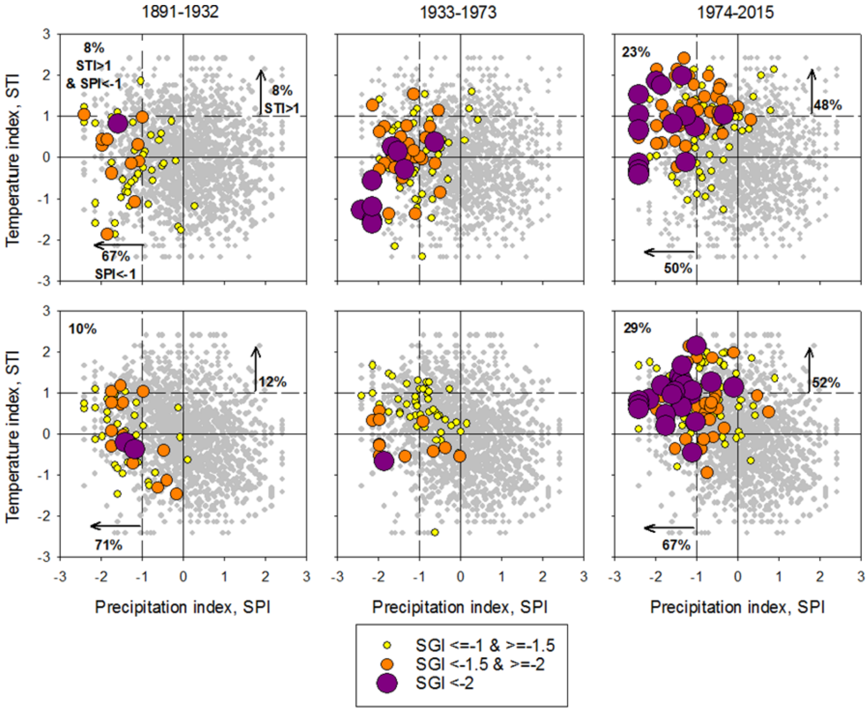


**Figure 4.** ~~**Changes in the incidence and magnitude of groundwater drought months since 1891 as a function of temperature and precipitation indices.**~~ **Occurrence of groundwater drought months as a function of SPI and STI at CH (upper panels) and at DH (lower panels), for the periods 1890-1932, 1933-1973 and 1974-2015. ~~(f~~For reference, all monthly values from 1891-2015 are shown as grey symbols and all months were SGI >-1 for a given period are shown as open white circles~~)~~.** ~~**Months with SGI between -1 and -1.5, yellow symbols; between -1.5 and -2, orange symbols; and < 2, purple symbols.**~~ **Black stars denote the centroid of the groundwater drought months for each of the three periods.** ~~**Percentages (rounded to the nearest integer) in the top left show the proportion of months in each period where STI is ≥ 1 and SPI is ≤ -1, in the top right where STI is ≥ 1 and in the bottom left where SPI is ≤ -1.**~~

### 4~~3~~.3 Changes in episodes of groundwater drought

There have been 45 episodes of groundwater drought at CH and 33 at DH between 1891 and 2015. Of these, 16 episodes at CH and 9~~8~~ episodes at DH had an average SGI intensity of ≤ -1 (Supplementary Information, Table S3). Across the observational record, groundwater droughts are more frequent but typically shorter and less intense at CH compared with DH (Figures 5 and 6). This is consistent with previous observations that the CH hydrograph has a shorter autocorrelation than that of DH, inferred to be due to differences in aquifer and catchment characteristics between the sites (Bloomfield and Marchant, 2013).

Episodes of groundwater drought are present throughout the observation record and are primarily driven by episodes of precipitation deficit. Episodes of groundwater drought ($SGI_e$) are almost entirely associated with dry episodes where mean SPI is <=0 (Figure 5). However, despite the limited number of episodes at each site, Figures 5 and 6 also show evidence of changes in the nature of episodes of groundwater drought associated with anthropogenic warming. The total number of episodes of groundwater drought at the sites is limited, and in large part reflects the natural variability of precipitation deficits. However, at both sites there is an increase in the frequency of episodes of groundwater drought between the first and last periods of analysis, i.e. from 12 to 19 and from 9 to 16 at CH and DH respectively for the periods 1891-1932 and 1974-2015 (Figure 6a and Tabls S3). Although note that at DH there were only 8 droughts in the middle analysis period 1933-1973, one less than in the first period. A year-long episode of groundwater drought started in December 1973 and ended in November 1974 at DH. This has been included in the statistics for the last analysis period. It illustrates the naturally 'noisy' nature of the relatively sparse data, reflects in part the temporal variability in the precipitation deficits that drive the occurrence of groundwater droughts at the site, and illustrates why we have chosen to analyse relatively coarse periods and use averages to characterise changes in drought characteristics across the record.

There is no consistent change in the mean duration of groundwater droughts at either CH or DH, with mean durations of about 11, 12 and 10 months across the three periods from 1891 to 2015 at CH, and mean durations at DH of 14, to 17, to 17 months for the same three periods. Although there is no clear tendency of change in mean SGI$_e$ duration, it appears that there may be a tendency for an increase both in the maximum drought duration and in the number of sub-annual episodes of groundwater drought, particularly at CH (Figure 6c). There is a tendency for the mean event magnitude and mean event intensity of groundwater droughts at both sites to increase with time, with mean event magnitude increasing more at DH that at CH, from about -12 to about -18, and mean event intensity to increasing more at CH than at DH, from -0.8 to -1.0 between the periods 1891-1932 and 1974-2015 (Figure 6b). The systematic increases in drought frequency, magnitude and intensity are associated with a large increase in mean STI across the three analysis periods, and are reflected in the change in relative position of the SPI-STI centroids of the data for SGI$_e$, shown as black stars, in the plots for each of the three periods in Figure 5.

~~There is evidence for systematic changes in the occurrence and nature of episodes of groundwater drought at both sites (Figures 5 and 6 and Supplementary Information, Table S3). There has been an increase in the frequency of groundwater droughts, particularly droughts with a mean SGI of ≤ -1, duration of droughts, and an increase in the intensity of groundwater droughts. Overall, between the first and last third of the record, the number of groundwater droughts has increased from 12 to 19 and from 9 to 16 at CH and DH respectively. Over the same periods, the number of groundwater droughts with a mean of SGI of ≤ -1 has increased from 2 to 9 and from 2 to 4 events at CH and DH. Figure 6, cumulative frequency-duration plots for groundwater droughts at CH and DH for the periods 1891-32 and for 1974-2015, shows that there has been a systematic increase in the duration of the episodes of groundwater drought. At the same time as there has been an increase in frequency and duration of groundwater droughts, there has also been a systematic increase in the average intensity of those droughts (as measured by the mean event SGI) between the first and last third of the records, from -0.71 to -1.0 and from -1.2 to -1.51 at CH and DH respectively (Figure 5). All these changes in groundwater droughts are associated with a very large increase in temperature anomalies during the groundwater drought events, with average STI during episodes of groundwater drought increasing from -0.26 to 0.67 and from -0.27 to 0.60 at CH and DH. However, the increases in groundwater drought frequency, duration and intensity between the first and last third of the records are not associated with any increases in precipitation deficits (i.e. lowered SPI during episodes of groundwater drought). Instead, they are actually associated with a small rise in event average SPI during episodes of groundwater drought, from -0.72 to -0.64 and from -0.9 to -0.55 at CH and DH respectively.~~

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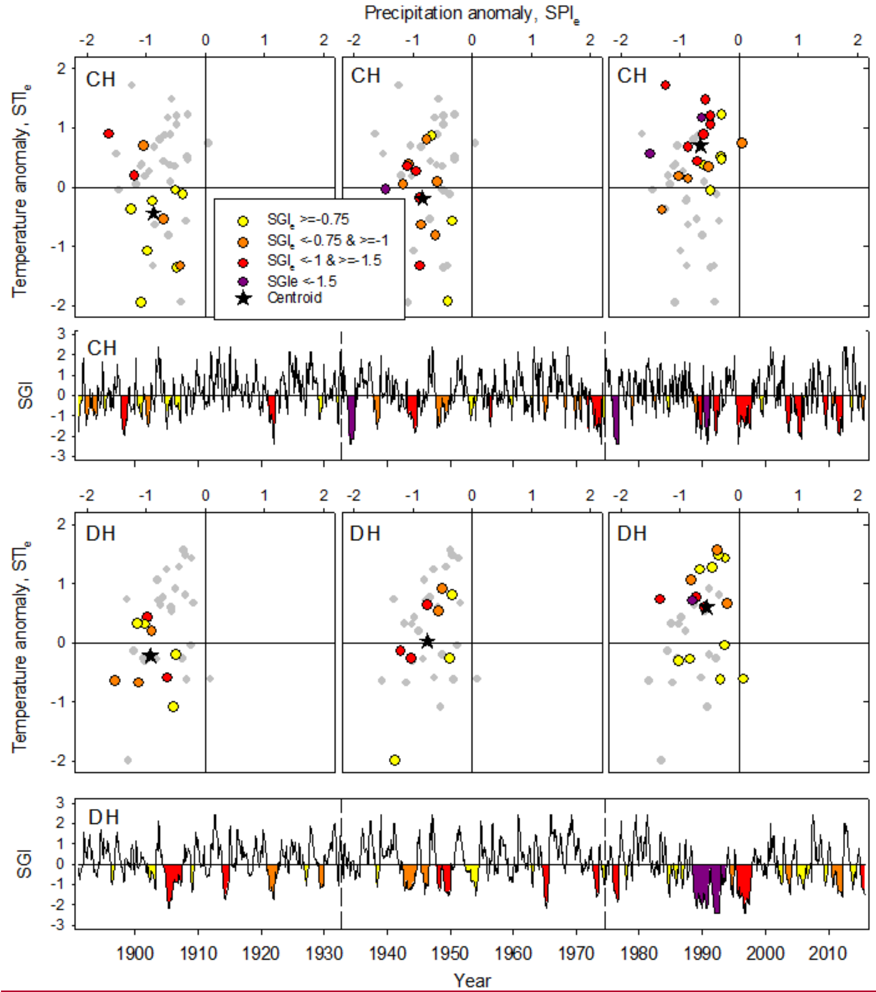

Precipitation anomaly, SPI$_e$
Temperature anomaly, STI$_e$
CH
DH
SGI$_e$ >=-0.75
SGI$_e$ <-0.75 & >=-1
SGI$_e$ <-1 & >=-1.5
SGIe <-1.5
Centroid
SGI
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
Year

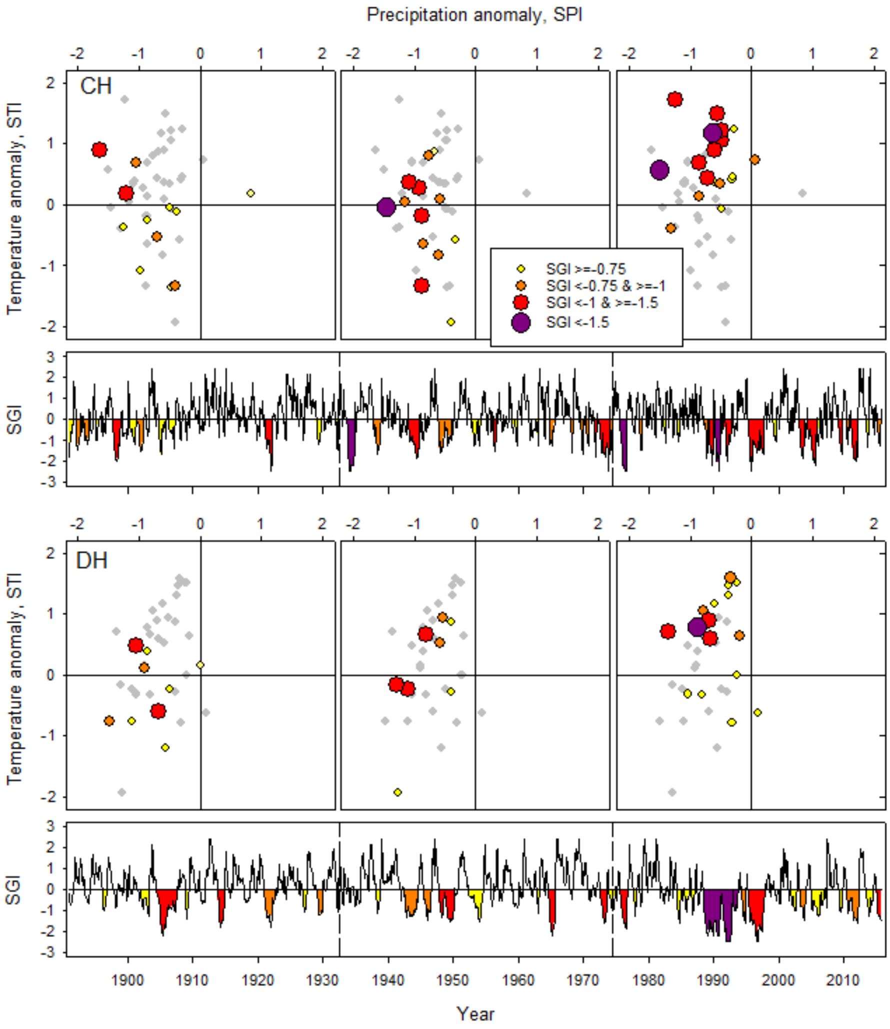
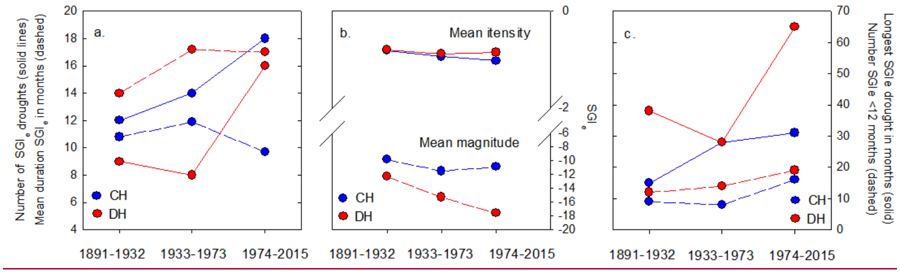


**Figure 5. Changes in the incidence and magnitude of episodes of groundwater drought since 1891 as a function of temperature and precipitation. Mean groundwater drought event intensity (mean $\text{SGI}_{e}$) as a function of mean event SPI and STI for the periods 1891-1932, 1933-1943, and 1944-2015. Grey symbols indicate all episodes of groundwater drought at a site. Yellow through to purple symbols indicate increasing mean SGI for the episodes of groundwater drought. The black star denotes the centroid of the episodes of SGI in each third of the observational record. The SGI time series are shown below the cross plots for reference with SGI drought events of a given magnitude highlighted ~~in the four colours~~. Data for CH is shown in the upper panels and DH in the lower panels.**



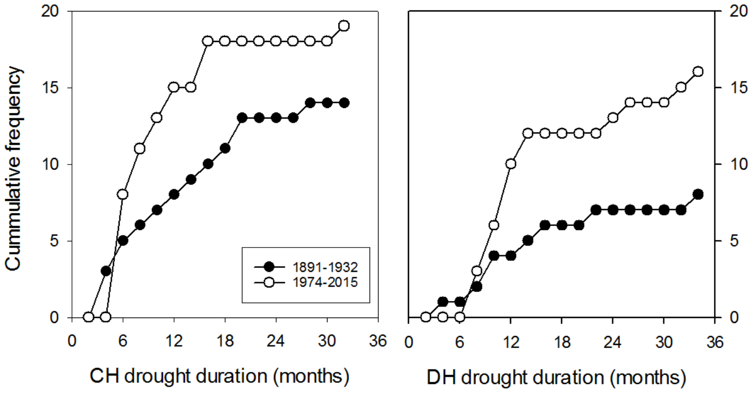


**Figure 6.** a. Change in total number of groundwater drought episodes and mean duration of $SGI_e$ at CH (blue) and DH (red) for the periods 1891-1932, 1933-1973 and 1974-2015. b. Change in mean intensity and mean magnitude of groundwater drought episodes over the three analysis periods at CH and DH. c. Change in maximum duration of $SGI_e$ and number of episodes of groundwater drought less than 12 months in duration.~~Cumulative frequency plots of drought duration for CH and DH for the first (closed symbols) and last (open symbols) third of the observational records.~~

In addition to changes in ~~average~~ mean STI ~~and SPI during~~ associated with episodes of groundwater drought, there have been changes in the coincidence of episodes of ~~groundwater drought,~~ hot periods ($STI_e$) ~~and precipitation droughts~~ with episodes of groundwater drought ($SGI_e$) (Figure 7). ~~Typically, e~~Episodes of groundwater drought generally coincide with precipitation droughts. Typically in a given period precipitation droughts are co-incident with between 75% and 89% of groundwater droughts with no systematic change in the frequency of co-incidence across the observational record at either site. ~~However, there has been a small decline in the coincidence of groundwater and precipitation droughts across the observational record (Figure 7). For the period 1891-1932, about 83% and 78% of groundwater droughts coincided with precipitation droughts at CH and DH respectively. This fell to about 79% and 75% for the period 1974-2015.~~ This is consistent with the observation that groundwater droughts at the sites are primarily driven by episodes of precipitation deficit. However, there has been a large, systematic increase in the coincidence of groundwater droughts with hot periods, from ~~about~~ 17~~25~~% to 29% to 79% at CH and from ~~and~~ 33~~22~~% to 50% to 63% ~~of groundwater droughts at CH and~~at DH during the 1891-1932, 1933-1973 and 1974-2015 periods respectively~~the first third of the record, to about 74% and 63% for the last third of the record~~ (Figure 7).

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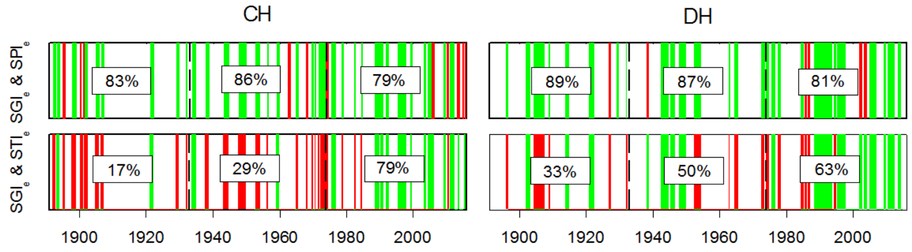
~~Of particular note, although unusual, there have been six episodes of groundwater drought not coincident with precipitation droughts and only coincident with hot periods (three episodes at both sites), and all but one of these (an eight month episode of groundwater drought ending in October 1938 at DH) have occurred since 2002.~~



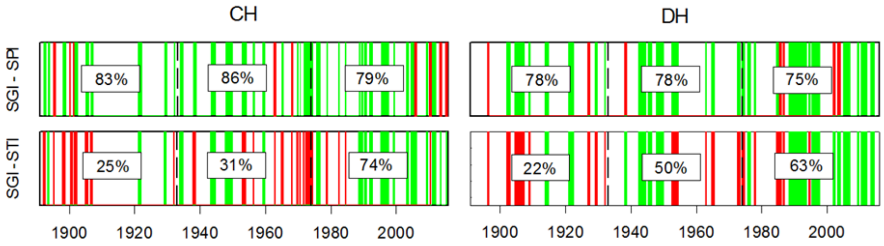


**Figure 7.** **~~Coincidence of episodes of groundwater drought with precipitation droughts and with hot periods.~~ Graphical representation of coincidence of groundwater droughts with precipitation droughts (SGI~~–~~-SPI) and with hot ~~events~~ periods (SGI~~–~~-STI) for CH (left panels) and DH (right panels), where green denotes coincident and red non-coincident ~~events~~episodes. Percentages ~~(rounded to the nearest integer)~~ indicate the fraction of coincident episodes for the first (1891-1932), middle (1933-1943) and last (1944-2015) thirds of the record (where periods are separated by vertical dashed lines).**

# ~~4~~5 Discussion and conclusions

## 5~~4~~.1 Controls on changes in groundwater drought on the Chalk aquifer

Precipitation deficit is the primary driver of groundwater drought (Tallaksen & Van Lanen, 2004; Van Loon, 2015). This is confirmed for CH and DH where dry months (SPI ≤ 0) are a broad prerequisite for groundwater drought months throughout the record at both sites (Figure 4) and where almost all episodes of groundwater drought (SGI ≤ -1) are associated with negative precipitation anomalies (SPI ≤ 0) ~~anomalies~~ (Figures 5 and 7). However, we have also shown that there is no significant difference in the probability of precipitation drought between the beginning and end of the records at CH and DH (section 4~~3~~.1) and that increases in groundwater drought frequency, ~~duration~~ magnitude and intensity ~~between the first and last third of the records~~ are not associated with any long-term increases in precipitation deficits~~, i.e. lowered SPI during episodes of groundwater drought (section 3.3)~~. Given these observations, and in the absence of major long-term changes in land cover and the absence of systematic effects of abstraction in the catchments (section 2.1), what are the controls on the observed changes in groundwater drought since 1891 at CH and DH?

Marsh et al (2007) and Marsh (2007) have previously noted that major hydrological droughts in the UK may persist for at least a year, and often substantially longer – a common feature of major groundwater droughts globally (Tallaksen & Van Lanen, 2004; Van Loon, 2015). This is confirmed ~~for CH and DH (Figure 6)~~in the present study with the mean duration of groundwater droughts at CH being about 11 months and at DH being about 16 months (Table S3) ~~majority of the groundwater droughts at both sites having durations typically well over 12 months~~. Marsh et al (2007) and Folland et al (2015) also noted that major hydrological droughts in the UK are almost always associated with more than one consecutive dry winter. However, there is no evidence for systematic changes~~an increase~~ in the frequency of consecutive dry winters either at CH or at DH across the observational record. If a dry winter is defined as below average mean monthly SPI for the winter half year (~~September~~ October to March~~February~~), there ~~has been~~ no consistent~~systematic~~ changes in ~~the frequency of episodes of~~ consecutive dry winter years ~~at~~ across the two sites~~either site~~. At CH there have been 16~~5~~, 12~~6~~ and 11~~6~~ ~~episodes of c~~consecutive dry winters years over the periods 1891-1932,~~;~~ 1933-1973,~~;~~ and 1974-2015 respectively and at DH 14, 16 and 18 consecutive dry winter years over the same periods. ~~. Similarly, at DH there have been 5, 6 and 6 episodes of consecutive dry winters over the same periods.~~ In addition, there appears to be no ~~strong,~~ systematic drying trend associated with the consecutive dry winters when they do occur. For example, the mean SPI for episodes of consecutive dry winters at CH is -0.~~5~~72,~~;~~ -0.89~~63;~~, and -0.78~~63~~ for the periods 1891-1932,~~;~~ 1933-1973,~~;~~ and 1974-2015, while the corresponding mean SPI for consecutive dry winters at DH it is -0.52,~~49;~~ -0.70~~42;~~, and -0.6~~9~~2. Since there is no clear driver for change in the nature of groundwater drought at CH and DH related to precipitation deficits, and given ~~the~~ that there is a significant increase in air temperature associated with anthropogenic warming across the observational record ~~at the two sites~~, we postulate that increased evapotranspiration (ET) associated with anthropogenic warming is a major contributing factor to the observed increasing occurrence of individual months of groundwater drought as well ~~increasing~~changes in the frequency, ~~duration~~ magnitude and intensity of episodes of groundwater drought.

In shallow, unconfined groundwater systems ET contributes to the formation and propagation of groundwater droughts (Tallaksen & Van Lanen, 2004; Van Lanen et al., 2013; Van Loon, 2015) in a complex, non-linear manner. As part of a study investigating the connections between groundwater flow and transpiration partitioning based on modelling of data from shallow North American aquifers, Maxwell and Condon (2016) have shown that ET is water limited below about 5m ~~how the partitioning of ET between bare soil evaporation (E) and plant transpiration (T) is controlled by depth to the water table.~~ (Maxwell and Condon, 2016, Figure 3). ~~Based on analysis of data from shallow North American aquifers. They identified a transition from a groundwater table depth where T is groundwater dependent and E is water limited to groundwater table depth where both E and T are water limited (i.e. where groundwater is effectively disconnected from the land surface resulting in relatively low T and E that are limited by precipitation) at groundwater depths of the order of 5 m below ground level. Given~~If this relationship holds for CH and DH~~e modelled results of Maxwell and Condon (2016)~~, ET should be expected to have a limited effect on groundwater drought formation and propagation at the two sites~~CH and DH~~ because the depth to groundwater at CH and DH associated with episodes of groundwater drought is typically in the range 35 to 45 m and 10 to 15 m below ground level respectively. Unlike many other aquifers, the Chalk has a thick capillary fringe and due to the micro-porous nature of the matrix remains saturated to at least 30 m above the water table (Price et al., 1993). This potentially enables ET to support the propagation of groundwater droughts even when the water table falls below 5m. Ireson et al. (2009) have shown how groundwater flow through the unsaturated zone of the Chalk is highly sensitive to fracture distributions and characteristics and so may be expected to vary significantly between sites on the Chalk as fracture characteristics vary spatially (Bloomfield, 1996). However, even though there is no data on the thickness of the capillary fringe at CH or DH, it can be estimated with some confidence due to the remarkable uniformity of the matrix of the Chalk across the UK (Price et al., 1993, Figure 3.3a; Allen et al., 1997, Figure 4.1.5). Saturation of the matrix of the Chalk is controlled primarily by the pore-throat size distribution of the matrix, which is characteristically less than 1 micron across the Chalk. Such pore throat sizes can support capillary pressure heads of 30m or more, and consequently it has been proposed that this corresponds to the typical depth of capillary fringe in the matrix of the Chalk aquifer (Price et al., 1993; Allen et al., 1997). From the above, we infer that ET may be expected to contribute to the formation and propagation of groundwater droughts at sites on the Chalk, such as at CH and DH, with water tables at least down to 30 m below ground level. Consequently, on aquifers such as the Chalk, groundwater drought formation and development may be particularly sensitive to the effects of changes in ET, and hence to anthropogenic warming.

~~The Chalk, however, is a dual porosity-dual permeability aquifer with a thick capillary fringe. Due to the micro-porous nature of the matrix it remains saturated to at least 30 m above the water table (Price et al., 1993; Ireson, 2009). Consequently, in the Chalk ET may be expected to contribute to the formation and propagation of groundwater droughts at sites with water tables at least down to 30 m below ground level and so groundwater drought formation and development may be particularly sensitive to the effects of changes in ET, and hence to anthropogenic warming.~~

### 5~~4~~.2 Implications for the changing susceptibility to global groundwater droughts

Given that the sites analysed here are representative of groundwater systems in temperate hydrogeological settings, we infer that anthropogenic warming may potentially be modifying characteristics of groundwater drought such as the frequency, ~~duration~~ magnitude and intensity of groundwater droughts globally wherever shallow, unconfined aquifers are present in temperate environments. If groundwater droughts are changing in their character due to anthropogenic warming and that these changes are mediated by ET ~~dominated by plant transpiration~~ (Maxwell and Condon, ~~(~~2016), how important might this phenomena be globally?

The partitioning of ET into plant transpiration, interception, soil and surface water evaporation at the continental to global scale is challenging, however, Good et al. (2015) have estimated that the majority of ET, about 64%, is due to plant transpiration. At the global scale, there is currently limited understanding of how plants use groundwater for evapotranspiration. In the first such global analysis, Koirala et al., (2017) modelled the spatial distribution of primary production and groundwater depth and found positive and negative correlations dependent on both climate class and vegetation type. Positive correlations, i.e. higher plant productivity associated with high (shallower) groundwater tables, were generally found under dry or temperate climate class conditions, whereas negative correlations were associated with high plant productivity but with lower (deeper) water tables predominately in humid environments. When just the temperate climate class was considered, grass, crop, and shrub vegetation types (similar to those found at CH and DH) were all associated with positive correlations between vegetative production and groundwater level, with only forests showing negative correlations. Fan et al. (2013) produced the first high resolution global model of depth to groundwater level depth, and, based on a conservative estimate of the maximum rooting depths of plants of 3 m below ground level, estimated that up to 32% of the global ground surface area has a water table depth or capillary fringe within rooting depth. Based on the observations above, it is clear that globally shallow groundwater systems are common, that in temperate environments shallow groundwater contributes to ET mediated by plant transpiration, and as such may be an important process effecting groundwater drought formation and propagation, and hence may be susceptible to changes due to anthropogenic warming. If the effect of future anthropogenic warming on groundwater droughts and more generally ET process in areas of shallow groundwater and/or thick capillary finges are to be modelled with any fidelity, there is clearly a need for a focus on improvements in modelling ET processes in shallow groundwater systems (Doble and Crosbie, ~~(~~2017).

### 5~~4~~.3 Conclusions

- In the fifth IPCC Assessment of Impacts, Adaptation, and Vulnerability it was noted that 'there is no evidence that … groundwater drought frequency has changed over the last few decades' (Jiménez Cisneros et al., 2014, p.232). Here we provide the first evidence for ~~an increase~~changes in groundwater drought frequency, ~~duration~~ magnitude and intensity associated with anthropogenic warming. This has been possible due to the unusually long and continuous nature of the groundwater level time series and supporting meteorological data that is available for the CH and DH sites.

- The observed increase in groundwater drought frequency, ~~duration~~ magnitude and intensity at CH and DH associated with anthropogenic warming is inferred to be due to enhanced evapotranspiration (ET). This is facilitated by the thick capillary fringe in the Chalk aquifer which may enable ET to be supported by groundwater through major episodes of groundwater drought.

- By extrapolation, as shallow groundwater systems are common and since in temperate environments shallow groundwater contributes to ET mediated by plant transpiration this may be a globally important process effecting groundwater drought formation and propagation. Wherever droughts in shallow groundwater systems and/or aquifers with relatively thick capillary fringes are influenced by ET it is inferred that they may be susceptible to changes due to anthropogenic warming.

### 6~~5~~. Author contributions

J.P.B. conceived and coordinated the project. A.A.M. prepared the SGI, SPI and STI data for analysis. B.P.M. performed statistical analyses. J.P.B. wrote the paper with input from A.A.M. and B.P.M.

### 7~~6~~. Competing interests

The authors declare that they have no conflict of interest.

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## 9~~8~~. References

Alexander, L. V., and Jones, P. D.: Updated Precipitation Series for the U.K. and Discussion of Recent Extremes. Atmospheric Science Letters, 1, 142-150, 2000.

Bloomfield, J. P.: Characterisation of hydrogeologically significant fracture distributions in the Chalk: an example from the Upper Chalk of Southern England. Journal of Hydrology, 184 , 355-379, 1996.

Bloomfield, J. P., and Marchant, B. P.: Analysis of groundwater drought building on the standardised precipitation index approach. Hydrol. Earth Syst. Sci., 17, 4769–4787, 2013.

Bloomfield, J. P., Marchant, B. P., Bricker, S. H., and Morgan, R. B.: Regional analysis of groundwater droughts using hydrograph classification. Hydrol. Earth Syst. Sci., 19, 4327–4344, 2015.

Bonferroni, C. E.: Teoria statistica delle classi e calcolo delle probabilità, Pubblicazioni del R Istituto Superiore di Scienze Economiche e Commerciali di Firenze, 1936.

British Geological Survey: National Groundwater Level Archive. http://www.bgs.ac.uk/research/groundwater/datainfo/levels/ngla.html Last downloaded November 2017

Chen, J., and Gupta, A. K.: Parametric statistical change point analysis, Pub. Birkhauser, 2000.

Dai, A.: Characteristics and trends in various forms of the Palmer Drought Severity Index during 1900-2008. J. Geophys. Res., 166, D12115, 2011.

Diffebaugh, N. S., Swain, D. L., and Touma, D.: Anthropogenic warming has increased drought risk in California. PNAS, 112, 3931-3936, 2015.

Doble, R.C., and Crosbie, R.S.: Review: Current and emerging methods for catchment-scale modelling of recharge and evapotranspiration from shallow groundwater. Hydrogeology Journal, 25, 3-23, 2017

Doll, P., Hoffmann-Dobreva, H., Portmanna, F.T., Siebert, S., Eicker, A., Rodell, M., Strassberge, G., and Scanlone, B.R.: Impact of water withdrawals from groundwater and surface water on continental water storage variations. J. Geodynamics, 59–60, 143–156, 2012

Doll, P., Schmied, H.M., Schuh, C., Portmann, F.T., and Eicker, A.: Global-scale assessment of groundwater depletion and related groundwater abstractions: Combining hydrological modelling with information from well observations and GRACE satellites. Wat. Res. Res., 50, 5698–5720, 2014

Downing, R. A., Price, M., and Jones, G. P.: The hydrogeology of the Chalk of north-west Europe. Clarendon Press, Oxford, UK. 1993.

Everitt, B. S.: The Cambridge Dictionary of Statistics, 2nd Edn., Cambridge University Press, Cambridge, UK. 2002.

Fan, Y., Li, H., and Miguez-Macho, G.: Global patterns of groundwater table depth. Science, 339, 940-943, 2013.

Fleig, A. K., Tallaksen, L. M., Hisdal, H., and Hannah, D. M.: Regional hydrological drought in north-western Europe: Linking a new regional drought area index with weather types, Hydrol. Process, 25, 1163–1179, 2011.

Folland, C. K., Hannaford, J., Bloomfield, J. P., Kendon, M., Svensson, C., Marchant, B. P., Prior, J., and Wallace, E.: Multiannual droughts in the English Lowlands: a review of their characteristics and climate drivers in the winter half-year, Hydrol. Earth Syst. Sci., 19, 2353–2375, 2015.

Gleeson, T., Wada, Y., Bierkens, M.F.P., and van Beek, L.P.H.: Water balance of global aquifers revealed by groundwater footprint. Nature, 488, 197-200, 2012

Green, T. R., Taniguchi, M., Kooi, H., Gurdak, J. J., Allen, D. M., Hiscock, K. M., Treidel, H., and Aureli, A.: Beneath the surface of global change: Impacts of climate change on groundwater. J. Hydrol. 405, 532–560, 2011.

Greve, P, Orlowsky, B., Mueller, B., Sheffield, J. Reichstein, M., and Seneviratne, S. I.: Global assessment of trends in wetting and drying over land. Nature Geoscience, 7, 716-721, 2014.

Good, S.P., Noone, D., and Bowen, G.: Hydrological connectivity constrains partitioning of global terrestrial water fluxes. Science, 349,(6244), 175-177, 205

Hannaford, J., Lloyd-Hughes, B., Keef, C., Parry, S., and Prudhomme, C.: Examining the large-scale spatial coherence of European drought using regional indicators of precipitation and streamflow deficit, Hydrol. Process., 25, 1146–1162, 2011.

Ireson, A.M., Mathias, S.A., Wheater, H.S., Butler, A.P. and Finch, J.: A model for flow in the chalk unsaturated zone incorporating progressive weathering. Journal of Hydrology, 365, 244-260, 2009.

Jackson, C. R., Bloomfield, J. P., and Mackay, J. D.: Evidence for changes in historic and future groundwater levels in the UK. Progress in Physical Geography, 39, 49-67, 2015.

Jackson, C.R., Wang, L., Pachocka, M., Mackay, J.D., and Bloomfield, J.P.: Reconstruction of multi-decadal groundwater level time-series using a lumped conceptual model. Hydrological Processes, 30, 3107-3125, 2016.

Jenkins, G. J., Perry, M. C., and Prior, M. J.: The climate of the United Kingdom and recent trends. Met Office Hadley Centre, Exeter, UK. 2008.

Jiménez Cisneros, B. E., Oki, T., Arnell, N. W., Benito, G., Cogley, J. G., Döll, P., Jiang, T., and Mwakalila, S.S.: Freshwater resources. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 229-269. 2014.

Karoly, D., and Stott, P.: Anthropogenic warming of Central England Temperature. Atmospheric Science Letters, 7, 81-85, 2006.

King, A. D., van Oldenborgh, G. J., Karoly, D. J., Lewis, S. C., and Cullen, H.: Attribution of the record high Central England temperature of 2014 to anthropogenic influences. Environmental Research Letters, 10, 054002, 2015.

Koirala, S., Jung, M., Reichstein, M., de Graaf, I. E. M., Camps-Valls, G., Ichii, K., Papale, D., Raduly, B., Schwalm, C.R., Tramontana, G., and Carvalhais, N.: Global distribution of groundwater-vegetation spatial covariation. Geophysical research Letters, 44, 4134-4142, 2017.

Lange, B., Holman, I., Bloomfield, J. P.: A framework for a joint hydro-meteorological-social analysis of droughts. Science of the Total Environment, 578, 297-306.

Lloyd, J. W.: The United Kingdom. In: (Downing, R. A., Price, M., and Jones, G. P., eds.) The Hydrogeology of the Chalk of North-Wwest Europe. Oxford Science Publications, Oxford, UK. p.220-249. 1993.

Lloyd-Hughes, B.: The impracticality of a universal drought definition. Theor. Appl. Climatol., 117, 607–611, 2014.

Lloyd-Hughes, B., and Saunders, M. A.: A drought climatology for Europe, Int. J. Climatol., 22, 1571–1592, 2002.

Lloyd-Hughes, B., Prudhomme, C., Hannaford, J., Parry, S., Keef, C., and Rees, H. G.: Drought catalogues for UK and Europe, Environment Agency Science Report SC070079/SR, Environment Agency, Bristol, UK. 2010.

Marchant, B. P., and Bloomfield, J. P.: Spatio-temporal modelling of the status of groundwater droughts. Journal of Hydrology, 564, 397-413, 2018

Marsh, T. J.: The 2004-2006 drought in southern Britain. Weather, 62, 191-196, 2007.

Marsh, T. J., Cole, G., and Wilby, R.: Major droughts in England and Wales, 1800–2006, Weather, 62, 87–93, 2007.

Maxwell, R. M., and Condon, E.: Connections between groundwater flow and transpiration partitioning. Science, 535 (6297), 377-380, 2016.

McKee, T. B., Doesken, N. J., and Kleist, J.: The relationship of drought frequency and duration to timescales. Proc. 8th Conf. App. Clim. 17–22 January 1993, Anaheim, California USA. 1993.

Met. Office: UKCP09: Gridded Observation Data Set. https://www.metoffice.gov.uk/climatechange/science/monitoring/ukcp09/ Last downloaded November 2017.

Milly, P C. D., and Dunne, K. A.: Potential evapotranspiration and continental drying. Nature Climate Change, 5, 946-951, 2016.

National Groundwater Level Archive: http://www.bgs.ac.uk/research/groundwater/datainfo/levels/ngla.html Last downloaded November 2017.

Ordnance Survey: Sussex (West), sheet XXXIV.14, 2nd edition, 25 inch series. Pub. Ordnance Survey, Southampton, U.K.1897.

Ordnance Survey: Yorkshire (East Riding), sheet CXCV.sw, 25 inch map series. Pub. Ordnance Survey, Southampton, U.K. 1911.

Ordnance Survey: 1:25,000 scale colour raster mapping of the U.K. Pub. Ordnance Survey, Southampton, U.K. 2015.

Osti, A. L., Lambert, M. F., and Metcalfe, A. V.: On spatiotemporal drought classification in New South Wales: Development and evaluation of alternative techniques, Aust. J. Water Resour., 12, 21–34, 2008.

Parker, D. E., and Horton, E.B.: Uncertainties in the Central England Temperature series since 1878 and some changes to the maximum and minimum series. International J. Climatology, 25, 1173-1188, 2005

Parker, D. E., Legg, T.P., and Folland, C.K.: A new daily Central England Temperature Series, 1772-1991. Int. J. Clim., 12, 317-342, 1992.

Peel, M. C., Finlayson, B. L., McMahon, T. A.: Updated world map of the Köppen–Geiger climate classification. Hydrol. Earth Syst. Sci. 11: 1633–1644, 2007.

Price, M, Downing, R. A., and Edmunds, W. M.: The Chalk as an aquifer. In: (Downing, R. A., Price, M., and Jones, G. P., eds.) The Hydrogeology of the Chalk of North-Wwest Europe. Oxford Science Publications, Oxford, UK. p. 35-58. 1993.

Senevirante, S., J., Luthi, D., Litchi, M., and Schar, C.: Land-atmosphere coupling and climate change in Europe. Nature 443, 205-209, 2006.

Sexton, D. M. H., Parker, D. E., and Folland, C. K.: Natural and human influences on Central England Temperature. Met Office Hadley Centre Technical Note HCTN 46, Met Office Hadley Centre, Exeter, UK. 2004.

Sheffield, J., Wood, E. F., and Roderick, M. L.: Little change in global drought over the past 60 years. Nature, 491, 435-438, 2012.

Stagge, J. H., Kingston, D. K., Talleksen, L. M., and Hannah, D.M.: Observed drought indices show increasing divergence across Europe. Scientific Reports, 7, 14045, 2017.

Stoll, S., Hendricks Franssen, H. J., Barthel, R., and Kinzelbach, W.: What can we learn from long-term groundwater data to improve climate change impact studies? Hydrol. Earth Syst. Sci., 15, 3861-3875, 2011.

Tallaksen, L. M., and Van Lanen, H. A. J.: Hydrological drought. Processes and estimation methods for streamflow and groundwater. Developments in Water Science, v.48. Elsevier Science, Amsterdam, Holland. 2004.

Taylor, V., Chappells, H., Medd, W., and Trentmann, F.: Drought is normal: the socio-technical evolution of drought and water demand in England and Wales, 1893–2006, J. Hist. Geogr., 35, 568–591, 2009.

Taylor, R. G., Scanlon, B., Döll, P., Rodell, M., Van Beek, R., Wada, Y., Longuevergne, L., Leblanc, M., Famiglietti, J. S., Edmunds, M., Konikow, L., Green, T.R., Chen, J., Taniguchi, M., Bierkens, M. F. P., MacDonald, A., Fan, Y., Maxwell, R. M., Yechieli, Y., Gurdak, J. J., Allen, D. M., Shamsudduha, M., Hiscock, K., Yeh, P. J-F., Holman, I., and Treidel, H.: Ground water and climate change. Nature Climate Change 3, 322–329, 2013.

Trenberth, K. E., Fasullo, J. T., and Kiehl, J.: Earth’s global energy budget. Bul. Am. Meteorol. Soc., 90, 311-323, 2009.

Trenberth, K. E., Fasullo, J. T., and Shepard, T.G.: Attribution of climate extremes. Nature Climate Change, 5, 725-730, 2015.

Trenberth, K. E., Dai, A., van der Schrier, G., Jones, P. D., Barichivich, J., Briffa, K.R., and Sheffield, J.: Global warming and changes in drought. Nature Climate Change, 4, 17-22, 2014.

Van Lanen, H. A. J., Wanders, N., Tallaksen, L.M., and Van Loon, A.F.: Hydrological drought across the world: impact of climate and physical catchment structure. Hydrol. Earth Syst. Sci., 17, 1715–1732. 2013.

UN. Water for a sustainable world. The United Nations World Water Development Report, 2015. ISBN 978-92-3-100071-3 http://unesdoc.unesco.org/images/0023/002318/231823E.pdf

Van Loon, A. F.: Hydrological drought explained. WIREs Water, 2, 359–392, 2015.

Van Loon, A. F., Gleeson, T., Clark, J., Van Dijk, A. I. J. M., Stahl, K., Hannaford, J., Di Baldassarre, G., Teuling, A. J., Tallaksen, L. M., Uijlenhoet, R., Hannah, D. M., Sheffield, J., Svoboda, M., Verbeiren, B., Wagener, T., Rangecroft, S., Wanders, N., and Van Lanen, H. A. J.: Drought in the Anthropocene. Nature Geoscience, 9, 89-91. 2016a.

Van Loon, A. F., Stahl, K., Di Baldassarre, G., Clark, J., Rangecroft, S., Wanders, N., Gleeson, T., Van Dijk, A. I. J. M., Tallaksen, L. M., Hannaford, J., Uijlenhoet, R., Teuling, A. J., Hannah, D.M., Sheffield, J., Svoboda, M., Verbeiren, B., Wagener, T., and Van Lanen, H. A. J.: Drought in a human-modified world: reframing drought definitions, understanding, and analysis approaches. Hydrol. Earth Syst. Sci., 20, 3631–3650, 2016b.

Vidal, J.-P., Martin, E., Franchistéguy, L., Habets, F., Soubeyroux, J.-M., Blanchard, M., and Baillon, M.: Multilevel and multiscale drought reanalysis over France with the Safran-Isba-Modcou hydrometeorological suite, Hydrol. Earth Syst. Sci., 14, 459–478, 2010.

Vincente-Serrano, S.M., Begueria, S., and Lopez-Moreno, J. I.: A multiscalar drought index sensitive to global warming: The standardized precipitation evapotranspiration index. J. Climatology, 23, 1696-1718, 2010.

Wada, Y., van Beek, L.P.H., van Kempen, C.M., Reckman, J.W.T.M., Vasak, S., and Bierkens, M.F.P.: Global depletion of groundwater resources. Geophys., Res. Letts., 37, L20402, 2010

Watts, G., Battarbee, R. W., Bloomfield, J.P., Crossman, J., Daccache, A., Durance, I., Elliott, J.A., Garner, G., Hannaford, J., Hannah, D. M., Hess, T., Jackson, C. R., Kay, A. L., Kernan, M., Knox, J., Mackay, J., Monteith, D. T., Ormerod, S.J., Rance, J., Stuart, M.A., Wade, A.J., Wade, S. D., Weatherhead, K., Whitehead, P. G., and

Wilby, R. L.: Climate change and water in the UK – past changes and future prospects. Progress in Physical Geography, 39, 6-28, 2015.

Wilby, R. L.: When and where might climate change be detectable in UK river flows? Geophys. Res. Letts., 33, L19407, 2006.

World Meteorological Organisation. Standardized Precipitation Index User Guide. M. Svoboda, M. Hayes and D. Wood. WMO-No. 1090. WMO Geneva, Switzerland. 2012.