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

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We would like to thank Anonymous Referee #1 for their helpful and insightful observations and comments. Here we respond to the six main review comments and two minor comments, and where appropriate include brief notes on how we propose to revise the manuscript. We believe that the proposed revisions will improve the manuscript markedly.

Response to review comment 1.

Figure 4 is a plot of changes in the incidence and magnitude of groundwater drought months since 1891 as a function of temperature and precipitation indices. The figure provides a picture of changes in the relationships between the three standardised indices, SPI, STI and SGI based on monthly data and illustrates where SGI is <-1, <-1.5 and <-2. We think that some of the confusion in the interpretation of this plot is due to i.) the assumption that the SGI <-2 highlighted data points represent multiple drought episodes, and ii.) that the groundwater drought analysis is based on months where SGI is <-2. For example the Reviewer refers to "the majority of the most intense groundwater episodes during the second period ...", and points to the apparently contrasting pattern in the distribution of SGI <-2 anomalies between the second and third periods at CH. Figure 4 does not show drought episodes, rather it shows monthly values of groundwater drought status. Groundwater drought episodes are shown in Figure 5. In fact, in Figure 4 eight of the nine months where SGI is <-2 in the second period at CH are associated with a single episode of groundwater drought (the 1933-34 drought), compared with five episodes of drought in the last period at CH. We note here that each major episode of groundwater drought at CH and DH has its own distinct characteristics associated with variations in antecedent conditions and the timing of onset and end of a drought episode, as seen in Figure 5. In this context, the occurrence of SGI <-2 months is of interest from the perspective of understanding the development of individual drought episodes, and we have included some illustrative additional background information (below) on the 1933-34 drought at CH. However, analysis of individual events is outside the scope of the current paper and we have avoided such analysis in the text. Instead, the focus of the analysis of the monthly data in Section 3.2 (as described in lines 266 to 274) is on comparative changes in monthly groundwater drought status across the observation record where groundwater drought is defined by analogy to the WMO definition, i.e. SGI <-1 (lines 246 to 256).

In summary, the differences in monthly values of SGI <-2 between the second and third periods at CH reflect both the response of the groundwater systems to noise in the driving drought climatology and the underlying change effect due to anthropogenic warming. The changes in drought incidence across the whole record are best described by changes in SGI <-1 months.

Note that in response to review comment 4 (see below), we propose to simplify Figures 4 and 5 so that all symbol sizes are the same in these figures. Hopefully this will give a more balanced view of the SGI monthly data populations across the three periods. In addition, we will also add some brief text to Section 3.4 reflecting the points outlined above.

Additional background information - evolution of the 1933-34 drought at Chilgrove House.

The major drought in the second period of the CH record associated with eight of the nine months where SGI is <-2 is the 1933-34 drought at Chilgrove House. This was the single most intense episode of groundwater drought at that site in the entire record, with a mean event SGI of -1.77 (see also Figure 5). We have included a short description here of the evolution of the 1933-34 drought at Chilgrove House as background information.

The 1933-34 groundwater drought at Chilgrove House started in September 1933, developed during the first half of winter 1933-34, and was maintained as a major groundwater drought through until a rapid end in November 1934 (see attached Figure 1 below). As illustrated below, the drought started following a period of above average temperature but was established due to a major deficit in precipitation with effectively no recharge during the normal winter and spring seasons. Temperature anomalies during this period would not be expected to make any significant contribution to the formation and propagation of the drought so that they were negative is not so relevant to this episode. The drought continued through the summer associated with a period of warming anomalies, and ended in November with a major episode of rainfall.

Response to review comment 2.

The Reviewer observes that they "would have expected to find also in the second period [at DH] an increase of the groundwater drought episodes with respect to the first period". However, depending on how groundwater droughts are identified, there has been either a small decrease or a small increase in groundwater drought episodes between the first and second periods at DH. At DH there have been 33 groundwater droughts between 1891 and 2015, nine in the first period, eight in the second, and 16 events in the last period. However, if we consider droughts where average SGI is <-1 there have been two, three, and four events respectively across the three periods (Figure 5 and Supplementary Information, Table S3). We also note that if monthly SGI values are considered rather than drought episodes, then there was a small increase in the percentage of months where SGI is <-1 between the first and second third of the record at DH, from 15.3% to 19.1% of the months.

We know that the change signals that we are characterising are relatively subtle compared to the variability of the driving meteorology (see response to review comment 1 above), and we have already noted the typically low signal to noise ratio of hydrological systems (see lines 40-43). Consequently, throughout the paper we have chosen to focus on the differences in drought characteristics between the first and last third of the record, in large part because the last third of the record (see lines 202-203) coincides with the period of greatest documented warming over the study area (Karoly and Stott, 2006). We suggest that the fact that there were only eight episodes of groundwater drought identified during the middle period of the DH record compared with nine in the first third is simply a reflection of the noise in hydrological drought signals rather than an absence of a change phenomenon associated with warming.

The Reviewer also observes that "the phreatic surface is approximately 40 m and 15 m below the topographic surface at CH and DH, respectively ... at DH (where the water table is much higher than at CH, potentially making the aquifer more sensitive to temperature changes)". As long as there is a capillary connection between the land surface/plant rooting depth and the capillary fringe, the capillary fringe should provide a means for direct transpiration from groundwater to take place. Our inference is that, for both CH and DH, the capillary fringe is thick enough to facilitate this exchange (see also response to Comment 3 below) and that there should be no relative ‘sensitivity’ related to the depth of the unsaturated zone as long as the capillary fringe exceeds the typical unsaturated zone thickness at both sites, which we postulate that it does.

We don’t propose to make any changes to the text in response to this review comment.

Response to review comment 3.

Unfortunately, the specific thickness of the capillary fringe at both sites is unknown. In addition, no direct measurements of matrix water content, matric potential, pore-size or pore-throat size distributions in the matrix of the Chalk are available for either of these sites. Notwithstanding this, the size of pore throats in the matrix of the Chalk is remarkably uniform across the UK (see for example Price et al., 1993, Figure 3.3a and discussion in Allen et al., 1997, Figure 4.1.5), being characteristically less than 1 micron. Such pore throat sizes correspond to pressure heads of more than 30 m and as Price et al. (1993) notes “at equilibrium the pore spaces of the Chalk matrix can be expected to be saturated to a height of about 30 m above the water table” (Price et al., 1993, p. 40). We state on page 16, lines 419 to 421 that “The Chalk, . . . is a dual porosity-dual permeability aquifer with a relatively 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)“. For clarification, we propose to extend the text slightly as follows: “Although the specific thickness of the capillary fringe at Chilgrove House and Dalton Holme is unknown, the size of pore throats in the matrix of the Chalk is remarkably uniform across the UK (Price et al., 1993, Figure 3.3a; Allen et al., 1997, Figure 4.1.5), being characteristically less than 1 micron. Such pore throat sizes correspond to pressure heads of more than 30 m, and it is reasonable to infer that the matrix of the Chalk remains saturated to at least 30 m above the water table at the two study sites.”

Response to review comment 4.

There are a couple of reasons why we have used standardised indices in the analysis. Firstly, standardised indices such as the Standardised Precipitation Index, SPI, (McKee et al., 1993) and the Standardised Groundwater level Index, SGI, (Bloomfield and Marchant, 2013) have been developed to enable direct comparisons to be made between meteorological or groundwater droughts across multiple sites. Although we are only comparing the response of groundwater levels at two sites, we still think that the use of standardised indices is helpful. For example, there is a small but systematic difference in the rainfall totals between the two sites. Figure S3 in the Supplementary Information shows the precipitation time series for the two sites. CH has a mean monthly precipitation of about 83 mm while DH has a mean monthly precipitation of 58 mm. We believe that removing such systematic differences in mean behaviour (in this case of precipitation) by standardising the two series makes any comparisons between the two sites more compelling. Secondly, as part of the analysis of the monthly data we wanted to formally test for significant differences in measures of precipitation, temperature and groundwater levels between the first and last third of the records (see lines 265 to line 272). By working with the standardised indices which are normally distributed we were able to assume that each of the standardised time series were a realisation of temporally auto-correlated Gaussian random function and hence test for any deviation in the observations from this assumption. We could not have performed this test on non-transformed, non-standardised data.

We thank the Reviewer for reminding us that the standardized indexes “are related to frequency (pdf) analysis . . . [and that] doubling of one index . . . does not mean doubling the intensity of the anomaly”. Throughout the text we have been careful to characterise changes in the various indices by talking about percentage changes in numbers of months or numbers of drought events above or below a given threshold. In Section 3.3, where we discuss changes in the episodes of groundwater drought, we describe absolute changes in mean event intensity between the first and last third of the records. However, in our commentary we only note the direction of change: we don’t analyse the absolute magnitude of those changes. Consequently, we don’t believe that the inherent non-linear scaling of the standardised indices is an issue for the text. We do, however, note that in Figures 4 and 5, the symbols indicating monthly SGI (Figure 4) and mean event SGI (Figure 5) thresholds are distinguished by both colour and symbol size. The latter is unnecessary and we will change all symbols on these two plots to the same size.

Response to review comment 5.

As noted in Section 3.2 (lines 236-244) groundwater levels typically display temporally lagged responses to precipitation. As a result, when relating SPI to SGI, SPI is usually accumulated over some period to establish the optimal relationship between the two standardised indices (McKee et al., 1993; Bloomfield and Marchant, 2013; Van Loon, 2015). In the Chalk aquifer of the UK optimal accumulation periods have previously been documented for a variety of sites in the range four to 28 months (Bloomfield & Marchant, 2013; Bloomfield et al., 2015). The relationship between SPI and SGI is purely phenomenological, enabling one index (the SPI) to be scaled so that it can be then correlated with the other (SGI) providing a process-independent description of the time varying relationship between rainfall and groundwater level response.

We don't propose to make any changes to the text in response to this review comment.

Response to review comment 6.

As suggested, we have revised Figure 6 (see below). In addition, we will include the standardised cumulative frequency plot for the middle period 1933-1973 for both sites, and will add additional histograms to show the change in absolute durations of groundwater drought events. We believe that this enables us to describe changes in the nature of the duration of events more effectively. Analysing the data in this manner shows that there is a small apparent increase in the probability of groundwater droughts up to durations of about 12 months at CH, but that overall the revised analysis is consistent with the assertion of the Reviewer that there is no clear shift of the overall duration probability distribution across the two sites. This is because, although the maximum duration events occur in the last third of the records at each site and there is a tendency for there to be more long duration (greater than 12 months) events later in each record, there is also an increase in the number of shorter episodes of groundwater drought later in each record too.

Consequently, we propose to make the following changes to the paper. We will add the revised Figure 6 (as described above); we will revise the text in Section 3.3 to reflect the observation that there is no clear shift in the duration probability distribution at the two sites; and, we will revise other references in the text related to drought duration in line with the above.

Minor remarks – response to review comments 7 and 8. We'll change the order of the sub-plots as suggested. We'll change the SGI notation on the graph to read 'Mean event SGI'

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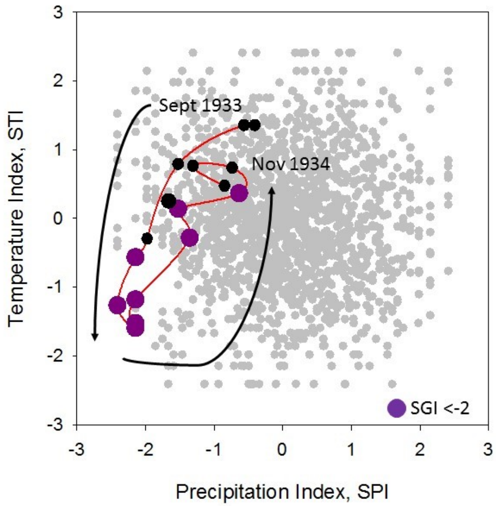

Fig. 1. Context to the 1933-34 drought

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Discussion paper