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Supplement of

Global-scale meteorological-to-groundwater drought propagation and the drivers and patterns of multi-year groundwater drought

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S1 Drought based groundwater model validation: drought duration

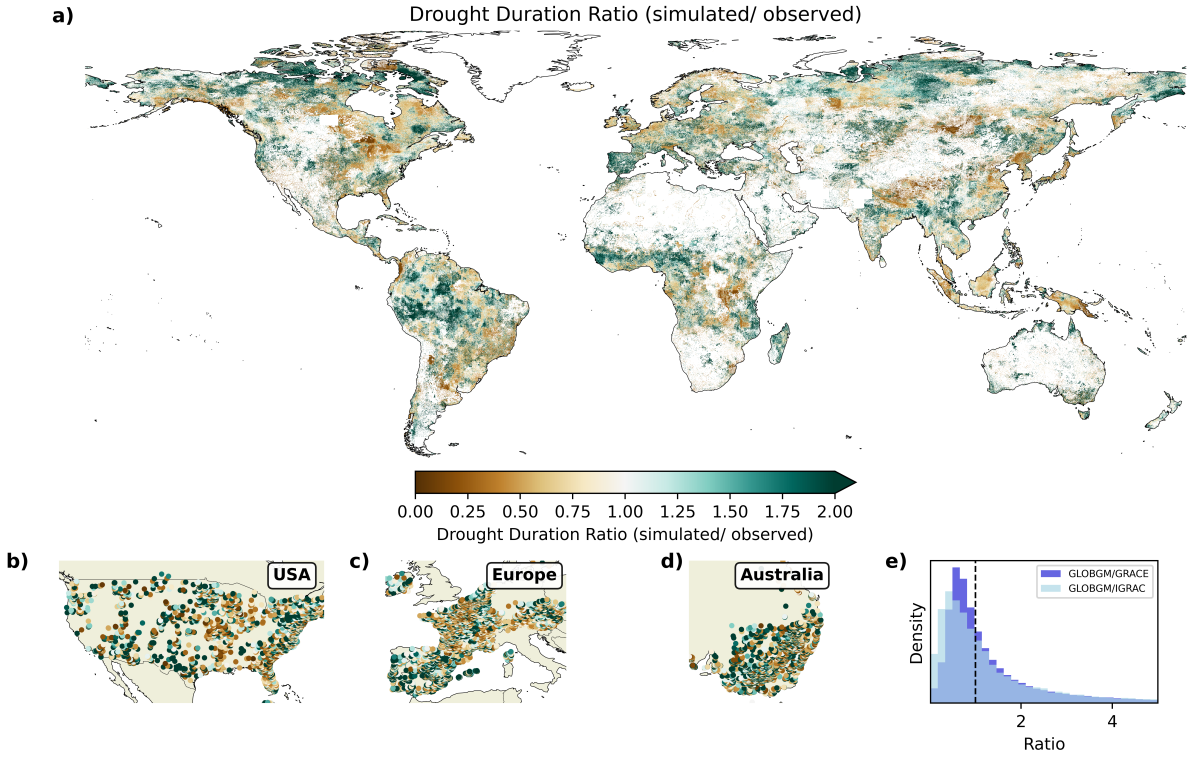


Figure S1: Ratio of average drought duration between a) observed GRACE and simulated groundwater data and b,c,d) point observations from the IGRAC data base and simulated groundwater data. 90% of all point observations in the IGRAC database (with sufficient data) are displayed in sub figures b, c, and d. e) compares the distribution of the drought duration ratio computed with GRACE and IGRAC datasets.

Figure S1 plots the ratio of the average drought duration as simulated by GLOBGM and the average drought duration calculated from the observed groundwater data. Figure S1a compares GLOBGM droughts to GRACE droughts and Figure S1b, c and d compare GLOBGM to observed point data from IGRAC. Values more than 1 imply that GLOBGM simulates longer droughts than those seen in the observational record, and visa versa, values less than one imply that the GLOBGM droughts are shorter than observed. Figure S1e shows the distribution of the drought duration ratio across the two observed datasets. The drought duration ratio is very varied across both observational datasets and there is no obvious global pattern. The distribution of drought duration ratios is also similar across both observational datasets. As mentioned in the main manuscript, the mean drought duration across the IGRAC observational data is 5.4 months and the median drought duration is 3.4 months. At the same locations, the simulated groundwater data has drought events with a mean duration of 6.4 months and a median duration of 2.9 months suggesting that the model records a greater number of long groundwater droughts at these locations which are not seen in the observational record. When comparing the global GRACE observational data to the simulated groundwater droughts, we see that GRACE records a mean drought duration of 5.5 months and a median of 4.3. Comparatively, in the regions which overlap with the GRACE coverage, the model simulates a mean drought duration of 9.9 months and a median of 5.4 months (note that this value differs from above because of only including data which overlaps with the observed data) suggesting that again the model simulates a greater number of long groundwater droughts.

S2 Meteorological drought duration (SPEI-12)

Figure S2 displays the global pattern of the average meteorological drought duration (calculated using SPEI-12). There is much less variation in this metric than observed in the groundwater (see Figure 2b in the main manuscript). The mean length of a meteorological drought is 6.7 months and the median is 6.3 months.

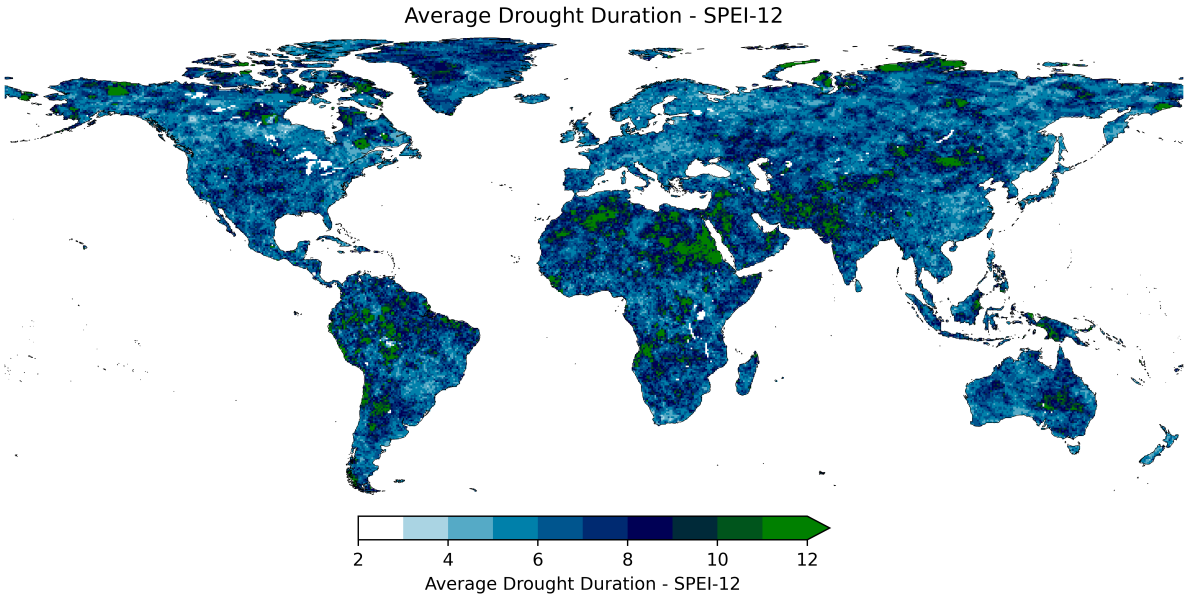


Figure S2: Global pattern of the average meteorological drought duration (calculated from SPEI-12).

S3 Distance to surface water

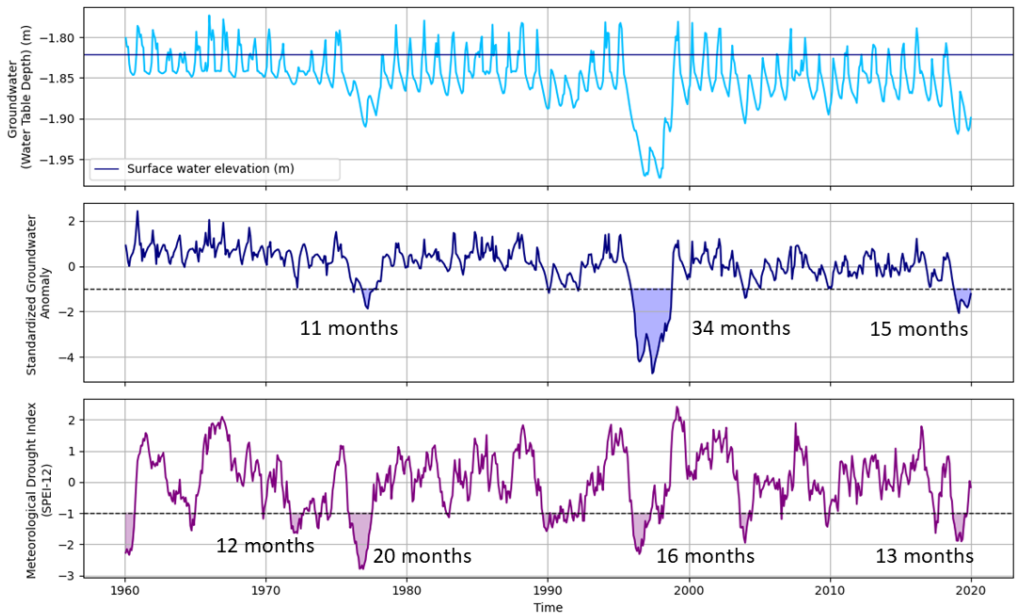


Figure S3: Timeseries displaying the raw groundwater water table depth (top), monthly standardized groundwater anomaly (middle) and SPEI-12 (bottom). The length of drought events has been annotated on. The timeseries in the top panel is accompanied by a line which shows the surface water elevation.

Figure S3 plots a representative timeseries from a location where the average groundwater drought duration is not multi-year despite spending more time in multi-year drought than normal drought. In the top panel, we observe the groundwater table depth rising above the surface water elevation annually. However, when there is a long meteorological drought, occasionally the groundwater table depth does not reach this threshold and instead the groundwater levels become disconnected from the surface water and we observe a long and often more intense groundwater drought. This is the same process as observed in Figure 4b in the main manuscript, but here the surface water elevation has been plotted alongside the raw groundwater timeseries. These long, more intense droughts are punctuated with several very short droughts which skew the average drought duration down.

S4 Dominant groundwater lag

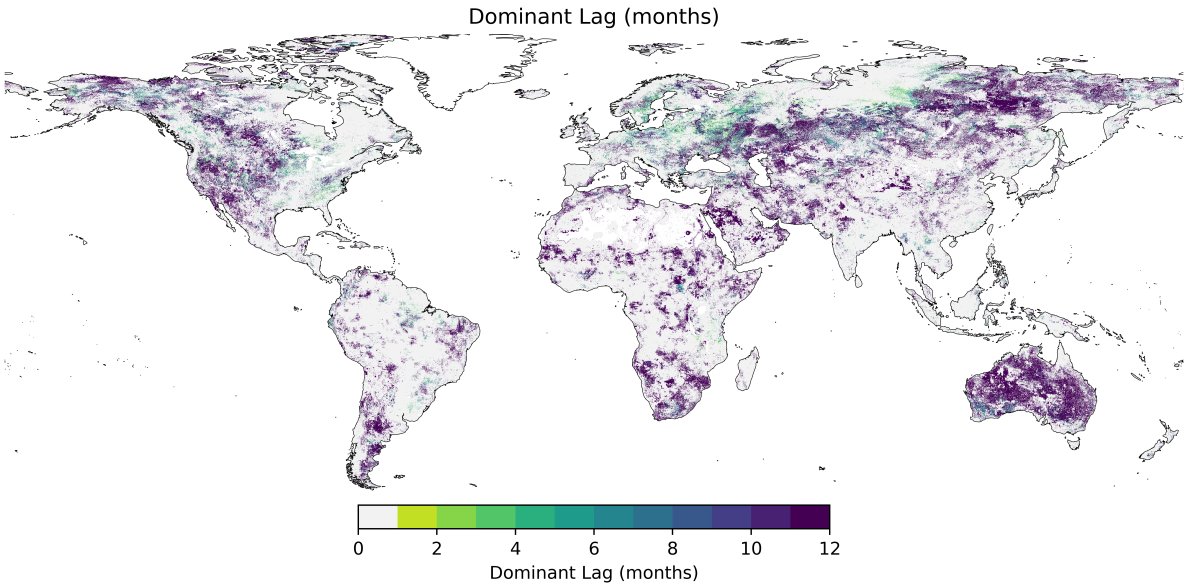


Figure S4: Global map demonstrating the spatial pattern in the dominant groundwater lag. The lag is calculated based on the anomaly correlation.

Figure S4 displays the global pattern of dominant groundwater lag. In 77% of the world, the groundwater does not have a significant lag, but where this is accounted for, the most common lag is 12 months (15% of global data). The regions with the dominant lag tend to be those which also have a multi-year groundwater drought duration, where the DDR is high.

S5 ROC AUC score relationships

Figure S5a plots the distribution of ROC AUC values, grouped based on the groundwater lag. We compare data from lag 0 - lag 12 and find that places with a higher lag tend to also have lower ROC AUC scores. Figure S5b demonstrates that points with a DDR closer to 1 also tend to have a high ROC AUC score. Points in the meteo>GW category tend to have higher ROC AUC scores than those in the meteo<GW category.

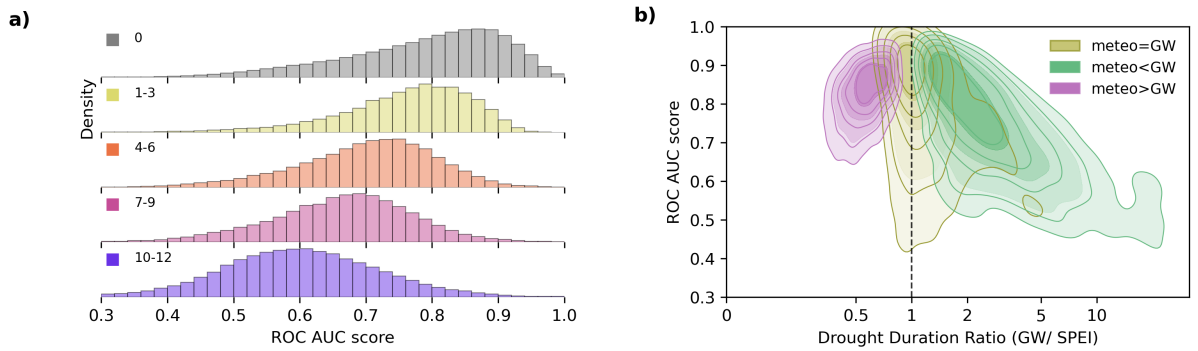


Figure S5: a) histogram displaying the distribution of ROC AUC scores for groundwater data with lags between 1 and 12 months. b) density plot representing the relationship between the ROC AUC score and the Drought Duration Ratio, plots are coloured based on their Drought Duration Ratio.

S6 Distribution fitting for drought definition

To check which statistical distribution best fit our modelled groundwater data, we performed a global, monthly-scale statistical distribution fitting analysis to determine which probability distribution (Normal, Gamma, or Log-normal) best represents the groundwater timeseries (Figure S6). We use the Akaike Information Criterion (AIC) to determine which distribution fits best. If no distribution achieves an AIC value below two then we assume no distribution fits well. We find that in 54% of the world, the normal distribution fits our groundwater data best, and thus justify our use of the standardized monthly anomaly (or Z-score) for calculating drought events. For consistency we used the normal-distribution also in the other regions to obtain consistent geographical drought patterns.

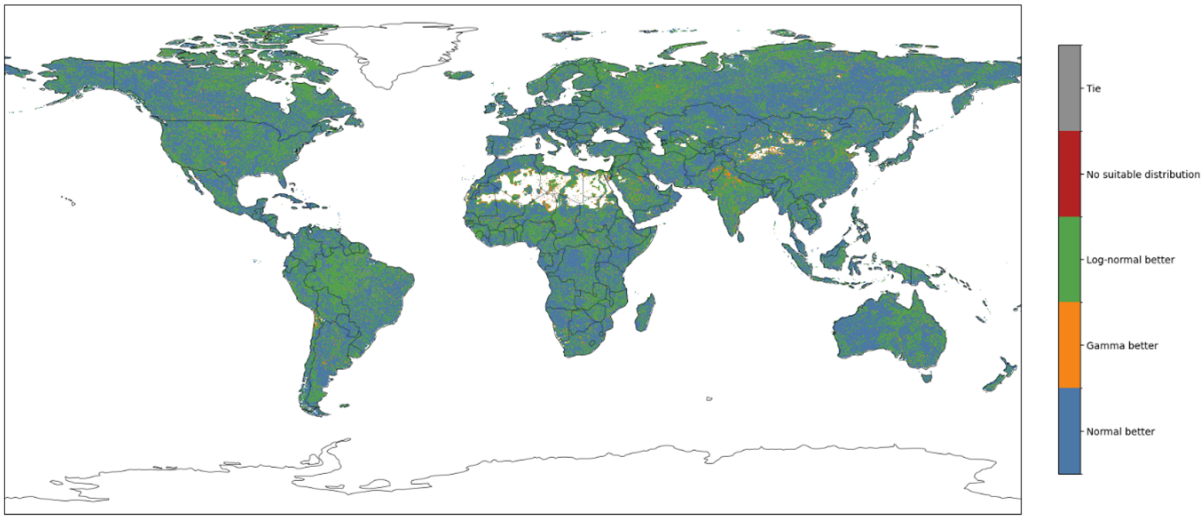


Figure S6: Global pattern of best fitting distribution according to an AIC test. We classify a location as having no suitable distribution when the AIC score is consistently above 2.

S7 SPEI accumulation period

After conducting a sensitivity analysis to evaluate how the SPEI accumulation period impacts the distribution of data across our three groundwater response types, we find that as the SPEI accumulation period increases, more data falls into the meteo>GW category (Figure S7). A longer accumulation period facilitates longer but less frequent meteorological drought, whilst a shorter accumulation period facilitates shorter but more frequent droughts. Whilst we acknowledge that there is variation in groundwater response times across the world, for this study we chose to maintain one constant SPEI accumulation period. We did this in order to maintain a constant multi-year drought definition and to ensure we used

a meteorological multi-year drought index which was in line with others used in the wider literature (van Mourik et al., 2025; Van der Wiel et al., 2023; Ruijsch et al., 2025; Tarafdar and Dutta, 2023; Pascale et al., 2025; Theron et al., 2021).

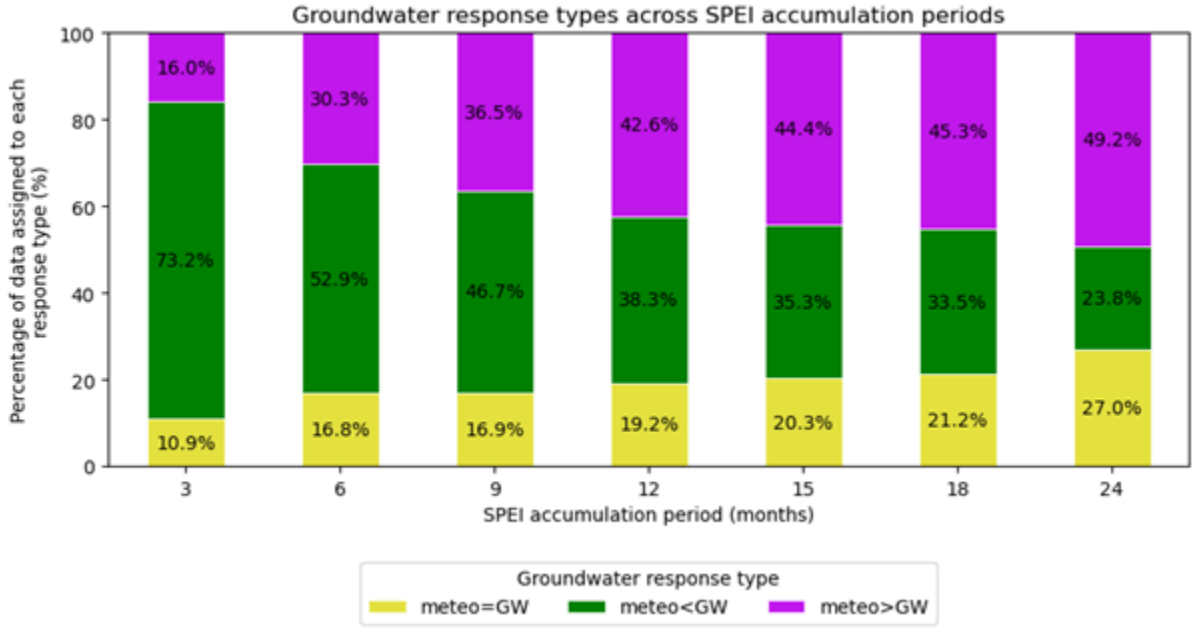


Figure S7: Proportion of data in each groundwater response type for SPEI accumulation periods from 3-24.

S8 Groundwater abstractions

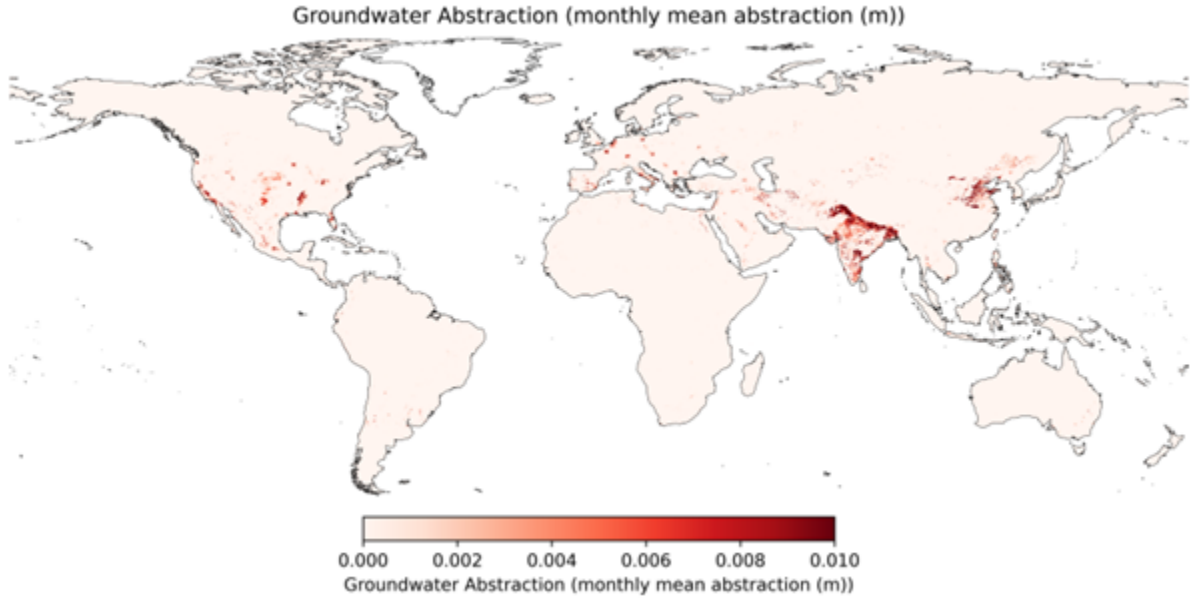


Figure S8: Proportion of data in each groundwater response type for SPEI accumulation periods from 3-24.

S9 Linking response types to physical properties

To link the groundwater response types to local characteristics, Figures S9 and S10 display the distribution of data across groundwater response types for different classes of water table depth and for climate zones according to the Koppen climate classification. Shallower water tables (0-15m) tend to be more associated with the meteo>GW response type, whilst deeper water tables (15m +) are more likely to be in the meteo<GW type (Figure S9). When considering the climate types, arid regions have the highest proportion of data in the meteo<GW type, and tropical regions have the largest proportion of data in the meteo>GW type, closely followed by temperate regions (Figure S10). These findings are in line with others in the literature, where arid climate zones have been found to have the weakest relationship with precipitation (Liu et al., 2023), and where deeper groundwater is known to be more disconnected from the meteorology (Ebeling et al., 2025; Hare et al., 2021).

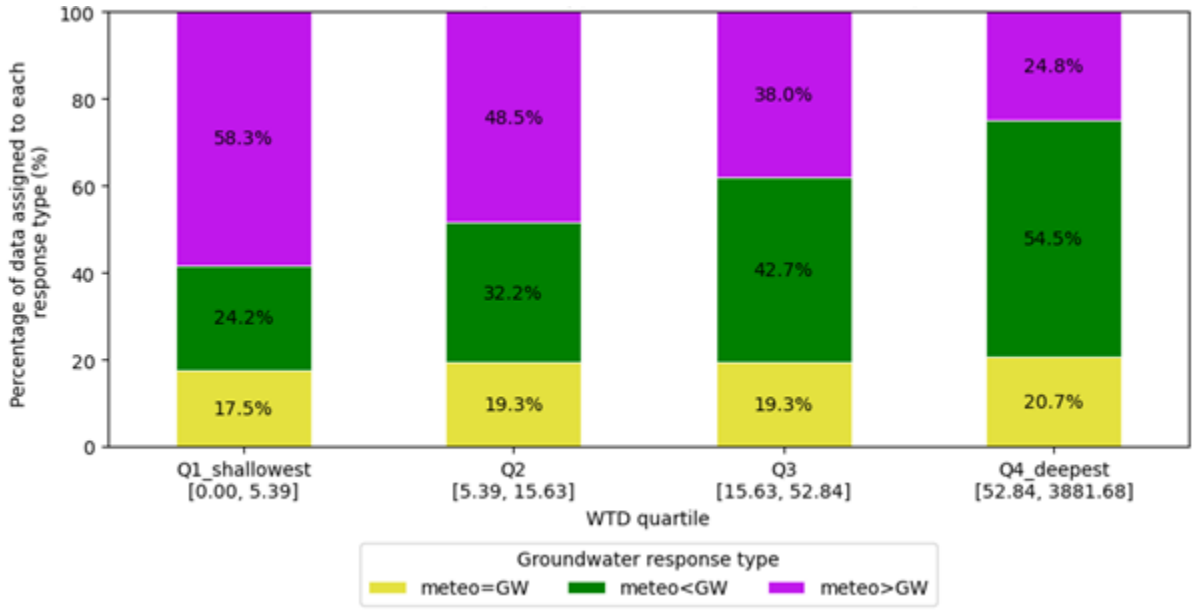


Figure S9: Distribution of data across groundwater response types for four quantiles of water table depth.

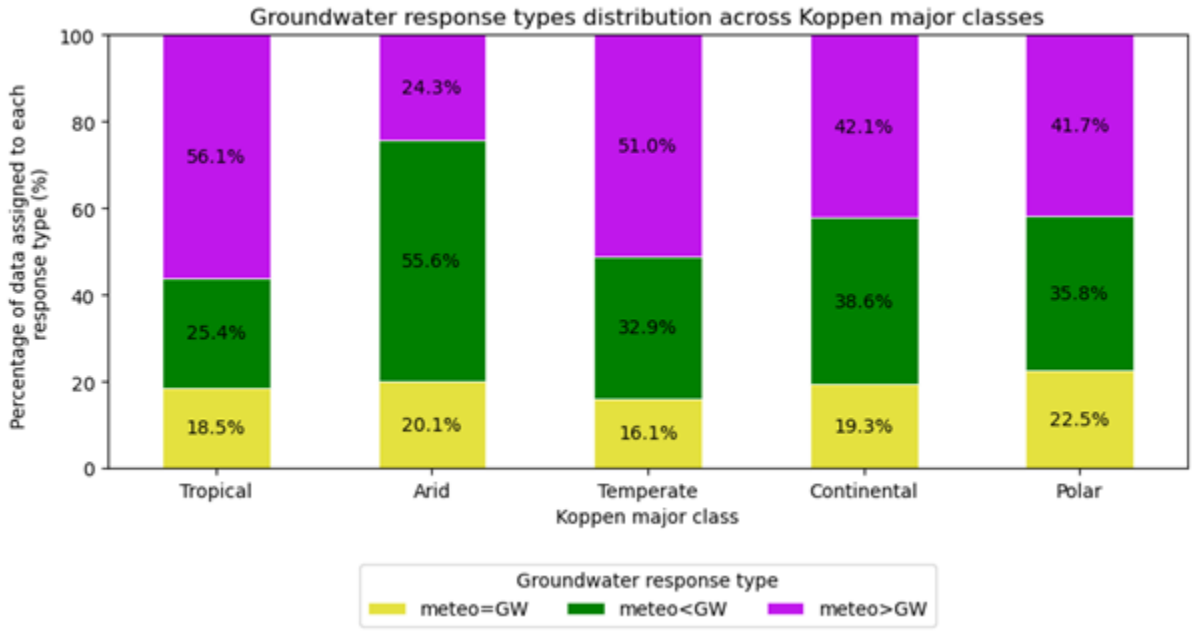


Figure S10: Distribution of data across groundwater response types for four quantiles for Koppen climate types (Beck et al., 2018).

S10 Groundwater drought threshold sensitivity

To test the sensitivity of our results to the chosen drought threshold, we selected a subset of points to assess the impact of the groundwater drought threshold on the frequency and duration of drought events. We selected approximately 11,000 random groundwater cells from across the globe (see Figure S11 for their spatial distribution) and looked at how the sample of drought statistics changed across three drought thresholds (-0.5, -1 and -1.5). We chose to cap the sample to only 11,000 points to reduce the computational burden of this analysis but still maintain global coverage.

As expected a lower drought threshold is associated with fewer drought events and on average shorter drought durations. The mean groundwater drought duration from this sample of points goes from 11 to 19 to 28 months as the threshold changes from -1.5 to -1.0 to -0.5 The median groundwater drought duration is much less sensitive to the threshold, starting at 3.5 months with a threshold of -1.5, rising to 4 months when using the -1.0 threshold, but remaining at 4 months with the -0.5 threshold, suggesting that the thresholds are more influential on the distribution of extreme drought events. With a -1.0 drought threshold 23% of the selected points have an average groundwater drought duration which is multi-year, this number rises to 28% with a -0.5 threshold and decreases to 14% with a threshold of -1.5. Our analysis confirms that the distribution of data across the global response types is conditional on the chosen drought thresholds.

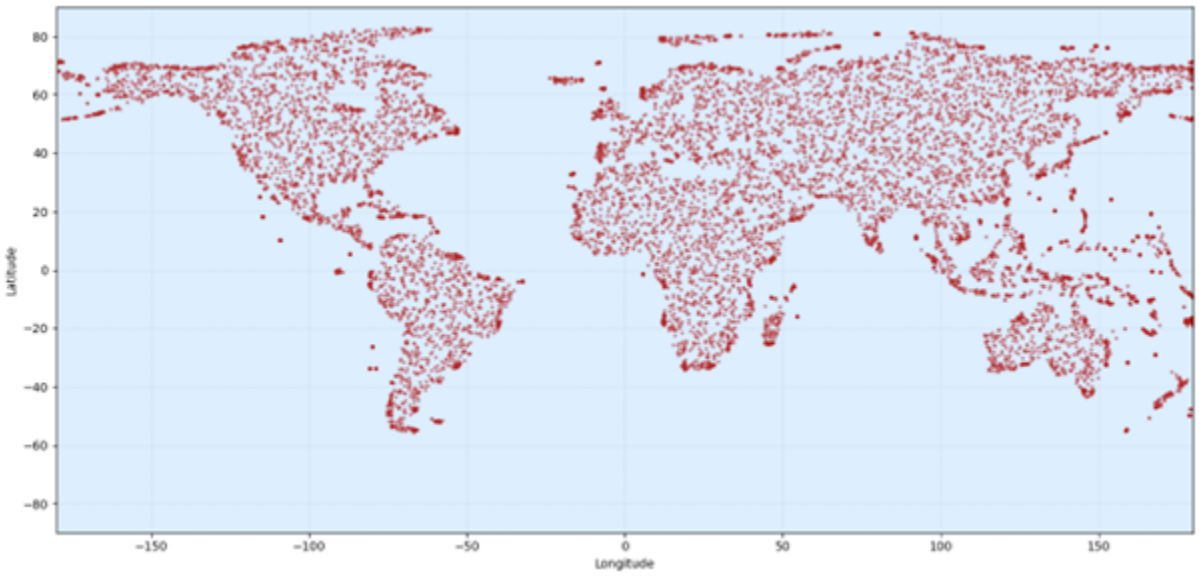


Figure S11: Global distribution of approximately 11,000 points used in drought threshold analysis.

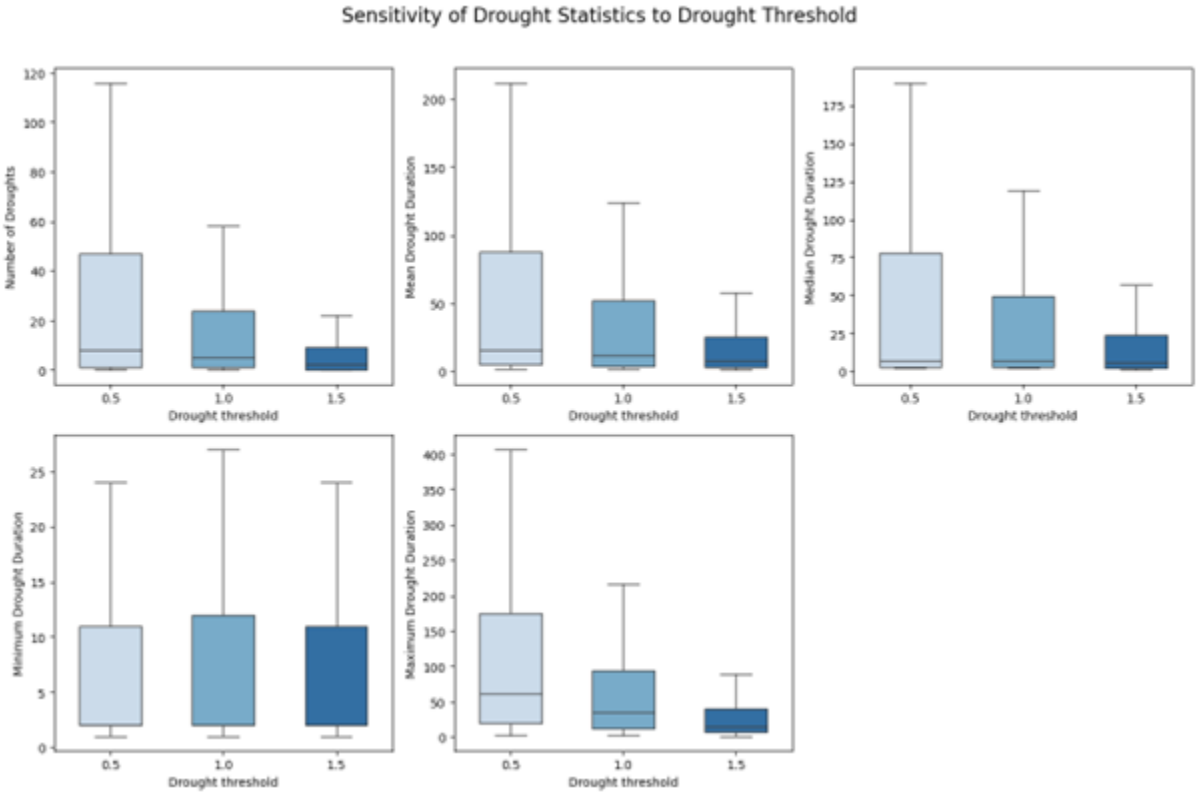


Figure S12: Box plots showing the sensitivity of several key groundwater drought statistics to changes in the drought threshold. Data comes from the points displayed in Figure 3.

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