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# Extreme dry and wet spells face changes in their duration and timing

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**Abstract**

Dry spells are sequences of days without precipitation. They can have negative implications for societies, including water security and agriculture. For example, changes in their duration and within-year timing can pose a threat to food production and wildfire risk. Conversely, wet spells are sequences of days with precipitation above a certain threshold, and changes in their duration and within-year timing can impact agriculture, flooding or the prevalence of water-related vector-borne diseases. Here we assess changes in the duration and within-year timing of extreme dry and wet spells over 60 years (1958–2017) using a consistent global land surface precipitation dataset of 5093 rain gauge locations. The dataset allowed for detailed spatial analyses of the United States, Europe and Australia. While many locations exhibit statistically significant changes in the duration of extreme dry and wet spells, the changes in the within-year timing are less often significant. Our results show consistencies with observations and projections from state-of-the-art climate and water resources research. In addition, we provide new insights regarding trends in the timing of extreme dry and wet spells, an aspect being equally important for possible future implications of extremes in a changing climate, which has not yet received the same level of attention and is characterized by larger uncertainty.

**1. Introduction**

Dry spells are sequences of days without precipitation [1]. They can affect societies in many ways, including negative effects on water security and food production [2–5]. The intensity and duration of droughts are directly proportional to the number of days without precipitation [6]. Extreme dry spells refer to meteorological droughts [4]. Long dry spells can increase, for example, the risk of agricultural losses or wildfires. Wet spells, on the other hand, are sequences of days with precipitation above a certain (minimum) threshold. Extremely long wet spells can lead to saturated soils and thus influence the flood hazard and, depending on the climatic conditions, can have direct impacts on agriculture and the prevalence of water-related vector-borne diseases [7]. Additionally, dry and wet spells can affect water quality [8–13]. For example, dry spells can lead to lower river flows, reduced velocities and thus higher water residence

times enhancing the potential for toxic algal blooms and low dissolved oxygen levels [14, 15]. Other effects include releases of water quality pollutants during a wet spell after a prolonged dry spell, such as sulphate [16, 17] or nitrate [18]. Dry and wet spell properties are also important for urban water management, for example in the design of water storage components [19]. Hence, although the underlying mechanisms can be complex, extreme dry and wet spells are an essential contribution to precipitation extremes related to droughts and floods and their various impacts.

While research has mainly focused on the changes of the duration or frequency of dry and wet spells [1, 20–25], changes in their timing have been poorly explored. Yet, trends in the timing of natural hazards can lead to considerable economic and environmental consequences, as societies and ecosystems have adapted to their average within-year timing [26]. Changes in the timing of dry spells can for instance

pose a threat to food production. Specific mechanisms make systems more sensitive to dry and wet spells in specific seasons. Crops are not only sensitive to water deficit and hence the duration of dry spells, but also to their timing with respect to sowing and developmental stages [27]. Provided the crop establishes, the highest sensitivity to excessive rain and water logging occurs during the vegetative phases [28] and to drought during the reproductive stages [27, 29]. Also, excessive rain can enhance the risk of lodging or pathogen development [30]. Further, in croplands, near soil saturation during sowing and harvesting make field operations impossible [31]. Similar, forests are most sensitive to drought when it occurs early in the growing season, when radial growth peaks [32]. The timing of extreme dry and wet spells has the potential to enhance their consequences, with dry spells being more impactful if occurring during warmer periods, when evaporation and transpiration rates are high; and wet spells potentially causing more intense runoff during colder months, in particular over frozen soils, except where precipitation occurs as snow.

Here, we estimate changes in the duration and the within-year timing (hereafter simply referred to as ‘timing’) of extreme dry spells (EDS) and extreme wet spells (EWS) over a period of 60 years using observations from 5093 rain gauges across the globe (figure 1). The dataset allowed for detailed spatial analyses of the United States, Europe and Australia which thus are in the main focus of our work. Asia had little missing data but a low spatial coverage of suitable rain gauges. Results for Asia are reported in the appendix (figure A1). Other regions (e.g. Africa and South America) are not considered in our analyses because of the lack of available rain gauges or extensive missing data. The three regions in focus have a population of about 1.1 billion people, accounted for a share of about 47% of the global GDP in 2018 according to the World Bank [33], and are important agricultural areas with a contribution of about 40% to the global production of important staple crops (barley, maize, oat, rye, sorghum, wheat) in 2018 [34]. We compare changes of the duration and timing of EDS and EWS between 1958 and 2017.

## 2. Methods

### 2.1. Study area and data

We took a global perspective by using the GHCN-Daily dataset [35] providing global rain gauge records of daily precipitation (figure 1). Dry days were defined as days with precipitation  $< 0.1$  mm. Wet days were defined as days with precipitation  $\geq 0.1$  mm. In a first step, rain gauges covering the period 1958–2018 (61 years) were extracted from the global GHCN-Daily dataset and all flagged records with potential errors were removed. From these 9519 available rain gauges, 5093 had 10% missing records or less, which is

the highest acceptable threshold for dry spell analyses as identified by Zolina *et al* [21]. The 10% restriction was applied separately to two periods, 1958–1987 and 1988–2018 to avoid pronounced imbalances of missing records in a subset of the dataset. The duration of EDS/EWS at each site was based on the annual maximum in the 60-year period 1956–2017 (2018 was added to the analysis as an EDS/EWS can start in 2017 but last until 2018), i.e. we focused on low-frequency events potentially causing the highest damage. Accordingly, the timing refers to the mean date of the annual maximum dry (wet) spell between 1958 and 2017. Analyses of dry spells put particularly strict requirements on data completeness [21], as missing values in longer dry spells can bias the results. To address this challenge, we applied a weather generation technique to fill the gaps of records. Data gaps were filled stochastically with a first-order two-state Markov chain rainfall model [36, 37]. The model was calibrated to calendar months to account for seasonality; the gap filling procedure was conducted separately in the periods 1958–1987 and 1988–2018 to maintain climatic properties of the two different (30-year, 31-year) periods. The gap filling was applied 50 times over the entire dataset, the median of these analyses was taken for our analyses. The network density and data availability allowed for detailed analyses of EDS/EWS for the United States, Europe and Australia. These three regions comprise 4645 (91.2%) of all rain gauges considered.

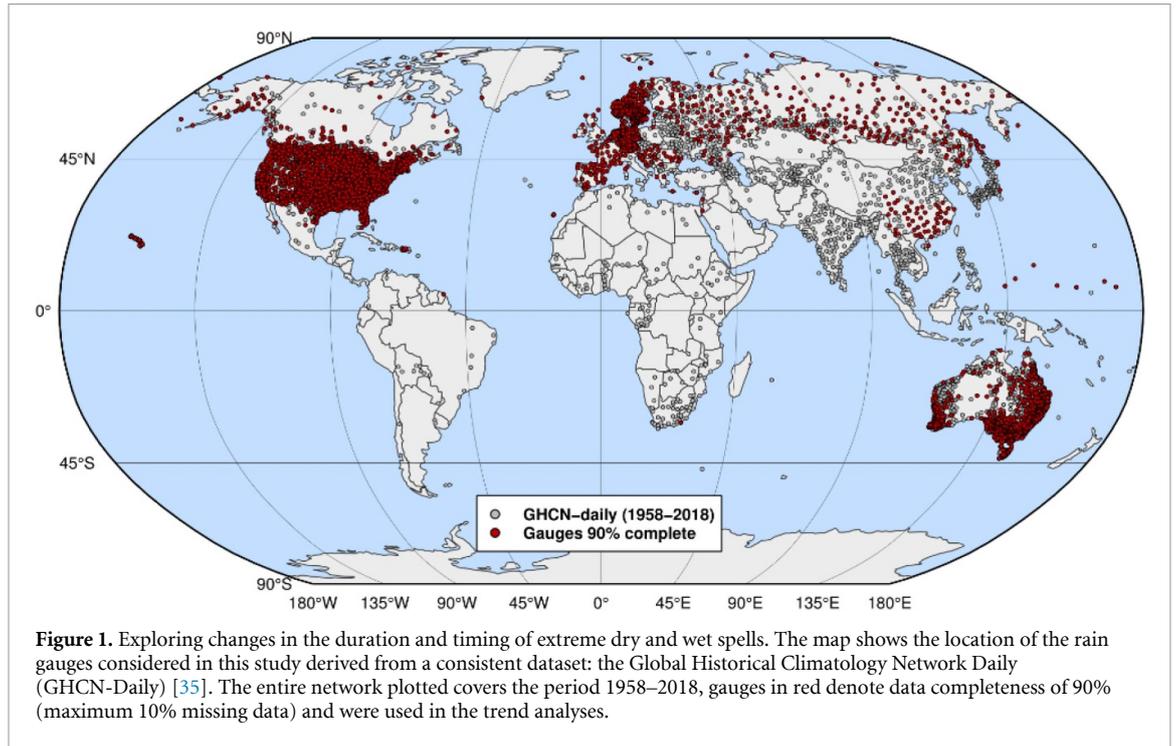
### 2.2. Linear trend model and mean dates

We applied a linear trend model to identify trends. The linear trend was estimated using the adjusted Theil–Sen slope estimator [26, 38], which is robust to outliers. The linear regression was applied for the duration of EDS/EWS (duration of annual maxima over 60 years) and the timing of EDS/EWS (starting date of annual maxima of EDS/EWS over 60 years, i.e. day 1 to 365/366). The generic Theil–Sen slope estimator is not directly applicable to the timing as the starting dates belong to the class of circular quantities. Thus, the Theil–Sen slope estimator was adapted for the timing [26]. The trend estimator  $\beta$  is the median of the difference of dates over all pairs of years ( $i$  and  $j$ ) in the time series, where the dates are centred around the average starting date of occurrence  $D$  (equation 1):

$$D_i^* = \begin{cases} D_i - D & \text{if } |D - D_i| < \bar{m} - |D - D_i| \\ \bar{m} - (D - D_i) & \text{if } |D - D_i| > \bar{m} - |D - D_i| \text{ and } D > D_i \\ (D_i - D) - \bar{m} & \text{if } |D - D_i| > \bar{m} - |D - D_i| \text{ and } D < D_i \end{cases}$$

$$\beta = \text{median} \left( \frac{D_j^* - D_i^*}{j - i} \right) \quad (1)$$

These adjustments consider the circular nature of the data and compare the relative delay and advance in the arrival date with respect to the mean date of occurrence;  $\beta$  has units of days per year.



We analysed the mean duration (i.e. average length) and timing (i.e. average starting date) of EDS/EWS. While an arithmetic mean is suitable for the duration, the mean of the timing requires directional statistics [26, 39, 40]. More specifically, the starting dates of the EDS/EWS were calculated as (equation 2):

$$\theta_i = D_i \frac{2\pi}{m_i} \quad 0 \leq \theta_i \leq 2\pi \quad (2)$$

where January 1 corresponds to  $D_i = 1$  and December 31 to  $D_i = m_i$ , i.e. the total number of days in that given year. The average starting date of occurrence  $D$  of the maximum dry (wet) spell at a station was calculated as (equation 3):

$$D = \frac{\bar{m}}{2\pi} \cdot \begin{cases} \frac{\pi}{2} - \text{atan2}(\bar{y}, \bar{x}) & \bar{x} \geq 0, \bar{y} \geq 0 \\ \frac{5\pi}{2} - \text{atan2}(\bar{y}, \bar{x}) & \bar{x} < 0, \bar{y} \geq 0 \\ \frac{\pi}{2} - \text{atan2}(\bar{y}, \bar{x}) & \bar{x} \leq 0, \bar{y} < 0 \\ \frac{3\pi}{2} - \text{atan2}(\bar{y}, \bar{x}) & \bar{x} > 0, \bar{y} \leq 0 \end{cases} \quad (3)$$

where  $\bar{x}$  and  $\bar{y}$  are the sine and cosine of the component of the average date, considering  $n$  the total number years (equation 4):

$$\begin{aligned} \bar{x} &= \frac{1}{n} \sum_{i=1}^n \sin(\theta_i) \\ \bar{y} &= \frac{1}{n} \sum_{i=1}^n \cos(\theta_i) \end{aligned} \quad (4)$$

These formulas differ from those found for example in Burn [41], because January first is taken to be (0,1) (most Northern point on the unit circle) and the succession of dates follows a clockwise rotation on the circle, instead of counter-clockwise.

### 2.3. Trend tests

At each location, a Mann–Kendall trend test was applied at the  $\alpha = 0.05$  level, both for the trends in the duration and the trends in the timing. For the latter, the differences of the (centred) occurrence dates were employed. Details of the Mann–Kendall test can be found for example in Yue *et al* [42]. However, although ignored most of the time [43], a problem can arise when applying multiple statistical tests across atmospheric field data, which is the problem of multiplicity or multiple hypothesis testing. Field significance addresses the question if a number of locally significant statistical tests occurred by chance [43–46]. We employ the procedure for controlling the false discovery rate (FDR) by Benjamini and Hochberg [45] in order to assess field significance of the trend tests. This approach controls the proportion of falsely rejected local null hypotheses and is conducted at a global significance level (which is set to  $\alpha_{global} = 0.05$ ). Global (field) significance can be declared if—after applying the FDR approach—at least one local null hypothesis is rejected [44]. A remarkable advantage of the FDR procedure is its robustness to spatial correlation [43, 47], as typically found in atmospheric data [43].

## 3. Results and discussion

We present the results split into the three main regions of the United States, Europe and Australia. The GHCN dataset also provided suitable rain gauges (i.e. 90% complete) in other regions (mainly in Asia, see figure 1), but the density was too low for detailed regional spatial analyses and thus robust conclusions.

For the sake of completeness, results for Asia (less densely gauged) are enclosed in the appendix (figure A1). For both EDS and EWS, we present four metrics: (i) the duration (ii) changes in the duration, (iii) the timing, and (iv) changes in the timing. The changes of the duration and timing are presented as the mean of the individual locations across hexagons with a cell size of  $1.5^\circ$ . By this we avoid presenting misleading trends across large regions without any rain gauge (which would result from generic interpolation techniques), such as in central Australia. For validation, we additionally generated means over hexagons in the US (due to its high gauge density) from ordinary kriging over a continuous grid of  $0.1^\circ$ . The similar patterns from ordinary kriging (see figure A2) and hexagon means (figure 2(b)) justify the selected approach. Field significance of the entire dataset was detected for trends in the duration of EDS and EWS. For the trends in the timing, field significance was detected for the EDS but not for the EWS. When ignoring the FDR, for the duration and timing of EDS, 995 and 313 gauges were locally significant, respectively. When considering the FDR, the numbers reduced to 283 and 4. For EWS and the duration and the timing, 1323 and 282 gauges were locally significant, respectively. The numbers reduced to 619 and 0 when considering the FDR. The detailed analysis of the FDR can be obtained from figure A3.

### 3.1. United States

In the US, a strong West-East gradient of the duration of EDS exists (figure 2(a)). EDS are longest in California, Nevada, Arizona and in the West of Texas. Durations are smaller in mountainous regions. The West-East gradient is the opposite for EWS, with the exception of the North of California and the North-West (Western parts of the states of Oregon and Washington) (figure 2(b)). EDS have become longer in the West and South-West of the US, and have become shorter in the East (figure 2(c)). The state of Florida has experienced an increase in the duration of EDS. The rest of the country is more scattered but is generally characterized by trends towards shorter durations. Our results of EDS are consistent with trends in annual precipitation in the period 1951–2010, as presented by the Intergovernmental Panel on Climate Change (IPCC) [48], where a decreasing trend has been identified for the West and an increasing trend for the East. Similar trends in the annual precipitation have been described by Wuebbles *et al* [49]. Analyses in the changes of EWS indicate regions of increasing extremes (figure 2(d)). For example, the North-West, large parts of the South and Florida in the South-East have experienced increasing durations of EWS (where also the duration of EDS has increased). Some regions such as California have been facing increasing duration of EDS and decreasing duration of EWS, indicating a trend towards a drier climate, which is consistent with the observation

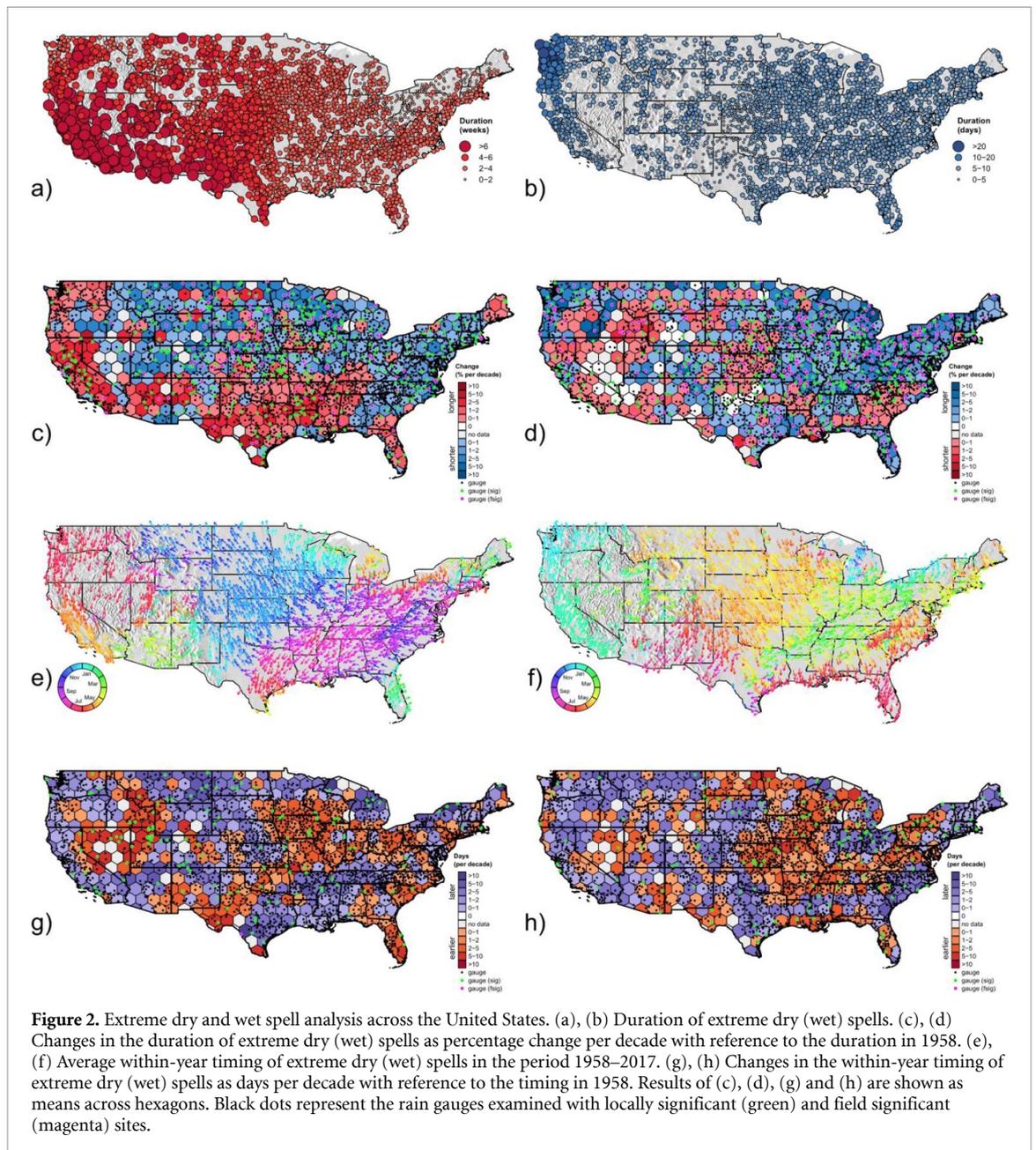
that drought conditions have become more and more devastating in this area [50]. As already indicated by the increase in the duration of EDS, the mean drying in the South-West throughout the 20th century is mainly related to an increase in dry days and not to significant trends in seasonal precipitation amounts [51], as the precipitation intensity has increased during the same period in most of the region [51]. That is, the (not significantly changed) seasonal precipitation tends to fall today on fewer days with profound consequences for wildfires, agriculture, and ecosystems and new challenges for water resource management.

There are pronounced differences in the timing of EDS (figure 2(e)). In the West, EDS start in the summer and fall. In the mountain regions starting dates have a high variability (Rocky Mountains and northern parts of the Appalachian Mountains). EDS start in the late fall across the Interior Plains, where winters are generally cold and dry. In most of the East, EDS start in the late summer and early fall. An exception in the South-East are the EDS in Florida, which start in winter and spring. There are three prominent regions where EDS starting dates have become earlier: the mountainous West, parts of the South, and large parts of the Midwest (figure 2(g)). In the East, there are trends towards earlier and later timing. The later timing in California is in line with projections suggesting a later wildfire season towards fall and winter in the future [52]. The timing of EWS is in many regions mirroring the timing of the EDS (figure 2(f)). Extreme wet spells occur in winter in the West, in spring across the Interior Plains, in summer in the South, and in spring and summer in the East. As in the case of EDS, starting dates of EWS are variable in the mountainous regions. Interestingly, spatial patterns of the changes in the timing of EWS (figure 2(h)) show large similarities to the changes in timing of the EDS (figure 2(g)). Exceptions are for example the North and South-East, where starting dates of EDS and EWS have become later and earlier, respectively.

### 3.2. Europe

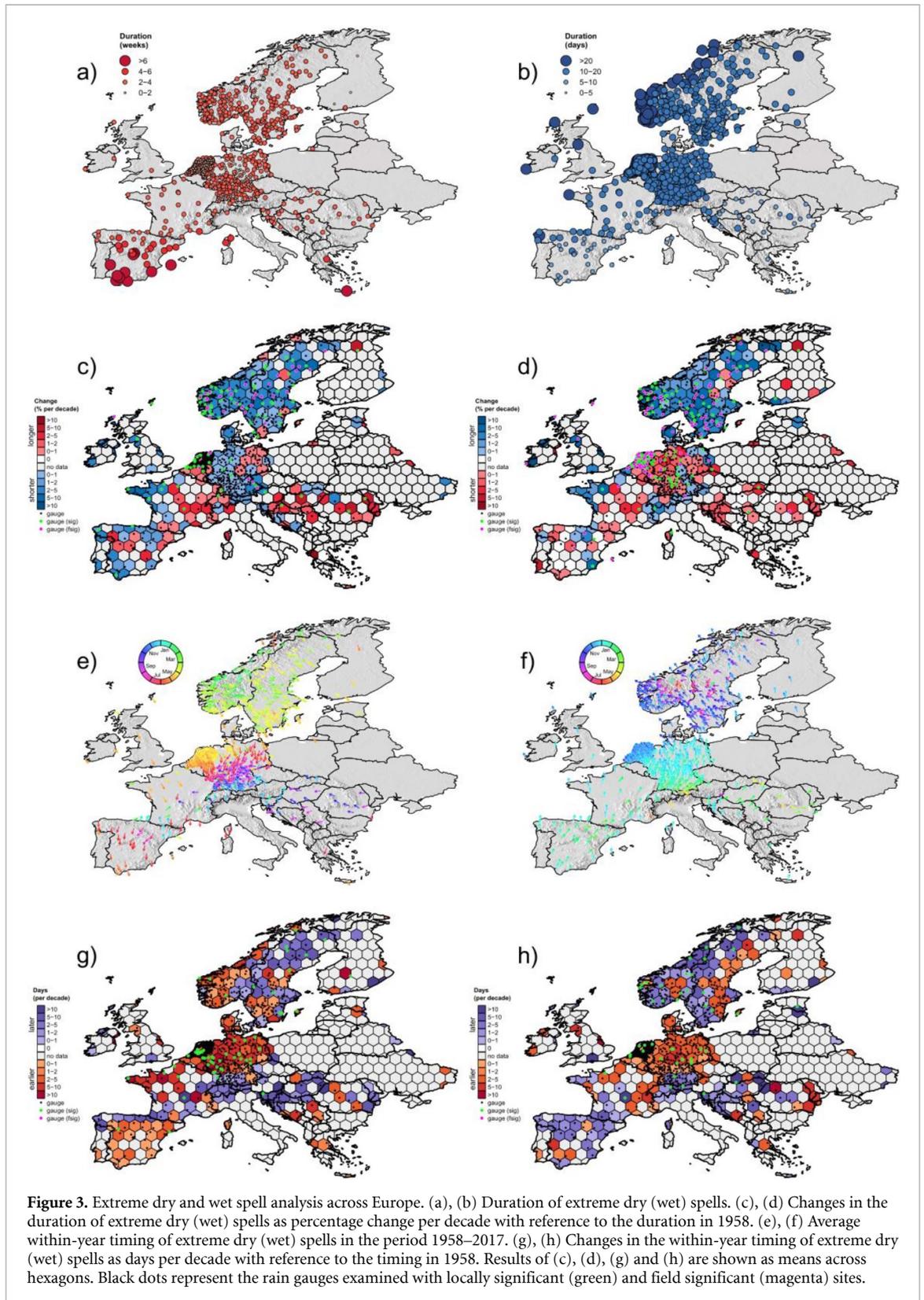
In Europe, there is a pronounced North-South gradient of the duration of EDS (figure 3(a)), with EDS becoming longer towards the South. The opposite applies to EWS, which tend to become shorter from the North towards the South (figure 3(b)).

The duration of EDS has become shorter throughout Scandinavia (figure 3(c)), which is in line with trends described by Kovats *et al* [53]. There are local exceptions such as the South of Sweden. Observations and climate simulations for Sweden suggest a trend towards drier summers in the South [54]. A shortening of EDS over southern Scandinavia during the warm season has also been observed by Zolina *et al* [55]. In Western Europe, there is a North-South gradient in regard to trends towards shorter (Denmark, most of Germany) and longer (Netherlands,



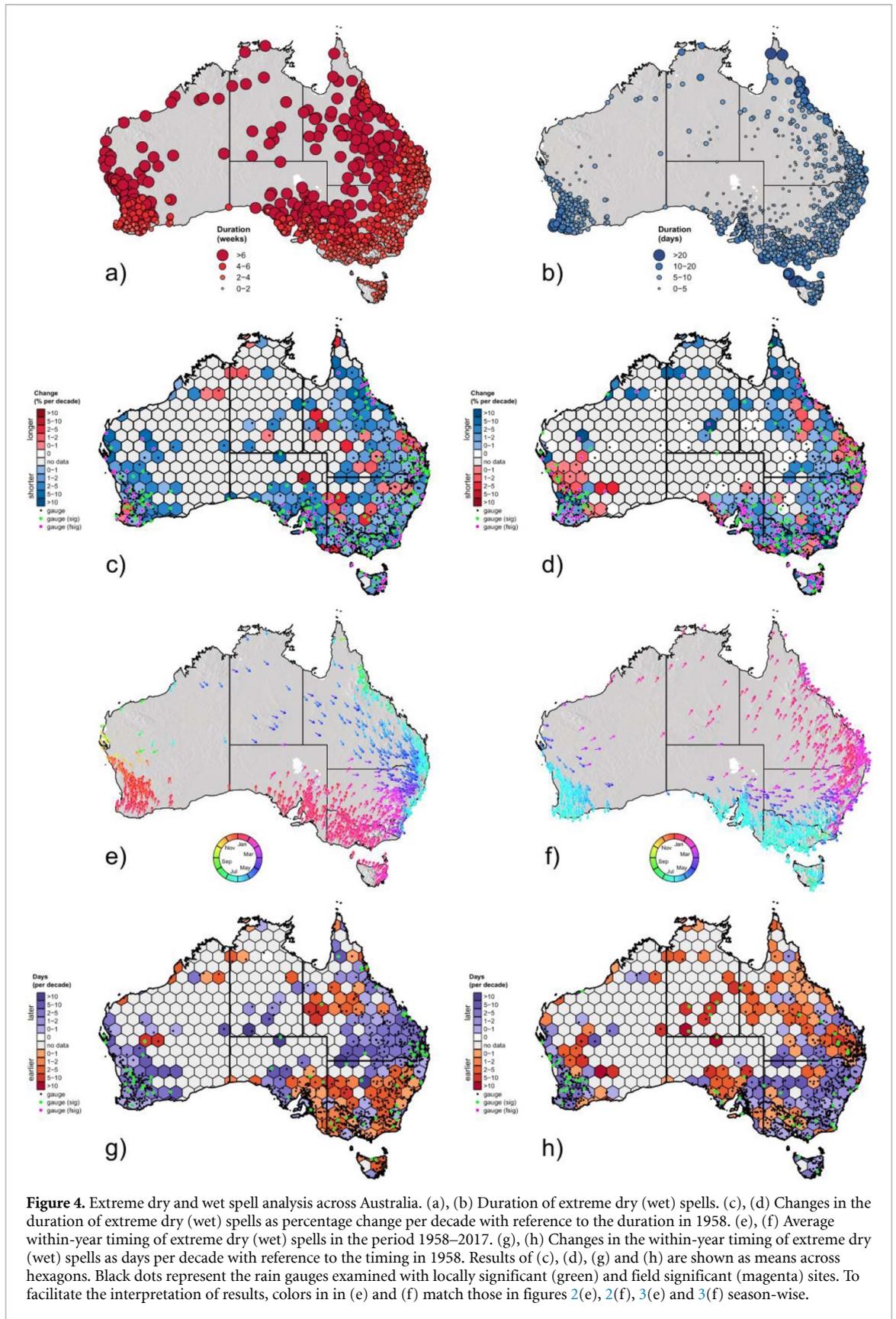
France without the Eastern parts) EDS. The East of Germany has been facing a small trend towards longer EDS, which is line with increased drought stress in the East of Germany as described by Zebisch *et al* [56]. Central and Southern France have experienced longer EDS, whereas EDS have become shorter in the West. Central Spain has experienced longer EDS, while the duration has decreased in the Southern Spain. Eastern Europe has been facing a general trend towards longer EDS (e.g. Slovakia, Hungary, and Romania). Not only is there a general tendency of EDS becoming longer in Southern Europe (a trend also projected for the future by the IPCC [53]), but also EWS show similar patterns, i.e. EWS become longer in Northern Europe and shorter in Southern Europe (figure 3(d)). Similarly, Zolina *et al* [55] showed that the duration of EWS in the Mediterranean region

decreases. The analysis of the durations gives some indication of a wetter climate in Northern Europe and a drier climate in Southern Europe throughout the year, although an extreme dry or wet spell does not necessarily provide certain information about trends in total rainfall amounts of a season, which may be different. However, an increasing tendency of the mean annual precipitation over northern Europe and a decreasing tendency over Southern Europe have been reported for the 20th century [57]. The increasing duration of EDS in Southern Europe may affect the wildfire seasons duration, which has been reported by Jolly *et al* [58], who reported a lengthening of the fire weather season in Southern Europe. As in the case of the US and its South-West, the drying trend in the South of Europe is mainly related to an increase in dry days, while the precipitation



intensity from an annual perspective has faced little changes in the 20th century (Kovats *et al* [53] reports more frequent short-time extreme precipitation for the winter season throughout most of Europe) but is projected to further increase by the end of the 21st century [51]. These different trends in various precipitation extremes demonstrate the complexity of the link between EDS or EWS and potential impacts.

Figures 3(e) and (g) show the timing and changes in timing of EDS, respectively. In the Central and Northern parts of Scandinavia, EDS on average start in spring, while they start in summer in the South. In the South of Scandinavia, EDS have been shifting towards earlier timing (i.e. for most sites towards earlier in spring), in the North of Scandinavia EDS have shifted towards later starting dates (i.e. towards



**Figure 4.** Extreme dry and wet spell analysis across Australia. (a), (b) Duration of extreme dry (wet) spells. (c), (d) Changes in the duration of extreme dry (wet) spells as percentage change per decade with reference to the duration in 1958. (e), (f) Average within-year timing of extreme dry (wet) spells in the period 1958–2017. (g), (h) Changes in the within-year timing of extreme dry (wet) spells as days per decade with reference to the timing in 1958. Results of (c), (d), (g) and (h) are shown as means across hexagons. Black dots represent the rain gauges examined with locally significant (green) and field significant (magenta) sites. To facilitate the interpretation of results, colors in (e) and (f) match those in figures 2(e), 2(f), 3(e) and 3(f) season-wise.

later in spring). In Denmark, the North of Germany, and the Netherlands, EDS usually start in summer and have shifted towards earlier timing (also reported by Demuth *et al* [59]), potentially negatively affecting

spring crop establishment but also improving sowing possibilities in spring—now the most commonly used window [60]. EDS start later in Central Germany (mainly fall) and the Mountainous Alpine parts of

Germany (late fall, winter). There is a trend towards later timing in the South (Alps). In France, EDS start in summer in the North and have shifted towards earlier timing. In the South of France and the Pyrenees, similar to the Alps, EDS set in in winter and show a trend towards later timing. Throughout Spain, EDS are a summer phenomenon. For most of Spain, there is a trend towards earlier starting dates, thus potentially shifting more towards the reproductive phase of winter crops. In Eastern Europe, EDS predominately start in the fall, and have shifted towards later timing in many regions. There are exceptions such as in Serbia (earlier timing). Our findings on the EDS are in agreement with a detailed study by Serra *et al* (2014), who used daily records from more than 250 rain gauges between the years 1951 and 2000 to improve the knowledge of drought over Europe. Also, Lehner *et al* [61] report that the timing of EDS may lead to a change in drought risk in Europe. Gudmundsson and Seneviratne [62] attributed the change in drought risk in northern Europe and the Mediterranean areas to anthropogenic climate change. EWS start in the fall in most of Scandinavia, and in summer in the central parts (figure 3(f)). In Western Europe, EWS start in the fall and winter. In Southern and Eastern Europe EWS are a spring phenomenon at most locations. Spatial patterns of the changes in the timing of EWS (figure 3(h)) shows similarities to the changes in timing of the EDS (figure 3(g)). Major differences are the South-East of Norway (later timing of EWS), South of Sweden (later timing of EWS) and Spain (primarily later timing of EWS).

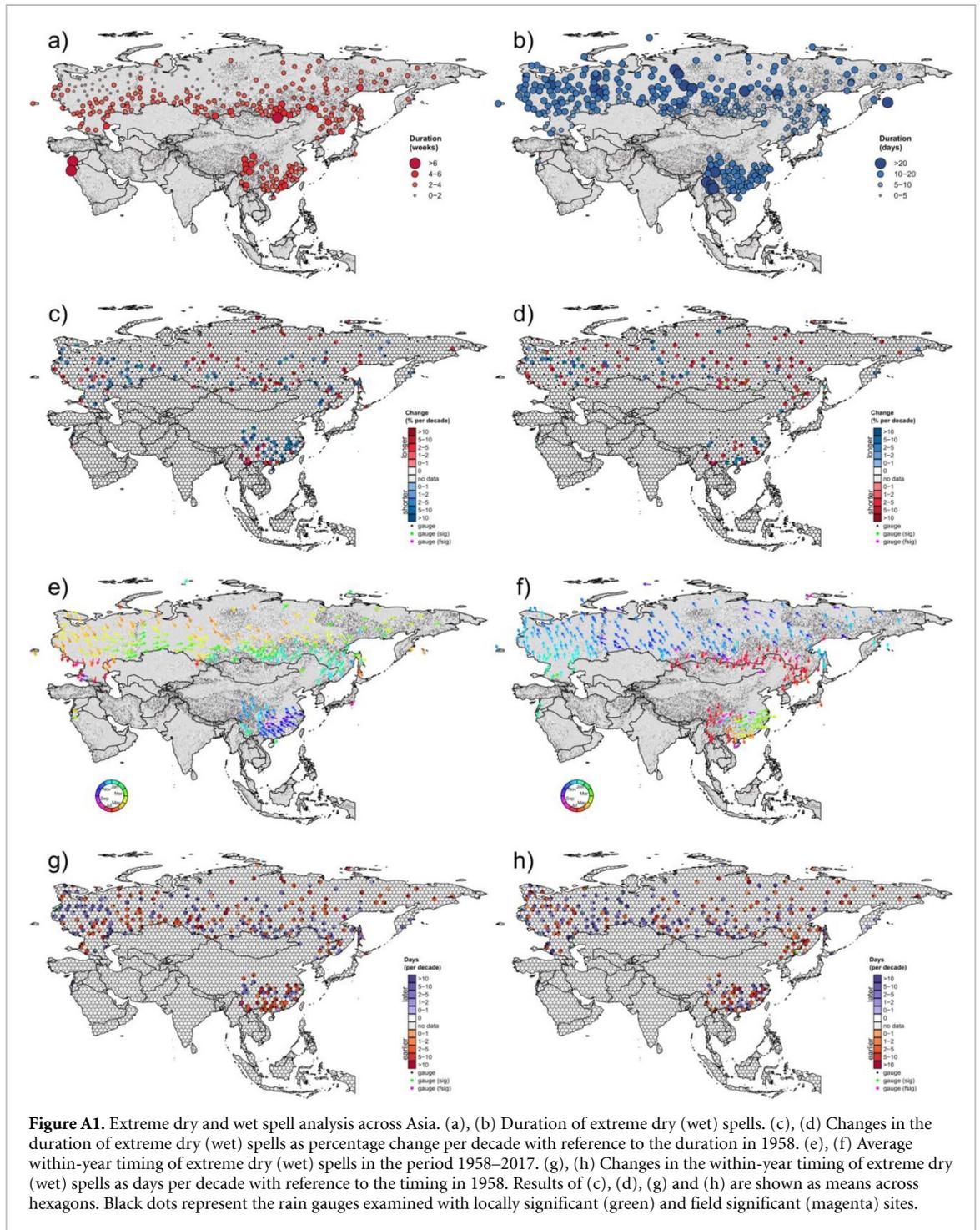
### 3.3. Australia

In Australia, EDS are generally long at locations distant from the coasts (figure 4(a)). EDS tend to exceed six weeks except for on the continental edges in the Southwest, Southeast and East. The opposite applies to EWS, which become longer along the continental edges (figure 4(b)). Trends in the duration of EDS are small across the country (especially along the continental edges) (figure 4(c)). There is a general small trend towards shorter EDS, with local exceptions. The small change is in line with the IPCC that describes no significant change in drought risk (analysis solely based on rainfall) between 1900–2007 [63]. In addition, Jolly, Cochrane, Freeborn, Holden *et al* [58] state that Australia has not been affected by a pronounced trend in wildfire season length. However they identified regional increments in the frequency of anomalously long wildfire seasons. As for the timing, in the North, EDS start in the fall and winter (figure 4(e)) and there is no consistent spatial pattern in the North in regard to the changes in timing (figure 4(g)). In the East, EDS on average start in fall and winter and there is a trend towards later timing (also reported by Murphy and Timbal [64]). In the South-East, EDS typically start in summer and there is a trend towards earlier timing. The earlier timing

in the South-East is consistent with observed trends [65, 66], indicating an earlier start of the bushfire season in the region. In the South-West, EDS are a summer phenomenon and there is a shifts towards later timing. In Western Australia, Power *et al* [67] recognized that the change in onset and duration of EDS could be characterized more as a regime shift of dry spells rather than a downwards trend. For most of Australia, EWS have become longer, except for a small region in the East near the coastline and a larger area in the South-West where the duration has decreased (figure 4(d)). Cook and Heerdegen [68] stated that in Northern Australia the duration of EWS decreases with increasing latitude also because of the effect of the El Niño Southern Oscillation. EWS are a summer phenomenon in the North, and typically start in the fall and winter in the South-East and South-West (figure 4(f)). In general, EWS have shifted towards earlier timing in the North and towards later timing in the South-East and South-West (figure 4(h)).

## 4. Conclusions

We presented a global analysis of changes in the duration and timing of EDS and EWS across three major continents over a period of 60 years (1958–2017). There is a larger number of statistically significant sites for trends in the duration. There is weaker evidence for significant changes in the timing. Specifically, field significance could be detected for the duration of EDS and EWS. For the timing, field significance could only be detected for EDS. However, for both, trends in duration and timing, we could not only demonstrate links between our study and other precipitation related research (such as in the case of precipitation trends across the US), but also find potential links between the observed trends in timing and trends in other environmental hazards. Hence, our analyses add to the evidence that the duration and timing of environmental hazards such as droughts are changing (for example in case of increasing duration of EDS and drought in the South-West of the US or shifts in the timing of EDS in Australia and the bushfire season). Yet, other changes in precipitation-related extremes such as changes in the precipitation intensity can also be important to come up with more detailed conclusions about EDS and EWS, and their possible implications for water resources management. It remains uncertain whether the uncovered trends of EDS and EWS will continue in the future, but the results demonstrate that a comprehensive disaster risk reduction approach may consider both changes in the magnitude and the timing of environmental hazards. For example, resilience in agriculture could be increased by developing crops or varieties with phenology and most sensitive periods that are best suited to the most likely periods of EDS. In addition, the feasibility of supplementary irrigation should be evaluated. However, as many other



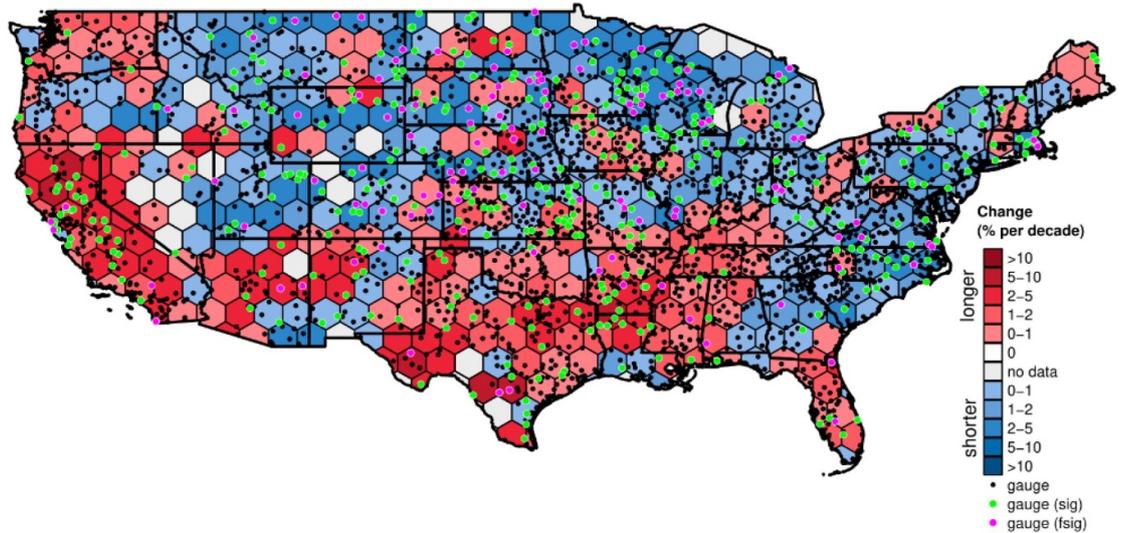
types of infrastructure, irrigation can create harmful social and environmental impacts [69, 70]. The methods presented here are universally applicable to any land surface precipitation dataset and can thus support future research in changes of the duration and within-year timing of extremes.

## Appendix

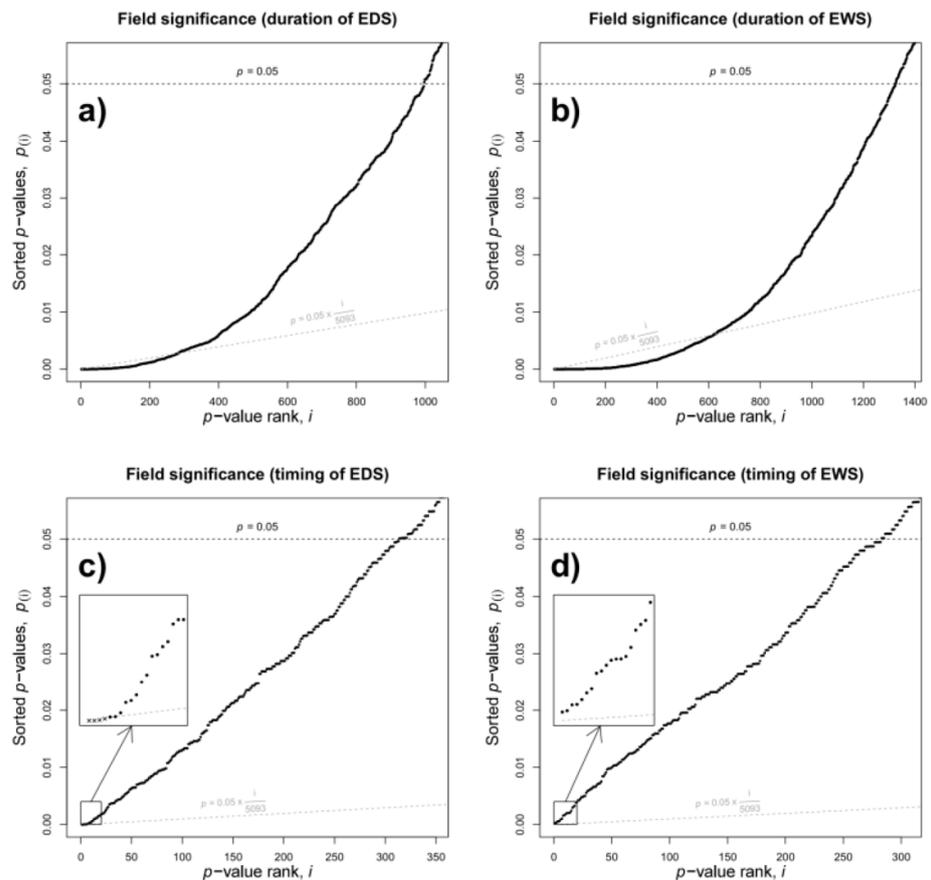
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**Figure A2.** Changes in the duration of extreme dry spells as percentage change per decade with reference to the duration in 1958. The figure shows means per hexagons, estimated from an interpolated grid of  $0.1^\circ$  from ordinary kriging. The interpolation provided values across the entire country, but hexagons that do not contain any rain gauge are grayed out to allow for better comparison with the hexagon means applied in the main part of the article (see figure 2(b)). Black dots represent the rain gauges examined with locally (green) and field significant (magenta) sites.



**Figure A3.** Illustration of the FDR approach for duration of EDS (a) and EWS (b) and the timing of EDS (c) and EWS (d), as suggested by, using  $\alpha_{FDR} = 0.05$  (dashed diagonal line) as control level, and the test level without considering FDR  $\alpha = 0.05$  (dashed horizontal line) indicating rejections at the local level. Plotted points in each subplot represent a part of the (sorted) smallest  $p$ -values of 5309 local tests. Points below the diagonal lines represent significant results according to the FDR control level. As can be seen, field significance (i.e. rejection of the global hypothesis  $H_{0, global} = \text{“no trend at all stations”}$ ) can be declared for (a)–(c), although for the latter only four local tests can be declared significant under the FDR approach (cross symbols). In general, when ignoring the FDR, a considerably larger number of local tests would be declared significant.

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## Data availability

The data that support the findings of this study are openly available at <https://www.ncdc.noaa.gov/ghcnd-data-access>.

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## References

- [1] Singh D, Tsiang M, Rajaratnam B and Diffenbaugh N S 2014 Observed changes in extreme wet and dry spells during the South Asian summer monsoon season *Nat. Clim. Change* **4** 456–61
- [2] Lesk C, Rowhani P and Ramankutty N 2016 Influence of extreme weather disasters on global crop production *Nature* **529** 84
- [3] Vicente-Serrano S M and Begueria-Portugues S 2003 Estimating extreme dry-spell risk in the middle Ebro valley (Northeastern Spain): a comparative analysis of partial duration series with a general Pareto distribution and annual maxima series with a Gumbel distribution *Int. J. Climatol.* **23** 1103–18
- [4] Van Loon A F *et al* 2016 Drought in the Anthropocene *Nat. Geosci.* **9** 89–91
- [5] Ye H C 2018 Changes in duration of dry and wet spells associated with air temperatures in Russia *Environ. Res. Lett.* **13** 034036
- [6] Dracup J A, Lee K S and Paulson E G 1980 On the Definition of Droughts *Water Resour. Res.* **16** 297–302
- [7] Breinl K, Di Baldassarre G, Lopez M G, Hagenlocher M, Vico G and Rutgersson A 2017 Can weather generation capture precipitation patterns across different climates, spatial scales and under data scarcity? *Sci. Rep.* **7** 5449
- [8] Goh S G, Bayen S, Burger D, Kelly B C, Han P, Babovic V and Gin K Y H 2017 Occurrence and distribution of bacteria indicators, chemical tracers and pathogenic vibrios in Singapore coastal waters *Mar. Pollut. Bull.* **114** 627–34
- [9] Wang X, Zhang J, Babovic V and Gin K Y H 2019 A comprehensive integrated catchment-scale monitoring and modelling approach for facilitating management of water quality *Environ. Modell. Softw.* **120** 104489
- [10] van Vliet M T H and Zwolsman J J G 2008 Impact of summer droughts on the water quality of the Meuse river *J. Hydrol.* **353** 1–17
- [11] Whitworth K L, Baldwin D S and Kerr J L 2012 Drought, floods and water quality: drivers of a severe hypoxic blackwater event in a major river system (the southern Murray-Darling Basin, Australia) *J. Hydrol.* **450** 190–8
- [12] Benotti M J, Stanford B D and Snyder S A 2010 Impact of drought on wastewater contaminants in an urban water supply *J. Environ. Qual.* **39** 1196–200
- [13] Sprague L A 2005 Drought effects on water quality in the South Platte River Basin, Colorado *J. Am. Water Resour. Assoc.* **41** 11–24
- [14] Whitehead P G, Wilby R L, Battarbee R W, Kernan M and Wade A J 2009 A review of the potential impacts of climate change on surface water quality *Hydrol. Sci. J.* **54** 101–23
- [15] Mosley L M 2015 Drought impacts on the water quality of freshwater systems; review and integration *Earth Sci. Rev.* **140** 203–14
- [16] Girija T R, Mahanta C and Chandramouli V 2007 Water quality assessment of an untreated effluent impacted urban stream: the Bharalu tributary of the Brahmaputra River, India *Environ. Monit. Assess.* **130** 221–36
- [17] Eng C T, Paw J N and Guarin F Y 1989 The environmental-impact of aquaculture and the effects of pollution on coastal aquaculture development in Southeast-Asia *Mar. Pollut. Bull.* **20** 335–43
- [18] Van Metre P C, Frey J W, Musgrove M, Nakagaki N, Qi S, Mahler B J, Wiczorek M E and Button D T 2016 High nitrate concentrations in some midwest United States streams in 2013 after the 2012 drought *J. Environ. Qual.* **45** 1696–704
- [19] Chowdhury R K and Beecham S 2013 Characterization of rainfall spells for urban water management *Int. J. Climatol.* **33** 959–67
- [20] Donat M G *et al* 2013 Updated analyses of temperature and precipitation extreme indices since the beginning of the twentieth century: the HadEX2 dataset *J. Geophys. Res. Atmos.* **118** 2098–118
- [21] Zolina O, Simmer C, Belyaev K, Gulev S K and Koltermann P 2013 Changes in the duration of European wet and dry spells during the last 60 years *J. Clim.* **26** 2022–47
- [22] Ratan R and Venugopal V 2013 Wet and dry spell characteristics of global tropical rainfall *Water Resour. Res.* **49** 3830–41
- [23] Marengo J A, Jones R, Alves L M and Valverde M C 2009 Future change of temperature and precipitation extremes in South America as derived from the PRECIS regional climate modeling system *Int. J. Climatol.* **29** 2241–55
- [24] Pachauri R K, Allen M R, Barros V R, Broome J, Cramer W, Christ R, Church J A, Clarke L, Dahe Q and Dasgupta P 2014 *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* ed R Pachauri and L Meyer (Geneva: IPCC)
- [25] Li X, Meshgi A and Babovic V 2016 Spatio-temporal variation of wet and dry spell characteristics of tropical precipitation in Singapore and its association with ENSO *Int. J. Climatol.* **36** 4831–46
- [26] Blöschl G, Hall J, Parajka J, Perdigão R A P, Merz B, Arheimer B, Aronica G T, Bilbashi A, Bonacci O and Borga M 2017 Changing climate shifts timing of European floods *Science* **357** 588–90
- [27] Troy T J, Kipgen C and Pal I 2015 The impact of climate extremes and irrigation on US crop yields *Environ. Res. Lett.* **10** 054013
- [28] Malik A I, Colmer T D, Lambers H, Setter T L and Schortemeyer M 2002 Short-term waterlogging has long-term effects on the growth and physiology of wheat *New Phytol.* **153** 225–36
- [29] Daryanto S, Wang L X and Jacinthe P A 2017 Global synthesis of drought effects on cereal, legume, tuber and root

- crops production: a review *Agric. Water Manage.* **179** 18–33
- [30] Berry P M, Sterling M, Spink J H, Baker C J, Sylvester-Bradley R, Mooney S J, Tams A R and Ennos A R 2004 Understanding and reducing lodging in cereals *Adv. Agron.* **84** 217–71
- [31] Trnka M et al 2011 Agroclimatic conditions in Europe under climate change *Glob. Change Biol.* **17** 2298–318
- [32] D'Orangeville L et al 2018 Drought timing and local climate determine the sensitivity of eastern temperate forests to drought *Glob. Change Biol.* **24** 2339–51
- [33] World Bank 2019 *World Bank Open Data* (<https://data.worldbank.org/>)
- [34] USDA 2018 United States Department of Agriculture: Foreign Agricultural Service (<https://www.fas.usda.gov/data>)
- [35] Menne M J, Durre I, Vose R S, Gleason B E and Houston T G 2012 An overview of the global historical climatology network-daily database *J. Atmos. Ocean. Technol.* **29** 897–910
- [36] Richardson C W 1981 Stochastic simulation of daily precipitation, temperature, and solar-radiation *Water Resour. Res.* **17** 182–90
- [37] Okoli K, Mazzolenni M, Breinl K and Di Baldassarre G 2019 A systematic comparison of statistical and hydrological methods for design flood estimation *Hydrol. Res.* **50** 1665–78
- [38] Theil H 1992 *Henri Theil's Contributions to Economics and Econometrics* (Dordrecht: Kluwer Academic) pp 345–81
- [39] Mardia K V and Jupp P E 2009 *Directional Statistics* vol 494 (London: Wiley)
- [40] Bayliss A C and Jones R C 1993 *Peaks-over-Threshold Flood Database* (Wallingford: Institute of Hydrology) IH Report No 121
- [41] Burn D H 1997 Catchment similarity for regional flood frequency analysis using seasonality measures *J. Hydrol.* **202** 212–30
- [42] Yue S, Pilon P and Cavadias G 2002 Power of the Mann-Kendall and Spearman's rho tests for detecting monotonic trends in hydrological series *J. Hydrol.* **259** 254–71
- [43] Wilks D S 2016 “The stippling shows statistically significant grid points” how research results are routinely overstated and overinterpreted, and what to do about it *Bull. Am. Meteorol. Soc.* **97** 2263
- [44] Wilks D S 2006 On “field significance” and the false discovery rate *J. Appl. Meteorol. Clim.* **45** 1181–9
- [45] Benjamini Y and Hochberg Y 1995 Controlling the false discovery rate—a practical and powerful approach to multiple testing *J. R. Stat. Soc. B* **57** 289–300
- [46] Murawski A, Zimmer J and Merz B 2016 High spatial and temporal organization of changes in precipitation over Germany for 1951–2006 *Int. J. Climatol.* **36** 2582–97
- [47] Mehrotra R, Srikanthan R and Sharma A 2006 A comparison of three stochastic multi-site precipitation occurrence generators *J. Hydrol.* **331** 280–92
- [48] Romero-Lankao P, Smith J B, Davidson D J, Diffenbaugh N S, Kinney P L, Kirshen P, Kovacs P and Villers-Ruiz L 2014 *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change* ed V R Barros et al (Cambridge, New York: Cambridge University Press) pp 1439–98
- [49] Wuebbles D J, Fahey D W, Hibbard K A, Dokken D J, Stewart B C and Maycock T K (ed) 2017 *Climate Science Special Report: Fourth National Climate Assessment vol I* (Washington, DC: US Global Change Research Program) (<https://doi.org/10.7930/J0J964J6>)
- [50] AghaKouchak A, Feldman D, Hoerling M, Huxman T and Lund J 2015 Water and climate: recognize anthropogenic drought *Nature* **524** 409–11
- [51] Tebaldi C, Hayhoe K, Arblaster J M and Meehl G A 2007 Going to the extremes—an intercomparison of model-simulated historical and future changes in extreme events *Clim. Change* **82** 233–4
- [52] Guzman-Morales J and Gershunov A 2019 Climate change suppresses santa ana winds of Southern California and sharpens their seasonality *Geophys. Res. Lett.* **46** 2772–80
- [53] Kovats R S, Valentini R, Bouwer L M, Georgopoulou E, Jacob D, Martin E, Rounsevell M and Soussana J F 2014 *Climate Change 2014: Impacts, Adaptation, And Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change* ed V R Barros et al. (Cambridge: Cambridge University Press) pp 1267–326
- [54] Ministry of the Environment 2007 *Sweden Facing Climate Change—Threats and Opportunities* (Stockholm: Swedish Government Official Reports) Report No. SOU 2007:60 (<https://www.government.se/legal-documents/2007/12/sou-200760/>)
- [55] Zolina O, Simmer C, Gulev S K and Kollet S 2010 Changing structure of European precipitation: longer wet periods leading to more abundant rainfalls *Geophys. Res. Lett.* **37** L06704
- [56] Zebisch M, Grothmann T, Schröter D, Hasse C, Fritsch U and Cramer W 2005 Climate change in Germany: vulnerability and adaption of climate sensitive sectors; Klimawandel in Deutschland. Vulnerabilität und Anpassungsstrategien klimasensitiver Systeme (Dessau: German Environment Agency (Umweltbundesamt))
- [57] New M, Hulme M and Jones P 1999 Representing twentieth-century space-time climate variability. Part I: development of a 1961–90 mean monthly terrestrial climatology *J. Clim.* **12** 829–56
- [58] Jolly W M, Cochrane M A, Freeborn P H, Holden Z A, Brown T J, Williamson G J and Bowman D M J S 2015 Climate-induced variations in global wildfire danger from 1979 to 2013 *Nat. Commun.* **6** 7537
- [59] Demuth S, Lehner B and Stahl K 2000 Assessment of the vulnerability of a river system to drought *Drought and Drought Mitigation in Europe (Advances in Natural and Technological Hazards Research vol 14)* ed J V Vogt and F Somma (Berlin: Springer) pp 209–19
- [60] Trnka M, Rotter R P, Ruiz-Ramos M, Kersebaum K C, Olesen J E, Zalud Z and Semenov M A 2014 Adverse weather conditions for European wheat production will become more frequent with climate change *Nat. Clim. Change* **4** 637–43
- [61] Lehner B, Doll P, Alcamo J, Henrichs T and Kaspar F 2006 Estimating the impact of global change on flood and drought risks in Europe: a continental, integrated analysis *Clim. Change.* **75** 273–99
- [62] Gudmundsson L and Seneviratne S I 2016 Anthropogenic climate change affects meteorological drought risk in Europe *Environ. Res. Lett.* **11** 044005
- [63] Reisinger A, Kitching R L, Chiew F, Hughes L, Newton P C D, Schuster S S, Tait A and Whetton P 2014 *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change* ed V R Barros et al (Cambridge: Cambridge University Press) pp 1371–438
- [64] Murphy B F and Timbal B 2008 A review of recent climate variability and climate change in southeastern Australia *Int. J. Climatol.* **28** 859–79
- [65] Clarke H G, Smith P L and Pitman A J 2011 Regional signatures of future fire weather over eastern Australia from global climate models *Int. J. Wildland Fire* **20** 550–62
- [66] Lucas C, Hennessy K, Mills G and Bathols J 2007 Bushfire weather in southeast Australia: recent trends and projected climate change impacts (Melbourne: Bushfire Cooperative Research Centre, Australian Bureau of Meteorology and CSIRO Marine and Atmospheric Research) (<https://doi.org/10.25919/5e31c82ee0a4c>)
- [67] Power S, Sadler B and Nicholls N 2005 The influence of climate science on water management in Western

- Australia—lessons for climate scientists *Bull. Am. Meteorol. Soc.* **86** 839
- [68] Cook G D and Heerdegen R G 2001 Spatial variation in the duration of the rainy season in monsoonal Australia *Int. J. Climatol.* **21** 1723–32
- [69] Di Baldassarre G, Wanders N, AghaKouchak A, Kuil L, Ramagecroft S, Veldkamp T I E, Garcia M, van Oel P R, Breinl K and Van Loon A F 2018 Water shortages worsened by reservoir effects *Nat. Sustain.* **1** 617–22
- [70] Thacker S, Adshead D, Fay M, Hallegatte S, Harvey M, Meller H, O'Regan N, Rozenberg J, Watkins G and Hall J W 2019 Infrastructure for sustainable development *Nat. Sustain.* **2** 324–31