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Increases in summertime concurrent drought and heatwave in Eastern China

Qinqin Kong [a,b,*], Selma B. Guerreiro [b], Stephen Blenkinsop [b], Xiao-Feng Li [b], Hayley J. Fowler [b]

[a] Key Laboratory of Land Surface Pattern and Simulation, Institute of Geographical Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing, 100101, China

[b] School of Engineering, Newcastle University, Newcastle upon Tyne, UK

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ABSTRACT

Droughts and heatwaves can have profound impacts on society and the environment, which can be exacerbated by their co-occurrence. However, in China, co-occurrence of droughts and heatwaves has not been explored. Here we assess concurrent drought and heatwave events (CONDH) in summer across eastern China (EC) for 1962–2015. We found that these events are more frequent in the North and South of EC (>20 events during 1962–2015) and less frequent in the central region. In the North and South regions, intensity of heatwaves is ~2–4 times higher during drought conditions than in average conditions. Also, in these two regions the number of CONDH events is more than double what would be expected if droughts and heatwaves were independent. When analyzing changes between 1962–1988 and 1989–2015, the dependence between drought and heatwave was shown to be stable, but the number of CONDH more than doubled in parts of the North and small areas in the South, and decreased by over 50% in the southern central region. We have shown that the North and South of EC are hotspots of compound droughts and heatwaves and therefore it is crucial to considering both events together when assessing how to adapt to present and future weather extremes.

1. Introduction

Climate extremes have received much attention due to their disproportionate societal and ecological impacts (IPCC, 2013). The largest impacts often stem from a combination of climatic events (termed a 'compound event' by the Intergovernmental Panel on Climate Change (IPCC, 2012)) which are not necessarily individually extreme (AghaKouchak et al., 2014; Hegerl et al., 2011; Leonard et al., 2014). Individual events may also be physically interrelated with potential feedbacks which can amplify the impacts (Leonard et al., 2014). Hence, conventional analyses of univariate extremes may significantly underestimate the impact of concurrent extremes (AghaKouchak et al., 2014; Fischer and Knutti, 2013; Gräler et al., 2013).

Droughts and heatwaves are two of the most important climate hazards around the world with profound impacts on society and the environment (Ciais et al., 2005; Easterling et al., 2000). Temperature and precipitation have been well recognized to be closely associated with each other at different timescales due to their thermodynamic relationship. For example, at seasonal and longer timescales negative correlations are dominant over land in summer (Adler et al., 2008; Crutcher, 1978; Déry and Wood, 2005; Huang & Van den Dool, 1993; Isaac and Stuart, 1992; Madden and Williams, 1978; Trenberth and Shea, 2005; Zhao and Khalil, 1993). It is reasonable to expect that such a negative correlation between temperature and precipitation may lead to a positive association between the occurrences of heatwaves and droughts (Zscheischler et al., 2018). Moreover, when drought and heatwave occur simultaneously, the magnitude of individual hazards can be intensified through soil moisture-atmosphere coupling (Shukla et al., 2015). High temperatures can substantially enhance evaporation, thereby aggravating drought severity (Dai, 2013; Dai et al., 2004); a dry surface is favorable for more sensible heating of the atmosphere and consequently elevated air temperatures (Greve et al., 2014; Mueller and Seneviratne, 2012; Seneviratne et al., 2006). The recent 2003 European, 2010 Russian, and 2014 California droughts and heatwaves are archetypes of concurrent extreme hot and dry conditions (AghaKouchak et al., 2014; Fink et al., 2004; Trenberth and Fasullo, 2012), with associated high fatalities and large economic losses. Understanding the drought-heatwave relationship is necessary for estimating the risk of

* Corresponding authorKey Laboratory of Land Surface Pattern and Simulation, Institute of Geographical Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing, 100101, China.

E-mail address: kongqq@igsnrr.ac.cn (Q. Kong).

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impacts associated with their concurrence. Further, identifying hotspots of drought-heatwave compound events and detecting their temporal changes are critical in preparing for their adverse effects and designing adaption strategies.

In this study, dependence refers to the tendency for two individual events to facilitate (positive dependence) or inhibit (negative dependence) each other in terms of occurrence, duration and/or intensity, and concurrence refers to a case in which two individual events occur simultaneously. Up to now, limited research has explored drought-heatwave (or dry-hot) dependence. Lyon (2009) revealed that the probabilities of heatwaves conditional on droughts are higher than the unconditional probabilities in the interior of South Africa. This drought-heatwave dependence did not substantially change in climate projections. Zscheischler and Seneviratne (2017) identified a positive correlation between the occurrences of hot and dry summers which leads to a much higher frequency of their concurrences than would be expected when assuming independence between them. Many other studies have found a contribution of low antecedent soil moisture or preceding precipitation deficits to summer hot extremes in transitional zones between wet and dry climates based on either modelling (Fischer et al., 2007a,b; Seneviratne et al., 2006) or observational datasets (Durre et al., 2000; Hirschi et al., 2011; Mueller and Seneviratne, 2012; Vautard et al., 2007). These studies, aimed at improving the prediction skill of summer hot events, employed time-lagged data with precipitation leading, and indicated soil moisture-temperature feedback as the potential mechanism.

Several studies have examined the statistics of concurrent extreme hot and dry events. Mazdiyasni and AghaKouchak (2015) reported increases in both the frequency and spatial extent of concurrent droughts and heatwaves across the United States from 1960 to 2010. Similar results were obtained by Sharma and Mujumdar (2017) over India. Using CMIP5 simulations, Zscheischler and Seneviratne (2017) found that in many regions globally, the frequency of concurrent hot and dry summers (temperature and dryness exceeding the historical 90th percentiles simultaneously) increases by a factor of 10 between 1870 and 1969 and the 21st century, mainly driven by long-term trends in temperature and precipitation. The negative inter-annual correlation between linearly detrended temperature and precipitation was found to intensify, consistent with a doubling in the likelihood of the 100-year concurrent event in some regions. Other research has categorized simultaneous temperature and precipitation anomalies into four modes, namely warm/wet, warm/dry, cold/wet, and cold/dry combinations, and investigated their changes in different regions (Beniston, 2009a; b; Estrella and Menzel, 2013; Hao et al., 2013). The general findings point to a pattern of significantly more frequent warm modes across the globe with some seasonal variations (Estrella and Menzel, 2013).

In China, drought and heatwave have been intensively studied as univariate extremes. Drought shows pronounced decadal variations since the mid-20th century, being more frequent and severe before the 1980s and in the 2000s compared with the 1980s and 1990s (Chen and Sun, 2015). Since the late 1990s, drought has become significantly more frequent, more severe, longer in duration and larger in extent across China, especially over northern regions (Chen and Sun, 2015; Shao et al., 2018; Yu et al., 2014; Zou et al., 2005). Heatwaves have increased significantly across the nation during recent decades, except for a slight decrease in central China (Ding et al., 2010; Wei and Chen, 2011). This increasing tendency is expected to continue in the future with increasing rates depending on the level of future greenhouse gas emissions (Guo et al., 2017; Yao et al., 2012; Zhou et al., 2014). Sun et al. (2014) projected that, by 2030s in eastern China (under RCP4.5 scenario), more than half of summers will be hotter than the 2013 summer when the number of hot days (daily maximum temperature > 35 °C) reached a historical high of 31 days.

However, the joint occurrence of drought and heatwave in summer has not been explored in China. This is an important research gap since co-occurring droughts and heatwaves have impacts that are potentially greater than the sum of the impacts of droughts and heatwaves. Impacts that could potentially be increased by co-occurrence include increased wildfire risk (Brando et al., 2014; Ruffault et al., 2018), widespread crop failure (Barnabás et al., 2008), tree mortality (Allen et al., 2010), and higher risk of failure of electric power plants (Bartos and Chester, 2015). Furthermore, potential future adaptation for heatwaves in urban areas include green spaces, water features, and the use of air-conditioning which assume the absence of drought conditions. Therefore, in this paper, we assess for the first time: 1) the number of concurrent drought and heatwave events (CONDH) in summer across eastern China (EC) for the period 1962–2015; 2) whether drought-heatwave (D-H) dependence is seen in observations; 3) changes in the number of CONDH from 1962 to 1988 to 1989–2015, and discuss possible drivers.

2. Data and methods

2.1. Data

We obtained 0.5° gridded monthly precipitation, monthly mean temperature and daily maximum temperature ($T_{\max}$) data for summer (JJA) during the period 1962–2015 in EC (east of 105°E). The dataset, developed by the National Meteorological Information Center (NMIC) of China, is a result of thin-plate spline interpolation based on observations from 2 472 meteorological stations and the GTOPO30 DEM data (Zhao, 2012). The NMIC assessed the quality of the dataset using in-situ observations (National Meteorological Information Center, 2012a, 2012b) (See Text S1 in the Supplementary Information, denoted henceforth as SI). In order to further assess the suitability of the gridded data for this analysis, in-situ observations of monthly precipitation and daily $T_{\max}$ covering the same period and region were obtained from the NMIC to enable comparison between results based on the gridded and gauge data. We used 367 meteorological stations without missing values. The gauge data were subject to a strict quality control procedure by the NMIC, including checks for high-low extreme values and time consistency (Li et al., 2004).

2.2. Definition of concurrent drought and heatwave

A CONDH was defined as an event with a heatwave occurring within a drought context. Multiple heatwaves within a drought correspond to multiple CONDH events. Here, drought was defined in meteorological terms, as a precipitation deficit over time relative to the climatology. The Standard Precipitation Index (SPI) was applied to quantify drought conditions. It is a normalization of precipitation values and can be calculated at different timescales (Mckee et al., 1993). In this study, drought was defined over a monthly timescale as 1-month SPI values (hereinafter referred to as SPI1) smaller than -1. The SPI values are expected to be normally distributed. However, this may not be true for arid climates or dry seasons on short time scales where the precipitation is highly positively skewed with many zero values (Wu et al., 2007). Hence, we conduct normality tests on the distribution of SPI1 values for each grid cell showing that the normal distribution was accepted consistently (See SI, Text S2).

Here, a heatwave refers to a spell of at least three consecutive days with $T_{\max}$ exceeding the 90th percentile of summer daily $T_{\max}$ calculated over the whole study period. Heatwave occurrence refers to the number of heatwaves during a certain period, say a month; heatwave duration was defined as the number of days within a heatwave; heatwave intensity was defined as the sum of the $T_{\max}$ excesses over the 90th percentile threshold over the duration of a heatwave. Heatwaves occurring across monthly boundaries were allocated to the month in which they started.

2.3. D-H dependence measure

The D-H dependence refers to the tendency for drought and heatwave to facilitate (positive dependence) or inhibit (negative dependence) each other in terms of occurrence, duration and/or intensity. In this study, the D-H dependence was quantified, in a statistical sense, through comparing the occurrence, duration, or intensity of heatwave conditional on the presence of droughts with the corresponding unconditional heatwave statistics. Specifically, the D-H dependence measure was constructed as the ratio of mean monthly accumulated heatwave occurrence, duration, or intensity for drought months to the corresponding statistics for all months in the record, respectively denoted as DH_O, DH_d, and DH_i:

$$DH_o = \frac{HO_D/DM}{HO/TM} \tag{1}$$

$$DH_d = \frac{HD_D/DM}{HD/TM} \tag{2}$$

$$DH_i = \frac{HI_D/DM}{HI/TM} \tag{3}$$

where HO_D (HO), HD_D (HD) and HI_D (HI) refer to accumulated heatwave occurrence, duration and intensity during drought (all) months; DM and TM respectively denote the number of drought months and all months in the record. A higher value indicates a stronger D-H dependence and vice versa.2.4 Quantifying the contribution of D-H dependence to CONDH occurrences.

We first examined the number of summertime CONDH for the period 1962–2015. To quantify the contribution of D-H dependence to CONDH occurrences, we compared the observed number of CONDH with the expected number of CONDH assuming independence between drought and heatwave occurrences (hereinafter referred as $CONDH_{ind}$). Given the observed number of CONDH, the remaining problem is therefore to calculate $CONDH_{ind}$:

If drought and heatwave occur independently, the D-H dependence ratio, DH_O, is expected to take the value 1. That is,

$$DH_o = \frac{HO_D/DM}{HO/TM} = \frac{CONDH_{ind}/DM}{HO/162} \tag{4}$$

where the number of CONDH ($CONDH_{ind}$), by definition, equals the number of heatwaves under droughts (HO_D), and there are 162 summer months in total during the study period. A rearrangement of equation (4) leads to:

$$CONDH_{ind} = \frac{HO}{162} DM \tag{5}$$

2.4. Bootstrap statistical significance test

This study employed a bootstrap approach for the test of statistical significance. The original monthly heatwave and SPI1 series (1962–2015) were resampled 10,000 times using a pairwise block method (with non-overlapping blocks comprising the three consecutive summer months of each year to take into account the intra-annual autocorrelation) (Guerreiro et al., 2018; Hirschi et al., 2011). For detailed information, see SI, Text S3.

3. Results and discussion

Fig. 1 maps the number of CONDH during the period 1962–2015. Both the station and gridded data show a similar spatially heterogeneous pattern with more CONDH occurrences in the south of EC and parts of the north (>20 events), and fewer in the central region. The southwest of EC stands out as a hotspot, with at least 26 CONDH events. Furthermore, the consistency between results for station and gridded data provides additional confidence in the validity of the gridded dataset for this analysis and so hereafter we present results using only this dataset.

Nevertheless, interpretations based on occurrence only may lead to incomplete results regarding the spatial distribution of the severity of such compound events. For example, it is possible that a region with fewer CONDH occurrences (namely a smaller number of heatwaves under drought conditions) could have the same or even more heatwave days under drought conditions than other areas if the heatwaves in that region are more persistent (since each heatwave will have more heatwave days). Therefore, we also assessed the accumulated heatwave duration and intensity conditional on drought for 1962–2015 (Fig. S1),

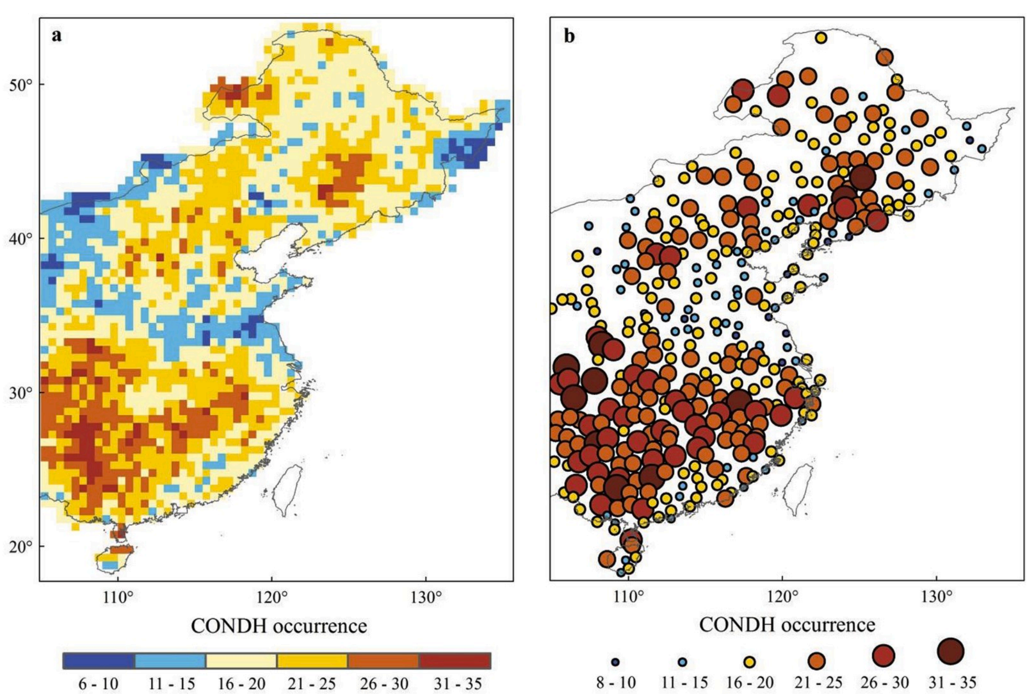

Fig. 1. The number of CONDH in summer (JJA) across eastern China for the period 1962–2015 based on (a) gridded and (b) gauge dataset. The definitions of SPI1<−1 for drought and 3d 90th percentile for heatwave were used.

showing a somewhat different distribution compared with CONDH occurrence. With regard to the number of heatwave days conditional on droughts, the south region, especially the Yangtze River basin, far outweighs other areas, possibly because heatwaves in the region are more persistent under the control of the Subtropical High in summer. In terms of heatwave intensity conditional on droughts, the north region becomes the hot spot, with more widespread high intensities than the south, especially the southern coastal area. This is probably associated with the variability of daily maximum temperature which is higher (lower) in the north (south) leading to larger (smaller) temperature threshold exceedances and consequently a higher (lower) accumulated heatwave intensity. The central area, in comparison, is less influenced by the CONDH events, for all three metrics.

Given the number of CONDH presented in Fig. 1, an interesting question to ask is whether there is a positive dependence between the occurrences of drought and heatwave, and if there is, the contribution of this dependence to the CONDH occurrence pattern.

Fig. 2 maps DH_i values, showing a significant positive D-H dependence across most of EC, especially in the north and south where the monthly accumulated heatwave intensity is 2–3.9 times higher during drought months than for all months.

The D-H dependence ratio and CONDH occurrences share a very similar spatial distribution (compare Figs. 1a and 2), indicating that the positive dependence between droughts and heatwaves may be able to explain why some regions experience concurrent events more often than others do. To verify this inference, we calculated the expected number of CONDH assuming that the occurrences of drought and heatwave are independent (Fig. 3a), and compared it with the observed number of CONDH (Fig. 1a). This shows that the positive D-H dependence contributes to significantly more CONDH occurrences throughout EC (Fig. 3b). For example, in the southwest, the number of CONDH is increased by a value between 12 and 23 (equivalent to more than a doubling) because of D-H dependence, making it the region most frequently hit by such compound events. In the north region, where there are fewest CONDH occurrences if drought and heatwave are independent (Fig. 3a), positive D-H dependence contributes to an increase of 8–23 (again equivalent to more than a doubling) concurrent events, making this region one of the hotspots of such compound events.

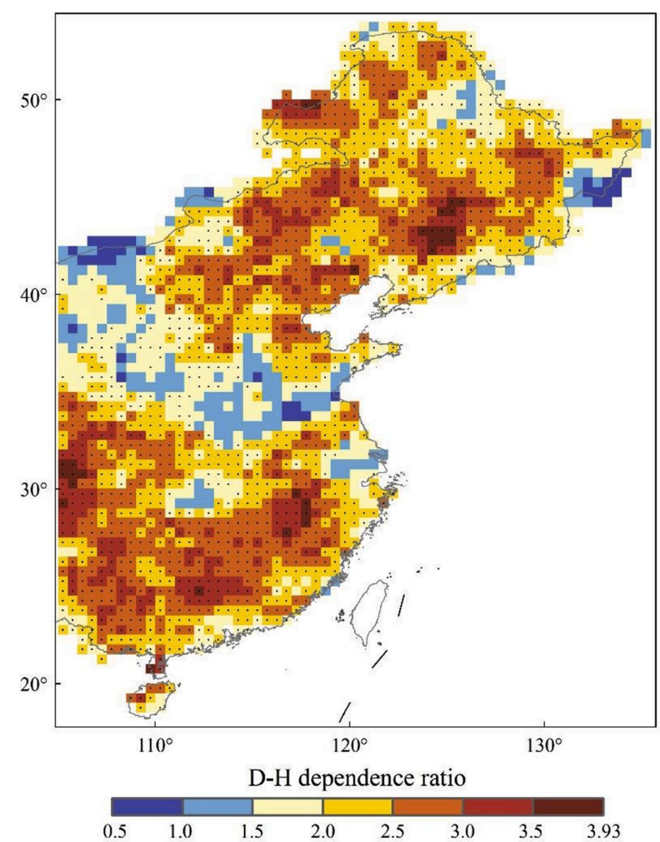

Fig. 2. The D-H dependence ratio, DH_i (mean heatwave intensity for drought months divided by mean heatwave intensity for all months), across eastern China during summer (JJA) for the period 1962–2015. Definitions of SPI1<-1 for drought and 3d 90th percentile for heatwave were used. Grids showing statistically significant positive D-H dependence (at 0.05 significance level) are marked by black dots.

The D-H dependence was also measured by DH_o and DH_d, with similar spatial patterns but consistently smaller magnitudes (Fig. S2). The reason for the higher values of DH_i may be associated with the way heatwave intensity was defined, i.e., as the sum of temperature excesses over the duration of a heatwave, therefore including the combined effects of both the number of heatwave days and temperature magnitudes. It indicates that there are not only more frequent heatwaves but also more intense and longer heatwaves under drought conditions, strengthening the justification for examining these two events concurrently.

We also examined the results obtained using different definitions of drought (SPI1<-1 and SPI1<-1.5) and heatwave (all combinations of 3d, 5d, and 7d for duration and 90th and 95th percentiles for daily Tmax threshold) to explore the nature of the D-H dependence for different types of heatwave and drought, and to test the robustness of the D-H dependence to the sample sizes of heatwave and drought (Fig. S3). All definitions show a consistent spatial pattern for D-H dependence (based on DH_i). However, a stronger D-H dependence was detected under more strict definitions of drought and heatwave, indicating a greater tendency for more severe droughts and heatwaves to occur together. For instance, under the definition of SPI1<-1.5 and 5d 95th percentile, the monthly accumulated heatwave intensity is 5–14 times higher during drought months than for all months in parts of the north and south of EC (Fig. S3, panel l). However, the statistical significance was maintained over a much smaller area for severe droughts and heatwaves due to smaller sample sizes – e.g. using SPI1<-1 and 3d 90th percentile creates 23–27 droughts and 46–88 heatwaves (Fig. S4a) while the strictest definition (SPI1<-1.5 and 7d 95th percentile) generates only 9–12 droughts and no more than 12 heatwaves (Fig. S4f).

Furthermore, the D-H dependence was examined for drought over longer timescales (SPI3<-1 and SPI6<-1) (Fig. S5). This showed that the D-H dependence is stronger for 1-month drought than 3- or 6-month droughts (except for some areas in the north). This discrepancy can be explained by the timescales of physical processes underlying the D-H dependence. Soil moisture-atmosphere coupling is an important contributing factor to D-H dependence by affecting the partitioning of latent and sensible heat fluxes (Zhang et al., 2011). It can support the association between positive temperature anomalies and precipitation deficits not only over the same few days but also during the preceding months because of the long memory of soil moisture. However, internal atmospheric processes can also play a role, such as the correspondence between clear skies and more incoming shortwave radiation (Trenberth and Shea, 2005) mediated by meso-scale circulation conditions, the cooling effects of rain on surface air (Bao et al., 2017; Lenderink et al., 2011; Waliser and Graham, 1993), and the common association of high temperatures and less rain with quasi-stationary anticyclonic systems. All these atmospheric processes operate at a synoptic scale, and hence can only support the dry-hot association within a relatively short time window. Therefore, the relative magnitude of D-H dependences between SPI1, SPI3, and SPI6 are probably modulated by the relative roles of soil moisture-atmosphere coupling and internal atmospheric processes in controlling the dependence between droughts and heatwaves. For example, the 3- and 6-month SPI indicate a stronger D-H dependence in some areas in the north, probably because soil moisture-atmosphere coupling plays a more prominent role in this region and thus the incorporation of antecedent precipitation results in a closer association

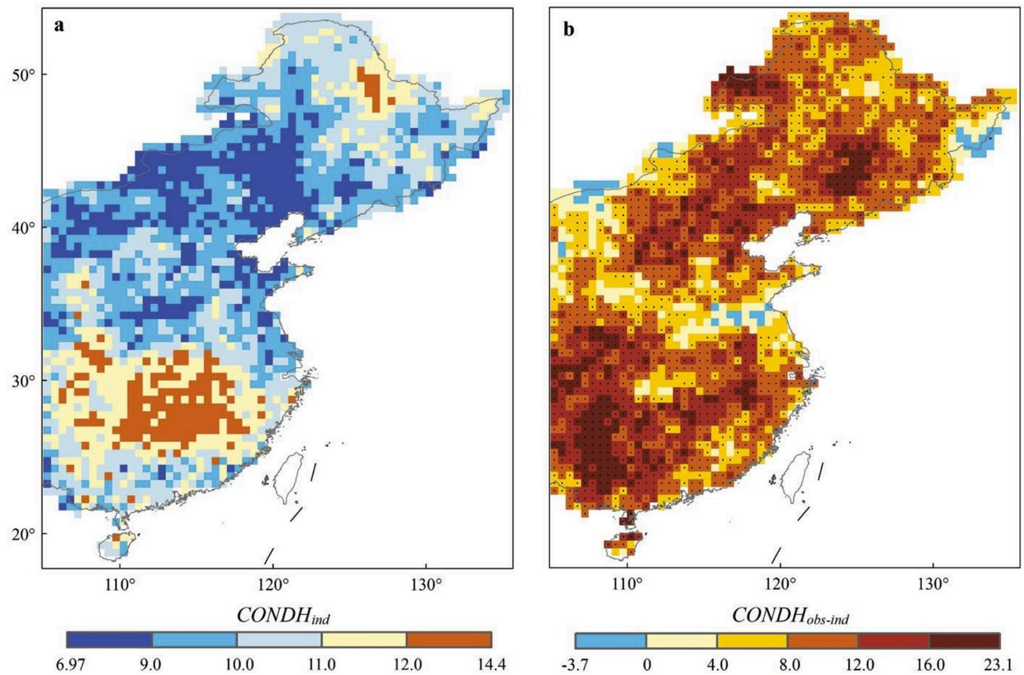

Fig. 3. (a) The expected number of CONDH in summer (JJA) across eastern China for the period 1962–2015 under the assumption that drought and heatwave are independent. (b) Differences between the observed number of CONDH ($CONDH_{obs}$) and the expected number of CONDH assuming independency between drought and heatwave ($CONDH_{ind}$), i.e. Fig. 1a minus Fig. 3a. The definitions of SPI1<−1 for drought and 3d 90th percentile for heatwave were used. Grids showing statistically significant differences between $CONDH_{obs}$ and $CONDH_{ind}$ (at 0.05 significance level) are marked by black dots in (b).

between drought and heatwave. Several previous studies have also reported significant contributions of antecedent precipitation deficits to summer hot extremes over North and Northeast China (Liu et al., 2014; Wu and Zhang, 2015; Zhang and Dong, 2010; Zhang et al., 2011), which have been identified as hot spots of land-atmosphere coupling (Koster et al., 2004, 2005). As demonstrated above, a stronger D-H dependence translates into a higher probability of CONDH events. Hence, these regions may be more prone to the concurrence of summer hot extremes and long-lasting droughts extending from spring to summer.

The consistency of D-H dependence and CONDH occurrence results were further checked using another widely used drought index, the standardized precipitation-evapotranspiration index (SPEI). The D-H dependence indicated by the SPEI shows a very similar spatial pattern with that derived using the SPI, but is substantially stronger possibly because the SPEI includes the effects of temperature in measuring drought condition. For details, please refer to the Supplementary Information (Text S4).

Finally, we investigated changes in the number of CONDH from 1962 to 1988 to 1989–2015. A significant increase by more than a factor of two was detected in parts of the north and small areas in the south, and a significant decrease by over 50% was found in the southern central region (Fig. 4a). Changes in compound events could be a result of changes in either marginal variables/processes or their dependence structure, or both. Here we present a preliminary and qualitative exploration of the possible drivers of changes in the number of CONDH, by comparing the separate changes of heatwave occurrence, drought occurrence and D-H dependence. As shown in Fig. 4b, the number of heatwaves significantly increased by over 50% (and by more than a factor of two in some areas) in parts of the north and, to a lesser extent, the south. Contrasting with the general warming trend, central China shows little increase in heatwaves, or even a cooling tendency, which has been recorded in many previous studies (Ding et al., 2010; Hu et al., 2003; Wei and Chen, 2011; Yu and Zhou, 2007). A possible cause is the wetting trend in central China induced by a weakening of the East Asian summer monsoon (Wei and Chen, 2009; Yu et al., 2004). The number of droughts has more than doubled in some northern grid cells and significantly decreased by over 50% in the southern central region (Fig. 4c). The D-H dependence however shows no significant change at most grid cells (Fig. 4d), with no coherent spatial pattern to the changes either. Hence, comparison between Fig. 4b and c suggests that increases in heatwaves are probably the main driver for the increased number of CONDH in the north and south, and that decreases in CONDH in the southern central region are probably mainly due to a reduction in drought occurrences.

4. Conclusions

Concurrent drought and heatwave is a common phenomenon in summer across eastern China with more occurrences (>20 events in 54 years) in the south and parts of the north, and fewer occurrences in the central region. Contrary to most studies in this field, we here focus on droughts and heatwaves, rather than dry and hot events (Beniston, 2009a, 2009b; Estrella and Menzel, 2013; Hao et al., 2013) which is more relevant from an impact perspective.

Our analyses detect a significant positive D-H dependence in the north and south of eastern China where the monthly accumulated heatwave intensity conditional on drought is ~2–4 times higher than the unconditional intensity. This positive D-H dependence contributes to at least 100% more CONDH occurrences in the southwest and north of EC than we would expect if heatwaves and droughts occurred independently, making these regions hotspots of such compound events. The positive D-H dependence found in China is consistent with results from a previous study in Europe (Fischer et al., 2007b) that reported more frequent heatwave events which are physically linked with lower soil moisture, as the drier land surface causes more heatwave events through modulation of the latent and sensible heat fluxes (Fischer et al., 2007b). However, the positive co-dependence presented here may also be partially due to the common association of low rainfall and heatwaves with large-scale quasi-stationary anticyclonic systems which generally produce dry and hot weather. Such anticyclonic circulation is common during summer in southern China when it is under the control of Western Pacific Subtropical High. Attributing the relative contribution of these physical processes that may lead to the observed co-dependence is though a non-trivial issue. Heatwave and drought are phenomena that are themselves typically measured and develop on different timescales, but their physical driving mechanisms also operate across multiple scales. For example, atmospheric circulation varies over days but also displays interannual variability, and its effects may be modulated by land-atmosphere interactions.

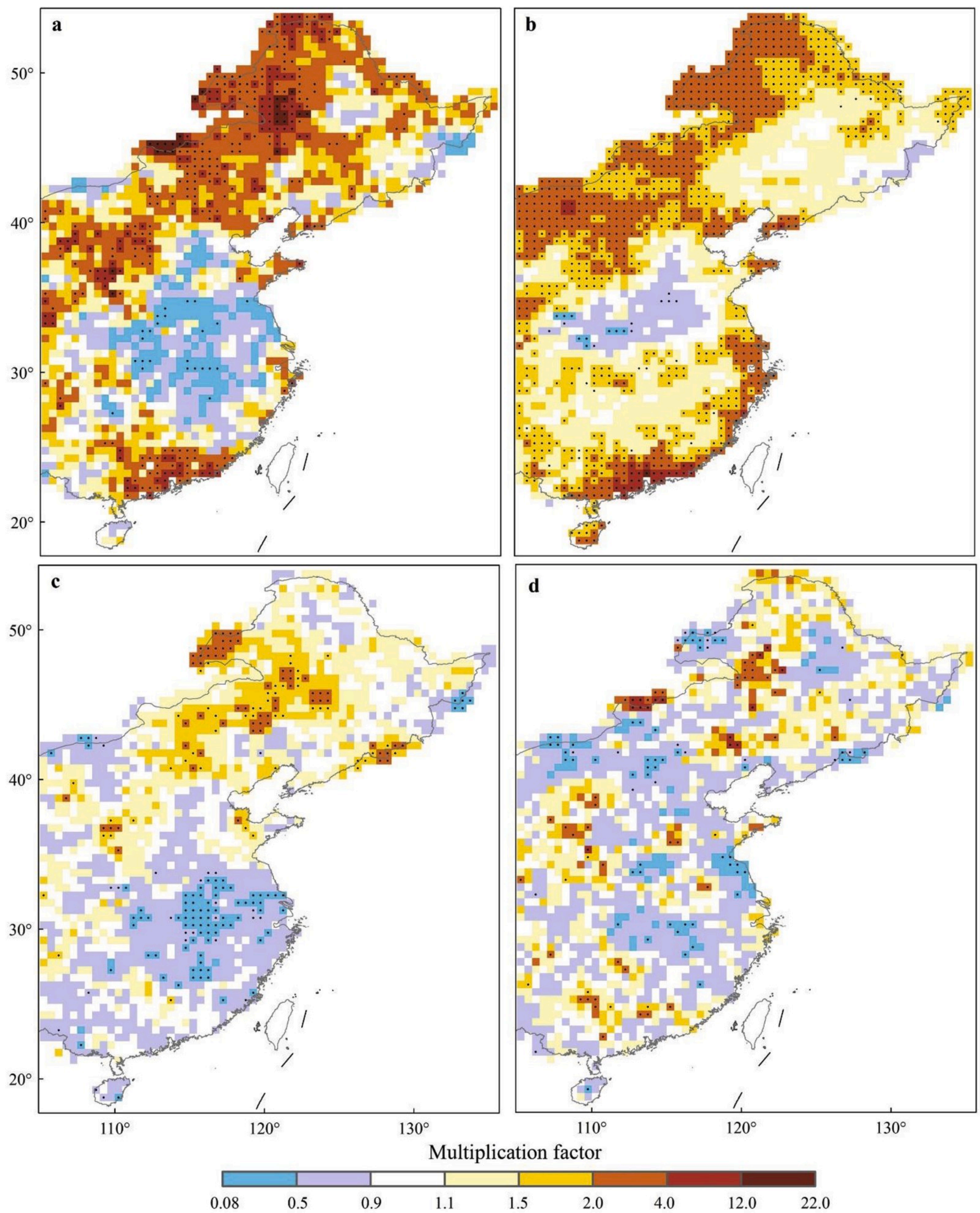

Fig. 4. Changes in the number of (a) CONDH events, (b) heatwaves, and (c) droughts, and (d) changes in D-H dependence ratio, DH_i, in summer (JJA) over eastern China from 1962 to 1988 to 1989–2015. The changes were measured by dividing the statistics for the latter period by those for the former period. The definitions of SPI1<−1 for drought and 3d 90th percentile for heatwave were used. Grids showing statistically significant changes (at 0.05 significance level) are marked by black dots.

From 1962 to 1988 to 1989–2015, we find no significant change for D-H dependence. But whether and how this D-H dependence will change in the future, in response to increasing greenhouse gas concentrations and transformation of land surface properties, are interesting questions deserving of further investigation. For instance, the poleward shift of climatic regimes as a consequence of global warming may create new transitional climate zones between wet and dry climates with strong land-atmosphere coupling (Koster et al., 2004, 2005; Seneviratne et al., 2006), which could subsequently change the D-H dependence. Zscheischler et al. (2018) showed a future strengthening of the correlation between hot and dry summers for most land areas in CMIP5 climate models and that the historical correlation is reasonably well represented by climate models when compared with reanalysis data. Future research that could build on the work presented here would take this further by using observed data and extreme events defined as droughts and heatwaves (instead of hot and dry seasons) which is more relevant for impacts.

From 1962 to 1988 to 1989–2015, we find the number of CONDH more than doubled in parts of the north and for small areas in the south, but significantly decreased by more than 50% in the southern central region. It is beyond the scope of this study to investigate the underlying mechanisms behind these decadal changes of CONDH occurrences in eastern China in summer. However, one direct cause might be the weakening of the East Asia Summer Monsoon (EASM) under global warming (Wang, 2001). A weaker EASM means the rainfall belt is less likely to be pushed poleward to northern China from the tropics and is instead mainly located over central south China in summer (as in Fig. 3c, Zhou et al. (2009)), resulting in a "southern China flood and northern China drought" rainfall pattern (Zhou et al., 2009). This may have contributed to the occurrence of more CONDH over northern China and fewer CONDH over central south China in recent decades. Further, the cooling trend indicated by a decrease in the number of heatwaves over central China (Fig. 4b), believed to be induced by increasing greenhouse gases and aerosols (He et al., 2013), may also contribute to the observed changes with fewer CONDH occurring over this area as a result. The physical mechanisms behind these changes deserve further exploration.

Moreover, whether the number of CONDH will further increase over northern China (and other areas) with global warming also deserves further investigation.

The clear evidence of a positive D-H dependence found in this research provides strong support for considering the concurrence of events when assessing the risk of extremes and potential impacts. The improved understanding of such events, their occurrence and the mechanisms that control this dependence is crucial for providing better forecasts and future projections of compound events under a warming climate. This is especially important for high-risk regions where such information could be used to better understand future risk and inform the long-term planning of adaptation measures as adaptation measures for heatwaves, such as green spaces, water features and the use of air-conditioning, assume the absence of drought conditions.

Declaration of competing interest

We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work, there is no professional or other personal interest of any nature or kind in any product, service and/or company that could be construed as influencing the position presented in, or the review of, the manuscript entitled.

Acknowledgments

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.wace.2019.100242.

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