Geophysical Research Letters

RESEARCH LETTER
10.1029/2022GL099647

Lengthening Dry Spells Intensify Summer Heatwaves

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Key Points:

- The average dry spell (DSL) length has increased by 0.46 day/decade over the global continents since the 1970s
- The robust and widespread relationships between the average DSL length and heatwave duration and severity were found
- The shortening average DSL length associated with heatwaves indicated an enhancing coupling process between DSL and heatwaves

Supporting Information:

Supporting Information may be found in the online version of this article.

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Citation:

He, B., Zhong, Z., Chen, D., Liu, J., Chen, Y., Miao, C., et al. (2022). Lengthening dry spells intensify summer heatwaves. *Geophysical Research Letters*, *49*, e2022GL099647. https://doi.org/10.1029/2022GL099647

Received 19 MAY 2022
Accepted 29 SEP 2022

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Abstract

A lengthening of dry spells (DSLs) has been reported by some regional studies, but its linkage with heatwaves via the feedback between soil moisture and air temperature is still not clear on the global and continental scales. Here we examine increases in the length of DSLs during summer over the global continents using in situ precipitation records. Globally, the average DSL has increased by 0.46 day/decade since the 1970s along with increased high-pressure anomalies which are found to be an important reason for the intensification of heatwaves as suggested by the robust and widespread relationships between the DSL and heatwave duration and severity in the northern extratropics. The average DSL associated with a heatwave declined over lands, implying a strengthening coupling between precipitation anomalies and heatwaves. The findings of this study suggest that the precipitation variations associated with changes in DSLs should be considered in attributions of temperature extremes.

Plain Language Summary

Despite the little change of global mean precipitation over continents during the past decades, it can exert a great impact on land surface energy exchange through changes in precipitation timing, frequency, and the interval between precipitation events. Our study suggests a general lengthening of dry spells (DSLs) in summer over continents, which is likely attributed to the strengthening of high-pressure anomalies. We also reveal a close and strengthening linkage between DSL length and summer heatwaves during the past decades. These findings are crucial for understanding the land-atmosphere feedback in the context of climate change.

1. Introduction

Climate change is altering both the spatial and temporal variations of precipitation (Dore, 2005; Fischer & Knutti, 2015). Precipitation changes associated with air temperature anomalies due to surface energy partition are of great concern (Hirschi et al., 2011; Mueller & Seneviratne, 2012; Seneviratne et al., 2006, 2010). For example, recent studies highlighted the critical role of surface soil moisture (SM) anomalies caused by precipitation deficits in amplifying the European metro-heatwaves (Fischer et al., 2007; Hirschi et al., 2011; Miralles et al., 2014; Liu et al., 2020; Teuling et al., 2010). Compared with the meteorological droughts or heatwaves events alone, compound dry-hot extremes, namely prolonged periods of precipitation shortage combined with extreme heatwaves, could cause more devastating natural disasters and socio-economic impacts (Alizadeh et al., 2020; Zscheischler & Seneviratne, 2017; Zscheischler et al., 2018).

Precipitation and temperature are both the key drivers of meteorological drought or heatwave. They interrelate with each other through a complex loop of feedback processes, which influences the coupled energy and water budgets. On one hand, the saturated water vapor pressure, namely the water-holding capacity of the atmosphere, increases by about 7% for every 1°C rise in temperature according to Clausius-Clapeyron relation (Barbero et al., 2017; Trenberth et al., 2003). As temperature and the water-holding capacity of the atmosphere increase, the duration between precipitation events can become longer because it will take more time to recharge the atmosphere with moisture (Yi et al., 2015). Previous research has established that the increasing atmospheric dryness associated with rising temperature could decrease the likelihood of precipitation, which could further favor the occurrence of meteorological droughts (Miralles et al., 2019; Santanello et al., 2013; Seneviratne et al., 2010).

Writing – original draft: Bin He, Ziqian Zhong, Yaning Chen, Ling Huang
Writing – review & editing: Deliang Chen, Junguo Liu, Chiyuan Miao, Ruiqiang Ding

On the other hand, precipitation deficits could induce a temperature rise through the process of SM–atmosphere interaction (Berg et al., 2015). The lack of precipitation reduces SM and decreases evapotranspiration, which leads to the increase of sensible heat flux and warms the temperature (Mo & Lettenmaier, 2016). Stronger interaction between precipitation and temperature anomalies may be expected due to the enhanced surface water and energy exchange in the context of climate change (Zhang et al., 2020). Despite the recent effort, the process by which summer temperature anomalies lead to changes in precipitation pattern or precipitation deficits which in turn influences the summer temperatures remains not to be fully understood (Barbero et al., 2017; Seneviratne et al., 2002; Wasko & Nathan, 2019).

Previous studies have suggested there exists longer dry or wet periods over many regions (Allen et al., 2013; Pendergrass & Knutti, 2018), which is likely due to changing blocking high dynamics (Zolina et al., 2013) or warming summer (Ye & Fetzer, 2019). A dry spell (DSL) is defined as a continuous period of days without significant rain. Previous studies show that DSLs are lengthening in some regions, such as Europe (Zolina et al., 2013), Russia (Ye & Fetzer, 2019), the Mediterranean (Raymond et al., 2016), and the United States (Groisman & Knight, 2008). The lengthening of DSLs has also been associated with accelerated warming (Du et al., 2020; Ye & Fetzer, 2019). However, it remains unclear whether it is a widespread phenomenon across continents. Additionally, little attention has been paid to the linkage between DSLs and heatwaves over all the continents in a systematic way.

Here, we examined the evolution of DSLs over the world's continents under the changing climate in recent decades and particularly their linkage with the occurrence of summer heatwaves on a global scale. We began by showing a general lengthening of DSLs over the continents, then examined the relationship between the length of DSL and the duration of each heatwave event (HWD) and the heatwave severity (HWS), and tried to reveal potential mechanisms which can explain how DSLs affect duration and severity of heatwaves.

2. Materials and Methods

2.1. In Situ Climate Observations

We use in situ climate records obtained from the Global Surface Summary of the Day (GSOD) database to quantify the changes in the DSL and the duration and severity of heatwaves. GSOD data set was developed from the Integrated Surface Hourly database by the US National Climatic Data Center. Records of meteorological variables including temperature, precipitation, and wind speed at over 9,000 weather stations are available, and the accuracy of the original observations has been checked extensively and corrected through a series of quality control procedures. The daily historical data for the period 1973–2018 with relatively complete records over 2,919 stations were selected for analysis.

2.2. ERA Reanalysis Data Set

Monthly geopotential height (GPH) and wind data with a spatial resolution of 0.25° × 0.25° for the period 1979–2018 and hourly climate data (temperature) and surface energy (latent and sensible fluxes) and SM reanalysis data with a spatial resolution of 0.25° × 0.25° for the period 1981–2018 were obtained from the ERA5 data set issued by the European Centre for Medium Range Weather Forecasts (https://www.ecmwf.int/) (Hersbach et al., 2020). This data set is a new generation of climate reanalysis replacing the original ERA-Interim reanalysis (Hoffmann et al., 2019) with improvements in data accuracy and temporal and spatial resolution. This product has been used extensively in climate change studies (Harrington & Otto, 2020; Oueslati et al., 2017; von Schuckmann et al., 2020).

2.3. Other Data Sets

Other datasets used in this study are monthly precipitation and potential evapotranspiration for the period 1973–2018 obtained from the Climatic Research Unit (CRU) TS Version 4.03 Google Earth Interface (1901–2018) (Harris et al., 2020), and the daily Global Precipitation Climatology Centre (GPCC) precipitation for the period 1982–2018, provided by national meteorological and hydrological services, regional and global data collections as well as World Meteorological Organization Global Telecommunication System-data. Additionally, We obtained data for global 0.25° daily root-zone SM from 1980 to the present from the Global

Land Evaporation Amsterdam Model (GLEAM) Version 3 (Martens et al., 2017). The Normalized Difference Vegetation Index (NDVI) data, with a spatial resolution of 0.083° × 0.083° for every 15-day interval, spanning the period 1982–2015, were derived from the Global Inventory Monitoring and Modeling System (GIMMS) NDVI3g data set (https://ecocast.arc.nasa.gov).

2.4. Calculation of Dry Spell and Heatwaves

A DSL is defined here as the number of consecutive days with precipitation less than 1 mm/day, which is a widely used definition in previous studies (Agnese et al., 2014; Brunetti et al., 2004; Groisman & Knight, 2008). We focused our analysis on summer (June–August in the Northern Hemisphere and December to the following February in the Southern Hemisphere) to reveal the potential relationship between DSLs and heatwaves. Stations, where more than 10% of the precipitation and temperature records were missing during summer over the period 1973–2018, were excluded from the analysis. For stations with <10% of data missing, we filled the gaps by linear interpolation (Du et al., 2020). This left 1,209 stations for analysis of the long-term DSL trend. The DSLs ranged from 1 day to more than 10 days and their frequencies were counted for each station.

A heatwave is defined as a period of consecutive days (at least 3 days) with maximum temperature exceeding the 90th percentile relative to the climatological maximum temperature in summer over the period 1973–2018 (Perkins et al., 2012; Pezza et al., 2012). The duration of each HWD was determined for each station. Furthermore, the HWS was also calculated as the sum of temperature exceedances above the 90th percentile threshold throughout the heatwave (Brown, 2020).

2.5. Relationship Between Dry Spell Length and Heatwaves

The long-term trends of annual summer mean DSL, HWD, and HWS were detected using the Mann–Kendall trend test. The partial correlations between annual summer mean DSL and HWD/HWS were analyzed, with annual summer mean precipitation controlled, to reveal the relationship between DSL and HWD/HWS.

3. Results and Discussion

3.1. Lengthening Dry Spells

Figure 1a shows the global pattern of the trend in the average DSL during summer from 1973 to 2018 recorded by 1,209 stations with continuous precipitation observations. We observed a clear, significant increase in DSL in 44% of the stations studied, mainly in China, southern Europe, and the western United States where there is a dense network of observations. In contrast, only 16% of stations had a significant decrease in DSL. Globally, the average DSL increased at a rate of 0.46 day/decade (Figure S1 in Supporting Information S1). At the continental scale (Vautard et al., 2010; Zeng et al., 2018), the largest increase in DSL was observed in Central Asia with a rate of 1.78 day/decade, followed by Europe, North America, and East Asia, with rates of 0.68 day/decade, 0.29 day/decade, and 0.19 day/decade, respectively. Figure S2 in Supporting Information S1 presents the trends of different DSLs ranging from shorter than 3 days to longer than 10 days during 1973–2018. Decreasing trends tend to be associated with relatively short DSLs, whereas increasing trends were often linked to longer DSLs. In addition, the total length of DSLs in summer was also counted, and demonstrates a similar pattern to Figure 1a (Figure S3 in Supporting Information S1), suggesting an increase in the total number of dry days in summer.

The occurrences of DSLs are generally associated with persistent abnormal high pressures (Schubert et al., 2014; Ye & Fetzer, 2019). To find causes for the lengthening of DSLs, we investigated the changes in the regional atmospheric circulations based on the ERA5 data set. Figure 2 shows the composite maps of GPH and wind anomalies at 500 hPa of the 8 years (10% of the total period) having the longer DSLs (Figures 2b–2d) and 8 years having the shorter DSLs (Figures 2e and 2f) during 1979–2018, respectively, for the three regions with significant lengthening DSL. Anomalies are relative to the climatological average for the period 1979–2018, excluding the 16 years with the longer or shorter DSLs. An opposite pattern of GPH was observed between periods with the longest DSL and shortest DSL. The three regions are controlled by high atmospheric pressure in the summer with long DSLs while low atmospheric pressures were linked with shorter DSLs. In addition, the GPH around the high-pressure center significantly increased, and presents a significant synchronism with the variation of DSL, implying that the strengthening of abnormal high pressures is a driver of the lengthening of DSLs across

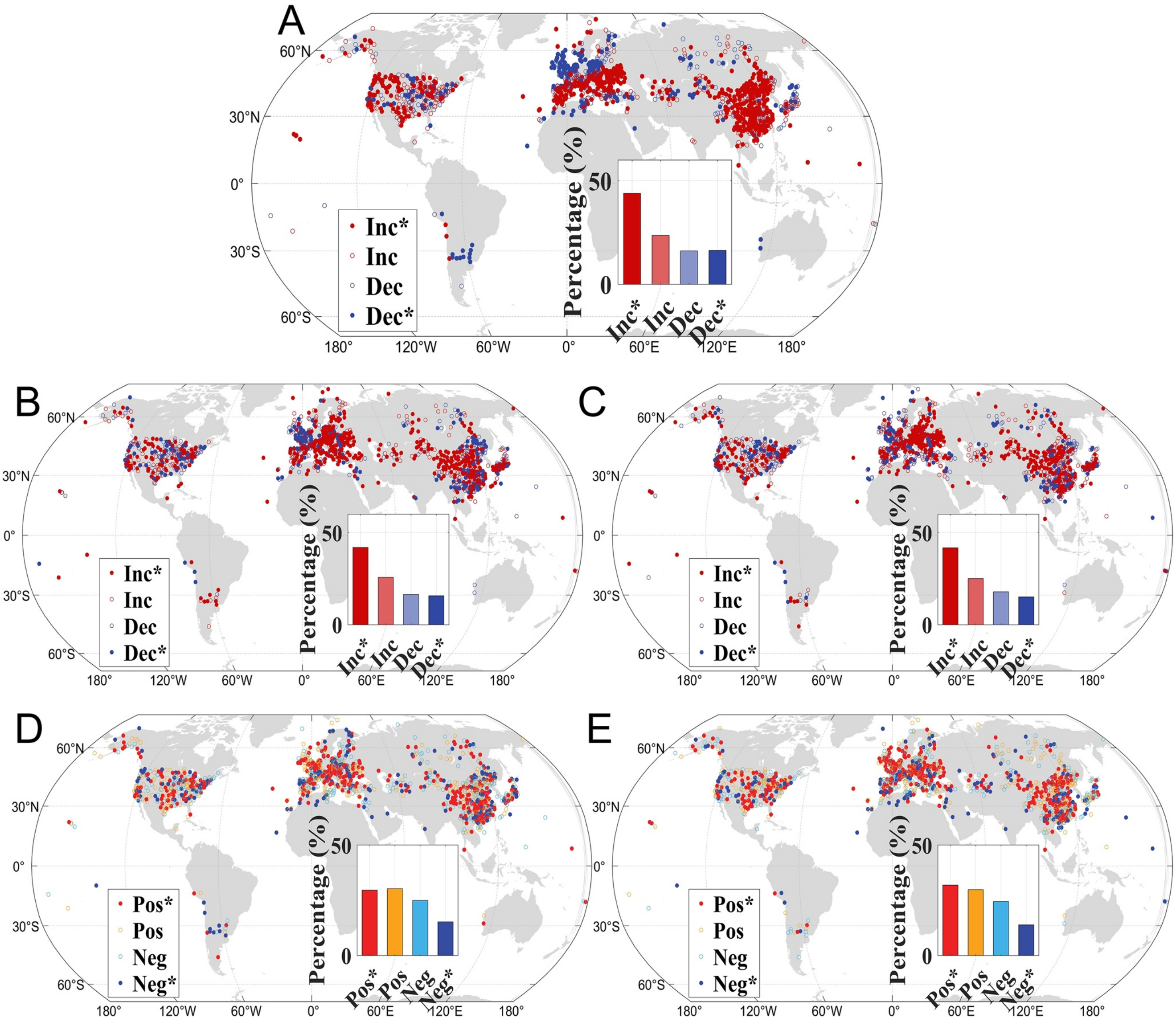

Figure 1. Spatial patterns of trends of dry spell length (DSL) and heatwaves, and annual correlations between DSL and heatwaves during summer from 1973 to 2018. (a–c) Trends of average DSL, heatwave duration, and heatwave severity. The insets indicated significant increase (Inc*; $p < 0.05$; dark red), increase (Inc; light red), decrease (Dec; light blue), and significant decrease (Dec*; $p < 0.05$; dark blue) trend, respectively. (d and e) Partial correlations between annual summer mean DSL and heatwave duration and severity, respectively, with annual summer mean precipitation controlled. The insets indicated significant positive correlations (Pos*; $p < 0.1$; dark red), positive correlations (Pos; yellow), negative correlations (Neg; light blue) and significant negative correlations (Neg*; $p < 0.1$; dark blue).

these three regions during 1979–2018 (Figures 2h–2j). In addition, a contrasting pattern between the north and the south of Europe with decreasing and increasing DSLs was observed. K-means clustering analysis (Arthur & Vassilvitskii, 2007) on GPH divides the whole region into distinct two regions with a decreasing GPH in the north and an opposite trend in the south (Figure S4 in Supporting Information S1). Strong correlations between GPH and DSL were observed for both regions, which further confirms the great impact of changes in atmospheric pressure on DSL variations.

3.2. Relationship Between Dry Spells and Heatwaves

Both HWD and HWS during summer have increased over the past four decades at the majority of stations (Figures 1b and 1c). The spatial pattern of trends of heatwave duration and HWS are generally consistent with the distribution of trends in DSLs in the northern extratropics during summer. Partial correlation analysis suggests a

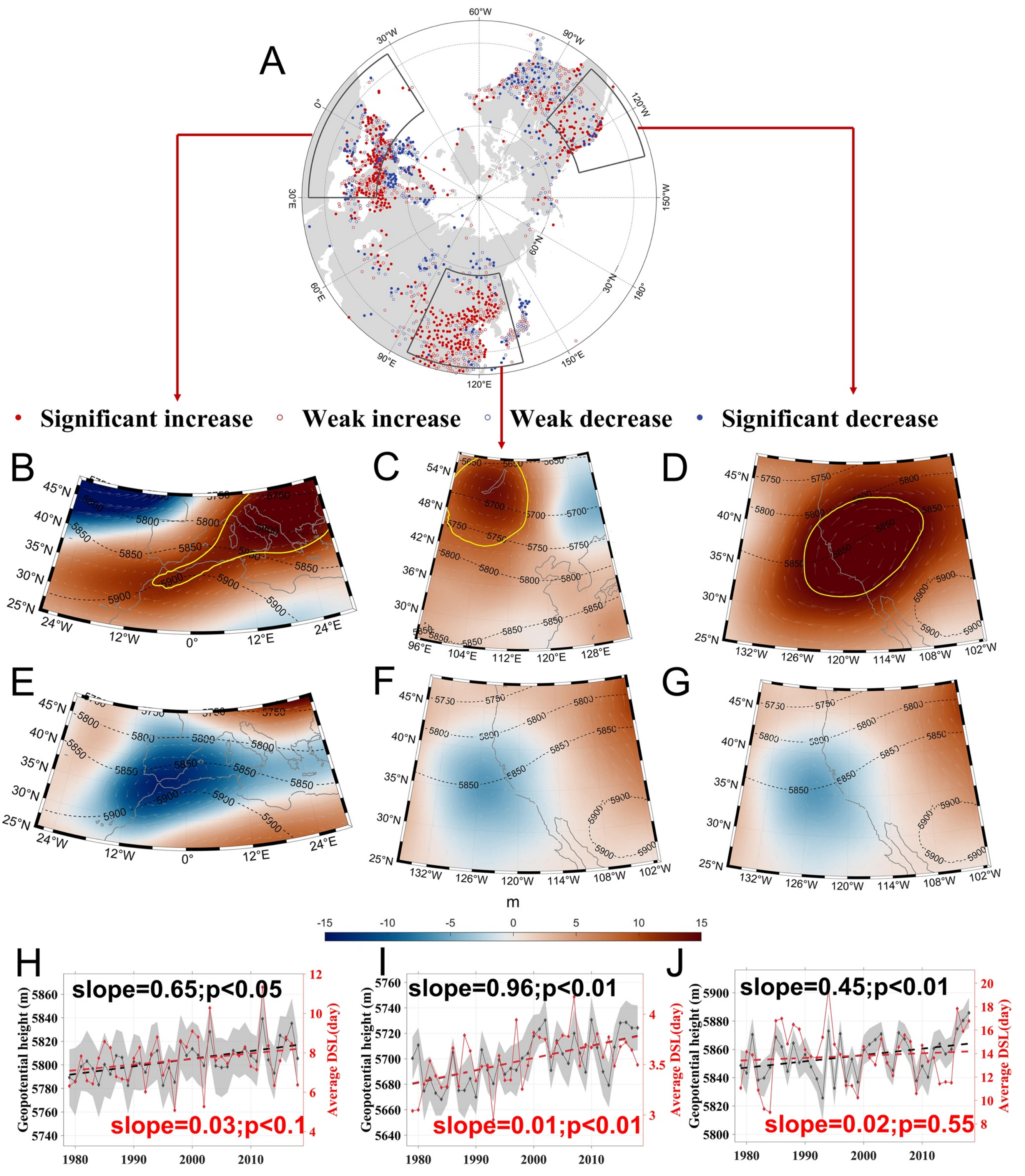

Figure 2. The relationship between summer geopotential height (GPH) and dry spells (DSLs) from 1979 to 2018. (a) Same with Figure 1a, trends of average DSL. Black frames mark the sampled areas. (b–g) Composite map of summer mean GPH and wind anomalies at 500 hPa for 8 years when DSLs were anomalously long (b–d) or short (e–g), respectively. The yellow line marks the grids where the GPH anomalies at 500 hPa over 80th quantile over the same period, which means the high-pressure center that controls these regions. Contour lines show the climatology of the GPH. (h–j) The summer average GPH over the regions marked by the yellow line in b–d, respectively, and the regional mean DSLs during 1979–2018. The partial correlation coefficient between GPH and DSL in H, I, and J are 0.64 ($p < 0.01$), 0.47($p < 0.01$), and 0.48 ($p < 0.01$), respectively, with summer mean precipitation controlled.

strong coupling between DSL and HWD and HWS. As shown in Figure 1c, positive correlations between DSLs, HWD, and HWS were observed over 722 and 744 stations (about 60% and 62% of total stations) suggesting that the lengthening of DSLs is often closely coupled to the intensification of heatwaves.

The observed close linkage between DSL and heatwave can be attributed to the coupling between SM deficits and high-temperature anomalies (Hirschi et al., 2011; Mueller & Seneviratne, 2012; Zhang et al., 2020). As atmospheric circulation anomalies develop, the reduced cloud cover and enhanced solar radiation associated with a DSL promote evapotranspiration and thus constrain the rapid increase of surface temperature (Figure S5 in Supporting Information S1). As the DSL lengthens, SM is gradually consumed and evapotranspiration is inhibited, and the increased sensible heat warms the surface air more. If there are no precipitation events to disrupt this warming process, a heatwave will be triggered (Liu et al., 2020). To test this hypothesis, we examined the surface energy exchange process during DSLs of European, Eastern Asia, and North America from 1982 to 2018. These regions have relatively dense weather stations (Figure 3). The energy fluxes and SM during DSLs whose lengths were longer than the 90th quantile was selected and averaged, and their anomalies relative to the first day of the DSL were calculated. Here we focus on the period 09:00–13:00 local time each day, during which heating at the land surface reaches a maximum and controls the magnitude of the diurnal temperature peak (Teuling et al., 2010). Considering the potential regulation of vegetation on energy distribution, the variation of energy fluxes during DSLs was analyzed for different vegetation greenness gradients (indicated by NDVI). In Europe (Figure 3a) and East Asia (Figure 3b), we observe an increase in latent heat (LE) flux, but a roughly invariant sensible heat flux in the earlier stages of DSLs across regions with high vegetation greenness (regions with NDVI ranging from 0.6 to 0.8). As SM decreases, the elevated sensible heat flux surpasses the latent flux and causes a rapid increase in surface temperature. However, in a region with lower vegetation greenness (regions with NDVI ranging from 0.2 to 0.4), the short-period roughly invariant sensible heat flux is not apparent, while a short-term increase of LE flux is also observed. The observed differences in the energy exchange processes among vegetation greenness gradients during the early stage of DSLs are likely due to the difference in plant water use strategy under drought stress (Liu et al., 2020). In contrast to lower vegetation greenness regions, the higher vegetation greenness regions are usually covered by forests with deep roots which can access deep soil water to maintain high evapotranspiration during the earlier stage of drought. This leads to a depressed increase in sensible heat flux. The short-period increasing LE flux and stable sensible heat flux were not found in areas with dry climates such as western North America (Figure 3c) which can be due to the limited SM, leaf evaporation, and transpiration there. Additionally, there was no close linkage between DSL and heatwave in monsoon regions due to the influence of ocean-atmosphere teleconnections (Qing et al., 2022). Specifically, even if the precipitation deficit during a DSL leads to decreasing SM and evapotranspiration, once the monsoon starts, the atmospheric humidity level tends to increase, and then the warming process was disrupted (Mo & Lettenmaier, 2016).

We discovered that summer heatwaves in extratropics are intensified by lengthening DSLs. This result is in accord with previous results that flash droughts increased significantly over China (Wang & Yuan, 2018; Yuan et al., 2019), while it seems to be contrary to other studies which have suggested that heatwave-induced flash droughts across the conterminous U.S. are in decline over the last century (Mo & Lettenmaier, 2015). This is because the process of a DSL associated with a heatwave is more like the process of flash drought caused by precipitation deficit than that driven by a heatwave. A flash drought could be triggered by abnormally high temperatures or precipitation deficits, and the heatwave-driven flash drought is caused by abnormally high temperatures. In contrast to heatwave-induced flash drought, flash drought caused by precipitation deficit has no obvious trend over the conterminous U.S. (Mo & Lettenmaier, 2016).

3.3. Dependence of DSL on Heatwaves

We then determined the average length of DSLs that were associated with a heatwave. This length was defined as the total number of dry days before the day when a heatwave occurred (Figure S6 in Supporting Information S1). A basic prerequisite for the assumption that the DSL causes heatwave but not the opposite condition is whether heatwaves are followed by DSLs. For each station, the specific lengths of the DSLs before each HWD were counted and averaged. Because this analysis does not require a complete daily record of temperature and precipitation, we included as many stations as possible. Here, a total of 2,919 stations with more than 30 years' precipitation and temperature records during summer from 1973 to 2018 were selected. We found that there was a DSL day before 87.6% of heatwaves (Figure S7 in Supporting Information S1). An average of 75.7%, 65.2%, and

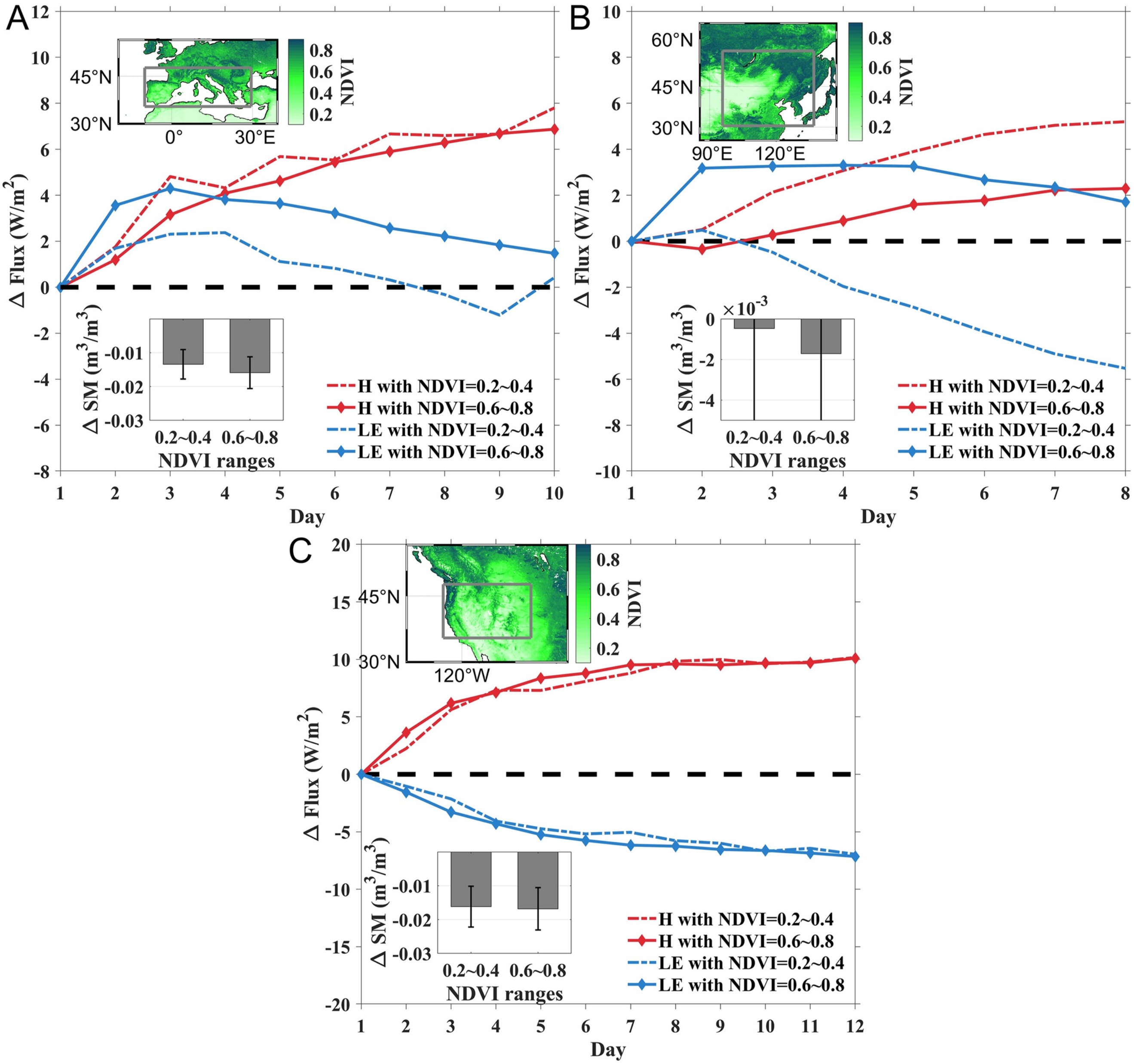

Figure 3. The sensible heat (h) and latent heat (LE) fluxes and soil moisture (SM) variation during dry spells (DSLs) across regions with different summer average NDVI during 1982–2018 in the Mediterranean region (a), East Asia (b), and western North America (c). Gray windows indicated the sampled locations, and the background maps are the multi-year (1982–2015) summer average NDVI, which indicated the greenness of vegetation. Only the DSLs whose lengths reached the 90th quantile were selected for analysis. The bar graph shows the changes of the SM during DSLs across regions with different climatological NDVIs, which is defined as the difference between the SM (m^3/m^3) on the last day (day 10) and that on the first day during DSLs.

56.5% of heatwaves were preceded by 2–4 consecutive dry days, respectively. Figure 4a illustrates the distribution of the average DSL associated with heatwave during 1973–2018. The study area was divided into eight domains characterized by the spatial distribution of average DSL associated with heatwaves. The longest average DSL associated with heatwaves was found in southern Central Asia (19.2 days), followed by the Mediterranean region (16.7 days), North America (14.7 days), midwestern North America (10.6 days), and northern Central Asia (9.0 days). We then analyzed the trend in average DSL associated with heatwaves relying on an 11-year moving window over lands. Globally, the average DSL associated with heatwave across all selected stations was significantly ($p < 0.01$) shorten by −0.08 day per decade (Figure 4b). As shown in Figures 4c–4j, the regional DSLs associated with heatwaves were significantly shortened in southern Central Asia (−1.1 day per decade, $p < 0.01$),

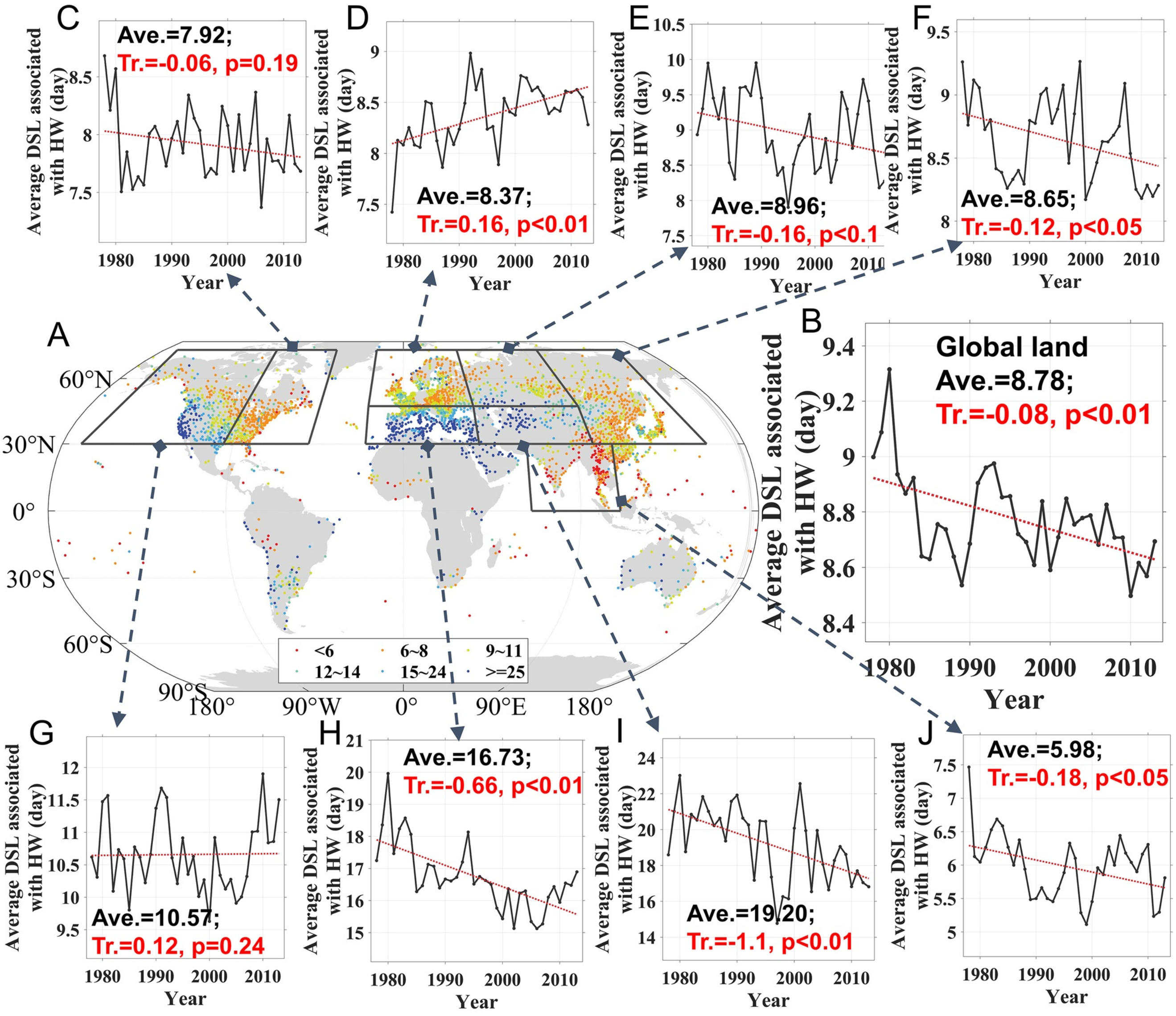

Figure 4. Average dry spell (DSL) for DSLs associated with heatwaves during 1973–2018. The length is defined as the total number of consecutive dry days before the day when a heatwave occurred. (a) Spatial patterns of the average DSLs that followed by heatwaves. For each station, all DSLs followed by heatwaves were counted and averaged. (b–j) Average value (**Ave.**, unit: day) and trends (**Tr.**, unit: day per decade) of average DSL associated with a heatwave in (b) Global land, (c) eastern North America, (d) mid-high latitude Europe, (e) northern Central Asia, (f) East Asia, (g) midwestern North America, (h) the Mediterranean region, (i) southern Central Asia and (j) South Asia.

the Mediterranean region (−0.66 day per decade, $p < 0.01$) South Asia (−0.18 day per decade, $p < 0.05$), northern Central Asia (−0.16 day per decade, $p < 0.1$), and East Asia (−0.12 day per decade, $p < 0.05$). The shortened DSLs associated with heatwaves indicate an enhanced coupling between DSLs and heatwaves during the study period (Zhang et al., 2020), and corroborated a recent finding that flash droughts appear to take less time to develop in most global land due to the joint influence of SM depletion and atmospheric aridity (Qing et al., 2022).

4. Summary

This study provides the first analysis of global land-based observations of the evolution of DSLs and their relationships with heatwaves. Despite global mean precipitation over continents experiencing little change over the past decades (Dore, 2005; Ren et al., 2013; Sheffield et al., 2012), the findings from this study suggest that precipitation exerts a great impact on land surface energy exchange through changes in precipitation timing, frequency, and the interval between rain events in the northern extratropics. The feedback between SM and air temperature during a DSL provides essential information for heatwave that follows the DSL. Furthermore, the temporal evolutions of DSLs and heatwaves provide a new angle for the understanding of the spatiotemporal variation of compound dry-hot extremes (Alizadeh et al., 2020; Mukherjee & Mishra, 2021) and flash drought (Mo & Lettenmaier, 2016; Otkin et al., 2018; Qing et al., 2022).

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

The in-situ climate data is available from the Global Surface Summary of the Day (GSOD) database (https://www.ncei.noaa.gov/data/global-summary-of-the-day/access/). The monthly precipitation and potential evapotranspiration are obtained from the Climatic Research Unit (CRU) TS Version 4.03 Google Earth Interface (http://dx.doi.org/10.5285/10d3e3640f004c578403419aac167d82). The daily precipitation data is available from the Global Precipitation Climatology Centre (GPCC) precipitation (https://opendata.dwd.de/climate_environment/GPCC/html/download_gate.html). Other climate products, including monthly GPH and wind data, and hourly temperature, latent and sensible fluxes, are available from the ERA5 data set issued by the European Centre for Medium Range Weather Forecasts. These are obtained from https://doi.org/10.24381/cds.f17050d7 and https://doi.org/10.24381/cds.adbb2d47, respectively. The root-zone SM is available from the Global Land Evaporation Amsterdam Model (GLEAM) Version 3 (https://www.gleam.eu/%23downloads). The Advanced Very High Resolution Radiometer GIMMS-NDVI3g is downloaded and processed by a *R* package which is available at https://CRAN.R-project.org/package=gimms.

Acknowledgments
This work is financially supported by the Cross Team Project of the "Light of West China" Program of Chinese Academy of Sciences (No: E0284101) and the Strategic Priority Research Program of the Chinese Academy of Sciences (Grant XDA20060402).

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