



Key Points:

- The long-term trend of dry spell length (DSL) during 1976–2019 was examined using the global observation data set of daily precipitation
- The global mean DSL significantly increased during 1976–1998 whereas that showed no significant trend during 1999–2019
- The variation of annual precipitation can modulate the spatiotemporal variations of DSL

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Citation:

Wang, X., Lu, H., & Yuan, W. (2022). Inter-annual variations of precipitation modulate the dry spell length. *GeoHealth*, 6, e2022GH000611. <https://doi.org/10.1029/2022GH000611>

Received 26 FEB 2022
Accepted 29 MAR 2022

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Inter-Annual Variations of Precipitation Modulate the Dry Spell Length

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Abstract Dry spell length (DSL), consecutive non-rainy days between two precipitation events, play an important role in regulating soil moisture dynamics, terrestrial energy exchange as well as vegetation growth. According to the Clausius-Clapeyron (C-C) relationship, global warming can result in prolonged DSL. However, usually the amount of precipitation and its characteristics coincidentally varied with the changes of DSL under global warming, it remains unclear how the inter-annual variation of precipitation interacts with the evolution of dry spells. In this study, the global long-term in-situ observation data set of daily precipitation during 1976–2019 was used to examine the spatiotemporal trends of growing season DSL and precipitation. Our results showed that the global mean growing season DSL significantly increased by 0.3 days decade⁻¹ during 1976–1998 while no significant trend of that was observed during 1999–2019. In contrast, the growing season precipitation (Prec_GS) showed no significant trend in 1976–1998 whereas significant increase trend of that was observed in 1999–2019. To explore the impacts of precipitation on the evolution of dry spells, we examined the relationship between the growing season DSL and Prec_GS. We found that prevalent negative relationship was observed between growing season DSL and Prec_GS in 88% and 86% stations during the period of 1976–1998 and 1999–2019, respectively. Spatially, the mean annual Prec_GS and DSL showed significantly negative relationship, that is, the stations with more precipitation showed shorter DSL in growing season, and vice versa. The changes of mean annual Prec_GS explained 81% spatial variation of growing season DSL. Moreover, during the period of 1999–2019 significant increase of precipitation frequency and decrease of dry day frequency were also observed in addition to the increase of Prec_GS in this period. The decreased dry day frequency further resulted in the decrease of growing season DSL. By excluded the impacts of precipitation, the DSL/Prec_GS ratio showed significant decreasing trend during 1999–2019. Our study suggested that the spatiotemporal variations of DSL were modulated by the variation of precipitation. The impacts of precipitation changes on ecosystem by altering the dry spell evolution should be considered in modeling the terrestrial carbon and hydrological cycling in response to climate changes.

Plain Language Summary Dry spell length (DSL) indicates the duration between two precipitation events. As an important precipitation characteristic, DSL can regulate terrestrial carbon-water cycling. However, it is still unclear how climate change influenced the evolution of DSL. Here, we examined the spatiotemporal trends of DSL globally during 1976–2019 using the long-term in-situ observation data set of daily precipitation. We found that the global mean growing season DSL significantly increased during 1976–1998 whereas no significant trend was observed during 1999–2019. The significant increase in the amount of precipitation during 1999–2019 contribute to the diminished increasing trend of DSL in this period. Our study suggested that the spatiotemporal variations of DSL were modulated by the variation of precipitation. The impacts of precipitation changes on ecosystem by altering the dry spell evolution should be taken into account in modeling the terrestrial carbon and hydrological cycling in response to climate changes.

1. Introduction

Climate change profoundly alters global hydrologic cycling (Lambert et al., 2008; Loaiciga et al., 1996; Wentz et al., 2007). Dry spell length (DSL), consecutive non-rainy days between two precipitation events, which associates with precipitation frequency, directly influence soil moisture dynamics, terrestrial energy exchange as well as vegetation growth (Chou et al., 2012). Theoretically, global warming can increase atmospheric water

vapor holding capacity by 7%/K according to the Clausius-Clapeyron (C-C) relationship (Trenberth et al., 2005). However, global evapotranspiration tends to increase at a lower rate than the C-C relationship restricted by global energy budget and the slower ocean warming (Trenberth et al., 2003). Given that, it would take a relative long recharge time for water vapor to replenish the atmosphere, that results in long dry spells. The extended dry spell could trigger drought, heatwaves and further impact on terrestrial carbon uptake (Ye & Fetzer, 2019). Thus, quantifying the spatiotemporal variation of DSL is essential for revealing the impacts of climate change on terrestrial carbon and water cycling.

The extend DSL across different geographical regions has been reported by previous studies basing on ground observations and global climate model experiments. Giorgi et al. (2011) indicated an overall increasing trend of either DSL or precipitation intensity during 1970–2000 across all regions except Australia and South America, using global ground station and gridded precipitation observation datasets. In North America continent, by analyzing the daily precipitation records during 1967–2006 from ground observing stations, it was found that the mean duration of consecutive dry episodes significantly increased in eastern and southwestern United States in recent decades (Groisman & Knight, 2008). In Europe, Zolina et al. (2013) found that DSL was extended by 1.5 to more than 2.5 days in central western and northern Europe during the past 60 years by analyzing data from 699 European rain gauge stations. Moreover, changes of DSL in different regions were also predicted by global and regional atmospheric models. Climate models indicate that longer duration of DSL are expected in Canada and tropical Africa (Bouagila & Sushama, 2013; Sushama et al., 2010). Based on the regional climate models, the duration of dry spells in summer was projected to increase by the end of this century in Switzerland (Fischer et al., 2015).

However, it remains unclear how the variations in amount of precipitation interact with DSL. Generally, the spatiotemporal changes of DSL were accompanied by the variations of precipitation in a lot of regions. Climate change alters both spatial and temporal variations of precipitation (Dore, 2005; Fischer et al., 2015). The inter-annual variations of precipitation are expected to alter the frequency of precipitation and dry days, that would further impact on the evolution of dry spells. For example, in central and northern Europe, the length of dry spells increased in recent decades, at the same time an increasing trend of precipitation (more than 20 mm per decade) has been observed (Caloiero et al., 2018; Zolina et al., 2013). The prolonged summer dry spell duration in last decades also have been observed in Russia (Ye & Fetzer, 2019), which was associated with decreased summer precipitation frequency and increased intensity during the same period (Lebedeva et al., 2016; Ye et al., 2016). Hence, it is necessary to examine the relationship between the patterns of annual precipitation and the evolution of dry spells.

In this study, the global long-term observations data set of daily precipitation deriving from in-situ weather stations was used to retrieve growing season DSL and precipitation characteristics. The primary objectives of this study were to (a) estimate the global spatiotemporal patterns of DSL and precipitation in growing season and (b) examine the relationship between the patterns of growing season precipitation and the evolution of dry spells.

2. Data and Methods

2.1. Global Precipitation Observation Data Set

In this study, the daily precipitation observations were used to explore the spatiotemporal changes of DSL and precipitation, the database was derived from the Global Surface Summary of Day (GSOD) data set (<https://www.ncei.noaa.gov/data/global-summary-of-the-day/>). The GSOD data set compiled precipitation records covering more than 9,000 stations across the globe, from 1929 to the present, with data from 1973 to the present being the most complete. To extract intact DSL information, we selected the precipitation observations from the GSOD data set by the following criteria: (a) the daily precipitation observation records of each year were complete (i.e., 365 or 366 records each year in a station) and (b) each station which was selected should have at least 35 years complete precipitation observations; In total, 1,596 stations were selected in this analysis, ranging from 1976 to 2019.

The DSL during growing season was extracted for each observation station. We use a threshold of 0.1 mm day⁻¹ to define a precipitation event (Sun et al., 2007), the day with daily precipitation less than 0.1 mm is defined as a dry day (non-rainy day). The number of consecutive non-rainy days between two precipitation events which was defined as DSL was extracted. Basing on that, we derived the mean DSL of growing season. The precipitation

frequency and dry day frequency during growing season were calculated by the ratio of rainy day and dry day to growing season days, respectively. In this study, the growing season is composed of all months where the mean monthly air temperature was above 0°C (Lu et al., 2021). The precipitation amount during growing season (Prec_GS) was also estimated for each station.

2.2. Data Analysis

In this study, we deployed the piecewise linear regression approach to detect the changes in trends of DSL, Prec_GS, precipitation frequency and dry day frequency in growing season during 1976–2019 (Toms & Lesperance, 2003; Yuan et al., 2019). The tipping point year were detected using following equations:

$$y = \begin{cases} \beta_0 + \beta_1 t + \varepsilon, & t \leq \alpha \\ \beta_0 + \beta_1 t + \beta_2(t - \alpha) + \varepsilon, & t > \alpha \end{cases} \quad (1)$$

where y indicates variables of the DSL, Prec_GS, precipitation frequency and dry day frequency in growing season; t is the year; α indicates the estimated the tipping point year; β_0 , β_1 , and β_2 are the regression coefficients; ε is the residual of the linear regression. β_1 and $\beta_1 + \beta_2$ represents the linear trend of each investigated variable before and after the tipping point year, respectively. α and other regression coefficients were estimated by least squares linear regression. The 5-year running mean were used 0.05 to quantify the tipping point year α . The statistical significance level is at $P \leq 0.05$.

The linear regression was performed to examine the temporal trend of DSL, Prec_GS, precipitation frequency and dry day frequency in growing season during the period of 1976–1998 and 1999–2019. For each station, only when there were at least 10 years valid data during the period (1976–1998 and 1999–2019) would the regression analysis be performed.

To examine the association between DSL with changes of precipitation during growing season, the linear and nonlinear regression analysis also was applied to explore the relationship between Prec_GS and DSL, Prec_GS and dry day frequency and dry day frequency and DSL, respectively.

3. Results

3.1. Changes of Global DSL and Precipitation Characteristics

The global mean trends of DSL, precipitation, precipitation frequency and dry day frequency were estimated from the precipitation observations of 1,596 stations. The observed global mean of growing season DSL showed significant increase by 0.3 days decade⁻¹ during 1976–1998 while no significant trend of that was shown during 1999–2019 (Figure 1a). On the contrary, there was no significant trend of growing season precipitation was observed during 1976–1998, whereas significant increase of that showed in 1999–2019 (Figure 1b). In line with the trend of precipitation, precipitation frequency and dry day frequency significantly increased and decreased during the period of 1999–2019, respectively (Figures 1c and 1d).

Spatially, the increasing trends of DSL in growing season were observed over 54% stations during 1976–1998, whereas only 37% stations showed increasing trend during 1999–2019. The diminished extending trends of DSL during the latter period mostly were observed in Europe (Figures 2a and 2b). Precipitation in growing season showed more obviously increasing trends during 1999–2019 (75% stations) than that in 1999–2019 (54% stations; Figures 2c and 2d). The increasing growing season precipitation mainly located in Europe and northwestern China, accordingly, decreasing trends of dry day frequency were observed in those regions (Figures 2e and 2f).

3.2. Associations of DSL With Changing Precipitation

To explore the impact of changes in growing season precipitation and dry day frequency on DSL, the linear regression was performed for each observation station. Over 88% stations showed negative relationship between DSL and growing season precipitation during study periods (Figure 3a). 54% stations which showed negative relationship between the dry day frequency and growing season precipitation during the entire study period

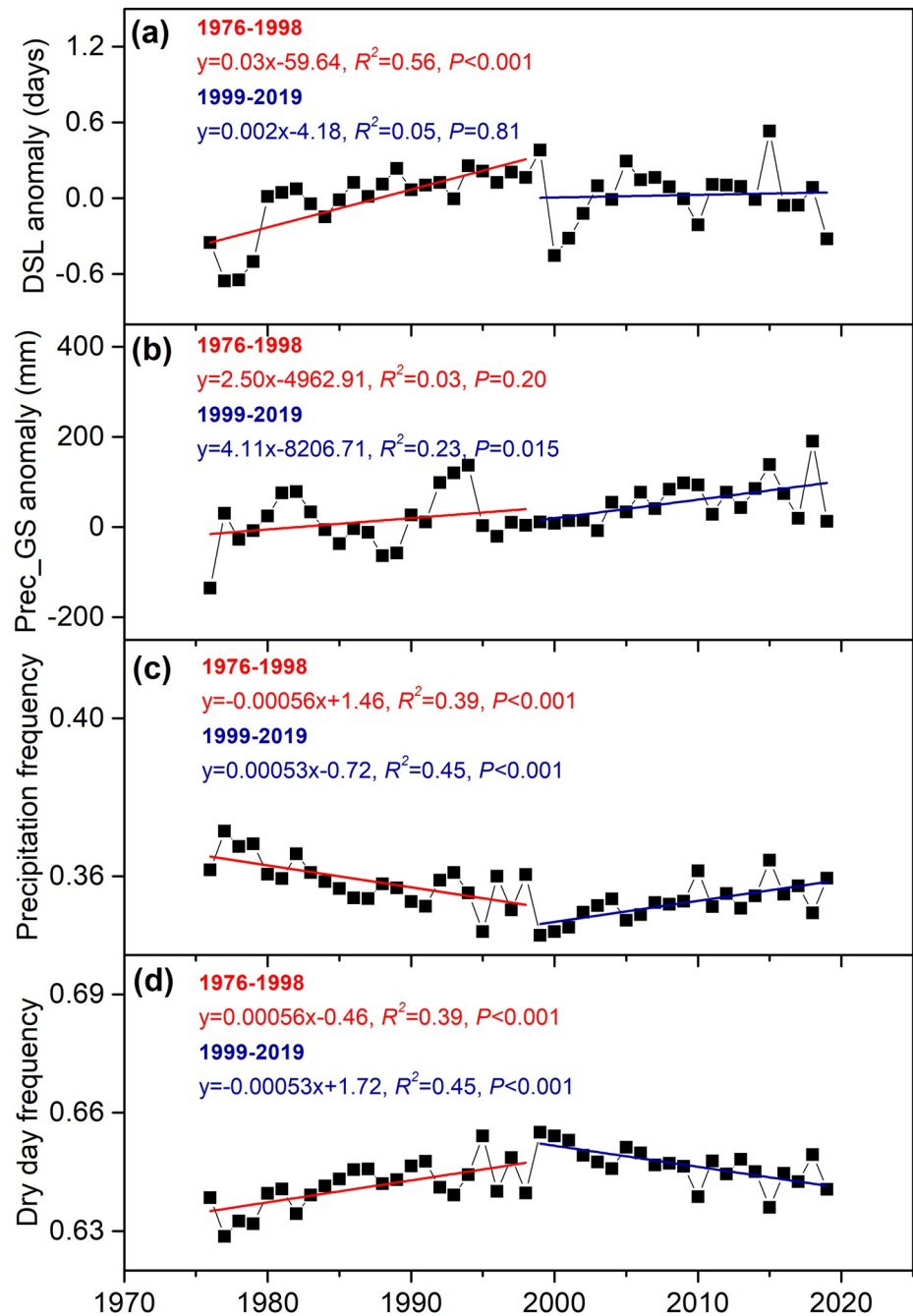


Figure 1. (a) Observed global mean dry spell length anomaly, (b) precipitation amount (Prec_GS) anomaly, (c) precipitation frequency, and (d) dry day frequency trends in growing season during 1976–2019.

(1976–2019). Nevertheless, the percentage of stations which showed significant ($P < 0.05$) negative relationship increased from 5% during 1976–1998 to 30% during 1999–2019, indicating that the increased growing season precipitation during the latter period resulted in less dry day frequency in more stations (Figure 3b). Comparing with the period of 1976–1998, more stations showed positive relationship of DSL and dry day frequency, especially the of percentage of stations which showed significant negative relationship sharply decreased from 21% during 1976–1998 to 6% during 1999–2019 (Figure 3c), suggesting that the decreased dry day frequency further induced shorter DSL. Moreover, spatially, significant negative relationship between averaged DSL and precipitation gradients was observed. The averaged DSL significantly decreased with the increase of mean growing

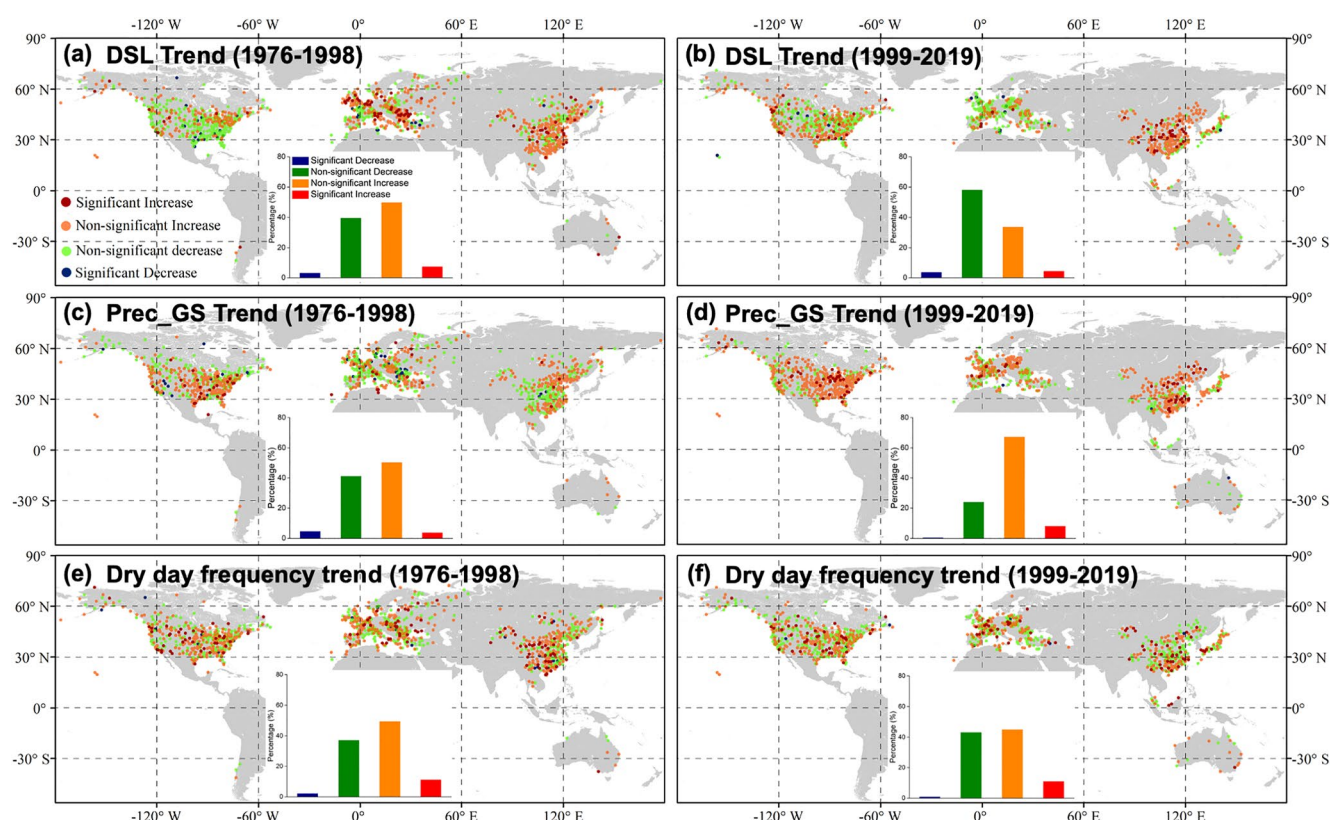


Figure 2. (a and b) Observed temporal trends of dry spell length, (c and d) precipitation, and (e and f) dry day frequency in growing season during the period of (left) 1976–1998 and (right) 1999–2019. The small insets indicate the percentage of significant increase ($P < 0.05$), non-significant increase, significant ($P < 0.05$), decrease and non-significant decrease stations.

season precipitation (Figure 4a). Changes of mean growing season precipitation explained 81% spatial variation of DSL, suggesting that growing season precipitation is one of the important regulators on DSL. Averaged DSL also showed significant positive correlation with dry day frequency spatially (Figure 4b).

To exclude the impact of growing season precipitation on DSL, we examined the temporal trends of the ratio of DSL to growing season precipitation (DSL/Prec_GS) for each station during the two periods. Our results indicated there was no significant difference between the trends of DSL and DSL/Prec_GS ratio during 1976–1998, 55% stations showed increasing trends in DSL/Prec_GS, which was very close to the percentage of 57% for DSL trend during this period (Figure 5a). Whereas, in the period of 1999–2019 where the growing season precipitation significantly increased, only 37% stations showed an increasing trend in DSL/Prec_GS ratio, this percentage is 18% less than that for DSL trend (increasing trend over 55% stations; Figure 5b). By excluded the impact of precipitation, the global mean DSL/Prec_GS ratio showed a significantly decreasing trend during 1999–2019, whereas during this period the global mean DSL had no significant trend (Figure 5c). The results suggested that the increase of growing season precipitation can result in shorter DSL during the period of 1999–2019. Another line evidence also supported this conclusion. To validate the regulation of growing season precipitation on DSL, stations which experienced significant ($P < 0.1$) changes in growing season precipitation were selected to examine the trend of DSL in each station. If the variations of growing season precipitation can exert negative effects on DSL, the DSL trends should be negative with the trend of growing season precipitation in those selected stations. The negative relationship between DSL trends and growing season precipitation trends was observed in 78% and 73% stations during the period of 1976–1998 and 1999–2019, respectively (Figure 6). In other words, the significant changes of growing season precipitation regulated the variation of DSL (i.e., significant increase of precipitation results in decrease of DSL, and vice versa) in most of the stations.

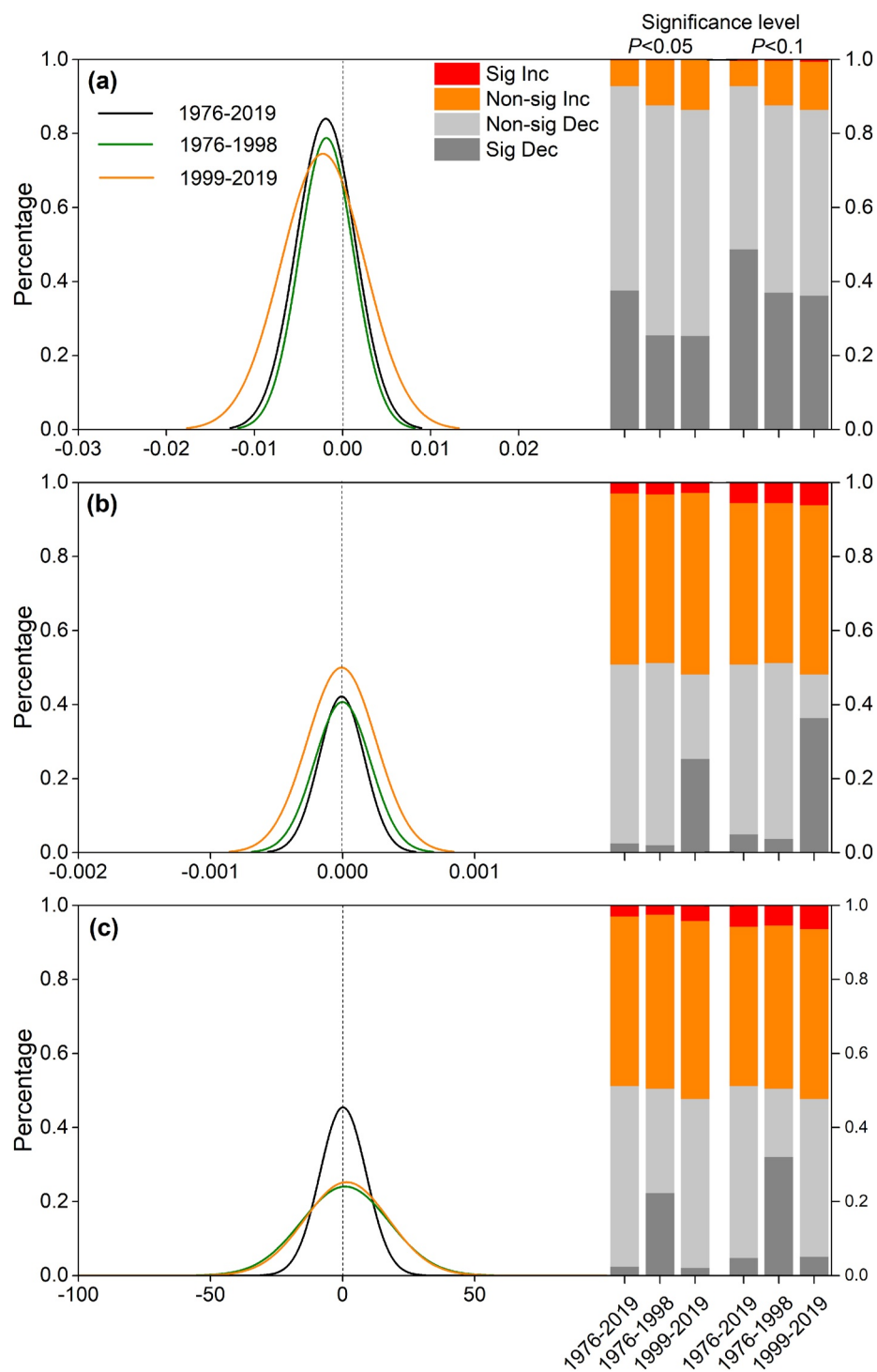


Figure 3. (a) The dependency of dry spell length (DSL) on precipitation, (b) dry day frequency on precipitation, and (c) DSL on dry day frequency in growing season during 1976–2019 over all stations. The probability density functions in left panels show the distribution of coefficients of linear regression between (a) DSL and precipitation, (b) dry day frequency and precipitation, and (c) DSL and dry day frequency, respectively. The stacked bar chart in right panels indicate the statistical results of the coefficients at significant level of 0.05 and 0.1.

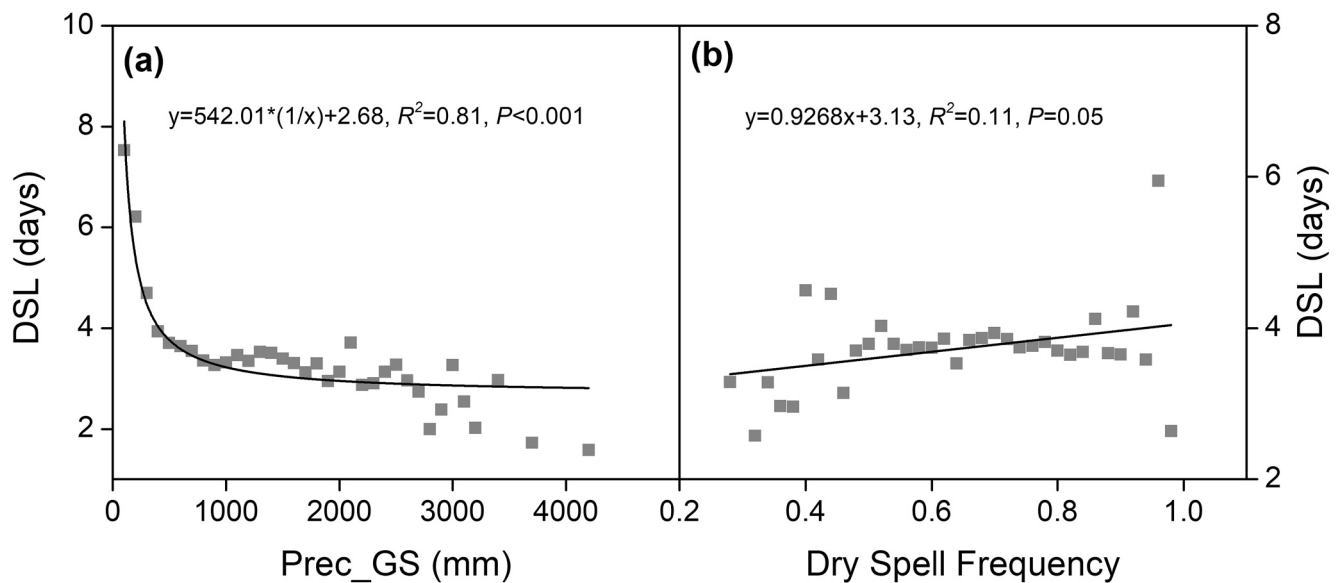


Figure 4. (a) The spatial dependency of dry spell length (DSL) on precipitation and (b) dry day frequency in growing season over all stations, respectively. The gray dots in (a) indicate the averaged DSL over all stations within each precipitation bin, the bin size is 100 mm. The gray dots in (b) indicate the averaged DSL over all stations within each dry day frequency bin, the bin size is 0.02.

4. Discussion

As one of the important aspects of climate change, changes in dry spell duration could trigger the alteration of regional carbon and hydrological cycling (Field et al., 2012). According to the Clausius-Clapeyron (C-C) relationship, global warming could result in prolonged dry spell duration (Allen & Ingram, 2002; Trenberth et al., 2003, 2005). In this study, we examined the spatiotemporal trend of growing season DSL during 1976–2019 using the global in-situ precipitation observation data set. We found that global mean DSL during growing season significantly prolonged in 1976–1998 whereas no significant trend of that was observed in 1999–2019. The increase of growing season precipitation contributed to the diminished increasing trend of DSL during 1999–2019. The results implied that the evolution of dry spells did not entirely obey the C-C relationship but also was modulated by the inter-annual variation of precipitation. The impacts of precipitation changes induced by the alteration of atmospheric circulation under global warming should be taken into account in the estimation of DSL. The shift in trend of DSL from the increase during 1976–1998 to the decrease during 1999–2019 was mainly observed in stations that located in Europe, that could be attribute to the significant decrease of dry day frequency resulting from the increase of precipitation during 1999–2019. Using the daily rain gauge data, Zolina et al. (2010) reported that the wet spells duration have become longer in Europe. Although the increase of growing season precipitation was observed in subtropics in China during 1999–2019 comparing with the period of 1976–1998, the decrease trend of dry day frequency was not shown that resulted in no significant decrease trend of DSL during this period. Ma et al. (2015) found that the frequency of heavy precipitation ($>25 \text{ mm day}^{-1}$) showed an increase trend after 2000, which indicated that the increased precipitation during 1999–2019 might be mainly from the heavy rain events and had little effects on the changes of DSL.

Changes in DSL can impact the terrestrial energy balance and ecosystem carbon and hydrological cycling. Ye and Fetzer (2019) examined the relationship between the dry spell duration and the increasing air temperature in summer during 1966–2010 basing on more than 500 stations in Russia, they found that hotter summers favor more frequent prolonged dry spells which could exacerbate drought and heat waves. Moreover, extended dry spells can enhance solar radiation which may result in the increase of evaporation and further induce the deficit of soil moisture. Increasing air temperature induced by prolonged DSL would result in the increase of atmospheric saturated water vapor capacity while the actual water vapor pressure would decrease resulting from the deficit soil moisture, that can result in the increase in vapor pressure deficit (VPD). In that case, the increased VPD would constraint the growth of terrestrial vegetation and further impact the ecosystem carbon and hydrological cycling (Yuan et al., 2019).

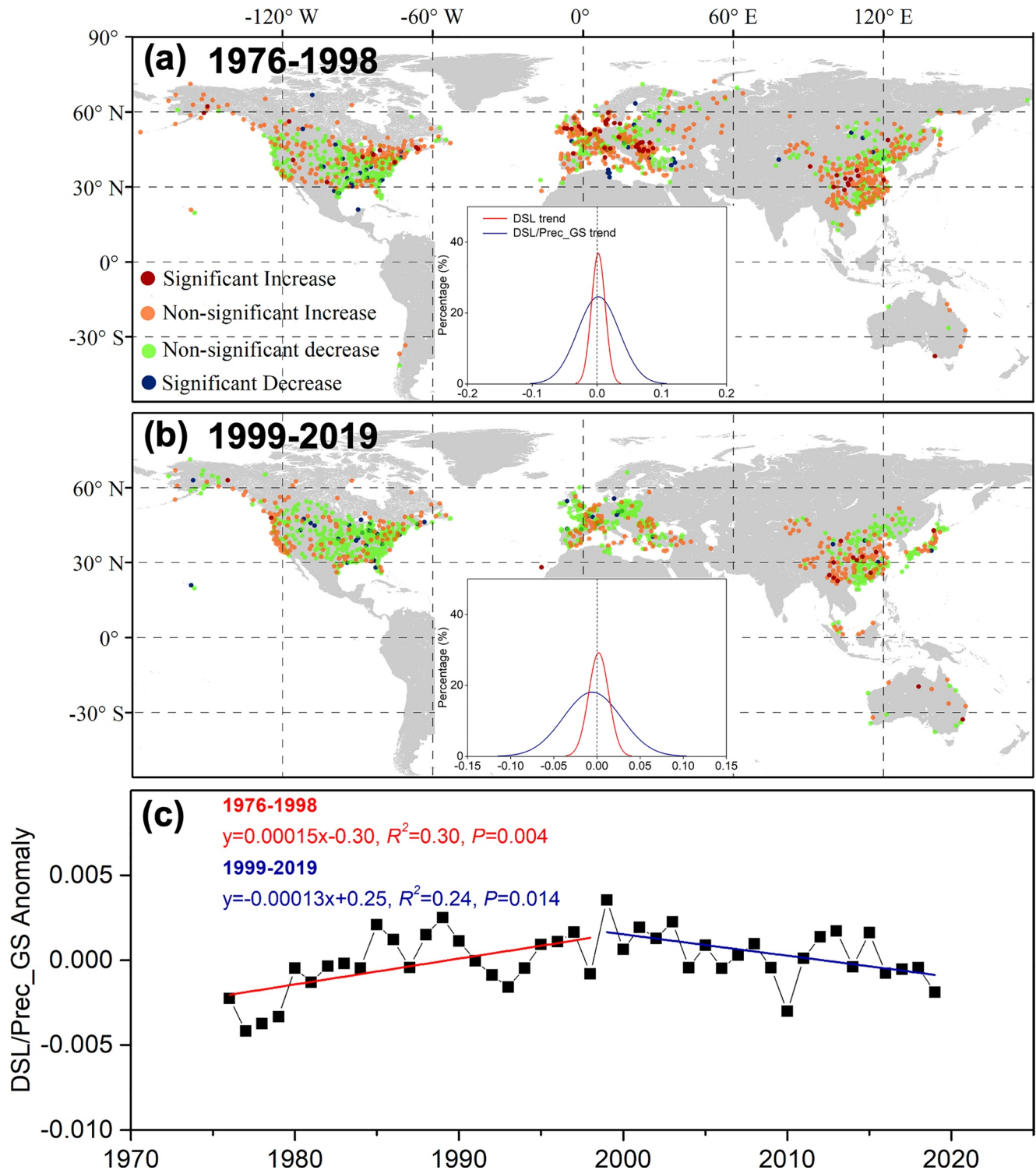


Figure 5. Spatial distribution of the trends of the ratio of dry spell length (DSL) to growing season precipitation (DSL/Prec_GS) during (a) 1976–1998 and (b) 1999–2019. Global mean trends of the DSL/Prec_GS ratio during 1976–2019 (c). The small insets in (a and b) show the probability distribution functions of the DSL/Prec_GS ratio trends during the two periods.

In this study, we found the trend of growing season DSL and precipitation shifted after the turning point year in 1998, the same turning point year was also reported by previous studies. Yuan et al. (2019) found that the global VPD showed a sharp increase trend after the late 1990s. The global mean surface air temperatures data indicated

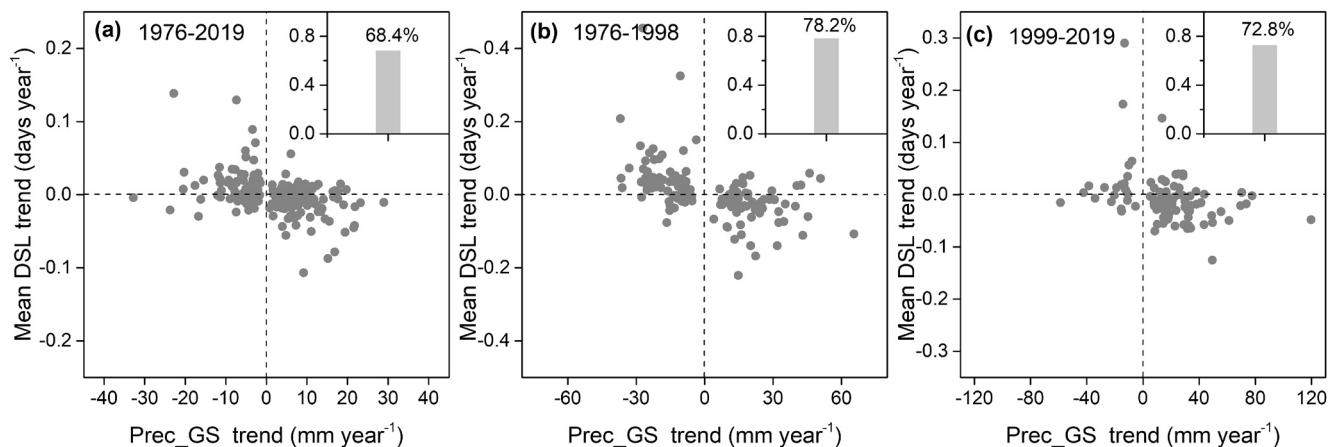


Figure 6. Dry spell length trends in stations which experienced significant ($P < 0.1$) changes in growing season precipitation during the period of 1976–2019, 1976–1998, and 1999–2019, respectively. The small insets indicate the percentage of stations which showed negative relationship of DSL trends with growing season precipitation trends during the three periods.

a global warming hiatus between 1998 and 2012 (Fyfe et al., 2016; Kaufmann et al., 2011; Medhaug et al., 2017). The warming hiatus can slow the increase of atmospheric saturate vapor pressure, that would further ease the increase of residence time of atmospheric vapor. Wang et al. (2019) also reported that the global vegetation phenology was lack of widespread trends after 1998. The 1997–1998 El Niño events was known to be one of the strongest in history, that affected the global precipitation changes (Kane, 1999). The linkages and interact mechanisms among the changes of DSL, increase of VPD as well as changes of growing season length should be explored in future studies.

5. Conclusion

Dry spell length plays an important role in regulating soil moisture dynamics, terrestrial energy exchange as well as vegetation growth. In this study, we examined the spatiotemporal trends of growing season DSL, basing on the global in-situ observation data set of daily precipitation from 1976 to 2019. The results showed the global mean growing season DSL significantly increased during 1976–1998 whereas no significant trend of that was observed during 1999–2019. The diminished increasing trend of DSL can attribute to the increase of growing season precipitation during 1999–2019. Our study indicated that the evolution of dry spells were modulated by the inter-annual variations of growing season precipitations. The linkages and interact mechanisms among the changes of DSL and precipitation characteristics should be explored in future studies.

Conflict of Interest

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

Data Availability Statement

All data used in this study are publicly available, can be download from <https://www.ncei.noaa.gov/data/global-summary-of-the-day/>.

Acknowledgments

This study was supported by the National Natural Science Foundation of China (Nos. 42101026, 31930072), Guangdong Basic and Applied Basic Research Foundation (2020A1515111145) and Innovation Group Project of Southern Marine Science and Engineering Guangdong Laboratory (Zhuhai) (No. 311021009).

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