

# Changes and driving factors of compound agricultural droughts and hot events in eastern China

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## ABSTRACT

Compound droughts and hot events (or hot droughts) have attracted increasing attention due to their far-reaching impacts. Previous studies on these events mostly focused on the concurrence of meteorological droughts and hot extremes. The compound agricultural droughts and hot events (CADHEs), which have direct impacts on agricultural production, have received limited attention to their variability and driving factors. In this study, we defined CADHEs based on summer temperature and soil moisture from the Global Land Data Assimilation System (GLDAS) and investigated their changes and potentially driving factors for the period 1949–2014 in eastern China. Results showed increases in the frequency of CADHEs in Northeast China, North China, and South China (with increases of 125%, 160%, and 83%, respectively) except for Central China (with a decrease of 39%). Furthermore, we analyzed the contributions from individual variables (i.e., soil moisture and temperature) and their dependence on CADHEs changes in quantitative manners. For most regions, the increased temperature was the dominant driving factor of increased CADHEs. Strengthened soil moisture-temperature dependence was shown to play an important role in the increase of CADHEs in Northeast China, highlighting the contributions of dependence changes on the variability of compound events. This study can improve the understanding of changes in compound droughts and hot extremes and provide useful insights for mitigation measures of agricultural losses under global warming.

## 1. Introduction

Eastern China is an important region for crop production and food security. Devastating natural hazards, such as droughts and heatwaves, can cause substantial reductions in crop yield and affect the ecosystem and socioeconomics (Ribeiro et al., 2019). Meanwhile, the response of crops and plants to droughts or heatwaves under global warming has been widely discussed (Hatfield and Prueger, 2015; Zhao et al., 2017). Moreover, compound extremes (i.e., multiple extremes occur concurrently or consecutively) may lead to large impacts than the sums of parts and a growing amount of research has focused on compound events or extremes (Hao et al., 2013; Feng et al., 2020; Zscheischler et al., 2020). The compound droughts and hot extremes may cause amplified and negative impacts on crop yield, risking food security (Zscheischler et al., 2018; Feng et al., 2019; Potopová et al., 2020; Ribeiro et al., 2020), as exhibited by many historical periods of crop yield losses in eastern China, such as those during 2001, 2007, and 2013 (Yu et al., 2014, 2018; Yuan et al., 2016). As such, it is important to understand the changing pattern and driving factors of compound droughts and hot events in

eastern China.

The changes in compound droughts and hot events in China have been explored in the past decade (Wu et al., 2019; Kong et al., 2020; Yu and Zhai, 2020a; Feng et al., 2021). For example, increased compound dry-hot events have been observed in most of China except for certain central regions (Wu et al., 2020; Yu and Zhai, 2020b). However, previous investigations on compound dry-hot events mostly focused on meteorological droughts (e.g., based on precipitation), while the studies on compound agricultural droughts and hot events (CADHEs) have been lacking. Agricultural droughts are commonly defined based on soil moisture-related indicators (Mishra and Singh, 2010; Ding et al., 2021; Han et al., 2021; Souza et al., 2021; Zhou et al., 2021), which can be used for characterizing the CADHEs. Recently, the CADHEs have attracted increasing attention due to their wide impacts on crop yields (Hao et al., 2018; Manning et al., 2018; Lesk and Anderson, 2021). For example, Lesk and Anderson (2021) used monthly soil moisture to define droughts and assessed changes in CADHEs in croplands, highlighting the enhanced risk of these compound events to global crops.

The changed characteristics of compound events can be related to

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the trends in individual variables and their dependencies (Zscheischler and Seneviratne, 2017; Bevacqua et al., 2019, 2020; Manning et al., 2019). A variety of studies have shown that the temperature increase dominated the increase of compound droughts and hot events at different regional scales (Sarhadi et al., 2018; Wu et al., 2020). In addition, several studies also highlighted the importance of changes in dependence between contributing variables to the increase of compound events (Zscheischler and Seneviratne, 2017; Hao and Singh, 2020). For example, Zscheischler and Seneviratne (2017) showed that the increase of concurrent hot and dry summers in many regions worldwide in the future is largely related to the enhanced precipitation-temperature dependence. These evaluations of the impacts of droughts/hot extremes or their dependence on changes in compound dry-hot events highlight the complicated driving factors (Manning et al., 2019). For the increase of the CADHEs, there is also an increasing interest in understanding the contribution of dependence changes. Lesk et al. (2021) found that the stronger temperature-moisture couplings aggravated the risk of crop yields in most regions across global cropland under climate warming. However, it is still unclear as to the relative importance of different driving factors (i.e., agricultural droughts, high temperature extremes, and their dependence) in explaining changes in CADHEs.

The main objective of this study is to quantify the relative contribution of different driving factors to recent changes in CADHEs during summers from 1949 to 2014 in eastern China. We defined CADHEs based on summer soil moisture and temperature and then evaluated the changes in different regions across eastern China. The relative contribution of individual variables and their dependence on the changes in CADHEs is then quantified, followed by a discussion on the implications and limitations. This study will aid the development of strategies for agricultural water management to cope with potentially high risks of concurrent agricultural droughts and hot extremes under global warming in eastern China.

## 2. Study area and data

We focus on eastern China (from 105 °E to the eastern coastlines) with a dense population and widespread cropland. The CADHEs occurring in this region may pose risks to food production in China. Following Li et al. (2015), eastern China is further divided into four sub-regions, including Northeast China (NE), North China (NC), Central China (CC), and South China (SC), as shown in Fig. S1. These sub-regions are used to explore the regional differences of changes and drivers of CADHEs.

The monthly air temperature and soil moisture data at a 0.25-degree resolution for the period 1949–2014 were obtained from Global Land Data Assimilation System Version 2.0 (GLDAS 2.0). The meteorological data from GLDAS 2.0 are entirely based on the Princeton Global Meteorological Forcing version 2 (PGF v2) (Sheffield et al., 2006), which merges reanalysis products with observation-based datasets. This forcing dataset has been evaluated and shows relatively good performance in China (Lai et al., 2016; Wang et al., 2016). GLDAS 2.0 provides the simulated soil moisture from the Noah land surface model, which uses the MODIS-based land surface parameters (e.g., static land cover from Modified IGBP MODIS 20-category vegetation). This simulated soil moisture dataset has been validated in China (Wang et al., 2016; Zhang et al., 2021a) and widely employed in previous studies for drought assessments (Han et al., 2019; Li et al., 2020). Soil moisture at four layers (i.e., 0–10 cm, 10–40 cm, 40–100 cm, and 100–200 cm) can be obtained from this dataset. Here, we selected the soil moisture between 0 and 100 cm to define agriculture droughts, which has been commonly used due to effective representation of the root zone of vegetation and crops (Martínez-Fernández and Ceballos, 2005; Han et al., 2021; Lesk and Anderson, 2021; McKinnon et al., 2021).

## 3. Method

### 3.1. Definition of CADHEs

Due to the higher risk of co-occurrence of dry and hot events in the warm season (Zscheischler and Seneviratne, 2017), we focus on the CADHEs during summer (June–July–August) in this study. The Standardized Soil moisture Index (SSI) and Standardized Temperature Index (STI) are used to characterize the agricultural droughts and hot events, respectively (Zscheischler et al., 2014; Hao et al., 2018). These indicators are computed by  $SSI = N^{-1}(P_s)$  and  $STI = N^{-1}(P_t)$ , where  $N^{-1}$  is the inverse of the standard normal distribution function, and  $P_s$  and  $P_t$  are the marginal probabilities of soil moisture and temperature, respectively. The marginal probability can be calculated by empirical Gringorten plotting position to avoid assumptions of parametric distributions (Hao et al., 2018). We use the 3-month SSI and STI in August to represent the summer droughts and hot conditions, respectively. The agricultural droughts are defined as  $SSI \leq -0.5$  (approximately 30th percentile) and the hot events are defined as  $STI > 0.5$  (approximately 70th percentile). The CADHEs are defined as the concurrence of agricultural droughts and hot events (i.e.,  $SSI \leq -0.5$  and  $STI > 0.5$ ) during the summer seasons. The frequency of CADHEs in a certain period is defined as the number of occurrences divided by the total number of the period. The study period is separated into two 33-year periods (1949–1981 and 1982–2014) to analyze the changes in CADHEs.

### 3.2. Return period

The return period (RP) of compound events is employed to represent the risk for the contribution analysis in the following sections. A low return period implies a high probability of CADHEs occurrences. The return period of CADHEs is expressed as the inverse of the bivariate probability based on the copula, which is given by:

$$RP = \frac{1}{P(SSi \leq s_0, STI > t_0)} = \frac{1}{u_{s_0} - C(u_{s_0}, u_{t_0})} \quad (1)$$

where  $C$  is the copula fitted to  $(u_s, u_t)$ ;  $u_s$  and  $u_t$  are marginal probability distributions of SSI and STI;  $s_0$  and  $t_0$  are the value of SSI and STI at which the joint probability is evaluated, respectively. Commonly used copula families, including Gaussian, Student's t, Frank, Gumbel, and Clayton, and their rotated versions are selected according to Akaike information criterion (AIC) and fitted by the inversion of Kendall's tau in each grid (Genest and Favre, 2007; Manning et al., 2019; Tavakol et al., 2020). The VineCopula R package is employed for the copula selection and parameter estimation in this study.

### 3.3. Contribution analysis

To unravel the relative contribution from changes in individual events and their dependence on the variation in CADHEs, we disentangle these factors using the method provided by Bevacqua et al. (2019). The key concept of this method is the three experiments to quantify how the return period or joint probability of CADHEs would change in the latter period (1982–2014) relative to the former period (1949–1981) when only one factor (i.e., soil moisture, temperature, and their dependence) changes. The relative change of return period for each experiment (i) can be expressed as:

$$\Delta RP_{exp,i} = 100 \cdot (RP_{exp,i} - RP1) / RP1 \quad (2)$$

where  $RP1$  is the return period for the former period and  $RP_{exp,i}$  is the return period computed by the following three experiments.

Experiment (a): contribution from soil moisture  $S$ . Given the variable  $S1$  (i.e.,  $S$  in the former period), we compute the associated empirical cumulative distribution (CDF)  $U_{S1}$ . Given the variable  $S2$  (i.e.,  $S$  in the latter period), we define the empirical CDF  $F_{S2}$ , which is used to

calculate  $S_a = F_{S2}^{-1}(U_{S1})$ . Then we use bivariate variables  $(S_a, T1)$  to compute  $RP_{exp,a}$  via Eq. (1). The  $(S_a, T1)$  use the marginal distribution of  $S$  in the latter period to reflect the influence of changes in soil moisture on return period variation.

Experiment (b): contribution from temperature  $T$ . Similar to Experiment (a) but exchanging  $S$  and  $T$ .

Experiment (c): contribution from  $S$ - $T$  dependence. Given bivariate variables  $(S1, T1)$  and  $(S2, T2)$ , we compute the empirical CDF  $S_c = F_{S1}^{-1}(U_{S2})$  and  $T_c = F_{T1}^{-1}(U_{T2})$ . The variables  $(S_c, T_c)$  have the same Spearman correlation as  $(S2, T2)$ , while keeping the marginal distributions in the former period. Then the  $RP_{exp,c}$  is computed based on  $(S_c, T_c)$ .

The return period changes ( $\Delta RP$ ) computed by the three experiments can represent the relative contribution of different factors. Note that the negative changes of  $\Delta RP$  (i.e., reduced return period or increased probability) indicate contributions to the increase in CADHES.

## 4. Results

### 4.1. Climatological frequency of CADHES

The Kendall's rank correlation coefficient is employed to measure the dependence between summer temperature and soil moisture during 1949–2014, as shown in Fig. 1(a). Negative correlations are statistically significant (at the 0.05 significance level) in most areas across eastern China. The negative soil moisture-temperature dependence can be explained by two pathways, including land-atmosphere feedback and synoptic-scale correspondence between cloud cover and incoming shortwave radiations (Trenberth and Shea, 2005; Zscheischler and Seneviratne, 2017). Specifically, the soil moisture deficit induced by low precipitation can lead to reduced evaporative cooling accompanied by increased sensible heat and increase surface air temperature. High-temperature anomalies can accelerate evapotranspiration, which further depletes the soil moisture (Miralles et al., 2019; Liu et al., 2020). In addition, the low cloud cover associated with low precipitation (and subsequent soil moisture deficit) tends to enhance the incoming shortwave radiation, resulting in the surface air temperature increases (Berg et al., 2015; Zscheischler and Seneviratne, 2017). The combination of these processes results in strong negative soil moisture-temperature dependence.

The climatological frequency of CADHES during summer for the period 1949–2014 in eastern China is shown in Fig. 1(b). The pattern of frequency of CADHES shows high consistency with the dependence between summer temperature and soil moisture. For example, North

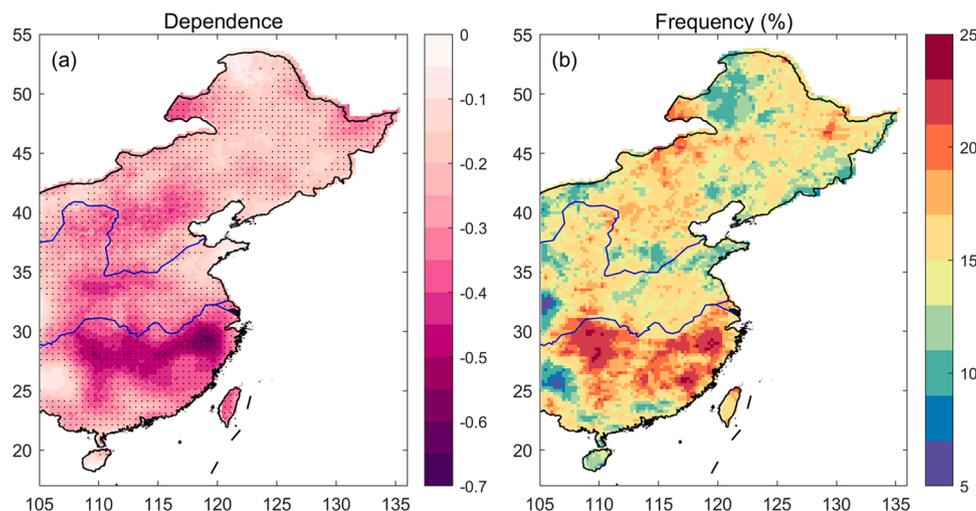
China, where strong land-atmosphere interaction has been shown (Zhang and Wu, 2011; Wu and Zhang, 2015), is among the regions with a high frequency of CADHES. In most parts of Central and South China (middle and lower reaches of the Yangtze River Valley), CADHES occur more frequently (Fig. 1(b)), which can be explained by stronger soil moisture-temperature dependence (Fig. 1(a)).

### 4.2. Changes in the frequency of CADHES and associated driving factors

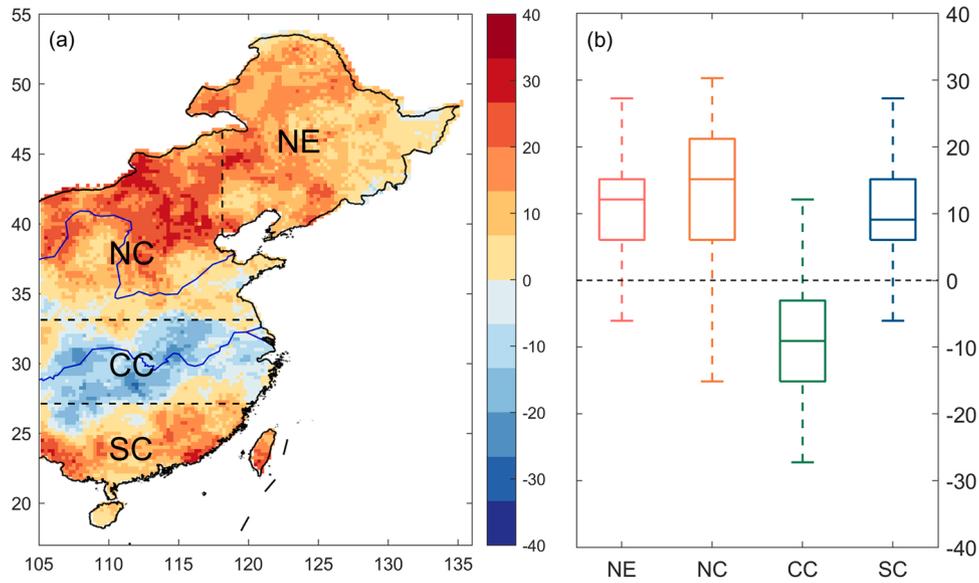
The changes in the frequency of CADHES in eastern China and four sub-regions for two equal periods 1949–1981 and 1982–2014 are shown in Fig. 2. Significant increases in the frequency of CADHES are found in NE, NC, and SC. Fig. 2(b) shows the larger increase in the frequency of CADHES in NC. We also compute the relative changes of the average frequency between two periods in each region. For NE, NC, and SC, the regional average frequency increases by 125%, 160%, and 83%, respectively. Meanwhile, CADHES in CC show a decrease in regional average frequency (–39%). This pattern (increased CADHES in most areas except for the CC) is consistent with the changes in compound meteorological droughts and hot events in previous studies (Wu et al., 2019, 2020).

Changes in the compound events are related to changes in each variable and the dependence between them (Zscheischler and Seneviratne, 2017). The scatterplots of regional average summer STI and SSI for two equal periods are shown in Fig. 3 (changes in summer SSI, STI, and dependence for each grid are shown in Fig. S2). The marginal distributions in each period are shown to represent the individual changes in soil moisture or temperature. The 95% confidence ellipses of the SSI-STI pairs in each period are constructed to characterize the joint changes of soil moisture and temperature. The marginal distribution of STI indicates that hot events have become more frequent in NE, NC, and SC in 1982–2014 relative to 1949–2014. The marginal distribution of SSI implies that agricultural droughts have become more frequent in NC and less frequent in CC (with heterogeneous changes in other regions). There are distinct displacements of the ellipses towards a warm and dry condition in NE, NC, and SC. The findings of this changing pattern of soil moisture and temperature agree with previous research (Wang et al., 2011; Lai et al., 2016; Hu et al., 2017; Ye et al., 2019). For example, the variation of SSI and STI over North China is consistent with previous studies showing that the co-variability of summer temperature and soil moisture has changed from cool-wet to warm-dry (Su and Wang, 2007).

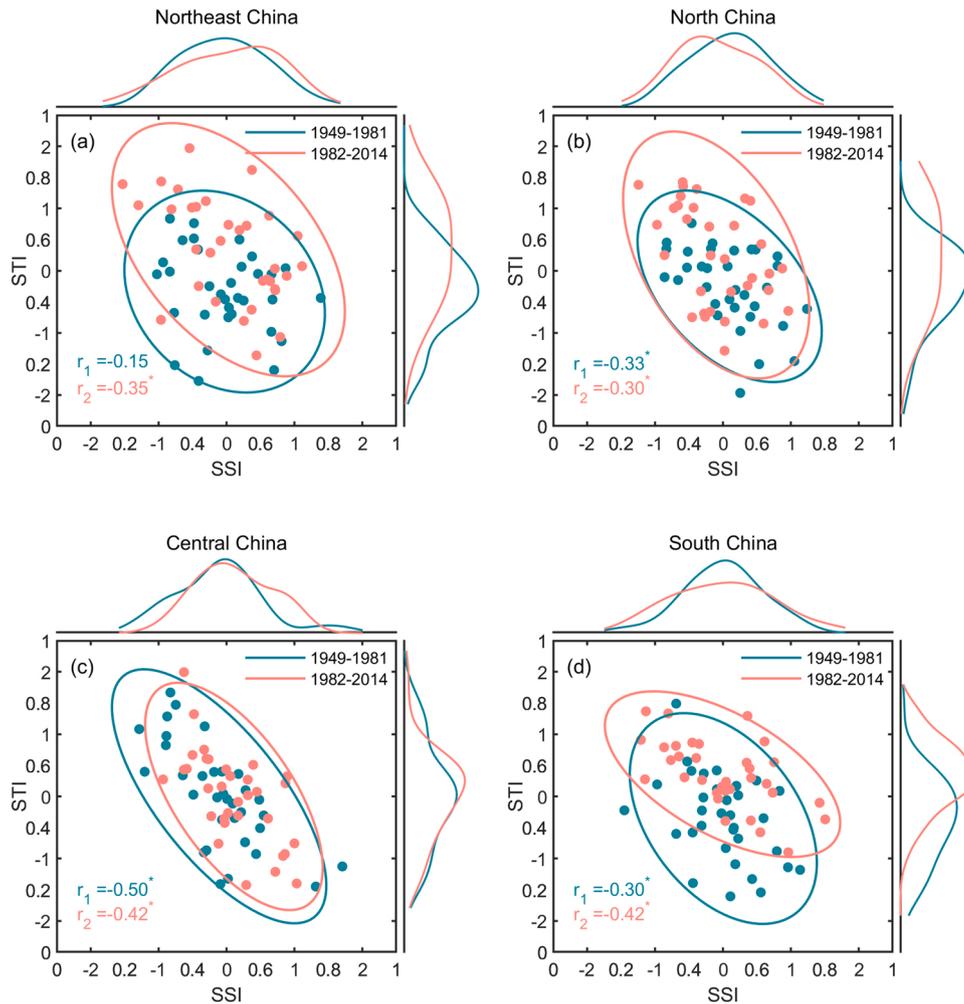
Previous studies have shown that enhanced dry-hot dependence could lead to more frequent compound dry and hot events (Zscheischler and Seneviratne, 2017; Hao and Singh, 2020). The dependence (i.e.,



**Fig. 1.** The soil moisture-temperature dependence and frequency of CADHES for the period 1949–2014 in eastern China. (a) Kendall's rank correlation between summer temperature and soil moisture (black stippling indicates significant correlations at the 0.05 significance level). (b) Climatological frequency of CADHES.



**Fig. 2.** Changes in the frequency (unit: %) of CADHES for the period 1982–2014 relative to 1949–1981 in eastern China. (a) Spatial distribution of the changes. (b) Boxplot of the changes in four sub-regions (i.e., NE, NC, CC, and SC).



**Fig. 3.** Scatterplots of summer SSI and STI for the period 1949–1981 and 1982–2014 in four sub-regions (i.e., NE, NC, CC, and SC). The curves on the sides represent the marginal distribution and the ellipses represent the 95% confidence ellipses. Kendall's rank correlation coefficients  $r_1$  and  $r_2$  for two equal periods are shown (\* indicates significant correlations at the 0.05 significance level).

Kendall's rank correlation) between SSI and STI has strengthened in NE and SC (from  $-0.15$  to  $-0.35$  and from  $-0.30$  to  $-0.42$ ), while weakened in NC and CC (from  $-0.33$  to  $-0.30$  and from  $-0.50$  to  $-0.42$ ). In particular, in NE, the correlation between soil moisture and temperature has shifted from insignificant correlations to significant correlations (at the 0.05 significance level), which indicates the interaction between temperature and soil moisture has strengthened remarkably. This implies that the increase of CADHES in NE partly results from the enhanced SSI-STI dependence. As for the regions with increased CADHES and weakened dependence (such as parts of NC), the individual trends (of soil moisture and temperature) may compensate for the effect of dependence changes. Considering the heterogeneous changes in the soil moisture and dependence (Fig. S2), the increase of temperature may be the main driver of increased CADHES. Meanwhile, these results also imply that the changed dependence may play a role in changes in the frequency of CADHES in certain regions.

#### 4.3. Disentanglement of driving factors

Previous sections mainly explain the variability of CADHES based on changes in soil moisture (SSI), temperature (STI), and their dependence from a qualitative manner. Following Bevacqua et al. (2019) and Manning et al. (2019), we further quantitatively disentangle the impact of these factors on changes in the return period (or probability) of CADHES, as shown in Fig. 4. The spatial distribution of the relative contribution illustrates that these factors have different degrees of contributions in different regions. Changes in STI tend to increase the CADHES in NE, NC, and SC, and decrease the CADHES in CC, as shown in Fig. 4(b). This is consistent with significant temperature increases in NE, NC, and SC, and the slight cooling trend in parts of CC, as shown in Fig. S2(b). The decrease in SSI contributes to CADHES increases in large parts of NC and SC (Fig. 4(a)), where soil moisture has a drying trend (Fig. S2(a)). Meanwhile, the wetting trend reduces the CADHES in CC significantly. Strengthened dependence between SSI and STI contributes to the CADHES increases in NE (Fig. 4(c)), where negative SSI-STI correlations become stronger in the later period (Fig. S2(c)).

To compare the relative contributions of each factor in different sub-regions, the boxplots of the contributions from three components are

shown in Fig. 5. In NE, changes in STI have the main contribution, followed by SSI-STI dependence, while the influence of SSI is negligible (median  $\Delta RP_{STI} = -57.8\%$ ,  $\Delta RP_{SSI} = 1.0\%$ ,  $\Delta RP_{Dep} = -18.8\%$ ). The results highlight the important contribution of the dependence changes on the variability of CADHES, though the temperature increase still plays the dominant role. In NC, changes in STI and SSI contribute the most to CADHES increase with the dependence change playing a minor role (median  $\Delta RP_{STI} = -53.9\%$ ,  $\Delta RP_{SSI} = -15.8\%$ ,  $\Delta RP_{Dep} = 4.9\%$ ). In SC, both the influences of SSI and dependence are slight with temperature increase playing the dominant role (median  $\Delta RP_{STI} = -50.4\%$ ,  $\Delta RP_{SSI} = -1.9\%$ ,  $\Delta RP_{Dep} = 0.5\%$ ). In CC, the negative effects of all three factors lead to decrease in CADHES (median  $\Delta RP_{STI} = 3.9\%$ ,  $\Delta RP_{SSI} = 26.0\%$ ,  $\Delta RP_{Dep} = 13.3\%$ ). The wetting trend in summer is the main cause of the decreased CADHES in CC, which is more important than the changes in temperature and dependence. In general, the increased temperature has a dominant influence on increased CADHES in most regions, while the contribution of soil moisture and dependence variation also play important roles in certain regions. Note that changes in dependence do not have a widespread spatial pattern with consistent symbols (except for NE) and may compensate each other at the regional scale (median  $\Delta T_{Dep}$  close to 0), such as in NC and SC.

## 5. Discussion

### 5.1. Implications

Concurrences of agricultural droughts and hot extremes have a wide range of impacts on agriculture. These events can reduce crop yields through decreasing water supply (i.e., low soil moisture) and increasing water demand in response to heat stress. We find increased risk of CADHES in most regions of eastern China where a variety of crops are widely planted. The increase of CADHES is shown to be induced by trends in soil moisture/temperature as well as changes in their dependence. Though temperature increase or regional warming has usually been shown to be a dominant driving factor, the dry-hot dependence change may also be at play in changes of compound events (Zscheischler and Seneviratne, 2017; Hao and Singh, 2020). For example, the increased dependence between summer soil moisture and temperature

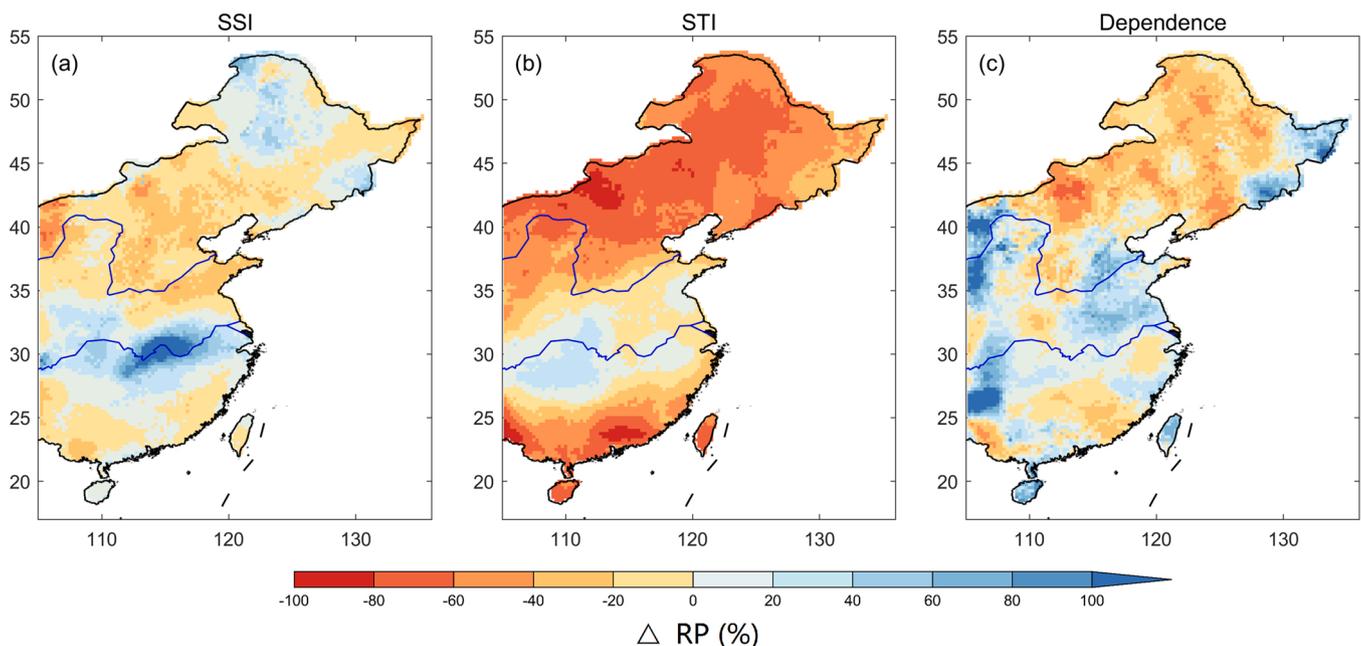
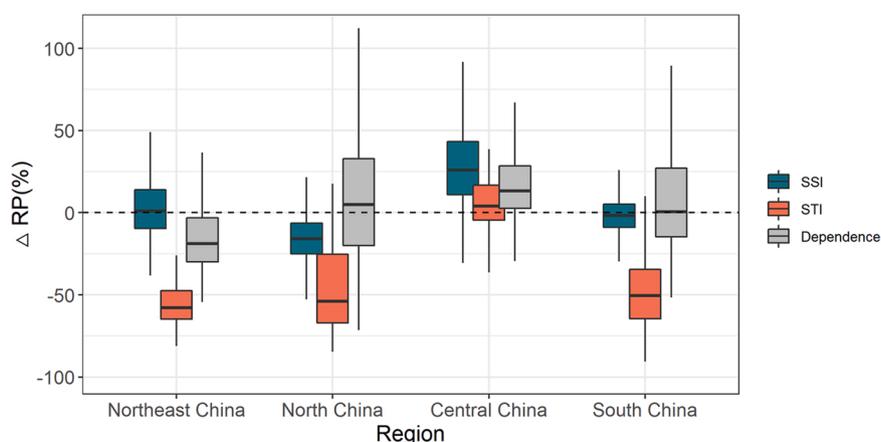


Fig. 4. Spatial distributions of relative contributions from changes in (a) SSI, (b) STI, and (c) dependence to changes in the return period (RP) of CADHES between two periods (1949–1981 and 1982–2014) in eastern China. The warm colors (or negative values) indicate that the changes of SSI, STI, or dependence contribute to increases in the probability of CADHES. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)



**Fig. 5.** The boxplot of contributions from three components (same as Fig. 4) in four sub-regions (i.e., NE, NC, CC, and SC) to changes in the return period (RP) of CADHES between two periods 1949–1981 and 1982–2014.

plays a relatively significant impact on changes in CADHES in NE. These results highlight the importance of dry-hot dependence in studying the variability of compound droughts and hot events. This further heightens the importance of accurately simulating the interaction between soil moisture and temperature (or soil moisture-temperature feedback) in land surface models (Miralles et al., 2019), which can improve our understanding of the variability of CADHES in historical periods and future projections.

Disentangling the impacts of different factors on changes in CADHES contributes to adaptation measures of the agriculture sector under global warming. Although our study focuses on the historical assessments of CADHES, these methods can also be employed to guide the future projection and adaptation of such compound events. For example, heat-resistant cultivars of the crop could be considered in the regions with CADHES increases driven by warming. Coordinated water resources management (i.e., increased irrigation) could be used to mitigate impacts of CADHES in the regions with CADHES increases driven by drying. Meanwhile, in the regions where CADHES increase is also induced by strengthened soil moisture-temperature dependence, more complex adaptation strategies need to be designed.

## 5.2. Limitations

Several limitations exist in this study that may induce uncertainties. To obtain large samples of compound events, GLDAS 2.0 with a relatively long-term record is employed in this study. However, errors in the simulated soil moisture from land surface modeling can affect the soil moisture-temperature dependences and associated co-variabilities. Specifically, the land surface model simulation used in this study is unable to reflect the land-use change (e.g., urbanization) as a result of the static vegetation and soil parameters. Meanwhile, the human water use (e.g., irrigation and exploitation of groundwater) is not considered in the model simulations, leading to biases in regions with intense human interference. To improve this representation of land surface conditions at regional or local scales, soil moisture from gauge measurements (e.g., China Meteorological Administration, CMA) and satellite remote sensing (e.g., European Space Agency Climate Change Initiative, ESA CCI) can be used as candidates for future studies (Liu et al., 2019; Chen and Yuan, 2020). We select the same depths of soil moisture and same season in this study without consideration of the root zone depth and growing periods for different crops. The consideration of crop-specific conditions is beneficial for reflecting the influence of CADHES, which is worth being explored further. In addition, we define CADHES on the seasonal scale, while events on sub-seasonal scales (e.g., daily and weekly) may have different change patterns and drivers (Brunner et al., 2021; Li et al., 2021; Mukherjee and Mishra, 2021). The

statistical attribution method used in this study can reflect the relative role of different driving factors to CADHES. However, the physical processes of these factors in affecting the variability of CADHES are not clear. As such, dynamical models can be used for further attribution analysis to disentangle the relative roles of different factors (Wehrli et al., 2019). For example, separating the influence of dependence by decoupling the soil moisture and temperature in the land surface model can quantify the contributions of dependence on CADHES. Furthermore, the underlying physical drivers for changes in individual events and dependence (e.g., global warming and large-scale atmospheric circulations) need to be understood (Hao and Singh, 2020; Sarhadi et al., 2018; Vogel et al., 2019; Zhang et al., 2021b). Overall, it is worth exploring other datasets, specific crops, attribution methods, and models to improve our understanding of the physical mechanisms of CADHES and the cause of their changes.

## 6. Conclusion

In this study, we investigated changes in compound agricultural droughts and hot events (CADHES) and contributing factors for the period 1949–2014 in eastern China. Results showed that CADHES occurred more frequently in CC and SC relative to other regions. CADHES exhibited significant increases in NE (125%), NC (160%), and SC (83%), whereas decreases in CC (–39%) for the period 1982–2014 relative to 1949–1981. The changes can be attributed to changes in soil moisture, temperature, and their dependence. Increased hot events and agricultural droughts were observed in NC and SC. Meanwhile, the dependence between SSI and STI has strengthened in NE and SC. We employed a statistical method to quantify the relative contributions of these factors. Results indicated that the increased temperature dominated the increased CADHES in most regions of eastern China (except for CC), and the strengthening dependence also had a significant influence in NE. The wetting trend had a major weakening effect on the changes in CADHES in CC. The results highlighted the importance of modeling the soil moisture-temperature dependence in understanding the variability of CADHES. Overall, our study showed an overall enhanced risk of CADHES towards agricultural production or crop yields. Seasonal prediction and future projection of these compound events are useful measures to mitigate their potentially negative impacts in eastern China.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.agwat.2022.107485](https://doi.org/10.1016/j.agwat.2022.107485).

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