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Spatiotemporal behavior of floods and droughts and their impacts on agriculture in China

Qiang Zhang [a,b,c,*], Xihui Gu [a,b], Vijay P. Singh [d], Dongdong Kong [a,b], Xiaohong Chen [a,b,c]

[a] Department of Water Resources and Environment, Sun Yat-sen University, Guangzhou 510275, China
[b] Key Laboratory of Water Cycle and Water Security in Southern China of Guangdong High Education Institute, Sun Yat-sen University, Guangzhou 510275, China
[c] Guangdong Key Laboratory for Urbanization and Geo-simulation, Sun Yat-sen University, Guangzhou 510275, China
[d] Department of Biological & Agricultural Engineering and Zachry Department of Civil Engineering, Texas A & M University, College Station, TX 77843-2117, USA

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ABSTRACT

China is an agricultural country with the largest population in the world. However, intensification of droughts and floods and amplification of precipitation extremes are having critical negative impacts on agriculture. In this study, flood- and drought-affected, flood- and drought-damaged crop areas, and also flood- and drought-induced agricultural loss from 29 provinces across China are analyzed in both space and time. Results indicate the following: (1) Large parts of China are dominated by intensified floods. Comparatively, spatial ranges dominated by intensifying drought hazards are smaller than those by intensifying flood hazards. (2) Drought intensity is increasing in northwest China with moderate changes in the degree of influence. Increasing flood intensity can be observed in northwest, southwest and central China. However, flood risks are higher in arid regions such as northwest China and drought risks are higher in humid regions such as southwest China. (3) Agreements are identified between abrupt behaviors of flood-affected and -destroyed crop areas. The change points of flood-affected and -destroyed crop areas is in the 1980s in northeast, north and central China and in the 1990s in south and southwest China. Nevertheless, spatial patterns of the change points in the drought-affected and -destroyed crop areas are sporadic but not confirmative. (4) Flood- and drought-induced losses of agricultural production have significant increasing trends in most parts of China. The loss rate and loss magnitude of agriculture before change points are significantly higher than those after change points. (5) Generally, amplifications of precipitation extremes, decreasing consecutive wet days and increasing consecutive dry days in both space and time are the major driving factors behind the changes of drought- and flood-affected, and -destroyed crop areas and their impacts on agriculture across China. These results are theoretically and practically relevant for planning and management of agricultural activities and may help provide a theoretical framework for similar studies in other regions of the globe.

1. Introduction

Human-induced climate warming has been well evidenced and warming climate has the potential to accelerate the global- and continental-scale hydrological cycle (Alan et al., 2003; Zhang et al., 2013). Under the influence of warming climate, prime hydrological components, such as precipitation, are subject to alteration. Decreasing rainfall trend has been observed in the Mediterranean area (Karl, 1998) and significant decreasing trends in extreme rainfall have been observed in Western Australia (Haylock and Nicholls, 2000). However, an increasing trend in extreme precipitation was identified in the United States (e.g., Kunkel, 2003) and no trend in extreme rainfall was found in Canada (Zhang et al., 2001). Due to diverse underlying properties and various human activities, precipitation changes in China are varying significantly in both space and time (e.g. Wang and Zhou, 2005; Zhang et al., 2011a). Furthermore, spatiotemporal alterations of precipitation regimes due to warming climate and ENSO events evidently alter spatiotemporal patterns of floods and droughts (Zhang et al., 2011a, 2013, 2015). It should be noted that the rain-fed agriculture shoulders the largest burden of providing food in the developing countries (Sharma, 2011). Impacts of droughts, floods and precipitation changes on agriculture and hence the food security have been drawing increasing attention from academic communities in recent decades (Devereux, 2007; Douglas, 2009; Zhang et al., 2012a; Qin et al., 2014).

The human society faces diverse challenges to food security due to persistent population growth and rapid diet transition to decreasing cropland area and insufficient production practices (Beddington et al., 2012). Climate changes have the potential to exacerbate the already-fragile global food production system and the natural resource base

* Corresponding author at: Department of Water Resources and Environment (Department Chairman), Sun Yat-sen University, Guangzhou 510275, China. Tel./fax: +86 20 84113730.
E-mail address: zhangq68@mail.sysu.edu.cn (Q. Zhang).

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(Ye et al., 2014). Global surface temperature has increased by 0.8 °C during the twentieth century; 3/4 of this increase occurred in the last three decades (Hansen et al., 2006; Ye et al., 2013, 2014). The acceleration in global warming and its associated changes in precipitation have already affected global agriculture and the food production system in many ways (Godfray et al., 2011; Ye et al., 2014). Due to catastrophic consequences of weather and hydrological extremes, such as floods, droughts, rainstorms, and heat waves and their negative effects on agricultural production, there have been a multitude of studies addressing agricultural loss as a result of agro-droughts and floods. Li et al. (2012) presented a preliminary methodology and an operational approach for assessing the risk of flood loss to the population, crops, housing, and the economy at the county level in China. Using a compatible crop model, Rosenzweig and Parry (1994) examined the potential impact of global change on food supply and price.

Agriculture is the major source of food and fiber, and it is particularly true for China. Besides, food security means a great deal for the stability of society in China. However, climate change adds a large degree of uncertainty to the projection of agricultural output, and food security will be the daunting challenge China will face. Therefore, it is important to evaluate spatiotemporal properties of droughts and floods in China and related impacts on agricultural production. Changes in precipitation and streamflow have been analyzed and their possible impacts on agriculture studied (Zhang et al., 2011b, 2012a,2012b). Qin et al. (2014) quantitatively modeled the relationship between agro-drought and Chinese grain production. However, these studies did not address the abrupt behavior of flood and drought hazards and their impacts on agricultural production. Moreover, influences of floods and droughts on some specific agricultural production, such as rice, have not yet been investigated. Therefore, the objectives of this study are to: (1) investigate spatial patterns of drought- and flood-affected, and drought- and flood-destroyed crop areas, flood intensity and drought intensity and abrupt behaviors of flooding and drought regimes and their impacts on agricultural production, such as maize, rice and so on; and (2) analyze relations between occurrences of floods and droughts and loss of agricultural production. This study is of theoretical and practical merit in the management of agricultural activities and alleviation of negative effects of floods and droughts on agriculture in China.

2. Data

Data were collected for flood- and drought-affected, and flood- and drought-destroyed crop areas from 29 provinces of China; locations of these provinces are shown in Fig. 1. Data on agricultural production per hectare for agricultural stuff, rice, maize, corn, and soybean were collected for 1961–2010 from Ministry of Agriculture, China. Besides daily precipitation data from 554 meteorological stations covering the period of 1961–2010 were also collected (Fig. 1). The data were provided by the National Climate Center (NCC) of the China Meteorological Administration (CMA). Moreover, data on effective irrigation areas and fertilization areas for the period of 1978–2010 were also collected from National Bureau of Statistics, China. In addition, information, such as longitude, latitude, construction time of 488 water reservoirs, was also collected and the locations of these water reservoirs are marked in Fig. 1.

3. Methodologies

3.1. Modified Mann–Kendall (MMK) trend test

Non-parametric trend detection methods have advantages over parametric statistics in terms of handling of outliers. Besides, the rank-based nonparametric Mann–Kendall (MK) test (Mann, 1945; Kendall, 1975) can test trends without requiring normality or linearity (Alan et al., 2003). However, negative influences of persistence on MK trends have been widely discussed and some techniques have been proposed to eliminate persistence effects (von Storch and Navarra, 1995). Hamed and Rao (1998) recommended the modified MK statistic (MMK) with amended variance when the lag-*i* autocorrelation coefficients were significantly different from zero at the 95% confidence level.

The pre-whitening procedure is accepted, if the lag-1 autocorrelation coefficient, c, is larger than 0.1, and then the time series $(x_1, x_2, \ldots, x_n)$ to be studied should be $(x_2 - cx_1, \ldots, x_n - cx_{n-1})$. However, the pre-whitening procedure tends to underestimate the trend of the time series (e.g. Yue et al., 2002). Moreover, significant lag-1 autocorrelation is often detected even after pre-whitening is done. This means that pre-whitening with consideration of only lag-1 autocorrelation is insufficient to remove the entire influence of serial correlation (Zhang et al.,

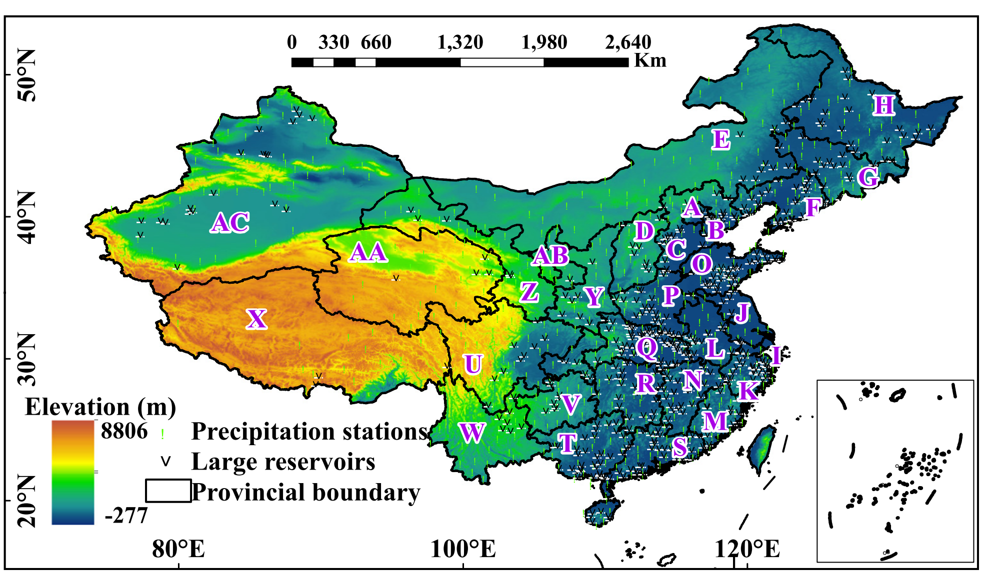

Fig. 1. Locations of water reservoirs and meteorological stations. A: Beijing; B: Tianjin; C: Hebei; D: Shanxi; E: Inner Mongolia; F: Liaoning; G: Jilin; H: Heilongjiang; I: Shanghai; J: Jiangsu; K: Zhejiang; L: Anhui; M: Fujian; N: Jiangxi; O: Shandong; P: Henan; Q: Hubei; R: Hunan; S: Guangdong; T: Guangxi; U: Sichuan; V: Guizhou; W: Yunnan; X: Tibet; Y: Shannxi; Z: Gansu; AA: Qinghai; AB: Ningxia; AC: Xinjiang.

2012a). Hamed and Rao (1998) have shown MMK with consideration of lag-*i* autocorrelation and related robustness to autocorrelation. Due to these advantages, MMK has been widely used (e.g. Daufresne et al., 2009). In this study, MMK was used to detect possible trends in flood- and drought-affected, flood- and drought-destroyed crop areas and other time series considered in this study. The confidence level for MMK was set at 95%. The magnitude of trends was evaluated by Sen's method (Gilbert, 1987), i.e.,

$$\beta = \text{Median}\left[\frac{(X_j - X_i)}{(j - i)}\right] \qquad i < j \tag{1}$$

where β is the slope, denoting the magnitude of trends.

3.2. Detection of change points

The performance of the change-point detection method was evaluated for ten techniques (Lei et al., 2007), that showed that the rank sum test, the Brown–Forsythe test, the sequential cluster analysis, the scanning T test, the Bayesian method, the Lee–Heghinian method performed well in the change point detection in terms of average; and the scanning F test performed well in the change point detection for variance. To avoid possible biased results, the Mann–Whitney U test, the moving runs test, the moving F test, the moving T test, the Lee Hamelin test, the sequential cluster test, and cumulative anomaly test, respectively, were used for the detection of change points.

3.3. Flood- and drought-induced loss of agricultural production

Data about flood- and drought-induced loss are for all agricultural crops, such as grain crops. While analyzing flood- and drought-induced losses of agricultural production weights were taken into consideration (Li et al., 2010):

$$F_d = \sum_{i=1}^{n} F_{di} = \sum_{i=1}^{n} (R_i \times A_{i1} \times Y_i \times P_1 + R_i \times A_{i2} \times Y_i \times P_2 + R_i \times A_{i3} \times Y_i \times P_3) \tag{2}$$

where F_d is the hazard-induced amount of loss in agricultural crops; n is the number of provinces considered in this study; F_{di} is the amount of loss of food crops of the ith province; R_i is the percentage of the crop to the agricultural crops in the ith province; A_{i1}, A_{i2} and A_{i3} are the hazard-affected areas, hazard-destroyed areas and the hazard-induced crop failure; Y_i is the level of grain of the ith province; P1, P2 and P3 are the decreasing magnitudes of food crops due to A_{i1}, A_{i2} and A_{i3}, respectively; and are defined as 20%, 45% and 80% based on the concepts of A_{i1}, A_{i2} and A_{i3} (Li et al., 2010),

4. Results and discussion

4.1. Trends in the intensity and degree of influence of floods and droughts and their influence on agriculture across China

In this study, intensity of natural hazards (HI), e.g. floods and droughts, was defined as HI = hazard-affected crop area/total crop area; and the degree of influence of natural hazards (ID) was defined as ID = hazard-destroyed crop area/hazard-affected crop area. Spatial patterns of trends in HI and ID are shown in Fig. 2 which shows that increasing flood intensity is observed mainly in southwest and northwest China and parts of central China, such as Shannxi and Ningxia provinces. Moreover, southwest and northwest China is also dominated by increasing drought intensity. Southeast China is characterized by increasing degree of influence of drought and flood hazards. The east parts of central China, such as Shandong province, Jiangsu province, Beijing and Tianjin provinces and Shanxi and Jilin provinces are dominated by not significant changes of ID or HI. Generally, most provinces east of 100°E are dominated by increasing flood intensity and parts of the provinces are characterized by increasing drought intensity, which implies fast transition of flood and drought conditions. Enhancing degrees of influence of floods and droughts are observed in southeast China (Fig. 2). Spatial patterns of trends in flood- and drought-affected crop areas and in flood- and drought-destroyed crop areas (Fig. 3) are similar when compared to those of flooding intensity, drought intensity, IDF and IDD (Fig. 2). The provinces in northwest China, such as Xinjiang, Ningxia and Gansu, are heavily influenced by floods and droughts. Increasing

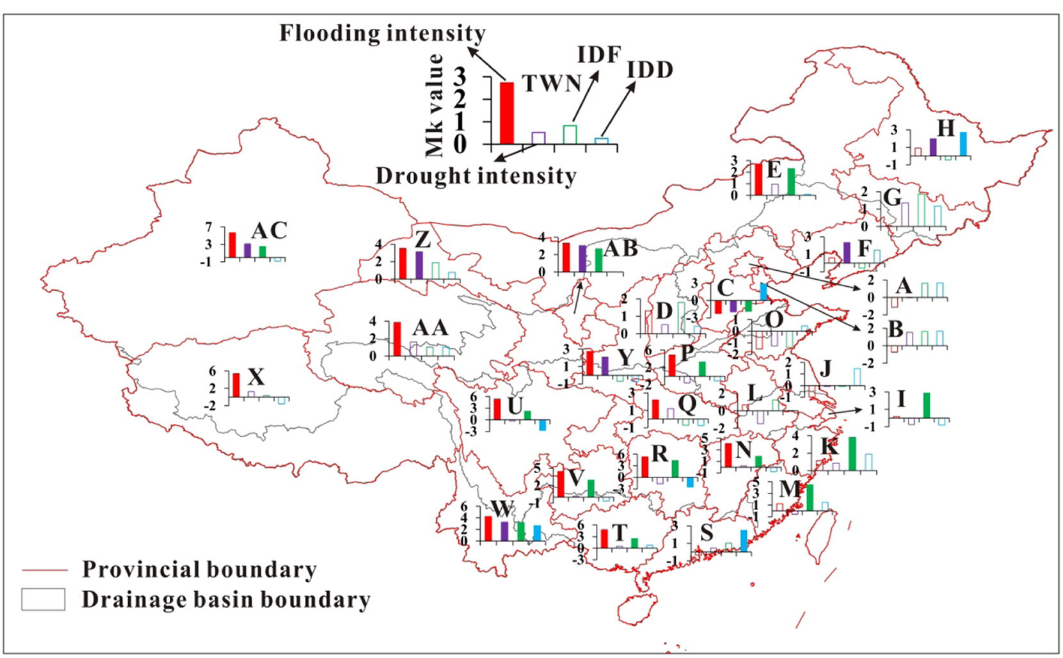

Fig. 2. Spatial distributions of trends in flood intensity, drought intensity, degrees of influence of floods (IDF) and degrees of influence of droughts (IDD). Notations of the capital letters are the same as those in Fig. 1. Capital letters denote provinces of China: A, Beijing; B, Tianjin; C, Hebei, D, Shanxi; E, Inner Mongolia; F, Liaoning; G, Jilin; H, Heilongjiang; I, Shanghai; J, Jiangsu; K, Zhejiang; L, Anhui; M, Fujian; N, Jiangxi; O, Shandong; P, Henan; Q, Hebei; R, Hunan; S, Guangdong; T, Guangxi; U, Sichuan; V, Guizhou; W, Yunnan; X, Tibet; Y, Shannxi; Z, Gansu; AA, Qinghai; AB, Ningxia; AC, Xinjiang.

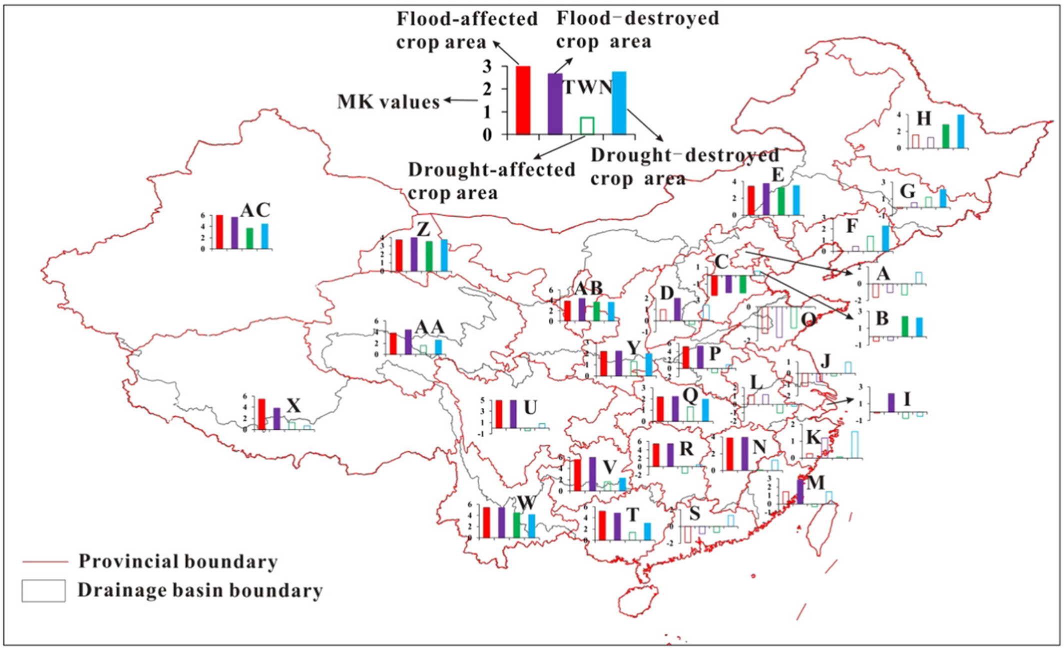

Fig. 3. Spatial distributions of trends in flood- and drought-affected crop areas and also in flood- and drought-destroyed crop areas. The filled bars indicate significant trends, and empty bars not significant trends. TWN indicates general trends for The Whole Nation (TWN), and it is the same for subsequent figures.

flood-affected and flood-destroyed crop areas are also identified in the provinces of southwest China, such as Sichuan, Guizhou, Guangxi and Yunnan (Figs. 2 and 3). Provinces in northeast China, such as Heilongjiang and Liaoning, are influenced mainly by droughts. However, influences of floods and droughts on flood- and drought-affected crop areas and flood- and drought-destroyed crop areas in the provinces in the east parts of central China, such as Beijing, Shandong, Jiangsu and Anhui, are not evident.

Northwest China is a typical arid region. Jiang et al. (2005) observed an increasing trend in flood disasters in Xinjiang during the second half of the 20th century, especially since the mid-1980s, which are attributed to abnormal precipitation changes. Besides, investigation of precipitation across China indicates that in northwest China, the number and total precipitation of maximum consecutive wet days are increasing annually as well as in winter, implying wetting tendency in northwest China (Zhang et al., 2011a). Long et al. (2014) showed that both the frequency and severity of droughts and floods over the Yunnan–Guizhou plateau have been intensified during the recent decade, when seen from three-decade total water storage anomalies (TWSA) generated by Gravity Recovery and Climate Experiment (GRACE) satellite data and artificial neural network (ANN) models. Liu et al. (2014) showed that the study area had generally become drier (regional mean annual precipitation decreased by 11.4 mm per decade) and experienced enhanced precipitation extremes in the past 60 years. Relatively a higher risk of drought in Yuanan and flood in Guangxi was observed, respectively. The above-mentioned results further corroborate the results of this study. Intensifying floods and droughts in northwest and southwest China have critical impacts on agricultural production in these regions. Wang and Zhou (2005) demonstrated that the annual mean precipitation decreased significantly in central, north, and northeast China. Increasing trends occurred in east China mainly in summer, while decreasing trends occurred in central, north, and northeast China in both spring and autumn. However, the provinces in the east parts of central China are dominated by massive agricultural irrigation (Zhang et al., 2011b, 2012a,2012b). Agricultural irrigation can alleviate negative influences of droughts and this could be the major reason behind not evident changes in flood- and drought-affected crop areas and in flood- and drought-destroyed crop areas (Fig. 3).

4.2. Abrupt behavior of flood/drought-affected and flood/drought-destroyed crop areas

Change points of the series of floods and droughts, flood- and drought-affected crop areas and also flood- and drought destroyed crop areas were analyzed using seven statistical methods, i.e. the Mann–Whitney U test, the moving runs test, the moving F test, the moving T test, the Lee Hamelin test, the sequential cluster test, and cumulative anomaly test, respectively (Fig. 4). It can be observed from Fig. 4 that the timing of the change points of flood-affected and flood destroyed crop areas is in good agreement. Generally, the change points occurred in about 1982 (Fig. 4a and b). The timing of change points is in the 1980s in northeast, north and central China. However, the timing of change points is in the 1990s in south and southwest China. Abrupt behaviors of floods are in line with those of precipitation regimes. Study of precipitation in the Yellow River basin (a large river basin in north China) indicated that short duration consecutive precipitation events are prevalent in the Yellow River basin and frequency and amount of short duration consecutive precipitation events are increasing after the mid-1980s (Zhang et al., 2014). Besides, it is observed that a higher risk of drought can be expected in spring and autumn and precipitation in winter is increasing, which implies evident seasonality and seasonal shifts of precipitation changes within the Yellow River basin (Zhang et al., 2014). However, analysis of precipitation regimes in the Pearl River basin, an important river basin in south China, indicated that the occurrence and fractional contribution of wet periods with longer durations are decreasing and are increasing again after the 1990s (Zhang et al., 2012b).

Comparatively, clear differences can be observed in the timing of abrupt behaviors of drought-affected and drought destroyed crop areas when compared to that of flood-affected and flood-destroyed crop areas (Fig. 4c and d). Besides, the timing of abrupt changes of drought-affected crop areas is also different from that of drought-destroyed crop areas, which definitely implies complexity of drought behavior. Human activities, such as agricultural irrigation, can greatly alleviate negative impacts of droughts on agricultural production (Zhang et al., 2011b, 2012a, 2015). Generally, abrupt changes of drought-affected crop areas occurred in 1970 and those of drought-destroyed

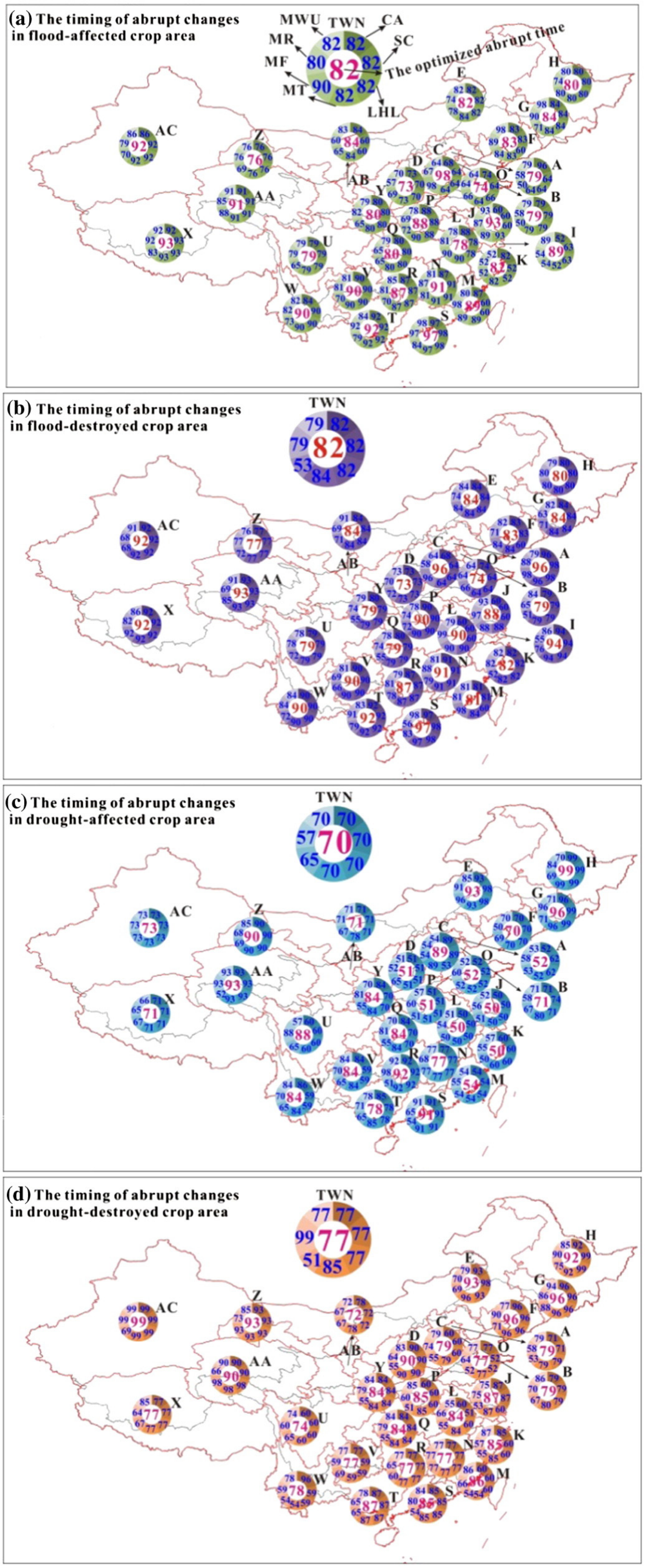

Fig. 4. Spatial distributions of the change-point timing for flood- and drought-affected crop areas and for flood- and drought-destroyed crop areas. Numbers of 61–99 indicate the change-point timing of 1961–1999; and 51–59 the change-point timing of 2000–2009. The number of 60 indicates no change point. MWU, MR, MF, MT, LHL, SC and CA denote the change-point test methods as Mann–Whitney U test, Moving runs test, Moving F test, Moving T test, Lee Hamelin test, Sequential cluster test, and Cumulative anomaly test, respectively.

crop areas in 1977. Besides, spatial patterns of the timing of change points in the drought-affected crop areas are not confirmative and fixed. The timing of abrupt changes of drought-affected crop areas is 2000 in east China and is 1984 in other regions. However, the change points of drought-destroyed crop areas occur in 1977 in south and north China. The timing of change points is 1984 in central and east China. The human-induced alleviation of negative impacts of droughts and complicated mechanisms behind drought occurrences are the driving factors behind complicated spatial patterns of drought behavior across China.

4.3. Trends and changing rates of flood/drought-affected and flood/drought-destroyed crop areas and related absolute agricultural losses

Fig. 5 illustrates the spatial patterns of trends in flood- and drought-affected and drought- and flood-destroyed crop areas prior and posterior to the change points. It can be seen from Fig. 5 that prior to change points, the flood-affected crop areas are increasing in the provinces of northwest and southwest China, and some provinces in central China, such as Henan and Tianjin. Most of the provinces are characterized by not significant changes in flood- and drought-affected and drought- and flood-destroyed crop areas. Nevertheless, the flood- and drought-affected and drought- and flood-destroyed crop areas are decreasing and the decreasing trends of flood-affected and flood-destroyed crop areas are statistically significant. Massive construction of water reservoirs and increased agricultural irrigation are one of the main causes behind not evident changes in drought-affected and drought-destroyed crop areas (Zhang et al., 2012a). There are 98,002 water reservoirs or hydraulic infrastructures with a storage capacity of > 0.1 million m^3, and the total storage capacity of the reservoirs is about 932.3 billion m^3, accounting for 34.5% of the total streamflow of all rivers in China (Sun et al., 2013). Damming and construction of water reservoirs have been continuing, and up to 2011, 756 large-scale water reservoirs with a total capacity of 749.99 billion m^3, 3938 moderate-scale water reservoirs with a total capacity of 111.98 billion m^3, and 93,308 small-scale water reservoirs with a total capacity of 70.35 billion m^3 have been built (Sun et al., 2013). The construction of these water reservoirs and other hydraulic infrastructures have greatly dampened flood peak flows and they provide water supply for agricultural irrigation (Zhang et al., 2011b, 2012a), and all these factors can alleviate negative effects of floods and droughts.

Even so, flood- and drought-affected and flood- and drought destroyed crop areas posterior to the change points are larger than those prior to the change points. It means that without consideration of change points, the general tendency of flood- and drought-affected and flood- and drought destroyed crop areas is increasing, showing considerable increasing floods and droughts on agricultural production in China. This viewpoint can be evidenced by Fig. 6 that shows that the flood-affected and flood-destroyed crop areas posterior to the change points are larger with large magnitudes when compared to those prior to the change points. It should be attributed to enhancing flood hazards due to intensifying precipitation regimes after the change points (Zhang et al., 2011a). However, the increases of drought-affected and drought destroyed crop areas after the change points are of smaller magnitude than those before the change points when compared to flood-affected and flood-destroyed crop areas.

For the determination of the influence of floods and droughts on agriculture in China, absolute agricultural loss as a result of flood and drought hazards was analyzed (Fig. 7). It can be seen from Fig. 7 that absolute agricultural loss of grain (with unit of 10^4 t) and the rate of grain loss have an increasing tendency in most provinces of China. Specifically, increasing tendency of flood-induced agricultural loss is found mainly in provinces of west China; however, drought-induced agricultural loss is observed mainly in the provinces of east China. The loss rate of grain, as a result of flood hazards, is about 4% prior to the change points and is about 4%–10% posterior to the change points. The drought-induced

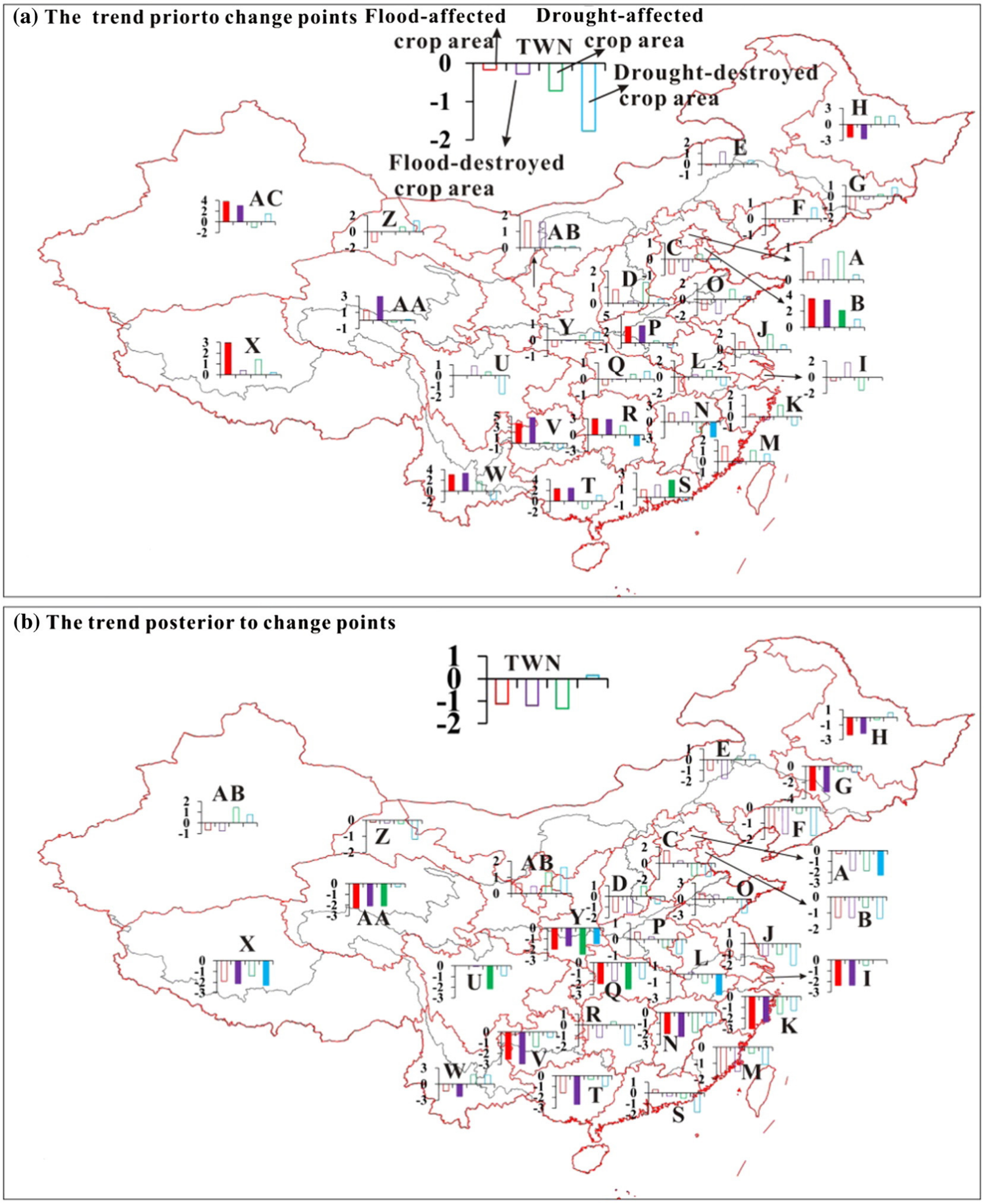

Fig. 5. Trends in flood- and drought-affected crop areas and flood- and drought-destroyed crop areas prior and posterior to change points, respectively.

rate of grain loss is larger than the flood-induced rate of grain loss. The largest drought-induced rate of grain loss is identified in north China, wherein the drought-induced rate of grain loss in Inner Mongolia and Shanxi provinces ranges 10%–14% before the change points. Nevertheless, the drought-induced rate of grain loss in east and south China does not have evident variations, while a larger drought-induced rate of grain loss is detected in north and northeast China, being about 14%–18%. When it comes to the absolute loss of grain, flood-induced absolute grain loss in east, southeast and northeast China is increasing, being 0–50 $\times$ 10^4 t before the change point and 50–150 $\times$ 10^4 t after the change point. The increase of absolute grain loss as a result of drought hazards is larger after the change point than that before the change point, e.g. the drought-induced absolute grain loss is 200–450 $\times$ 10^4 t in northeast China, and provinces like Shanxi, Hubei and Guizhou.

4.4. Precipitation changes and human activities behind flood- and drought-induced agricultural losses

For further understanding of causes behind drought- and flood-induced losses of agricultural products, precipitation regimes from a seasonal perspective were investigated across China (Fig. 8). Besides, human activities that can alleviate negative effects of flood and drought hazards were also analyzed (Fig. 9). The summer season in northeast China is the time period when the water requirement of rice reaches the highest (Liu et al., 2012). However, summer precipitation in northeast China is decreasing and a decreasing tendency is also observed for maximum consecutive wet days (CWD) in summer, while maximum consecutive dry days (CDD) are having significantly increasing trends (Fig. 8c, h and o). Drought hazards have been intensifying in recent years. Fig. 9a indicates increasing crop areas with effective agricultural

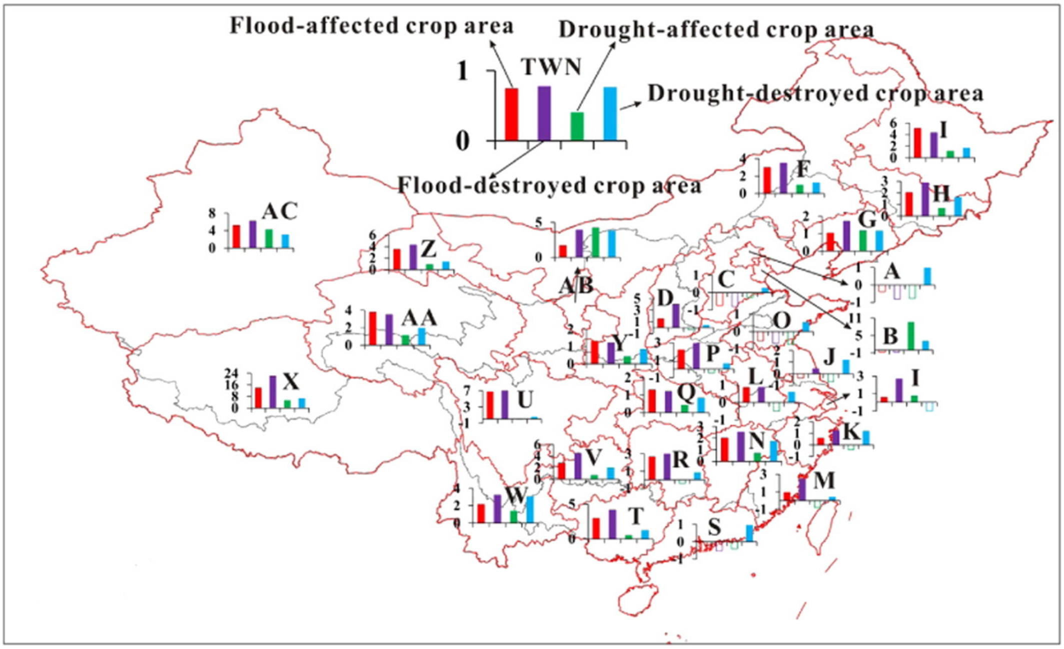

Fig. 6. Changing rate of flood- and drought-affected crop areas and of flood- and drought-destroyed crop areas prior and posterior to change points, respectively. Changing rate = (crop area after change point − crop area before change point) / crop area before change point. The crop area here denotes flood- and drought-affected crop areas, and flood- and drought-destroyed crop areas.

irrigation in northeast China. However, the ratio of effectively irrigated crop areas to the total crop areas is low when compared to other provinces of China, being 31%, 33% and 37%, respectively (Fig. 9c). The total reservoir capacity is also low when compared to other provinces in China (Fig. 9d). These factors result in an increasing tendency or significant increasing trends in drought-affected and drought-destroyed crop areas (Fig. 2). North China, including Beijing, Tianjin, Hebei, Shanxi and Inner Mongolia, are characterized by decreasing precipitation amounts in summer, autumn and winter (Fig. 8a–d) with decreasing CWD but increasing CDD (Fig. 8i–p). Decreasing precipitation has caused increased drought-destroyed crop areas; however, drought-affected crop areas are having significant changes (Fig. 2). Besides, drought intensity and degrees of influence of droughts do not have significant trends (Fig. 3). Nevertheless, some provinces, such as Hebei, are dominated by significant decreases of drought-affected crop areas (Fig. 2). As mentioned in the above sections, irrigation in north China is prevalent (Zhang et al., 2013). Sufficient agricultural irrigation greatly alleviates negative effects of drought hazards on agricultural production (Fig. 9a). Besides, the increase of dryland crops is another factor behind decreasing drought-affected crop areas (Fig. 9h).

Northwest China is undergoing warm and wet phases (Shi et al., 2003). The seasonal precipitation amount is increasing and the largest

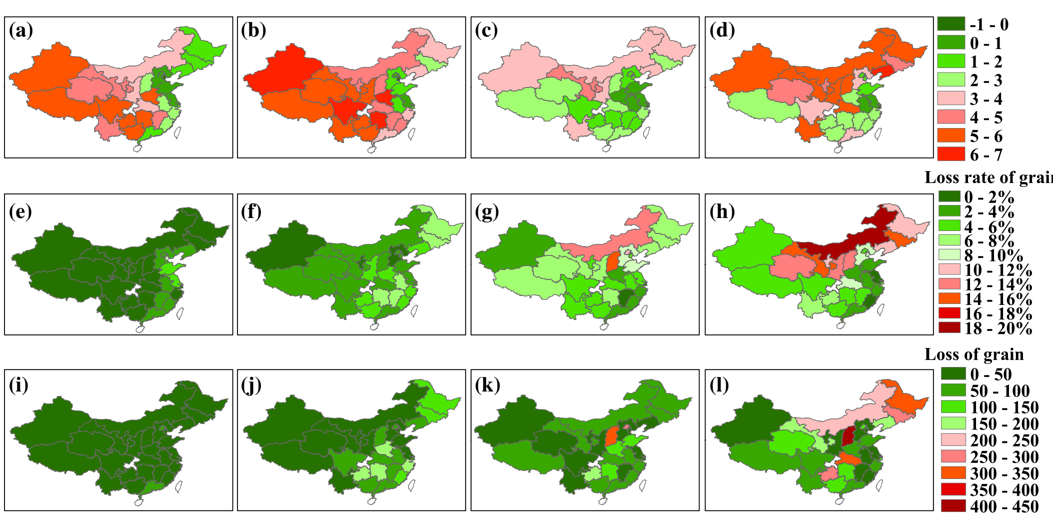

Fig. 7. Spatial distributions of flood-induced loss or rate of grain loss and drought-induced loss or rate of grain loss across China. The unit is 10^4 t. (a): Trends in the flood-induced rate of grain loss; (b): Trends in the flood-induced loss of grain; (c); Trends in the drought-induced rate of grain loss; (d), Trends in the flood-induced loss of grain; (e): The mean flood-induced rate of grain loss prior to change points; (f): The mean flood-induced rate of grain loss posterior to change points; (g): The mean drought-induced rate of grain loss prior to change points; (h): The mean drought-induced rate of grain loss posterior to change points; (i): The mean flood-induced loss of grain prior to change points; (j): The mean flood-induced loss of grain posterior to change points; (k): The mean drought-induced loss of grain prior to change points; (l): The mean drought-induced loss of grain posterior to change points.

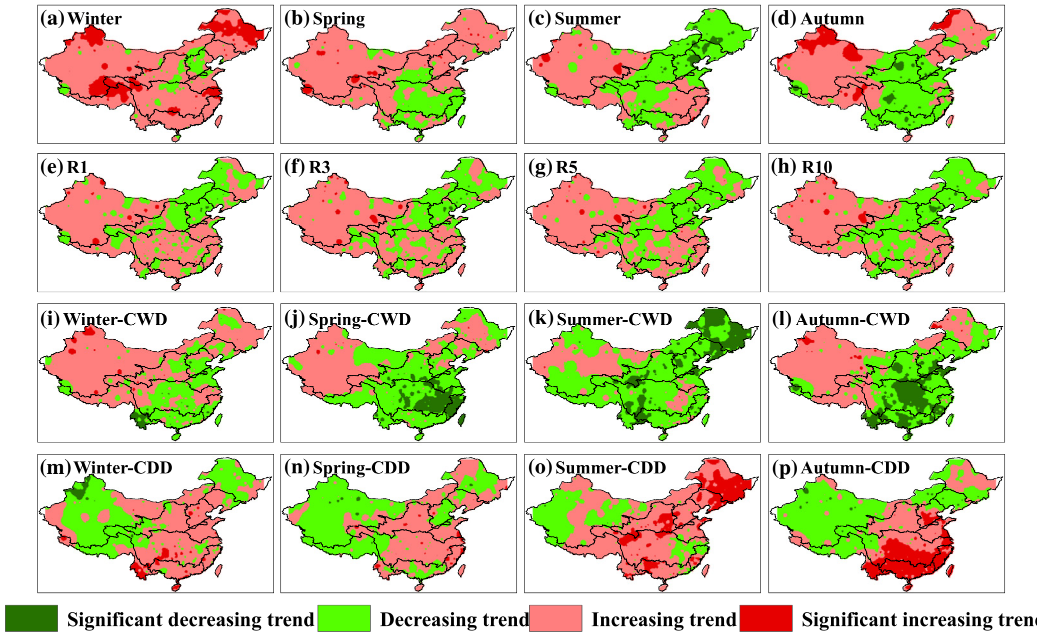

Fig. 8. Modified Mann–Kendall trends of precipitation indices across China. The precipitation indices are seasonal precipitation amount; annual largest 1-, 3-, 5- and 10-day precipitation amount; the seasonal maximum consecutive wet days (CWD) and seasonal maximum consecutive dry days (CDD).

1-, 3-, 5- and 10-day precipitation amounts are also increasing. Increasing CWD and decreasing CDD are also detected in northwest China (Fig. 8). Increase of precipitation amounts triggers intensifying flood hazards in northwest China, as seen in recent decades (Fig. 2) (Jiang et al., 2005). Moreover, droughts are common in northwest China and more concern has been given to human mitigation of drought hazards but not floods. Thus, siltation of reservoirs and loss of flood control structures are partly responsible for the increase of flood-damaged areas (Jiang et al., 2005), which further enhance the negative effects of flood hazards on agricultural production in northwest China. Besides, alterations of precipitation regimes cause the intensification of drought hazards. Decrease of CWD and increase of CDD are identified in the provinces of northwest China, such as Shannxi, Gansu and Ninxia (Fig. 8j–l, n–p). In recent years, rice areas have been increasing in

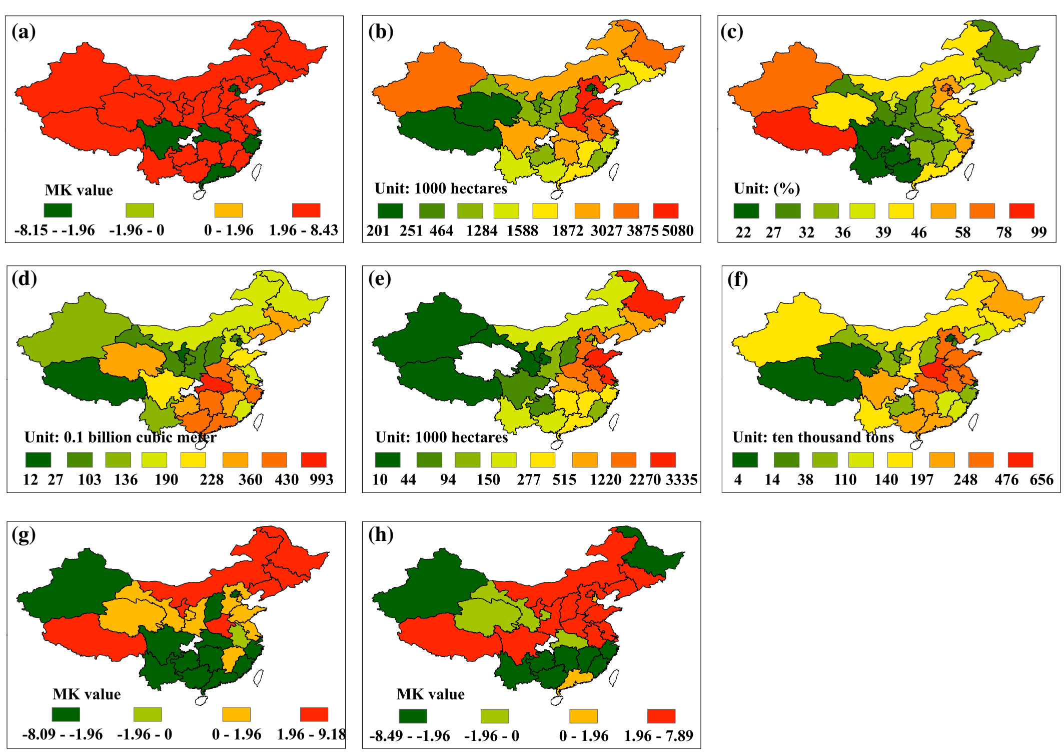

Fig. 9. Human activities that can alleviate negative effects of flood and drought hazards. The human activities are: effective irrigated areas, the total capacity of water reservoirs, flood-drained area, fertilization amount; percentage of rice area to the total crop area; percentage of upland crops to the total crop areas. (a): The trend of effective irrigation area; (b): The effective irrigation area; (c): Percentage of the effective irrigation area to the total arable area; (d): The total reservoir capacity; (e): Flood-drained areas; (f): Fertilization amount; (g): Trend in the percentage of rice to the total crop area; (h): Trend in the percentage of upland crops to the total crop area.

Shannxi, Gansu, Qinghai and Ningxia provinces and dryland crop areas decreasing (Fig. 9g, h). These changes in agriculture planting can enhance negative influences of droughts on agricultural production (Fig. 9g, h). Fig. 8e–h indicate increasing precipitation extremes and increasing flood-affected crop areas (Fig. 2). It is should be noted here that summer and autumn precipitation is decreasing in southwest China with decreasing CWD and increasing CDD (Fig. 8c, d, i–p), which are the major causes behind higher frequencies of drought hazards (Fig. 2). Furthermore, irrigated crop areas are lower than in other provinces and specifically the ratio of effective irrigation areas to the total crop areas is only 24%, 23% and 27% in the Yunnan, Guizhou and Sichuan provinces (Fig. 9c). Besides, the water capacities of water reservoirs in Yunnan and Sichuan provinces are not enough for mitigation of drought hazards (Fig. 9d).

Central China is characterized by increasing precipitation extremes (Fig. 8e–h), causing increasing frequencies of floods (Fig. 2). Besides, precipitation amounts in spring and autumn are decreasing with increasing CDD (Fig. 8m–p) and decreasing CWD in Hubei, Hunan and Jiangxi provinces (Fig. 8j, l). Although the precipitation amount is decreasing, some provinces in central China, such as Hubei, Hunan and Jiangxi provinces, are located in the Yangtze River basin and irrigation is sufficient (Zhang et al., 2012a) and hence, drought-affected and drought destroyed crop areas are small. Fertilization activities are also another factor behind the sensitivity of agriculture to drought hazards. Persistent and massive fertilization results in acidification and soil hardening which enhance sensitivity and vulnerability of agriculture to drought hazards (Fig. 9f).

5. Conclusions

Flood- and drought-affected crop areas, flood- and drought-damaged crop areas, and flood- and drought-induced agricultural loss from 29 provinces across China are analyzed in both space and time. Furthermore, the underlying causes are investigated by analyzing precipitation regimes and human activities, such as construction of water reservoirs, irrigation and so forth. From analysis the following conclusions are drawn:

(1) Large parts of provinces in China are dominated by intensified floods and specifically in central, west parts of central and northwest China. Spatial ranges, dominated by intensifying drought hazards, are smaller than those by intensifying flood hazards and are mainly in northwest and northeast China and also in the Yunnan province. Moderate changes of floods and droughts are found in east China and the Guangdong province.

(2) Drought intensity is increasing in northwest China. However, the degrees of influence of droughts show moderate changes. Increasing intensity of floods can be observed in northwest, southwest and central China. Besides, significant increasing degrees of influence of floods are detected in east and south China. Except north and northeast China, intensity and degrees of influence of floods are enhancing and also negative impacts of floods on agriculture are amplifying. Surprisingly, flood risks are tending to be higher in arid regions, such as northwest China and drought risks are found to be higher in humid and semi-humid regions, such as southwest China. This alteration of spatial patterns of floods and droughts is attributed to different regional responses of the hydrological cycle to climate changes and human activities.

(3) Agreements are found between abrupt behaviors of flood-affected and flood-destroyed crop areas. The timing of change points of flood-affected and flood-destroyed crop areas is in the 1980s in northeast, north and central China and is in the 1990s in south and southwest China. Nevertheless, the spatial patterns of the timing of change points in the drought-affected and drought-destroyed crop areas are not confirmed but are sporadic: the timing of the change points is 2000 in east China and is 1984 in other provinces of China. The change points of drought-destroyed crop areas are in 1977 in south and north China, and are in 1984 in central and east China. Statistically, no evident changes can be detected for drought-affected and drought-destroyed crop areas before and after change points. However, significant decreases of flood-affected and flood-destroyed crop areas can be identified after the change points. However, the higher mean value of flood-affected and flood-destroyed crop areas after the change points than that before the change points implies increased flood- and drought-induced agricultural loss after the change points.

(4) The loss of agricultural production due to flood and drought hazards is having significant increasing trends in most parts of China. Hence, food security of China is not so optimistic. The rate of loss and the magnitude of loss of agricultural products as a result of floods and droughts are evidently higher in west and north China. These losses before change points are significantly higher than those after change points. Besides, this study indicates an apparently higher drought-induced loss rate and loss magnitude of agriculture than those of floods, showing crucial negative impacts of droughts on agriculture in China. This suggests that human mitigation of droughts should be greatly enhanced.

(5) Alterations of precipitation regimes are the major causes behind changes of the drought- and flood-affected, and drought- and flood-destroyed crop areas. Generally, amplifications of precipitation extremes, decreasing consecutive wet days and increasing consecutive dry days in both space and time are the driving factors behind the intensification of droughts and floods and their impacts on agriculture across China. Generally, northwest China is an arid region and human mitigation of droughts is common; southwest and south China are humid regions and human mitigation of floods is prevailing. However, alterations of precipitation regimes in both space and time and seasonal shifts of precipitation changes trigger alterations in the spatiotemporal patterns of floods and droughts. Due to different regional responses of droughts and floods to climate change, human activities should be modified to better mitigate floods and droughts in different provinces of China. These results are theoretically and practically relevant for planning and management of agricultural activities and modifications of human mitigation of floods and droughts and may also provide a theoretical framework for similar researches in other regions of the globe.

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