



Global warming determines future increase in compound dry and hot days within wheat growing seasons worldwide

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Abstract

Compound dry and hot extremes are proved to be the most damaging climatic stressor to wheat thereby with grave implications for food security, thus it is critical to systematically reveal their changes under unabated global warming. In this study, we comprehensively investigate the global change in compound dry and hot days (CDHD) within dynamic wheat growing seasons during 2015–2100 under 4 socio-economic scenarios (SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5) based on the latest downscaled Coupled Model Inter-comparison Project Phase 6 (CMIP6) models. Our results demonstrate a notable increase in CDHD's frequency ($CDHD_f$) and severity ($CDHD_s$) worldwide under all SSPs, such increase is sharper over southern Asia in winter wheat growing season, and southern Canada, northern America, Ukraine, Turkey and northern Kazakhstan in spring wheat growing season. As the top 10 wheat producer, India and America will suffer much more detrimental CDHD in their wheat growing season. Adopting a low forcing pathway will mitigate CDHD risks in up to 93.3% of wheat areas. Positive dependence between droughts and heats in wheat growing season is found over more than 74.2% of wheat areas, which will effectively promote the frequency and severity of CDHD. Global warming will dominate the increase of CDHD directly by increasing hot days and indirectly by enhancing potential evapotranspiration thereby aggravating droughts. This study helps to optimize adaptation strategies for mitigating CDHD risks on wheat production, and provides new insights and analysis paradigm for investigating future variations in compound extremes occurring within dynamic crops growing seasons.

Keywords Compound dry and hot days · Wheat growing season · Future · Global warming · CMIP6

1 Introduction

Under global warming, the frequency and severity of climate extremes have increased disproportionately around the globe (IPCC 2021), furthermore, relationships between climate extremes have been changed as well: the concurrence of climate extremes (known as “compound extremes”) are becoming more frequent (AghaKouchak et al.

2014; Zscheischler et al. 2018). Drought and hot extremes are two of the most detrimental climate extremes, compound dry and hot extremes have attracted raised attention nowadays because of their massive impacts that even greater than the sum of the impacts caused by individual drought or heat alone (Zscheischler et al. 2014). Despite the diversity of definitions, previous studies have demonstrated the substantial increase in compound dry and hot extremes for past decades, including their spatial extent, frequency and severity (Mazdiyasi and AghaKouchak 2015; Manning et al. 2019; He et al. 2022a). Given their amplified impacts on ecosystem and society (Gazol and Camarero 2022; Li et al. 2022; Libonati et al. 2022), it is vital to sift the compound dry and hot extremes from individual droughts or heat, and systematically understand how they will change in the future.

Food security has been a major challenge worldwide. Food production is threatened seriously by drought and heat extremes associated with global warming (Lobell et al. 2013). Wheat is the first rainfed crop and the second irrigated crop after rice, which is widely planted globally with great implication for food security (Lobell and Gourdjji 2012). Wheat is highly sensitive to climate stresses, among of them, compound dry and hot extremes are proved to be the most damaging climate stressor for wheat production (Guerreiro et al. 2018), which has been identified as critical. The reasons are as follow. Firstly, drought and heat are typically triggered by similar synoptic circulation anomalies (Trenberth and Shea 2005), thus leading to a significant correlation between them (Zscheischler and Seneviratne 2017). Secondly, when drought and heat coincide, they will be both intensified by local- and regional-scale land-atmosphere feedback (Miralles et al. 2019). Thirdly, compound dry and hot stress has synergistic effects on wheat and then aggravate their adverse impacts (Suzuki et al. 2014). For instance, plant's vulnerability to high temperature will increase under drought condition, because drought can limit the plant's evaporative cooling thus reduce its ability to regulate temperature (Neukam et al. 2016).

Past decade has witnessed considerable progress in investigating compound dry and hot extremes, including their causative mechanisms (Hao et al. 2018), variations (Wang et al. 2020), exposure (Zhang et al. 2022a; Wang et al. 2023) and impacts/risks (Ribeiro et al. 2020; Hao et al. 2021). Raised attention has been given to investigate compound dry and hot extremes related with crops growing, previous studies have been devoted to revealing their change characteristics during crops growing seasons and/or over crops planting regions (Feng et al. 2021; He et al. 2022a; Li et al. 2022), and further, quantifying the impacts/risks on crops yield (Feng et al. 2019; Ribeiro et al. 2020; Li et al. 2022). However, there is still a lack of systematic understanding for future changes in compound dry and hot extremes within crops' growing seasons, especially within dynamic crops' growing season, which is a vital and necessary cognition for food security risk reduction and climate change adaptation.

In this study, we investigate the changes in compound dry and hot days (hereafter CDHD) within dynamic wheat growing seasons of 2015-2100 over dynamic wheat planting regions globally under different socio-economic scenarios, including their frequency and severity. The objectives of this study are based on the following research questions: (a) How will CDHD change during dynamic wheat growing seasons under different socio-economic scenarios (Section 3.1)? (b) How will the correlation between drought and heat affect CDHD (Section 3.2)? (c) How will global warming dominate the increase of CDHD (Section 3.3)?

2 Data and methodology

2.1 Data

2.1.1 NEX-GDDP-CMIP6

The latest version of NASA Earth Exchange Global Daily Downscaled Projections (NEX-GDDP) is derived from the GCM simulations of CMIP6, providing a set of high-resolution, bias-corrected climate change projections on global scale that can be used to investigate climate change impacts (Thrasher et al. 2022). In this study, we employ a multi-model ensemble containing 10 global climate models (GCMs) from NEX-GDDP (Table S1). Variables including daily precipitation, daily mean temperature and daily maximum temperature are available at $0.25^\circ \times 0.25^\circ$ spatial resolution, covering historical (1950-2014) and future (2015-2100) under 4 different socio-economic scenarios: SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5, which correspond to the projected global warming magnitude of 2.2°C, 3.3°C, 4.3°C and 5.1°C at the end of 21 century respectively (Tabari and Willems 2022). The period 1995-2014 is selected as “reference period” because it is supposed to be the based period in IPCC sixth assessment report (IPCC AR6). In addition, two future periods, 2041-2060 and 2081-2100, are selected to represent “mid-term future” and “long-term future” respectively, which also based on IPCC AR6.

2.1.2 GCAM land use change projection

The projected wheat areas used in this study are derived from the Global Change Assessment Model (GCAM) land use change projection dataset. This dataset provides projections of planting area percentage for 32 plant functional types at $0.05^\circ \times 0.05^\circ$ resolution over 2005–2100 (in 5 years-step length) under 15 SSP-RCP scenarios (Chen et al. 2020). In this study, projected wheat planting area percentages (including rainfed wheat and irrigated wheat) under SSP1-RCP2.6, SSP2-RCP4.5, SSP3-RCP6.0 and SSP5-RCP8.5 are used to match climate variables under SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5, respectively.

To keep consistent with climate data, wheat planting area percentage data are aggregated from the original 0.05° resolution to 0.25° resolution, and then grids with planting area percentage larger than 0 are identified as “wheat planting grids”. Since wheat planting area percentage is projected at 5-year resolution, we assume that the planting area percentage remains unchanged in each 5-year period. Since this dataset does not distinguish winter wheat and spring wheat, the current distributions of winter wheat and spring wheat are obtained from Crop Calendar Dataset (at 5-min resolution) (Sacks et al. 2010). Based on the original winter/spring wheat distributions and the projections of rainfed/irrigated wheat from GCAM dataset, the planting area of rainfed winter wheat, rainfed spring wheat, irrigated winter wheat and irrigated spring wheat over 2005-2100 at 5-year resolution are obtained, as shown in Fig. S1-S5.

2.1.3 GGCM phase 3 crop calendar

GGCMI Phase 3 crop calendar is a composite product merging various observational data sources, providing static planting date and maturity date for 18 crops at $0.5^\circ \times 0.5^\circ$ resolution. This crop calendar dataset separates rainfed and irrigated systems, and grid cells

outside of currently cultivated areas are spatially extrapolated and original data gap-filled (Jagermeyr et al. 2021). In this study, the current planting date and maturity date of wheat, including rainfed winter wheat, rainfed spring wheat, irrigated winter wheat and irrigated spring wheat, are obtained from GGCM Phase 3 crop calendar (Fig. S6), representing the current state of wheat growing season. To keep consistent with climate data, the crop calendar data are downscaled from the original 0.5° resolution to 0.25° resolution, that is, data in a 0.5° grid will be used in the four 0.25° grids in this 0.5° grid.

2.2 Methodology

2.2.1 Dynamic wheat growing season

In this study, we only focus on the CDHD that occurring within wheat growing seasons rather than whole period. Previous studies usually used a fixed crop calendar based on historical observations without considering the changes of crops growing seasons influenced by climate and anthropogenic factors thereby amplifying results' uncertainties. In this study, we try to improve wheat growing season from static to dynamic by considering the impacts of global warming on the length of wheat growing season. Although it should be noted that the changes in crop growing seasons are affected by both climate conditions and technological developments, this study is initial and helpful exploration in the context of global warming.

Temperature can substantially affect wheat physiological processes thus controlling wheat phenology and the length of the required growing period (Wang et al. 2017). In this study, we assume the planting date and cultivar selection will be fixed in the future, the length of growing season is determined by the required time for reaching maturity under the impacts of global warming, according to Jagermeyr et al. (2021). The phenology scheme for wheat is adopted from LPJmL4 model, the phenological development of wheat is driven by temperature through the accumulation of heat units (HU) (Schaphoff et al. 2018). HU is accumulated daily, the daily HU increment (HU_i) is the difference between the daily mean temperature of day i ($T_{mean,i}$) and the base temperature (T_b , here is 0°C based on Schaphoff et al. (2018) (Eq. 1). The phenological heat units (PHU) is the sum of HU_i from planting date to maturity date, describing the total heat requirement over the growing season (Eq. 2) (Qiao et al. 2020). Based on the planting date and maturity date provided by GGCM Phase 3 wheat crop calendar, the total heat requirement (THR) of a wheat planting grid is calculated as the average of PHU for the reference period 1995-2014 (Eq. 3):

$$HU_i = \begin{cases} 0 & T_{mean,i} \leq T_b \\ T_{mean,i} - T_b & T_{mean,i} > T_b \end{cases} \quad (1)$$

$$PHU = \sum_{i=planting\ date}^{i=maturity\ date} HU_i \quad (2)$$

$$THR = \frac{\sum_{y=1995}^{y=2014} PHU_y}{20} \quad (3)$$

For each wheat planting grid, maturity date in each year of the future is the first day for HU accumulation reaching its total heat requirement (THR). Based on this, we calculate the maturity date for each wheat planting grid and for each wheat growing season of

2015–2100 under 4 SSPs. The detailed changes in growing season of rainfed winter wheat, irrigated winter wheat, rainfed spring wheat and irrigated spring wheat are shown in Fig. S7–S11.

2.2.2 CDHD definition

Agricultural drought is a comprehensive phenomenon that comprising precipitation shortages, evapotranspiration reduction and soil moisture deficits (Łabędzki and Bąk 2015). The Standardized Precipitation Evapotranspiration Index (SPEI) is produced by standardizing climate water balance, that is, the difference between water supply (precipitation) and demand (potential evapotranspiration, PET) (Vicente-Serrano et al. 2010), which is more sensitive to drought conditions due to the evaporative demand component, and more robust in revealing droughts influenced by rising temperature in the context of global warming (Sein et al. 2021). Furthermore, SPEI has higher correlation with crops yield (Tian et al. 2018). Here we calculate 1-month SPEI for each month during 1951–2100, the calculation method is shown in “1.2 SPEI calculation method” of Supporting information. In this study, a drought event is defined as monthly $SPEI \leq -1$ for both winter wheat and spring wheat, based on this, we identify all drought events occurring within each wheat growing season of 2015–2100 in each wheat planting grid.

Heat stress is frequent during wheat growing season. A hot day is defined as daily maximum temperature (T_{max}) greater than heat threshold. Here we summarize heat thresholds for each wheat phenological phase according to previous studies, as shown in Table S2. Since wheat is proved to be highly sensitive to heat stress during anthesis and grain-filling phase (Bergkamp et al. 2018), we use the intermediate heat thresholds in these two phenological phases: T_{max} greater than 30°C is set as the heat threshold for winter wheat, T_{max} greater than 34°C is set as the heat threshold for spring wheat. Based on this, we identify all hot days occurring within each wheat growing season of 2015–2100 in each wheat planting grid. We use heating degree days (HDD, °C·day) to assess the severity of heat stress in each growing season (Butler and Huybers 2013). HDD is given as:

$$HDD = \begin{cases} \sum_{i=1}^n T_{max,i} - T_{thre}, & T_{max,i} > T_{thre} \\ 0, & T_{max,i} \leq T_{thre} \end{cases} \quad (4)$$

where n is the total number of days in a wheat growing season, $T_{max,i}$ is the daily maximum temperature of day i , T_{thre} is the heat threshold (30°C for winter wheat, 34°C for spring wheat).

After defining drought events and hot days, a compound dry and hot day (CDHD) is defined as a hot day coincides with a drought event within wheat growing season. Based on this definition, we identify all CDHD within each wheat growing season of the reference period 1995–2014 and future period 2015–2100 (under SSP1–2.6, SSP2–4.5, SSP3–7.0 and SSP5–8.5) in each wheat planting grid. The methodology of CDHD identification is shown in Fig. 1.

Here we use two indices, the frequency of CDHD ($CDHD_f$) and the severity of CDHD ($CDHD_s$) in each growing season, to characterize the changes in CDHD. $CDHD_f$ describes the frequency of CDHD occurring within a wheat growing season, that is, the total number of hot days that coinciding with drought events in a wheat growing season. The calculation method of $CDHD_s$ in this study is improved based on Zhang et al. (2022b), which is the average of the product of the -SPEI (convert SPEI to positive number) and the daily standardized value of T_{max} for each CDHD:

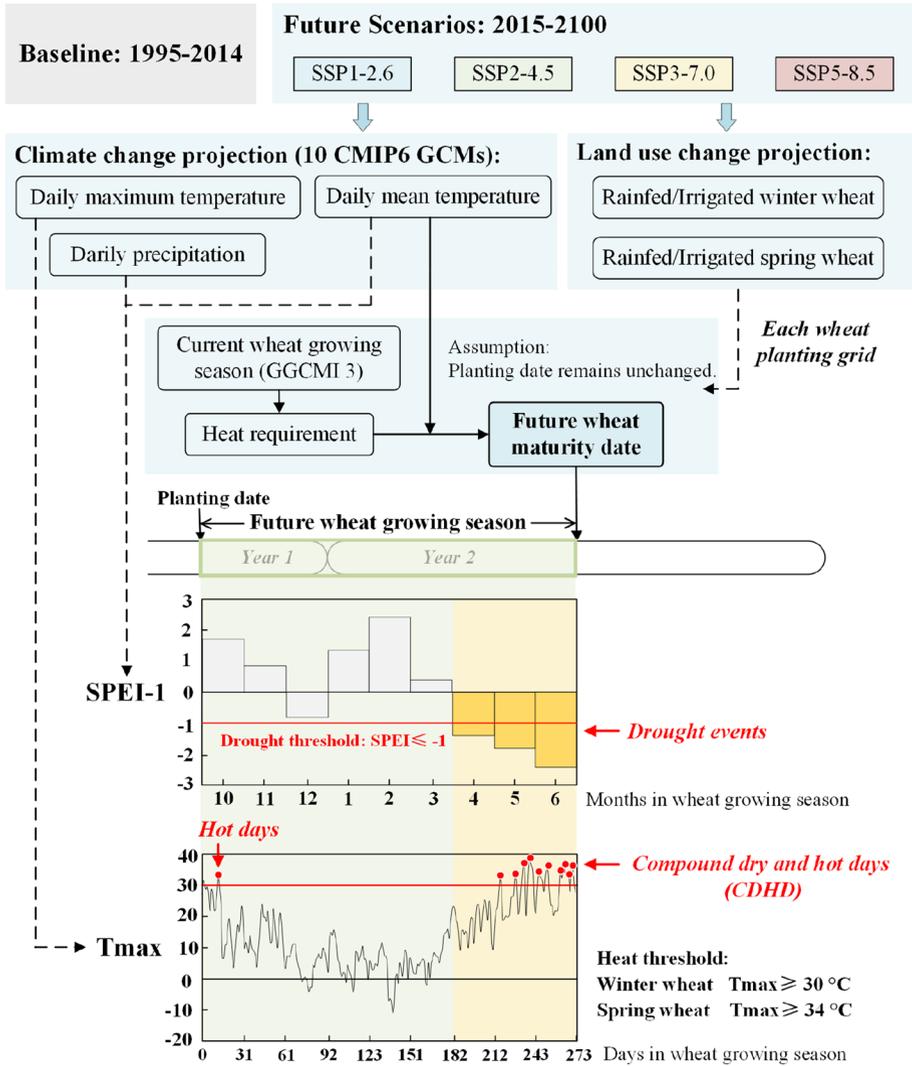


Fig. 1 Methodology of identifying CDHD in future wheat growing season

$$CDHD_s = \frac{\sum_{i=1}^{CDHD_f} (-1 * SPEI_i) * \left(\frac{T_{max,i} - T_{thre}}{T_{thre} - T_{base}} \right)}{CDHD_f} \tag{5}$$

where $CDHD_s$ is the severity of CDHD in a wheat growing season, $CDHD_f$ is the frequency of CDHD in this wheat growing season, $SPEI_i$ is the value of monthly SPEI of the month that containing the $CDHD_i$, $T_{max,i}$ is the daily maximum temperature of $CDHD_i$, T_{thre} is the heat threshold (30°C for winter wheat, 34°C for spring wheat), T_{base} is the base temperature representing the minimum biology temperature for wheat, here we use 5.5°C according to existing studies (Zhu and Troy 2018; He et al. 2022b). Based on this, we calculate the $CDHD_f$ and $CDHD_s$ for each wheat growing season of the reference period

1995-2014 and future period 2015-2100 (under SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5) in each wheat planting region worldwide.

3 Result

3.1 Future changes in CDHD within wheat growing seasons

Figure 2 shows the global average changes in drought events, SPEI (average monthly SPEI of a wheat growing season), hot days, HDD, $CDHD_f$ and $CDHD_s$ in each wheat growing season during historical period (1951-2014) and future period (2015-2100), including winter wheat (Fig. 2a–f) and spring wheat (Fig. 2g–l), SPEI value and HDD represent the severity of drought and heat respectively (smaller SPEI value indicates more severe drought, larger HDD value indicates more severe heat). Trends are calculated based on Mann-Kendall trend test method (see “1.3 Mann-Kendall trend test” of Supporting information). As shown in Fig. 2a, b for winter wheat and Fig. 2g, h for spring wheat, global average SPEI in wheat growing season will decrease significantly during 2015-2100 under all 4 SSPs, correspondingly, drought events will increase significantly, indicating that both frequency and severity of drought events in wheat growing season will increase under all 4 SSPs. As shown in Fig. 2c, d for winter wheat and Fig. 2i, j for spring wheat, both frequency (represented by hot days) and severity (represented by HDD) of heat stress in wheat growing season will increase significantly under all 4 SSPs. As shown in Fig. 2d, f for winter wheat and Fig. 2k, l for spring wheat, driven by the increase in the frequency and

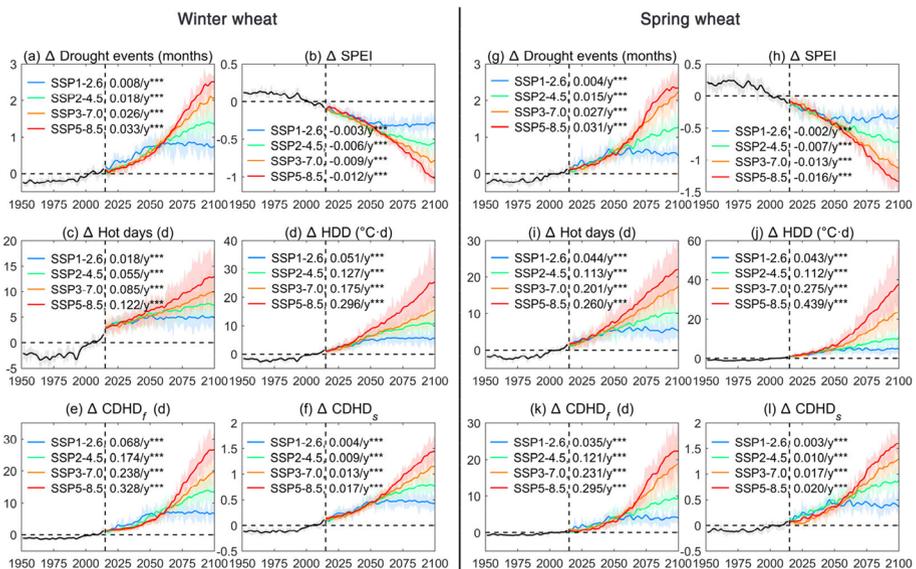


Fig. 2 Global average changes in drought events, SPEI, hot days, HDD, $CDHD_f$ and $CDHD_s$ for each winter wheat growing season (a–f) and spring wheat growing season (g–l) during 1951-2100 (historical: 1951-2014; future: 2015-2100, under 4 SSPs) with reference to 1995-2014. “***” means the trend is significant at 0.001 level. Solid lines represent 10 GCMs ensemble averages, the top and bottom boundaries of shades represent the 75th and 25th percentiles of 10 GCMs ensemble

severity of drought and heat, global average $CDHD_f$ and $CDHD_s$ are projected to increase significantly under all 4 SSPs. By 2100, $CDHD_f$ in winter/spring wheat growing season is projected to increase by 6.7 days/3.6 days, 11.9 days/10.2 days, 17.4 days/17.9 days, 23.7 days/20.8 days with reference to 1995-2014 under SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5, respectively. Furthermore, we find that $CDHD_f$ in winter and spring wheat growing season will increase even faster than hot days under all SSPs (except spring wheat under SSP1-2.6), indicating that more and more hot days will coincide with drought events rather than occur individually. This indicates that agriculture sector should realize that compound dry and hot stressor will be increasingly important in wheat production in the future, adaptation measures should be formulated not only for individual drought or heat, but also, what is more important, for simultaneous dry and hot stresses.

There are some similarities among the changes in drought, heat and CDHD. Firstly, increasing trends are similar among the 4 SSPs before ~2060s, while after that, differences in drought events, hot days and CDHD among different SSPs will increase continuously over time. Secondly, under SSP1-2.6, drought events, hot days and CDHD will increase at first and then stagnate with a turning point at ~2060s, while under other 3 SSPs, drought events, hot days and CDHD will keep increasing with a stable or even increased speed until the end of the century. Thirdly, during 2015-2100, due to different warming levels, the largest increase of drought, heat and CDHD will occur under SSP5-8.5, followed by SSP3-7.0, SSP2-4.5 and SSP1-2.6. In conclusion, global average frequency and severity of drought, heat and CDHD are projected to increase significantly during 2015-2100 under all 4 SSPs, higher warming-level scenarios correspond to larger increases.

The spatial distributions of the changes in $CDHD_f$ and $CDHD_s$ for mid-term future (2041-2060) and long-term future (2081-2100) relative to 1995-2014 are shown in Figs. 3 and Fig. S12, respectively. We find that $CDHD_f$ will increase over 96.8-97.9% and 97.0-98.5% of wheat areas for mid- and long-term future, $CDHD_s$ will increase over 96.1-98.2% and 97.2-98.6% of wheat areas for mid- and long-term future. In the mid-term future, increment of CDHD (including $CDHD_f$ and $CDHD_s$) are relatively small and similar among the 4 SSPs, while in the long-term future, obvious differences are observed among different SSPs: increment of CDHD under SSP5-8.5 is the largest, followed by SSP3-7.0, SSP2-4.5 and SSP1-2.6. In the long-term future under SSP5-8.5, 60.7% of wheat areas will suffer more than 10 CDHD in a wheat growing season, 12.6% of wheat areas will suffer at least 30 CDHD in a wheat growing season.

From spatial heterogeneity, southern Asia has the largest increment of $CDHD_f$ and $CDHD_s$, where most of wheat areas will suffer more than 30 CDHD in wheat growing season in the long-term future under SSP5-8.5. Besides, the increases in $CDHD_f$ and $CDHD_s$ over southern Canada, northern America, Ukraine, Turkey and northern Kazakhstan are much more significant, especially under SSP3-7.0 and SSP5-8.5. Based on the definition of CDHD, we know that the changes in CDHD are driven by the changes in drought events and hot days, thus we display their spatial distributions in Fig. S13 and Fig. S14. From Fig. S13-S14 and the spatial distributions of winter/spring wheat areas shown in Fig. S2-S5, we find that southern Asia is one of main winter wheat areas, where the substantial increase of $CDHD_f$ is attributed to the prominent growth of both drought events and hot days. Besides, southern Canada, northern America, Ukraine, Turkey and northern Kazakhstan are main spring wheat areas, where the increase of $CDHD_f$ is mainly driven by the great increase of hot days.

CDHD will lead to larger risks to global food security if they occur in key wheat producing areas, thus more attention should be paid to the changes of CDHD in these regions. Here we focus on the top 10 countries with largest total wheat production in 2020: China,

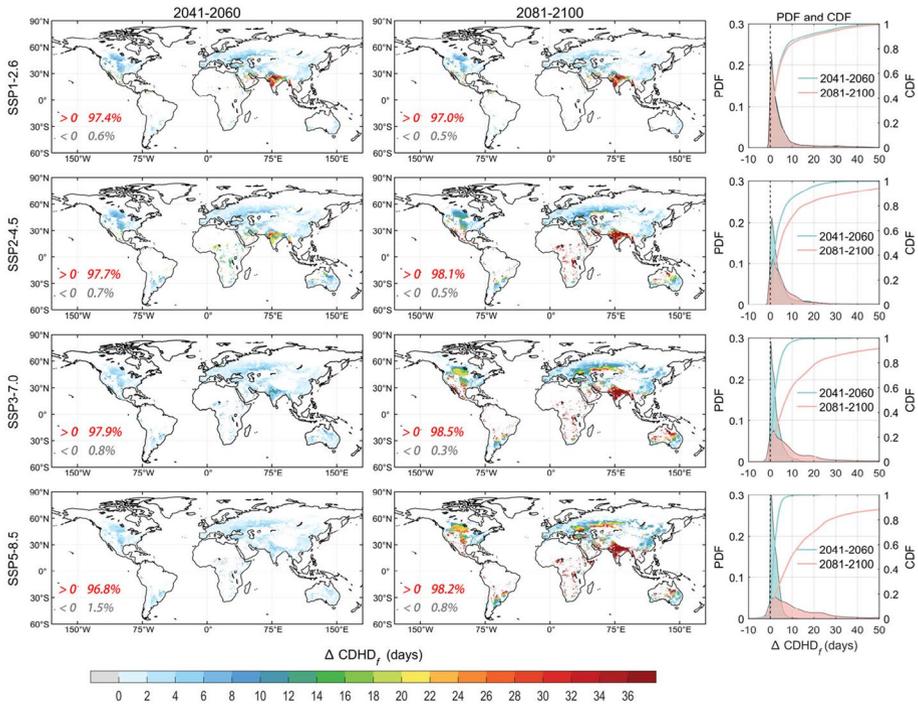


Fig. 3 Spatial distribution, probability density function (PDF) and cumulative distribution function (CDF) of the changes in $CDHD_f$ for mid-term future (2041-2060) and long-term future (2081-2100) with reference to 1995-2014 under SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5

India, Russia, America, Canada, France, Pakistan, Ukraine, Germany and Turkey, whose wheat production and planting area account for 70.4% and 63.1% of the global total. $CDHD_f$ and $CDHD_s$ of the top 10 countries for mid- and long-term future under the 4 SSPs are shown in Fig. 4 and Fig. S15 respectively, detailed values are shown in Table S3-S4.

As Fig. 4 and Fig. S15 show, a consistent finding is, in the mid-term future, $CDHD_f$ and $CDHD_s$ under SSP1-2.6 is the largest, although the differences among the 4 SSPs are relatively mild. In the long-term future, $CDHD_f$ and $CDHD_s$ under SSP5-8.5 is the largest, followed by SSP3-7.0, SSP2-4.5 and SSP1-2.6, differences among the 4 SSPs are more pronounced than that in the mid-term future, indicating that CDHD will be more substantially promoted after mid-term future, thereby aggressive adaptation strategies should be taken as soon as possible. By comparing the CDHD of the 10 countries, we find that wheat in India, America and Turkey will suffer more CDHD under all SSPs, wheat in India, America and Russia will suffer higher-severity CDHD under all SSPs. In conclusion, India and America will be the hot spots whose wheat production will suffer more risks from CDHD in the future under all SSPs.

Given the obvious differences in $CDHD_f$ and $CDHD_s$ among different SSPs in the long-term future (2081-2100), we calculate the difference value (D-value) that $CDHD_f$ (and $CDHD_s$) in the long-term future under SSP2-4.5, SSP3-7.0, SSP5-8.5 minus that under SSP1-2.6, to investigate what differences will happen if adopting low forcing pathway (SSP1-2.6). As shown in Fig. 5, if adopting low forcing pathway, $CDHD_f$ will be reduced

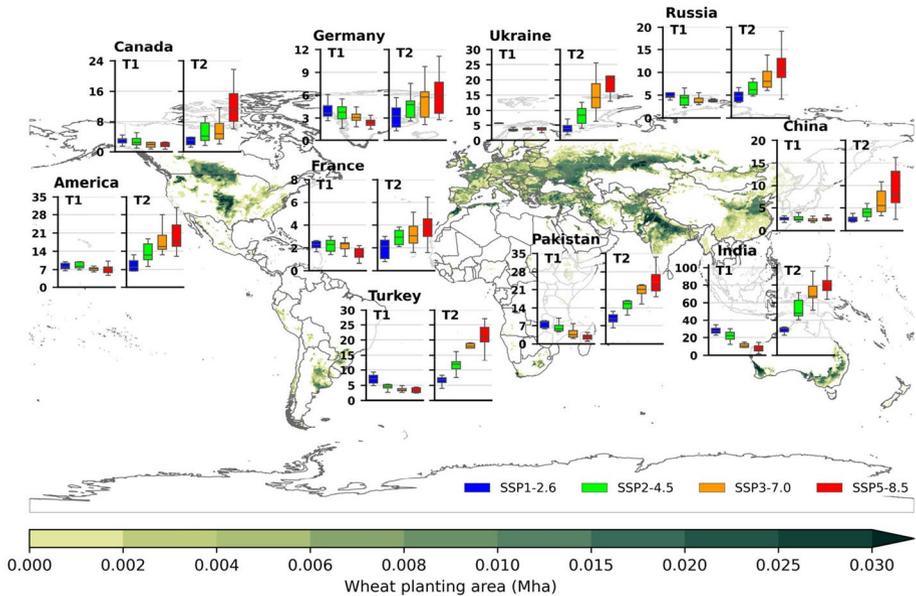


Fig. 4 Projected $CDHD_f$ (days) of the top 10 wheat producing countries for mid-term future (2041-2060, T1) and long-term future (2081-2100, T2) under the 4 SSPs. The boxplots display the spread of $CDHD_f$ projected by 10 GCMs that represent uncertainties of GCMs ensemble, the background is the spatial distribution of wheat planting area in 2020

over 93.3-96.6% of wheat areas, and $CDHD_s$ will be reduced over 95.5-98.1% of wheat areas, in other words, adopting low forcing pathway can mitigate CDHD risks in at least 93.3% of wheat areas. It is found that the higher warming-level scenarios correspond to larger D-value of $CDHD_f$ and $CDHD_s$, highlighting the importance of controlling the greenhouse gas emissions to alleviate CDHD risks. $CDHD_f$ and $CDHD_s$ over south Asia, Turkey, southern Canada and northern America will respond more strongly (in other words, more sensitive) to warming level increasing. Therefore, they will benefit more if adopting low forcing pathway in the future.

3.2 Dependence between droughts and heats and its impacts on CDHD

The correlations or interactions between droughts and heats can profoundly affect changes in CDHD, thus we assess the dependence between droughts and heats in wheat growing season of 2015-2100, which is compared with CDHD in 2081-2100 that as a consequence to explore what impacts will such dependence cause on CDHD. Here we use the Kendall rank correlation coefficient (Kendall's τ) (Kendall 1990), which is a nonparametric measure of dependence (Wahl et al. 2015). We know that the frequency of CDHD is affected by the frequency of drought events and hot days, the severity of CDHD is driven by the severity of droughts and heats, therefore, we compare the spatial distributions of $CDHD_f$ and the Kendall's τ between drought events and hot days (frequency dependence), and, we compare the spatial distributions of $CDHD_s$ and the Kendall's τ between -SPEI (represents the severity of drought) and HDD (represents the severity of heat) (severity dependence), as shown in Fig. 6 and Fig. S16 respectively.

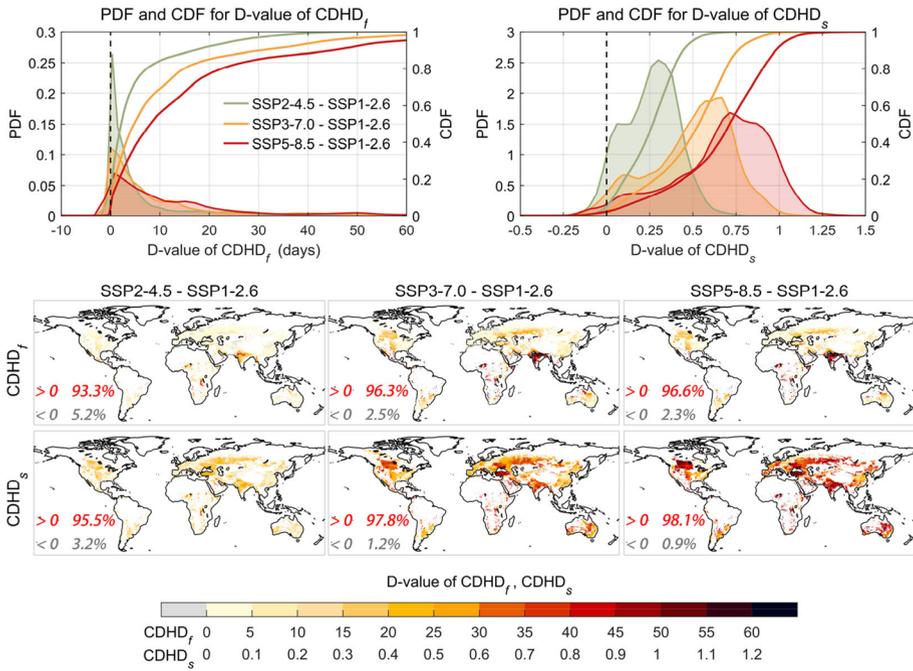


Fig. 5 The probability density function (PDF), cumulative distribution function (CDF) and spatial distributions of the difference value (D-value) of $CDHD_f$ and $CDHD_s$ for the long-term future (2081-2100) between SSP2-4.5 and SSP1-2.6, between SSP3-7.0 and SSP1-2.6, between SSP5-8.5 and SSP1-2.6

The correlation coefficient τ between drought events and hot days is positive over 74.2-90.1% of wheat areas, the correlation coefficient τ between -SPEI and HDD is positive over 78.2-94.9% of wheat areas, indicating that drought and heat will be positively correlated over most of wheat areas in the future. Stronger positive dependence occurs in south Asia, southern Canada, northern America, Ukraine, Turkey and northern Kazakhstan. Besides, the percentage of wheat areas with medium or high level of positive dependence ($\tau \geq 0.4$) will increase alongside with warming level increasing, under SSP5-8.5, Kendall's τ will be greater than 0.4 over 63.0% of wheat areas for frequency dependence and 72.7% of wheat areas for severity dependence. An important finding is, the spatial distributions of Kendall's τ are highly consistent with the spatial distributions of CDHD in both Fig. 6 and Fig. S16, in other words, higher positive correlation coefficient τ corresponds to larger (stronger) CDHD, indicating that the positive correlation between droughts and heats (including frequency dependence and severity dependence) can effectively promote the frequency and severity of CDHD, highlighting the critical importance of considering the synergistic interactions between droughts and heats when explaining the changes in compound dry and hot extremes.

From the analysis above, we have known that the dependence between droughts and heats can significantly affect the changes in CDHD. Here we would like to explore the relationships respectively between drought events and CDHD, and between hot days and CDHD. We calculate the Kendall rank correlation coefficient (Kendall's τ) between the changes in drought events (Δ drought events) and CDHD ($\Delta CDHD_f$), and between the

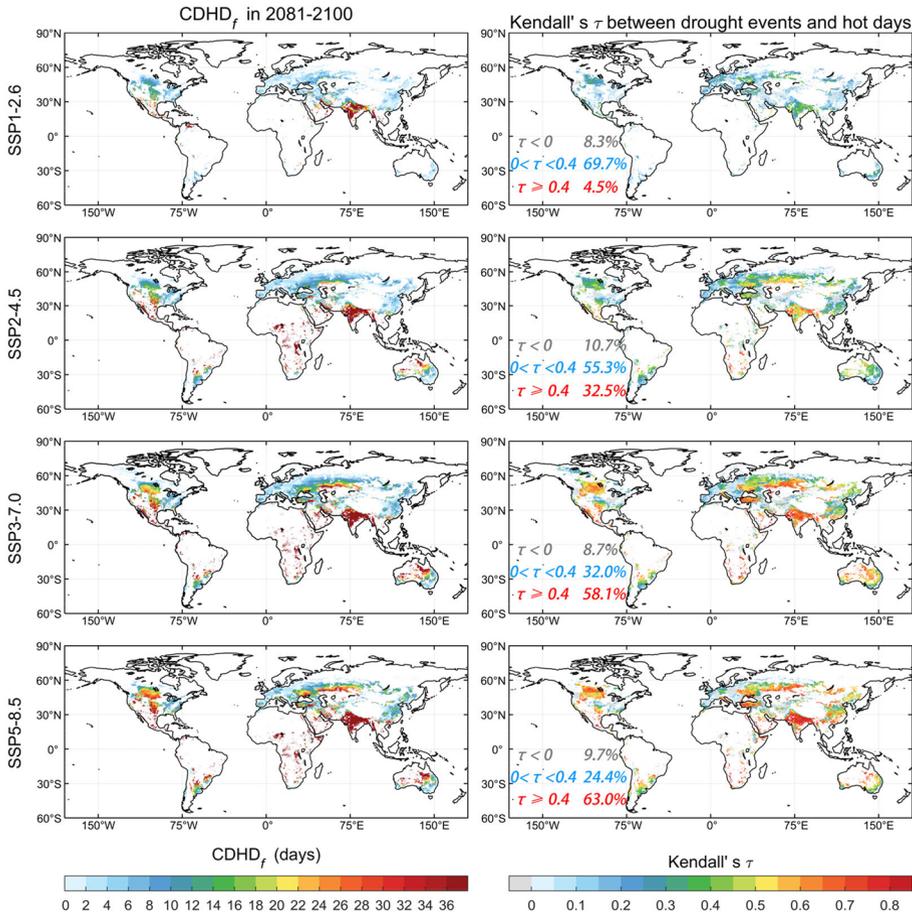


Fig. 6 Spatial distribution of $CDHD_f$ in the long-term future (2081-2100), and the Kendall rank correlation coefficient (Kendall's τ) between drought events and hot days in wheat growing seasons during 2015-2100 under SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5

changes in hot days (Δ hot days) and $CDHD$ ($\Delta CDHD_f$) for the long-term future (2081-2100) relative to 1995-2014 under the 4 SSPs, for both winter wheat and spring wheat, as shown in Fig. 7.

Positive and significant correlations are found between Δ drought events and $\Delta CDHD_f$, and between Δ hot days and $\Delta CDHD_f$ under all SSPs, indicating that the increase of drought events and hot days will make positive contributions to $CDHD$. Kendall's τ between Δ drought events and $\Delta CDHD_f$ is 0.49-0.54 for winter wheat, 0.31-0.42 for spring wheat. Kendall's τ between Δ hot days and $\Delta CDHD_f$ is 0.5-0.61 for winter wheat, 0.65-0.78 for spring wheat, we find that Kendall's τ between Δ hot days and $\Delta CDHD_f$ are always greater than that between Δ drought events and $\Delta CDHD_f$, in other words, Δ hot days are more closely correlated with $\Delta CDHD_f$, indicating that the increase of hot days is presumably the main contributor to the increase of $CDHD$. Besides, Kendall's τ between Δ drought events and $\Delta CDHD_f$ for winter wheat is always larger than that for spring wheat under all SSPs, while Kendall's τ between Δ hot days and $\Delta CDHD_f$ for spring wheat is

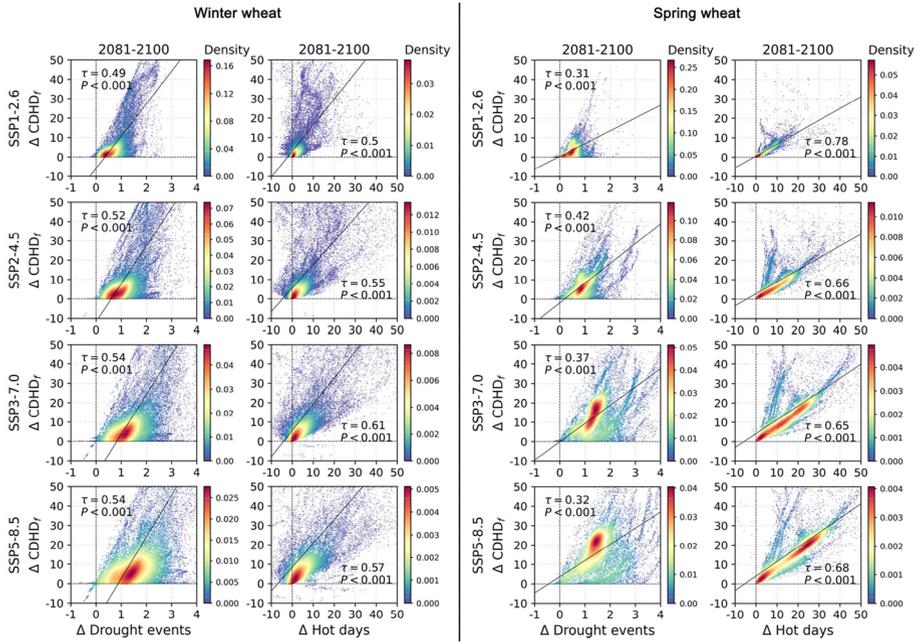


Fig. 7 The density of wheat planting grids with changes in drought events, hot days and $CDHD_f$ for 2081-2100 relative to 1995-2014 under SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5, and their Kendall rank correlation coefficient (Kendall’s τ) with significance level (P)

always larger than that for winter wheat, indicating that the impacts of drought events on $CDHD_f$ is more obvious for winter wheat, while the impacts of hot days on $CDHD_f$ is more obvious for spring wheat, possibly because spring wheat growing season contains nearly the entire summer (as shown in Fig. S6) when hot days are more likely to occur, thus Δ hot days for spring wheat are greater than that for winter wheat.

3.3 Global warming will dominate the increase of $CDHD_f$

In this section, we would like to investigate who will dominate the increase of $CDHD_f$ in the future: precipitation or temperature. This study uses SPEI as drought indicator because it has higher correlation with crops yield (Tian et al. 2018), however, we should note that SPEI is affected by temperature because it is produced by standardizing the difference between precipitation and potential evapotranspiration (PET), wherein, PET is highly positively correlated with temperature (Eq. 10 in Supporting information), thus SPEI is also already an indicator of compound dry and hot conditions to some extent (Vogel et al. 2021). In order to separate the impacts of precipitation and temperature on $CDHD_f$, we introduce another drought indicator, Standardized Precipitation Index (SPI), which is similarly calculated with SPEI but only based on precipitation (“1.1 SPI calculation method” in Supporting information).

Figure 8 shows the changes in global average PET, SPI, SPEI, drought events based on SPI ($SPI \leq -1$) and SPEI, and $CDHD_f$ based on SPI and SPEI under the 4 SSPs, for both winter wheat and spring wheat (spatial distributions of the differences between SPEI and

Fig. 8 Global average PET (a), SPI and SPEI (b), drought events based on SPI and SPEI (c), $CDHD_f$ based on SPI and SPEI (d) in winter wheat and spring wheat growing season during 2015–2100 under SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5. “****” means the trend is significant at 0.001 level

SPI are shown in Fig. S17). Global average PET in wheat growing season is projected to increase significantly because of global warming. Global average SPI will significantly increase in winter wheat growing season under all SSPs, indicating that precipitation in winter wheat growing season will increase. SPEI will decrease substantially for both winter wheat and spring wheat because intense increase of PET will reduce the difference between precipitation and PET, or even exceed precipitation thereby causing water deficit. Obvious differences can be observed in SPEI- and SPI-based drought events, which is attributed to the substantial increase of PET determined by global warming. And then, such differences between SPEI- and SPI-based drought events lead to substantial differences between SPEI- and SPI-based $CDHD_f$, these differences will expand alongside with temperature rising until the end of the century. Therefore, we can draw the conclusion: (1) the substantial increase of PET caused by global warming is the dominator of the increase of drought events, rather than precipitation deficits, thus warming-induced droughts should be paid more attention in the future in agricultural production; (2) global warming will determine the increase of SPEI-based $CDHD_f$ via two pathways: on the one hand, temperature rising will substantially promote PET thereby causing significant increase in drought events; on the other hand, temperature rising will directly increase hot days.

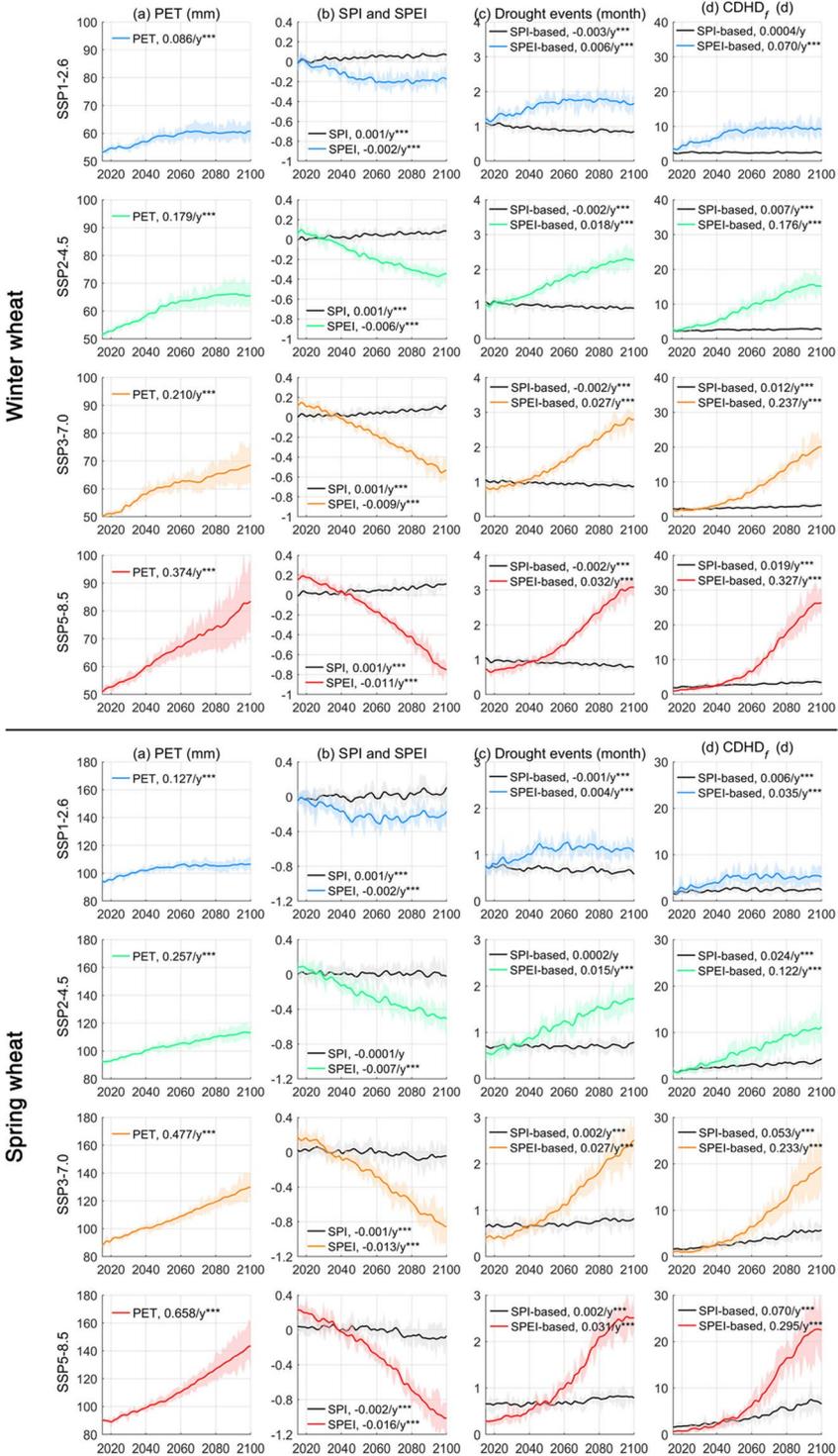
Consistent conclusions can be found in previous studies proving that temperature rising is the major driver of the increase of compound dry and hot extremes (Sarhadi et al. 2018; Yu and Zhai 2020; Zhang et al. 2022b). Our study further reveals that global warming will dominate the future increase of CDHD directly by increasing hot days and indirectly by enhancing PET then aggravating droughts. Furthermore, the substantial increase of PET caused by global warming will become the dominator of droughts, especially under high warming-level scenarios. Also, drought indices solely based on precipitation (such as SPI) cannot reveal warming-induced changes in droughts thus they will underestimate droughts' severity thereby underestimate CDHD.

4 Discussion

4.1 Difference in CDHD between static and dynamic wheat growing season

In this study, we use dynamic growing season instead of static growing season by taking the impacts of global warming on the length of growing season into consideration. We assume that the planting date will keep consistent in the future, the length of growing season depends on when heat units' accumulation reaches the total heat requirement. As shown in Fig. S7–S11, the length of wheat growing season (or the total growing days) will be shortened globally because temperature rising will accelerate heat accumulation process thereby lead to early maturation, which is in consistent with the findings in Kukal and Irmak (2018) and Ahmad et al. (2023). Higher temperature rising level corresponds to faster growing speed and shorter wheat growing season, that is why the reduction of growing season under SSP5-8.5 will be the largest.

The difference in drought events, hot days and CDHD between dynamic growing season and static growing season is shown in Fig. 9 (spatial distributions are shown in



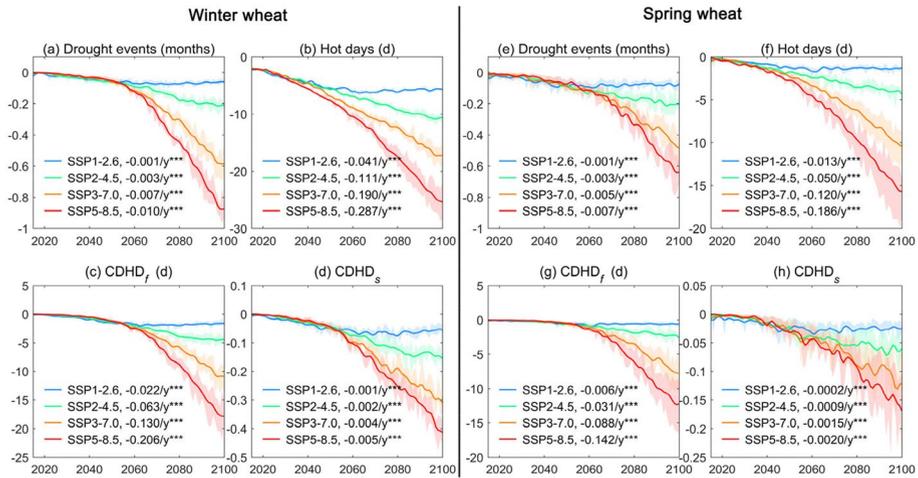


Fig. 9 Global average difference in drought events, hot days, $CDHD_f$ and $CDHD_s$ between dynamic growing season and static growing season for winter wheat and spring wheat during 2015-2100 under SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5. *** means the trend is significant at 0.001 level

Fig. S18-19). Under the impact of shortened growing season caused by climate warming, drought events, hot days and $CDHD$ in dynamic growing season is smaller than that in static growing season, furthermore, their differences will expand until the end of the century because growing season will be shortened continually alongside with temperature rising. Differences under SSP5-8.5 is the largest because of the largest reduction of growing season.

There exists a trade-off between the benefit and risk of shortened growing season: on the one hand, the reduction of growing duration can lead to the reduction of climate extreme events (such as $CDHD$ in this study), which is benefit for wheat; while on the other hand, accelerated phenological development in response to a warmer climate will limit the dry matter accumulation in grain thus resulting in yield reduction (both in terms of quality and quantity) (Ahmad et al. 2023). Adopting late-maturity varieties is a common agricultural management strategy for extending crops growing time thereby increasing dry matter accumulation, however, we should note that extending crops growing time may cause wheat suffering more climate extremes, such as $CDHD$ in this study. Since global warming will not only shorten crop's growing time but also cause more climate extremes, extending crops' growing time and enhancing crops' resilience to climate extremes are equally important and should be considered simultaneously in developing breeding techniques.

4.2 Difference in the findings with existing studies

There are some existing studies investigating the compound dry and hot extremes in the future at global scale, such as Wu et al. (2020); Zhang et al. (2022b) and De Luca and Donat (2023), all of them projected a significant increase in compound dry and hot events during the 21st century over global land regions. The difference between previous studies and this study is, previous studies investigated compound dry and hot extremes occurring in the whole future period over global all land regions, while our study only focus on $CDHD$ occurring in dynamic wheat growing seasons over dynamic wheat areas in order to

provide well-targeted understandings on wheat production. Besides, we pay more attention to the key wheat producers because CDHD will cause more risks when occurring here. Furthermore, as far as we know, this study is the first to use dynamic crop growing season in investigating compound extremes.

The topic that who will determine the changes in compound dry and hot extremes has also been discussed in previous studies. Due to the difference in research object (mean trends or extremes), spatial and temporal scales, definition of compound events, understanding of “contribution”, uncertainty in data and methodology, previous studies seem to be contradictory but actually reflect the consistent essence. For instance, Bevacqua et al. (2022) proposed that local warming will be large enough in the future, thus droughts will always coincide with hot extremes, while precipitation trends are often weak and equivocal in sign, therefore, precipitation trends will determine the future occurrences of compound dry and heat events. Bevacqua et al. (2022) precisely proved the importance of warming, in our findings, the impact of global warming is proved to be large enough to overshadow the changes in precipitation, thereby dominating the increase of CDHD by increasing hot days and enhancing PET thereby aggravating droughts.

4.3 Uncertainty and limitations of the study

This study is subjected to some uncertainties and limitations, which should be noted when interpreting the results. Firstly, we assume that the planting date remains fixed throughout the research period, however, in reality, it is not fixed and will change in each growing season. Besides, the length of wheat growing season projected in this study is only reflected the impacts of global warming, while the anthropogenic management factors such as using improved cultivar, the improvement of irrigation efficiency, are not taken into account. Therefore, implementing dynamic planting date and considering the impacts of anthropogenic management factors on wheat growing duration can further improve the results. Secondly, agricultural drought is a comprehensive phenomenon that comprising precipitation shortages, evapotranspiration reduction and soil moisture deficits (Łabędzki and Bąk 2015). Although SPEI can reflect the impacts of both precipitation and temperature on droughts, and has been proved to be the most representative of soil moisture conditions (Tian et al. 2018), further research can explore indicators that can better capture agricultural droughts in crops growing process. Thirdly, due to the lack of wheat phenological phase, this study uses consistent thresholds, 30°C for winter wheat and 34°C for spring wheat, for the whole growing season because wheat is more sensitive to heat stress during anthesis and grain-filling phase, however, according to Table S2, heat thresholds of different phenological phase are different. Therefore, implementing suitable heat thresholds for each phenological phase can further improve the results.

5 Conclusion

This study provides a comprehensive analysis of the changes in compound dry and hot days (CDHD) occurring within dynamic wheat growing seasons of 2015–2100 over dynamic wheat planting regions worldwide under SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5, including CDHD's frequency ($CDHD_f$) and severity ($CDHD_s$). This study sought to fill the gap in knowledge by identifying the CDHD occurring within dynamic crops growing seasons, clarifying the correlations between droughts and heats as well as their impacts on

CDHD, and revealing the driven mechanism of global warming for the increase of CDHD. The main findings are summarized as follows.

$CDHD_f$ and $CDHD_s$ are projected to increase substantially and significantly in both winter and spring wheat growing season during 2015–2100 under all SSPs, such increases are sharper over southern Asia in winter wheat growing season, and southern Canada, northern America, Ukraine, Turkey and northern Kazakhstan in spring wheat growing season. India and America will be the hot spots where wheat will suffer more detrimental CDHD. Higher warming-level scenarios correspond to higher $CDHD_f$ and $CDHD_s$, adopting low forcing pathway (SSP1-2.6) can reduce CDHD over at least 93.3% of wheat areas worldwide.

Drought events and hot days, -SPEI and HDD in wheat growing season show positive dependence (reflected by Kendall's τ) over 74.2–90.1%, 78.2–94.9% of wheat areas, respectively. Higher warming-level scenarios correspond to higher positive dependence level between droughts and heats. Such positive dependences between droughts and heats can effectively promote the frequency and severity of CDHD. Changes in hot days are more closely correlated with changes in $CDHD_f$, thus the increase of hot days is presumably the main contributor to the increase of CDHD.

Driven by global warming, PET in wheat growing season is projected to increase significantly under all SSPs, which is the dominator of drought events' increase, rather than precipitation deficit. Drought indicator solely based on precipitation cannot reveal warming-induced changes in droughts thereby underestimate CDHD. Global warming will dominate the increase of CDHD directly by increasing hot days and indirectly by enhancing PET then aggravating droughts.

This study provides an analysis framework for investigating future variations of compound extremes occurring in dynamic crops growing seasons worldwide. Our results reveal the substantial increase in CDHD, the most threatening climatic stress for wheat, during dynamic wheat growing seasons of 2015–2100 under different socio-economic scenarios, improve the understanding of how the correlations between droughts and heats affect CDHD, and how global warming dominator the increase of CDHD in the future, highlighting the importance and urgency of implementing adaptation measures to response CDHD risks for safeguarding wheat production and food security.

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Author contributions Y.H: Methodology, Software, Formal analysis, Investigation, Visualization, Writing – original draft. Y.Z: Conceptualization, Writing – review & editing, Supervision, Funding acquisition. S.S: Writing – review & editing. J.F: Writing – review & editing, Validation. Y.Z: Writing – review & editing. Qing Sun: Writing – review & editing. Li Liu: Writing – review & editing. Y.D: Writing – review & editing, Supervision. X.H: Visualization. P.S: Writing – review & editing, Supervision.

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Data availability The NEX-GDDP data is available at <https://www.nccs.nasa.gov/services/data-collections/land-based-products/nex-gddp-cmpip6>. The projections of gridded wheat planting area percentage (including rainfed wheat and irrigated wheat) are obtained at <https://data.pnnl.gov/group/nodes/dataset/13192>. Global

gridded wheat growing season is obtained from GGCM Phase 3 crop calendar (<https://zenodo.org/record/5062513>).

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication All authors have read and approved the manuscript, and agreed to submit it to *Climatic Change*.

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