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LETTER

Compound extreme climate events intensify yield anomalies of winter wheat in France

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Abstract

Compound extreme climate events (ECEs) are increasingly recognized for their potential to exacerbate food insecurity risks beyond those posed by isolated events. The notion of 'compound event' encompasses not only co-occurring ECEs but also multiple ECEs across (different) growth stages (mECEs). The additional effects of these mECEs on crop yield, particularly considering various types of ECEs and regional scales, remain poorly understood. To close this knowledge gap, we consider droughts, pluvials, heatwaves, and coldwaves, and further identify which types of compound events have additional effects on winter wheat yield in France, using statistical methods and datasets encompassing 94 counties over a 68-year period. Our results indicate co-occurring drought heatwaves in summer and spring, along with co-occurring pluvial heatwaves and pluvial coldwaves in winter, have negative additional effects on yield compared with single ECEs. We further identify the types of mECEs that have intensified effects, with the majority showing negative effects on yield. Key interactions leading to intensified yield loss include droughts in winter or spring combined with summer co-occurring drought heatwaves, pluvials across multiple growth stages, pluvials combined with coldwaves, and the transition between droughts and pluvials, with the most severe anomaly attaining −17.2%. Coldwaves are the main ECE related to intensified yield increases, while their frequency is decreasing. Overall, this study stresses the interactions among ECEs on crop yield, and the identified types of mECEs could serve as foundational information for designing control experiments and improving process-based crop models.

1. Introduction

Extreme climate events (ECEs), generally defined as periods abnormally deviating from the climate normal, significantly increase the risk of crop failure, posing a profound threat to global food security (Lesk *et al* 2016, Beillouin *et al* 2020, Hasegawa *et al* 2021). ECEs are expected to change in magnitude and frequency as a direct effect of anthropogenic-induced climate change (Taylor *et al* 2012, Ummenhofer and Meehl 2017), such as an increase in heatwaves, a decrease in coldwaves, and some seasons being drier or wetter (Perkins *et al* 2012, Chou *et al* 2013, Pendergrass *et al* 2017, Sharma and Mujumdar 2017, Ghavidel and Motalebizad 2024). These evolving patterns contribute to more uncertain crop yield projections, complicating efforts to ensure food security (Tito *et al* 2018). What makes risk adaptation more challenging is that different ECEs may interact with each other in one growth stage or across different ones, referred to as compound events in this paper, which can lead to unique and extreme effects of greater magnitude than the individual ones (Lesk *et al* 2022). Co-occurring ECEs (hereafter **cECEs**) are typical compound events as they may trigger a unique molecular response in plants, which cannot be directly extrapolated from the response to single ECEs individually (Rizhsky *et al* 2002, 2004). Another important category of compound events consists of multiple ECEs across the growth stages of a crop (hereafter **mECEs**), as adaptations to one ECE may increase the susceptibility to another (Dickin and Wright 2008, Li *et al* 2015), resulting in intensified anomalies in final crop yield. However, most research so far has been devoted to assessing the effects and exploring the risk adaptation for co-occurring droughts and heatwaves in summer (Prasad *et al* 2011, Feng *et al* 2019, Heino *et al* 2023). The interactions resulting from other types of compound events deserve a timely exploration.

Disentangling the effects of compound events on crop yield is challenging due to the variety of effects caused by different types of ECEs in different growth stages. For this purpose, manipulated experiments by setting different ECE conditions to simulate their effects on yield are limited, in terms of the vast resources required to enumerate each possible interaction of ECEs (Webber *et al* 2022), although they are critical to establish the cause-and-effect relationships (Dickin and Wright 2008, Zhu *et al* 2020, Feng *et al* 2023). On the modelling side, process-based crop models, which describe various physiological processes of crop growth as equations and incorporate climate factors (Feng *et al* 2023), seem to be a cheaper and more flexible way to simulate compound events. However, they show important limitations in reproducing crop responses to certain types of ECEs due to an incomplete understanding, such as overestimating yield under pluvial conditions (Feng *et al* 2019, Li *et al* 2019, Júnior *et al* 2023), and few crop models have documented approaches for multiple stressors (Webber *et al* 2022). Therefore, crop models may likely fail to reproduce crop responses to compound ECEs accurately. These drawbacks inevitably limit our exploration of compound precipitation and temperature extreme events based on manipulated experiments or crop models. As a result, the potential effects of their interactions on crop yield remain largely unclear, particularly concerning the effects of multiple ECEs across growth stages (mECEs) (Lesk *et al* 2022). The increasing availability of regional long-term observation data (climate variables and crop yield) combined with proper statistical analyses may allow us to overcome these limitations.

To bridge these knowledge gaps, we focus on the intensified effects of compound events (cECEs and mECEs), which are combinations of four typical types of ECEs: drought (d), pluvial (p), heatwave (h), and coldwave (c). See figure 1 for a schematic representation. We statistically identify which types of compound events have additional effects on winter wheat yield, using datasets encompassing 94 counties over a 68-year period in France. We define these ECEs in a relative way compared with the climate normals and identify them on a daily scale for each county. We compare average crop yield anomalies and their probability distributions in order to identify additional effects (see methods for details). We ignore the possible temporal and spatial variation of the effects across years and counties in France.

2. Materials and methods

2.1. Yield and climate data

We obtained crop yield data in France in the period from 1951 to 2018 from the study by Schauberger *et al* (2022), covering 94 counties, excluding Haute-Corse and Corse-du-Sud on Corsica. For each county, we applied a detrending method to the crop yield data to remove the long-term effects attributable to technological improvements within the study period (Ben-Ari *et al* 2018). Crop yield anomalies Y_{p} (%) expressed as percentages are defined as:

$$Y_{\mathrm{p},c,r} = \frac{C_{c,r} - \mu_{c,r}}{\mu_{c,r}} \times 100\%,$$

where $C_{c,r}$ is the yield value and $\mu_{c,r}$ is the expected yield value in county c in year r. $\mu_{c,r}$ is estimated using local regression (loess) with a span width of 0.66, in line with Schauberger *et al* (2021).

The winter wheat growing season starts with sowing in October, undergoes a vernalizing period in winter, and ends at harvest in the following July (Ben-Ari *et al* 2018). Its cycle includes the foundation (October to March), construction (April to May), flowering (June), and ripening growth stages (July) (AHDB 2023), as illustrated in figure 1(b).

We used daily precipitation and maximum/minimum temperature data from the E-OBS dataset (Cornes *et al* 2018), spanning 1951 to 2018 on a 0.25-degree regular grid. This dataset, a compilation from the European Climate Assessment & Dataset (ECA&D) project's station network, has been applied in many studies, e.g. (Vautard *et al* 2013, Ridder *et al* 2018, Rivoire *et al* 2021). We aggregated these precipitation and temperature data into each county to match the spatial resolution of the crop yield data.

2.2. Definition and identification of ECEs and compound events

Drought (d), pluvial (p), heatwave (h), and coldwave (c) are defined and identified consistently on a daily scale and across four seasons, as they might occur in any season and may affect crop yield (Kim *et al* 2023, Shan *et al* 2024a). We define an ECE as a period during which the climate variable significantly deviates from its expected normal values during this period in that county. A pluvial (resp. drought) is defined as a period of excessively high (resp. low) precipitation compared with the expected normal precipitation. A heatwave (resp. coldwave) is defined as a period of excessively high (resp. low) temperatures compared with the expected normal temperatures. The specific identification process is the same as in our former studies (Shan *et al* 2024a, 2024b), in which we consider the non-stationarity of climate variables,

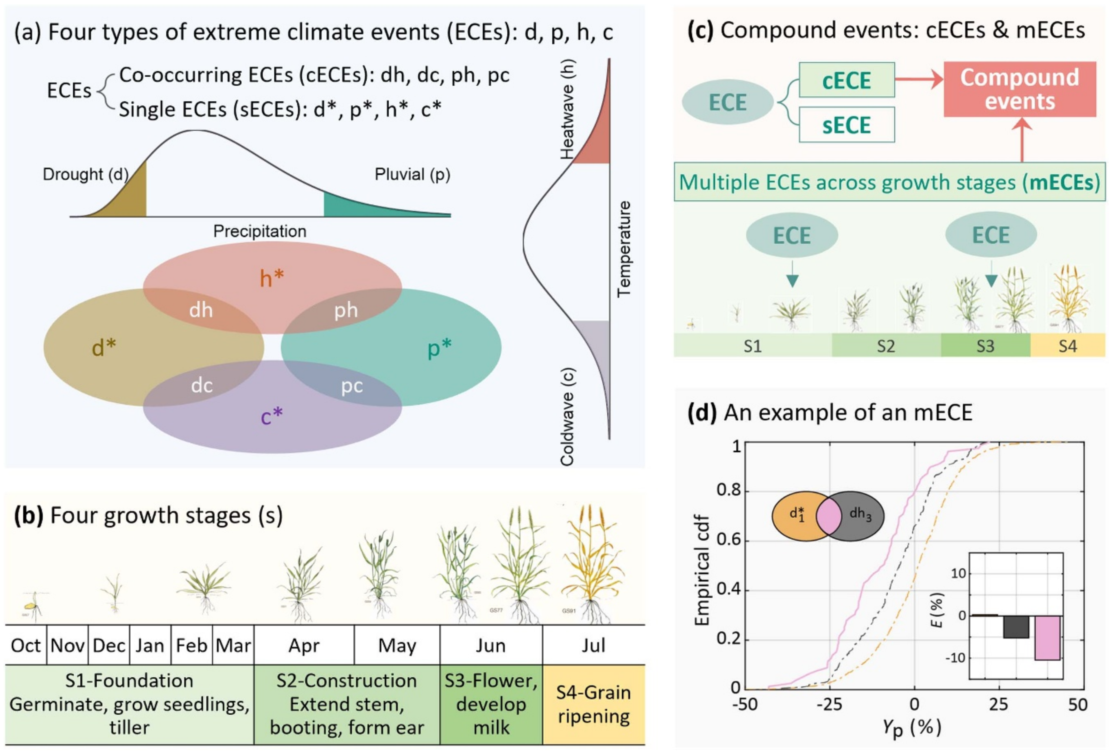

Figure 1. (a) A graphical visualization of extreme climate events (ECEs). (b) The life cycle of winter wheat in France includes four growth stages. (c) Compound events include cECEs and mECEs (multiple ECEs across the growth stages of the winter wheat). (d) Empirical cumulative distribution function (CDF) values for crop yield anomalies (Y_p, %) and average crop yield anomalies (E, %) when d_1^* and dh_3 occur in a life cycle, d_1^* occurs in isolation, or dh_3 occurs in isolation, where d_1^* stands for a single drought in stage S1 and dh_3 stands for co-occurring droughts and heatwaves in stage S3.

calculate the Standardized Precipitation Index (SPI) and Standardized Heatwave Index (SHI), exclude minor periods, and merge the dependent periods. Figure S1 illustrates the procedure of identification for one county, and see section S1 in the supplementary material for equations of SPI and SHI.

To explore the possible different effects of univariate ECEs and multivariate ECEs, we divide ECEs into two categories: co-occurring ECEs (cECEs, i.e. dh, dc, ph, and pc) and single ECEs (sECEs, i.e. d^*, p^*, h^*, and c^*), as illustrated in figure 1(a). For example, cECE dh is defined as the intersection of a drought and a heatwave, whereas sECE d^* refers to drought in isolation, explicitly excluding scenarios where a drought co-occurs with either a heatwave or a coldwave. The cECEs make up one category of compound events.

As a crop's life cycle typically spans several months, including various growth stages, crops can be subjected to more than one ECE (sECEs or cECEs) within a life cycle, which may intensify yield anomalies. Such multiple ECEs occurring across growth stages constitute a second category of compound events, which we will refer to as mECEs, illustrated in figure 1(c).

2.3. Identification of additional effects

We consider four types of sECEs and four types of cECEs, which can occur in any of the four growth stages. In this way, there are $(2^{32} - 1 - 32)$[3] possible types of mECEs, and we seek to determine which types of mECEs may lead to significant additional effects. To achieve this aim, we consider the number of occurrences, average crop yield anomalies, and the distribution of crop yield anomalies. We use $\{d_1^*, dh_3\}$ as an example (figure 1(d)) to introduce the method details, as follows:

(1) The number of occurrences of both d_1^* and dh_3 within the same life cycle across all years and all counties should exceed a predetermined threshold (30 in this study). If this condition is satisfied, we proceed to step (2).

(2) We calculate the average crop yield anomalies when both d_1^* and dh_3 occur, when d_1^* occurs in isolation (without dh_3), as well as when dh_3 occurs in isolation (without d_1^*), denoted as $E_{\{d_1^*, dh_3\}}$, E_1, and E_2 respectively. The term 'additional effects' is defined as $E_{\{d_1^*, dh_3\}}$ should be larger than both E_1 and E_2 (i.e. $E_{\{d_1^*, dh_3\}} > \max(E_1, E_2)$), or smaller than as well E_1 as E_2 (i.e. $E_{\{d_1^*, dh_3\}} < \min(E_1, E_2)$). The criterion is $E_{\{d_1^*, dh_3\}} < \min(E_1, E_2)$ or $E_{\{d_1^*, dh_3\}} > \max(E_1, E_2)$. If this condition is satisfied, we proceed to step (3);

[3] 32 is calculated as (4 sECEs + 4 cECEs) × 4 growth stages. The total number of non-singleton combinations is $2^{32} - 1 - 32$.

(3) The distribution of crop yield anomalies when both d_1^* and dh_3 occur should be different from those when d_1^* or dh_3 occurs in isolation (resp. without dh_3 or without d_1^*). We use the two-sample Kolmogorov–Smirnov test (KS test) (Massey 1951) to determine whether these differences are statistically significant (with a significance level of $\alpha = 0.05$).

If condition (3) is satisfied, we record $\{d_1^*, dh_3\}$ as having a significant additional effect. If not, we exclude any combination that includes $\{d_1^*, dh_3\}$—such as $\{d_1^*, dh_3, dh_4\}$, $\{d_1^*, dh_3, p_1^*\}$, $\{d_1^*, dh_3, p_1^*, p_2^*\}$, and so forth—from further considerations. Although this pruning process is efficient, we acknowledge that it is heuristic in the sense that it does not guarantee that any of these larger combinations could still have a significant additional effect. We continue this process until we have evaluated all $(2^{32} - 1 - 32)$ types. We detail the identification steps for another example $\{d_1^*, dh_3, dh_4\}$ in section S2 in the supplementary material. We also use the same idea to identify which cECEs may lead to significant additional effects, see section S3 in the supplementary material for details. This approach concentrates on the occurrence of ECEs in each growth stage, whether occurring only one day or persisting throughout the stage. It does not account for the duration or intensity of these events.

3. Results and discussion

3.1. Additional effects of cECEs

Co-occurring ECEs intensify yield anomalies of winter wheat in France, and their additional effects vary among types of cECEs and growth stages (figure 2). dh_2, dh_3, dh_4, dc_4, ph_1, and pc_1 all have significant additional effects, which tend to be negative except for dc_4. Next, we will analyze each type of cECE.

cECE dh in the construction, flowering, and grain ripening stages have negative additional effects on winter wheat yield. The average winter wheat yield anomalies when d or h occur in isolation and when dh occurs are: in the construction stage, $E_{d_2^*} = -2.5\%$, $E_{h_2^*} = 0.4\%$, whereas $E_{dh_2} = -6.0\%$; in the flowering stage, $E_{d_3^*} = 1.7\%$, $E_{h_3^*} = 0.2\%$, whereas $E_{dh_3} = -6.7\%$; and in the grain ripening stage, $E_{d_4^*} = 2.6\%$, $E_{h_4^*} = -0.4\%$, whereas $E_{dh_4} = -4.1\%$. cECE dh in summer is typically the focus of previous studies, but our results also point out the significant negative effects of spring dh on the final winter wheat yield. We also found that droughts in isolation in the flowering or grain ripening stage tend to have positive effects, whereas droughts co-occurring with a heatwave shift the positive effect to a negative one. This difference addresses the importance of distinguishing between the sECEs and cECEs when investigating the effects of ECEs on crop yield.

cECEs ph and pc in the foundation stage tend to have negative additional effects compared with sECEs. The average yield anomalies are $E_{p_1^*} = -0.7\%$, $E_{h_1^*} = 0.4\%$, and $E_{c_1^*} = 0.2\%$ whereas $E_{ph_1} = -3.5\%$ and $E_{pc_1} = -3.5\%$, i.e. $E_{ph_1} < \min(E_{p_1^*}, E_{h_1^*})$ and $E_{pc_1} < \min(E_{p_1^*}, E_{c_1^*})$. As the foundation stage of winter wheat in France ranges from October to March, these results highlight that cECEs in winter do matter for winter wheat yield. cECEs ph and pc in the other three growth stages have no intensified effects but rather compensating effects, as E_{ph_s} (resp. E_{pc_s}) is in between $E_{p_s^*}$ and $E_{h_s^*}$ (resp. $E_{c_s^*}$), see figures 2(c) and (d).

As an exception, cECE dc in the grain ripening stage shows a positive additional effect on winter wheat yield, as shown in figure 2(b). Droughts or coldwaves in isolation in the grain ripening stage have a positive effect ($E_{d_4^*} = 2.6\%$ and $E_{c_4^*} = 1.4\%$), and their co-occurrence further amplifies the positive effect ($E_{dc_4} = 5.8\%$, $E_{dc_4} > \max(E_{d_4^*}, E_{c_4^*})$). However, the occurrence of this cECE is relatively infrequent, with dc_4 being recorded 62 times across 94 counties from 1951 to 2018.

3.2. Additional effects of mECEs

Our identification method efficiently processed billions of potential types of mECEs, successfully identifying 94 ones that exert significant additional effects (figure 3). Figure S9 shows three types of mECEs: $\{c_2^*, p_2^*, p_4^*\}$, $\{dc_1, dc_2, c_4^*\}$, and $\{c_3^*, c_4^*\}$, which are identified as having a significant negative additional effect, a significant positive one, and a non-significant one, respectively. The identification results for mECEs emphasize the need for distinguishing between sECEs and cECEs, as their effects can be largely different. For example, for d_1^* and dc_1, the identified types of mECEs related to d_1^* tend to have negative effects, whereas those related to dc_1 tend to have positive effects. $E_{\{d_1^*, h_3^*\}} = -2.3\%$, whereas $E_{\{dc_1, h_3^*\}} = 2.3\%$. sECE d_2^* and cECE dc_2 also present a similar pattern.

Multiple precipitation- and/or temperature-related extreme events interacting across possibly different growth stages can significantly increase or decrease winter wheat yield losses. Of the 94 types of mECEs identified, 55 have negative effects (figure 3(a)), whereas 39 have positive effects (figure 3(b)). The most severe average yield anomaly reaching -17.2% was caused by the type $\{c_2^*, p_2^*, p_4^*\}$.

Most of the 55 types of mECEs with negative effects contain droughts in winter and spring (d_1^*, d_2^*), pluvials in any growth stage (p_s^*, $s \in \{1, 2, 3, 4\}$), co-occurring droughts and heatwaves in spring and

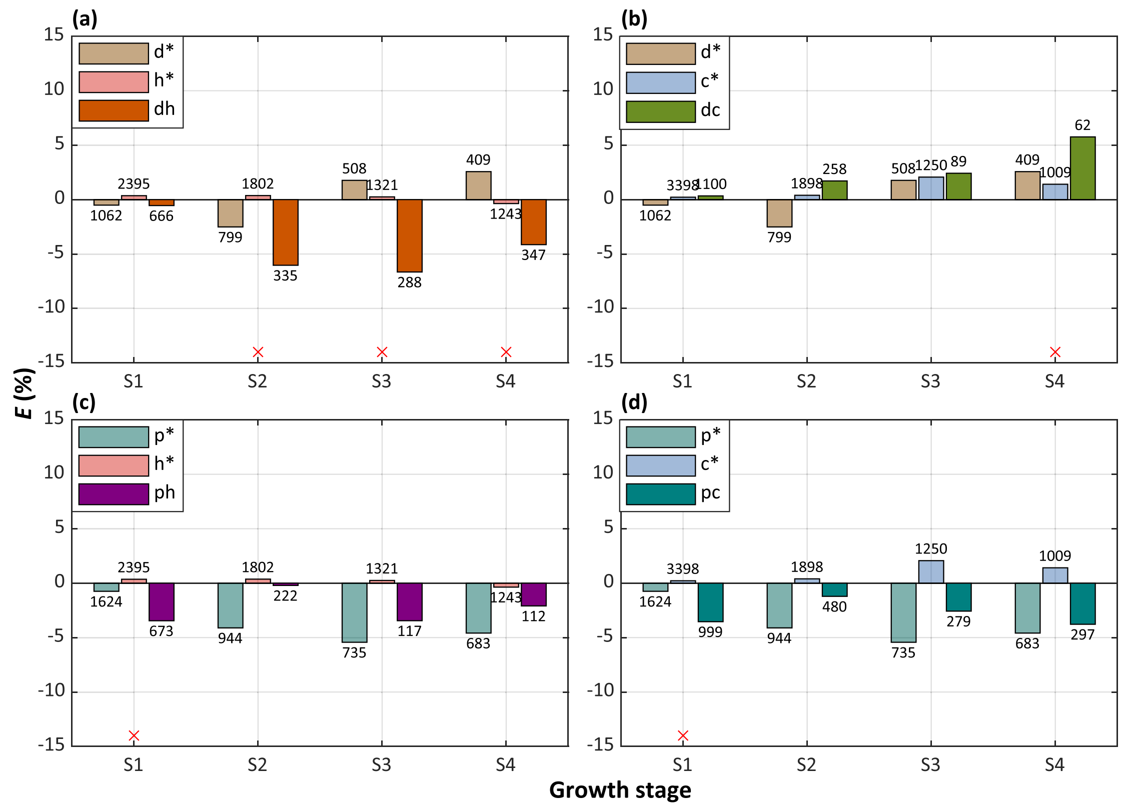

Figure 2. Additional effects on winter wheat yield of co-occurring ECEs (cECEs) in each growth stage compared with the corresponding single ECEs (sECE). E represents the average crop yield anomaly. (a)–(d) represent various types of cECEs: drought and heatwave (dh), drought and coldwave (dc), pluvial and heatwave (ph), and pluvial and coldwave (pc). The number at the end of each bar indicates the frequency of occurrence, with a red cross denoting a significant additional effect (with a significance level of $\alpha = 0.05$). Here, S1, S2, S3, and S4 represent the foundation, construction, flowering, and grain ripening stage, respectively.

summer (dh_s, $s \in \{2,3,4\}$), or co-occurring pluvials and coldwaves in winter and summer (pc_s, $s \in \{1,3,4\}$). We generally summarize them into five categories according to the possible interaction mechanisms (figure 3(a)):

(1) Droughts in winter or spring (d_1^* or d_2^*) interacting with co-occurring droughts and heatwaves in summer (dh_3 and/or dh_4). For example, $\{\mathrm{d}_1^*, \mathrm{dh}_3, \mathrm{dh}_4\}$ has an average yield anomaly of $E_{\{\mathrm{d}_1^*, \mathrm{dh}_3, \mathrm{dh}_4\}} = -12.8\%$.
(2) Pluvials across multiple growth stages. For example, $E_{\{\mathrm{p}_2^*, \mathrm{p}_4^*\}} = -10.9\%$ with a frequency of 115.
(3) Pluvials interacting with coldwaves. For example, $E_{\{\mathrm{c}_2^*, \mathrm{p}_3^*\}} = -10.0\%$ with a frequency of 241.
(4) The transition between droughts and pluvials, such as d_3^* and p_1^*, p_3^* and d_4^*, pc_1 and dh_2. This result indicates that the transition from precipitation-related ECEs to inverse ones can also contribute to an intensified winter wheat yield loss.
(5) Other types that cannot be summarized into the four categories. For example, $\{\mathrm{h}_1^*, \mathrm{c}_2^*, \mathrm{p}_3^*\}$, containing heatwaves in overwintering periods, coldwaves in spring, and pluvials in June, has significant negative additional effects with an average yield anomaly of -13.3%.

Most of the 39 types of mECEs with positive effects contain coldwaves in spring and summer (c_3^*, c_4^*), and co-occurring droughts and coldwaves in winter and spring (dc_1, dc_2). We generally summarize them into four categories (figure 3(b)):

(1) Droughts interacting with coldwaves. For example, $E_{\{\mathrm{dc}_1, \mathrm{dc}_2, \mathrm{c}_4^*\}} = 15.0\%$. This category is the largest among the four, containing 15 of the 39 types of mECEs.
(2) Single coldwaves across multiple growth stages. For example, $E_{\{\mathrm{c}_2^*, \mathrm{c}_3^*\}} = 3.7\%$.
(3) Single heatwaves interacting with coldwaves. For example, $E_{\{\mathrm{h}_1^*, \mathrm{pc}_2, \mathrm{c}_3^*\}} = 6.5\%$
(4) Other types, such as $\{\mathrm{dh}_1, \mathrm{c}_3^*\}$ and $\{\mathrm{pc}_2, \mathrm{c}_3^*\}$.

Although mECEs can lead to both positive and negative effects on winter wheat yield, they more frequently lead to small positives and large negatives (see figure 3(c)). This result indicates that mECEs could be an important driver of large harvest failures. Moreover, conditions that are favorable for increasing winter wheat yield are becoming less frequent with

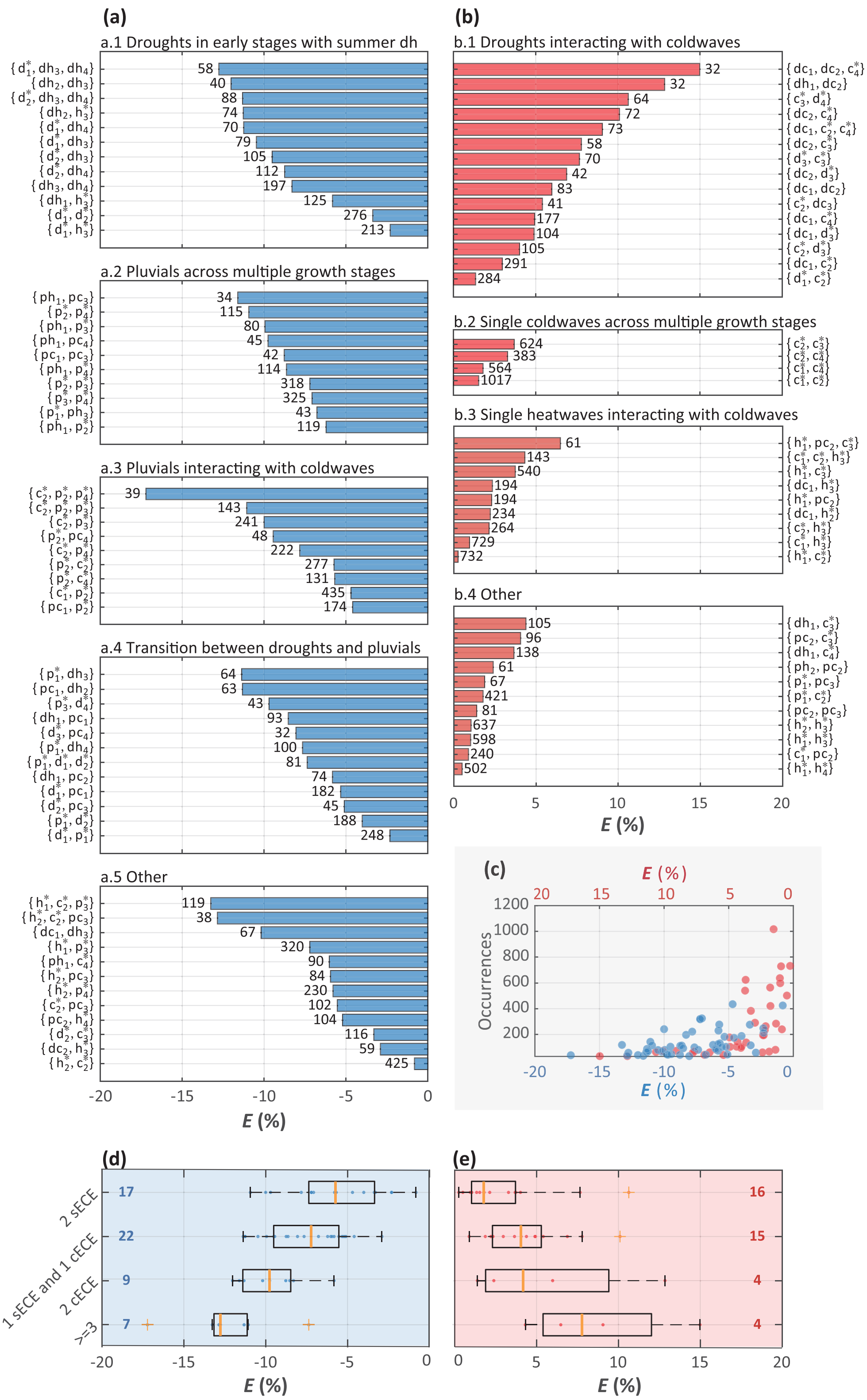

Figure 3. Ninety-four types of multiple extreme climate events across the growth stages of a crop (mECEs) with additional effects on winter wheat yield in France, of which 55 have a negative average crop yield anomaly (E) in (a) and 39 have a positive E in (b). We summarize these 55 types of mECEs into five and 39 ones into four categories based on their interaction mechanisms, and then sort them in descending order by their absolute yield anomaly, respectively. Each bar represents a type of mECE and the number at the end indicates its number of occurrences. (c) The number of occurrences and average yield anomalies of 55 (blue) and 39 (red) types of mECEs. (d) and (e) We further divide the 55 and 39 types of mECEs into four categories: '2 sECEs', '1 sECE and 1 cECE', '2 cECEs', and '$\geqslant$ 3 ECEs', respectively. Each point represents one type of mECE; the numbers indicate the number of types in that category. The average yield anomaly of all types belonging to that category is presented in the box plot.

global warming. Coldwaves are the most important driver of the positive additional effects. Among the 39 types of mECEs with a positive average yield anomaly, 37 involve coldwaves (c^*, dc or pc). However, these mECEs were less frequent in the period from 1985 to 2018 compared with the period from 1951 to 1984. This trend is especially pronounced in the southern part of France, more so than in the north (see figure S10). Thus, we recommend increased vigilance regarding the risks that mECEs can pose to food security due to their substantial negative effects and the decreasing frequency of mECEs favorable for yield gains.

Interactions between one sECE and one cECE across different growth stages can result in more significant effects than interactions between two sECEs. In figure 3(d), of the 55 types of mECEs with a negative average yield anomaly, there are 17, 22, and 9 types of mECEs categorized as '2 sECEs', '1 sECE and 1 cECE', and '2 cECEs', and their median *E* is -5.8%, -6.5%, and -9.8%, respectively. Seven types are categorized as '$\geqslant$ 3 ECEs', with a median average yield anomaly of -12.8%. These results indicate that '1 sECE and 1 cECE' are more likely to have more significant negative effects than 2 sECEs; furthermore, 2 cECEs are more likely to have more significant negative effects than 1 sECE and 1 cECE. In figure 3(e), of the 39 types of mECEs with a positive average yield anomaly, there are 16, 15, and 4 types of mECEs categorized as '2 sECEs', '1 sECE and 1 cECE', '2 cECEs' are 16, 15, and 4, and their median average yield anomaly is 2.0%, 4.1%, and 4.2%, respectively. Four types are categorized as '$\geqslant$ 3 ECEs', with a median average yield anomaly of 7.8%. We also found that '1 sECE and 1 cECE' are more likely to have more significant positive effects than 2 sECEs, which shows a similar pattern with the combinations as for negative effects.

3.3. Discussion

In this study, we comprehensively analyzed the effects of sECEs, cECEs, and mECEs on winter wheat yield, covering four types of ECEs and their interactions. Our research confirms some known effects and shares fresh insights. Highlighted below are three key examples that illustrate the alignment over previous studies:

(1) Co-occurring droughts and heatwaves in the summer can have negative additional effects. This result corresponds to research on plant mechanisms, which reveals that cECE dh triggers a unique molecular response in plants. Normally, plants open their stomata to cool their leaves through transpiration in heatwaves. However, when this stress coincides with a drought, plants are unable to open their stomata, leading to increased leaf temperatures (Rizhsky *et al* 2002, Mittler 2006). This impediment to normal physiological processes results in reduced photosynthesis, ultimately contributing to agricultural yield losses.

(2) Pluvials in the construction, flowering, and grain ripening stages adversely affect winter wheat yield in France, and pluvials across multiple stages further intensify the magnitude of the loss. These findings align with existing research. Pluvials contribute to waterlogging stress, which inhibits root respiration and leads to the accumulation of toxic substances. This detrimentally affects both vegetative and reproductive growth, ultimately resulting in yield losses (Pan *et al* 2021, Tian *et al* 2021). In France, wheat production is more negatively affected by pluvials than droughts, which aligns with findings by Zampieri *et al* (2017).

(3) Drought in the construction stage can result in greater yield losses compared with those experienced in the flowering and grain ripening stages. This finding is consistent with experimental results (Suzuki *et al* 2014, Ding *et al* 2018).

Besides aligning with existing studies, our identification results provide a list of mECEs with intensified effects, offering insights that, to our knowledge, have not been previously reported, though our study may have overlooked some types due to setting a threshold of at least 30 occurrences. These identification results serve as a new reference for re-reviewing the conclusions of existing research. For example, Dickin and Wright (2008) conducted control experiments to investigate the effects of winter waterlogging and summer drought on winter wheat yield in the UK. They found that drought during grain filling decreased yield, but there was no evidence that winter waterlogged plants were more susceptible to damage from drought the following summer. Similarly, we do not identify the additional effects of winter pluvials and summer droughts on winter wheat yield in France. However, we identified that pluvials in winter and cECE dh in summer have negative additional effects, see combinations $\{p_1^*, dh_3\}$, and $\{p_1^*, dh_4\}$. For example, the average yield anomalies of $\{p_1^*\}$, $\{dh_3\}$, and $\{p_1^*, dh_3\}$ are -0.7%, -6.7% and -11.4%, respectively. Besides global warming, climate change models predicted that precipitation in the UK and France may increase in winter whereas it is likely to decrease in summer, thus increasing the risks of winter pluvials, and summer co-occurring droughts and heatwaves (Hulme 2002, Dickin and Wright 2008, Terray and Boé 2013). As a result, we suggest new experiments to investigate the effects of winter pluvials as well as summer co-occurring droughts and heatwaves, further comparing them to winter waterlogging and summer droughts.

Experiments may have advantages over statistical analyses in exploring the underlying mechanisms of how compound ECEs interact; however, only a few types of interactions of compound events have been explored through control experiments. There are calls for more extensive studies to systematically investigate them, with the goal of better adapting to and mitigating the impacts of climate change (Rötter *et al* 2018, Júnior *et al* 2023). Our study used a statistical method and explored which types of compound events across plant growth stages may have additional effects on the basis of long-term surveyed crop yield data and climate data. Our identification results point to the research priority of a large number of compound events and could support designing control experiments and further investigating physiological mechanisms.

The occurrence frequency of mECEs has changed over the years. Pluvial- and heatwave-related compound events with negative additional effects have become more frequent in France. For instance, the occurrences of $\{h_1^*, p_3^*\}$, $\{h_2^*, p_4^*\}$, and $\{p_3^*, p_4^*\}$ have increased from 114, 71, and 139 in 1951–1984 to 206, 159, and 186 in 1985–2018, respectively (see figure S11). In contrast, coldwave-related compound events have become less frequent, such as pluvials interacting with coldwaves, droughts interacting with coldwaves, and single coldwaves across multiple growth stages. How these changes in compound events affect food security is still uncertain and requires more study.

We examined various pre-identification thresholds for identifying ECEs, specifically $+/-0.75$, $+/-1$ (used in the main text), and $+/-1.5$, which correspond to the 22.7%, 15.9%, and 6.7% percentiles, respectively. The findings and conclusions are robust across the three thresholds, underscoring the efficacy of the statistical methods employed and the reliability of the results (see section S4 in the supplementary material).

We studied winter wheat yield at the county level and aggregated data from all 94 counties in France for the least frequent compound ECEs. This approach assumes a uniform effect of each type of ECE and compound event on crop yield across France. However, this assumption does not account for the spatial heterogeneity (within or across counties) in climate conditions, soil properties, terrain variations, and agricultural management practices that can significantly influence the magnitude of climate extremes' impacts on crop yield. Figure S10 in the supplementary material shows this heterogeneity in the frequency of certain mECEs, for example, 74% of occurrences of the mECE d_1^*, dh_3, dh_4 are concentrated in the southern part of France, with the remaining 26% in the northern regions. This suggests that the intensified effects of mECEs at a finer spatial scale may diverge from those at the national level. Additionally, we did not consider irrigation—a factor that could mitigate the impact of ECEs on yield. That is because irrigation in France is rather marginal for winter wheat (0.3% in 2000 and 2.5% in 2010) and long-term data are not available at the county level (Gammans *et al* 2017, Schauberger *et al* 2021).

4. Conclusions

Compound ECEs, including co-occurring ECEs (cECEs) and multiple ECEs across the growth stages of a crop (mECEs), significantly intensify crop yield anomalies, as evidenced by our regional case study on winter wheat in France. Our results reveal the negative additional effects of cECE dh not only in summer but also in spring, as well as cECEs ph and pc in winter. cECE dc in July has positive additional effects on winter wheat yield.

We further identified 94 types of mECEs, of which 55 have negative and 39 have positive effects on yield. Key interactions leading to intensified yield loss include droughts in winter or spring combined with cECE dh in summer, pluvials across multiple growth stages, pluvials combined with coldwaves, and the transition between droughts and pluvials. The most severe anomaly is -17.2%, caused by the type $\{c_2^*, p_2^*, p_4^*\}$. Conversely, key interactions leading to intensified yield increases include coldwaves combined with droughts, single coldwaves across multiple growth stages, and heatwaves combined with coldwaves. However, these favorable mECEs were less frequent in the recent period from 1985 to 2018 compared with 1951–1984. We highlight that the types of mECEs containing an sECE and a cECE are more likely to have more significant effects than those containing two sECEs.

This study provides new insights into which compound ECEs, particularly mECEs, impact crop yield. Our identification results can be used to support designing control experiments, investigating physiological mechanisms, and enhancing crop models for more accurate yield projections.

Data availability statement

The climate data are from the E-OBS dataset (Cornes *et al* 2018). Crop yield data in France in the period from 1951 to 2018 are attributed to Schauberger *et al* (2022), available at https://doi.org/10.5880/PIK.2021.001. The codes for calculating the indices and identifying extreme climate events are developed by Shan (2024), available at https://doi.org/10.5281/zenodo.11397269.

All data that support the findings of this study are included within the article (and any supplementary files).

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