Characteristics of Compound Drought-Heatwave Events in Inner Mongolia during 1980-2100

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Abstract

Against the background of global warming, extreme climate events have occurred frequently, among which compound drought–heatwave events (CDHEs) pose serious threats to the ecosystem and socioeconomic development of Inner Mongolia. Based on CN05.1 gridded observational data and CMIP6 global model data under the medium-emissions scenario (SSP2-4.5) and high-emissions scenario (SSP5-8.5), the daily-scale standardized precipitation index (SPI) and standardized heatwave index (SHI) were used to identify four types of CDHEs in Inner Mongolia during the historical period (1980—2014) and future period (2015—2100), and the spatiotemporal variation characteristics were analyzed using univariate linear regression. The results show that, during the historical period, all indicators of the four types of CDHEs exhibited significant upward trends in the western and northern regions, with the growth rates of union-type events (D-or-H) and drought-conditioned heatwave events (D-cond-H) being higher than those of intersection-type events (D-and-H) and heatwave-conditioned drought events (H-cond-D). Under the SSP2-4.5 scenario, compared with the historical period, CDHEs generally show shorter duration, higher intensity, and a further expanded affected area. The SSP5-8.5 scenario indicates further intensification compared with SSP2-4.5, with the heatwave intensity of the four types of CDHEs increasing significantly across different periods, suggesting that high-temperature heatwaves are the dominant factor driving changes in CDHE trends. The findings can provide a scientific basis for regional climate risk assessment and the formulation of adaptation strategies.

Full Text

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Characteristics of Compound Drought–Heatwave Events in Inner Mongolia during 1980–2100

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Abstract: Against the background of global warming, extreme climate events are occurring frequently, among which compound drought–heatwave events (CDHEs) pose a serious threat to the ecosystems and socioeconomic systems of Inner Mongolia. Based on CN05.1 gridded observational data and CMIP6 global model data under the medium-emissions scenario (SSP2-4.5) and high-emissions scenario (SSP5-8.5), this study used the daily standardized precipitation index (SPI) and the standardized heatwave index (SHI) to identify four types of CDHEs in Inner Mongolia during the historical period (1980–2014) and the future period (2015–2100), and analyzed their spatiotemporal variation characteristics using a univariate linear regression method. The results show that, during the historical period, all indicators of the four types of CDHEs exhibited significant upward trends in western and northern Inner Mongolia. Among them, the union type (D-or-H) and the drought-conditioned heatwave type (D-cond-H) showed higher growth rates than the intersection type (D-and-H) and the heatwave-conditioned drought type (H-cond-D). Under the SSP2-4.5 scenario, compared with the historical period, CDHEs generally show characteristics of continuously shortened duration, increased intensity, and further expanded affected area; under the SSP5-8.5 scenario, they are further intensified relative to SSP2-4.5. The heatwave intensity of the four types of CDHEs increases significantly in different periods, indicating that high-temperature heatwaves are the dominant factor driving changes in CDHE trends. The findings can provide a scientific basis for regional climate-risk assessment and the formulation of adaptive strategies.

Keywords: standardized precipitation index; standardized heatwave index; compound drought-heatwave events; CMIP6; Inner Mongolia

The Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) points out that human activities have caused the global mean surface temperature to rise by approximately 1.07 °C over the past 20 years, and that the global warming trend is significant[1]. Under the influence of global warming, the frequency, intensity, and spatial extent of compound extreme climate events have all shown increasing trends[2–6], resulting in serious socioeconomic losses and damage to the ecological environment[7–8]. Among them, compound drought-heatwave events, a compound disaster phenomenon in which drought and high temperature occur coupled in time and space[9], can lead to a series of negative impacts such as frequent wildfires, deterioration of air quality, shortages of water resources, impeded crop growth, and reduced human health[10–11]. Therefore, research on compound drought-heatwave events is of great significance for protecting the ecological environment, preventing and reducing disasters, and responding to future extreme climate change.

Effective identification of compound drought and heatwave events (Compound Drought and Heatwave Events, CDHEs) is the basis for in-depth analysis of their evolutionary characteristics and for the prevention of disaster events. In the identification process, drought and heatwave events must first be identified as two independent events. The identification of drought events usually relies on various indices, such as the standardized precipitation index (SPI), Palmer drought severity index (PDSI) and its self-calibrating version (sc_PDSI), and standardized precipitation evapotranspiration index (SPEI)[12–14]. However, most of these traditional indices are constructed on a monthly scale and may overlook short-term drought conditions within a month; therefore, adopting drought indices at shorter time scales can capture drought characteristics more accurately[15–16]. Heatwave events are usually identified according to the IPCC definition, by determining whether variables such as daily maximum or minimum temperature exceed a specified threshold for several consecutive days[17], and their intensity can also be quantified using accumulated temperature[18]. To identify compound events by combining the two, the commonly used method is to temporally overlay independently identified drought and heatwave events[19–20]. For example, the overlapping portion of a drought period defined by the 3-month-scale SPI and a heatwave period at the daily scale is regarded as a CDHE[21]. However, the scale discrepancy between this coarse drought index and the more refined heatwave index can bias analyses of the true onset and end times, duration, and severity of compound events. To address this issue, scholars have raised the analytical scale of drought events to weekly or even daily resolution[22–23], thereby reducing biases caused by scale inconsistency. In addition, most current studies remain limited to summer or the warm season[24–25], resulting in insufficient consideration of compound events on an annual scale.

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there remains a lack of systematic identification of such events[26]. Against this background, Shan et al.[26] proposed a daily-scale framework for identifying compound drought-heatwave events. Through a standardization approach, this framework unified the metrics for drought and heatwaves at the daily scale, overcoming the problem of scale mismatch. This method can not only effectively remove minor events and merge mutually dependent consecutive events, but also reveal the complex interaction patterns between droughts and heatwaves by constructing four different types of CDHEs.

Inner Mongolia lies in arid and semi-arid regions, has complex and diverse terrain, is relatively sensitive to climate change, and has a highly fragile ecological environment. Frequent droughts and heatwaves affect the livelihoods of local farmers and herders, and also threaten livestock production, the stability of grassland ecosystems, and food security in northern China. Year-round compound drought-heatwave events can also trigger anomalous climatic phenomena such as warm winters and winter-spring droughts, further aggravating ecosystem vulnerability and threats to agriculture and animal husbandry[27-29]. At present, studies of compound drought-heatwave events in Inner Mongolia mainly focus on identifying single types of events in summer or in the warm season[30-31], and lack analyses of multiple types of compound events under different seasonal dry-hot backgrounds[32]. Therefore, based on precipitation, daily maximum temperature, and daily minimum temperature data from global climate models in the Sixth Coupled Model Intercomparison Project (CMIP6), this study adopts the compound drought-heatwave event identification framework proposed by Shan et al.[26]. Using the standardized precipitation index (SPI) and standardized heatwave index (SHI), it constructs a technical system for identifying compound drought-heatwave events, and extracts the frequency, duration, and intensity characteristics of compound drought-heatwave events in Inner Mongolia during the historical period (1979-2014) and under the future (2015-2100) medium-forcing SSP2-4.5 and high-forcing SSP5-8.5 scenarios. It also analyzes the spatial distribution patterns and spatiotemporal evolution laws under different historical and future emission scenarios. The results of this study can provide a scientific basis for monitoring and early warning, risk assessment, and management of compound extreme events in Inner Mongolia.

1 Data and Methods

1.1 Overview of the study area

The Inner Mongolia Autonomous Region (97°12′-126°04′E, 37°24′-53°23′N) is located in the northern frontier region of China, with a total area of 1.18×10^6 km^2. The terrain is generally high in the west and low in the east (Fig. 1), with an average elevation of about 1,580 m and complex and diverse landforms. Inner Mongolia has a temperate continental climate and is strongly influenced by the East Asian monsoon. Its climatic characteristics include large temperature differences, low precipitation, and high variability. Winters are long, severely cold, and dry, under the control of the Siberian-Mongolian high. Summers are warm, with precipitation highly concentrated and transported mainly by the southeastern monsoon. The multi-year mean temperature shows a spatial pattern of increasing from northeast to southwest[33-34]. The region' s geomorphology includes multiple types such as plateaus, hills, mountains, and plains[35]. In terms of climatic regionalization, it spans the mid-temperate arid, semi-arid, semi-humid, and cold-temperate humid zones[36]. Internal climatic differences are significant; for example, the annual mean precipitation in Ulanqab is 150-450 mm, while annual evaporation reaches as high as 2,161-2,600 mm, representing a typical semi-arid climate[37]. In contrast, the annual precipitation in the irrigation area on the south bank of the Yellow River is only 281.7-301.8 mm, with more pronounced arid characteristics[38].

Fig. 1 Overview of the study area

1.2 Data sources

Daily-scale observed temperature and precipitation data for Inner Mongolia were obtained from the CN05.1 gridded observational dataset (Table 1). This dataset can be downloaded from the Climate Change Research Center, Chinese Academy of Sciences (https://ccrc.iap.ac.cn/resource/detail?id=228). The dataset has a daily temporal resolution and a spatial resolution of 0.25°$×0.25°.DataforInnerMongoliafrom1980to2014wereselectedforTaylordiagrammodelvalidation.Daily
sup > [39] < /sup >, acquiredfromtheNationalTibetanPlateau/ThirdPoleEnvironmentDataCenter(https :
//doi.org/10.11888/Atmos.tpdc.301122).ThisdatasetcoverstheSSP2–4.5andSSP5–8.5SharedSocioeconomic
resolution(0.25°×$0.25°) daily climate data for 1980–2100.

1.3 Research methods

1.3.1 Identification of compound drought-heatwave events

(1) Identification of daily drought and heatwave events. This paper uses the standardized precipitation index (SPI) and the standardized heatwave index (SHI) to characterize, respectively,

Table 1 Data sources

Tab. 1 Data source

<table>
<tr><th>Data type</th><th>Dataset name</th><th>Spatial resolution</th><th>Temporal scale</th><th>Time range</th></tr>
<tr><td>Observational data</td><td>CN05.1 gridded observational dataset</td><td>0.25°$×0.25°|Daily|1980–2014||CMIP6 model data|HiCPC dataset|0.25°×$0.25</td><td>Daily</td><td>1980–2100</td></tr>
</table>

drought and heatwaves [26]. In the calculation, for leap years, the precipitation and air-temperature values on February 29 and February 28 were uniformly averaged and then filled to February 28. SPI is based on accumulated precipitation over the preceding 90 d. Zero precipitation and positive precipitation are modeled separately: the probability of zero precipitation is calculated independently as the no-precipitation frequency for the same period in the historical record; for the positive-precipitation component, a cumulative distribution function is constructed by fitting an optimal distribution and is then transformed into an SPI value following the standard normal distribution [26]. SHI is based on the mean air temperature of the current day and the preceding 2 d. Using data for the same period over the past 30 a as a reference, the temperature distribution is fitted, quantiles are calculated, and the results are then transformed into standard normal values [26]. This paper selects −0.5 and 0.5 as the thresholds for drought events and heatwave events, respectively [40–41], and constrains the duration of a single event to within 120 d [26].

(2) Merging and elimination of drought and heatwave events. To achieve the following objectives: merging consecutive events whose durations are close based on a proximity threshold (example 1 in Fig. 2); eliminating minor events based on a duration threshold (example 2 in Fig. 2), this study uses objective thresholds for excluding minor periods and merging mutually dependent periods. The thresholds are determined on the basis that event severity must follow a generalized extreme-value distribution, while arrival intervals must follow an exponential distribution, thereby ensuring that events are both extreme and independent [26].

(3) Identification of compound drought–heatwave events (CDHEs). As shown in Table 2 and Fig. 2, CDHEs are divided into four types of events. Frequency refers to the number of occurrences of drought or heatwave events within a year (events $\cdot$ a^{-1}). Duration refers to the cumulative total number of days of compound drought–heatwave events occurring within a year, with units of $d \cdot a^{-1}$. Drought intensity is quantified by the cumulative negative SPI values on each day during the event period, while heatwave intensity is quantified by the cumulative positive SHI values on each day during the event period. Both drought intensity and heatwave intensity are dimensionless indicators.

Table 2 CDHEs event type definition

Event type	Definition
Intersection type (D-and-H)	Events in which drought and heatwave occur simultaneously
Union type (D-or-H)	Events in which at least one of drought or heatwave occurs, and the two overlap in time
Heatwave under drought conditions (D-cond-H)	Heatwave events that occur during the duration of a drought event
Drought under heatwave conditions (H-cond-D)	Drought events that occur during the duration of a heatwave event

1.3.2 Taylor diagram

A Taylor diagram is a two-dimensional statistical chart used to concisely evaluate model performance [42]. It is used to quantify the model's ability to simulate the spatial distribution of annual mean precipitation, annual mean daily maximum temperature, and daily minimum temperature data values [43–44]. The simulation results of six CMIP6 models for the historical period were compared with CN05.1 observational data. The model with the best performance in terms of spatial correlation, standard deviation, and root-mean-square error was selected as the basis for subsequent climate-scenario simulations. As shown in Fig. 3, the Taylor diagram provides a comprehensive evaluation based on three aspects: the highest correlation coefficient, a standard deviation close to the observed value, and the smallest root-mean-square error. For precipitation simulation, the mean values of the three types of indicators for all models were 0.363, 1.324, and 1.614, respectively. Among them, CanESM5 performed best, with a spatial correlation coefficient of 0.427, a standard deviation of 1.366, and a root-mean-square error of 1.531. For air-temperature simulation, the mean values of the three indicators for maximum temperature across all models were 0.935, 13.717, and 5.163, respectively. Among them, MPI-ESM1-2-HR performed best, with a spatial correlation coefficient of 0.937, a standard deviation of 13.727, and a root-mean-square error of 5.055. For minimum temperature, the mean values of the indicators for all models were

Figure annotations: threshold; time; SHI; SPI; identification of different event types; event type II: union type; event type I: intersection type; event type III: drought–heatwave type; event type IV: heatwave–drought type; first merge; second merge; example 1: merging; merging process; example 2: elimination; elimination process.

Fig. 2 CDHEs concept map

Fig. 3 Taylor charts of precipitation, maximum temperature, and minimum temperature

0.957, 13.827, and 4.113, respectively. Among them, MPI-ESM1-2-HR also performs best, with a spatial correlation coefficient of 0.962, a standard deviation of 13.890, and a root-mean-square error of 3.892. Therefore, CanESM5 is selected as the base model for precipitation scenario simulation, and MPI-ESM1-2-HR is selected as the base model for temperature scenario simulation.

1.3.3 Simple linear regression analysis

A simple linear regression method is used to analyze the spatial change trends of CDHEs characteristics:

$$slope = \frac{n \times \sum_{i=1}^{n}(i \times \mathrm{Var}_i) - \left(\sum_{i=1}^{n} i\right)\left(\sum_{i=1}^{n} \mathrm{Var}_i\right)}{n \times \left(\sum_{i=1}^{n} i^2\right) - \left(\sum_{i=1}^{n} i\right)^2}$$

where *slope* is the regression slope, representing the rate of change in CDHEs characteristics; n is the total number of years in the study period; i is the time sequence number; and Var_i is the CDHEs characteristic value corresponding to the i-th year. When $slope > 0$, the event characteristic shows an increasing trend; otherwise, it shows a decreasing trend. After obtaining the slope of the event characteristic, an F-test is further used to determine the significance level of the trend. At the 0.05 significance level, the trends are classified into two categories: significant and nonsignificant changes.

2 Results and Analysis

2.1 Characteristics of CDHEs in the historical period

2.1.1 Temporal evolution characteristics and trend analysis During the historical period, the indicators of the four types of CDHEs events in Inner Mongolia all show increasing trends (Fig. 4), but the rates of increase differ significantly among different event types. Among them, D-or-H and D-cond-H events increase faster than the other events, and among the four indicators, the heatwave intensity indicator increases most significantly, showing significant strengthening trends at rates of 0.6056 and 0.5228 per year, respectively. Although all indicators of D-and-H events show upward trends, they do not pass the significance test; the drought intensity of H-cond-D events even shows a non-significant decreasing trend. This indicates that, during the historical period, compound events dominated by drought have strengthened more rapidly than events dominated by heatwaves.

2.1.2 Spatial distribution pattern and trend analysis According to the annual mean maps of CDHEs in Inner Mongolia during the historical period (Fig. 5) and the significance test maps (Fig. 6), the high-frequency areas of CDHEs are mainly concentrated in the western and northern regions. Among them, D-and-H events and H-cond-D events can reach more than 2 occurrences $\cdot$ a^{-1}, and the occurrence frequency of all four types of events shows a significant increase in western Xilin Gol League and in parts of the northeastern region. The areas with significant increases in duration characteristics are similar to those for frequency, but the affected area is smaller than that for frequency, and the high-value areas are mainly concentrated in southern Hulunbuir City and surrounding areas. Among them, the duration of D-or-H and D-cond-H events can reach up to 110 $d \cdot a^{-1}$. The high-value areas of drought intensity and heatwave intensity are similar, mainly concentrated in southern Hulunbuir and the central-western region. The increasing trend in heatwave intensity is more significant; the areas with significant increases for D-or-H and D-cond-H events account for 18.29% and 16.37%, respectively. Overall, CDHEs in Inner Mongolia show significant increasing trends in the western and northern regions, with the strengthening of heatwave intensity being the most prominent. The areas with significant increases account for 16%–18% of the total area, indicating that compound drought–heatwave events occur more frequently in the above regions than in other regions.

2.2 Projection analysis of CDHEs in the future period (2015–2100)

2.2.1 Temporal evolution characteristics and trend projections Figures 7 and 8 reveal the future evolution characteristics of the four types of CDHEs in Inner Mongolia under the SSP2-4.5 and SSP5-8.5 emission scenarios. Under the SSP2-4.5 medium-emission scenario, the occurrence frequency and duration of D-or-H and D-cond-H events both show decreasing trends, whereas the frequency and duration of D-and-H and H-cond-D events do not show significant changes. In terms of intensity indicators, under the SSP2-4.5 scenario, changes in D-and-H and H-cond-D events are not significant, while the drought intensity of D-or-H and D-cond-H events shows a significant weakening trend and the heatwave intensity shows a significant strengthening trend. Under the SSP5-8.5 scenario, the change trends of the indicators for all types of events are basically consistent with those under the SSP2-4.5 scenario; among them, the heatwave intensity of D-or-H and D-cond-H events is 2.4% and 3.9% higher, respectively, than under the SSP2-4.5 scenario. These results indicate that future CDHEs in Inner Mongolia will be characterized by enhanced intensity of individual events.

2.2.2 Spatial distribution pattern and trend projections Figures 9 and 10 show the spatial distribution of CDHEs in Inner Mongolia under the SSP2-4.5 scenario.

Fig. 4. Temporal variation chart of CDHEs characteristics during the historical period (1980–2014)

Visible axis labels: Frequency /(events · a^{-1}); Duration /(d · a^{-1}); Drought intensity; Heatwave intensity; Year.

Visible panel labels and annotations:

- **(a) D-and-H**: *slope* = 0.0141, $P = 0.083$
- **(b) D-or-H**: *slope* = 0.007, $P = 0.058$
- **(c) D-cond-H**: *slope* = 0.0074, $P = 0.056$
- **(d) H-cond-D**: *slope* = 0.0137, $P = 0.084$
- **(e) D-and-H**: *slope* = 0.1818, $P = 0.117$
- **(f) D-or-H**: *slope* = 0.2111, $P = 0.655$
- **(g) D-cond-H**: *slope* = 0.1431, $P = 0.754$
- **(h) H-cond-D**: *slope* = 0.2462, $P = 0.072$
- **(i) D-and-H**: *slope* = −0.2242, $P = 0.119$
- **(j) D-or-H**: *slope* = −0.2548, $P = 0.669$
- **(k) D-cond-H**: *slope* = −0.2634, $P = 0.659$
- **(l) H-cond-D**: *slope* = −0.2141, $P = 0.136$
- **(m) D-and-H**: *slope* = 0.2239, $P = 0.135$
- **(n) D-or-H**: *slope* = 0.6056, $P = 0.01$
- **(o) D-cond-H**: *slope* = 0.5228, $P = 0.012$
- **(p) H-cond-D**: *slope* = 0.3032, $P = 0.09$

Visible map-panel labels and legends below Fig. 4:

- **(a) D-and-H**; north arrow **N**; Frequency /(events · a^{-1}); legend ticks: 0, 0.3, 0.5, 1, 2.2
- **(b) D-or-H**; north arrow **N**; Frequency /(events · a^{-1}); legend ticks: 0, 0.3, 0.5, 1, 1.5
- **(c) D-cond-H**; north arrow **N**; Frequency /(events · a^{-1}); legend ticks: 0, 0.3, 0.5, 1, 1.6

- **(d) H-cond-D**; north arrow **N**; Frequency /(events · a^{-1}); legend ticks: 0, 0.3, 0.5, 1, 2
- **(e) D-and-H**; north arrow **N**; Duration /(d · a^{-1}); legend ticks: 0, 5, 10, 15, 20
- **(f) D-or-H**; north arrow **N**; Duration /(d · a^{-1}); legend ticks: 0, 25, 45, 65, 110
- **(g) D-cond-H**; north arrow **N**; Duration /(d · a^{-1}); legend ticks: 0, 25, 45, 65, 110
- **(h) H-cond-D**; north arrow **N**; Duration /(d · a^{-1}); legend ticks: 0, 5, 10, 15, 27

(i) D-and-H –Drought intensity
Color scale: 0, −5, −10, −15, −20

(j) D-or-H –Drought intensity
Color scale: 0, −30, −50, −75, −105

(k) D-cond-H –Drought intensity
Color scale: 0, −30, −50, −75, −105

(l) H-cond-D –Drought intensity
Color scale: 0, −5, −10, −15, −22

(m) D-and-H –Heatwave intensity
Color scale: 0, 5, 10, 15, 25

(n) D-or-H –Heatwave intensity
Color scale: −10, 0, 10, 15, 29

(o) D-cond-H –Heatwave intensity
Color scale: −15, −10, 0, 10, 16

(p) H-cond-D –Heatwave intensity
Color scale: 0, 10, 15, 25, 37

Scale: 0–1000 km

Fig. 5 Spatial distribution of multi-year mean values of CDHEs characteristic indicators in Inner Mongolia from 1980 to 2014

Fig. 5 Spatial distribution map of multi-year mean values of CDHEs characteristic indicators in Inner Mongolia from 1980 to 2014

(a) D-and-H frequency

(b) D-or-H frequency

(c) D-cond-H frequency

(d) H-cond-D frequency

(e) D-and-H duration

(f) D-or-H duration

(g) D-cond-H duration

(h) H-cond-D duration

(i) D-and-H drought intensity

(j) D-or-H drought intensity

(k) D-cond-H drought intensity

(l) H-cond-D drought intensity

(m) D-and-H heatwave intensity

(n) D-or-H heatwave intensity

(o) D-cond-H heatwave intensity

(p) H-cond-D heatwave intensity

Scale: 0–1000 km

Legend: significant increase; nonsignificant increase; nonsignificant decrease; significant decrease

Fig. 6 Spatial distribution of changing trends and significance tests of CDHEs characteristic indicators in Inner Mongolia from 1980 to 2014

Fig. 6 Spatial distribution map of the changing trends and significance tests of CDHEs characteristic indicators in Inner Mongolia from 1980 to 2014

Fig. 7 Temporal variation of CDHEs characteristics under the SSP2-4.5 scenario during the future period (2015-2100) in Inner Mongolia

Visible panel annotations:

- Frequency / (times $\cdot$ a^{-1})
  - (a) D-and-H: $slope = -0.0002$, $P = 0.907$
  - (b) D-or-H: $slope = -0.0016$, $P = 0.083$
  - (c) D-cond-H: $slope = -0.0016$, $P = 0.065$
  - (d) H-cond-D: $slope = -0.0001$, $P = 0.957$
- Duration / (d $\cdot$ a^{-1})
  - (e) D-and-H: $slope = -0.0039$, $P = 0.849$
  - (f) D-or-H: $slope = -0.445$, $P = 0.001$
  - (g) D-cond-H: $slope = -0.4537$, $P = 0.001$
  - (h) H-cond-D: $slope = 0.0042$, $P = 0.857$
- Drought intensity
  - (i) D-and-H: $slope = 0.0122$, $P = 0.645$
  - (j) D-or-H: $slope = 0.5096$, $P = 0.003$
  - (k) D-cond-H: $slope = 0.5103$, $P = 0.003$
  - (l) H-cond-D: $slope = 0.0118$, $P = 0.66$
- Heatwave intensity
  - (m) D-and-H: $slope = -0.0034$, $P = 0.902$
  - (n) D-or-H: $slope = 0.1847$, $P = 0$

  - (o) D-cond-H: $slope = 0.1742$, $P = 0$
  - (p) H-cond-D: $slope = 0.0067$, $P = 0.835$

Visible panels of the following figure:

- Frequency / (times $\cdot\ a^{-1}$)
  - (a) D-and-H: $slope = 0.0008$, $P = 0.605$
  - (b) D-or-H: $slope = -0.0012$, $P = 0.185$
  - (c) D-cond-H: $slope = -0.0013$, $P = 0.176$
  - (d) H-cond-D: $slope = 0.0009$, $P = 0.584$
- Duration / (d $\cdot\ a^{-1}$)
  - (e) D-and-H: $slope = 0.0222$, $P = 0.425$
  - (f) D-or-H: $slope = -0.3894$, $P = 0.007$
  - (g) D-cond-H: $slope = -0.4089$, $P = 0.003$
  - (h) H-cond-D: $slope = 0.0412$, $P = 0.22$

(i) D-and-H
Drought intensity; $slope = -0.0273$, $P = 0.411$; Year: 2020, 2060, 2100.

(j) D-or-H
Drought intensity; $slope = 0.4084$, $P = 0.012$; Year: 2020, 2060, 2100.

(k) D-cond-H
Drought intensity; $slope = 0.4068$, $P = 0.012$; Year: 2020, 2060, 2100.

(l) H-cond-D
Drought intensity; $slope = -0.0258$, $P = 0.448$; Year: 2020, 2060, 2100.

(m) D-and-H
Heatwave intensity; $slope = 0.0294$, $P = 0.442$; Year: 2020, 2060, 2100.

(n) D-or-H
Heatwave intensity; $slope = 0.2234$, $P = 0.003$; Year: 2020, 2060, 2100.

(o) D-cond-H
Heatwave intensity; $slope = 0.1981$, $P = 0.003$; Year: 2020, 2060, 2100.

(p) H-cond-D
Heatwave intensity; $slope = 0.0539$, $P = 0.24$; Year: 2020, 2060, 2100.

Fig. 8 Temporal variation of CDHE characteristics under the SSP5–8.5 scenario in the future period (2015–2100)

Fig. 8 Temporal variation graph of CDHEs characteristics under the SSP5–8.5 scenario in the future period (2015–2100)

(a) D-and-H
N; Frequency /(times $\cdot\ a^{-1}$): 0, 0.3, 0.5, 1, 3.5.

(b) D-or-H
N; Frequency /(times $\cdot\ a^{-1}$): 0, 0.3, 0.5, 0.8, 1.0.

(c) D-cond-H
N; Frequency /(times · a^{-1}): 0, 0.3, 0.5, 0.8, 1.0.

(d) H-cond-D
N; Frequency /(times · a^{-1}): 0, 0.3, 0.5, 1.0, 3.5.

(e) D-and-H
N; Duration /($d \cdot a^{-1}$): 0, 5, 8, 10, 15.

(f) D-or-H
N; Duration /($d \cdot a^{-1}$): 5, 25, 45, 55, 85.

(g) D-cond-H
N; Duration /($d \cdot a^{-1}$): 5, 25, 45, 55, 85.

(h) H-cond-D
N; Duration /($d \cdot a^{-1}$): 0, 5, 10, 15, 17.

(i) D-and-H
N; Drought intensity: 0, −3, −5, −10, −13.

(j) D-or-H
N; Drought intensity: −5, −25, −40, −55, −75.

(k) D-cond-H
N; Drought intensity: −5, −25, −40, −55, −75.

(l) H-cond-D
N; Drought intensity: 0, −5, −10, −15, −19.

(m) D-and-H
N; Heatwave intensity: 0, 5, 10, 15, 17.
Scale: 0–1000 km.

(n) D-or-H
N; Heatwave intensity: −5, 0, 10, 15, 25.

(o) D-cond-H
N; Heatwave intensity: −5, 0, 5, 10, 15.

(p) H-cond-D
N; Heatwave intensity: 0, 5, 10, 15, 25.

Fig. 9 Spatial distribution of the multi-year mean values of CDHE characteristic indicators under the SSP2–4.5 scenario in the future period (2015–2100)

Fig. 9 Spatial distribution map of multi-year mean values of characteristic indicators of SSP2–4.5 CDHEs in the future period (2015–2100)

Fig. 10. Trends and significance tests of CDHEs characteristics under the SSP2–4.5 scenario in the future period (2015–2100)

Subpanels:
(a) D-and-H frequency; (b) D-or-H frequency; (c) D-cond-H frequency; (d)

H-cond-D frequency;
(e) D-and-H duration; (f) D-or-H duration; (g) D-cond-H duration; (h) H-cond-D duration;
(i) D-and-H drought intensity; (j) D-or-H drought intensity; (k) D-cond-H drought intensity; (l) H-cond-D drought intensity;
(m) D-and-H heatwave intensity; (n) D-or-H heatwave intensity; (o) D-cond-H heatwave intensity; (p) H-cond-D heatwave intensity.

Legend: significant increase; nonsignificant increase; nonsignificant decrease; significant decrease.
Scale: 0–1000 km.

Regarding changes in the spatial pattern, the frequency and duration of the four types of events show nonsignificant changes over most areas ($P > 0.05$). High-value areas are mainly distributed in the central-western region, such as southwestern Alxa League and southern Ulanqab City, while areas with a significant increasing trend are mainly located in southern Hulunbuir City. The high-value areas of the drought-intensity indicators for the four types of events are generally concentrated in the eastern and southern parts. Among them, the proportions of areas with significantly enhanced drought intensity for D-and-H and H-cond-D events are 1.13% and 1.18%, respectively, whereas for D-or-H and D-cond-H events the proportion of areas with significantly enhanced drought intensity is 27.61%, with a continuous spatial distribution. The increasing trend in heatwave intensity is more pronounced: the proportions of areas with significant enhancement for D-or-H and D-cond-H events are 35.45% and 35.65%, respectively, covering eastern Inner Mongolia. These results indicate that, under the SSP2–4.5 scenario, the spatial pattern of CDHEs in Inner Mongolia exhibits east–west differences: the eastern region is characterized by a significant increase in heatwave intensity, whereas the central-western region shows a significant increase in the frequency of the four types of events.

Under the high-emissions SSP5–8.5 scenario, CDHEs characteristics will be further intensified (Figs. 11 and 12). D-and-H and H-cond-D events exhibit lower frequencies (0.3–1.0 events $\cdot$ a^{-1}) and shorter durations (5–30 d), with 4.37%–5.79% of the area showing significant increasing trends, mainly concentrated in the central-western and eastern regions. In contrast, D-or-H and D-cond-H events exhibit higher occurrence frequencies (0.6–1.0 events $\cdot$ a^{-1}) and longer durations (25–104 d), with significantly increasing areas mainly concentrated in western Alxa League. For D-and-H and H-cond-D events, the drought-intensity and heatwave-intensity indicators show significant strengthening trends only in small areas of western Alxa League. D-cond-H and D-or-H events show significant strengthening trends in drought intensity over about 20% of the area, while heatwave intensity increases significantly over 27.97% and 29.69% of the area, respectively. These results indicate that, under the SSP5–8.5 scenario, the same indicators for different types of CDHEs in Inner Mongolia exhibit differential changes. Among the four indicators, the differences in heatwave intensity are significant, leading to significant enhancement of D-cond-H and D-or-H events.

(a) D-and-H
Frequency/(events · a^{-1}): 0, 0.3, 0.5, 1.0, 5.3

(b) D-or-H
Frequency/(events · a^{-1}): 0, 0.2, 0.4, 0.6, 1.0

(c) D-cond-H
Frequency/(events · a^{-1}): 0, 0.2, 0.4, 0.6, 1.0

(d) H-cond-D
Frequency/(events · a^{-1}): 0, 0.3, 0.5, 1.0, 5.3

(e) D-and-H
Duration/(d · a^{-1}): 0, 5, 10, 15, 30

(f) D-or-H
Duration/(d · a^{-1}): 5, 25, 35, 55, 104

(g) D-cond-H
Duration/(d · a^{-1}): 5, 25, 35, 55, 102

(h) H-cond-D
Duration/(d · a^{-1}): 0, 5, 10, 15, 30

(i) D-and-H
Drought intensity: 0, −5, −10, −15, −26

(j) D-or-H
Drought intensity: −10, −25, −40, −55, −77

(k) D-cond-H
Drought intensity: −10, −25, −40, −55, −78

(l) H-cond-D
Drought intensity: 0, −5, −10, −15, −26

(m) D-and-H
Heatwave intensity: 0, 5, 10, 15, 34

(n) D-or-H
Heatwave intensity: −5, 0, 5, 10, 30

(o) D-cond-H
Heatwave intensity: −5, 0, 5, 10, 20

(p) H-cond-D
Heatwave intensity: 0, 5, 10, 15, 35

Scale: 0–1000 km

Fig. 11 Spatial distribution map of multi-year mean values of CDHEs characteristic indicators under the SSP5–8.5 scenario in the future period (2015–2100)

Fig. 11 Spatial distribution map of multi-year mean values of CDHEs characteristic indicators under the SSP5-8.5 scenario in the future period (2015–2100)

(a) D-and-H frequency

(b) D-or-H frequency

(c) D-cond-H frequency

(d) H-cond-D frequency

(e) D-and-H duration

(f) D-or-H duration

(g) D-cond-H duration

(h) H-cond-D duration

Figure 12 (continued; visible panels)

- (i) D-and-H drought intensity
- (j) D-or-H drought intensity
- (k) D-cond-H drought intensity
- (l) H-cond-D drought intensity
- (m) D-and-H heatwave intensity
- (n) D-or-H heatwave intensity
- (o) D-cond-H heatwave intensity
- (p) H-cond-D heatwave intensity

Scale: 0–1000 km

Legend: significant increase; non-significant increase; non-significant decrease; significant decrease.

Fig. 12 Trend and significance test maps of CDHEs characteristics under the SSP5-8.5 scenario in the future period (2015–2100)

2.3 Comparative analysis of different event types

In Inner Mongolia during 1980–2100, the frequency and duration of the four types of events all show decreasing trends, whereas drought intensity and heatwave intensity show increasing trends (Fig. 13). Among the four types of events, D-or-H and D-cond-H intensify significantly. The growth rate of drought intensity is 1.83–4.46 times higher than that of heatwave intensity; however, under the SSP5-8.5 scenario, the increase in heatwave-intensity indicators is more pronounced than under the SSP2-4.5 scenario, with the growth rate being about 21% higher. Compared with the medium-emission scenario SSP2-4.5, the high-emission scenario exhibits more extreme intensity characteristics, indicating that the intensity-characteristic indicators of compound drought–heatwave events will be strengthened under high-emission conditions.

Figure 14 shows the proportion of significant-area coverage for each CDHEs indicator under different emission scenarios during 1980–2100; under the SSP5-8.5 scenario

Figure 13 (visible panels)

- (a) D-and-H
  Frequency (events $\cdot\, a^{-1}$); Year; Historical / Future
  HIS-SSP2-4.5: $slope = -0.0029,\ P = 0.0052$
  HIS-SSP5-8.5: $slope = -0.0026,\ P = 0.0210$
- (b) D-or-H
  Frequency (events $\cdot\, a^{-1}$); Year; Historical / Future
  HIS-SSP2-4.5: $slope = -0.0022,\ P = 0.0001$
  HIS-SSP5-8.5: $slope = -0.0023,\ P = 0.0001$
- (c) D-cond-H
  Frequency (events $\cdot\, a^{-1}$); Year; Historical / Future
  HIS-SSP2-4.5: $slope = -0.0024,\ P = 0.0001$
  HIS-SSP5-8.5: $slope = -0.0024,\ P = 0.0001$
- (d) H-cond-D
  Frequency (events $\cdot\, a^{-1}$); Year; Historical / Future
  HIS-SSP2-4.5: $slope = -0.0027,\ P = 0.0078$
  HIS-SSP5-8.5: $slope = -0.0025,\ P = 0.0257$
- (e) D-and-H
  Duration ($d \cdot a^{-1}$); Year; Historical / Future
  HIS-SSP2-4.5: $slope = -0.0194,\ P = 0.1738$
  HIS-SSP5-8.5: $slope = -0.0036,\ P = 0.8321$
- (f) D-or-H
  Duration ($d \cdot a^{-1}$); Year; Historical / Future
  HIS-SSP2-4.5: $slope = -0.2635,\ P = 0.0009$
  HIS-SSP5-8.5: $slope = -0.2326,\ P = 0.0049$

- (g) D-cond-H
  Duration ($d \cdot a^{-1}$); Year; Historical / Future
  HIS-SSP2-4.5: $slope = -0.2599$, $P = 0.0008$
  HIS-SSP5-8.5: $slope = -0.2378$, $P = 0.0031$
- (h) H-cond-D
  Duration ($d \cdot a^{-1}$); Year; Historical / Future
  HIS-SSP2-4.5: $slope = -0.0223$, $P = 0.1832$
  HIS-SSP5-8.5: $slope = 0.0022$, $P = 0.9146$
- (i) D-and-H
  Drought intensity; Year; Historical / Future
  HIS-SSP2-4.5: $slope = 0.0231$, $P = 0.2015$
  HIS-SSP5-8.5: $slope = 0.0056$, $P = 0.7870$
- (j) D-or-H
  Drought intensity; Year; Historical / Future
  HIS-SSP2-4.5: $slope = 0.3016$, $P = 0.0025$
  HIS-SSP5-8.5: $slope = 0.2914$, $P = 0.0024$

Visible panels of Fig. 13

- **(k) D-cond-H**
  Y-axis: drought intensity; X-axis: year. Boundary labels: historical / future.
  Legend: HIS-SSP2-4.5: $slope = 0.3021$, $P = 0.0024$; HIS-SSP5-8.5: $slope = 0.2907$, $P = 0.0023$.
- **(l) H-cond-D**
  Y-axis: drought intensity; X-axis: year. Boundary labels: historical / future.
  Legend: HIS-SSP2-4.5: $slope = 0.0224$, $P = 0.2163$; HIS-SSP5-8.5: $slope = 0.0057$, $P = 0.7839$.
- **(m) D-and-H**
  Y-axis: heatwave intensity; X-axis: year. Boundary labels: historical / future.
  Legend: HIS-SSP2-4.5: $slope = 0.0208$, $P = 0.2684$; HIS-SSP5-8.5: $slope = 0.0003$, $P = 0.9891$.
- **(n) D-or-H**
  Y-axis: heatwave intensity; X-axis: year. Boundary labels: historical / future.
  Legend: HIS-SSP2-4.5: $slope = 0.0724$, $P = 0.0251$; HIS-SSP5-8.5: $slope = 0.1426$, $P = 0.0008$.
- **(o) D-cond-H**
  Y-axis: heatwave intensity; X-axis: year. Boundary labels: historical / future.

Legend: HIS-SSP2-4.5: $slope = 0.0765$, $P = 0.0092$; HIS-SSP5-8.5: $slope = 0.1350$, $P = 0.0004$.

- **(p) H-cond-D**
  Y-axis: heatwave intensity; X-axis: year. Boundary labels: historical / future.
  Legend: HIS-SSP2-4.5: $slope = -0.0246$, $P = 0.2694$; HIS-SSP5-8.5: $slope = 0.0078$, $P = 0.7773$.

Fig. 13 Temporal variations in CDHE characteristics under different scenarios from 1980 to 2100

Visible text in Fig. 14

Legend: significant increase; non-significant increase; non-significant decrease; significant decrease.

Columns: D-and-H; D-or-H; D-cond-H; H-cond-D.

Rows: frequency; duration; drought intensity; heatwave intensity.

Y-axis: area proportion / %.
X-axis categories: historical period; SSP2-4.5; SSP5-8.5.

Fig. 14 Changes in the proportion of significant CDHE regions from 1980 to 2100

scenario, compared with the SSP2-4.5 scenario, the affected area of CDHEs will expand. For the four types of CDHEs, the area with a significant increase in frequency indicators expands by 2.6–3.2 times, and the area with a significant increase in duration indicators expands by 3.1–5.4 times. Among the intensity indicators, D-or-H and D-cond-H events account for the largest proportions of areas with significant increases, averaging 27.61% under the SSP2-4.5 scenario; under the SSP5-8.5 scenario, the corresponding area proportion is projected to decrease by about 7.2%. These results indicate that, under a high-emissions scenario, the affected range of CDHE intensity indicators will further expand.

3 Discussion

The overall strengthening trend of CDHEs in Inner Mongolia revealed in this study is consistent with the global trend reported by Mukherjee et al. [22]. In this study, D-or-H and D-cond-H events have longer durations and higher intensities than other events, which is consistent with the results of Shan et al. [26], and can be attributed to the fact that the length of heatwaves limits the duration of compound events under heatwave conditions. In addition, the finding that heatwaves are the dominant factor in CDHEs is consistent with the result of Shan et al. [26] that the increase in CDHE events is mainly attributable to the increase in heatwave events. The significant increase in heatwave intensity during different periods for D-or-H and D-cond-H events further corroborates this view. This feedback may be nonlinear: that is, the amplifying effect of drought on heatwaves is not a simple superposition, but instead exhibits an intensifying tendency [45]. The results show that, under the SSP2-4.5 scenario, CDHEs in Inner Mongolia generally exhibit shorter duration, greater intensity, and a further expansion of their affected area compared with the historical period; under the high-emissions SSP5-8.5 scenario, the changing trend is further strengthened relative to SSP2-4.5. This is consistent with the view in the IPCC report that higher temperatures not only directly raise the intensity of heatwaves, but also, together with enhanced land-atmosphere feedbacks and more persistent atmospheric circulation anomalies, lead to a disproportionate increase in the intensity of compound extreme events [46].

This study uses a combination of SPI and SHI indices to provide a standardized quantitative framework for identifying four types of compound events. However, the sensitivity of the results to threshold selection for different types of drought-heatwave events still requires further investigation [20,26]. In terms of the ability of the CMIP6 model ensemble to simulate the four types of compound drought-heatwave events, inter-model inconsistencies and systematic biases remain key factors affecting the reliability of projections. Therefore, future research should further strengthen analyses of the relationships between the four types of compound drought-heatwave events and their impacts on key sectors such as agriculture, water resources, and ecosystems, and should more deeply reveal the physical causes and mutual transformation mechanisms of different types of compound drought-heatwave events.

4 Conclusions

Based on CN05.1 gridded observational data and CMIP6 global model data, this paper identifies CDHEs using the SPI and SHI indices and analyzes the spatiotemporal characteristics of extreme climate change in Inner Mongolia during 1980-2100. The main conclusions are as follows:

(1) During the historical period, all indicators of the four types of compound events show strengthening trends. Among them, D-or-H and D-cond-H events have higher growth rates and annual mean values than D-and-H and H-cond-D events. Spatially, significant increasing trends occur in the western and northern regions.

(2) Under the SSP2-4.5 scenario, CDHEs in Inner Mongolia generally exhibit shorter duration, higher intensity, and a further expansion of their affected area compared with the historical period. Under the high-emissions SSP5-8.5 scenario, the changing trend is further strengthened relative to SSP2-4.5. Among them, D-or-H and D-cond-H events change more significantly than the other events.

(3) The significant enhancement of heatwave intensity indicators for the four types of events in different periods indicates that heatwave factors are the dominant factor in CDHE changes in Inner Mongolia.

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Characteristics of compound drought and heatwave events in Inner Mongolia from 1980 to 2100

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Abstract: Under global warming, extreme climate events are occurring with increasing frequency. Among these, compound drought and heatwave events (CDHEs) pose a severe threat to both the ecosystem and socioeconomic stability of Inner Mongolia. This study utilizes the CN05.1 gridded observational dataset and Coupled Model Intercomparison Project Phase 6 (CMIP6) global climate model data under medium (SSP2-4.5) and high (SSP5-8.5) emission scenarios to identify four types of CDHEs in Inner Mongolia from 1980 to 2100 using the daily-scale Standardized Precipitation Index and Standardized Heatwave Index (SHI). Their spatiotemporal characteristics are analyzed via ordinary linear regression. The results indicate that during the historical period, all metrics of the four CDHEs types showed significant increasing trends in the western and northern regions. Among these, the union type (D-or-H) and drought-conditioned heatwave type (D-cond-H) exhibited higher metric values and growth rates than the intersection type (D-and-H) and heatwave-conditioned drought type (H-cond-D). Under the SSP2-4.5 scenario, CDHEs generally feature shorter duration yet higher intensity than in the historical period, accompanied by a further expansion of the affected area. These characteristics are further intensified under the SSP5-8.5 scenario. Across all periods, the heatwave intensity of the four CDHEs types increased significantly, indicating that high-temperature heatwaves are the dominant factor driving changes in CDHEs. These findings provide a scientific basis for regional climate risk assessment and the development of adaptation strategies.

Keywords: standardized precipitation index; standardized heatwave index; compound drought and heatwave events; CMIP6; Inner Mongolia

Note: Figure translations are in progress. See original paper for figures.