We thank the editor and reviewer for the helpful comments. We have taken all of these into account and have also made some minor changes of our own. The responses (highlight in blue) and modifications (highlight in red) are outlined below.

Referee #1:

- Powerful machine learning approaches were applied. What were the degrees of freedom of the machine learning approaches? What is the ratio of the degrees of freedom over the rather small number of 81 meteorological drought events?

RESPONSE: It seems these two problems were posed in order to investigate whether more degrees of freedom would cause the model to overfit the training data. In general, Regularization techniques and optimal model architectures are employed to ensure machine learning models are not overfitted and maintain low generalization errors. Therefore, degrees of freedom and model complexity always correspond very poorly (Janson et al., 2013), which is generally much less than the number of parameters in the model (Gao and Jojic, 2016). In this study, we used a Python package called PyCaret to construct these classifiers. L2 regularization method was selected in each model to avoid overfitting and maintain high calculation efficiency. The relevant description will be added to Section 2.4.3 in **Line 207-Line 214 in the Track-change files**.

MODIFICATION: In this study, each binary classifier was constructed using a Python package called PyCaret, which wraps several machine-learning libraries, including scikit-learn, XGBoost, LightGBM, CatBoost, spaCy, Optuna, and Hyperopt (Ali, 2020). The tune_model() function in the PyCaret package offers simple selection of optimal hyperparameters of each model. A 5-fold cross-validation was used to train and validate the classifiers in each model by setting "fold=5" in the create_model() function. In using the compare_models() function, the classifier with the highest summation of accuracy, precision, recall, F1 score, and Matthews correlation coefficient was selected as the

optimal model. To avoid overfitting and maintain high calculation efficiency, the L2 regularization method was selected for each model by setting the parameter "penalty='l2'".

- According to Fig. 7 propagation probability is nearly exclusively determined by the severity of the meteorological drought which would meet common expectations. In contrast, any effect of duration or area is hardly discernible. Please compare the performance of the machine learning approaches to that of a multivariate linear regression

RESPONSE 1: We agree and can see your point. In this study, machine learning models were used to determine whether a meteorological drought event has propagating potential. It is therefore a binary classification question. We have added Figure 9 and a description related to it in **Line 300-301 in the Track-changed file**.

MODIFICATION 1:

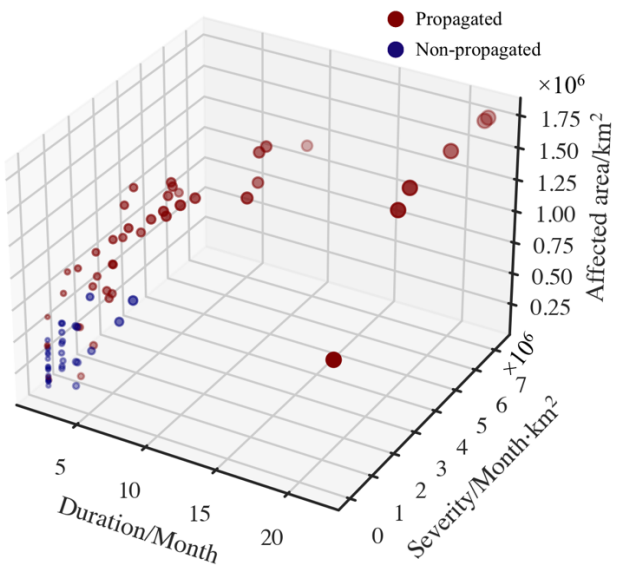

Figure 9 Three-dimensional diagram showing characteristics of meteorological drought events. Larger circles indicate greater severity.

As can be seen in Figure 9, propagated meteorological droughts have greater severity, larger affected area, and longer duration than non-propagated droughts.

RESPONSE 2: We agree that any effect of duration or area is hardly discernible. In this study, meteorological drought and ecological drought with genetic relationship were

extracted on the basis of a certain spatio-temporal matching rule. Therefore, the model constructed in this study only includes meteorological drought and ecological drought events that have genetic relationships. As a result, only 103 out of 184 ecological drought events were induced by 81 out of 108 meteorological drought events. The severity of ecological drought thus can be predicted based on the characteristics of meteorological drought. We have added the relevant description below in **Line 344-348 in the Track-changed file**.

MODIFICATION 2: Using this method, two types of drought events without spatial connection would be excluded (only 103 out of 184 ecological drought events were induced by 81 out of 108 meteorological drought events), and more drought characteristics, such as affected area and migration path could be extracted. This addresses the limited applicability of the traditional method to regions with large spatial extent, and provides more reliable information for quantifying relationship between characteristics of meteorological drought and ecological drought.

RESPONSE 3: We have included your recommendation and added multivariable linear regression in **Line 328-Line 335** in the **Track-changed file**.

MODIFICATION 3: For comparison, ternary linear and ternary quadratic models were constructed based on 46 pairs of meteorological-ecological drought events (Table 8). The comparisons were made in terms of three independent variables, M_DS, M_DD, and M_DA, and one dependent variable, E_DS. As shown in Table 8, the R^2 of the ternary quadratic model was evidently higher than that of the ternary linear model, whereas the RMSE, AIC, and BIC were lower. This illustrates that M_DS, M_DD, M_DA, and E_DS follow a nonlinear relationship, and that the ternary quadratic model is more suitable for simulating their relationship. According to the ternary quadratic model, E_DS equals 1.4×10^6 month·km^2 when M_DA > 17.6×10^5 km^2 ∩ M_DD > 11.8 month ∩ M_DS > 7.5×10^6 month·km^2. These values correspond to the thresholds of moderate (1.7×10^6 month·km^2), severe (2.4×10^6 month·km^2), and extreme (4.6×10^6 month·km^2) ecological

drought.

Table 8 Modelling E_DS with polynomial functions based on meteorological drought characteristics

Model types	Expression	Assessment metrics			
		RMSE	AIC	BIC	R^2
Ternary linear model	$E\_DS=4.85\times10^5+0.15M\_DS+4099.35M\_DD-1.20M\_DA$	9.24×10^5	1350.67	1357.89	0.58
Ternary quadratic model	$E\_DS=1.54-0.05M\_DS-16.91M\_DD-0.08M\_DA-1319.23M\_DD^2+0.03M\_DD\times M\_DA$	7.29×10^5	1085.75	1100.20	0.85

- Please check the use of definite and indefinite articles and the use of plural “s”.

RESPONSE: Thanks for the hint. We have checked them carefully to avoid grammar errors in the revised version and marked them with red color.

Details:

- 53-55: Who is “they”?

RESPONSE: Thanks for the hint. The sentence "In other words, they considered temporal connection of two drought types and ignored their spatial overlap, which may result in the miscalculation of drought propagation in regions with large spatial extent." has been changed to " In other words, the temporal connection between two drought types is only considered in the traditional statistical methods, but their spatial overlap is ignored, which may result in the miscalculation of drought propagation in regions with large spatial extent." **in Line 53-Line 56 in the Track-changed file.**

- 73-79: Section “2 Study area” comprises only 6 lines and should be merged with the subsequent section 3, or at least with section “3.1 Datasets”.

RESPONSE: We agree. Section 2 has been changed to Section 2.1 in the **Track-changed file.**

- 82-85: Verb is missing.

RESPONSE: Thanks for the hint. The sentence " Monthly meteorological data, including surface reflectance, temperature, relative humidity, atmospheric pressure, downward

shortwave radiation, wind speed, and longwave radiation, obtained from the ERA5-land reanalysis dataset (https://cds.climate.copernicus.eu) issued by European Centre for Medium-Range Weather Forecasts (ECWMF), which has a spatial resolution of $0.1^{\circ} \times 0.1^{\circ}$ and covers the period of 1981–2021" has been changed to " Monthly meteorological data, including surface reflectance, temperature, relative humidity, atmospheric pressure, downward shortwave radiation, wind speed, and longwave radiation, was obtained from the ERA5-land reanalysis dataset (https://cds.climate.copernicus.eu) issued by European Centre for Medium-Range Weather Forecasts (ECWMF), which has a spatial resolution of $0.1^{\circ} \times 0.1^{\circ}$ and covers the period of 1981–2021." in **Line 93-Line 96 in the Track-changed file.**

- 91: Use lowercase letter in “Root”.

RESPONSE: Thanks for the hint. We have corrected it to "root" in **Line 102 in the Track-changed file**.

- 98: Replace “deep phreatic buried depth” by “great depth to groundwater”.

RESPONSE: Thanks for the hint. We have corrected it to " great depth to groundwater " in **Line 109 in the Track-changed file.**

- 112: Both “SEWDI” and “SEBS” need to be explained in a concise way. Referring to the Jiang et al. (2021) paper does not suffice.

RESPONSE: Thank you for the suggestion. We have explained it in **Line 124-Line 130** in the **Track-changed file**.

MODIFICATION: SEWDI follows a similar procedure as SPI, which includes the calculation of ecological water deficit (EWD), the selection of an optimal distribution for fitting monthly EWD series, and the inverse normal transformation of the cumulative density distribution of EWD. EWD is the difference between ecological water requirement (EWR) and ecological water consumption (EWC) (Chi et al., 2018; Jiang et al., 2021). Among them, EWR was calculated using the single crop coefficient method recommended by the Food and Agriculture Organization (FAO). EWC equals the actual evapotranspiration, which is

derived from latent heat fluxes calculated by the surface energy balance system (SEBS) algorithm.

- 124: Should be “three steps”, not “two steps”.

RESPONSE: Thanks for the hint. We have corrected it to " three steps " in **Line 142 in the Track-changed file**.

- 147: Delete “to”.

RESPONSE: Thanks for the hint. We have deleted "to".

- 200: Do you mean “Johnson S_B distribution”?

RESPONSE: Thanks for the hint. We have corrected "johnsonsb" to "Johnson S_B" in the full text.

- 224: What does “DS” mean?

RESPONSE: DS represents drought severity. We have changed the name to its full form.

- 265: Please explain “itau method”.

RESPONSE: We have added " The Copula estimation can be eased by the itau method, which inverts Kendall's tau method (Demarta and McNeil, 2005)." in **Line 312-Line 313 in the Track-changed file** for explaining "itau method".

- 280-297: Section 5.1 should be either part of the methods or of the results section.

RESPONSE: Thanks for your suggestion, we have moved Section 5.1 to the results section (Section 3.1) **in the Track-changed file**.

- 349-352: Verb is missing.

RESPONSE: Thanks for the hint. The verb has been added to this sentence in **Line 93-96 in the Track-changed file**.

MODIFICATION: Monthly meteorological data, including surface reflectance, temperature, relative humidity, atmospheric pressure, downward shortwave radiation, wind speed, and longwave radiation, was obtained from the ERA5-land reanalysis dataset (https://cds.climate.copernicus.eu) issued by European Centre for Medium-Range Weather Forecasts (ECWMF), which has a spatial resolution of $0.1^{\circ} \times 0.1^{\circ}$ and covers the

period of 1981–2021.

- Figure 3: I guess that the drought event numbers reflect chronological order, is that right? The colour scale indicates about the same meteorological-ecological drought event number for very different ecological and meteorological drought event numbers. E.g., green symbols show up for ecological drought event number 1-10, 30-50 and >150. How can that be? Is there something wrong with the colour coding of the symbols?

RESPONSE: You are right, we have corrected this mistake. Figure 3 has been replaced with the figure below in Figure 4 **in the Track-changed file**.

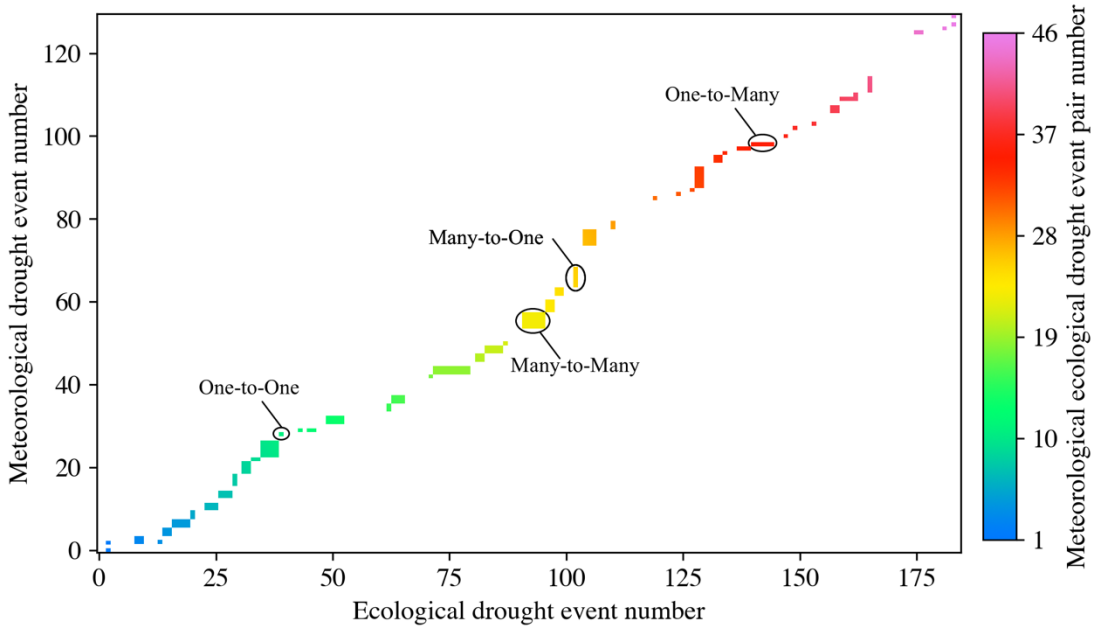

Figure 4: Identification results of paired meteorological and ecological drought events

- Figure 7: In the figure caption correct “exceeding” to “exceed”.

RESPONSE: Thanks for the hint. We have corrected “exceeding” to “exceed”.

References:

Ali, M.: PyCaret, PyCaret: An open source, low-code machine learning library in Python, 2020.

Demarta, S. and McNeil, A. J.: The t Copula and Related Copulas, International Statistical Review / Revue Internationale de Statistique, 73, 111–129, 2005.

Gao, T. and Jojic, V.: Degrees of Freedom in Deep Neural Networks, https://doi.org/10.48550/arXiv.1603.09260, 2016.

Janson, L., Fithian, W., and Hastie, T.: Effective Degrees of Freedom: A Flawed Metaphor, https://doi.org/10.1093/biomet/asv019, 2013.

Referee #2:

First of all, thank you very much for the helpful comments and your kind feedback, your comments are listed below, along with our responses to each one.

- Some works, e.g., the systematic literature review of propagation probability model, need to be added into the Introduction or Discussion sections.

RESPONSE: Thanks for your advice. The purpose of this section is to introduce the use of Bayesian model to explore probabilistic relationships among different types. We have rewritten this section based on your advice. You can find it in **Line 58-Line 75 in the Track-changed file**.

MODIFICATION: The probability information of one type of successive drought events is contained in another type of associated drought (Wu et al., 2021). Therefore, a number of studies have attempted to assess the propagation relationships between the two drought types based on the probabilistic method. A Bayesian network is a probabilistic model that acquires probabilistic inferences over interacting variables of interest based on a graphical structure. Therefore, this method has been proven to be suitable for quantifying the probability relationship between different drought types (Ayantobo et al., 2018; Chang et al., 2016; Das et al., 2020). For example, Guo et al. (2020) calculated the occurrence probability of hydrological drought based on different intervals of duration and severities of meteorological drought. Sattar et al (2019) identified the occurrence probability of different classes and lag times of hydrological drought according to the intensity of meteorological drought. Xu et al. (2021) found that the probability of agricultural drought severity increased

synchronously with meteorological drought in different regions of China. Jehanzaib et al. (2020) concluded that in the Korean Peninsula, the probability of meteorological drought propagating into hydrological drought increased significantly under climate change. In general, these studies primarily focused on the relationship between duration and severity between the two drought types but ignored the relationships among affected areas. Xu et al. (2015a) found that the probability of drought occurrence would be underestimated if drought affected areas are not considered. Therefore, the traditional probabilistic model of drought propagation can be improved by introducing the three-dimensional clustering method, which would provide more drought information (Liu et al., 2019).

- Line 214 (i.e., Eq. (10)), the "n – 1" is shown in the inner product should be revised as "n – i". Moreover, please define or explain the symbols that appeared in this and some other equations, e.g., the term c is not defined. Please carefully check them.

RESPONSE: Thanks for your hint. We indeed made a mistake when typing Eq.(10). We have corrected it and added the explanation of the symbols. Furthermore, all equations have been carefully checked to ensure no errors would occur. The modification is located in **Line 237-Line 239 in the Track-changed file**.

MODIFICATION:

$$f(x_1,\ldots,x_n)=\prod_{i=1}^{n} f_i(x_i)\times\prod_{i=1}^{n-1}\prod_{j=1}^{n-i} c_{i,i+j|1:(i-1)}\left\{F(x_i\mid x_1,\ldots,x_{i-1}),F(x_{i+j}\mid x_1,\ldots,x_{i-1})\right\} \quad (10)$$

where $f(x_1,...,x_n)$ represents the joint density function. c represents bivariate Copula densities, which includes Gumbel, Gaussian, Frank, and Clayton Copula function; F represents cumulative distribution function of marginal distribution. i and j represent root nodes.

- For Section 4.2, please provide specific information about paired drought events so that we can identify the characteristics of four paired categories. At the same time, I found the statement "Among them, the peaks of the meteorological drought event appeared two months ahead (December 2007) that of ecological drought (February

2007)" may be wrong in Lines 250-251. As you know, the duration between December 2007 and February 2007 is far more than two months. Please revise it.

RESPONSE: This is a good suggestion. We have provided specific information about paired drought events to show the characteristics of four paired categories. The relevant description will be added in Section 3.3 in **Line 276-Line 279**.

MODIFICATION: Meteorological drought of OMT type showed a longer duration, a larger affected area, and a greater severity than ecological drought. However, this is contrary to type MTO. Simultaneously, ecological drought of type MTO showed a longer duration, a larger affected area, and a greater severity than those of type OTM (Figure 5).

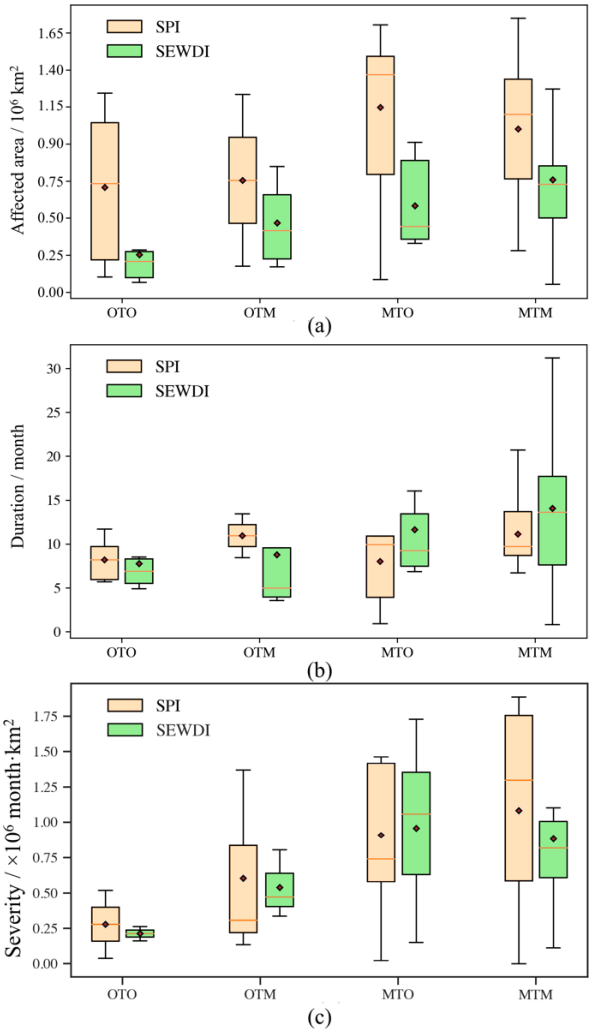

Figure 5. A box plot showing the intensity, duration, and affected area of paired meteorological-ecological drought among different types

MODIFICATION: The statement “Among them, the peaks of the meteorological drought event appeared two months ahead (December 2007) that of ecological drought (February 2007)” was corrected to " Among them, the peaks of the meteorological drought event appeared two months ahead (December 2007) that of ecological drought (February 2008)." in **Line 295-Line 297 in the Track-changed file**.

- An essential part of this article is the use of machine learning to solve a binary classification problem. In this context, I suggest adding a plot that shows the severity, duration, and affected area of meteorological droughts propagated and didn't propagate.

RESPONSE: That is an excellent suggestion. Thank you very much for that as well! In this study, machine learning models were used to determine whether a meteorological drought event has propagating potential. We have added Figure 9 and related descriptions in Section 3.4 with reference to the advice of Referee#1.

MODIFICATION:

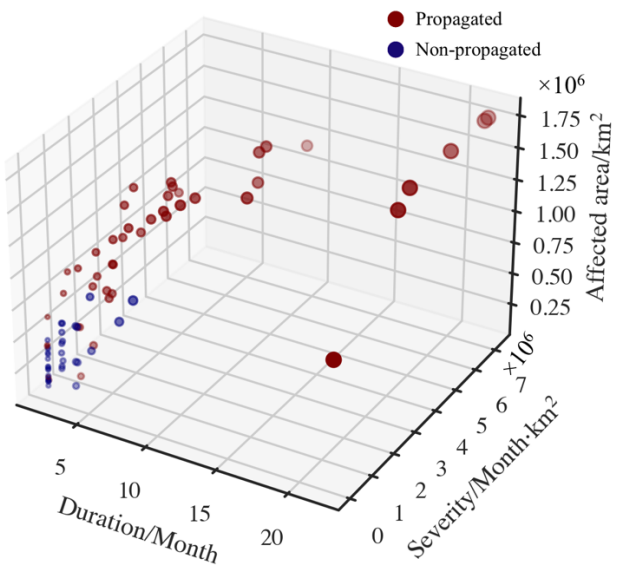

Figure 9 Three-dimensional diagram showing characteristics of meteorological drought events. Larger circles indicate greater severity.

As can be seen in Figure 9, propagated meteorological droughts have greater severity, larger affected area, and longer duration than non-propagated droughts.

- I suggest replacing "Three-dimensional drought identification method" with "Three-dimensional clustering method".

RESPONSE: We agree and can see your point. We will replace "Three-dimensional drought identification method" with "Three-dimensional clustering method" in the text.

Details:

- Lines 24-25, for specification, the drought classification should be changed as the "drought types". Please revise it.

RESPONSE: Thanks for the hint. We have corrected "drought classification" to "drought types" in **Line 27 in the Track-changed file**.

- Lines 66-68, “Taking a typically ecological fragile region … to meteorological drought”, I suggest revising it as “Taking a typically ecological fragile region, Northwestern China (NWC), as an example, the motivation of this study, from a three-dimensional perspective, is proposed a novel hybrid machine learning-Copula method to investigate the response probability of ecological drought to meteorological drought” to highlight the novelty of this paper.

RESPONSE: Thanks. We have followed your advice and changed it.

- Line 94-99, authors should refine their explanation of why SPI-3 is used to represent meteorological drought.

RESPONSE: Thanks for the hint. Line 94-99 has been changed to " Previous studies found that the standardized precipitation evaporation index (SPEI) overestimated the meteorological drought in NWC where actual atmospheric water demand is determined by precipitation variation (Ayantobo and Wei, 2019; Zhang et al., 2019a; Zhang et al., 2021b). Additionally, precipitation is the main water resources for vegetation growth in most regions of NWC due to the great depth to groundwater (Cao et al., 2021). Standardized

precipitation index (SPI) was thus used in the current study to represent meteorological drought. SPI at different time scales was calculated by aggregating *n*-month moving sums, allowing the identification of various drought types (McKee et al., 1993). At short time scales, drought events are characterized by high frequency and short duration, while at long time scales, they have longer duration and lower frequency. SPI–3 has been reported to be highly representative of the impacts of meteorological conditions on vegetation as vegetation variation is sensitive to precipitation accumulated over three months (McKee et al., 1993; Vicente-Serrano et al., 2012; Vicente-Serrano et al., 2010). Therefore, SPI-3 was used to characterize meteorological drought in this study." **in Line 106-Line 118 in the Track-changed file.**

- Section 3.3.2, the number of steps regarding the Spatiotemporal connection of two drought types may be disordered, e.g., the statements of steps were listed as Firstly and Secondly in Lines 154-155, but that remained as the Secondly in Line 163. Please check it.

  RESPONSE: Thanks for the hint. We will revise "Secondly" in line 163 in original manuscript to "Thirdly" in **Line 180 in the Track-changed file**.

- Lines 206-207, please revised the “Cramer-von Mises (CM) test” as the “Cramer-von Mises (CvM) test” based on common sense.

  RESPONSE: Thanks for the hint. We have corrected it to "Cramer-von Mises (CvM) test" in **Line 230 in the Track-changed file.**

- Line 224, I recommended the authors revised the caption of this section as “Top ten meteorological and ecological drought events according to drought severity”.

  RESPONSE: We agree and can see your suggestion. The caption of this section has been revised to "Top ten meteorological and ecological drought events according to drought severity" **in Line 267 in the Track-changed file.**

- For Figure 5, as the double y axes are used, I suggest the authors display them with different colors, e.g., the red and blue y-axes are used to display the extent of area and

severity. Similarly, please revise Figure 8.

RESPONSE: Thanks for the hint. We have revised Figure 5 and Figure 8 according to your suggestion. Now, they have been changed to Figure 7 and Figure 3 **in the Track-changed file**.

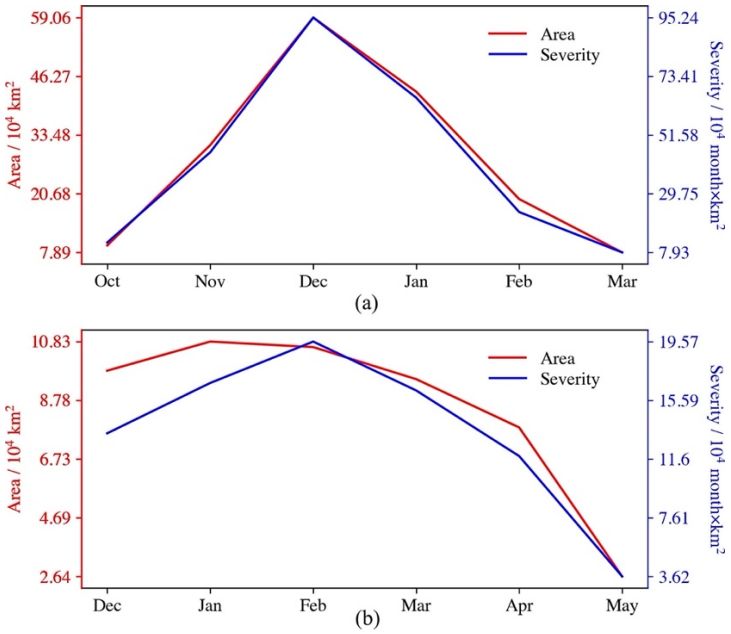

Figure 7: Temporal evolution of DS and DA of (a) meteorological drought event No. 87 and (b) ecological drought event No. 127.

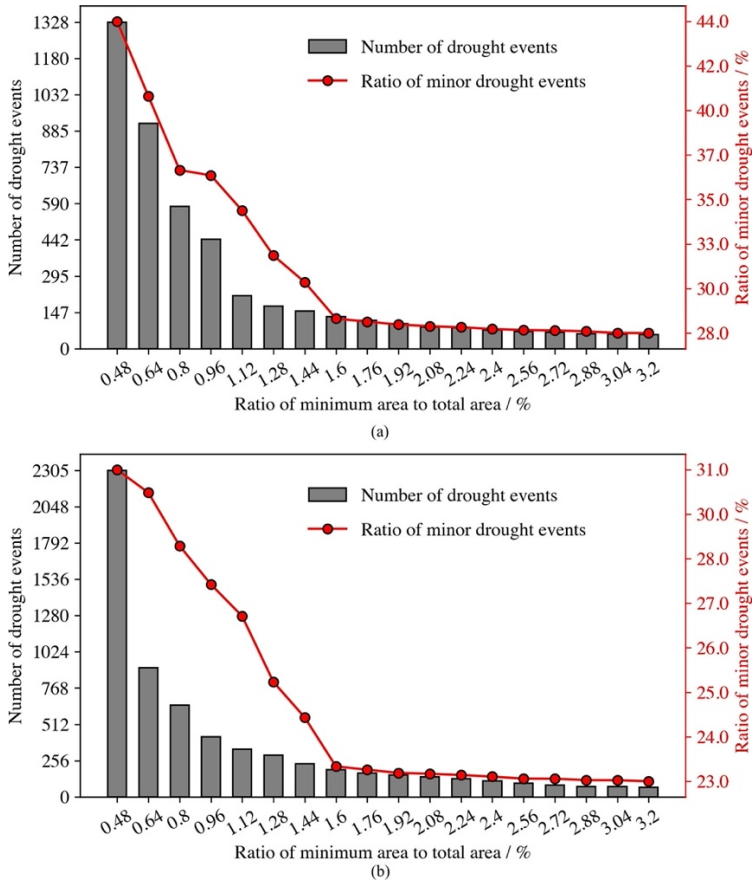

Figure 3: Sensitivity test of overlapping areas of drought patches between two adjacent months.

- Line 255-256, the “of five-fold cross-validations” should be removed from the latter part of this sentence as the relevant statement has been presented in the former.

  RESPONSE: Thanks for the hint. We have deleted the “of five-fold cross-validations” in the latter part of this sentence.

- Line 257-258, the GP and MP should be listed as full names when they appear for the first time.

  RESPONSE: Thanks for the hint. We have corrected it to " Most models showed good performance except for Gaussian Process and Multi-layer Perceptron." in **Line 304-305 in the Track-changed file**.

- In Figures 2 and 7, based on the terms commonly used, the drought levels regarding the “serious” should be revised as “severe”. Of course, the same statement about this need

to be changed throughout the manuscript.

RESPONSE: Thanks for your advice, we have revised "serious" to "severe" in Figure 2, Figure 7 (it has been changed to Figure 10 in the revision version), and related content throughout the manuscript.

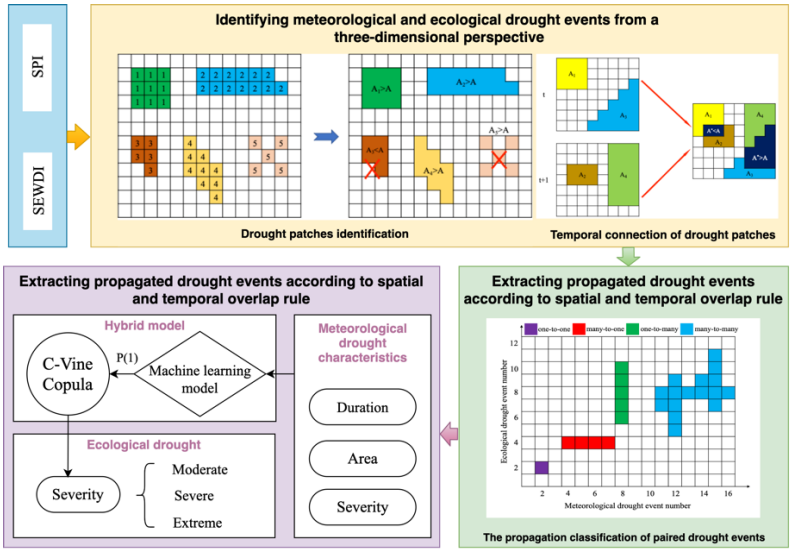

Figure 2: A schematic diagram illustrating the procedure of the drought propagation identification method.

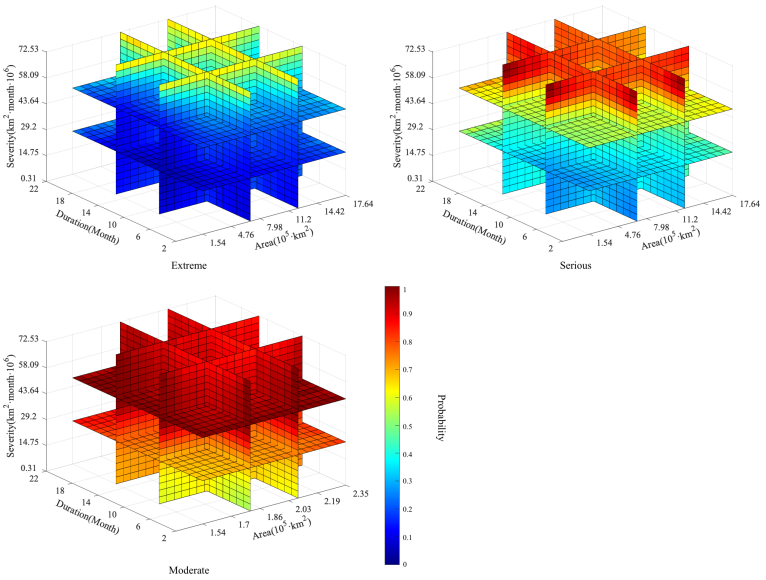

Figure 10: Conditional probability of ecological drought at (a) extreme, (b) severe, and (c) moderate levels, given that characteristics of meteorological drought exceed a certain value.

- In Figure 2, I think the title in purple color should be changed to "Constructing response

model of ecological drought to meteorological drought".

RESPONSE: Thanks, we have changed it according to your suggestion.

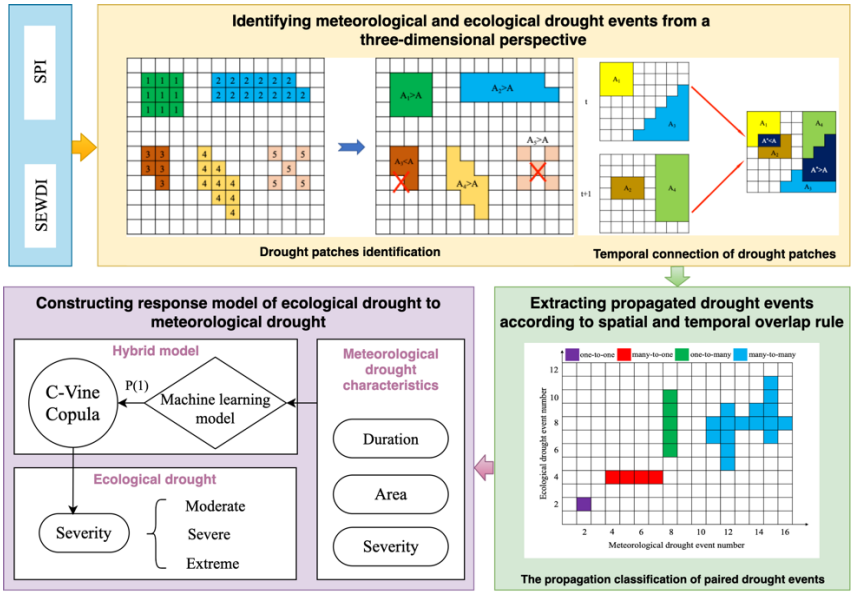

Figure 2: A schematic diagram illustrating the procedure of the drought propagation identification method.

- In the caption of Figure 7, the “different levels” should be pointed out to increase the readability, e.g., (a) extreme, (b) severe, and (c) moderate. Please check it.

RESPONSE: Thanks, we have changed it according to your suggestion.

MODIFICATION:

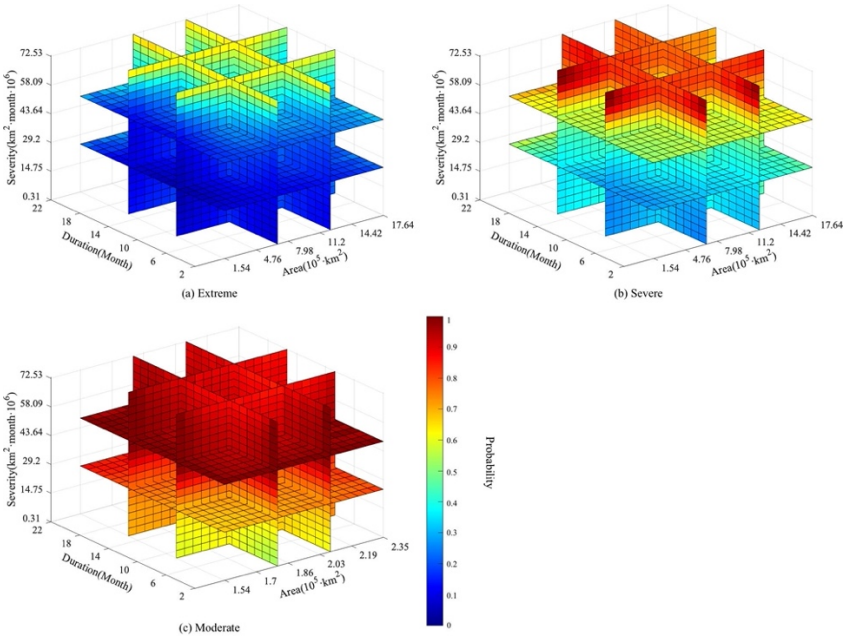

Figure 7: Conditional probability of ecological drought at (a) extreme, (b) severe, and (c) moderate levels, given that characteristics of meteorological drought exceed a certain value.

References:

Jehanzaib, M., Sattar, M. N., Lee, J.-H., and Kim, T.-W.: Investigating effect of climate change on drought propagation from meteorological to hydrological drought using multi-model ensemble projections, STOCHASTIC ENVIRONMENTAL RESEARCH AND RISK ASSESSMENT, 34, 7–21, https://doi.org/10.1007/s00477-019-01760-5, 2020.

Xu, Y., Zhang, X., Hao, Z., Singh, V. P., and Hao, F.: Characterization of agricultural drought propagation over China based on bivariate probabilistic quantification, JOURNAL OF HYDROLOGY, 598, https://doi.org/10.1016/j.jhydrol.2021.126194, 2021.