Dear Editor and the reviewers,

We do appreciate your constructive, thoughtful, careful, and helpful comments and suggestions. After careful discussions, calculations, and analyses, we finished the preparation of responses to you. There are totally four parts: “Response to Reviewer 1”, “Response to Reviewer 2”, “Response to Short Comments” and a clean version of the manuscript “Risk Zoning of Typhoon Disasters in Zhejiang Province, China”.

If there are any new comments or suggestions, please let us know.

Best Regards

Yi Lu and the coauthors

Response to Reviewer 1

1. In the "2. Study Area" section, it is better to give a background introduction of typhoon disasters in the study area; otherwise, it is not unstoodable why you use Zhejiang Province as a case.

Reply: We do appreciate the helpful suggestion.

Mainly according to the suggestion, some modifications have been done. The modifications include:

(1) The structure of the paper has been changed. Considering that Section 2 is so thin and unbalanced to other sections, “2 Study Area” is merged into “3 Data and Methods” and then the Section numbers hereafter are changed.

(2) In the last paragraph of “Introduction”, a sentence “In this study, Zhejiang province, which is frequently affected by the strongest landfall typhoons (Ren et al., 2008) and experiences most serious typhoon disasters (Liu and Gu, 2002) in the mainland of China, is selected as the study area.” has been added.

The following two new references have been added:

Liu, T. J. and Gu, J. Q.: A statistical analysis of typhoon disasters in Zhejiang province, Journal of Catastrophology, 17 (4): 64-71, 2002. (in Chinese)

Ren, F. M., Wang, X. L., Chen, L. S., and Wang, Y. m.: Tropical cyclones landfalling on mainland China, Hainan and Taiwan and their correlations, Acta Meteorologica Sinica, 66 (2): 224-235, 2008. (in Chinese)

2. For the meteorogical data, how many stations are there in Zhejiang Province? The authors said 2419 stations provided by NMIC; it is not clear if they are distributed throughout China or only in Zhejiang province. It needs to be clarified.

Reply: Thanks so much for the comment. In this paper, the OSAT method need to identify typhoon wind and precipitation from wide range than Zhejiang province, so 2419 stations of precipitation data and 2479 stations of wind data over the mainland of China are used, which all contained 71 stations corresponding to counties in Zhejiang province.

We add following sentences at the end of L80 in original section 3.1.1.

“In addition, the OSAT method need to identify typhoon wind and precipitation from a wider range than Zhejiang province (please see detail in section 2.2.1), so 2419 stations of precipitation data and 2479 stations of wind data over the mainland of China are used, which all contained 71 stations corresponding to counties in Zhejiang province.”

3. Canonical Correlation Analysis is the main tool for this study, which is however not introduced to readers at all. It is necessary to give an introduction of this method and how it is applied in this study.

Reply: Thanks for your suggestion. According to the suggestion, we have added introduction and application of Canonical Correlation Analysis (CCA) in this paper.

We add following sentences at the end of L102 in original section 3.2.2.

"In statistics, canonical correlation analysis (CCA) is a way of inferring information from cross-covariance matrices. If we have two vectors X = (X1, ..., Xn) and Y = (Y1, ..., Ym) of random variables, and there are correlations among the variables, then CCA can find linear combinations of the Xi and Yj which have maximum correlation with each other (Hardoon et al., 2014). The method was first introduced by Hotelling in 1936 (Hotelling, 1936). The main point of CCA is to separate linear combination of new variables from the two sets of variables. In this case, the correlation coefficient between new variables reaches the maximum. In this paper, we chose factors causing typhoon disasters as a set of variables, and typhoon disaster as another. Under the maximum canonical correlation coefficient, the linear combination coefficients (typical variable coefficients) of factors causing typhoon disasters can be used as weight coefficients of this group of variables. Then we can determine the impact of factors causing typhoon disasters."

The added references are as follows:

Hardoon, D. R., Szedmak, S., and Shawetaylor, J.: Canonical Correlation Analysis: An Overview with Application to Learning Methods, Neural Computation, 16(12):2639-2664, 2014.

Hotelling, H.: Relations between two sets of variates, Biometrika, 28(3/4), 321-377, 1936.

4. In Section 3.2.4, it is necessary to introduce how the so-called SoVI is used to calculate the population vulnerability index.

Reply: Thanks very much for the suggestion. According to the suggestion, we have added introduction and application of SoVI in this paper.

We add following sentences at the beginning of L109 in original section 3.2.4.

"County-level socioeconomic and demographic data are used to construct an index of social vulnerability to environmental hazards named the Social Vulnerability Index (SoVI). Principal Component Analysis (PCA) is the primary statistical technique for constructing the SoVI. The PCA method captures multi-dimensionality by transforming the raw dataset to a new set of independent variables. Then a few components can represent the dimensional data, and underlying factors can be identified easily. These new factors are placed in an additive model to compute a summary score—SoVI (Cutter et al., 2003)."

The added reference is as follows:

Cutter, S. L., Boruff, B. J., and Shirley, W. L.: Social Vulnerability to Environmental Hazards, Social Science Quarterly, 84(2):242-261, 2003.

5. The data source of typhoon disaster losses?

Reply: Typhoon disaster losses used in this paper are obtained from the National Climate Center who collected these disaster data from local meteorological departments. The data source can be seen in lines 82-83 of original section 3.1.2.

6. How is "typhoon rainstorm" defined? Its probability is an important issue in this study. How the probability is determined? It is not introduced at all.

Reply: Thanks very much for the comment and suggestion. According to the suggestion, we have added a definition of “typhoon rainstorm” and “typhoon torrential rainstorm”. In original section 4.1, we did some research about risk of typhoon rainstorm. Typhoon rainstorm in this study means daily typhoon precipitation over 50mm, and typhoon torrential rainstorm means daily typhoon precipitation over 100mm. The probability is the annual possibility of the occurrence of typhoon rainstorms. The probability denominator is the total number of years, and the numerator is the annual frequency of typhoon precipitation. If a station experiences typhoon precipitation in one year, the numerator increases by one.

We add following sentences at the end of original L133 before “Based on”.

“Typhoon rainstorm in this study means daily typhoon precipitation over 50mm, and typhoon torrential rainstorm means daily typhoon precipitation over 100mm. The probability is the annual possibility of the occurrence of typhoon rainstorms. ”

7. In Eq(1), it is not clear how population and economic loss are both included. Only for population or economic loss? Why in the form of "Ax+By", not a "multiplying" form?

Reply: Thanks for the comment. As we explained in question 3, the main point of CCA is to separate linear combination of new variables from the two sets of variables. In this paper, we chose typhoon disaster-causing factors as a set of variables, and typhoon disaster as another. Typhoon disaster-causing factors (typhoon wind and precipitation) and typhoon disasters (affected population and economic loss) are both contained. When the typical correlation coefficient pass the significance test, weight discrimination can be made to determine A and B. Both typhoon rainstorm and high wind will bring certain disasters. When reaching a certain critical value, they will have a superposition effect. However, the effects of wind and rain on disaster are different. Therefore, it is necessary to determine their influence through typical correlation analysis, which is a typical variable coefficient. So the form is "Ax+By", not a multiplier.

8. P12 L205, it says, after "performing factor analysis"..... How is the factor analysis performed? In the title of Table 3, principal component analysis is mentioned. How is the principal component analysis performed? Factor analysis is the principal component analysis? If these methods are used, they need to be introduced in the methodology section.

Reply: Thanks very much for the comment and suggestion. The factor analysis performed here is Principal Component Analysis (PCA), which is the primary statistical procedure for constructing the SoVI. According to the suggestion, we have added detailed explanations of PCA in original section 3.2.4, which have been answered in question 4.

We add following sentences at the beginning of L109 in original section 3.2.4.

“County-level socioeconomic and demographic data are used to construct an index of social vulnerability to environmental hazards named the Social Vulnerability Index (SoVI). Principal Component Analysis (PCA) is the primary statistical technique for constructing the SoVI. The PCA method captures multi-dimensionality by transforming the raw dataset to a new set of independent variables. Then a few components can represent the dimensional data, and underlying factors can be identified easily. These new factors are placed in an additive model to compute a summary score—SoVI (Cutter et al., 2003). ”

9. In Table 4, the derived disaster risk index are divided into 5 grades. How are the thoresholds are determined? It is not mentioned.

Reply: Thanks for the comment. The classification of typhoon disaster risk index is based on the natural breaks method (Jenks) provided by Arcgis. Then we divide disaster risk index into 5 grades, which represent five risk zones for typhoon disasters in Zhejiang province.

We add following sentences at the end of original L248.

"The classification of typhoon disaster risk index is based on the natural breaks method (Jenks) provided by Arcgis."

Response to Reviewer 2

1. The English of the manuscript is need be improved.

Thanks for your comment. According to the suggestion, modifications include:

(1) The first half of Abstract has been rewritten.
(2) "Province" has been changed into "province".
(3) "Comprehensive Risk Index for Typhoon Disasters" has been changed into "Typhoon Disaster Comprehensive Risk Index".
(4) The second half of the last paragraph in Introduction has been rewritten.
(5) The structure of the paper has been changed. Considering that Section 2 is so thin and unbalanced to other sections, "2 Study Area" is merged into "3 Data and Methods" and then the Section numbers hereafter are changed.
(6) Analyses for the figures have been revised especially these for Figure 7.
(7) For grammar, all past tense have been changed into present tense.
(8) Other specific modifications can be seen in detail in the text with revision-tracing.

2. Extend data from 2012 to 2016?

Thanks very much for the suggestion.

As county-level typhoon disaster data is so limited and it's hard to get new data, we can't extend data from 2012 to 2016.

3. The background of typhoon disaster over Zhejiang province must be introduced.

According to the suggestion, modifications include:

(1) In the last paragraph of "Introduction", a sentence "In this study, Zhejiang province, which is frequently affected by the strongest landfall typhoons (Ren et al., 2008) and experiences most serious typhoon disasters (Liu and Gu, 2002) in the mainland of China, is selected as the study area." has been added.

(2) The following two new references have been added:

Liu, T. J. and Gu, J. Q.: A statistical analysis of typhoon disasters in Zhejiang province, Journal of Catastrophology, 17 (4): 64-71, 2002. (in Chinese)

Ren, F. M., Wang, X. L., Chen, L. S., and Wang, Y. m.: Tropical cyclones landfalling on mainland China, Hainan and Taiwan and their correlations, Acta Meteorologica Sinica, 66 (2): 224-235, 2008. (in Chinese)

4. L74-75. Add reference about best track data from CMA.

Reply: Thanks for your suggestion. According to the suggestion, we have added references about best track data from CMA, and cite them in original section 3.1.1.

New references are added in "References".

Eunjeong, C. and Ying, M.: Comparison of three western North Pacific tropical cyclone best track datasets in seasonal context, Journal of the Meteorological Society of Japan, 89(3):211-224, 2009.

Li, S. H. and Hong, H. P.: Use of historical best track data to estimate typhoon wind hazard at selected sites in China, Natural Hazards, 76(2):1395-1414, 2015.

5. Describe more detail about the OSAT methods.

Reply: Thanks very much for the suggestion. According to the suggestion, we have added more detail about the OSAT method.

We add following sentences in L96 of original section 3.2.1 before " Lu".

"The OSAT method is a numerical technique to separate tropical cyclone induced precipitation from adjacent precipitation areas. Based on the structural analysis of precipitation field, it can be divided into different rain belts. Then, according to the distances between a TC center and these rain belts, typhoon center and each station, typhoon precipitation is distinguished."

6. L103: In this section, authors describe the methods of standardization. But corresponding variables are unknown.

Reply: Thanks for the comment. According to the comment, we have added introduction of corresponding variables.

We add following sentences at the end of L107 in original section 3.2.3.

"Z-score standardization is used for calculating intensity index of factors causing typhoon disasters. Both typhoon precipitation and typhoon maximum wind speed are standardized by this method. When calculating typhoon disaster comprehensive risk index (R), we use MIN-MAX standardization to standardize the intensity index of the factors causing typhoon disasters (I) and the population vulnerability index (SoVI)."

7. Introduce the method of calculating probability of typhoon rainstorms.

Reply: Thanks very much for the suggestion. According to the suggestion, we have added a definition of "typhoon rainstorm" and "typhoon torrential rainstorm". In original section 4.1, we did some research about risk of typhoon rainstorm. Typhoon rainstorm in this study means daily typhoon precipitation over 50mm, and typhoon torrential rainstorm means daily typhoon precipitation over 100mm. The probability is the annual possibility of the occurrence of typhoon rainstorms. The probability denominator is the total number of years, and the numerator is the annual frequency of typhoon precipitation. When a station has experienced typhoon precipitation in one year, the numerator increases by one.

We add following sentences at the end of original L133 before "Based on".

"Typhoon rainstorm in this study means daily typhoon precipitation over 50mm, and typhoon torrential rainstorm means daily typhoon precipitation over 100mm. The probability is the annual possibility of the occurrence of typhoon rainstorms. "

8. L148: Do you sure about "over six sites"?

Reply: Thanks for your question. We feel sorry for that it is a translation error. This should be referred to Typhoon wind over 6 grade (≥10.8 m/s). Figure 6 shows average duration (days) of typhoon winds at each station in Zhejiang province from 1980 to 2014. We have modified original L148.

Original L148 is modified as follows.

"The average duration (days) of typhoon winds (over 6 grade) is calculated in Zhejiang province (Figure 6). "

9. Durations of data in different parts are different. Could durations of different kinds of data are uniformed?

Reply: Thanks for the comment. In the original paper, we used three durations of data, including typhoon precipitation during 1960 - 2013, typhoon wind during 1980 - 2014, and typhoon disaster data during 2004 - 2012. According to the suggestion, durations of daily precipitation and wind have been uniformed with 1980–2014. Duration of typhoon disaster data remains unchanged. Detailed reasons are as follows.

(1) First of all, because of limited access to county-level typhoon disaster data, we have only obtained data during 2004 to 2012 from National Climate Center. So all analyses of intensity index of factors causing typhoon disasters are during 2004 to 2012, which remains unchanged. However, this duration is short for risk analyses of typhoon precipitation and typhoon wind. Therefore, longer time-series data are needed.

(2) We feel sorry for that it is a expression mistake to say "The statistics showed a rapid increase in the number of automated wind measurement stations from 1980" in original L77. As Lu et al. (2016) mentioned, considering the homogeneity and continuity of wind data, we use daily wind data during 1980 - 2014 to to identify typhoon wind.

(3) Considering the consistency between wind and precipitation data, 1980 to 2014 is selected as the period of study. In addition, the OSAT method need to identify typhoon wind and precipitation from wide range rain belts, so 2419 stations of precipitation data and 2479 stations of wind data over the mainland of China are used, which all contained 71 stations corresponding to counties in Zhejiang province.

According to the suggestion, modifications include:

(1) The introduction of daily precipitation and wind data in original section "3.1.1 Typhoon, Precipitation and Wind Data" are rewrote as follow.

"Daily precipitation data for 2479 stations and daily wind data for 2419 stations during the time period 1960 - 2014 over the mainland of China are obtained from National Meteorological Information Center. The maximum wind speed is given as the maximum of 10-minute mean. In this paper, two time periods of precipitation and wind data are used.

Because of limited access to county-level typhoon disaster data, we have only obtained data during 2004 to 2012. So when calculating intensity index of factors causing typhoon disasters, time period of typhoon precipitation and typhoon wind are the same as typhoon disasters, which is 2004 - 2012.

For risk analyses of typhoon precipitation and typhoon wind (please see detail in sections 3.1 and 3.2), suppose future probability is the same as historical probability, we then select the period of 1980 – 2014. As Lu et al. (2016) mentioned, considering the homogeneity of wind data, we use the period of 1980 - 2014 for wind analysis. To ensure the consistency between wind and precipitation data, 1980 - 2014 is selected as the period. In addition, the OSAT method need to identify typhoon wind and precipitation from a wider range than Zhejiang province (please see detail in section 2.2.1), so 2419 stations of precipitation data and 2479 stations of wind data over the mainland of China are used, which all contained 71 stations corresponding to counties in Zhejiang province."

(2) The analyses in original section "4.1 Risk of Typhoon Rainstorms" are modified. All time periods in this section have been changed to 1980 - 2014, with corresponding changes of calculations and pictures.

10. L178: What criterions are used in calculating precipitation or wind?

Reply: Thanks for the comment. If a typhoon disaster occurs and there is a corresponding typhoon wind or typhoon precipitation, it will be included in the sample.

11. L181: The distribution of sample sizes?

Reply: Good comment. The total valid disaster records of Zhejiang province from 2004 to 2012 are 421. To establish an intensity index of typhoon disaster-causing factors, we carry out CCA analysis. Taking the county as a unit, we select all the typhoons that affected the population, which means all records with an affected population greater than 0. The total precipitation and daily maximum wind speed during affected typhoons measured in each county are used. The total sample size is 322. Then, we do CCA analyses for all the typhoons that caused direct economic losses in the same way, and the total sample size is 404.

According to the suggestion, modifications include:

(1) We add following sentences at original L179 after "factors causing typhoon disasters".

" The total sample size is 322. ".

(2) We add following sentences at original L182 before "(Table 1)".

", and the total sample size is 404.".

12. L194: the intensity index is calculated for each typhoons and each stations? And how get the distribution of intensity indices in figure 8?

Reply: Thanks for the comment. The intensity index is calculated for each typhoon at each station. Then we average all intensity indices at each station, and we can get the distribution of intensity indices in figure 8.

13. L199-L238. I am confused by the section 5.2. Each factor or component in factor 1 to factor7 in equation 2 or seven components in table 3 is a vector with 29 variables? Please describe more details about factors or components. The signs of vectors from PCA maybe opposite of real meaning. Do you do detail analysis on the relations of variables in a vector and between vectors? The equation 2 is must be evaluated carefully.

Reply: Thanks very much for the comments and suggestions.

(1) For the first question, component 1 to component 7 are vectors in table 3 with 29 variables. After performing PCA of the 29 variables, 7 components with eigenvalue equal to or greater than 1 are extracted.

(2) For the second question, 7 components are examined manually as to whether they increase (+)

or decrease (−) vulnerability and they are assigned a cardinality on that basis. Then the vulnerability index is produced by summing all the components using equal weighting, following the Chen (2013) approach.

To conveniently describe details about 7 components, we rename 29 variables (Table 2). After PCA, we obtain 7 components. The signs and contained variables of 7 components are shown in Table 3. We can see 6 components increase (+) vulnerability and a component decrease (−) vulnerability. For example, the first component, which reflects the income of the population and the employment situation, is positive because the more property there is in an area, the higher the vulnerability to damage. The second component, which reflects education level of the population, is negative because if education level is higher, then the population's awareness of disaster prevention and reduction is greater and their vulnerability is lower.

According to the comments and suggestions, modifications include:

(1) We rename the 29 variables in Table 2.

Table 2. The 29 variables affecting vulnerability in Zhejiang province.

	variables	Name
1	Per capita disposable income of urban residents (yuan)	UBINCM
2	Percentage of female (%)	QFEMALE
3	Percentage of minority (%)	QMINOR
4	Median age	MEDAGE
5	Unemployment rate (calculated - unemployed population / (unemployed + total population)	QUNEMP
6	Population density	POPDEN
7	Percentage of urban population (%)	QUBRESD
8	Percentage of non-agricultural household population (%)	QNONAGRI
9	Percentage of households that living in rented houses (%)	QRENT
10	Percentage of employees working in primary industries and mining (%)	QAGREMP
11	Percentage of employees working in secondary industries (%)	QMANFEMP
12	Percentage of employees working in tertiary industries (%)	QSEVEMP
13	Household size (person / household)	PPUNIT
14	Percentage of population with college degree (25 years old and older)	QCOLLEGE
15	Percentage of population with high school degree (20 years old and older)	QHISCH
16	Percentage of illiterate people (15 years old and older)	QILLIT
17	Population growth rate (2000-2010)	POPCH
18	Average number of rooms per household (inter / household)	PHROOM

19	Per capita housing construction area (m^2 / person)	PPHAREA
20	Percentage of premises without tap water (%)	QNOPIPWT
21	Percentage of premises without a kitchen (%)	QNOKITCH
22	Percentage of premises without a toilet (%)	QNOTOILET
23	Percentage of premises without a bath (%)	QNOBATH
24	Number of beds per 1000 person in health care institutions	HPBED
25	Number of medical personnel per 1000 resident population	MEDPROF
26	Percentage of people under 5	QPOPUD5
27	Percentage of population over 65 years old	QPOPAB65
28	Population dependency ratio (%)	QDEPEND
29	Percentage of population covered by subsistence allowances (%)	QSUBSIST

(2) We add contained variables of 7 components with different signs in Table 3.

Table 3. The seven components extracted by PCA.

Components	Contained variables	Name	(Sign)
1	QMANFEMP, UBINCM, QAGREMP, QRENT, POPCH, QDEPEND, QSUBSIST, QPOPAB65, POPDEN, MEDAGE, QNOKITCH, QILLIT, PHROOM, PPHAREA	Employment and poverty	(+)
2	QHISCH, QCOLLEGE, QNONAGRI, QSEVEMP, HPBED, MEDTECH	Education	(-)
3	QNOBATH, QNOTOILET, PPUNIT	Number of dilapidated houses	(+)
4	QILLIT, QDEPEND, QPOPUD5, MEDAGE	Illiteracy and juvenile population	(+)
5	QFEMALE, PHROOM, PPHAREA, QSEVEMP	Household size and ratio of women	(+)
6	QMINOR	Ethnic minority	(+)
7	QUNEMP, QNOPIPWT	Unemployment and housing size	(+)

(3) To distinguish the 7 components and 29 variables more clearly, we replace all "factor" with "component" in this section.

14. Could you find data of 29 variables in table 2 in early year? If the difference of population vulnerability between 2010 to early year is analyzed, the manuscript will to be more valuable.

Reply: Thanks for your thoughtful suggestion. The population data used in this paper is obtained from the sixth national population census of the Population Census Office of the National Bureau of Statistics of China and the 2010 statistical yearbooks of each city in Zhejiang province published by the cities' statistical bureaus. There exist many missing and abnormal records in the original data, which take a long time to be processed. This article focuses on typhoon disaster risk zoning in Zhejiang province, so we didn't discuss the difference of population vulnerability between 2010 to early year. The variation of population vulnerability is an interesting topic. Maybe we can discuss it in future work.

Response to Short Comments

1. Please use word "Tropical Cycle" instead of Typhoon.

Reply: Thanks for your comment. Considering to be consistent with some published researches (Chen, 2007; Chen et al., 2011; Ding et al., 2002; Niu et al., 2011), we tend to introduce a definition of typhoon rather than change the name. At the beginning of "Introduction", "Tropical cyclones cause" has been changed into "Typhoon, which means tropical cyclone in this paper, often causes".

2. In your paper, you mentioned many times risk. In my knowledge, risk is future probability of hazard events. However, your paper studied the disaster events happened during 2004-2012. In this period, I would not like to mention risk. In your paper, you can only name disaster probability.

Reply: We do appreciate the comment.

We agree and understand that risk is future probability of hazard events. However, suppose future probability is the same as historical probability for a specific period, we can understand risk by learning from past events. We tend to make a specific statement about this rather to change "risk" into "disaster probability". According to the comments, modifications include:

(1) A sentence "As risk is future probability of hazard events, when suppose future probability is the same as historical probability for a specific period, we can understand risk by learning from past events." is added and becomes the first sentence of "Abstract".

(2) A sentence "For risk analyses of typhoon precipitation and typhoon wind (please see detail in sections 3.1 and 3.2), suppose future probability is the same as historical probability, we then select the period of 1980 – 2014." is added as the first sentence of the third paragraph in original section 3.1.1.

3. Wind and precipitation data. Please clarify wind and precipitation data during TC events or not.

Reply: Thanks for your suggestion. As described in original section 3.1.1, the original daily precipitation data and maximum wind speed in this paper are from the National Meteorological Information Center. Then we distinguish typhoon precipitation and winds by using the OSAT method (original section 3.2.1). Therefore, all typhoon wind and rain mentioned later in this paper were during TC events.

To clarity wind and precipitation data, last sentence in original section 3.2.1 is rewrote as follows.

“With the application of the OSAT method, daily precipitation and wind data over the mainland of China during 1980 to 2014 are used for identifying typhoon precipitation and wind data.”.

4. The figure should be redrawed as figures have no latitude and longitude.

Reply: Thanks for your suggestion. Figures have been modified according to the suggestion.

5. Latest references should be cited.

Reply: Thanks for your suggestion. According to the suggestion, we have added some latest references in “1 Introduction ” and “References”.

At the end of original line 44, we add following sentences.

“Recently, some research built quantitative assessment in some provinces and carried out preliminary studies on pre-evaluating typhoon disasters (Huang and Wang, 2015; Yin and Li, 2017).”

At the end of original line 56, we add following sentences.

“Xu et al. (2015) comprehensively assessed the impact of typhoons across China using the geographical information system. The future direction of tropical cyclone risk management is quantitative risk models (Chen et al., 2017).”

Added references:

Chen, W. F., Duan, Y. H., and Lu, Y.: Review on Tropical Cyclone Risk Assessment, Journal of Catastrophology, 32(4), 2017. (in Chinese)

Huang, W. K. and Wang, J. J.: Typhoon damage assessment model and analysis in Taiwan, Natural Hazards, 79(1), 497-510, 2015.

Xu, X., Sun, D., and Guo, T.: A systemic analysis of typhoon risk across china, Natural Hazards, 77(1), 461-477, 2015.

Yin, Y. Z. and Li, H. L.: Preliminary study on pre-evaluation method of typhoon disaster in China, Meteorological Monthly, 43(6):716-723, 2017. (in Chinese)

Risk Zoning of Typhoon Disasters in Zhejiang Province, China

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Abstract As risk is future probability of hazard events, when suppose future probability is the same as historical probability for a specific period, we can understand risk by learning from past events. Based on precipitation and wind data over the mainland of China during 1980 - 2014, disaster and social data at the county level in Zhejiang province from 2004 to 2012, a study on risk zoning of typhoon disasters is carried out. Firstly, characteristics of typhoon disasters and factors causing typhoon disasters are analyzed. Secondly, an intensity index of factors causing typhoon disasters and a population vulnerability index are developed. Thirdly, combining the two indices, a comprehensive risk index for typhoon disasters is obtained and used to zone areas of risk. Above analyses show that, southeastern Zhejiang is the area most affected by typhoon disasters. The annual probability of the occurrence of typhoon rainstorms >50 mm decreases from the southeast coast to inland areas, with a maximum in the boundary region between Fujian and Zhejiang, which has the highest risk of rainstorms. Southeastern Zhejiang and the boundary region between Zhejiang and Fujian province and the Hangzhou Bay area are most frequently affected by typhoon extreme winds and have the highest risk of wind damage. The population of southwestern Zhejiang is the most vulnerable to typhoons as a result of the relatively undeveloped economy, mountainous terrain and the high risk of geological disasters in this region. Vulnerability is lower in the cities due to better disaster prevention and reduction strategies and a more highly educated population. The southeast coastal areas face the highest risk of typhoon disasters, especially in the boundary region between Taizhou and Wenzhou cities. Although the inland mountainous areas are not directly affected by typhoons, they are in the medium-risk category for vulnerability.

Keywords: typhoon disasters, factors causing typhoon disasters, vulnerability, comprehensive risk

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index, risk zoning

1 Introduction

Typhoon, which means tropical cyclone in this paper, often causes some of the most serious natural disasters in China, with an average annual direct economic loss of about $9 billion. The arrival of typhoon is often accompanied by heavy rain, high winds and storm surges, with the main impacts in southern coastal areas of China (Zhang et al., 2009). Zhejiang province is seriously affected by typhoons—for example, in 2006, the super-typhoon Sang Mei caused 153 deaths in Cangnan county of Wenzhou city, with 11.25 billion yuan of direct economic losses. Therefore it would be of practical significance to develop a system for the risk assessment of typhoon disasters in Zhejiang province.

Major risk assessment models include the disaster risk index system of the United Nations Development Program (global scale, focusing on human vulnerability), the European multiple risk assessment (with emphasis on factors causing disasters and vulnerability) and the American HAZUS-MH hurricane module and disaster risk management system. Vickery et al. (2009) and Fang et al. (2012, 2013) had reviewed the factors causing typhoon disasters. Rain and wind are direct causes of typhoon disasters (Emanuel, 1988, 1992, 1995; Holland, 1997; Kunreuther and Roth, 1998); stronger typhoons produce heavier rain and stronger winds, resulting in a greater number of casualties and higher economic losses. Many of the researches on the factors causing typhoon disasters used a grade index and the probability of occurrence (Chen et al., 2011; Su et al., 2008; Ding et al., 2002; Chen, 2007). Recently, some research built quantitative assessment in some provinces and carried out preliminary studies on pre-evaluating typhoon disasters (Huang and Wang, 2015; Yin and Li, 2017).

In terms of vulnerability, Pielke et al. (1998, 2008) combined the characteristics of typhoons and socioeconomic factors, suggesting that both the vulnerability of the population and economic factors were important in estimating disaster losses. The vulnerability of a population is a pre-existing condition that influences its ability to face typhoon disasters. Among the most widely used indices is the Social Vulnerability Index (SoVI) (Cutter et al., 2003; Chen et al., 2011). Other researches have focused on the vulnerability of buildings, obtaining a fragility curve by combining historical loss with the characteristics of buildings and typhoons (Hendrick and Friedman, 1966; Howard et al., 1972; Friedman, 1984; Kafali and Jain, 2009; Pita et al., 2014). Studies in China have assessed vulnerabilities to typhoon disasters (Yin et al., 2010; Niu et al., 2011). Evaluation indexes for the assessment of disaster losses were established based on the number of deaths, direct economic losses, the area of crops affected and the number of collapsed houses. These indexes were used to construct different disaster assessment models (Liang and Fan, 1999; Lei et al., 2009; Wang et al., 2010). Xu et al. (2015) comprehensively assessed the impact of typhoons across China using the geographical information system. The future direction of tropical cyclone risk management is quantitative risk models (Chen et al., 2017).

Previous studies have concentrated on semi-quantitative, large-scale research, with less emphasis on quantitative research at county level based on large amounts of accurate data. In addition, the studies have paid more attention to disaster losses and few studies have focused on a comprehensive risk assessment of typhoon disasters coupled with factors causing typhoon disasters and population vulnerability. In this study, Zhejiang province, which is frequently affected by the strongest landfall typhoons (Ren et al., 2008) and experiences most serious typhoon disasters (Liu and Gu, 2002) in the mainland of China, is selected as the study area. Section 2 introduces the data and methods used in this study. Section 3 provides analyses on typhoon disaster losses and causing factors. Section 4 presents risk assessment and regionalization of typhoon disasters. Summary and discussions are given in the final section.

2 Data and Methods

This study is carried out in Zhejiang province (Figure 1) including 11 cities along the Yangtze River Delta. Zhejiang province is in the eastern part of the East China Sea and south to Fujian province, which is one of the most economically powerful provinces in China.

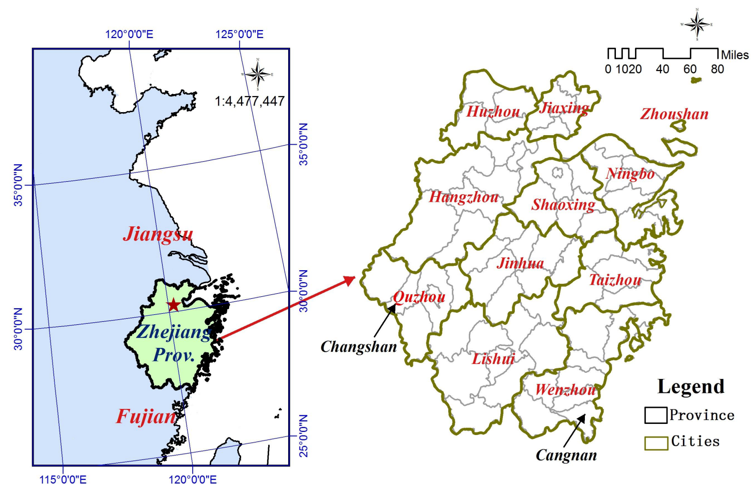

Figure 1. Maps of Zhejiang province, China showing location and major cities.

2.1 Data

2.1.1 Typhoon, Precipitation and Wind Data

The typhoon data used in this study are the best-track tropical cyclone datasets from Shanghai Typhoon Institute for the time period 1960 - 2014 (Eunjeong and Ying, 2009; Li and Hong, 2015). Daily precipitation data for 2479 stations and daily wind data for 2419 stations during the time period 1960 - 2014 over the mainland of China are obtained from National Meteorological Information Center. The maximum wind speed is given as the maximum of 10-minute mean. In this paper, two time periods of precipitation and wind data are used.

Because of limited access to county-level typhoon disaster data, we have only obtained data during 2004 to 2012. So when calculating intensity index of factors causing typhoon disasters, time period of typhoon precipitation and typhoon wind are the same as typhoon disasters, which is 2004 - 2012.

For risk analyses of typhoon precipitation and typhoon wind (please see detail in sections 3.1 and 3.2), suppose future probability is the same as historical probability, we then select the period of 1980 – 2014. As Lu et al. (2016) mentioned, considering the homogeneity of wind data, we use the period of 1980 - 2014 for wind analysis. To ensure the consistency between wind and precipitation data, 1980 - 2014 is selected as the period. In addition, the OSAT method need to identify typhoon wind and precipitation from a wider range than Zhejiang province (please see detail in section 2.2.1), so 2419 stations of precipitation data and 2479 stations of wind data over the mainland of China are used, which all contained 71 stations corresponding to counties in Zhejiang province.

2.1.2 Disaster and Social Data

Disaster data for each typhoon that affected Zhejiang province from 2004 to 2012 are obtained from the National Climate Center and the number of records for each county is shown in Figure 2. Of the 11 cities in Zhejiang province, Wenzhou and Taizhou record the most typhoon disasters, with a maximum being 17. Fewer typhoon disasters are recorded in the central and western regions of Zhejiang province, particularly in Changshan and Quzhou, which may be because the strength of typhoons weakened after landfall. The population data in 2010 are obtained from the sixth national population census

(Population Census Office of the National Bureau of Statistics of China), and the 2010 statistical yearbooks of each city in Zhejiang province published by the cities' statistical bureaus. Basic geographical data are obtained from the National Geomatics Center of China.

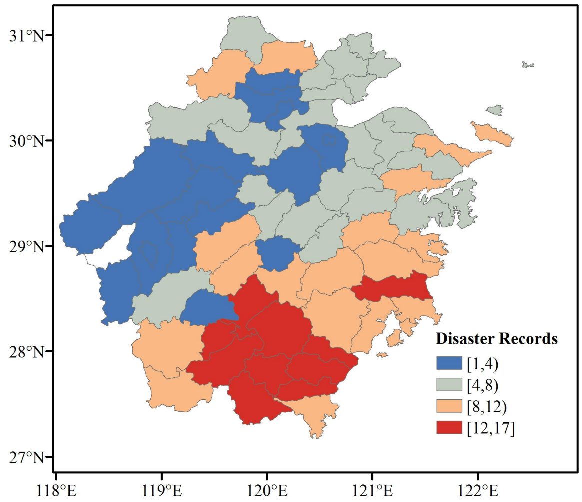

Figure 2. Number of records of typhoon disasters in Zhejiang province from 2004 to 2012.

2.2 Methods

2.2.1 Objective Synoptic Analysis Technique

The widely used objective synoptic analysis technique (OSAT) proposed by Ren et al. (2001, 2007, 2011) is used to identify precipitation due to typhoons in this study. The OSAT method is a numerical technique to separate tropical cyclone induced precipitation from adjacent precipitation areas. Based on the structural analysis of precipitation field, it can be divided into different rain belts. Then, according to the distances between a TC center and these rain belts, typhoon center and each station, typhoon precipitation is distinguished. Lu et al. (2016) improved the OSAT method and applied it to identify typhoon winds. With the application of the OSAT method, daily precipitation and wind data over the mainland of China during 1980 to 2014 are used for identifying typhoon precipitation and wind data.

2.2.2 Canonical Correlation Analysis (CCA)

We use the canonical correlation analysis method to determine the relationship between the affected population, the rate of economic damage, and typhoon precipitation and winds. In statistics, canonical correlation analysis (CCA) is a way of inferring information from cross-covariance matrices. If we have two vectors X = (X1, ..., Xn) and Y = (Y1, ..., Ym) of random variables, and there are correlations among the variables, then CCA can find linear combinations of the Xi and Yj which have maximum correlation with each other (Hardoon et al., 2014). The method was first introduced by Hotelling in 1936 (Hotelling, 1936). The main point of CCA is to separate linear combination of new variables from the two sets of variables. In this case, the correlation coefficient between new variables reaches the maximum. In this paper, we chose factors causing typhoon disasters as a set of variables, and typhoon disaster as another. Under the maximum canonical correlation coefficient, the linear combination coefficients (typical variable coefficients) of factors causing typhoon disasters can be used as weight coefficients of this group of variables. Then we can determine the impact of factors causing typhoon disasters.

2.2.3 Data Standardization

We adopt two methods: Z-score standardization and MIN-MAX standardization. The Z-score standardized method is based on the mean and standard deviation of the raw data. The MIN-MAX standardization is a linear transformation of the original data so that the original value maps the interval [0, 1]. Z-score standardization is used for calculating intensity index of factors causing typhoon disasters. Both typhoon precipitation and typhoon maximum wind speed are standardized by this method. When calculating typhoon disaster comprehensive risk index (R), we use MIN-MAX standardization to standardize the intensity index of the factors causing typhoon disasters (I) and the population vulnerability index (SoVI).

2.2.4 Vulnerability Assessment (SoVI, PCA)

County-level socioeconomic and demographic data are used to construct an index of social vulnerability to environmental hazards named the Social Vulnerability Index (SoVI). Principal Component Analysis (PCA) is the primary statistical technique for constructing the SoVI. The PCA method captures multi-dimensionality by transforming the raw dataset to a new set of independent variables. Then a few components can represent the dimensional data, and underlying factors can be identified easily. These new factors are placed in an additive model to compute a summary score—SoVI (Cutter et al., 2003). Based on the SoVI designed for disaster social vulnerability in America, Chen et al. (2014) collects 29 variables as proxies to build a set of vulnerability indexes for the social and economic environment in China. We use this method to calculate the population vulnerability index for Zhejiang province.

3 Typhoon Disaster Losses and Factors

Based on the distribution of typhoon disaster losses in Zhejiang province from 2004 to 2012 (Figure 3), the affected areas are mainly locates in the southeast corner of the province. The centers with the largest affected population (Fig. 3a), the largest area of affected crops (Fig. 3c) and the highest direct economic losses (Fig. 3d) are in Wenzhou and Taizhou cities, although the losses in Ningbo City are also relatively high. Only part of the plain area is affected by serious agricultural disasters; the other losses are far lower than in the southeast of Zhejiang province. Cangnan in Wenzhou City is the most severely affected, with the highest cumulative death toll (Fig. 3b). The losses in the affected counties are associated with the frequency and intensity of typhoons. We therefore analyze the risk of typhoon precipitation and winds in every county in Zhejiang province to provide a reference dataset for the factors causing typhoon disasters.

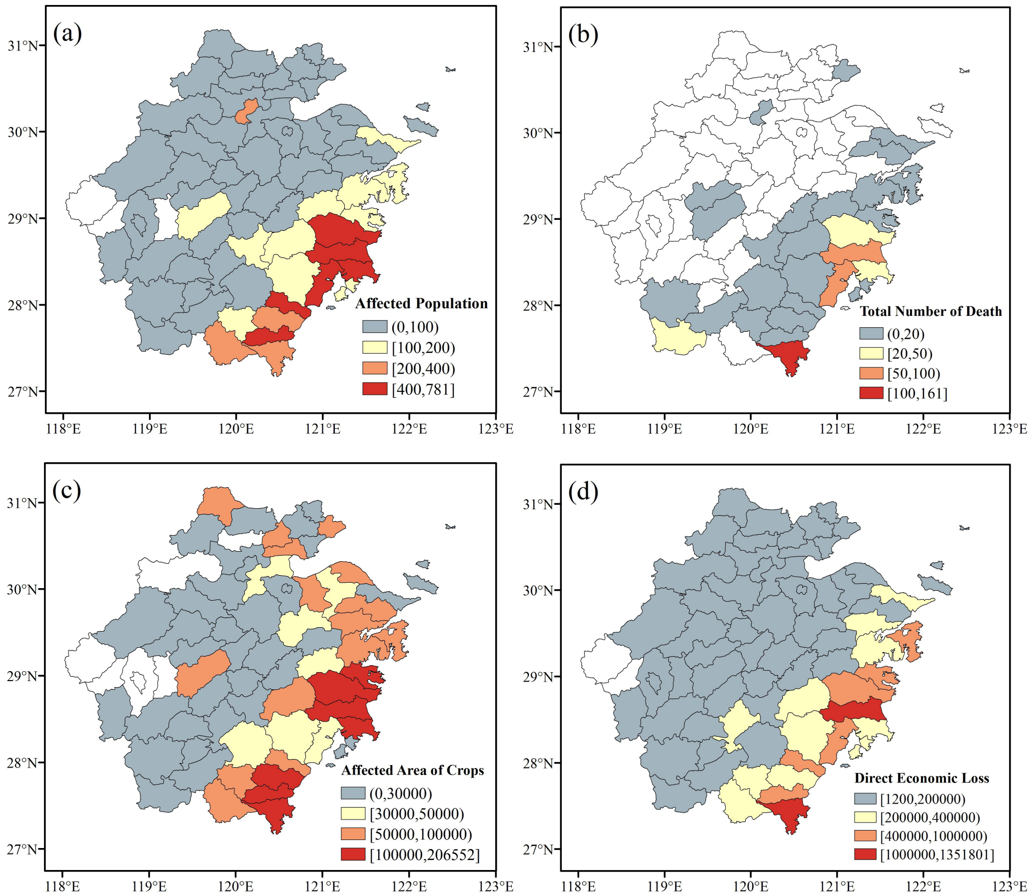

Figure 3. Distribution of typhoon disaster losses in Zhejiang province from 2004 to 2012. (a) Affected population (unit: millions); (b) total number of deaths (unit: person); (c) area of affected crops (unit: hectares); and (d) direct economic losses (unit: millions yuan).

3.1 Risk of Typhoon Rainstorms

The main hazard of typhoon precipitation is concentrated precipitation, so the average duration (days) of typhoon precipitation at each station in Zhejiang province is counted from 1980 to 2014 (Figure 4). The duration of typhoon rainfall is less in inland areas, especially in Quzhou City. Persistent precipitation is concentrated in Wenzhou, Taizhou and Ningbo cities, where there may have been a higher risk of typhoon disasters. Typhoon rainstorm in this study means daily typhoon precipitation over 50mm, and typhoon torrential rainstorm means daily typhoon precipitation over 100mm. The probability is the annual possibility of the occurrence of typhoon rainstorms. Based on the probability of typhoon rainstorms occurring in each county in Zhejiang province (Figure 5), we found that the annual probability of the occurrence of typhoon rainstorms is highest over the southeast coast of Zhejiang province from 1980 to 2014, especially in Taizhou City, where the annual probability is 83%. The annual probability of typhoon rainstorms with precipitation >100 mm is lower, but the distribution of probability is consistent with the rainstorms with lower precipitation. The probability of typhoon torrential rainstorms decreases rapidly in the western and central regions of Zhejiang province, although the range increases. There are three centers of high risk: Taizhou, Wenzhou and Ningbo cities.

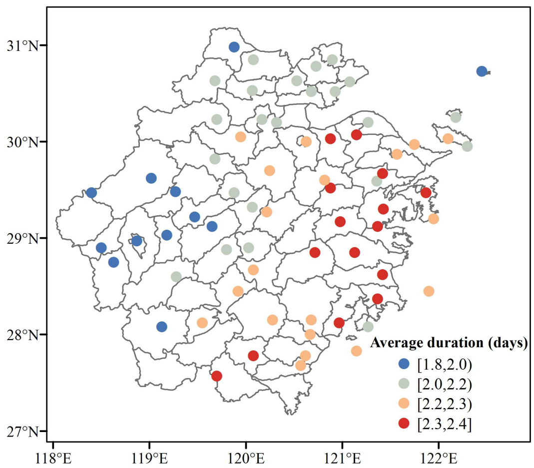

Figure 4. Average duration (days) of typhoon precipitation at each station in Zhejiang province from 1980 to 2014.

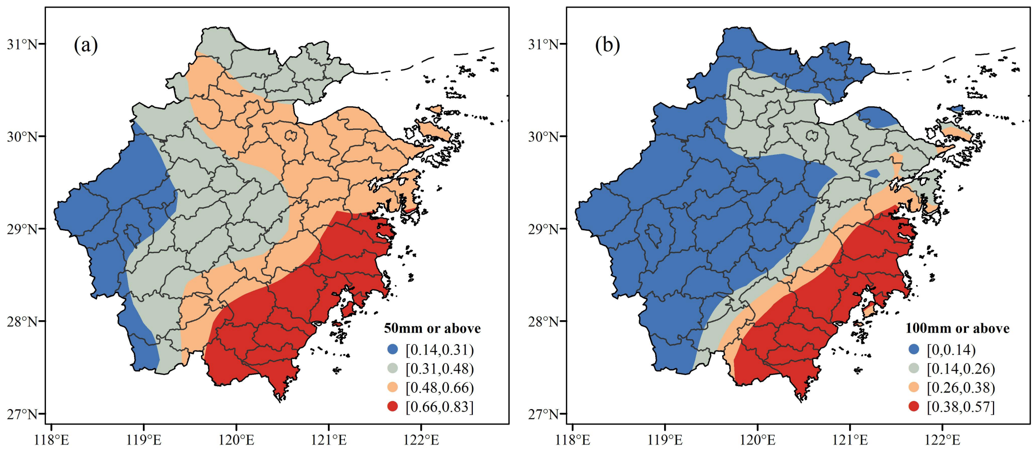

Figure 5. Probability of the occurrence of typhoon rainstorms in Zhejiang province: (a) rainstorms with precipitation >50 mm; and (b) torrential rainstorms with precipitation >100 mm.

3.2 Risk of Typhoon Winds

The average duration (days) of typhoon winds (over 6 grade) is calculated in Zhejiang province (Figure 6). The duration of typhoon winds is relatively short in the central and western regions and the typhoon winds are concentrated in the coastal areas of Wenzhou, Taizhou and Ningbo cities. The longest duration of typhoon winds occurs over the offshore islands.

The main hazard from typhoon winds is manifested in the destructive force of strong winds. Therefore we calculate the probability of annual occurrence of typhoon winds at or above grades 6 and 12 at each station from 1980 to 2014 (Figure 7). Typhoon winds at or above grade 6 mainly occur along the coastal areas, with rare occurrence in the mountainous areas. Meanwhile, the probability of typhoon winds at or above grade 8 is generally 0.5~0.9 along the coast, and below 0.25 in the inland mountainous areas. Typhoons winds at or above grade 10 or 12 are much less likely and only seen in the coastal areas and islands, with a rapidly decreasing probability from the coastal areas to the inland mountainous areas. The areas at high risk of typhoon winds are consistent with those with typhoon rainfall, i.e. Wenzhou, Taizhou and Ningbo cities. The risk of typhoon extreme winds is much higher in coastal areas than inland.

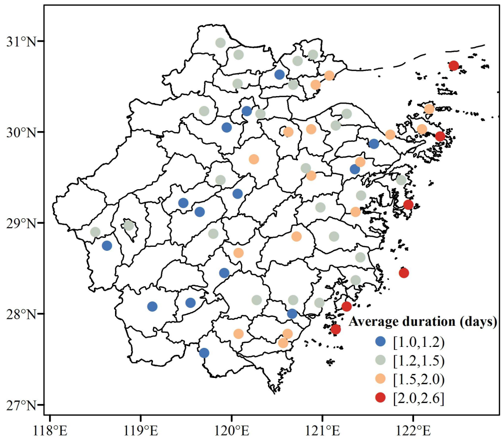

Figure 6. Average duration (days) of typhoon winds (over 6 grade) at each station in Zhejiang province from 1980 to 2014.

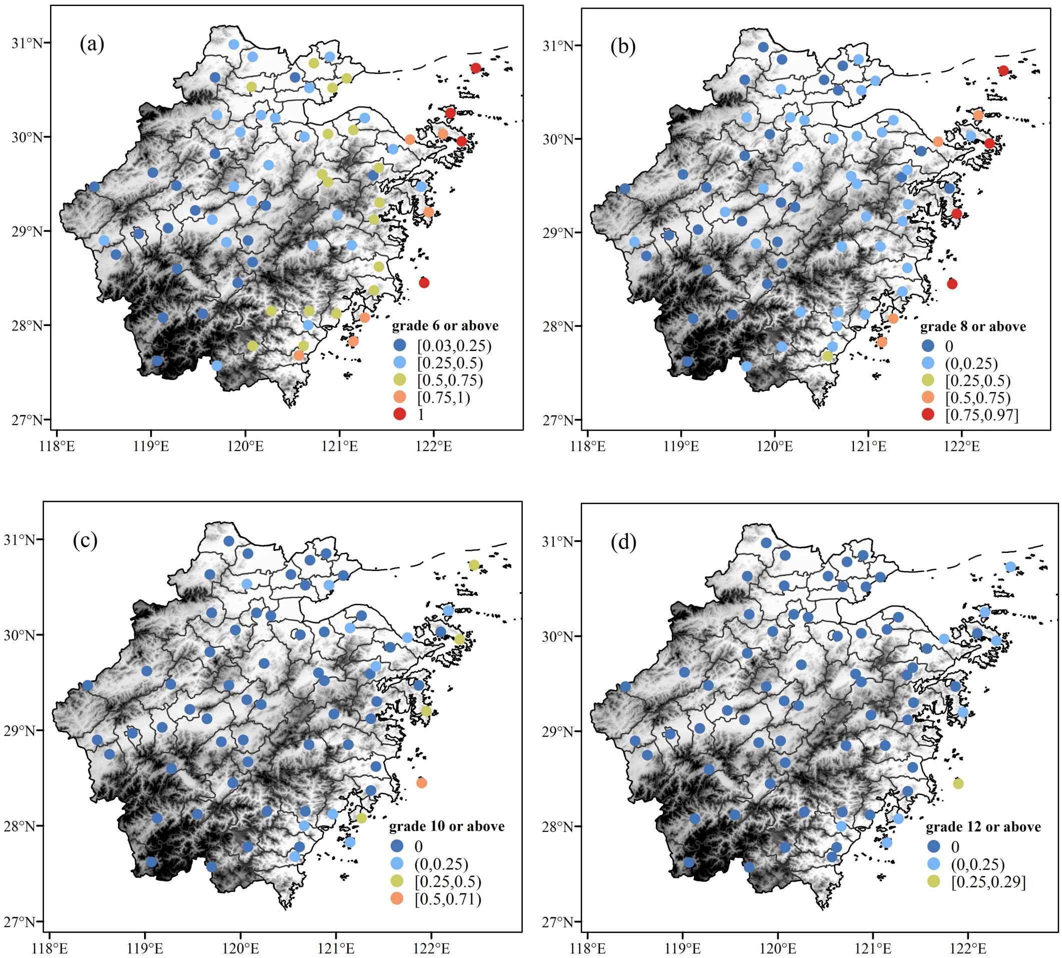

Figure 7. Probability of the occurrence of typhoon winds in Zhejiang province at (a) grade 6 or above, (b) grade 8 or above, (c) grade 10 or above and (d) grade 12 or above.

4 Risk Assessment and Regionalization of Typhoon Disasters

4.1 Intensity Index of Factors Causing Typhoon Disasters

The main factors causing typhoon disasters are rainstorms, winds and storm surges. The level and intensity of a single factor cannot fully represent and describe the impact. Therefore we establish a comprehensive intensity index that include typhoon precipitation and winds. Taking the county as a unit, we select all the typhoons that affected the population of Zhejiang province from 2004 to 2012. The total precipitation and daily maximum wind speed during typhoons measured in each county are used to describe the factors causing typhoon disasters. The total sample size is 322. Using CCA, we determine the impact of typhoon precipitation and winds on the population. We then do CCA for all the typhoons that caused direct economic losses in Zhejiang province from 2004 to 2012, and the total sample size is 404 (Table 1). The effect of typhoon precipitation on both the population and direct economic losses is always greater than that of typhoon winds. By averaging typical coefficients for both precipitation and wind, weight coefficients of 0.85 and 0.65 are obtained within the intensity index for precipitation and winds, respectively.

Table 1. Canonical correlation analysis of factors causing typhoon disasters.

Disastes	Canonical correlation coefficient	Canonical variable coefficient	
		Typhoon precipitation	Typhoon wind
Affected population	0.45	0.84	0.651
Direct economic losses	0.477	0.863	0.655

Based on the weight coefficients in Table 1, an intensity index of factors causing typhoon disasters is established:

$$I = Ax + By \tag{1}$$

where I is the intensity index of factors causing typhoon disasters, X is the standard typhoon precipitation and Y is the maximum wind speed of the typhoon. A and B are the weight coefficients for typhoon precipitation and typhoon winds, respectively. Using Equation (1), we average the intensity indexes of typhoons at each station (Figure 8). Based on the distribution of these average intensity indexes, three high value centers, namely Wenzhou, Taizhou and Ningbo cities, which are consistent with the results of Chen et al. (2011), can be found.

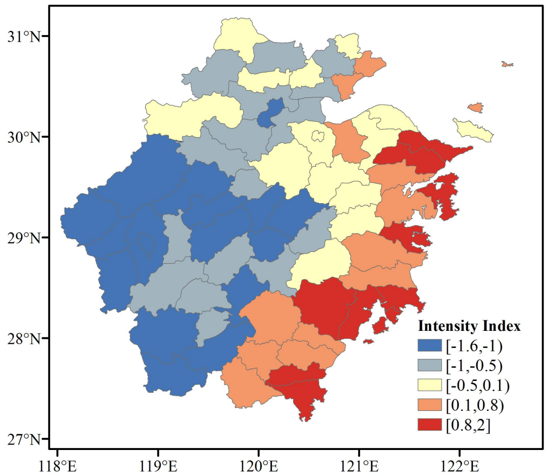

Figure 8. Intensity indices of factors causing typhoon disasters at each station in Zhejiang province.

4.2 Population Vulnerability Index

Natural disasters are social constructions and the basic causes of losses are the attributes of human beings and their social system (Jiang 2014). The index system of Chen et al. (2011) is used to evaluate the vulnerability of Zhejiang province. Based on the extracted population information, 29 variables are identified that may affect vulnerability (Table 2).

Table 2. The 29 variables affecting vulnerability in Zhejiang province.

	variables	Name
1	Per capita disposable income of urban residents (yuan)	UBINCM
2	Percentage of female (%)	QFEMALE
3	Percentage of minority (%)	QMINOR
4	Median age	MEDAGE
5	Unemployment rate (calculated - unemployed population / (unemployed + total population)	QUNEMP
6	Population density	POPDEN
7	Percentage of urban population (%)	QUBRESD
8	Percentage of non-agricultural household population (%)	QNONAGRI
9	Percentage of households that living in rented	QRENT

	houses (%)	
10	Percentage of employees working in primary industries and mining (%)	QAGREMP
11	Percentage of employees working in secondary industries (%)	QMANFEMP
12	Percentage of employees working in tertiary industries (%)	QSEVEMP
13	Household size (person / household)	PPUNIT
14	Percentage of population with college degree (25 years old and older)	QCOLLEGE
15	Percentage of population with high school degree (20 years old and older)	QHISCH
16	Percentage of illiterate people (15 years old and older)	QILLIT
17	Population growth rate (2000-2010)	POPCH
18	Average number of rooms per household (inter / household)	PHROOM
19	Per capita housing construction area (m^2 / person)	PPHAREA
20	Percentage of premises without tap water (%)	QNOPIPWT
21	Percentage of premises without a kitchen (%)	QNOKITCH
22	Percentage of premises without a toilet (%)	QNOTOILET
23	Percentage of premises without a bath (%)	QNOBATH
24	Number of beds per 1000 person in health care institutions	HPBED
25	Number of medical personnel per 1000 resident population	MEDPROF
26	Percentage of people under 5	QPOPUD5
27	Percentage of population over 65 years old	QPOPAB65
28	Population dependency ratio (%)	QDEPEND
29	Percentage of population covered by subsistence allowances (%)	QSUBSIST

After Principal Component Analysis (PCA) of the 29 variables, seven components with eigenvalue >1 are extracted. Based on the variable meanings in each component, these 7 components are named as table 3. The first component, which reflects the income of the population and the employment situation, contribute 30.1% of the total variance. This component is positive because the more property there is in an area, the higher the vulnerability to damage. The second component, which reflects education level of the population, occupies 15.6% of the total variance. This component is negative because if education level is higher, then the population's awareness of disaster prevention and reduction is greater and their vulnerability is lower. The third component, which reflects the number of dilapidated houses, takes up 8.7% of the total variance. This component plays a positive part in vulnerability. The fourth component, which reflects the illiteracy and the number of young people, is positive and represents 8.4% of the total variance. The fifth component, which reflects the household size and the percentage of women, explains 7.7% of the total variance and is positive. The sixth component, which reflects the number of ethnic minorities, contributes 6.1% of the total variance and is positive. The seventh component, which represents 5.3% of the total variance, reflects the unemployment rate and the housing area and is positive.

The total variance explained by these seven components is up to 81.9%, which can be used to represent the population vulnerability of Zhejiang province. The distributions of the first (positive) component and the second (negative) component are shown in Figure 9. Areas with a low employment rate have high vulnerability, but the vulnerability is low in urban areas with higher levels of education. The seven components thus represent the real situation of the population vulnerability in Zhejiang province to the effect of typhoons. The population vulnerability index in Zhejiang province (SoVI) is calculated as:

$$\text{SoVI} = \text{component } 1 - \text{component2} + \text{component } 3 + \text{component } 4 + \text{component } 5 + \text{component } 6 + \text{component } 7 \quad (2)$$

By calculating the vulnerability indexes of each county, the distribution of population vulnerability in Zhejiang province is obtained (Figure 10). The areas with high vulnerabilities are mountainous regions where the economy is relatively undeveloped, whereas the vulnerability is low in cities, such as Hangzhou and Huzhou cities, where there is a greater awareness of disaster prevention and reduction and houses are of high quality.

Table 3. The seven components extracted by PCA.

Components	Contained variables	Name	(Sign)
1	QMANFEMP, UBINCM, QAGREMP, QRENT, POPCH, QDEPEND, QSUBSIST, QPOPAB65, POPDEN, MEDAGE, QNOKITCH, QILLIT, PHROOM, PPHAREA	Employment and poverty	(+)

2	QHISCH, QCOLLEGE, QNONAGRI, QSEVEMP, HPBED, MEDTECH	Education	(-)
3	QNOBATH, QNOTOILET, PPUNIT	Number of dilapidated houses	(+)
4	QILLIT, QDEPEND, QPOPUD5, MEDAGE	Illiteracy and juvenile population	(+)
5	QFEMALE, PHROOM, PPHAREA, QSEVEMP	Household size and ratio of women	(+)
6	QMINOR	Ethnic minority	(+)
7	QUNEMP, QNOPIPWT	Unemployment and housing size	(+)

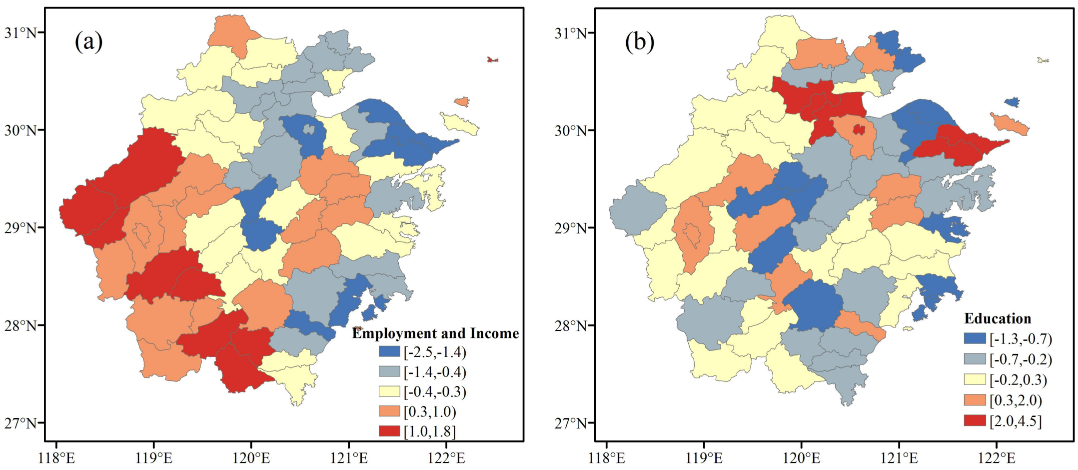

Figure 9. Distribution of population vulnerability index of (a) component 1 (employment and income) and (b) component 2 (education).

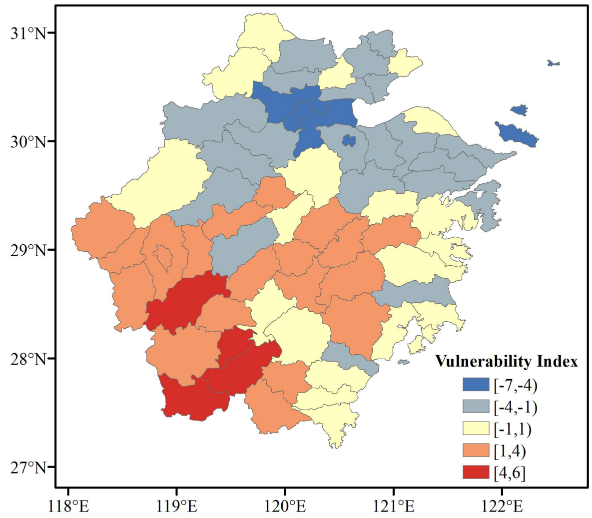

Figure 10. Distribution of population vulnerability index of counties.

4.3 Typhoon Disaster Comprehensive Risk Index and Zoning

The typhoon disaster risk assessment system is mainly composed of the factors causing disasters, the population vulnerability and the environment. In this paper, typhoon disaster comprehensive risk index is obtained by combining the factors causing typhoon disasters and vulnerability, without taking the sensitivity of the environment into account. After standardizing the intensity index of factors causing typhoon disasters and the population vulnerability index, the typhoon disaster comprehensive risk index (R) is obtained as follows:

$$R = \text{intensity index of factors causing typhoon disasters } (I) \times \text{vulnerability index (SoVI)} \quad (3)$$

Based on the comprehensive risk index, five risk grades for typhoon disasters are defined (Table 4) , and risk zoning of typhoon disasters in Zhejiang province has been done as shown in Figure 11. The classification of typhoon disaster risk index is based on the natural breaks method (Jenks) provided by Arcgis.

Table 4. Disaster risk index and grading.

Risk grade:	High	High–medium	Medium	Medium–low	Low
Risk index:	(0.3	0.18–0.3	0.13–0.18	0.07–0.13	(0.07

Figure 11 shows that, the index presents a good reflection of the distribution of typhoon disasters in Zhejiang province (Figure 3), especially in the southeastern coastal areas. The southeast coastal areas face the highest risk, especially in the boundary regions between Zhejiang and Fujian province, and

Taizhou and Wenzhou cities. Overall, the risk of typhoon disasters decreases from the coast to inland areas. Cities are at medium to low risk as a result of their developed economy, high-quality houses and better educated population. The inland mountainous areas have a high vulnerability. Although they are not directly affected by typhoons, they are still in the middle risk areas as a result of their poorly developed economy.

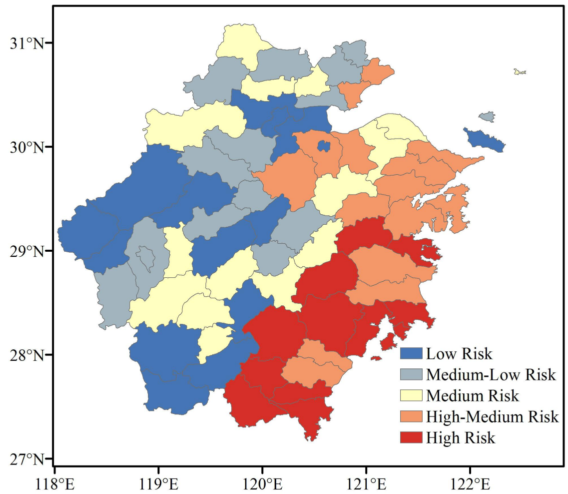

Fig. 11. Risk zoning of typhoon disasters in Zhejiang province.

5 Discussion and Conclusions

(1) An intensity index of factors causing typhoon disasters is developed, with highest values in Wenzhou, Taizhou and Ningbo cities. A comparison between the distributions of the intensity index and actual typhoon disasters in Zhejiang province from 2004 to 2012 shows that the index is a good reflection of the possibility of typhoon disasters.

(2) Seven components are extracted after PCA of 29 variables affecting vulnerability. These seven factors represent 81.9% of the total variance and are a good reflection of the index of population vulnerability in Zhejiang province. Southwestern Zhejiang is the most vulnerable as it has a relatively undeveloped economy, more mountainous areas and a higher risk of geological disasters. Vulnerabilities are lower in cities as a result of better disaster prevention and reduction measures and better educated population.

(3) Typhoon disaster comprehensive risk index is obtained by combining the factors causing typhoon disasters and population vulnerability. Based on the comprehensive risk index, risk zoning of

typhoon disasters in Zhejiang province is achieved. The southeast coastal areas are at high risk, especially the boundary regions between Zhejiang and Fujian province, and Taizhou and Wenzhou cities. The risk of typhoon disasters decreases quickly from coastal areas to inland regions. Cities are at medium to low risk because of their developed economy, high-quality houses and better educated population.

Although some interesting results have been obtained in this study, there are still some problems that require further studies. As a result of the limited data on typhoon disasters, it is currently impossible to give a long time trend for high-resolution typhoon disaster analysis. It is also unclear whether this methodology can be applied to other regions.

Acknowledgments

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References

Chen, H. Y., Yan, L. N., and Lou, W. P.: On assessment indexes of the strength of comprehensive impacts of tropical cyclone disaster-causing factors, Journal of Tropical Meteorology, 27(1), 139-144, 2011. (in Chinese)

Chen, W. F., Xu, W., and Shi, P. J.: Risk assessment of typhoon disaster at county level in the Yangtze river delta of china, Journal of Natural Disasters, 4, 77-83, 2011.

Chen, W. F., Duan, Y. H., and Lu, Y.: Review on Tropical Cyclone Risk Assessment, Journal of Catastrophology, 32(4), 2017. (in Chinese)

Chen, X.: Vulnerability diagnosis and assessment of typhoon disaster system at coastal regions, a case study of Fujian province, Journal of Catastrophology, 22(3), 6-10, 2007. (in Chinese)

Cutter, S. L., Boruff, B. J., and Shirley, W. L.: Social Vulnerability to Environmental Hazards, Social Science Quarterly, 84(2):242-261, 2003.

Ding, Y. and Shi, P. J.: Fuzzy risk assessment model of typhoon hazard. Journal of Natural Disasters, 11(1), 34-43, 2002. (in Chinese)

Emanuel, K. A.: The maximum intensity of hurricanes, Journal of the Atmospheric Sciences, 45(7), 1143-1155, 1988.

Emanuel, K. A.: The dependence of hurricane intensity on climate, American Institute of Physics, 277, 25-33, 1992.

Emanuel, K. A.: Sensitivity of tropical cyclones to surface exchange coefficients and a revised steady-state model incorporating eye dynamics, Journal of the Atmospheric Sciences, 52(22), 3969-3976, 1995.

Eunjeong, C. and Ying, M.: Comparison of three western North Pacific tropical cyclone best track datasets in seasonal context, Journal of the Meteorological Society of Japan, 89(3):211-224, 2009.

Fang, W. H. and Lin, W.: A review on typhoon wind field modeling for disaster risk assessment, Progress in Geography, 32(6), 852-867, 2013. (in Chinese)

Fang, W. H. and Shi, X. W.: A review of stochastic modeling of tropical cyclone track and intensity for disaster risk assessment, Advances in Earth Science, 27(8), 866-875, 2012. (in Chinese)

Friedman, D. G.: Natural hazard risk assessment for an insurance program, The Geneva Papers on Risk and Insurance - Issues and Practice, 9(1), 57-128, 1984.

Hardoon, D. R., Szedmak, S., and Shawetaylor, J.: Canonical Correlation Analysis: An Overview with Application to Learning Methods, Neural Computation, 16(12):2639-2664, 2014.

Hendrick, R. L. and Friedman, D. G.: Potential impacts of storm modification on the insurance industry, University of Chicago Press, Chicago, 227-248, 1966.

Holland, G. J.: The maximum potential intensity of tropical cyclones, Journal of Atmospheric Sciences, 54(21), 2519-2541, 1997.

Hotelling, H.: Relations between two sets of variates, Biometrika, 28(3/4), 321-377, 1936.

Howard, R. A., Matheson, J. E., and North, D. W.: The decision to seed hurricanes. Science, 176(4040), 1191-202, 1972.

Huang, W. K. and Wang, J. J.: Typhoon damage assessment model and analysis in Taiwan, Natural Hazards, 79(1), 497-510, 2015.

IPCC: Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation, Cambridge, UK, and New York, NY, USA, 2012.

Jiang, T., Li, X. C., and Chao, Q. C.: Highlights and understanding of climate change 2014: impacts, adaptation, and vulnerability, Advances in Climate Change Research, 10(3), 157-166, 2014.

Kafali, C. and Jain, V.: A Methodology for Estimating Typhoon Losses to Building Environment in Japan, in: Proceedings of the 11th Americas Conference on Wind Engineering, San Juan, Puerto Rico, 2009.

Kunreuther, H. and Roth, R. J.: The Status and Role of Insurance Against Natural Disaster in the United States, Washington Joseph Henry Press, 1998.

Lei, X. T., Chen, P. Y., Yang, Y. H., and Qian, Y. Z.: Characters and objective assessment of disasters caused by typhoons in china, Acta Meteorologica Sinica, 67(5), 875-883, 2009. (in Chinese)

Li, S. H. and Hong, H. P.: Use of historical best track data to estimate typhoon wind hazard at selected sites in China, Natural Hazards, 76(2):1395-1414, 2015.

Liang, B. Q., Liang, J. P., and Wen, Z. P.: Study of typhoon disasters and its affects in china, Journal of Natural Disasters, 1, 84-91, 1995. (in Chinese)

Liang, B. Q. and Fan, Q.: A fuzzy mathematic of the disaster bytropical cyclones, Journal of Tropical Meteorology, 4, 305-311, 1999. (in Chinese)

Liu, T. J. and Gu, J. Q.: A statistical analysis of typhoon disasters in Zhejiang province, Journal of

Catastrophology, 17 (4): 64-71, 2002. (in Chinese)

Lu, Y., Zhu, W. J., Ren, F. M., and Wang, X.: Changes of Tropical Cyclone High Winds and Extreme Winds During 1980-2014 over China, Advances in Climate Change Research, 12(5), 413-421, 2016. (in Chinese)

Niu, H. Y., Liu, M., and Lu, M.: Risk assessment of typhoon disasters in china coastal area during last 20 years, Scientia Geographica Sinica, 31(6), 764-768, 2011. (in Chinese)

Pielke, R. A. and Landsea, C. W.: Normalized hurricane damages in the united states: 1925-95, Weather & Forecasting, 13(3), 621--631, 1998.

Pielke, R. A, Gratz, J., and Landsea, C. W.: Normalized hurricane damage in the united states: 1900–2005, Natural Hazards Review, 9(1), 29-42, 2008.

Pita, G., Pinelli, J. P., and Gurley, K.: State of the art of hurricane vulnerability estimation methods: a review, Natural Hazards Review, 16(2), 04014022, 2014.

Ren, F. M., Byron, G., and David, E.: A Numerical Technique for Partitioning Cyclone Tropical Precipitation, Journal of Tropical Meteorology, 17(3), 308-313, 2001. (in Chinese)

Ren, F. M., Wang, Y., Wang, X., and Li, W.: Estimating Tropical Cyclone Precipitation from Station Observations, Advances in Atmospheric Sciences, 24(4), 700-711, 2007.

Ren, F. M., Wang, X. L., Chen, L. S., and Wang, Y. m.: Tropical cyclones landfalling on mainland China, Hainan and Taiwan and their correlations, Acta Meteorologica Sinica, 66 (2): 224-235, 2008. (in Chinese)

Ren, F. M. and Wu, G. X.: Tropical cyclone over the past 60 years, China Meteorological Press, Beijing, 2011. (in Chinese)

Su, G. L., Miao, C. M., and Mao, Y. D.: Typhoon hazard in zhejiang province and risk assessment of its influence on agriculture, Journal of Natural Disasters, 17(5), 113-119, 2008. (in Chinese)

Vickery, P. J., Masters, F. J., and Powell, M. D.: Hurricane hazard modeling: the past, present, and future, Journal of Wind Engineering & Industrial Aerodynamics, 97(7–8), 392-405, 2009.

Wang, X. R., Wang, W. G., and Ma, Q. Y.: Model for general grade division of typhoon disasters and application, Meteorological Monthly, 36(1), 66-71, 2010. (in Chinese)

WMO: Seventh International Workshop on Tropical Cyclones (IWTC-VII), available at: http://www.wmo.int/pages/prog/arep/wwrp/tmr/IWTC-VII.html/, 2010.

Xu, X., Sun, D., and Guo, T.: A systemic analysis of typhoon risk across china, Natural Hazards, 77(1), 461-477, 2015.

Yin, Y. Z. and Li, H. L.: Preliminary study on pre-evaluation method of typhoon disaster in China, Meteorological Monthly, 43(6):716-723, 2017. (in Chinese)

Yin, Z. E., Xu, S. Y., Yin, J., and Wang, J.: Small-scale Based Scenario Modeling and Disaster Risk Assessment of Urban Rainstorm Water-logging, Acta Geographica Sinica, 65(5), 553-562, 2010. (in Chinese)

Zhang, Q., Wu, L. G., and Liu, Q. F.: Tropical cyclone damages in china 1983-2006, Bulletin of the American Meteorological Society, 90(4), 489-495, 2009.