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 three parts: "Response to Reviewer 1", "Response to Reviewer 3", and a marked-up 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. What is typhoon disaster? Many losses along the coastal countries are caused by storm surges and waves. So, how representative do rainfall and wind are?

We do appreciate the comment.

(1) For the first question, the typhoon disasters in this paper refer to affected population or direct economic losses caused by typhoons in Zhejiang province. In order to clarify the criteria for typhoon disaster, we have added following definition in the beginning of the abstract.

"a study on risk zoning of typhoon disasters (typhoon disasters in this paper refer to affected population or direct economic losses caused by typhoons in Zhejiang province) is carried out."

(2) For the second question, we explain this from following three aspects.

A. In this paper, we agree that typhoon disasters usually cause three disasters: heavy rain, high winds and storm surges, which has been pointed out at the beginning of "Introduction".

B. The reasons for choosing typhoon rain and typhoon wind are mainly based on following two considerations: 1) the typhoon storm surge disaster in Zhejiang province is relatively small compared to the other two disasters; 2) considering the consistency of coastal and inland areas in the study, we finally choose considering the effects of typhoon rain and typhoon wind. Therefore, the typhoon rain and typhoon wind in this paper can basically represent the factors causing typhoon disasters.

C. This is the limitation of the study, and we will explore the role of storm surges in future work.

(3) To explain this clearly in this paper, we have added the following explanation at the end of section 1:

"This paper does not consider the impact of storm surges. The factors causing typhoon disasters are represented by typhoon rain and typhoon wind."

And the following discussions have been added at the end of section 5 "Discussion and Conclusions".

"This paper mainly considers the effects of typhoon rain and typhoon wind, without considering the impact of storm surge. This is the limitation of the study, and we will explore the role of storm surges in future work."

2. "Risk of Typhoon Rainstorms" shall be "Probability of Typhoon Rainstorms". So does "Risk of Typhoon Winds".

Thanks so much for the suggestion. According to the suggestion, "Risk of Typhoon Rainstorms" all have been changed into "Probability of Typhoon Rainstorms". So does "Risk of Typhoon Winds".

3. Risk Assessment (by using hazards, i.e., rainfall, wind and social vulnerability) results shall be validated with historical losses. How good/valid/bad/invalid is the assessment?

Thanks for your suggestion. In this paper, typhoon disaster comprehensive risk index is obtained by combining the factors causing typhoon disasters and vulnerability, which is a dimensionless result. Based on the comprehensive risk index, five risk grades for typhoon disasters are defined.

To illustrate the quality of the assessment, the distribution of typhoon disaster losses in Zhejiang province from 2004 to 2012 are given at the beginning of section 3.

Comparing the high and low value areas of Figure 3 and Figure 11, we find that the index in Figure 11 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.

We have given a conclusion at the beginning of the last paragraph in Section 4.3 to clarify that the evaluation results are good.

4. Social vulnerability has always been changing along time. The authors developed the index based on methods of past studies. The question is, how representative of the data (of one year, of several years) could be? Explanation shall be given. (btw, simplified social vulnerability as an index can be useful, but it could also be highly misleading for many risk management scenarios.)

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. The census data is updated every six years, and the 2010 census results are exactly during 2004-2012 which is the research period. Therefore, the population data for 2010 in this paper can basically represent the population vulnerability of this period. In addition, 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.

To clarify the representative of the population data used in this study, we have added following sentences in section 2.1.2 "Disaster and Social Data".

"The census data is updated every six years, and the 2010 census results are exactly during 2004-2012 which is the research period. Therefore, the population data for 2010 in this paper can basically represent the population vulnerability of this period.".

5. In this paper, there are quite some mis-used/well-defined terms (risk).

Thanks very much for the suggestion.

According to the suggestion, "Risk of Typhoon Rainstorms" all have been changed into "Probability of Typhoon Rainstorms". So does "Risk of Typhoon Winds", and the corresponding conclusions and abstracts have been revised. The specific amendments are as follows.

"3.1 Risk of Typhoon Rainstorms" have been changed into "3.1 Probability of Typhoon Rainstorms".
"3.2 Risk of Typhoon Winds" have been changed into "3.2 Probability of Typhoon Winds".
The last sentence of section 3.1 have been modified as "There are three centers of high probability: Taizhou, Wenzhou and Ningbo cities.".
The last two sentences of section 3.2 have been modified as "The areas at high probability of typhoon winds are consistent with those with a high probability of typhoon rain, i.e. Wenzhou, Taizhou and Ningbo cities. The probability of typhoon extreme winds is much higher in coastal areas than inland.".

Response to Reviewer 3

General Comments:
1. Manuscript required a lot of editing for proper English language usage. Some of this reviewer's recommended changes may have changed the intent of the authors. If that is the case, then the sentence or paragraph should be rewritten.
We do appreciate the comment. Based on your suggestions, we have rewritten or revised the paper one by one. Details are shown in answers to "Specific Comments".

2. The study mentions storm surge as one of the three factors affecting "typhoon" disasters, yet there is no assessment of the effects of storm surge. Storm surge kills many more people than wind. If wind intensity is used as a proxy for storm surge, that should be indicated. Tropical cyclone size is an important consideration for storm surge and is sometimes more important than intensity. This should be mentioned as a limitation of the study.
Thanks very much for the comments and suggestions. We explain this from following three aspects.
A. In this paper, we agree that typhoon disasters usually cause three disasters: heavy rain, high winds and storm surges, which has been pointed out at the beginning of "Introduction".
B. The reasons for choosing typhoon rain and typhoon wind are mainly based on following two considerations: 1) the typhoon storm surge disaster in Zhejiang province is relatively small compared to the other two disasters; 2) considering the consistency of coastal and inland areas in the study, we finally choose considering the effects of typhoon rain and typhoon wind. Therefore, the typhoon rain and typhoon wind in this paper can basically represent the factors causing typhoon disasters.
C. This is the limitation of the study, and we will explore the role of storm surges in future work.
In addition, To explain this clearly in this paper, we have added the following explanation in original section 1:
"This paper does not consider the impact of storm surges. The factors causing typhoon disasters are represented by typhoon rain and typhoon wind."
And the following discussions have been added at the end of section 5 "Discussion and Conclusions".
"This paper mainly considers the effects of typhoon rain and typhoon wind, without considering the impact of storm surge. This is the limitation of the study, and we will explore the role of storm

surges in future work."

3. The first line of the Introduction equates "typhoon" to "tropical cyclone". The term "tropical cyclone" generally includes tropical depressions, tropical storms, and typhoons. This should be clarified at the beginning.

Thanks for your comment. According to your suggestion, we have clarified "typhoon" at the beginning of "Abstract". Following sentence has been added.

" In this paper, typhoon simply means tropical cyclone.".

4. How do you define a disaster? What are the criteria?

Thanks for your question. The typhoon disasters in this paper refer to affected population or direct economic losses caused by typhoons in Zhejiang province. In order to clarify the criteria for typhoon disaster, we have added following definition in the first sentence of the abstract.

"a study on risk zoning of typhoon disasters (typhoon disasters in this paper refer to affected population or direct economic losses caused by typhoons in Zhejiang province) is carried out."

5. For consistency, use either "indices" or "indexes".

Thanks for your comment. According to your suggestion, we use "indexes" uniformly in this paper.

Specific Comments:

1. Abstract:

a. Lines 463-464: Doesn’t make sense: Do you mean "Assuming that risk signifies probability of hazard events and that future probability is the same as historical probability for a specific period, we can understand risk by learning from past events." If not, please rewrite the sentence.

b. Line 465: "…over mainland China during 1980-2014 and disaster and …"

c. Line 470: "The above analyses…"

d. Line 474: Locate Hangzhou Bay on your map.

e. Lines 475-477: Move this sentence to the end of the paragraph (after line 482).

Reply:

a. Your understanding is what we means. Supposing future probability is the same as historical probability for a specific period, we can understand risk by learning from past events.

Suggestion b and c have been applied in this paper.

d. We have located Hangzhou Bay on the map according to the suggestion.

e. Considering that we have analyzed population vulnerability before discussing typhoon disaster comprehensive risk of Zhejiang province, we tend not to move this sentence to the end of the paragraph.

2. Introduction:

a. Lines 486-487: See Iten 3 under General Comments.

b. Line 490: Delete "the".

c. Line 497: Delete "had"

d. Line 504: I believe that this reference is for R. A. Pielke, Jr. (not his father Sr.). Check this out here and at lines 857-860 in the reference section.

e. Lines 521: Consider making two separate sentences: "…disaster loses. Few studies…"

Reply:

a. According to your suggestion, we have clarified "typhoon" at the beginning of "Abstract".

Amendments have been made according to the suggestion b c and e.

d. Line 504: we have checked this out here and revised Lines 857-860 in the reference section as follows.

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

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

3. Data and Methods:

a. Line 531: Do you mean "north of" instead of "south of"?

b. Line 534 and Figure 1: Identify Hangzhou Bay on the map and add to Legend. The legend is not as clear as stating "(in red)" after ‘major cities" and add "in provinces (in black)". Also, does the scale need to be in kilometers as well as in miles?

c. Line 540: "…from the National…"

d. Line 544: ";;;from 2004 to 2012. So when calculating the intensity index of factors causing typhoon disasters, the time…"

e. Lines 547-549: Do you mean: "…(see details in section 3.1 and 3.2), we assume that future probability is the same…"? Otherwise, please rewrite.

f. Line 551: "…period for both. In addition, the Objective Synoptic Analysis Technique (OSAT) method…"

g. Line 552: "…details…"

h. Line 559: "…being 17 at XXXX" ; add either Wenzhou or Taizhou. Also, se General comments Item 4.

i. Where is "Quzhou"; indicate on the map.

j. Figure 2, line 566: See comment in General Comments Line 4.

k. Line 572: "…structural analysis of a precipitation…

l. Line 584: "…combinations…"

m. Line 595: "…calculating the intensity…"

n. Line 597: "…calculating the typhoon…"

o. Lines 592-599: Reference "MIN-MAX standardization" and "Z-score standardization" techniques’ Explain rationale for selecting the Z-score technique as you did for the MAXMIN technique.

p. Lines 607-608: Consider: "Based on various SoVIs derived for disaster social vulnerability in America, Chen et al. (2014) selected 29 variables as proxies…"

q. Line 609: Consider: "…. We then use these vulnerability indexes to calculate the population…"

Reply:

a. Yes, it should be "north", we have modified it.

b. According to the suggestions, we have redrawn Figure 1.

Suggestion c d f g h k l m n j p and q have been applied in this paper.

e. Yes, your understanding is what we mean.

h. To clarify the criteria for typhoon disaster, we have added following definition in the first sentence of the abstract.

"a study on risk zoning of typhoon disasters (typhoon disasters in this paper refer to affected population or direct economic losses caused by typhoons in Zhejiang province) is carried out."

i. "Quzhou" have been indicated on the original map, please check.

o. To explain rationale for selecting the Z-score technique, we have rewrote sentence "The Z-score standardized method is based on the mean and standard deviation of the raw data.".

"The Z-score standardized method is based on the mean and standard deviation of the raw data, which is prepared for CCA method.".

4. Typhoon Disaster Losses and Factors:

a. Page 19: Discuss Figure 3c and 3d in the text. Do not need the term "unit" in the caption.

b. Line 630: Locate "Quzhou city" on the map.

c. Line 632: "…typhoon disasters, "typhoon rainstorm" means…and "torrential rainstorm" means…"

d. Lines 652-661: I assume that "grades" pertains to some kind of typhoon wind damage scale. Is that correct. In any event, you need to define wind values for Grades 6, 8, 10, and 12.

e. Line 661: "…and are only…"

f. Line 663: Do you mean: "…with those with a high risk of typhoon…"

g. Line 667: Rewrite: "…typhoon winds of (a) grade 6 or above, (b) grade 8 or above, (c) grade 10 or above, and (d) grade 12 or above."

Reply:

a. According to the suggestions, we have added following discuss of Figure 3c and 3d in the text.

"According to the statistical yearbooks of each city in Zhejiang province, Jiaxing, Shaoxing, Hangzhou in the northeast, and Wenzhou, Jinhua and Taizhou in the southwest are the regions with the largest agricultural planting area, with more agricultural population in the southwest. Only parts of the plain area were affected by serious agricultural disasters in the northeast. The agricultural disaster areas in the southwest are wider. (Fig. 3c). According to the main indicators of Zhejiang's national economy (total GDP and per capita GDP), the central cities such as Hangzhou in the northeast had the most developed economy, and the urban economies of Wenzhou and Taizhou in the southwest were also relatively good. However, the economic losses in southwestern Zhejiang are severe, much higher than in the northeastern cities. (Fig. 3d).".

b. "Quzhou" have been indicated on the original map, please check.

c. To clarify the criteria for typhoon disaster, we have added a definition in the first sentence of the abstract.

d. and g. According to national standards of China for tropical cyclone ratings (GBT 19201-2006), tropical cyclones are classified into six grades according to the maximum wind speed on the ground near the center, including Grade 6-7, Grade 8-9, Grade10-11, Grade 12-13, Grade 14-15 and Grade 16 or above. In this paper, we give 4 grades to describe typhoon winds in Zhejiang province. To clarify these grads, we have added definitions in Figure 7 as follows.

"Figure 7. Probability of the occurrence of typhoon winds in Zhejiang province at (a) grade 6 or above (≥ 10.8 m/s), 672 (b) grade 8 or above (≥ 24.5 m/s), (c) grade 10 or above (≥ 32.7 m/s) and (d) grade 12 or above (≥ 41.5 m/s) ".

Suggestion e and f have been applied in this paper.

5. Risk Assessment and Regionalization of Typhoon Disasters

a. Line 676: Are factors and hazards used interchangeably? Storm surge is mentioned again as a "main factor", yet there is not storm surge losses or assessments in then study.

b. Line 680: "…includes…"

c. Table 1, line 690, first row of Table: Spelling/typo: "Disasters"

d. Lines 699-700: "…and Ningbo cities are identified, which is consistent with the nresults of Chen et al. (2011).…"

e. Line 708, Table 2: Define how "primary", "secondary' and "tertiary" industries differ.

f. Lines 744 and 766, Figures 10 and 11: Why is the island northeast of Ningbo city of "low risk", while Ningbo is medium to high risk?

g. Lines 777-778: "…and a better educated population."

h. Line 787: "…further study…."

Reply:

a. Yes, factors and hazards here can used interchangeably. However, we use "factors" uniformly in this part, which represent typhoon precipitation and typhoon wind causing disasters.

For the second question, this paper mainly considers the effects of typhoon precipitation and typhoon wind, without considering the impact of storm surge, which have been answered in General Comments 2. To make it clear, we modified this sentence as follows.

"The main factors causing typhoon disasters, which are considered in this study, are rainstorms and winds.".

Suggestion b c d and g h have been applied in this paper.

e. The definitions of "primary", "secondary' and "tertiary" industries are formulated in accordance with the National Economic Industry Classification (GB/T4754-2002). This is a consensus, so it is not specified in the Table 2. The primary industry refers to agriculture, forestry, animal husbandry and fishery. The secondary industry refers to the mining, manufacturing, electricity, gas and water production and supply industries, and the construction industry. The tertiary industry refers to other industries except the primary and secondary industries.

f. The island northeast of Ningbo city is Zhoushan city. Typhoon disaster comprehensive risk index is obtained by combining the factors causing typhoon disasters and population vulnerability, and these two indexes in Ningbo city are higher than in Zhoushan. According to the statistical yearbooks of each city in Zhejiang province, the population density of Ningbo City is much larger than that of Zhoushan, where population was more vulnerable. In addition, Ningbo city was more affected by typhoon and precipitation and typhoon wind in 2004-2012. So Zhoushan city is low risk, while Ningbo is medium to high risk.

6 References:

a. Lines 798, 846, and 888: Capitalize: "China".

b. Line 859: Capitalize "United States"

c. Lines 857-860 Check Pielke Jr vice Pielke (the father).

Reply:

Suggestions have been applied in this paper.

Risk Zoning of Typhoon Disasters in Zhejiang Province, China

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Abstract In this paper, typhoon simply means tropical cyclone. 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 and , disaster and social data at the county level in Zhejiang province from 2004 to 2012, a study on risk zoning of typhoon disasters– (typhoon disasters in this paper refer to affected population or direct economic losses caused by typhoons in Zhejiang province) 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 indicesindexes, a comprehensive risk index for typhoon disasters is obtained and used to zone areas of risk. The aAbove 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

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medium-risk category for vulnerability.

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

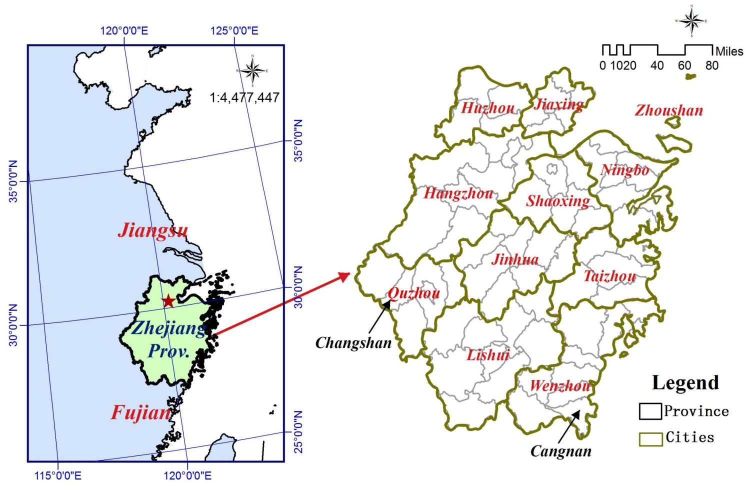
Major risk assessment models include the disaster risk index system of the United Nations Development Program (global scale, focusing on human vulnerability), the European multiple risk assessment (with emphasis on factors causing disasters and vulnerability) and the American HAZUS-MH hurricane module 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~~indexes 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. F 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. This paper does not consider the impact of storm surges. The factors causing typhoon disasters are represented by typhoon rain and typhoon wind. 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 north to Fujian province, which is one of the most economically powerful provinces in China.



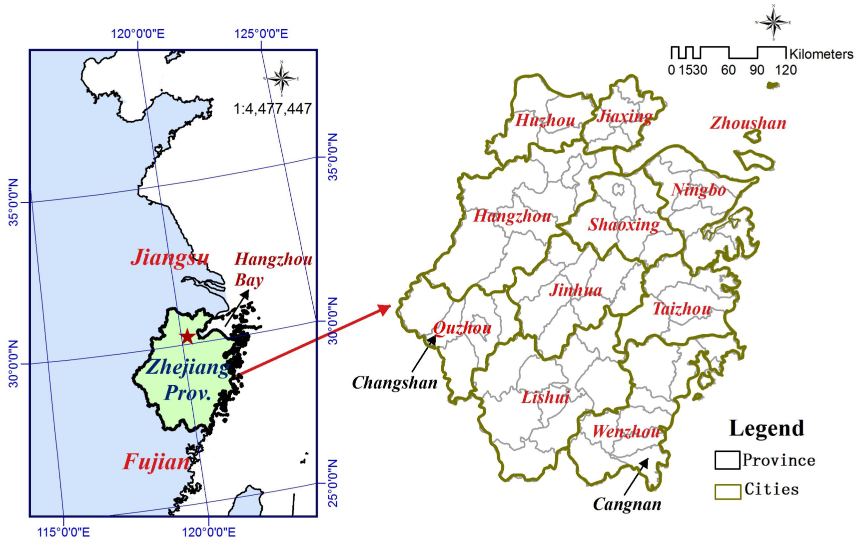


Figure 1. Maps of Zhejiang province, China showing location and major cities.

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 the 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, the 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 Objective Synoptic Analysis Technique (OSAT) method need to identify typhoon wind and precipitation from a wider range than Zhejiang province (please see details 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 at Wenzhou. 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. The census data is updated every six years, and the 2010 census results are exactly during 2004-2012 which is the research period. Therefore, the population data for 2010 in this paper can basically represent the population vulnerability of this period. Basic geographical data are obtained from the National Geomatics Center of China.

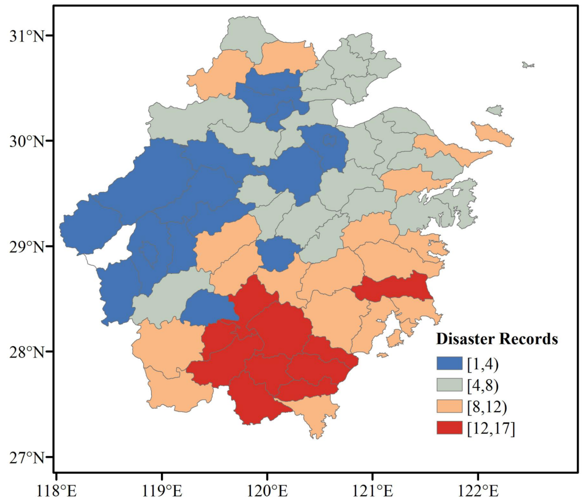


Figure 2. Number of records of typhoon disasters in Zhejiang province from 2004 to 2012.

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 combinations 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

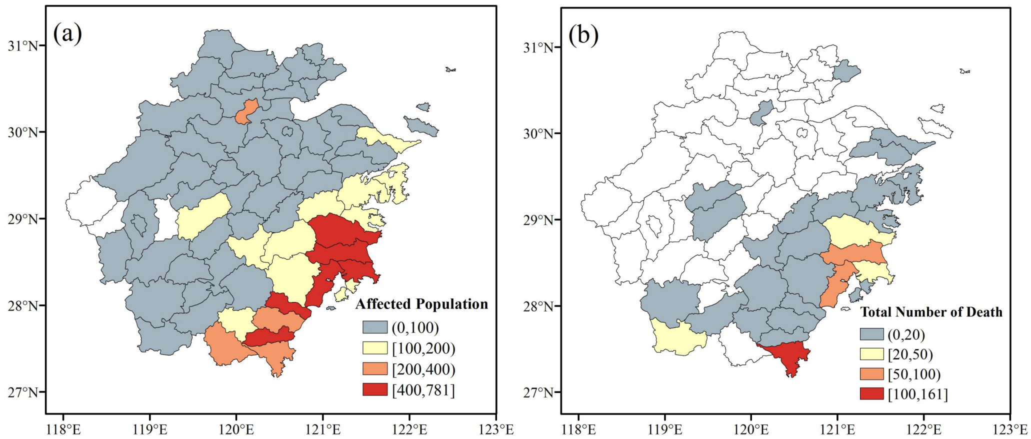
We adopt two methods: Z-score standardization and MIN-MAX standardization. The Z-score standardized method is based on the mean and standard deviation of the raw data, which is prepared for CCA method. The MIN-MAX standardization is a linear transformation of the original data so that the original value maps the interval [0, 1]. Z-score standardization is used for calculating the intensity index of factors causing typhoon disasters. Both typhoon precipitation and typhoon maximum wind speed are standardized by this method. When calculating the 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 various SoVIs derived 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 then use these vulnerability indexes 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). According to the statistical yearbooks of each city in Zhejiang province, Jiaxing, Shaoxing, Hangzhou in the northeast, and Wenzhou, Jinhua and Taizhou in the southwest are the regions with the largest agricultural planting area, with more agricultural population in the southwest. Only parts of the plain area were affected by serious agricultural disasters in the northeast. The agricultural disaster areas in the southwest are wider. (Fig. 3c). According to the main indicators of Zhejiang's national economy (total GDP and per capita GDP), the central cities such as Hangzhou in the northeast had the most developed economy, and the urban economies of Wenzhou and Taizhou in the southwest were also relatively good. However, the economic losses in southwestern Zhejiang are severe, much higher than in the northeastern cities. (Fig. 3d). 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.



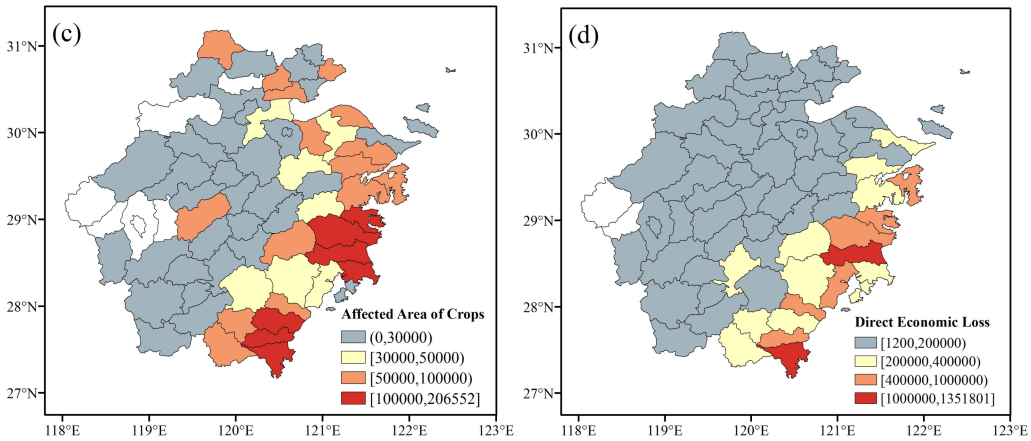


Figure 3. Distribution of typhoon disaster losses in Zhejiang province from 2004 to 2012. (a) Affected population (~~unit:~~ millions); (b) total number of deaths (~~unit:~~ person); (c) area of affected crops (~~unit:~~ hectares); and (d) direct economic losses (~~unit:~~ millions yuan).

3.1 ~~Risk of Typhoon Rainstorms~~Probability 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. 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. 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~~probability: Taizhou, Wenzhou and Ningbo cities.

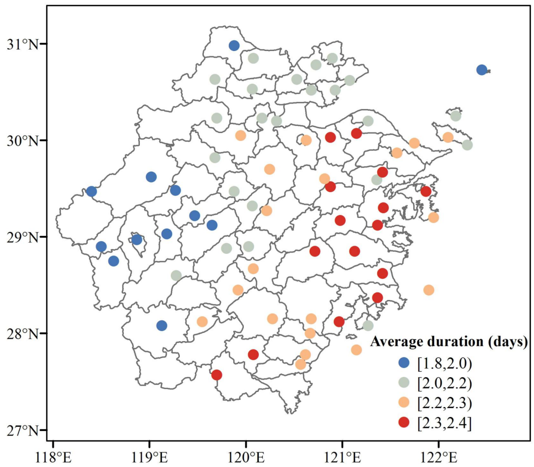


Figure 4. Average duration (days) of typhoon precipitation at each station in Zhejiang province from 1980 to 2014.

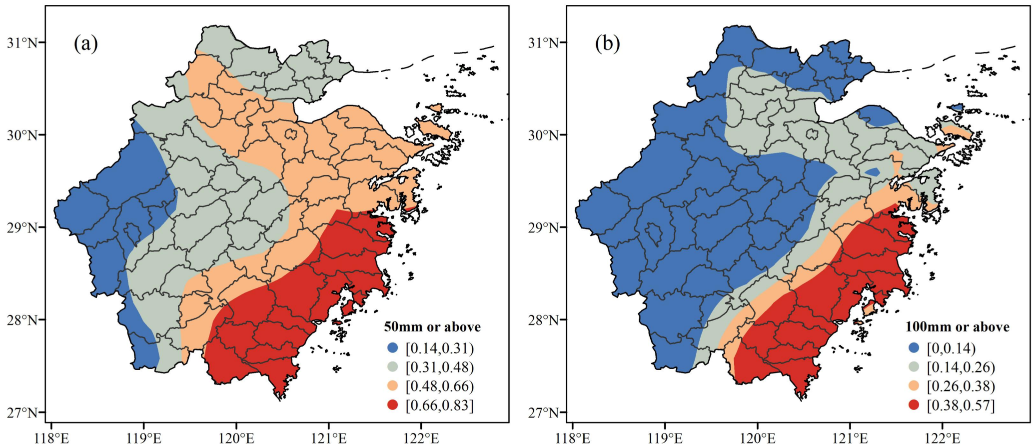


Figure 5. Probability of the occurrence of typhoon rainstorms in Zhejiang province: (a) rainstorms with precipitation >50 mm; and (b) torrential rainstorms with precipitation >100 mm.

3.2 Probability 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 are 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~~probability of typhoon winds are consistent with those with a high ~~with typhoon rainfall~~probability of typhoon rain, i.e. Wenzhou, Taizhou and Ningbo cities. The ~~risk~~probability of typhoon extreme winds is much higher in coastal areas than inland.

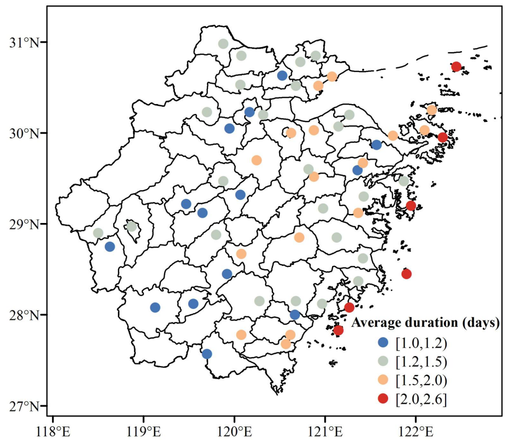
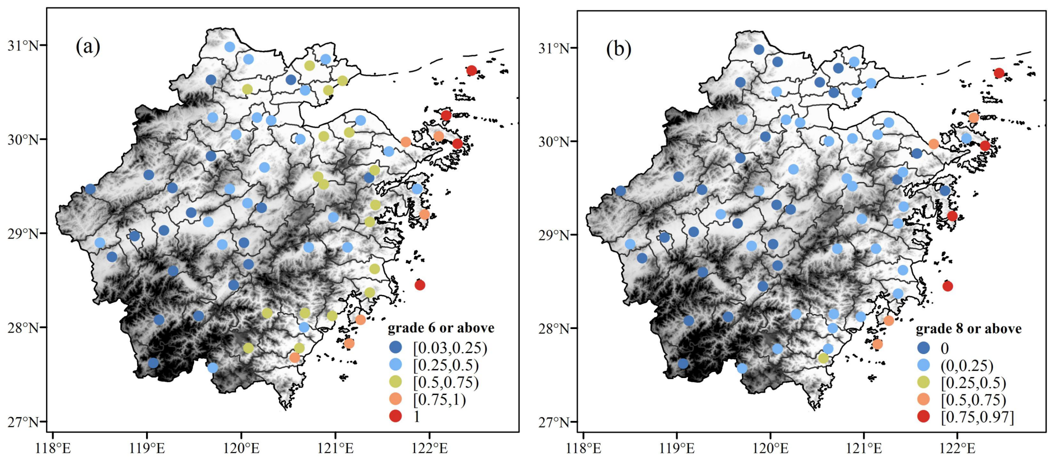


Figure 6. Average duration (days) of typhoon winds (over 6 grade) at each station in Zhejiang province from 1980 to 2014.



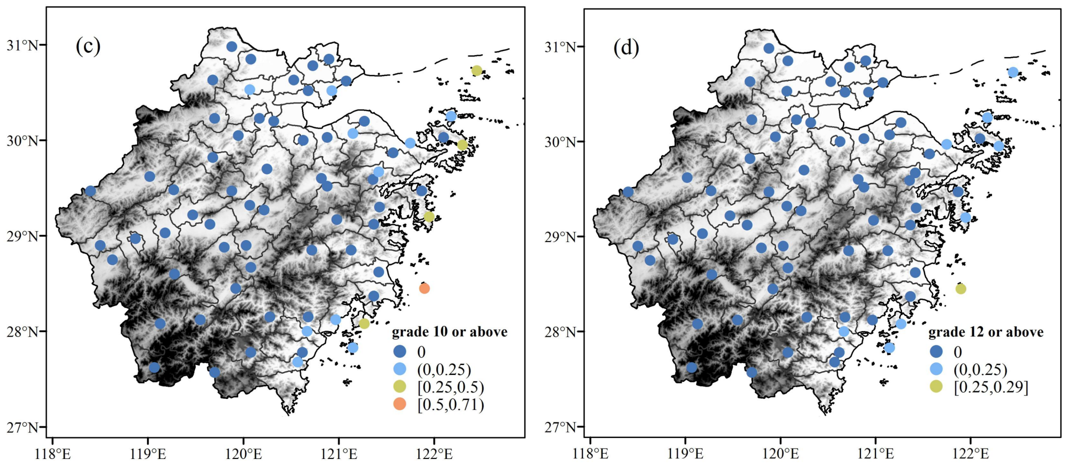


Figure 7. Probability of the occurrence of typhoon winds in Zhejiang province at (a) grade 6 or above (≥ 10.8 m/s), 672 (b) grade 8 or above (≥ 24.5 m/s), (c) grade 10 or above (≥ 32.7 m/s) and (d) grade 12 or above (≥ 41.5 m/s) ~~(a) grade 6 or above, (b) grade 8 or above, (c) grade 10 or above and (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 main factors causing typhoon disasters, which are considered in this study, are rainstorms and winds. The level and intensity of a single factor cannot fully represent and describe the impact. It is necessary to determine their influence through typical correlation analysis, and then typhoon wind and rain effect are superimposed by the weight coefficients. Therefore we establish a comprehensive intensity index that includes 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.

Disasters	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:

$$I = Ax + By \quad (1)$$

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, and Ningbo cities are identified, which is consistent withwhich are consistent with the results of Chen et al. (2011), can be found.

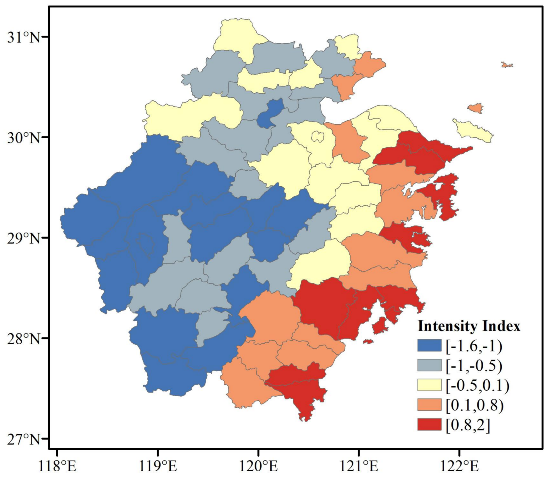


Figure 8. Intensity ~~indicees~~indexes of factors causing typhoon disasters at each station in Zhejiang province.

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 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

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	(+)

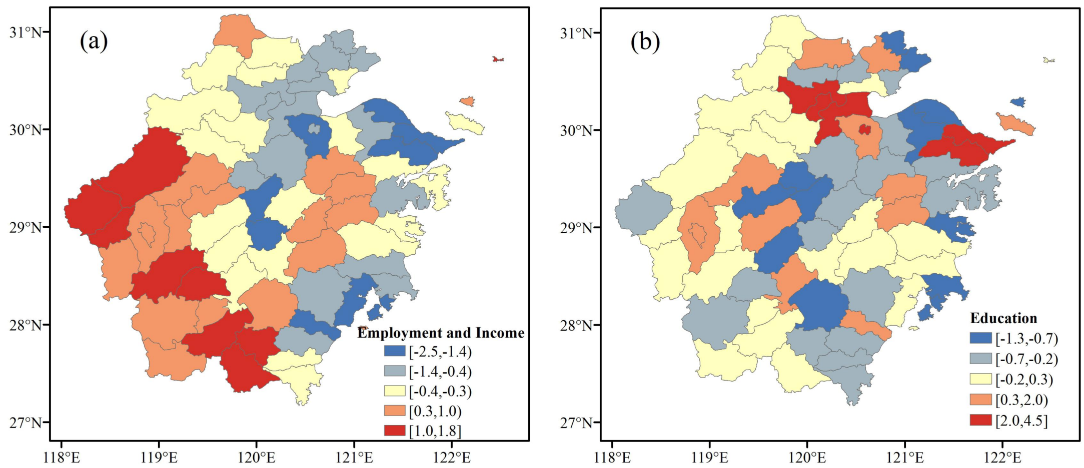


Figure 9. Distribution of population vulnerability index of (a) component 1 (employment and income) and (b) component 2 (education).

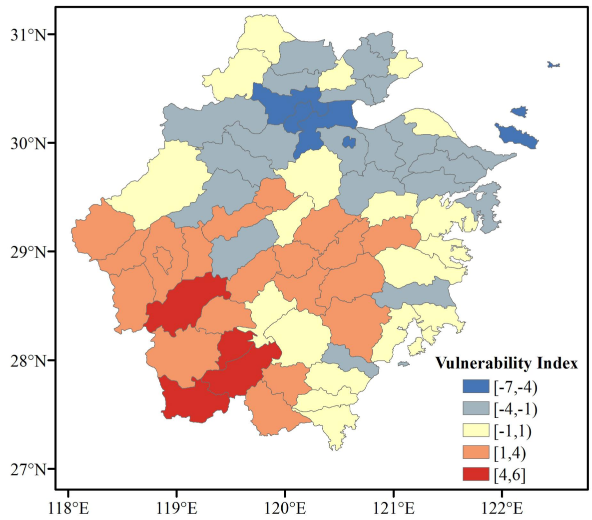


Figure 10. Distribution of population vulnerability index of counties.

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:

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

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.

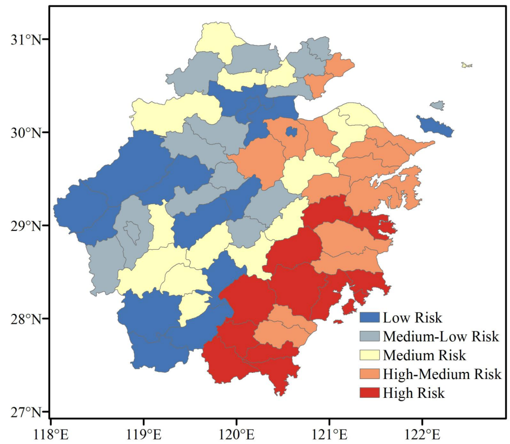


Fig. 11. Risk zoning of typhoon disasters in Zhejiang province.

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 a 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 study. 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. This paper mainly considers the effects of typhoon rain and typhoon wind, without considering the impact of storm surge. This is the limitation of the study, and we will explore the role of storm surges in future work.

Acknowledgments

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