Risk assessment of typhoon disaster for the Yangtze River Delta of China

Yong Zhang a, Gaofeng Fan b, Yue He b and Lijuan Cao c

a Meteorological Observation Centre, China Meteorological Administration, Beijing, China; b Zhejiang Climate Center, Zhejiang Province Meteorological Bureau, Hangzhou, China; c National Meteorological Information Center, China Meteorological Administration, Beijing, China

ABSTRACT
A typhoon is one of the most dangerous natural disasters in the Yangtze River Delta of China. Based on an integrated assessment of the disaster risk elements, including hazard factor, exposure, and vulnerability, the risk level of a typhoon disaster for the Yangtze River Delta as a county-level unit was ultimately determined. The result shows that the risk levels of typhoon hazard factor are gradually weakened from the southeastern coastal areas to the northwest, and the highest-risk areas are located in the southeastern coastal regions. Due to many towns, dense population, a developed economy, and a huge disaster-bearing body in the north of the Yangtze River Delta, which is also located on the plain for a high susceptibility to a disaster-breeding environment, the exposure risk level in the northern areas is higher than in the south. The most vulnerable counties are Chun’an, Xianju, Tiantai, and Sanmen in Zhejiang Province, and Baoying and Xinghua in Jiangsu Province. The highest-risk areas for a typhoon disaster are primarily located in the southeastern coastal areas of Zhejiang Province, Hangzhou Bay, and Shanghai near the Yangtze River Estuary, while the lowest-risk areas are distributed in the western portion of Hangzhou and the northern area of the Yangtze River Delta.

1. Introduction
A typhoon is a natural disaster that causes casualties at a slightly lower level than floods in the world, and a typhoon is also one of the most serious natural disasters in China. Typhoons mainly impact the eastern coastal regions of China, where the population is extremely dense, the economy is highly developed, and social wealth is notably concentrated (Chan and Shi 1996). Corresponding to the main trend of global warming, climate change, which is mainly climate warming, has taken place in China. The recent research shows that in the 20th century, the average temperature in China has increased by 1.52 °C per century (Cao et al. 2013), and the warming trend increased greatly from 1960 to 2014 (approximately 0.27 °C per decade (Cao et al. 2016)). Meanwhile, the frequency of extreme climate events, such as heat waves, droughts, floods, storms, and typhoons, will increase considerably, which could have a critical impact on human society, the ecosystem, and the environment (Zhang et al. 2006; Cao et al. 2011; Peng et al. 2012). In the last 50 years, economic damage from typhoon disasters around the coastal regions of China has increased dramatically. According to the China Meteorological Administration’s (CMA’s) data-sets of typhoon tracks from 1961 to 2014, there are, on average, eight typhoon landfalls in China annually. The Yearbook of Tropical
Cyclones in China shows that from 2000 to 2014, on average, typhoon disasters caused economic losses of 45.784 billion Yuan (RMB), 244 deaths, and affected 37.77 million of people per year. Several super typhoon disasters brought even worse consequences. For example, according to data from the Yearbook of Meteorological Disasters in China of 2014, super typhoon ‘Fitow’ landing in Fuding County in southeastern China’s Fujian Province on 7 October 2013 caused economic losses worth over 63.1 billion Yuan and 11 deaths, and 121.6 billion people were affected.

Disaster risk assessment is a relatively advanced measurement or technique for disaster prevention and mitigation and disaster management over the world. Academic societies pay close attention to the studies in this field, and disaster risk assessment is becoming the key study and frontier topic in disaster science and earth science. Because of the complex relationship between the typhoon disaster risk and its influencing factors, the linear simulation method is difficult to apply to the problem of typhoon disaster risk assessment. Yu (2015) applied the intuitionistic fuzzy theory to the evaluation of the problem of typhoon disasters in Zhejiang Province, China. In one perspective of disaster system theory, the risk of natural disaster is jointly determined by the intensity and frequency of hazard factors, susceptibility to a disaster-breeding environment, and exposure and vulnerability of the disaster-bearing body (Kenneth 1997; Amendola et al. 2000; Shi 2009; IPCC 2012; IPCC 2014). Risk assessment of typhoon disasters is the prerequisite to achieve better prevention of typhoon disasters and the basis to make decisions. Typhoon risk assessment has great significance for improving the ability of regionally preventing and combating typhoon disasters (Emanuel 2005).

At present, the research on typhoon disaster risk assessment primarily focuses on causal factors of disaster but pays less attention to estimating a disaster-bearing body and a disaster-breeding environment, even though they have the same important positions in the whole process of disaster analysis and assessment (Gao et al. 2013). In addition, the work on the construction of disaster prevention facilities and engineering structures, disaster prevention and emergency response according to the results from disaster risk assessment has just started. There are relatively large gaps between the achievements in natural disaster risk assessment and the requirements for disaster prevention and disaster risk transfer. Disaster risk assessment plays a limited role in routine disaster risk management (Malmstadt et al. 2010). Therefore, it is extremely important to increase the work in natural disaster risk assessment, especially the risk assessment and discrimination of typhoon disaster from other severe natural disasters.

In this study, we investigate the typhoon disaster for the Yangtze River Delta, located in the southeastern coastal region of China, which is severely affected by typhoons in the summer and autumn. According to the data of 2010 from the National Bureau of Statistics, the 16 cities of the Yangtze River Delta contain 11.65% of the population and produce 21.29% of China’s entire gross domestic product (GDP). The rapid economic development and a sharp increase in population exacerbate the risks caused by the increased typhoon disasters in the Yangtze River Delta. To explore the measurement of risk assessment of typhoon disasters, to identify regions of high risk and to provide scientific support for typhoon disaster prevention and mitigation, methods based on the geographic information system (GIS) were used to assess the typhoon disaster risk in the Yangtze River Delta.

2. Data and methods

The data-sets used for risk assessment of typhoon disaster in this analysis include (1) the position and intensity of each tropical cyclone generated in the Northwest Pacific from 1961 to 2014 for every six hours were obtained from ‘The Dataset of the Best Paths for Northwest Pacific Tropical Cyclones’ at the website: www.typhoon.gov.cn; (2) Daily precipitation, daily maximum wind speed and daily extreme wind speed data-sets of 105 national weather stations in the Yangtze River Delta during 1961–2014 collected from the China National Stations’ Fundamental Elements Datasets V3.0 (Ren et al. 2012); (3) the 1:50,000 basic geographic information data provided by National Basic Geographic Information Center, including the administrative division layer in the Yangtze River Delta.
Delta, terrain contour layer, water system distribution layer, road network layer, railway network layer, and residential area layer, land use; (4) Data-set from the statistical yearbook from 2000 to 2014 in the Yangtze River Delta, mainly containing the natural growth rate of the population, the density of the population, the proportion of agricultural population, per capita GDP, average household population, proportion of female population, ground mean GDP, fixed assets per square kilo-

There are four essential conditions for the formation of a typhoon disaster. The first condition is the hazard factor inducing a typhoon disaster, such as strong winds, heavy rain, and storm surge brought by the landing typhoon. The second condition is a disaster-breeding environment, including topography, water system distribution, vegetation cover and other factors, which can amplify or reduce the influence of a hazard factor. The third condition is a disaster-bearing body, including population, economy, and infrastructure. The spatial distribution of a disaster-bearing body in the disaster-breeding environment determines the extent of its exposure. The vulnerability of the disaster-bearing body determines the degree of damage due to the typhoon hazard factor. The last is the interaction between the hazard factor and the disaster-bearing body (Le 2000; Lin et al. 2010).

According to the United Nations Development Programme (2005), natural disaster risk is understood to be the probability of harmful consequences, i.e. expected loss of lives, injuries to people, and disruption to properties, livelihoods, and economic activities (or environmental damage) resulting from interactions between natural or human-induced hazards and vulnerable conditions. In this study, we adopt the index risk assessment model proposed by Davidson and Lambert (2001) to estimate the typhoon disaster risk, as shown by formula (1).

\[
R = H^a \times E^b \times V^\delta
\]

where \( R \) is the risk level of a typhoon disaster, \( H \) is the hazard factor, \( E \) is the exposure of the disaster-bearing body, \( V \) is the vulnerability of the disaster-bearing body, and \( \alpha, \beta, \) and \( \delta \) are the weighting coefficients of the above three elements. In this study, we adopt the analytic hierarchy process (AHP) method to determine the weighting coefficients. The AHP method provides an appropriate way to transfer the experience of experts into an objective weight value (Li et al. 2006; Chen 2007).

3. Results

3.1. Estimates of a typhoon hazard factor

According to the CMA’s data-sets of typhoon tracks from 1961 to 2014, there are 27 typhoon landfalls on the Yangtze River Delta of China and 0.5 annually. The number of typhoon landing on this region does not have an increasing trend, but the strength of typhoon landfalls is significantly intensified. The averaged frequency of typhoon impact on the cities of the Yangtze River Delta is 58 per year. The frequencies of Taizhou, Zhoushan, Ningbo, Shaoxing, Shanghai, Hangzhou, and Jiaxing are above the average value, while those of other cities in this region are below the average value. Taizhou City, located in the southernmost part of this region, experienced the most typhoons at 82 with 1.5 typhoons per year. Yangzhou City, located in the northwestern part of this region, has the lowest typhoon frequency, only 40 times with 0.7 typhoon per year. The annual mean typhoon frequencies in different cities follow the Poisson distribution and pass the goodness-of-fit test at the 95% confidence level.

The risk level of a typhoon hazard factor is determined by the strong winds and heavy rainfall of typhoon landfalls. To select the representative scope of a meteorological observation station influenced by a typhoon, a circle of 200 km radius is determined to be a buffer region (Li and Li 2011). The maximum wind speed, daily precipitation, and typhoon process precipitation are selected as the three main aspects to indicate the risk level of the typhoon hazard factor. For the aspect of extreme
wind speed and wind day number of 8, 9, 10, 11, 12, and more than 13 levels are determined as assessment indices. From the aspect of daily precipitation, the maximum daily precipitation, number of days of rainstorms, number of days of large rainstorms, and number of days of extraordinary rainstorms are determined as assessment indices. From the aspect of typhoon process precipitation, the maximum process precipitation, the frequency of rainfall from 100 to 200 mm, the frequency of rainfall from 200 to 300 mm, and the frequency of rainfall above 300 mm are determined as assessment indices. The above indices were calculated and normalized for each meteorological observation station in the Yangtze River Delta.

Both the maximum daily precipitation and the process precipitation induced by a typhoon over the Yangtze River Delta demonstrate a spatial pattern in which large values concentrate in the east and small values in the west, where the largest values above 300 mm were occurring in the coastal regions, especially in the Yangtze Estuary and southeastern coastal areas. The maximum wind speeds induced by a typhoon in Zhoushan, Taizhou, and Ningbo cities are above 60 m/s, while in Shanghai, Shaoxing, and Hangzhou cities, the values are approximately 50 m/s, and in Taizhou (in the North) and Yangzhou, the two cities located in the north of the Yangtze River Delta, the values are less than 30 m/s. The distribution of the maximum wind speeds induced by a typhoon over different cities shows that several cities located in the south coastal regions of the Yangtze River Delta are likely to suffer a super typhoon.

The spatial distribution of typhoon hazard factors for the Yangtze River Delta is shown in Figure 1. As shown in this figure, the areas with the highest risk of typhoon hazard factors are found in the southeastern coastal regions and the inlands, including the major part of Taizhou (in the South) and coastal areas of Ningbo and Zhoushan. The risk levels of the typhoon hazard factor in Shanghai and Hangzhou Bay are also moderately high. The risk level of the typhoon hazard factor decreases from the southeast coastal regions to the northwest, with the lowest risk of typhoon hazard factor distributed in Nanjing, Yangzhou, and the northern areas of Taizhou (in the North).

### 3.2. Exposure assessment of typhoon disaster

The exposure risk level of the disaster-bearing body is determined by two factors. The first factor is the number of disaster-bearing bodies that directly determines the extent of exposure. The second factor is the disaster-breeding environment, where sensitivity level also has a large impact on the extent of exposure because disaster-breeding bodies are distributed in the disaster-breeding environment (Turner and Meyer 1991; Nobuo 2000). We considered three factors regarding the number of the disaster-bearing body, including population, region GDP, and land use. The data of population, region GDP, and land use are collected from the National Bureau of Statistics for 2014 about each county in the Yangtze River Delta. Both the population density and ground mean GDP are calculated and normalized. The distribution of land use types reflects the spatial distribution of natural ecological values and socio-economic values. According to the socio-economic value level associated with different types of land use and the impact of a typhoon on these levels, land use types are categorized with a number of 0.1–0.9 according to the correspondent relationship in Table 1 to determine the land use index of the disaster-bearing body. Concerning to the sensitivity of the disaster-breeding environment, topography and water system are two main factors to be considered. The topography factor includes elevation and topographic relief. The elevation has more influence on the probability of the occurrence of waterlogging. Topographic relief determines the degree of difficulty for the runoff to converge in the gullies and discharge. In the water system aspect, there are two factors to be considered, that is, river density and river buffer. The denser the river network is, the more possibility of being influenced by the floods resulting from a typhoon disaster.

Using the exposure risk assessment model of typhoon disasters, the values of population index, region GDP index, land use type index, topography index, and water system index can be calculated separately, and the results are shown in Figure 2. Generally, the spatial distribution of exposure risk level of a typhoon disaster-bearing body over the Yangtze River Delta demonstrates a pattern...
Table 1. Economic value grades of the disaster-bearing body for different types of land use.

| Types of land use | Urban land | Rural land | Arable land | Wet land | Forest land | Grass land | Unused land |
|------------------|------------|------------|-------------|----------|-------------|------------|-------------|
| Value grade      | 0.9        | 0.8        | 0.6         | 0.4      | 0.3         | 0.2        | 0.1         |

Figure 1. Risk level of typhoon hazard factors in the Yangtze River Delta.
Figure 2. Exposure risk level of a typhoon disaster in the Yangtze River Delta.
with high values in the northern part and low values in the southern part. The north part of the Yangtze River Delta is in the Yangtze River estuary plain, which has flat terrain, a dense river network, and numerous lakes. These factors play a limited role in reducing the risk of the typhoon hazard factor; therefore, the sensitivity of the disaster-breeding environment is generally high. In addition, because there are many cities and towns, a high population density, and relatively developed economics in the Yangtze River Delta, the exposure extent of a disaster-bearing body in these areas is relatively large. In the southern part, because there are many mountains with high altitude and violently fluctuating terrain, the river network is also sparse, which has the advantage of reducing the risk of the typhoon hazard factor, so the sensitivity of the disaster-breeding environment is generally low. Moreover, because of the relatively small population, undeveloped economy, and small number of disaster-bearing bodies, the exposure extent of the disaster-bearing body in these areas is generally small.

3.3. Vulnerability assessment of typhoon disaster

Despite the diversity in the concepts of vulnerability, there are two predominant perspectives in its conceptualization (Wu et al. 2002). The first perspective considers the status of people and property at risk, and studies of this point focus on the potential exposure to a physical hazard. The second perspective takes exposure as given and searches for the patterns of differential losses among the people affected. The vulnerability of the hazard-bearing body is a condition or process resulting from physical, social, economic, and environmental factors, which determine the likelihood and scale of damage from the impact of a given hazard. The purpose of the vulnerability assessment is to create an index of overall vulnerability from a suite of indicators. However, constructing a vulnerability index raises several problems in the aggregation of these indicators, including the decision of assigning the weights (Rygel et al. 2006). In this study, the administrative division unit is considered the disaster-bearing body, with vulnerability generally reflected by socio-economic, population structure, land use, medical and health, and other social statistical indices. First, according to the collection of socio-economic data and the characteristics of each county in the Yangtze River Delta, a set of indicators for the vulnerability risk assessment index was selected as shown in Table 2. Based on the analytic procedure of Cutter 2003 and Shi et al. 2014, we determined the method of impact of each indicator for the vulnerability risk assessment index.

Using the projection pursuit dynamic cluster model (Ni et al. 2006), the values of 11 indicators for the vulnerability risk assessment were calculated from 2000 to 2014, and the vulnerability risk assessment index of each county was obtained for the Yangtze River Delta. The result of the estimated vulnerability risk of typhoon disaster in county-level units is reflected in Figure 3. The counties with the higher vulnerability risk level are Chun’an, Xianju, Tiantai, Sanmen in Zhejiang Province, and Baoying, Xinghua in Jiangsu Province. The risk level of Linhai City in Zhejiang Province is highest, while the districts with the lowest vulnerability risk level are found in the

| No. | Indexes                                      | The way of impacts |
|-----|---------------------------------------------|-------------------|
| 1   | Natural growth rate of population (%)       | +                 |
| 2   | Density of population (person/km²)          | +                 |
| 3   | Proportion of agricultural population (%)   | +                 |
| 4   | Per capita GDP (10,000 Yuan)                | —                 |
| 5   | Average household population (persons)      | +                 |
| 6   | Proportion of female population (%)         | +                 |
| 7   | Ground mean GDP (10,000 Yuan/km²)           | —                 |
| 8   | Fixed assets per square kilometre (10,000 Yuan/km²) | + |
| 9   | Proportion of the first industry (%)        | +                 |
| 10  | Income per capita (10,000 Yuan)             | —                 |
| 11  | Number of hospital beds per 1000 persons (beds) | — |
Figure 3. Vulnerability risk level of a typhoon disaster in the Yangtze River Delta.
Figure 4. Integrated risk level of a typhoon disaster in the Yangtze River Delta.
southeastern areas of Jiangsu Province, most of Shanghai City, and the northeastern areas of Zhejiang Province.

3.4. Integrated risk assessment of typhoon disaster

The integrated risk index of a typhoon disaster for the counties of the Yangtze River Delta can be obtained by formula (1), as previously mentioned, based on the risk assessment of hazard factors, and the exposure and vulnerability of the disaster-bearing body. The values of the above three factors were normalized to the range of 0–1, respectively, next, the AHP method was used to determine their weights. Using the ArcGIS software system, the levels of the typhoon disaster risk in the Yangtze River Delta were divided into five types using the technique of natural breakpoint classification, including the levels of highest, higher, medium, lower, and lowest. Thus, the integrated risk assessment of a typhoon disaster in the Yangtze River Delta is realized. The value of the risk level is shown in Figure 4.

Among the administrative counties of the Yangtze River Delta, the typhoon disaster risk level of Jiangsu Province is significantly lower than others, except for the eastern parts of Nantong and Suzhou, which are medium and higher. The typhoon disaster risk level in downtown Shanghai is relatively higher than in its suburbs. The spatial distribution of the typhoon risk level over Zhejiang Province varies widely. Hangzhou Bay, the northern coastal areas of Ningbo, Zhoushan, and most of Taizhou are higher or the highest level. In contrast, because of the numerous mountains, sparse population, and low economic density, the western portion of Hangzhou, the southern portion of Shaoxing, and the southwestern portion of Ningbo are lower or the lowest.

The summary for the area and percentage of different typhoon disaster risk levels in all prefecture-level cities of the Yangtze River Delta are reflected in Table 3. The table shows that the typhoon disaster risk levels in most areas of Shanghai are medium or higher. In Jiangsu Province, the typhoon disaster risk levels of most of the prefecture-level cities are lower, except for Wuxi, Suzhou, and Nantong Cities. The typhoon disaster risk levels in most of Wuxi City are at the lower or medium level, which accounts for 86.97% of the area. The areas of Nantong City (81.26%) are at the medium risk level. Areas of Suzhou City (52.65%) are also at the medium risk level, but 21.73% of the areas of Suzhou City are at the lower risk level, and 22.07% areas are at the higher risk level. The typhoon disaster risk levels in the prefecture-level cities of Zhejiang Province are generally higher than the typhoon disaster risk levels of Jiangsu Province, especially in Ningbo, Zhoushan, and Taizhou Cities, which are in the southeastern coastal regions of the Yangtze River Delta, and the areas of the highest risk level all account for above 25%. The areas of the higher risk levels in Jiaxing and Huzhou Cities are 70.2% and 44%, respectively.

Table 3. Risk level of a typhoon disaster in the Yangtze River Delta.

| City         | Lowest (km²) | Lower (km²) | Middle (km²) | Higher (km²) | Highest (km²) |
|--------------|--------------|-------------|--------------|--------------|---------------|
| Shanghai     | 39.09 (0.65) | 270.44 (4.47) | 3125.12 (51.69) | 2073.31 (34.29) | 538.28 (8.90) |
| Nanjing      | 899.82 (13.77) | 3995.16 (61.12) | 1613.02 (24.68) | 28.16 (0.43) | 0.00 (0.00) |
| Wuxi         | 405.24 (10.32) | 1685.61 (42.92) | 1729.93 (44.05) | 106.85 (2.72) | 0.00 (0.00) |
| Changzhou    | 303.17 (6.92) | 2895.48 (66.13) | 1169.13 (26.70) | 104.08 (0.24) | 0.00 (0.00) |
| Suzhou       | 125.64 (2.02) | 1353.88 (21.73) | 3280.43 (52.65) | 1374.90 (22.07) | 95.50 (1.53) |
| Nantong      | 1.53 (0.02) | 774.34 (9.61) | 6550.02 (81.26) | 729.24 (9.05) | 5.62 (0.07) |
| Yangzhou     | 844.08 (12.80) | 4974.13 (75.42) | 774.40 (11.74) | 2.21 (0.03) | 0.00 (0.00) |
| Zhenjiang    | 453.59 (12.48) | 2845.69 (78.32) | 333.99 (9.19) | 0.00 (0.00) | 0.00 (0.00) |
| Taizhou (North) | 189.01 (3.36) | 3913.68 (69.98) | 1468.08 (26.25) | 21.45 (0.38) | 0.00 (0.00) |
| Hangzhou     | 8220.46 (49.89) | 3628.37 (22.02) | 1206.03 (7.32) | 2176.84 (13.21) | 1246.56 (7.56) |
| Ningbo       | 776.32 (9.69) | 1802.00 (22.49) | 1372.65 (17.13) | 2057.90 (25.69) | 2002.78 (25.00) |
| Jiaxing      | 4.00 (0.10) | 42.71 (1.08) | 876.07 (22.20) | 2769.78 (70.20) | 259.24 (6.41) |
| Huzhou       | 1403.52 (24.30) | 1205.39 (20.88) | 231.49 (4.01) | 2538.74 (43.98) | 393.00 (6.81) |
| Shaoxing     | 3521.44 (44.10) | 1304.22 (16.34) | 1057.29 (13.25) | 1842.98 (23.09) | 255.06 (3.20) |
| Zhoushan     | 2.84 (0.59) | 218.76 (45.21) | 11.08 (2.29) | 105.04 (21.71) | 146.18 (30.21) |
| Taizhou      | 59.44 (0.68) | 2462.07 (28.03) | 2102.49 (23.94) | 1251.00 (14.24) | 2907.61 (33.11) |
4. Conclusions

Risk assessment of typhoon disasters for the Yangtze River Delta of China is conducted by an integrated analysis of hazard factor, exposure, and vulnerability to typhoon disaster. Risk assessment of typhoon disasters employs three indices of maximum wind speed, daily precipitation, and typhoon process precipitation based on the data-set from the National Meteorological Information Center from 1961 to 2014 to estimate the hazard factor risk of a typhoon disaster. Risk assessment of typhoon disasters employs two factors, the number of disaster-bearing bodies and the disaster-breeding environment to estimate the exposure risk of typhoon disaster, and the risk assessment employs 11 elements, including socio-economic, population structure, land use, medical, and health categories to calculate the vulnerability risk of typhoon disaster. The results indicate that the high-risk regions for typhoon disaster in the Yangtze River Delta are located primarily in the southeastern areas of Jiangsu Province, the coastal areas of Zhejiang Province, Hangzhou Bay, and the areas in Shanghai near the Yangtze River Estuary, where the area ratio of high risk is very large, and the risk for most of the counties is higher. Specifically, coastal counties in Hangzhou Bay and the southeastern coastal areas of Zhejiang Province are subject to the highest risk.

An integrated national risk assessment is necessary to reduce the negative effects of a typhoon disaster. If the administration does not consider taking the appropriate mitigation measures before such problems become irreversible, large numbers of people and large amounts of infrastructure, ecosystems, and economic activities would be exposed to strong winds, heavy rain, and the storm surge from a typhoon disaster. This study could provide a scientific basis for China’s typhoon disaster risk management. Future change in hazard factors, exposure, vulnerability to a typhoon disaster resulting from natural climate variability, anthropogenic climate change, and socio-economic development can alter the impact of typhoon disaster on the coastal areas. Therefore, further work should be conducted to consider not only the future climate change but also rapid urbanization and excessive migration to the Chinese coastal areas. When considering the risk assessment for a particular disaster-bearing body, such as the coastal zone and rural houses, the integrated investigation of socio-economic data would need to be conducted in a future study.

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ORCID

Yong Zhang http://orcid.org/0000-0002-5315-5909
Gaofeng Fan http://orcid.org/0000-0002-9514-8037
Yue He http://orcid.org/0000-0001-7605-2155
Lijuan Cao http://orcid.org/0000-0002-3565-4069
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