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A Preliminary Study on the Intensity of Cold Wave Storm Surges of Laizhou Bay

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Abstract Dike failure and marine losses are quite prominent in Laizhou Bay during the period of cold wave storm surges because of its open coastline to the north and flat topography. In order to evaluate the intensity of cold wave storm surge, the hindcast of marine elements induced by cold waves in Laizhou Bay from 1985 to 2004 is conducted using a cold wave storm surge–wave coupled model and the joint return period of extreme water level, concomitant wave height, and concomitant wind speed are calculated. A new criterion of cold wave storm surge intensity based on such studies is developed. Considering the frequency of cold wave, this paper introduces a Poisson trivariate compound reconstruction model to calculate the joint return period, which is closer to the reality. By using the newly defined cold wave storm surge intensity, the 'cold wave grade' in meteorology can better describe the severity of cold wave storm surges and the warning level is well corresponding to different intensities of cold wave storm surges. Therefore, it provides a proper guidance to marine hydrological analysis, disaster prevention and marine structure design in Laizhou Bay.

Key words Laizhou Bay; cold wave grade; Poisson trivariate compound reconstruction model; cold wave storm surge intensity

1 Introduction

As a semi-enclosed sea located in the northern part of China, the Bohai Sea experiences and is vulnerable to frequent meteorological disturbances. Laizhou Bay in the southern Bohai Sea, with its coastline open to the north and flat topography is particularly threatened by storm surges and concomitant wave hazards during frequent passages of strong northeasterly wind systems in winter. Southward invasion of cold air with rapid cooling and strong wind induces cold wave processes. This kind of storm was named as the cold wave storm surge by Feng (1982), and has regarded as a unique storm type in the northern China. However, similar storm surges have also been found around the world, such as abnormal storm waves in the East Sea of Japan (Lee *et al.*, 2010; Lee, 2015), Bora storm surges in the Adriatic Sea of Italy (Benetazzo *et al.*, 2014). Different from other sea areas, the ultra-shallow Bohai Sea has more remarkable response to cold wave storm surge processes.

At present, more attention has been paid to extratropical and tropical cyclone. But coastal damage and marine losses due to cold wave storm surges can be quite serious (Wang *et al.*, 2012, 2015). Cold wave storm surges can happen within a short period of time from the starting to ending stage (Qiu, 1975). Currently the studies of cold waves mainly focus on typical cold wave processes in the 1950s and 1960s (Zhao and Ding, 1992), including studies on mechanisms of cold waves (Qiu and Wang, 1983), cold wave forecasting methods (Zhang *et al.*, 2010) and characteristics analysis of cold waves (Liu *et al.*, 2015), and case studies of cold wave storm surges (Zheng *et al.*, 2010). No research has been conducted on the intensity of cold wave storm surges yet.

'Cold wave grade' (GB/T 21987-2008) adopts two indexes to identify cold waves into three grades, the indexes being the decreasing amplitude of daily minimum temperature (or daily average temperature) and the daily minimum temperature of cold wave influenced area in a certain period. Wu and Du (2010) defined a composite indicator by maximum decreasing amplitude, minimum temperature, influence range and temperature fall duration to evaluate cold wave processes in Guangdong Province. The indicator divides cold waves into four grades as super-strong, strong, medium and weak. However, those classifications mentioned above are all considering meteorological parameters, whose applicability to cold wave storm surge intensity and consistency with marine environmental elements are still unclear. Besides, on account of the considerable latitude and longitude spans and temperature range over China, different regions should utilize different standards in defining and classifying cold wave surge intensity. Given that the return period is an intuitive reflection of the severity of marine environmental elements, it is utilized as the criteria of a newly defined cold wave surge intensity in this paper to describe marine in-

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fluence of cold waves, and to offer a scientific basis to cold wave storm surge intensity.

In the study of storm surges, the influence of various marine environmental elements should be considered because of the limitation of the hydrological statistical analysis of a single element in representing the actual storm surge process. Therefore, a joint probability study of multiple environmental elements has attracted wide attention in recent years. Coles and Tawn (1994) proposed a negative bivariate logistic model to calculate the joint distribution of extreme wave height, period and storm surge on the southeast coast of England; Liu *et al.* (2001) used grey theory and random simulation method to calculate environmental elements of flood, storm surge and huge waves in three different types of coastal and estuarine cities and gave different disaster fortification standards. Considering the contribution of high water level and wave height induced by typhoons, Dong *et al.* (2015) calculated the return period of typhoon-induced storm surges in Qingdao area, and proposed a new standard to judge the disaster intensity of typhoon-induced storm surges. Based on complete and reliable data and multi-variable models, the joint probability method is generally accepted.

In marine hydrological analysis, many serious marine disasters happen intermittently. On these occasions long-term distributions of annual extreme values are unable to meet the requirement. Since the concept of compound distribution was first proposed in entomological and bacteriological research (Neyman, 1939), it has been applied and extended in various disciplines. Feller (1943) constructed a compound distribution family with universal applicability, and presented the concept of compound Poisson distribution. Liu and Ma (1976) introduced the compound distribution into the statistical analysis of marine elements. Dong *et al.* (2005, 2009) constructed different forms of compound Poisson distribution to analyze the return values of storm surge, typhoon-induced wave height and wind speed.

Considering the frequency of cold waves, a compound trivariate extreme value distribution is constructed to calculate the joint return period of extreme water level and its concomitant data in this paper. A new criterion of cold wave storm surge intensity is defined and compared with ‘cold wave grade’ in meteorology.

2 Data

2.1 Cold Wave Grade

According to the cold wave grade in meteorology (Table 1), a total of 75 cold wave processes occurred in Laizhou Bay from 1985 to 2004. Based on statistical analysis of cold wave elements, a cold wave process defined by meteorological indicators does not always occur with strong wind. However, ocean engineers are more concerned about the effect of storm surges due to the cold wave process and its concomitant strong wind on coasts. Therefore, it is necessary to add wind speed as an influence factor to classify the intensity of storm surge induced by cold wave. Referring to ‘cold wave yearbook’ in China (1983), a total of 7 levels of wind conditions are classified for cold wave storm surges.

Table 1 Cold wave grade

Grade	Decreasing amplitude of temperature (℃)			Minimum temperature (℃)
	24 h	48 h	72 h	
Cold wave	≥8	≥10	≥12	≤4
Strong cold wave	≥10	≥12	≥14	≤2
Extremely strong cold wave	≥12	≥14	≥16	≤0

Considering the characteristics of storm surge disasters, the predominant marine element in the coastal zone is water level, which plays a vital role in the determination of structural parameters. Therefore, the extreme water level is chosen as a main extreme value for a cold wave storm surge process. Its concomitant wave height and wind speed are adopted to analyze the intensity of cold wave storm surges of Laizhou Bay. All these three marine elements are obtained from the hindcast by the storm surge-wave coupled model developed for Laizhou Bay.

2.2 Cold Wave Storm Surge-Wave Coupled Model

The wind field used in this paper is the ERA-Interim wind, a global atmospheric reanalysis product provided by ECMWF (European Centre for Medium-Range Weather Forecasts). The 4D-Var assimilation technology is used to solve fundamental problems in ERA-40 data and improve data accuracy. Storm surge calculations employ the ADCIRC (Advanced Circulation Model), which is a cross-scale hydrodynamic model based on finite element method. The ADCIRC (Luettich and Westerink, 2000) has a higher resolution in the areas where water depth changes sharply and the coastline is complex, while a relatively low resolution with slowly changing topography. The simulation of waves uses the third generation wave model, SWAN (Simulating Waves Near-shore) model. The SWAN model is suitable for simulation of wind wave generation and evolution in near-shore zones by using energy input terms, dissipation terms (bottom friction, wave breaking, whitecap), and wave-wave nonlinear interaction terms in the spectrum balance equation (The SWAN team, 2011).

The wave radiation stress tensors calculated in SWAN plug wave shoaling into storm surge model, while the time series of water level and current obtained by ADCIRC are the input for SWAN. Then the interaction between waves and current can be simulated and near-shore wave-storm surge coupling calculations can be conducted (Sebastian *et al.*, 2014).

2.3 Bathymetry and Topography

In order to accurately simulate the variations of water level and wave height in strong wind, the calculation area should be large enough to reduce the influence of the boundary condition on the computational results. Small grid, small time step, and accurate topography data are needed to describe nonlinear interaction between waves and current field in the nearshore area. Therefore, the calculation domain includes the whole Bohai Sea and part of the Yellow Sea. The minimum resolution of 1km is specified along the Bohai Sea coastal boundary. The model uses a triangular mesh which has 122588 elements and 62505 nodes, as shown in Fig.1. The land topography data are supplied by National Oceanic and Atmospheric Administration (NOAA) and the water bathymetry data are extracted from the Bohai Sea coastal chart. The water depth contours of the region are drawn in Fig.2.

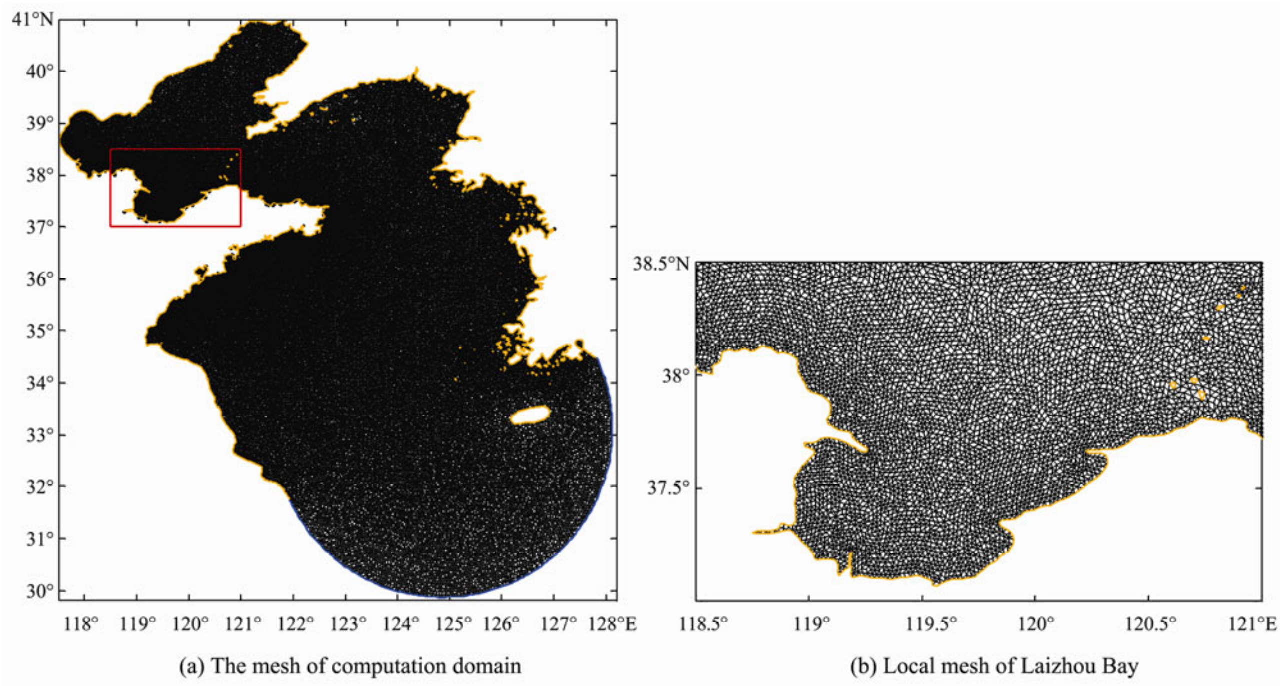

Fig.1 The triangular model mesh.

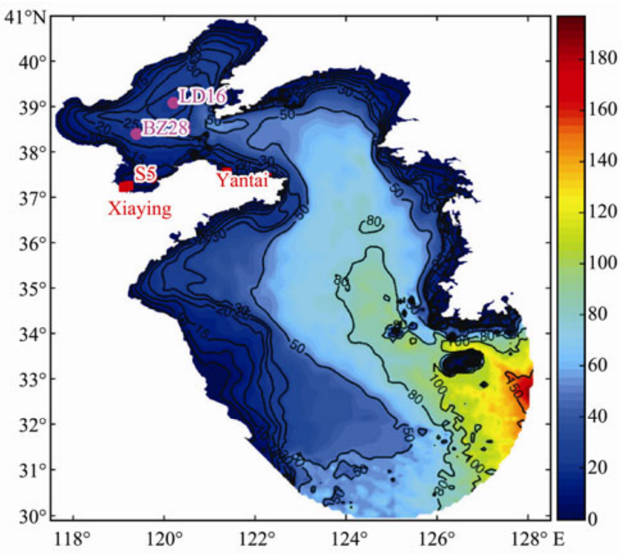

Fig.2 Water depth contour in computation domain and station location.

2.4 Verification

In order to validate the storm surge-wave coupled model, several cold wave processes are selected to perform further model calculations and analysis. Corresponding results are shown in Table 2 and the location of observation stations are shown in Fig.2.

Considering the peak values during a cold wave process are much more important for coastal structural design, the comparison between measured and calculated peak values of each cold wave process is listed in Table 2. Comparing Fig.3 with Fig.4, it can be seen that during the cold wave C8303, the Yantai station located in the south of Bohai strait had a slight surge at the beginning, then a significant water level drop, with the relative error for the peak value −3.73%, while the Xiaying station in Laizhou Bay experienced a significant surge during cold wave C8903, with a slightly higher relative error of 11.36% due to the estuarine effect. The relative error of the peak surge level is 5.37% at Platform LD16 during cold wave C8910, and the measured and calculated data at Platform BZ28 coincide well in the process of cold wave C9601. Therefore, the relative errors of peak surge levels in all the cold wave processes are within 15%. The correlation coefficients are all above 0.90, which indicates that the model-hindcast results fit the measured data very well. The coupled model can be used to analyze the cold wave storm surge intensity in the Bohai Sea and Laizhou Bay.

Table 2 Information of cold wave processes and measured data and calculated results

Cold wave		Variables	Station	Peak value (m)		Correlation coefficient
Serial number	Duration			Measured	Calculated	
C8303	1983.03.15–1983.03.18	Storm surge	Yantai	1.08	1.12	0.98
C8903	1989.03.03–1989.03.03	Storm surge	Xiaying	1.28	1.42	0.90
C8910	1989.10.17–1989.10.19	Wave height	LD16	2.00	1.89	0.90
C9601	1996.01.06–1996.01.09	Wave height	BZ28	3.21	3.26	0.95

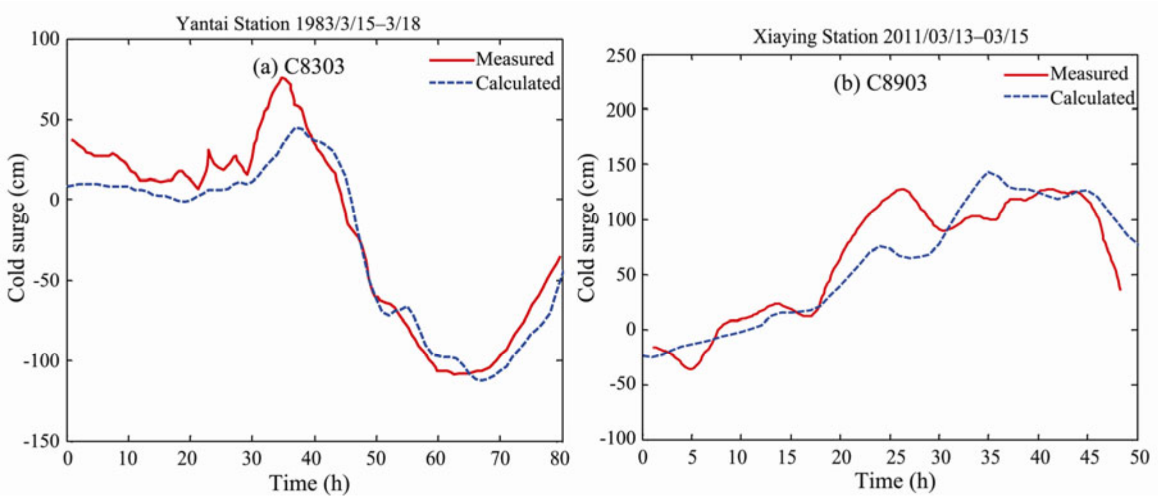

Fig.3 Storm surge level comparisons between measured and calculated data.

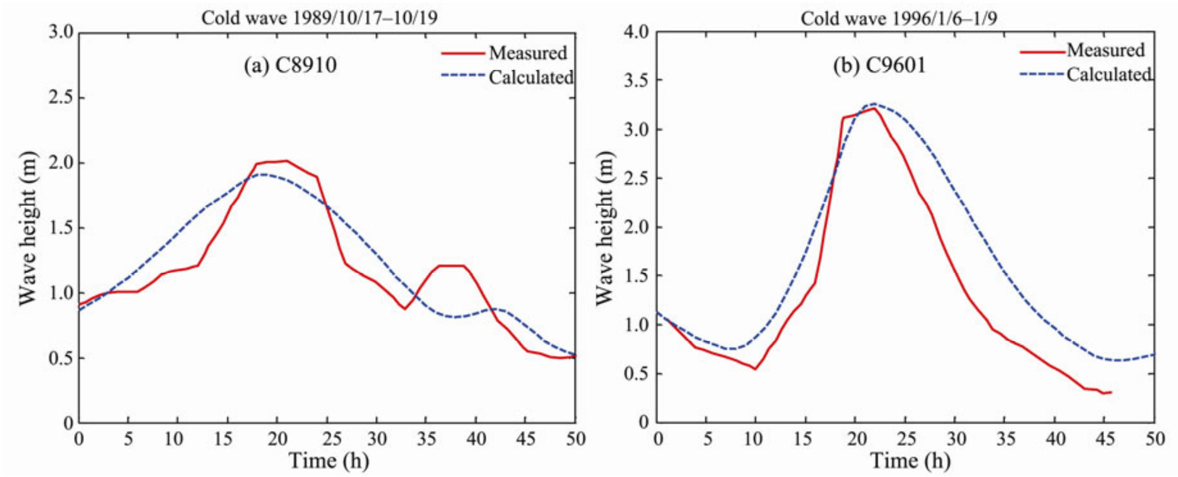

Fig.4 Wave height comparisons between measured and calculated data.

After numerical simulation of each cold wave storm surge in Laizhou Bay from 1985 to 2004, the sequences of extreme water level and its concomitant wave height and wind speed at 5 m water depth (S5) are shown in Fig. 5. In the 64 cold wave storm surges, there are only one extremely-strong cold wave and 11 strong cold waves. However, the definition of cold wave process in 'cold wave grade' is based on meteorological factors (air temperature), which have no direct relationship with marine elements. According to the hindcast, there are 12 cold waves with extreme water level exceeding average warning level (Xu and Lv, 1991), 9 cold waves with extreme water level higher than 3 m, 3 cold waves with extreme water level higher than 3.5 m, and the highest water level is 3.91 m. Cold wave processes with concomitant extreme wave height over 1.25 m account for 48%, among which there exist 6 cold waves exceeding 2 m, and the maximum concomitant wave height reaches 2.35 m. With regard to concomitant wind speed, there are 4 cold wave processes with a wind speed higher than level 10 (24.5 $m\,s^{-1}$), the maximum being up to 30 $m\,s^{-1}$. However, the peak surge level, wave height and wind speed during the only extremely-strong cold wave are 2.26 m, 1.36 m and 17.05 m s^{-1}, respectively. These simultaneously occurring values are not extremely high. On the contrary, the 3 cold wave processes, whose peak surge level, concomitant wave height, concomitant wind speed are (3.91 m, 0.67 m. 20.78 $m\,s^{-1}$), (2.99 m, 2.35 m, 23.64 $m\,s^{-1}$) and (2.57 m, 1.97 m, 29.96 $m\,s^{-1}$), respectively, are all classified as ordinary cold wave. It is clear that the cold wave grade by meteorological parameters is not accurate to delineate cold wave-induced storm surges described by marine elements.

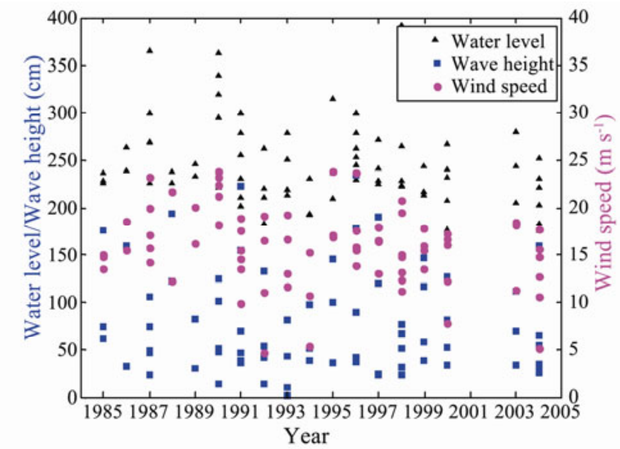

Fig.5 Scatter diagram of data sequences at 5 m water depth.

3 Trivariate Compound Extreme Value Distribution Model

The multivariate compound extreme value distribution model (Liu *et al.*, 2004) is available for probability analysis, but its applications are limited. In this paper a trivariate reconstruction probability model is developed with two-dimensional copula functions between main extreme and concomitant values; then the Poisson distribution describing cold wave frequencies is used to establish the Poisson trivariate compound extreme value distribution model.

The marginal distributions suitable for marine variables must be determined before the construction of trivariate probability model. The most commonly used univariate distributions are Gumbel distribution, Weibull distribution, lognormal distribution, Pearson III distribution and generalized extreme value (GEV) distribution. In order to select the best marginal distribution, we compare the fitting curves of these five distributions, and parameters are estimated by the moment method. Algorithm solutions can be found in literature (Rao and Hamed, 2000). The two-dimensional copula function used in this paper is the Frank copula (Tao *et al.*, 2013) and is able to link the joint distribution and its marginal distribution.

3.1 Trivariate Reconstruction Probability Model

According to the multidimensional Sklar theorem (Nelsen, 2006), a copula function can be used to connect marginal distributions to a multivariate probability model, and the d-dimensional distribution can be obtained by two (d-1)-dimensional marginal distributions which have (d-2) same variables (Michele *et al.*, 2007). Make a three-dimensional random vector (X, Y, Z) correspond to extreme water level E, concomitant wave height H and concomitant wind speed W, respectively, during each cold wave process, where X is the main extreme value. Then the trivariate reconstruction probability model based on two-dimensional conditional copula functions is obtained as follows:

$$G_{XYZ}(x,y,z)=\int_{-\infty}^{x} C_{YZ}(G_{Y|X}(y|t),G_{Z|X}(z|t))\,\mathrm{d}\,G_X(t)\,, \quad (1)$$

where $C_{YZ}(\cdot,\cdot)$ is the two-dimensional connection function between conditional variables $Y|X$ and $Z|X$:

$$G_{Y|X}(y|x)=P(Y\le y|X=x)=H_{YX}(G_Y(y),G_X(x))\,, \quad (2)$$

$$G_{Z|X}(z|x)=P(Z\le z|X=x)=H_{ZX}(G_Z(z),G_X(x))\,. \quad (3)$$

In the above equations, $G_X(x)$, $G_Y(y)$, $G_Z(z)$ are the univariate marginal distributions, and

$$H_{AB}(a,b)=\partial_b C_{AB}(a,b)=\partial C_{AB}(a,b)/\partial b\,. \quad (4)$$

Hence $C_{XY}(\cdot,\cdot)$ and $C_{ZY}(\cdot,\cdot)$ are the two-dimensional connection functions of (X, Y) and (Z, Y), respectively. In this paper, the copula function is Frank copula; its distribution function $C(a, b)$ is listed below, and its relevant parameter θ is a nonzero number.

$$C(a,b)=-\frac{1}{\theta}\ln\left(1+\frac{(\mathrm{e}^{-\theta a}-1)(\mathrm{e}^{-\theta b}-1)}{(\mathrm{e}^{-\theta}-1)}\right)\,. \quad (5)$$

3.2 Poisson Trivariate Compound Reconstruction Model

Assuming that n cold waves occur each year, and n follows a discrete distribution independent of marine variables. When the discrete distribution is Poisson distribution with the parameter λ, its probability function is described as:

$$P_k=\mathrm{e}^{-\lambda}\frac{\lambda^k}{k!}\,,\ k=0,1,2,\cdots\,. \quad (6)$$

In a year when cold waves occur, water level ξ_1 is taken as the main extreme value for each cold wave process, together with concomitant wave height and wind speed (ξ_2, ξ_3), the analytical samples (ξ_{1i}, ξ_{2i}, ξ_{3i}, i=1,2,···, n) are composed. Assuming that ξ_1, ξ_2, ξ_3 are independent and their joint distribution is $G(x, y, z)$, the marginal distribution of ξ_1 can be expressed as $G_{\xi1}(x)$. For a year without a cold wave process, the maximum water level, concomitant wave height and wind speed are represented by η_1, η_2, and η_3, respectively. If they are independent, the joint distribution can be expressed as $Q(x, y, z)$. Therefore, the annual extreme value of water level X, concomitant wave height Y and concomitant wind speed Z can be expressed as:

$$(X,Y,Z)=\begin{cases}(\eta_1,\eta_2,\eta_3) & ,\ n=0\\ (\xi_{1i},\xi_{2i},\xi_{3i})\,|\,\xi_{1i}=\max\limits_{1\le j\le n}\xi_{1j} & ,\ n\ge 1\end{cases}\,, \quad (7)$$

where n=0 represents the year without any cold wave process, and n≥1 indicates the year with at least one cold wave process. Therefore, when the Poisson distribution, the optimal marginal distributions and the trivariate reconstruction model are confirmed, the Poisson trivariate compound reconstruction extreme value (PTCR) model can then be constructed as

$$F(x,y,z)=1-P=\mathrm{e}^{-\lambda}+\lambda\mathrm{e}^{-\lambda}\cdot\int_{-\infty}^{z}\int_{-\infty}^{y}\int_{-\infty}^{x}\left[\mathrm{e}^{\lambda G_{\xi_1}(u_1)}\cdot g(u_1,u_2,u_3)\right]\mathrm{d}u_1\mathrm{d}u_2\mathrm{d}u_3\ ,\quad (8)$$

where P is the cumulative frequency, which is the reciprocal of return period T, $g(x, y, z)$ is the probability density function of $G(x, y, z)$.

4 Definition of Intensity Grade of Cold Wave Storm Surges

4.1 Fitting Test of Univariate Marginal Distributions

In order to select the most appropriate distribution for marine elements, fitting tests are carried out for each variable. The fitting degree between the sample empirical function and the distribution is evaluated using the Kolmogorov-Smirnov (K-S) test, the Ordinary Least Square (OLS) criterion and the Akaike Information Criterion (AIC), and the maximum relative error *AE* between experience dots and distribution function is used as a reference to select distributions. The optimal marginal distribution is selected with comprehensive consideration. Making α=0.05, the critical value of the K-S test, $D_{n,\alpha}$ can be obtained, and the statistical results of main extreme water level (*E*), concomitant wave height (*H*) and concomitant wind speed (*W*) under different testing criteria are listed in Table 3.

As shown in Table 3, D_n of the fitted distributions are all less than $D_{n,\alpha}$, indicating that all the distributions can pass K-S test with good fitting. For the fitting of water level, the differences of statistical value *AE* between the five distributions are small, so *AE* is not a proper parameter to measure distribution fitting. The D_n AIC value and *AE* of Gumbel distribution are all small and present the best fitting. The Pearson III distribution has a small OLS value, but a large AIC value, while all the statistical values of the GEV distribution are slightly larger than that of the Gumbel distribution. The statistical values of the Weibull distribution and the lognormal distribution are larger. As shown in Fig.6, their tail values are small and may cause errors in return period calculations and are

Table 3 Fitting results of univariate marginal distributions

Distributions	D_n			$D_{n,\alpha}$	OLS			AIC			*AE*		
	E	*H*	*W*		*E*	*H*	*W*	*E*	*H*	*W*	*E*	*H*	*W*
Gumbel	0.077	0.102	0.125	0.167	0.033	0.049	0.048	655	682	412	25.303	23.017	5.972
Weibull	0.096	0.089	0.103	0.167	0.046	0.033	0.046	663	679	353	26.430	19.738	3.630
lognormal	0.113	0.069	0.150	0.167	0.050	0.024	0.062	659	681	364	34.805	119.135	4.341
Pearson III	0.079	0.078	0.069	0.167	0.033	0.029	0.027	670	695	382	29.521	20.769	5.972
GEV	0.080	0.067	0.091	0.167	0.034	0.027	0.050	658	677	350	27.022	59.865	3.518

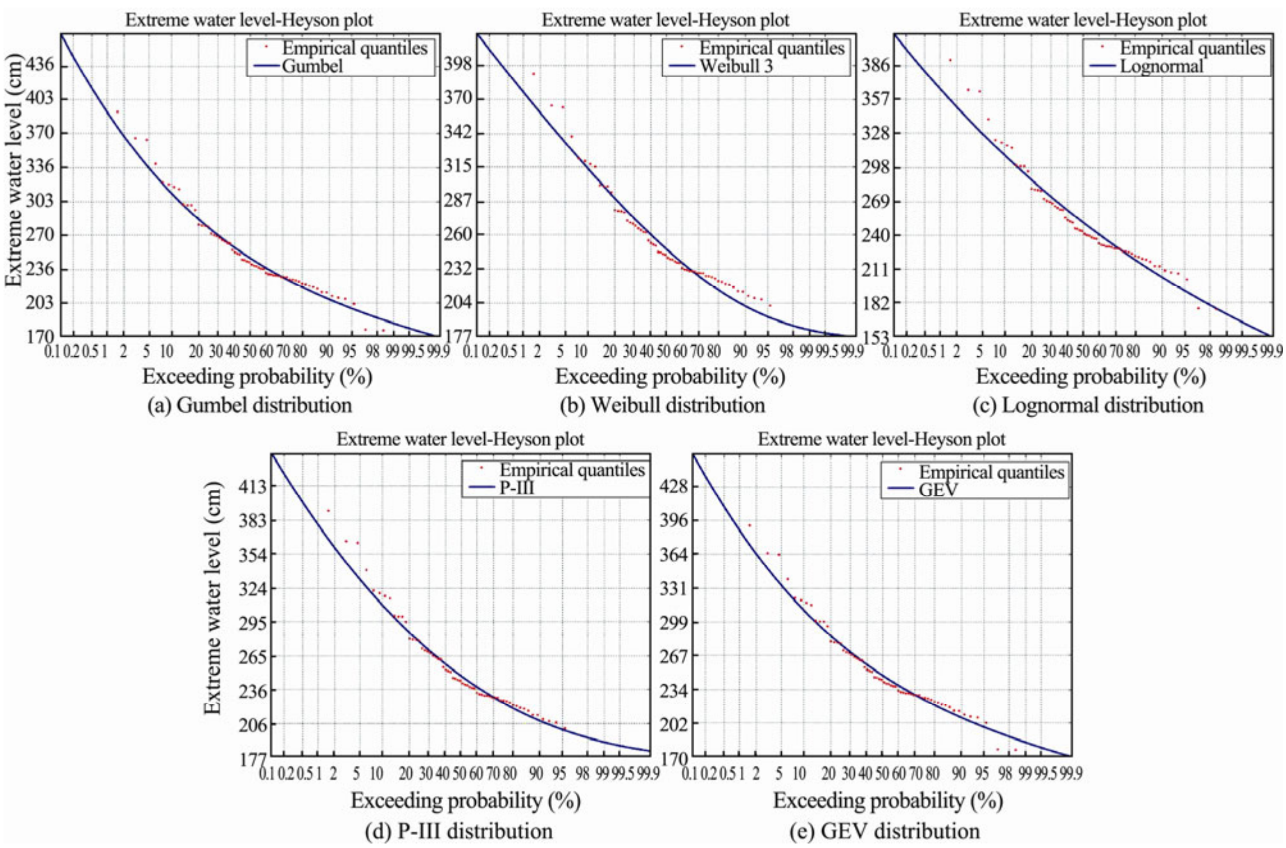

Fig.6 Fitting curves of different distributions.

therefore worse fittings. From comparing these test results, the Gumbel distribution is the optimal distribution for extreme water level, and its location and scale parameters are −234.875 and 33.903, respectively. Similarly, the Weibull distribution and the Pearson III distribution can be used as marginal distributions of concomitant wave height and concomitant wind speed respectively, and the corresponding location, scale and shape parameters are 80.343, 1.313, 1.979 and 21.745, 1.577, 2.897, respectively.

4.2 Fitting Tests of Poisson Trivariate Compound Reconstruction Model

Testing shows that the frequency of cold wave storm surges follows the Poisson distribution with parameter λ=64/20. The Poisson trivariate compound reconstruction (PTCR) model in section 3.2 is utilized to calculate the return periods of main extreme water level and concomitant wave height, and wind speed. Testing results of bivariate joint distributions and the PTCR model are presented in Tables 4 and 5 and bivariate joint density contours are drawn in Fig.7, which shows that D_n values are all less than $D_{n,\alpha}$, and therefore demonstrates that all the distributions pass K-S test and present good fittings.

Table 4 Fitting tests of bivariate joint distributions

Elements	Copula parameter		K-S test		OLS	AIC
	θ	Range	D_n	$D_{n,\alpha}$ (α=0.05)		
(E, H)	−0.570	$\theta\neq0$	0.076	0.167	0.030	1335
(E, W)	7.235	$\theta\neq0$	0.066	0.167	0.027	997
(H, W)	0.505	$\theta\neq0$	0.064	0.167	0.022	1063

Table 5 Fitting tests of PTCR model

Model	D_n	$D_{n,\alpha}$(α=0.05)	$D_{n,\alpha}$(α=0.01)	OLS	AIC
PTCR	0.087	0.167	0.200	0.030	1663

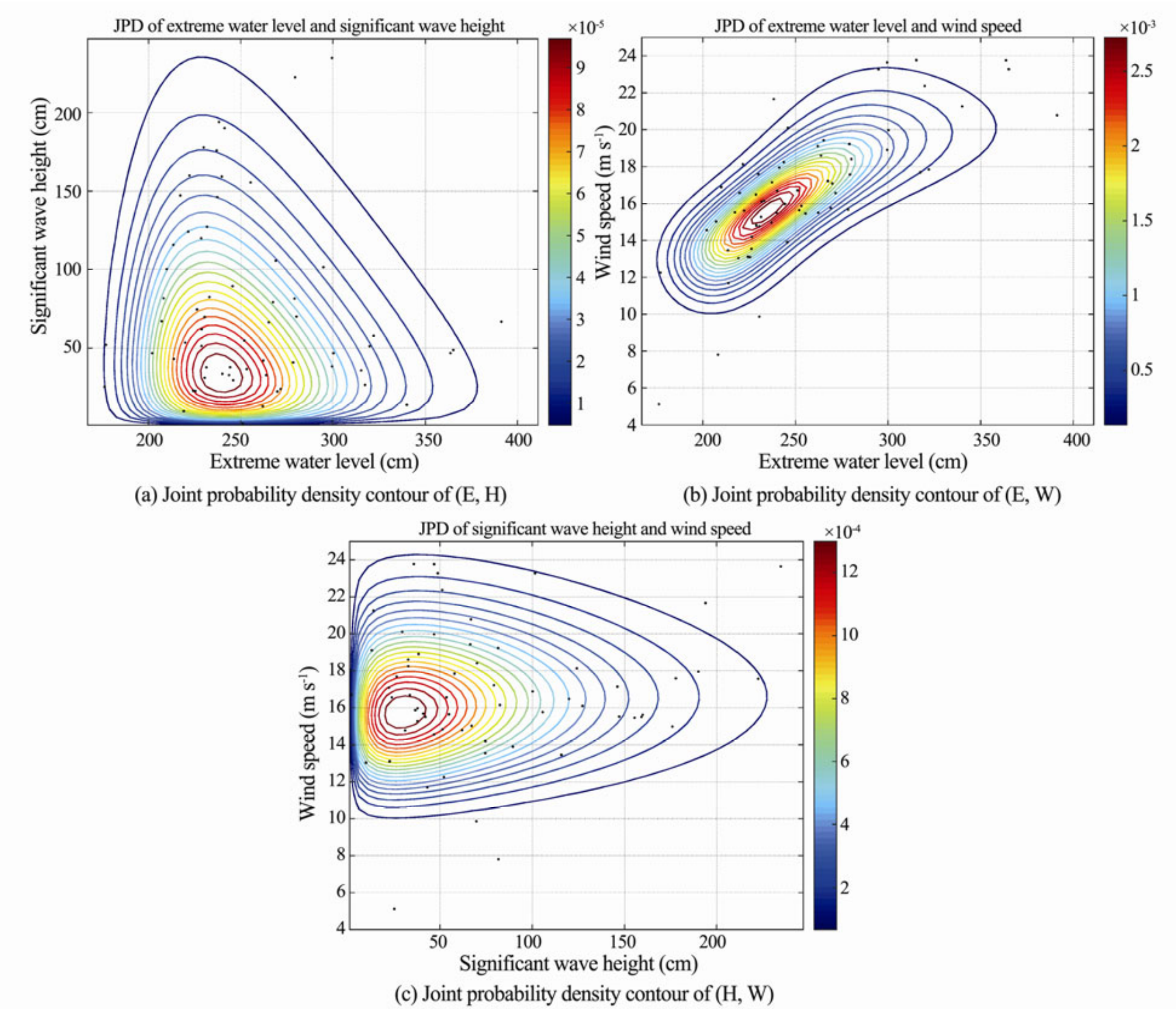

Fig.7 Joint probability density contours of bivariate marginal distributions.

4.3 Intensity of Cold Wave Storm Surges

According to the calculating results of the PTCR model and the return period listed in Table 6, cold wave storm surges of Laizhou Bay are classified into 4 grades, which are Mi (Mild), Mo (Moderate), Se (Severe) and Ss (Super Severe). In order to compare the new grading system with the old one in 'cold wave grade', cold wave, strong cold wave and extremely-strong cold wave are represented by 1, 2 and 3, respectively. The calculated results show that there are 51 mild cold wave storm surges, 7 moderate cold wave storm surges and 6 severe cold wave storm surges from 1985 to 2004. Here, ten typical cold wave processes are taken as examples to analyze the difference between cold wave grade and cold wave storm surge intensity grade (Table 7). It is clear that those two grades are not corresponding to each other, which verifies that cold wave grade in meteorology cannot describe the severity of a cold wave storm surge. As shown in Table 7, the extreme water level of grade 3 cold wave is no more than 2.5 meters, and its concomitant wave height and wind speed are small as well. Therefore, even though the amplitude of grade 3 cold waves decreases greatly, the accompanying wind is not strong enough to trigger a severe cold wave storm surge. Meanwhile, the cold waves in 1988, 1996 and 1998 are all grade 1 waves, but the ocean responses induced by the cold waves result in at least severe cold wave storm surges (grade Se). Therefore, only with the meteorological cold wave grade, the extreme ocean environment may not be properly evaluated, which may cause huge economic losses.

In ocean engineering, when marine structure and environment suffer from extreme ocean conditions, they are often subjected to great loadings, which are incorporated in the evaluation of the newly defined cold wave storm surge intensity. For instance, the water level of the 2014 cold wave exceeds the warning level with a small concomitant wave height, but the return period of these marine elements is merely 6 years and the cold wave storm surge intensity is ranked as grade Mi. However, the 1988 cold wave, though with relatively low water level, is ranked as grade Se surge, because its concomitant wave height and wind speed are both significant. It is noteworthy that the 1996 cold wave, with a high extreme water level exceeding warning level and a large concomitant wind speed close to the maximum, has a joint return period much larger than that specified as grade Se, so it is defined as a super severe (Ss) cold wave storm surge.

In summary, the cold wave storm surge intensity defined in this paper can describe ocean conditions more directly, and present the severity of cold wave storm surge more adequately. It is of great importance to marine hydrological analysis, disaster prevention and ocean engineering design in Laizhou Bay.

Table 6 Classification of cold wave storm surge intensity grade

Intensity grade	Joint return period interval (year)
Mild (Mi)	[0,20)
Moderate (Mo)	[20,100)
Severe (Se)	[100,500)
Super severe (Ss)	[500,∞)

Table 7 Comparison between the two cold wave grades of typical cold wave processes

Year	E (m)	H (m)	W (m s^{-1})	T (a)	Storm surge	Cold wave
1985	2.26	0.75	13.54	3	Mi	3
1987	3.65	0.49	23.27	188	Se	2
1988	2.38	1.94	21.66	201	Se	1
1990	2.95	1.01	23.27	103	Mo	2
1993	2.79	0.82	19.23	10	Mi	1
1995	3.15	0.36	23.77	67	Mo	1
1996	2.99	2.35	23.64	2106	Ss	1
1997	2.41	1.90	17.95	45	Mo	1
1998	3.91	0.67	20.78	159	Se	1
2004	3.17	0.26	17.69	6	Mi	2

5 Conclusion

Laizhou Bay severely suffers from cold wave storm surge. In order to assess the influence of cold wave storm surge in Laizhou Bay, a Poisson trivariate compound reconstruction model is developed for cold wave processes. The joint return period is then calculated and used as the classification criterion to update the intensity grade of cold wave storm surges.

In the calculation of joint return period, PTCR model not only uses optimal marginal distributions, but also takes cold wave frequency into account. The extreme values and concomitant results are consistent with the surveyed data.

Through the analysis of 10 typical cold wave processes, it is found that the cold wave grade in meteorology cannot reflect the intensity of cold wave storm surge accurately, and the warning level is not well corresponding to different intensities of cold waves. The newly defined intensity of cold wave storm surges based on joint return periods is associated with extreme water level, concomitant wave height and concomitant wind speed, and directly reflects the ocean conditions under cold wave storm surge in Laizhou Bay. The development provides the guidance to marine hydrological analysis, disaster prevention, and coastal engineering design. Furthermore, it can be applied to other coastal areas for disaster assessment under extreme ocean conditions.

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