Marine Environment Element Statistic Characteristics Analysis

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Abstract. In this paper, we derived a probability distribution model that considers joint probability of discrete and continuous distribution models to estimate extreme values of ocean environment factors. We aim to improve the design standard research in ocean engineering projects. We use this new model to calculate the joint extreme value of multiple ocean environment factors in typhoon-affected sea area. Our model showed comprehensive information on the randomness and interactive-relationship of extreme values of ocean environment elements. The asymmetric relative structure formula of Poisson-Nested-Logistic distribution gives us ocean environment information, like correlation and stratification. We evaluated our model by three different case studies based on real historical datasets.

Keyword: Probability model, Ocean environment, Typhoon-affected sea area

1. Introduction

The ocean occupies two-thirds of earth and its changing mechanism is highly unpredictable. Thus, it is crucial yet challenging to accurately model its mechanism. Mathematical statistics is a powerful method to identify the oddness in the data, which gives it an advantage in revealing seawater movement, environment evolvement and their resulted disaster. For example, mathematical statistics enables us to accurately define unexpected hydrological events and their statistical patterns by observing, experimenting, calculating and analyzing random waves [1-5]. Multi-dimension probability distribution has seen increasing interest and application in recent years [6-8], which can be utilized in hydrological events joint occurrence probability calculation in fields including water resource planning, hydrological analysis, hydraulic risk analysis. The multi-dimensional joint probability analysis of data is an important first steps in foundation building in all fields [9-13]. Especially in the modern-day research, with abundant data, the ability of tackle problems from different angle, interactive perspective would benefit scientific research tremendously and may lead to results that have compounded benefits [14-17].

Random vectors can be described as discrete or continuous depending on their physical interpretation. Appropriate definition of probabilistic distribution models is crucial to accurately...
describe the characteristics of random vectors. Due to the difficulties in determining the probability
distribution model of random variables, the convention in defining random variables in coastal
engineering is to consider them to be either discrete [18-22] or continuous [23-26]. Such convention is
often seen in research that focus on issues like sea water movement generalization, marine disaster
prediction and offshore pollution propagation. [27-30] However, hydrological events in ocean
engineering often involve both discrete and continuous probability distributions. Valuing both would
benefit analysis by providing a more accurate probability characteristic description of actual events
[31-32] (The method has been studied or applied in other fields).

In this paper, we derived a new probability distribution model, and then applied it on the hot issue
in ocean engineering: the standard of ocean environment parameter design under extreme conditions.
Thereafter, this new model was applied to perform a joint probability analysis of ocean environment
conditions including wind, wave and current. We observe that our new model is capable of extracting
more information from the data and is capable of replicating the interactions and hierarchy between
different variables.

In practical application, the discrete random variable in the new model could be the annual
frequency of typhoon in different sea areas or hydrological data sample numbers over a threshold,
while the continuous random variable could be the extreme sea conditions caused by typhoon. Our
enables better utilization of the data, has the potential to provide vital support, and may lead to original
and ground-breaking research, in fields including the discovery of statistical regularities of sea water
movement, marine disaster prediction and marine ecological risk assessment.

The rest of this paper is organized as follows: the theoretical derivation of our proposed model is
presented in Section 2. Evaluation of our model is presented in Section 3. Lastly, conclusions and
discussions are summarized in Section 4.

2. Theoretical Deviation of New Probability Model

2.1. Theorem 1

Assume the distribution functions of random vector \((\xi', \eta', \varsigma')\) and \((\xi', \eta', \varsigma')\) are \(Q(x, y, z)\) and \(G(x, y, z)\),
respectively. The joint probability density function of \(G(x, y, z)\) exists and is \(G_{xy}z\). Let the i-th individually
observed value of random vector \(\xi\) and its two corresponding random vectors \(\eta, \varsigma\) be \((\xi, \eta, \varsigma)\)
\((i=1,2,\ldots)\). They are independent, and have the same distribution. \(n\) is a none-negative random variable
that is independent of \(\xi, \eta, \varsigma\) and \(\xi, \eta, \varsigma\); its probability distribution rates are as following:
\[ P(N = i) = p_i, \sum_{i=1}^{\infty} p_i = 1, i = 1, 2, 3, \ldots \]

Define random vector \((X, Y, Z)\) as:
\[ (X, Y, Z) = \begin{cases} (\xi', \eta', \varsigma') & n = 0 \\ (\xi, \eta, \varsigma) & n = 1, 2, \ldots \end{cases} \]

Then the joint distribution function of \((X, Y, Z)\) is:
\[ F(x, y, z) = p_0 Q(x, y, z) + \sum_{i=1}^{\infty} p_i \int_{-\infty}^{x} \int_{-\infty}^{y} \int_{-\infty}^{z} G_i(u) g(u, v, w) \, du \, dv \, dw \]  \hspace{1cm} (1)

where \(G_i(u)\) is the marginal distribution of \(G(x, y, z)\): \(G_i(u) = G(u, +\infty, +\infty)\).

The design standard of ocean environment is derived by setting a design frequency \(P\), as \(P = 1 - R\),
and \(0 < R < 1\), where
\[ R = P(\xi < x, \eta < y, \varsigma < z) . \]

Then we can solve:
\[ F(x, y, z) = R \] \hspace{1cm} (2)

Set the return period to be \(T\), which is
If \((x, y, z)\) satisfies equation (2), then we call \((x, y, z)\) the “T-year return period”. We usually look for the eigenvalue greater than that of 10-year (or 100-year) return period value, which is \(0.9 \le R \le 1\) (or \(0.99 \le R \le 1\)). It means that there exists a lower limit \(R_0\) for \(R\). So, when solving function (2), we often set:

\[
R_0 \le R \le 1
\]

If \(p_0 = 0\), then \(F(x, y, z) = F_0(x, y, z)\),

\[
F_0(x, y, z) = p_0 + \sum_{i=1}^{n} p_i \cdot e^{-\int_{-\infty}^{x} \int_{-\infty}^{y} \int_{-\infty}^{z} G_i(u) g(u, v, w) \, du \, dv \, dw}.
\]

When \(p_0 \neq 0\), \(F(x, y, z)\) is the limit of the distribution function sequence. If \((\xi^*, \eta^*, \zeta^*)\) has upper limit \(P(\xi^* > x_{h_1}, \eta^* > y_{h_1}, \zeta^* > z_{h_1}) = 0\),

\[
F_0(x, y, z) = R
\]

Then (5) and (2) co-exist.

Suppose \(f(x)\) is decreases monotonically on \([0, 1]\), then exists simple function sequence \(\{f_n(x)\}\) in the form of

\[
f_n(x) = \sum_{i=1}^{n} a_i I_{B_n}(x)
\]

That makes

\[
\lim_{n \to \infty} f_n(x) = f(x), x \in R
\]

Where \(a_i > 0, i = 1, 2 \cdots n\), \(B_n = \left(-\infty, b_n\right), i = 1, 2 \cdots n\). \(>\) is used to mark that the end points of the interval. I is the indicator function on \(B_n\).

Prove: let \(a_i = i/n, i = 1, 2 \cdots n\)

\[
B_n = \left\{ x : f(x) \ge i/n \right\}
\]

Because \(f(x)\) is a monotonically decreasing function, \(B_n, i = 1, 2 \cdots n\) as the form stated in the lemma, let

\[
f_n(x) = \sum_{i=1}^{n} a_i I_{B_n}(x).
\]

\[
|f(x) - f_n(x)| \le 1/n, i = 1, 2 \cdots n
\]

\[
\lim_{n \to \infty} f_n(x) = f(x), x \in R
\]

This completes the proof.

Let the distribution function of \((\xi, \eta, \zeta)\) be \(G(x, y, z)\). For any given \(z\), is the monotonically decreasing function of \(x\), then

\[
i \cdot \int_{-\infty}^{x} \int_{-\infty}^{y} \int_{-\infty}^{z} G_i^{-1}(u) dG(u, v, w) \le \int_{-\infty}^{x} \int_{-\infty}^{y} \int_{-\infty}^{z} dG(u, v, w)
\]

To all \((x, y, z)\) \(\in \mathbb{R}^3, k \ge 1\) exists.

Prove:
\[ \int_{-\infty}^{\xi} \int_{-\infty}^{\eta} \int_{-\infty}^{\zeta} G_i^{-1}(u) \, dG_i(u, v, w) = E\{I_{(v, w)}(\xi)I_{(z, w)}(\eta, \zeta)G_i^{-1}(\xi)\} = E\{E\{I_{(v, w)}(\xi)I_{(z, w)}(\eta, \zeta)G_i^{-1}(\xi)\|E\} \}
\]

Because to any given \((y, z) \in \mathbb{R}^2\), \(F_{y,z}(y, z|x)\) decreases monotonically to \(x\), and from theorem 2 there exists
\[
 f_r(u) = \sum_{n=1} a_n f_{x_n}(u) \quad (10)
\]
\[
 F_{y,z}(y, z|u) = \lim_{u \to \infty} f_r(u) \quad (11)
\]

\(B_n = (-\infty, b_n), i = 1, 2 \cdots n\), notice that \(b_n\) is relevant to \(y, z\), take it to the equation above, according to the dominated convergence theorem, we have
\[
 \int_{-\infty}^{\xi} \int_{-\infty}^{\eta} \int_{-\infty}^{\zeta} G_i^{-1}(u) \, dG_i(u, v, w) = \lim_{u \to \infty} \int_{-\infty}^{\xi} \int_{-\infty}^{\eta} \int_{-\infty}^{\zeta} a_n f_{x_n}(u) \, dG_i(u, v, w) = \lim_{n \to \infty} \sum_{n=1} a_n \int_{-\infty}^{\xi} \int_{-\infty}^{\eta} \int_{-\infty}^{\zeta} G_i^{-1}(u) \, dG_i(u) \]

For any constant \(c\), we have:
\[
 \int_{-\infty}^{\xi} \int_{-\infty}^{\eta} \int_{-\infty}^{\zeta} G_i^{-1}(u) \, dG_i(u) = G_i^*(c) = \lim_{n \to \infty} \sum_{n=1} a_n \int_{-\infty}^{\xi} \int_{-\infty}^{\eta} \int_{-\infty}^{\zeta} G_i^{-1}(u) \, dG_i(u) \]

Notice that \(a_n > 0, i = 1, 2 \cdots n\), as a result, we have:
\[
 \int_{-\infty}^{\xi} \int_{-\infty}^{\eta} \int_{-\infty}^{\zeta} G_i^{-1}(u) \, dG_i(u) = \lim_{n \to \infty} \sum_{n=1} a_n \int_{-\infty}^{\xi} \int_{-\infty}^{\eta} \int_{-\infty}^{\zeta} f_{x_n}(u) \, dG_i(u) = \int_{-\infty}^{\xi} \int_{-\infty}^{\eta} \int_{-\infty}^{\zeta} dG_i(u, v, w) = G_i(x, y, z)
\]

This completes the proof.

If to all \(x, P(\xi^* < x) \geq P(\xi < x)\), we can denote the following equations:
\[
 F(x_{R}, y_{R}, z_{R}) = R, \quad F_{x}(x_{R}, y_{R}, z_{R}) = R, \quad F(x_{R}, y_{R}, z_{R}) = R', \quad T = 1 / (1 - R), \quad T = 1 / (1 - R') \]
\[
 (1 - p_0)T \leq T' \leq T
\]

As a result, as long as \(\xi^*\) is smaller than \(\xi\) (i.e., \(P(\xi^* < x) \geq P(\xi < x)\)), substituting (2) with (5) could at most make the derived return period be a smaller value, i.e., \(p_0\) times of the original value \((0 < p_0 < 1)\). In practical problems, \(p_0\) of common Poisson distribution or binary distribution are relatively small. For example, in Poisson distribution, when \(\lambda = 3\), the error of reoccurring period would be no more than 5%. And when \(\lambda = 4\), 1.8%, when \(\lambda = 5\), 0.67%. As for binary distribution, \(p_0\) is too small to notice.

When marine environment elements are in different forms, our model (1) could be expressed in different, specific forms: Poisson-Logistic distribution model, the Poisson-Mixed-Gumbel distribution mode, Poisson-Nested-Logistic distribution mode, etc. We could get values like the century-occurring design wave height value, platform deck standard design height in areas affected by typhoon using our model.

This new model covers previous extreme value models, whose continuous variables can be 1-D, 2-D, to multi-dimension. For instance, in engineering, common continuous variables include: Pearson-III (13), Generalized extreme value distribution (14), Maximum entropy distribution (15) and 2D Mixed Gumbel Distribution (16-17).

\[
 f(x) = \begin{cases} 
 \frac{\beta^\alpha}{\Gamma(\alpha)} x^{\alpha-1} e^{-\beta x}, & x > 0 \\
 0 & \text{otherwise}
\end{cases}
\]

\[
 f(x) = \frac{1}{\sigma} \exp \left[ -\left( 1 + \frac{x - \mu}{\sigma} \right)^{-\kappa} \right] \left( 1 + \frac{x - \mu}{\sigma} \right)^{-\left( 1+\kappa \right)}
\]

where \(\sigma > 0\)
\[ f(x) = \alpha x^\gamma e^{-\beta x^\gamma}, x > 0 \]  

\[ G(x, y) = G(x)G(y) \exp \left\{ -\theta \left[ \frac{1}{\ln G(x)} + \frac{1}{\ln G(y)} \right] \right\} \quad (0 \leq \theta \leq 1) \]  

Where \( G(x) \) and \( G(y) \) are the edge distributions of random variables \( x \) and \( y \), respectively:

\[ G_x(x) = \exp \left( -\exp \left( -\frac{x - \mu_x}{\sigma} \right) \right) \quad G_y(y) = \exp \left( -\exp \left( -\frac{y - \mu_y}{\sigma} \right) \right) \]

\[ \theta = 2\left[1 - \cos\left(\pi \frac{\rho}{\sqrt{6}}\right)\right], \quad 0 \leq \rho \leq 2/3 \]

\[ \rho \] is the Linear correlation coefficient of \( X \) and \( Y \):

\[ \rho = \frac{E[(X - \mu_x)(Y - \mu_y)]}{\sigma_x \sigma_y} \]  

In practical application, if we apply the new probability distribution model (1) or (5) to equation (4) or (2), then the new method could be used to in ocean-environment joint design parameter estimation and calculation. This would bring ground-breaking foreshadowing in many API research areas that has not been solved for many years. It could also provide an accurate calculation and reasonable design standard to the existing ambiguous American fixed-platform-design specification.

3. Application of the New Probability Distribution Model in Oceanic Engineering

Different meanings can be assigned to the discrete and continuous random vectors based on specific engineering background and needs. For example, the discrete random variable could be the annual frequency of typhoon, hurricane, and cold current or great wind over different sea areas. It could also be the number of random samples of data under randomness principal. The multi-variable continuous probability distribution is an ocean-environment parameter chosen under the demand. An example application can be the calculation of design wave height shown below.

3.1. Case Study 1: An island in Huanghai Area

We first investigate the joint probability analysis of an island in Huanghai area based on the 26-year data from 1963 to 1988. This dataset includes the wave height, wind speed and period, together with the corresponding typhoon data.

Then, based on the wave height, the accompanying wind speed and the period, the thresholds of the edge distribution are estimated and the parameters are estimated for 19 years. The wave height, wind speed and period threshold are 5m, 17 and 6.5s respectively, as shown in Figure 1.

![Wave height results](image1) ![Wind speed results](image2) ![Frequency results](image3)

**Figure 1** Average remaining lifetime results.
Figure 2. Wave height as the main factor. Figure 3. Wind speed as the main factor.

(a) probability, (b) quantile, (c) return level, (d) density

We further select samples from the dataset and plot Figures 2 and 3 further to illustrate the probability, quantile, return level and density diagnostic test results of “wave height as the main factor”, “wind speed as the main factor” and “frequency as the main factor”.

We observe from these figures that the selected threshold samples are well fitted with the generalized extreme value distribution, and all of the reproduction levels are within the 95% confidence interval. Meanwhile, the density curve is also close to the real case, which validates the correctness of our threshold selection.

Figure 4. Distribution function. Figure 5. Density function.

(a) z3=2, (b) z3=6, (c) z3=8.5, and (d) z3=9.5

Figure 4 and 5 are the joint distribution functions and joint probability density functions under different frequencies. To further observe the properties and characters of the new probability model, we plot these two functions’ contour lines in Figure 6 and 7.

Figure 6. Contour lines of joint distribution function. Figure 7. Contour lines of joint probability density function.

(a) z1=5, (b) z1=6, (c) z1=8, and (d) z1=9
### Table 1. Results of different calculation methods.

| Calculation method                                      | Return period      | Wave height (m) | Wind speed (m/s) | Period (sec) |
|---------------------------------------------------------|--------------------|-----------------|-----------------|--------------|
| 3D compound extreme value distribution mode              | 100-year joint return period | 10.8            | 39.7            | 11.9         |
| API suggested method 3                                   | 100-year return period  | 12.8            | 44.9            | 13.0         |
| 3D compound extreme value distribution mode              | 500-year joint return period | 14.0            | 43.1            | 12.2         |
| API suggested method 3                                   | 500-year return period  | 14.2            | 47.6            | 13.8         |

### 3.2. Case Study 2: Wave in Chengsi Area

We next evaluate our model based on wave datasets in Chengsi area. We divided the 77 groups wave data of Shengsi from 1961 to 1980 into two groups – the sequence of greatest wave during typhoon effects (No.1 to 5), and the sequence of annually greatest wave (No.6 to 10). Tables 2 and 3 are the calculated wind-wave values using Poisson-Mixed-Gumbel (PMG) model and Mixed-Gumbel (MG) model when the joint CDF is 0.98 and 0.99. Additionally, Tables 2 and 3 compared the derived wave heights of these two different modes when the wind speed is $x=40m/s$ and when the wave height is $y=12.5m$, respectively. The wind speed $x=40m/s$ and wave height $y=12.5m$ are arbitrary values, aiming to compare the results of these two models. In the chart, $\Delta$ represents the difference between calculated results of 12-year data (No. 2-5, 7-10) and 20-year data (No. 1 and 6). $\sigma$ represents the standard deviation of the results of different data.

### Table 2. Calculated wave heights of the two models given wind speed $x = 40m/s$.  

| Data No. | Data Duration (year) | Method          | Joint cdfPr(X<=x, Y<=y)=0.98 | Joint cdfPr(V<=v, H<=h)=0.99 |
|----------|----------------------|-----------------|-----------------------------|-----------------------------|
|          |                      |                 | Wave height y               |                         |
|          |                      |                 | $\Delta$                    | $\sigma$                   | Wave heighty   | $\Delta$ | $\sigma$ |
| 1        | 20 (61-80)           | PGMD Model      | 11.06                       | 0                          | 12.16          | 0       |
| 2        | 12 (61-72)           |                 | 11.58                       | 0.52                       | 12.85          | 0.69    |
| 3        | 12 (63-74)           |                 | 11.01                       | -0.05                      | 12.13          | -0.03   |
| 4        | 12 (65-76)           |                 | 10.89                       | -0.17                      | 11.99          | -0.17   |
| 5        | 12 (67-78)           |                 | 10.72                       | -0.34                      | 11.79          | -0.37   |
| 6        | 20 (61-80)           | Gumbel Mixed    | 10.37                       | 0                          | 11.42          | 0       |
| 7        | 12 (61-72)           | Model           | 9.72                        | -0.65                      | 10.49          | -0.93   |
| 8        | 12 (63-74)           |                 | 9.88                        | -0.49                      | 10.70          | -0.72   |
| 9        | 12 (65-76)           |                 | 8.97                        | -1.40                      | 9.67           | -1.75   |
| 10       | 12 (67-78)           |                 | 9.40                        | -0.97                      | 10.19          | -1.23   |

### Table 3. Calculated wind speeds of the two models ($h=12.5m$).

| Data No. | Data Duration (year) | Method          | Wind Speed x | $\Delta$ | Standard deviation $\sigma$ | Wind Speed x | $\Delta$ | Standard deviation $\sigma$ |
|----------|----------------------|-----------------|--------------|----------|-----------------------------|--------------|----------|-----------------------------|
| 1        | 20 (61-80)           | PGMD Model      | 33.15        | 0        | 1.133                       | 37.15        | 0        | 1.002                       |
| 2        | 12 (61-72)           |                 | 34.58        | 1.43     | —                           | —            | —        | —                           |
| 3        | 12 (63-74)           |                 | 32.61        | -0.54    | 36.71                       | -0.44        | 1.002   |
| 4        | 12 (65-76)           |                 | 31.96        | -1.19    | 35.61                       | -1.54        | 1.002   |
| 5        | 12 (67-78)           |                 | 31.75        | -1.4     | 34.96                       | -2.19        | 1.002   |
| 6        | 20 (61-80)           | Gumbel Mixed    | 33.63        | 0        | 36.77                       | 0            | 1.002   |
| 7        | 12 (61-72)           | Model           | 30.02        | -3.61    | 34.60                       | -2.17        | 3.882   |
| 8        | 12 (63-74)           |                 | 26.21        | -7.42    | 27.91                       | -8.86        | 3.882   |
| 9        | 12 (65-76)           |                 | 26.72        | -6.91    | 28.38                       | -8.39        | 3.882   |
| 10       | 12 (67-78)           |                 | 30.76        | -2.87    | 33.02                       | -3.75        | 3.882   |
From Table 2 and 3, $\Delta$ and $\sigma$ of new model’s design value are smaller than those of Mixed-Gumbel models’. These results showed the derived result of design values of new model is closer to the long-term data-derived result (20 year) when there’s only short-term data available (12 year).

3.3. Case Study 3: Water Level in Wusong Area
Lastly, we investigate water level in Wusong area. Table 4 is the derived design water level in 100-year joint return period. It is calculated based on the observed data between 1970 and 1990 when Wusong was affected by typhoon, dominated by storm surge and under the Poisson-Nested-Logistic distribution mode.

Table 4. Suggested water level design standard of Wusong.

| Joint return period(year) | Flood (m) | Storm (m) | Astronomical tide (m) | Design water level (m) |
|---------------------------|-----------|-----------|----------------------|------------------------|
| 100                       | 0.43      | 1.32      | 4.14*                | 5.89*                  |
| 500                       | 0.59      | 1.43      | 5.06*                | 6.98*                  |

* close to the Wusong datum plane.

The 1000-year return period flood-preventing water level of Shanghai using traditional single-factor extension method is 5.86 meter. From Table 4, this value is close to the derived joint 100-year return period value using the new model.

4. Conclusions and Discussions
In this paper, we derived a new probability distribution, and gave examples of its application towards engineering issues in forms of Poisson-Logistic, Poisson-Mixed-Gumbel and Poisson-Nested-Logistic distribution,

1. Using the wave height data, with the aid of wind speed and corresponding wind-wave synchronizing data, we calculated the 100-year return period design standard;
2. We calculated the design water level under the joint effect of astronomical tide and the water increase due to run-off of Changjiang and storms, based on the observed data of Wusong under extreme environment conditions, considering the co-occurrence of multiple disadvantageous factors.
3. Lastly, we proved with observed data that the result of new model is closer to the long-term data-derived result when there’s only short-term data available such as 100-year return period joint design wave of wind speed and wave height derived from Shengsi wind-wave synchronous data, showing our model’s stability and reliability on limited data.

Compared to the current model that uses only either discrete or continuous distribution, the new model considers the joint probability distribution of extreme values of ocean environment factor. By doing so, the new model showed comprehensive information on the randomness and interactive-relationship of extreme values of ocean environment elements. The asymmetric relative structure formula of Poisson-Nested-Logistic distribution, in particular, covers ocean environment information, like correlation and stratification. As a result, the new model (equation (1) and (5)) is a new probability distribution model that better utilizes data.

This new probability distribution model could also be used in fields including reliability of structures, long-term probability analysis of costal sand movement, joint probability distribution analysis of sea-ice, the flood peak, volume and duration analysis in a flood frequency analysis, etc. These applications are still unseen internationally.

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