Dear Editor,

Thank you very much for your suggestions on our manuscript (eggsphere-2022-847). We have revised the manuscript according to the reviewers' suggestions, and proof-read the manuscript to minimize typographical, grammatical, and bibliographical errors. We prepared three documents as requested: (1) a point-to-point reviewer response document including original comments, our response, and corresponding revisions made in the manuscript, (2) a marked-up manuscript version showing all the detailed modifications in the manuscript, and (3) a revised manuscript.

We appreciate your kind help in the process of review and revision. We look forward to further updates from you.

Sincerely,
Weihua Fang
On behalf of the co-authors

General response: We sincerely thank the editor and all the reviewers for their valuable feedback, which we have used to improve the quality of our manuscript. The reviewer comments are provided below in **bold font,** and specific concerns have been numbered. Our responses are given in normal font, and changes/additions to the manuscript are given in blue text.

Responses to Referee #1

General comments

Even if the theory is classic, the topic of the paper is original for three points: 1) the joint probability analysis is applied spatially on a large area; 2) a design criteria is proposed combining simultaneous probability and joint probability; 3) an analysis of change of return period protection standards is presented.

Response: We greatly appreciate your comments and suggestions. Please kindly find the detailed responses and revisions below.

1. **The notations 5a, 10a, ... is not known by the reviewer. Does it mean 5 years, 10 years, ... ? It should be understood easily by the reader.**

   Response: Thank you for your comment, the notations 5a, 10a, ... mean 5 years, 10 years,.... respectively. Following your suggestion, we have modified the 5a, 10a to 5-year, and 10-year return periods in the revised manuscript.

   Line 259-260: Based on the univariate return period formula (Eq. 5), the SH and SWH are estimated for six typical return periods of 5-year, 10-year, 20-year, 50-year, 100-year, and 200-year at all nodes.

   Line 293-295: In addition, based on the formula of bivariate probability (Eq. 6 and Eq. 8), $P_{\cap}$ and $P_{\cup}$ of SH and SWH are calculated for all nodes with a combination of 10-year, 20-year, 50-year, and 100-year return periods.

   Line 299-300: $P_{\cap}$ is greatest when the return period of SH and SWH is 10-year, which is higher than 0.05. $P_{\cap}$ is the smallest for SH and SWH of 100-year return period, which is generally lower than 0.009.

   Line 305-308: $P_{\cup}$ is highest when the return period of SH and SWH is 10-year, which is greater than 0.13 overall. $P_{\cup}$ is smallest when the return period for SH and SWH is 100-year, which is less than 0.015. When the return period of SH or SWH is 50-year or

100-year, the regional variation in $P_{\cup}$ are relatively small.

Line 316-318: Under the condition that the return period of SWH is 10-year, $P_{|}$ for SH with a return period of 10-year are concentrated between 0.55 and 0.75, and $P_{|}$ is generally less than 0.08 if the return period for SH is 100-year.

Line 344-346: Therefore, we calculate the change values in $P_{\cap}$, $P_{\cup}$, and $P_{|}$ for all nodes when the design return period criterion for a given variable is increased from 5-year, 10-year, 20-year, and 50-year to 10-year, 20-year, 50-year, and 100-year, respectively.

Line 352-354: When the return period of one variable is 10-year or 20-year, the decline in $P_{\cap}$ increases when the protection standard of another variable is raised. If the design criteria increase from a 50-year to a 100-year return period, the change value of $P_{\cap}$ decreases.

Line 370-373: When the protection standard for one variable is a 10-year or 20-year return period, the decrease in bivariate $P_{|}$ tends to increase when the design criterion for the other variable's return period is raised, but the decrease in $P_{|}$ is slightly reduced when the design criterion of the other variable is increased from a 50-year to a 100-year return period.

Line 384-387: When $RP_{\cup}$ is a 5-year return period, the design criteria of SH are between 1.5 m and 2.5 m in the eastern coastal area of the Leizhou Peninsula and fall below 0.5 m in the southeastern coastal region of Hainan Island. As the return period increases, the design surge height gradually increases, and when $RP_{\cup}$ is a 200-year return period, the design surge height in the eastern coastal area of the Leizhou Peninsula is generally higher than 3.0 m.

Line 392-393: When $RP_{\cup}$ is a 5-year return period, the design criteria of SWH in the coastal areas of the Leizhou Peninsula and Hainan Island are less than 2.5 m overall.

Line 394-396: When $RP_{\cup}$ is a 200-year return period, SWH along the coast of the Leizhou Peninsula is generally less than 6.0 m, while the design SWH along the Qiongzhou Strait and southeastern Hainan Island is relatively high.

2. **One main clarification is needed: even if the proposal is mathematically clean, the constraint condition of equation 12 based on joint probability should be discussed.**

   A figure presenting the constraint and the objective function in the plane (x,y) could be firstly useful.

   Secondly, what is the physical sense of this choice? What do we practically design with this constraint condition? The authors refer to coastal protection standards. Other standards relative to coasts exist like overtoppings rate, erosion rate or wave set-up, ... Can these standards be compared with the joint probability? Do we need a

constraint condition on-shore or off-shore?

Response: Thanks for your suggestion. The revised manuscript gives the meaning of the constraint condition in Equation 12. In addition, a schematic diagram of the constraints and the objective function is given to facilitate the reader's understanding of estimating the optimal design values for storm surge and wave combinations based on bivariate simultaneous return periods and joint return periods. The coastal protection criteria in this study only consider the SHs and SWHs, while other indicators are not currently considered and are subject to further research.

Line 59-63: In addition, as the intensities of the bivariates and their simultaneous probability are three-dimensional surfaces, the cross-section at a given return period is a curve rather than a specific scale value, so the joint probability of SHs and SWHs alone can not be used directly as a reference value for engineering design criteria. In order to obtain two specific scalars for SH and SWH, other constraints, such as their preferred simultaneous return periods are needed (Xu et al., 2022).

Line 69-73: The change in bivariate occurrence probability after increasing the engineering design criteria for the SHs and SWHs is quantitatively assessed. Finally, with the maximum bivariate simultaneous return period as the objective function and the bivariate joint return period as the constraint, the optimum engineering design values of SHs and SWHs are solved by the non-linear programming method.

Line 420-424: Therefore, developing appropriate design criteria for the SHs and SWHs can effectively reduce the impact of tropical cyclone marine hazards in coastal areas. Since the joint probability distribution of the bivariate is a three-dimensional surface, to obtain specific scalar values for these two hazards as design criteria, in this study, the optimal design criteria for storm surge and waves under the objective of minimum bivariate simultaneous return period are estimated using a non-linear programming approach with their estimated joint return periods as constraints.

Line 224-241: Based on the binary Copula function, the bivariate joint probability of extreme storm surges and waves under different joint return periods is available. In order to achieve the optimal protection effects, it is natural that we need to set the maximum bivariate simultaneous probability of SH and SWH as target functions (Eq. 16) and use joint probability as constraints (Eq. 17).

According to the non-linear programming method (Bazaraa et al., 2006), for a combined event of extreme SHs and SWHs, a series of (x, y) shall be iterated to minimize $P(X > x, Y > y)$ for a given joint return period to obtain the best cost-benefit effect. Therefore, the optimal values of SH and SWH can be solved, as illustrated in Figure 4. Since we have the estimation of the joint probability for the study area instead of some specific locations, the optimal design criteria for all the eastern coasts of the Leizhou Peninsula and Hainan Island can be estimated.

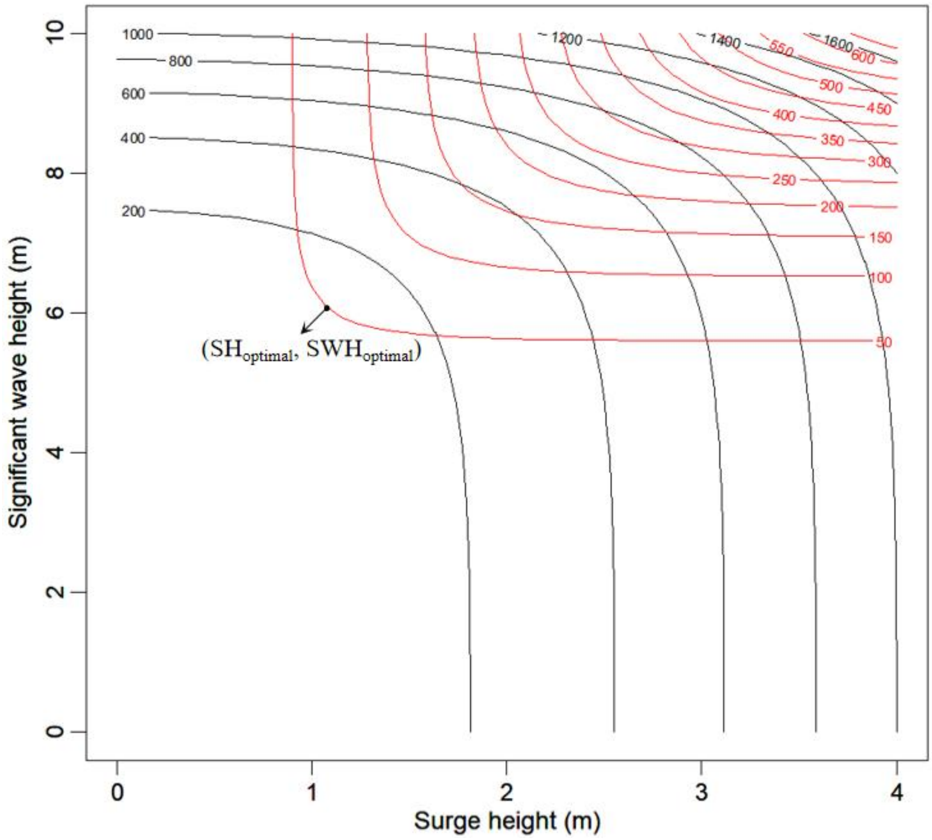

Figure 4: Diagram of determining SH and SWH based on their joint and simultaneous return periods (red curves are joint return periods ($RP_{\cup}$), black curves are simultaneous return periods ($RP_{\cap}$), and black dots (x, y) is the optimal SH and SWH).

Responses to Referee #2

General comments

The authors have not addressed several comments. In particular, the following answers should be revised:

Response: Thanks for your suggestion. We answered some of the questions in our previous response without including all of them in the manuscript text. Following your advice, we made further explanations and added some equations to the revised manuscript. Please kindly find our response below in detail.

1. **the criteria adopted for the generation of the unstructured grid are not clear.**

   Response: SMS software is used in the model to construct a refined and unstructured offshore grid of the eastern Leizhou Peninsula. A description of the unstructured grid can be found as follows:

   Line 97-102: The calculation region for the large-area is 105.5° E-121.2° E and 3.3° N-26.4° N, and the calculation region for the small-area is 105.5° E-116.5° E and 14.7° N-23.1° N (Figure 2a). And a gradient resolution is used to set the resolution for different regional grids. In the large-area model, the whole large-area contains 9,331 triangular grid nodes and 18,068 triangles; the resolution of the shoreline in the area near Zhanjiang is 0.07°-0.1°, while the resolution in other area is about 1 km-2 km. In the small-area model, the whole small-area contains 41,153 triangular grid nodes and 79,889 triangles; the resolution of the shoreline near Zhanjiang port is 0.0039°-0.01, the resolution of the open boundary is set to 0.1°-0.3°.

   Line 128-130: The calculation region for the large-area is 15° N-22° N, 110.5° E-118.5° E, which has a spatial step of 0.083° × 0.083°; the calculation region for the small-area is 21° N-21.2° N, 110° E-110.5° E, which has a spatial step of 0.0033° × 0.0033° (Figure 2b).

2. **explain also how the boundary conditions of SWAN were set.**

   Response: Thank you for your suggestion. We have added the boundary conditions for the storm surge and wave models to the revised manuscript. The details are as follows:

   Line 114-116: The boundary condition to force the surge in the subdomain is the time series of the water level on each boundary nodes, which includes both the tide elevation of 8 major constituents (M2, S2, N2, K2, K1, O1, P1, and Q1) in that area from OSU Tidal Prediction Software and the surge elevation extracted from the full domain results (Liu et al., 2018).

Line 130-135: The SWAN model includes land boundaries and water boundaries, which need to be set up separately. The model assumes that the land boundary does not generate waves and assumes that the land boundary can fully absorb waves that cross or leave the shoreline. As the southern and eastern boundaries of the large-area model are open boundaries and are far from the shoreline, which is the focus of this study, the incoming wave energy at the open boundaries of the large-area model can be ignored, and the open boundary conditions for the small-area are calculated from the large-area model (Li et al., 2016).

3. **the equations should be added in the manuscript.**

Response: Thank you for your suggestion. We have added the governing equations for the SWAN and ADCIRC models to the revised manuscript. The equations are as follows:

Line 135-138: The governing equations of the SWAN model are as follows:

$$\frac{\partial N}{\partial t}+\frac{\partial}{\partial \lambda}[(c_\lambda+U)N]+cos^{-1}\varphi\frac{\partial}{\partial \varphi}\left[\left(c_\varphi+V\right)N\cos\varphi\right]+\frac{\partial}{\partial \theta}[c_\theta N]+\frac{\partial}{\partial \sigma}[c_\sigma N]=\frac{S_{tot}}{\sigma} \quad (4)$$

The wave action density $N(t,\lambda,\varphi,\sigma,\theta)$ is allowed to evolve in time (t), geographic space (λ,φ) and spectral space (with relative frequencies σ and directions θ), (c_λ,c_φ) is the group velocity, (U,V) is the ambient current, and c_θ and c_σ are the propagation velocities in the θ- and σ- spaces, the source terms S_{tot} represent wave growth by wind.

Line 104-113: ADCIRC computes water levels via the solution of the Generalized Wave Continuity Equation (GWCE), which is a combined and differentiated form of the continuity and momentum equations:

$$\frac{\partial^2\zeta}{\partial t^2}+\tau_0\frac{\partial\zeta}{\partial t}+Sp\frac{\partial\widetilde{J_\lambda}}{\partial\lambda}+\frac{\partial\widetilde{J_\varphi}}{\partial\varphi}-SpUH\frac{\partial\tau_0}{\partial\lambda}-VH\frac{\partial\tau_0}{\partial\varphi}=0 \quad (1)$$

and the currents are obtained from the vertically-integrated momentum equations:

$$\frac{\partial U}{\partial t}+S_pU\frac{\partial U}{\partial\lambda}+V\frac{\partial U}{\partial\varphi}-fV=-gS_p\frac{\partial}{\partial\lambda}\left[\zeta+\frac{P_s}{g\rho_0}-\alpha\eta\right]+\frac{\tau_{s\lambda,winds}+\tau_{s\lambda,winds}-\tau_{b\lambda}}{\rho_0H}+\frac{M_\lambda-D_\lambda}{H} \quad (2)$$

$$\frac{\partial V}{\partial t}+S_pU\frac{\partial V}{\partial\lambda}+V\frac{\partial V}{\partial\varphi}-fU=-g\frac{\partial}{\partial\varphi}\left[\zeta+\frac{P_s}{g\rho_0}-\alpha\eta\right]+\frac{\tau_{s\varphi,winds}+\tau_{s\varphi,winds}-\tau_{b\varphi}}{\rho_0H}+\frac{M_\varphi-D_\varphi}{H} \quad (3)$$

where $H=\zeta+h$ is total water depth; ζ is the deviation of the water surface from the mean; h is bathymetric depth; $Sp=cos\varphi_0/cos\varphi$ is a spherical coordinate conversion factor and φ_0 is a reference latitude; U and V are depth-integrated currents in the $x-$ and $y-$ directions, respectively; $Q_\lambda=UH$ and $Q_\varphi=VH$ are fluxes per unit width; f is the Coriolis parameter; g is gravitational acceleration; Ps is atmospheric pressure at the surface; ρ_0 is the reference density of water; η is the Newtonian equilibrium tidal potential, and α is the effective earth elasticity factor; $\tau_{s,winds}$ and $\tau_{s,waves}$ are surface stresses due to winds and waves, respectively; τ_b is bottom stress; M are lateral stress gradients; D are momentum dispersion terms; and τ_0 is a numerical parameter that optimizes the phase propagation properties.

4. **add a proper physical explanation for the phenomenon.**

Response: Thanks for your suggestion. In the revised manuscript, we have explained the significant increase in surge heights on the eastern side of Hainan Island.

Line 262-266: As shown in Figure 4, the SH shows a significant increasing trend as it approaches the coastline. SHs along the eastern coast of the Leizhou Peninsula are higher than most other regions. Frequent TC events, TC moving direction (Figure 1), and pocket-shaped coastal topography (Figure 2) are all favorable factors to water accumulation in this area. Another area with high SHs is located to the east of Hainan Island. Besides frequent TCs, this area is at the transition zone from the continental shelf to the continental slope, where bathymetry changes rapidly and can bring strong storm surges easily.

5. **How the dispersion phenomena were simulated offshore? Is a wave height of 30 m justifiable? This wave height was estimated precisely where the surge height shows strange values (see Figure 4).**

Response: Thanks for your comments. The SWHs under the specific return periods fitted by the extreme value function show an overall spatial distribution pattern of high in the southeast and low in the north. The maximum value of SWH for the 100-year event is around 20 m, and only for the return period of 200 years, the wave height is near 30m.

We also tried to explain the reasons for this:

1) The SWAN-based model simulations used in this study yielded a historical maximum wave height of about 15 m during a tropical cyclone event, which is closer to the SWH under a 100-year event than the SWH data simulated by Jian Shi and Benxia Li for coastal China. In contrast, based on SWH reanalysis data published by the ECMWF (European Centre for Medium-Range Weather Forecasts), wave reanalysis data values are significantly lower than actual observations or model simulations during tropical cyclone impacts. Therefore, in practical applications, wave model simulation data allows for more accuracy and is closer to the actual situation.

2) The 100-year and 200-year events fitted based on extreme value functions are infrequent, and the SWHs could be as high as 30m.

3) Besides the reasons mentioned above, there might be another reason. Errors could be introduced in fitting the extreme value function due to the sample size and sampling method, so there is a degree of overestimation of the effective wave height at typical recurrence periods.

Line 269-277: As shown in Figure 5, the SWHs near the shore are generally smaller than that in the open sea, and there is a significant decreasing trend in SWH as it gets closer to the coastline. This is mainly attributed to the shallow shore depth, island obstruction, wave breaking, and seabed friction attenuation. Among them, the SWHs in the eastern Leizhou Peninsula are lower than that of other seas, which is mainly influenced by the curved depressed coastline and the topography of the shore section. The SWHs are influenced by the frequency, duration, and intensity of TCs, so the SWH is higher in the east and south of Hainan Island than in the north. In addition, the east side of Hainan Island from the continental shelf to the continental slope causes a wave-breaking effect and dissipation caused by the dramatic change in seafloor topography height, which results in a more significant gradient in SWH. In addition, it shall be noted that errors may be introduced during the estimation of SWHs with GEV due to the limited number of TC events as well.