Applications of a Sea-surface Roughness Parameterization Scheme to the Nested Model of Storm Surge, Current and Wave Coupling

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Abstract

The sea surface roughness parameterization scheme developed by Pan, Sha et al. (PS07) bears a relation to wave age, and the dimensionless form of roughness length can be expressed with the relation with significant wave height. Based on 4 experiments (HEXMAX, RASEX, BIO steady platform, Lake Ontario Data), we make an attempt to validate the suitability of the PS07 scheme under different wind fetch and sea state. We found that the calculated results based on PS07 are close to that given by the eddy correlation method. We also conducted an experiment in which the PS07 was combined with the nested model of waves coupling in datasets of 4 typhoons occurred at the Zhanjiang Seaport. The comparison results between the calculated and observed Zhanjiang seaport water-level rise and waves around the Naozhou Island indicate that the PS07 scheme has a good applicability.

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Keywords: sea-surface roughness; parameterization scheme; significant wave height; wave age; COARE algorithm.

1. Introduction

Sea – air interactions trigger change in climate and environment mainly through exchange of momentum, heat and vapor between ocean and atmosphere. Generally, accurate determination of sea-surface momentum exchange hinges chiefly upon 1) reasonable description of its dependence on stability,
and 2) accurate determination of sea-surface aerodynamic roughness, in which Monin-Obukhov similarity theory can well depict the dependence. However, how to precisely establish sea-surface aerodynamic roughness has to date been a heated issue.

The Charnock relationship serves as a typical parameterization scheme for sea-surface roughness[1]. In previous studies the Charnock parameter varies in value for a limited fetch or lake-scale. In the scheme of Yelland and Taylor[2] (called YT96 hereafter) the parameter is taken as a linear expression for winds at 10~18 m/s. As indicated by many contemporary investigators, the roughness is related to wave features. Oost et al[3] noted that sea-surface roughness is the function of wave age and frictional velocity, presenting a parameterization scheme (called O02 hereafter). Now the two schemes are included in the latest-version COARE. We formulated a sea-surface aerodynamic roughness parameterization scheme that is known as PS07[4], which indicates the dependence of dimensionless roughness length $z_0/Hs$ on wave age, with its good applicability found in many experiments and models. The present paper is devoted to the applicability to the model of coupling storm surge, currents and waves, the findings being of much significance to providing the basis for parameter value determination for further understanding sea-air interface energy transport, constructing and improving models of climate, wave and sea wind.

2. Effects of wind zone, wind duration and water depth upon sea surface roughness length

2.1. For Fully Developed Waves

For the deep sea part the shape of the bottom exerts very small impacts on surface motions, during which the wave structure depends upon wind velocity alone, with the turbulence field and momentum exchange at the air – sea interface only in relation to the velocity. From the logarithmic wind profile theory we can have the relationship of significant wave height and spectral peak period to wind velocity at 10 m level. Using PS07 scheme calculation was performed of the drag coefficient for the open sea based on long fetch data from HEXMAX (Humidity Exchange over the Sea Main Experiment) and BIO (Bedford Institute of Oceanography) Steady Platform Experiment, which was compared to that given by the eddy correlation method. As shown in Fig.1a, both types of results have good linear correlation at $R = 0.93$, indicating that the PS07-given drag coefficient was slightly lower than that from experimental data, with normalized standard error’s error reaching 15.6%, thereby illustrating that the coefficient is better from PS07 for the open sea.

![Fig. 1. (a) Compare of the drag coefficient from computation with PS07 and HEXMAX and BIO experiments. (b) Compare of the drag coefficient from computation with PS07 and BIO experiment and AD96 data.](image)
2.2. Wave Development in Relation to Wind Fetch and Duration

There is a relationship of wave development to wind fetch and duration. If the duration is long enough, then the development depends only on the fetch. When observing in the open sea, the determination of wind duration and fetch is rather difficult so that wave development is typically expressed by means of wave age. In general, the wave age ranges over 5~30, reaching 30 when wave makes full development. A wave expression relative to wind fetch and duration was proposed by Carter\(^5\) by dint of JONSWAP spectrum. For \(D>1.167X_{0.7}U_{10n}^{-0.4}\), where \(X\) denotes the wind fetch and \(D\) the duration, we assume that there is a finite fetch over the sea. The PS07 calculated drag coefficient for finite fetch data was compared with that from the eddy correlation method (Fig.1b), showing their good fit at the correlation coefficient of \(R = 0.92\) and 12% for NSEE, leading to a better drag calculated in the finite fetch.

2.3. Impacts of Water Depth on Wave Development

Normally, for the depth smaller than half wavelength, the zone is defined as a shallow water region, where wave velocity is associated only with water depth, independent of wave properties. In this case, for finding the significant wave height and spectral peak period the Tucker formulation\(^6\) is made use of in which \(k\) represents the wavenumber and \(H_{s0}\) the significant wave height in the deep sea.

In the context of RASEX (Riso Air-Sea Exchange Experiment) dataset comparison was performed of a drag coefficient coming from PS07 and experiment.

Note that the significant wave height and period were computed from the equation without the observations of the RASEX experiment. Fig.2 shows that most data points are concentrated around the 1:1 line except a few points that were markedly overestimated from the original experiment (see the points on the left side of the dash-dotted line), in which \(R = 0.36\) and NSEE = 17.8%, maybe associated with observational errors. In their estimation of errors in the directly-derived Charnock parameter in the RASEX, Johnson et al.\(^7\) indicated that most of the points of frictional velocity observed fall within 10% error bounds.

3. Application of PS07 to the nested model of storm surge, current and wave coupling

3.1. Brief Description of the Model

the nested model of storm surge, current and wave coupling consisted of the tropical cyclone wind field, pressure field model, SWAN (Simulating Waves Nearshore) model and Storm Surge model.

(1) Model of Pressure and Wind Field Model for the Tropical Cyclone

For the tropical cyclone, pressure and wind fields were calculated by the self-developed asymmetric pressure model for sea-surface pressures, and sea-surface winds were found, according to the principle of gradient winds, together with outer-zone winds of the cyclone offered by NCEP reanalysis data or numerical products and the winds were also assimilated by single-station observations on a synchronous
basis. The initial field originated from the model winds, corrected on the basis of actual observations, thus led to an accurate and rational wind field for an actual typhoon.

(2) SWAN Model
The wave model employed in the nested model is the third-generation SWAN model, which includes sufficient physical processes with wave growth described both linearly and exponentially. The exponential growth is depicted only by the Komen expression[^8], and the roughness is offered by PS07. For energy dissipation, the mainly considered factors are white cap effect, bottom friction and depth-induced breaks.

(3) Model of Storm Surge
The model was that of implicit self-adapting curved mesh 2D currents solved by flow speed reverse-change tensors and contained fairly complete physical processes, to which are added pressure gradient force, spherical curvature, horizontal turbulent diffusion, and wave radiating stress. Correction is made partially of the differencing scheme so that the model was made to calculate currents in a narrow channel.

3.2. Computational Domain, Boundary and Initial Conditions

Computational Domain is a fanned self-adaptive mesh for the South China Sea (SCS) with a self-adaptive mesh for the Zhanjiang seaport. The large-scale mesh covered the whole SCS, while the grid spacing near the seaport was on the order of 5 km, and the grid length increased up to 80 km farther away from the seaport. This mesh can guarantee a big enough computational domain to allow errors in handling at the open boundary that may affect the seaport to be ignorable to greater degree, thus reducing the processing difficulty at such a boundary, and meanwhile, a high enough resolution near the seaport was reached for computational accuracy in the context of a small number of grids for calculation.

(1) Shore Boundary Conditions
Following the features of the shallow-water bay, the displacement of shore boundary was realized by recognizing dry and wet grids thereon. A normal-direction reverse change tensor speed of zero was applied as the kinetic condition.

(2) Open Boundary Condition
The large domain regarded the SCS as a closed region, without considering tidal wave to be imported and for the smaller domain, the open boundary consisted of changes in water level simulated in the large domain and tidal wave imported.

(3) Initial Condition
Apart from the open boundary, zero initial condition was put for the computational domain, with integration starting from the rest.

3.3. Validation of Wave Simulation

Data of tropical cyclones 7818, 8208 and 9713 were taken to test our simulations, with calculated water level rise in the seaport and wave height around the Naozhou Island compared with measurements to validate the applicability of the three schemes used. No wave observing sites were available in the seaport so that wave measurements from the oceanic hydrological station on the Naozhou Island were taken for comparison to modelings. The observation was made 4 times a day (0800, 1100, 1400 and 1700 BST). To effectively test waves we took in use the wave heights as the cyclone began to significantly affect the observing station, with which to calculate the relative error in simulations and measurements.

Tables 1 present the wave height observations made around the Naozhou Island under the effect of the given tropical cyclones, in comparison with the predictions from YT96, O02 and PS07, separately, indicating PS07-calculated significant wave height closest to the observation, leading to minimum mean
errors, but O02 calculations were overestimated markedly, and owing to no wind effects of sea surface condition taken into account, YT96 calculated $H_s$ were maximum, resulting in biggest mean errors among the three schemes. It is seen that for the three cases the $H_s$ between 0.6~3.8 m were closest to PS07 results over a rough sea compared to the equivalents.

Table 1. Mean error of predictions vs. observations for the cyclone 7818, 8208 and 9713 around the Naozhou Island

| Typhoon code | Dif. $H_{s\_O02}$ | Dif. $H_{s\_YT96}$ | Dif. $H_{s\_PS07}$ |
|--------------|---------------------|---------------------|---------------------|
| 7818         | 0.744               | 0.823               | 0.568               |
| 8208         | 0.478               | 0.508               | 0.305               |
| 9713         | 0.973               | 1.050               | 0.596               |

*Dif. = Mean error

3.4. Test of Modeled Storm-Caused Water-Level Rise

Fig.3 show the surge level and total tide level of Zhanjiang seaport by 7818 and 9615 tropical cyclone respectively, indicting the surge level and total tide level of Zhanjiang seaport simulated with PS07 roughness scheme are close to the observations.

For the error estimation in testing the simulations of the cyclone-caused water-level rise, analysis of peak-value errors and analysis of error in the level change process were utilized.

Analysis of peak-value errors that is the common method for validating items of storm surge, including the comparison of peak water-level rise and its occurring time between observation and calculation.

Analysis of error in the level change process is a technique that deals with errors in total water-level curve-like process during a storm. The analysis was done in such a way that the total of water-level rises calculated and measured at the same time were employed to find the mean square error, which is indicative of the fitness between curves of the calculated to observed total water level change, with the error bound requirement higher compared to the above method.

![Fig.3](image)

Table 2-given statistic findings show that the water rise is in excess of 100 cm for these cyclones, with PS07 simulated peak rise of 4.15% for mean relative error compared to 6.33% when the original scheme was used, with the mean error in the simulation of total water-level rise during the storm reaching 12.93 and 14.01% from PS07 and original scheme, respectively. Thus, the parameterization scheme PS07
is superior to the original method. Also, the time difference in peaked rise ranged from 1 to 3 hrs, averaging 1.67 hr.

Table 2. Test of simulated storm-triggered water-level rise

| Typhoon | ΔHmax | Time   | ΔHmax_sim | Time_sim | RE  | timedif. | ETWLC |
|---------|-------|--------|-----------|----------|-----|----------|-------|
| 7818    | 257   | 08/22/12 | 235.86    | 08/22/15 | 8.23| 3        | 19.93 |
| 8208    | 185   | 10/02/06 | 184.79    | 10/02/05 | 0.11| 1        | 6.99  |
| 9713    | 147   | 09/09/13 | 153.05    | 09/09/14 | 4.12| 1        | 11.87 |

Notes: ΔHmax, Time, ΔHmax_sim and Time_sim are Measured and simulated the biggest rise and time; RE is relative error (%); dif. Is difference (hr); ETWLC is error in total water level change (%).

4. Conclusions

The sea surface roughness parameterization scheme developed by Pan, Sha et al. bears a relation to wave age, and the dimensionless form of roughness length can be expressed with the relation with significant wave height. Based on 4 experiments (HEXMAX, RASEX, BIO steady platform, Lake Ontario Data), we make an attempt to validate the suitability of the PS07 scheme under different wind fetch and sea state. We found that the calculated results based on PS07 are close to that given by the eddy correlation method. PS07 gives the results closest to in situ measurements. Later, PS07 scheme is utilized in the model of storm surge, currents and waves coupling by use of 4 typhoon datasets recorded in the Zhanjiang seaport, with which to compute seaport water-level rise and waves around the Naozhou island, which are compared to observations, indicating its good applicability.

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