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Sensitivity of Input Parameters in the Spectral Wave Model

Hyo-Bong Park*

**Research Center for Ocean Industrial Development, Pukyong National University, Busan, Korea*

KEY WORDS: Sensitivity test, Spectral resolution, Source and sink terms, SWAN (Simulating WAves Nearshore), TOMAWAC (TELEMAC-based Operational Model Addressing Wave Action Computation) model, East Anglian coast

ABSTRACT: *Many researches have been done to define the physical parameters for the wave generation and transformation over a coastal region. However, most of these have been limited to the application of particular conditions, as they are generally too empirical. To yield more reasonable wave estimation using a spectral wave model, it is important to understand how they work for the wave estimation. This study involved a comprehensive sensitivity test against the spectral resolution and the physical source/sink terms of the spectral wave model using SWAN and TOMAWAC, which have the same physical background with several different empirical/theoretical formulations. The tests were conducted for the East Anglian coast, UK, which is characterized by a complex bathymetry due to several shoals and offshore sandbanks. For the quantitative and qualitative evaluation of the models' performance with different input conditions, the wave elements and spectrums predicted at representative sites the East Anglia coast were compared/analyzed. The spectral resolution had no significant effect on the model results, but the lowest resolution on the frequency and direction induced underestimations of the wave height and period. The bottom friction and depth-induced breaking terms produced relatively high variations in the wave prediction, depending on which formulation was applied. The terms for the quadruplet and whitecapping had little effect on the wave estimation, whereas the triads tended to predict shorter and higher waves by energy transferring to higher frequencies.*

1. Introduction

There are a number of wave models that can be used for the prediction of waves in coastal environments. However, limited observational data are generally available for tuning the wave models to yield reasonable results. Besides, most wave processes in the wave models are relied on the theoretical and mathematic bases and each physical components are not easily identified from the field observation (Rogers et al., 2003). The understanding for the works of models' input parameters in the real field applications may provide essential guideline to adjust the models in the real field applications. Therefore, the study examined the sensitivity of main control parameters available for the model construction in the spectral wave model, to provide better knowledge of their performance in the wave prediction.

Two spectral wave models, SWAN (Booij et al., 1999; Ris et al., 1999) and TOMAWAC (Benoit, 2002), are implemented in the test to consider more alternative formulae for the source/sink terms available in these models. Although these wave models were developed with stage of the art formulations for physical processes, little work has occurred to understand sensitivity of model results to various parameters or to validate the model in a variety of shallow coastal setting (Booij et al., 1999; Ris et al., 1999; Kuang and Stansby, 2004). The study conducted the sensitivity test of input parameters with a bathymetry of East Anglia coast, UK (Fig. 1), where is expected to induce comprehensive wave

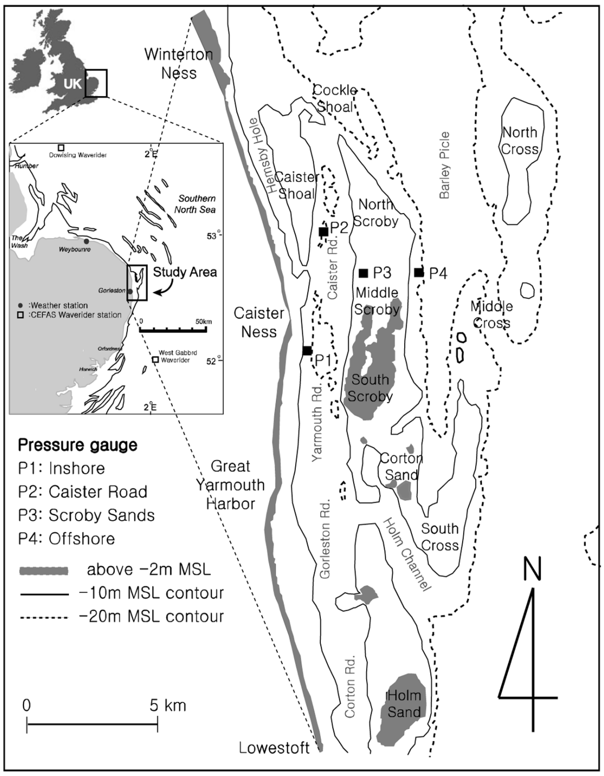

Fig. 1 Bathymetry of East Anglian coast, UK

교신저자 박효봉: 부산광역시 남구 대연3동 599-1, 051-629-7071, hb_park@pknu.ac.kr

transformation due to the complex bathymetry such as shoals and offshore sandbanks called Scroby sandbank system (Park, 2007).

2. Spectral Wave Models

SWAN and TOMAWAC are full spectral wave models with an explicit representation of the physical processes relevant for wave evolution and which give a two-dimensional description of the sea state (Komen, 1994). SWAN (Simulating WAves Nearshore) was developed by the Technical University of Delft in the Netherlands (Booij et al., 1999; Ris et al., 1999) and is a public domain model. TOMAWAC (TELEMAC-based Operational Model Addressing Wave Action Computation) is one of wave simulation codes in the TELEMAC system developed by the EDF R&D's Laboratoire National d'Hydraulique et Environment in France (Benoit, 2002). They are generally used for the transformation of wave energy spectra in relatively large coastal areas and in particular for areas with complex bathymetric features. They use different grid systems, numerical schemes and adopts different formulations for source and sink terms (Table 1).

Both models are based on the spectral action balance equation with sources and sinks given by

$$\frac{\partial}{\partial t}N+\frac{\partial}{\partial x}c_xN+\frac{\partial}{\partial y}c_yN+\frac{\partial}{\partial \sigma}c_\sigma N+\frac{\partial}{\partial \theta}c_\theta N=\frac{S}{\sigma} \qquad (1)$$

$$\text{where} \quad S(\sigma,\theta)=S_{in}+S_{nl}+S_{wc}+S_{bf}+S_{br}+S_{tr}$$

Table 1 Details of SWAN and TOMAWAC wave models

		SWAN	TOMAWAC
Size		Small scale (~25km)	Small~Large scale
Area		Coastal region~ Shelf sea	Coastal region~ Oceanic
Grid system		Finite differences + Nesting option	Finite elements
Spatial resolution		50~1000m (regular spacing)	Flexible (Unstructured triangular meshes)
Frequency range and resolution		0.04~1H$_z$	0.04~0.4H$_z$ N_f = 15~25
Directional resolution		15°~10° (wind sea) 5°~2° (swell)	15°~30°
Computational time		Relatively cheap	Expensive
Numerical scheme	Propagation	BSBT method, SORDUP method, S&L scheme	Characteristics method
	Source terms	Implicit upwind scheme	Semi-implicit scheme

Table 2 Source and sink terms formulations available in SWAN and TOMAWAC

Source sink		SWAN	TOMAWAC
Deep water	S_{in}	Komen et al. (1984) Janssen (1989; 1991)	Snyder et al. (1981) Janssen (1989; 1991)
	S_{wc}	Komen et al. (1984) and Janssen (1991)	
	S_{nl}	Hasselmann et al. (1985)	
Shallow water	S_{tr}	Eldeberky (1996)	Eldeberky and Battjes (1995),
	S_{tr}	Battjes and Janssen (1978)	Battjes and Janssen (1978) Thornton and Guza (1983) Roelvink (1993) Izumiya and Horikawa (1984)
	S_{bf}	Hasselmann et al. (1973) Collins (1972) Madsen et al. (1988)	Hasselmann et al. (1973)

where N is the action density, equal to the energy density divided by the relative wave frequency σ; θ is the wave direction. The 1st term represents the local rate of change of action density in time, the 2nd and 3rd terms represent propagation of action in geographical x and y space with propagation velocities c_x and c_y; the 4th term represents shifting of the relative frequency due to depths and currents with propagation velocity c_σ in σ space; the 5th term represents depth and current-induced refraction with propagation velocity c_θ in θ space. The term S signifies the energy source and sink terms representing the effects of wind wave generation S_{in}, energy dissipation due to depth limits S_{br}, seabed friction S_{bf} and wave steepness S_{wc}, and nonlinear wave-wave interactions, e.g. quadruplets S_{nl} and triads S_{tr}. All source and sink terms are included in SWAN and TOMAWAC, and generally are available with alternative formulations for each term as shown in Table 2.

3. Sensitivity Tests of Spectral Wave Models

The sensitivity tests were conducted against the following parameters.

- Spectral resolutions: frequency and directional dimension
- Source and sink terms: depth induced breaking, bottom friction, white-capping, nonlinear wave-wave interaction such as quadruplets and triads

Wind wave generation term is defined by Janssen's (1989; 1991) exponential growth, common option in these models, and it is excluded in the sensitivity test of this study. For the depth-induced breaking and bottom friction, the model results computed with different options are compared, whereas tests of triads, quadruplets, and white-capping, which has limited options are conducted with 'on' and 'off' switches in the models to determine differences of the model results when the elements are included or excluded from the calculation.

3.1 Model environmental setting

The finite difference grid, which consist of equally spaced points with a grid spacing $\Delta x = \Delta y = 50$ m, is constructed in SWAN; the resultant grid dimension is 344 × 544. The TOMAWAC mesh is based on the unstructured linear triangular finite elements which is built considering local water depths; the resultant total numbers of nodes and elements of the model domain are 10759 and 20986 with the edge lengths of meshes ranging between 36 m and 636 m. The model domains and bathymetry used in two wave models are the same.

Two types of boundary conditions are applied along the outer computational boundaries. The offshore boundary defined as the parameterized JONSWAP spectrum specified by easterly waves of $H_s = 1$ m and $T_p = 6$ sec, and the rest boundaries are defined that they fully absorb the wave energy by leaving the computational domain or crossing a coastline. The direction spreading of waves in these models is taken account by multiplying the frequency spectrum by a spreading function $\cos^n\theta$. A value of 1 for the power n is commonly used in the test. The wind input are given by spatially uniform wind blowing from the same direction of the wave. The numerical method used in the test with the models are presented in Table 2; the computational is done in the stationary mode.

Table 3 Details of a default run for the sensitivity test of the spectral wave model

	Details
Spectral waves	JONSWAP spectrum: Easterly wave of $H_s = 1$ m, $T_p = 6$ sec
Spectral resolution	$N_d = 24$ ($\Delta\theta = 15^\circ$), $N_f = 30$ for the range of frequencies [0.04~0.4] Hz
Source/ sink term	Wave growth (Janssen's exponential growth), Quadruplet on, White-capping on, Bottom friction (JONSWAP, 0.067 m^2/s^3), Depth-induced breaking (Battjes and Janssen, 1978: $\gamma = 0.73$)
Boundary condition	Shoreline: absorbing wave energy Offshore boundary: JONSWAP spectrum Rest boundaries: penetrate wave energy
Inputs	Water-level: Mean Sea Level Easterly wind of 10 m/s
Numerical Method	Propagation: BSBT method (SWAN), Characteristics method (TOMAWAC) Source/Sink terms: Implicit upwind scheme (SWAN), Semi-implicit scheme (TOMAWAC)

3.2 Method of sensitivity tests

The options for the default run in the test is defined as those in Table 3, which are implemented in the model validation of the same region against wave observations (Park, 2007). The model results are mainly evaluated by comparing the resultant wave parameters obtained at the four representative locations of the East Anglian coast between pairs of runs (Fig. 1).

- P1: 'Inshore' representing the inshore region
- P2: 'Caister Road' representing deep channel in lee side of Scroby Sands
- P3: 'Scroby Sands', large scale offshore sandbank region
- P4: 'Offshore', offshore region

The resultant wave parameters from SWAN and TOMAWAC are computed as the following equations.

$$H_s = 4\sqrt{m_0}, \quad T_m = \frac{m_0}{m_1}$$
$$where\ m_n = \int_{\theta=0}^{2\pi}\int_{f=0}^{\infty} f^n E(f,\theta)\, df\, d\theta,$$
$$n = 1, 2, 3, \cdots \tag{2}$$

For the quantitative and qualitative evaluation of the sensitivity test with SWAN and TOMAWAC, the study used the following evaluation parameters $|H_s|$, $|T_m|$, and $|\theta|$ (Eqs. (3)~(4)); these are the relative differences between the values computed with the default option and the values calculated with other alternative options.

$$|H_s| \text{ and } |T_m|\ (\%) = \frac{(\text{result of default option}) - (\text{result of other option})}{(\text{result of default option})} \times 100 \tag{3}$$

$$|\theta|\,(^\circ) = |(\text{result of default option}) - (\text{result of other option})| \tag{4}$$

$|H_s|$ and $|T_m|$ can be either positive or negative; if it is positive, the default option predicts larger values than other options. As no equivalent published index to normalize the significant difference for the sensitivity have been identified for the wave statistics, a 10% difference is adopted as the limit of significant sensitivity or accuracy in the resolution tests for the H_s and T_m. Concerning wave direction, a 15° difference in a $|\theta|$ is used as a default value for directional resolution.

3.3 Results

3.3.1 Spectral resolutions

The sensitivity to the spectral resolution in the computation

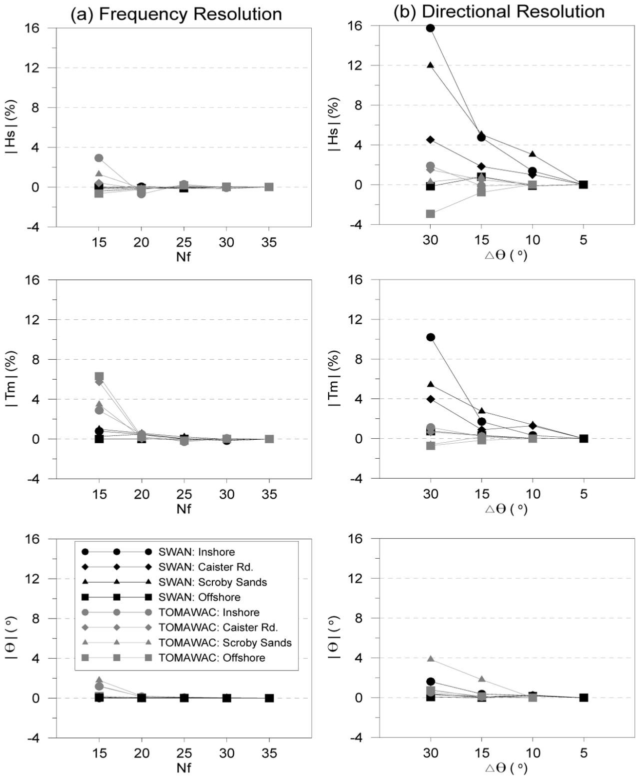

Fig. 2 Sensitivity to the spectral resolution. (a) frequency resolution (default option: N_f = 35), (b) directional resolution (SWAN: $\Delta\theta$ = 5°, TOMAWAC: $\Delta\theta$ = 10°)

of the wave models is tested by varying the number of frequency and direction in the spectral discretization, and their results are compared in Fig. 2. In the sensitivity tests to the spectral resolution, the default run is equivalent to the run with high resolution in each case and in each model.

The frequency range is defined by a minimum of 0.04 H_z and a maximum of 0.4 H_z; the frequency resolution is determined by N_f, the number of frequencies, between 15 and 35 in increments of 5; N_f of 35, the highest resolution case, is taken to be the default in the test. Both models predicted nearly consistent results on H_s, T_m, and θ with different frequency resolution. TOMAWAC predicts slightly lower and shorter wave with N_f = 15, the lowest resolution, but it is negligible with differences less than 6%.

The directional resolutions are also defined by the size of directional bin, $\Delta\theta$ (or the number of directional bins, N_d) from 5° to 30° with an increment of 5°. The directional bin size of 5° and 10° are respectively defined as the default option of SWAN and TOMAWAC for estimating the relative differences. Unlike the results of the sensitivity tests for the frequency resolution, SWAN presents slightly more sensitive to the directional resolution by underpredicting the H_s and T_m up to 16%, whereas TOMAWAC has minor influences with directional division of spectrum with differences less than 4%. The differences of θ in the both models' test against spectral resolution are negligibly small.

3.3.2 Source and sink terms

(1) Dissipation by bottom friction

The bottom friction is the most dominant factor in the source/sink terms concerning the dissipation of wave energy especially in sandy coastal regions. This term has different mechanisms depending on the bottom condition; sediment type, bed roughness length, the presence or absence of ripples and the dimensions of ripples, etc. The general expression of bottom friction dissipation term in the wave models is

$$S_{bf}(\sigma,\theta) =- C_{bottom}\frac{\sigma^2}{g^2\sinh^2(kh)} = E(\sigma,\theta) \qquad (5)$$

in which C_{bottom} is a bottom friction coefficient.

There is no field data evidence to give preference to a particular friction model considering the large variations in bottom conditions in coastal areas. This study consider the JONSWAP empirical constant (C_{bottom} = 0.067 m^2/s^3), commonly employed in both models, as a default option in the test of this term. The JONSWAP bottom friction constant performs well in many different conditions, although it does not interpret bottom dissipation in terms of a physical mechanism such as percolation, friction or bottom motion (Padilla-Hernandez and Monbaliu, 2001). The sensitive test of the bottom friction term is conducted using SWAN, as it provides two more alternatives such as a nonlinear formulation based on the drag law model of Collins (1972), and an eddy-viscosity model of Madsen et al. (1988). The result with the other three alternatives including the JONSWAP constant of C_{bottom} = 0.038 m^2/s^3 are compared in Figs. 3~4. The JONSWAP constant with C_{bottom} = 0.038 m^2/s^3 and the Collins (1972) model predict nearly the same; the resultant wave parameters which are bigger H_s (~13%) and longer T_m (~5%) compared to the results of the default (Fig. 3) and their spectrums are also nearly corresponding (Fig. 4). However, the formulation of Madsen et al. (1988) estimates ~30% smaller H_s and T_m than those of the default run (Fig. 3), and produces significant energy reduction on the frequencies > 0.1 H_z (Fig. 4). The different bottom friction formulations do not affect the mean wave direction, θ.

(2) Dissipation by depth-induced breaking

The process of depth-induced breaking is still poorly understood and little is known about its spectral modeling. The general expression of this term is:

$$S_{br}(\sigma,\theta) = \frac{D_{tot}}{E_{tot}}E(\sigma,\theta) \qquad (6)$$

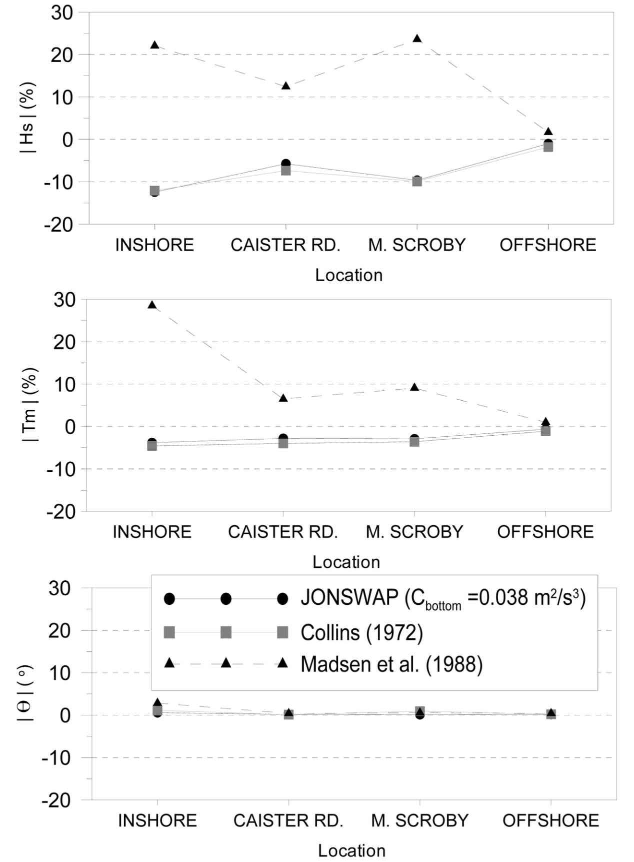

Fig. 3 Sensitivity of the bottom friction formulae in SWAN; The default option is JONSWAP constant, C_{bottom} = 0.067 m^2/s^3

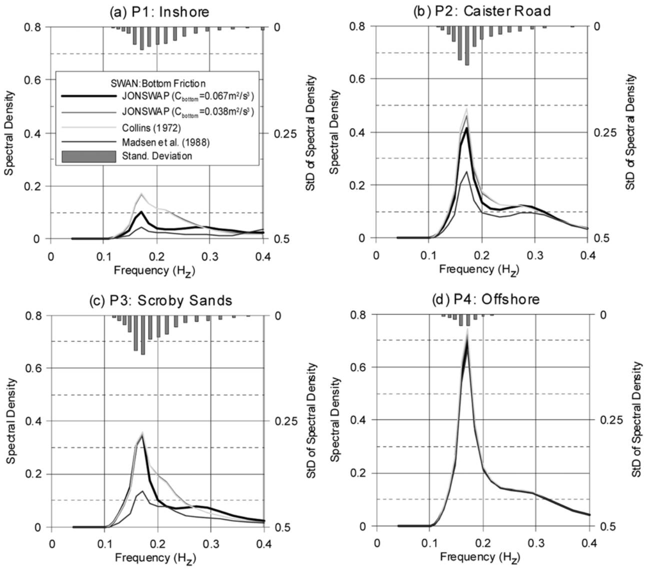

Fig. 4 Spectrum at four sites in East Anglian coast computed with different bottom friction formulations by SWAN

where E_{tot} is the total wave energy and D_{tot} is the dissipation rate of E_{tot} due to the depth-induced wave breaking. The bore-based model of Battjes and Janssen (1978) is commonly used in both models and D_{tot} is critically determined by the breaking parameters γ.

$$H_m = \gamma h \quad (\gamma = 0.73\text{: Battjes and Janssen (1978)}) \tag{7}$$

in which H_m is the maximum wave height in the local water depth h. Battjes and Stive (1985) proposed values for the breaker parameter γ varying between 0.6 and 0.83 for different types of bathymetry with an average of 0.73 from the re-analyses of wave data from a number of laboratory and field experiments. Equation (7), a default option in SWAN, is set as a default option in the test for the depth induced breaking term. The sensitivity experiment conducts with TOMAWAC against its available formulations of Thornton and Guza (1983), Roelvink (1993), and Izumiya and Horikawa's (1984) turbulence model, as SWAN has only one availble option, Battjes and Janssen's (1978) brealomg parameter, for the term. The results are compared in Figs. 5~6.

The different depth-induced breaking formulations induced large variations on the significant wave height, H_s (Fig. 5). The formulations of Thornton and Guza (1983) and Roelvink (1993) predicted the smaller and longer waves than those with

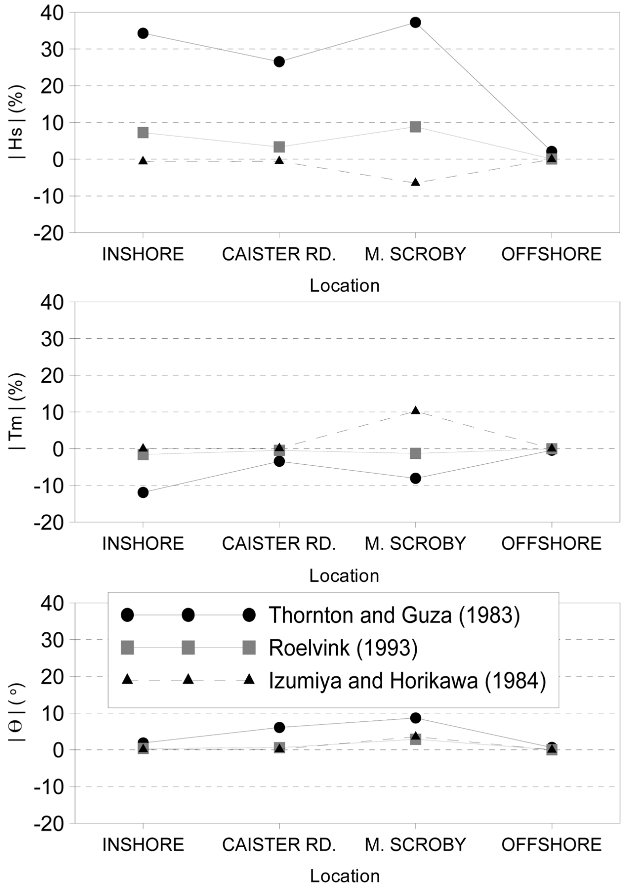

Fig. 5 Sensitivity to the depth-induced breaking in TOMAWAC; The default option is Battjes and Janssen's (1978) γ = 0.73

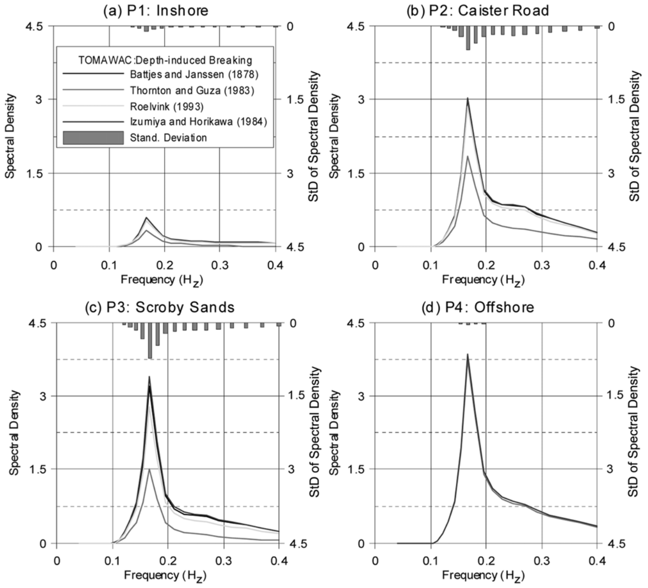

Fig. 6 Spectrum at four sites in East Anglian coast computed with different depth-induced breaking by TOMAWAC

default option, whereas the Izumiya and Horikawa (1984) model predicts slightly larger and shorter waves. In general, the waves predicted with three formulations are quite similar except for the one of Thornton and Guza (1983) model which is different by ~40% in H_s and ~15% in T_m. The differences for the wave direction, θ due to the different formulae of depth-induced breaking are again minor. The resultant spectrums at representative four sites with different options of depth induced breaking term, present only energy changes over the frequencies, and their shapes are nearly consistent with the same peak frequency (Fig. 6). The choice of the formulation of the depth-induced breaking most affects the Middle Scroby site where is characterized by shallow water depth of about 5 m, compared to other sites.

(3) Dissipation by white-capping

White-capping is the dissipation term generally occurring in deep water and primarily controlled by the wave-steepness (Booij, 1999). White-capping is probably the least understood deep water source/sink mechanism, since this dissipation is not easily measured (Rogers et al., 2003).

The general expression for the wave energy dissipation due to white-capping is derived from the pulse-based model of Hasselmann (1974) reformed in terms of wave number k and is

$$S_{wc}(\sigma,\theta) = -\Gamma\tilde{\sigma}\frac{k}{\tilde{k}}E(\sigma,\theta) \tag{8}$$

$$\text{where } \Gamma = C_{wc}\left((1-\delta)+\delta\frac{k}{\tilde{k}}\right)\left(\frac{\tilde{S}}{\tilde{S}_{PM}}\right)^{P}$$

where $\tilde{\sigma}$ and $\tilde{k}$ denote the mean frequency and the mean wave number, respectively. Γ is a steepness dependent coefficient (Janssen, 1991); $\tilde{S}$ is the overall wave steepness and $\tilde{S}_{PM}$ is the value of $\tilde{S}$ from the Pierson-Moskowitz spectrum. The C_{wc}, δ and P are tunable coefficients and are given by C_{wc} = 4.1e-05, δ = 0.5 and P = 4 (Janssen, 1991) which is for fully developed wind seas. The sensitivity to the white-capping is tested by simply turning it 'on' and 'off' in both models.

The SWAN and TOMAWAC results of tests with the white-capping term are quite similar. With the white-capping term in the model computations, waves become smaller and longer, but all changes made by this option at four sites in the East Anglian coast are insignificant with differences < 5% of their magnitudes (Fig. 7). Spectrums computed by SWAN and TOMAWAC including the whitecapping are different; TOMAWAC predicts slightly smaller energy over frequencies > 0.2 H_z over all sites, whereas SWAN estimated relatively sensitive changes on the spectral density over all frequencies of 0.04~0.4 H_z (Figs. 8~9).

(4) Quadruplets and triads

Four-wave interactions, plays an important role in the wind

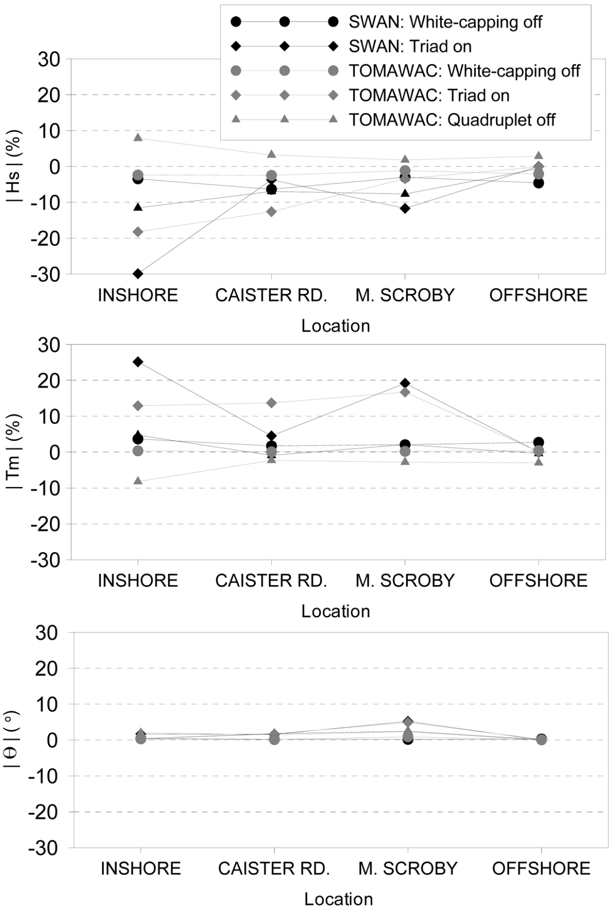

Fig. 7 Sensitivity to white-capping, triads and quadruplets

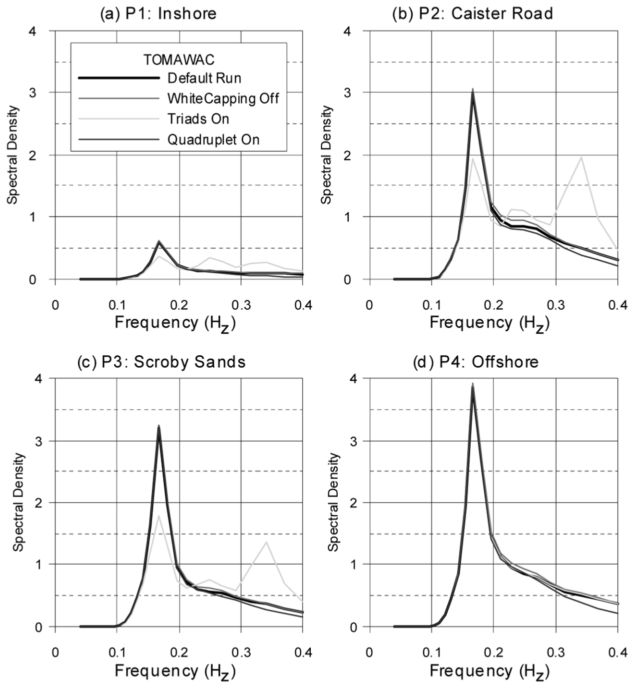

Fig. 8 Spectrums at four sites in East Anglian coast computed with white-capping and nonlinear interactions by TOMAWAC

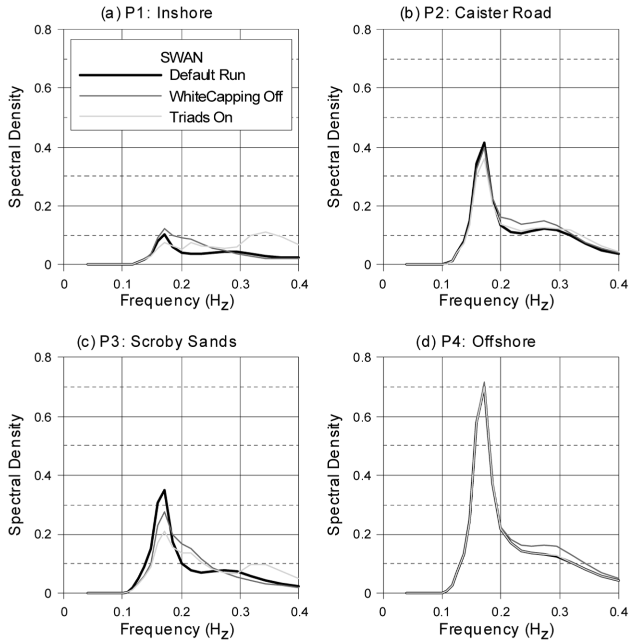

Fig. 9 Spectrums at four sites in East Anglian coast computed with white-capping and nonlinear interactions by SWAN

wave evolution in deep water depths, have the effect of transferring energy from the spectral peak to lower and higher frequencies (Booij et al., 1999). The energy transfer to lower frequencies leads to lowering of the spectral peak frequencies, and the transfer to higher frequencies leads to increased dissipation by breaking. The effect of quadruplets on the waves at four sites is tested by TOMAWAC, as the term works in any way with the wind input in SWAN. Quadruplets does not give significant changes on the H_s and T_m (~10%), but it tends to produce waves that are bigger and shorter (Fig. 7). As seen from the estimated spectrums (Fig. 8), the quadruplets dissipates the waves energy over the relatively higher frequencies (> 0.2 $\mathrm{H_z}$), but it does not induce transferring of the spectral peak frequency in this test.

Triads transfer energy from the peak frequency to higher and lower frequencies in steep waves in very shallow water (Booij et al., 1999). Ris et al. (1999), from the sensitivity tests of the SWAN model, concluded that the triad wave-wave interactions do not, on average, affect the significant wave height, and they only mildly decrease the mean wave period (average bias 8% increasing the discrepancy with the observation). Wolf et al. (2002), from tests using SWAN at the Holderness site, found that overall wave heights unrealistically increase, and small peaks in the frequency spectrum occurred at double the frequency of the main peaks; Wolf et al. (2002) concluded the triad interaction term had more influence on the results than the wind input term in SWAN. The study tested the triad term with SWAN and TOMAWAC by a simple switch in their steering file. Unlike to the quadruplet interaction, the triads significantly affect the magnitudes of H_s and T_m tending to increase H_s and shorten T_m; this is clearly observed in shallower waters, e.g. Inshore and Scroby Sands (Fig. 7). Triads effect on the frequency spectrum are generally occurred that the energy transfer to higher frequencies (Figs. 8~9). Especially the energy at frequencies of 0.3~0.4 $\mathrm{H_z}$ which is higher than peak frequency are significantly increased, and the transferring energy to higher frequencies induces higher peak frequency (e.g. Caister Road in TOMAWAC test, and Inshore in SWAN test).

5. Conclusions and Discussion

SWAN and TOMAWAC which are the spectral wave model based on the different numerical system are tested to investigate the works of input parameters on the wave prediction in the real field. The spectral resolution and source/sink terms are used as control parameters to examine the model's sensitivity in the resultant wave parameters and frequency spectrums. The conclusions from this study are summarized as below;

(1) Frequency resolution has no significant influences on the model prediction in both models. SWAN demonstrates relatively higher sensitivity to the directional division, whereas TOMAWAC shows reasonably similar results to the

all directional resolution. Overall, the study recommends $N_d > 12$ with SWAN and $N_f > 15$ in the frequency range of 0.04-0.4 H_z with TOMAWAC. The differences in the results between both models against the spectral resolution is probably due to that they have different numerical and grid systems, such as the finite difference and the finite element, although they are the spectral wave model based on the same physical background.

(2) In general, the dissipation terms due to the bottom friction and the depth-induced breaking significantly influence the results in relatively shallower areas, e.g. Inshore and Middle Scroby in the East Anglia coast. However, the values of θ remain nearly constant with all the different options used in the sensitivity tests.

(3) Nonlinear wave-wave interaction, e.g. triads and quadruplets, tend to predict steeper waves by increasing H_s and shorten T_m. Quadruplets which is significantly occurred in deep water induce the energy reduction of higher frequencies, but the magnitudes are negligible small. Triads occurred mainly in shallow waters causes energy transfer to higher frequencies inducing the rise of the peak frequency and the multi-peak spectrum, so the triad has to be considered with care in the wave prediction.

There are several limitations in this sensitivity tests which we have to bear in mind, and they are summarized as below:

(1) Model applications to identify model's sensitivity against spectral resolution and physical parameters are conducted to one bathymetric case with one representative wave condition. To provide generality on the results from this study, more tests with different bathymetric sites and wave inputs will be required.

(2) There are no measurements for comparison with the sensitivity results run with different formulations in the source/sink terms. Therefore, the tests with different models of the source/sinks terms focus on the understanding of the wave characteristics depending on the option and the geological condition rather than to identify the proper option for wave modeling of the study area.

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