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Evaluation of WAVEWATCH III performance with wind input and dissipation source terms using wave buoy measurements for October 2006 along the east Korean coast in the East Sea

Han Soo Lee [a,b,*]

[a] Graduate School of Science and Engineering, Saitama University, 255 Shimo-okubo, Sakura-ku, Saitama, Saitama 338-8570, Japan
[b] International Institute for Resilient Society, Saitama University, Saitama, Japan

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A B S T R A C T

In the winter, in the East Sea (ES), storm waves due to moving developed lows are frequently reported and cause extensive coastal disasters. During October 2006, there were extensive damages along the east Korean coast due to high storm waves induced by winter storms passing over the ES. This paper investigates the performance of a wave model, WAVEWATCH III, for the rough sea conditions in October 2006 with respect to the wind input and dissipation terms because the wave-breaking dissipation is the least known source term, which acts as a tuning knob for the closure of the action balance equation. Three package-like wind input-dissipation parameterizations, the WAM3 type (WAM-equiv), Tolman and Chalikov terms (TC96), and WAM4 type and its variant (WAM4+), are used experimentally for their performances under the same wind forcing obtained from atmospheric modelling with WRF. Overall, all experiments illustrate good accordance with observed wave characteristics. Among them, the WAM4+ results exhibit the best performance based on the Taylor diagram and index of agreement. In terms of dissipation behaviour, the TC96 results depict high energy losses at high frequency over 0.25 Hz, whereas the WAM-equiv runs display less dissipation at the same frequency. The WAM4+ results lie between those of the WAM-equiv and TC96.

1. Introduction

1.1. Wave modelling

The third generation wind-wave models, such as WAM (WAMDI, 1988), WAVEWATCH III (Tolman, 2009) (hereinafter, WW3), and SWAN (Booij et al., 2004), are based on a balance equation for wave spectrum and widely used in theoretical studies and practical applications for global and regional operational forecasts in terms of the wind-wave process at sea. The balance equation, first proposed by (Hasselmann, 1960), is described by $DN/Dt = S/\sigma$, where D/Dt is the total derivative, $N(k,\theta) \equiv F(k,\theta)/\sigma$ is the action density spectrum, and S represents the net source and sink terms for the spectrum F. The k, θ, and σ are the wavenumber, direction, and relative frequency, respectively. Then, the balance equation for the action density used in WW3 takes the following conservative form

$$\frac{\partial N}{\partial t} + \nabla_x \cdot (\mathbf{C}_g + \mathbf{U})N + \frac{\partial}{\partial k}\dot{k}N + \frac{\partial}{\partial \theta}\dot{\theta}N = \frac{1}{\sigma}(S_{in} + S_{nl} + S_{ds} + S_{db} + S_{bf}) \quad (1)$$

$$\dot{k} = -\frac{\partial \sigma}{\partial d}\frac{\partial d}{\partial s} - \mathbf{k} \cdot \frac{\partial \mathbf{U}}{\partial s} \quad (2)$$

$$\dot{\theta} = -\frac{1}{k}\left[\frac{\partial \sigma}{\partial d}\frac{\partial d}{\partial m} - \mathbf{k} \cdot \frac{\partial \mathbf{U}}{\partial m}\right] \quad (3)$$

where $\mathbf{k}$, d, and $\mathbf{U}$ are the wavenumber vector, the mean water depth, and the depth- and time- averaged current velocity, respectively. $\mathbf{C}_g$ is given by c_g, the group velocity, and θ. s is a coordinate in the direction of θ and m is a coordinate perpendicular to s. The left-hand side of Eq. (1) represents the evolution of the wave action density spectrum, N, which considers linear wave propagation as a result of physical processes in the right-hand side (Young and Babanin, 2006). The physical processes are mainly the wind input from the atmosphere, S_{in}, the non-linear wave–wave interactions within the spectrum, S_{nl}, the wave energy dissipation due to whitecapping, S_{ds}, and the wave decay due to bottom friction in shallow water, S_{bf}. For extremely shallow water, the wave energy dissipation due to depth-induced breaking, S_{db}, is introduced from WW3 version 3.14 (Tolman, 2009).

* Correspondence address: Graduate School of Science and Engineering, Saitama University, 255 Shimo-okubo, Sakura-ku, Saitama, Saitama 338-8570, Japan. Tel./fax: +81 48 858 3571.
E-mail address: hslee@mail.saitama-u.ac.jp

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This is based on Battjes and Janssen (1978), which is identical to the depth-induced breaking used in SWAN (Booij et al., 1999).

With respect to wave modelling, Cavaleri et al. (2007) gives a comprehensive overview of the current status of wind-wave modelling from numeric to source terms. The evolution of spectrum for idealized fetch-limited conditions under deep water is reasonably well known, whereas the knowledge of the source terms in Eq. (1) is much more limited, particularly for finite-depth conditions (Babanin and Soloviev, 1998; Donelan et al., 1985; Young et al., 2005). Among the source terms, the understanding of the whitecapping dissipation term remains so poor that its physical process does not have an established validity for all regions and conditions in any case, whereas the other source terms are incomplete but still rational based either on experimental or analytical (or both) approaches. The current dissipation term incorporated in wave models is actually similar to a tuning knob and estimated to fit to an existing analytical model (Cavaleri et al., 2007; Kalantzi et al., 2009; Lee et al., 2013b; Young and Babanin, 2006). Therefore, the resulting wave characteristics, such as significant wave height and period, largely depend on the source terms, in particular the wind input and whitecapping dissipation terms.

1.2. *Wintertime East Sea storm waves*

The East Sea (ES) is a semi-enclosed marginal sea with an average depth of approximately 1500 m that is surrounded by Korean Peninsula in the west, Japan in the south and east, and Russia in the north (Fig. 1). It has three connections to adjacent seas and the ocean via shallow (less than 150 m) and narrow straits such as the Korea Strait to the East China Sea, the Tsuruga Strait to the western North Pacific, and the Soya and Tartar Straits to the Okhotsk Sea (Choi and Yoon, 2010).

In the ES during the winter, mean surface winds over the sea are northeasterly and generally strong due to two synoptic-scale features, the Siberian High and the Aleutian Low, in the context of the cold and dry East Asian winter monsoon. In Dorman et al. (2004), the mean weather state over the ES, modified by alternating highs and lows, is characterized by four types: (A) the dominant flow of cold Asian air towards the southeast over the ES; (B) passage of a weak low towards the northeast over the southern ES with an outbreak of cold-air in a southerly direction on the backside of the low; (C) passage of a moderate low towards the northeast along the northwestern side of the ES; and (D) an occasional very cold Siberian air outbreak towards the south and southwest. With respect to abnormal storm waves in the ES in the winter, Lee et al. (2010, 2008) give a comprehensive overview based on a literature review and numerical simulations, and Lee and Yamashita (2011) categorize the movements of strong developed lows (e.g., winter storms or extra-tropical cyclones) into three patterns (Fig. 1):

(*Pattern I*) A low pressure system on the continent to the west of Korean Peninsula moves east while developing over the ES. Another low pressure system is developing and is located east of Hokkaido, Japan, over the Pacific Ocean. Due to the interaction between the two lows, the first low pressure moves slowly or becomes stagnant with strong counterclockwise winds near Hokkaido over the ES.
(*Pattern II*) It shows very similar movement pattern with the first one, but a low pressure system is generated and starts over the East China Sea. Then, it moves to the northeast slowly or becomes stagnant near Hokkaido due to another developed low pressure system.
(*Pattern III*) A low pressure system over the north of the Korean Peninsula moves to the southeast across the ES passing through the west Japan.

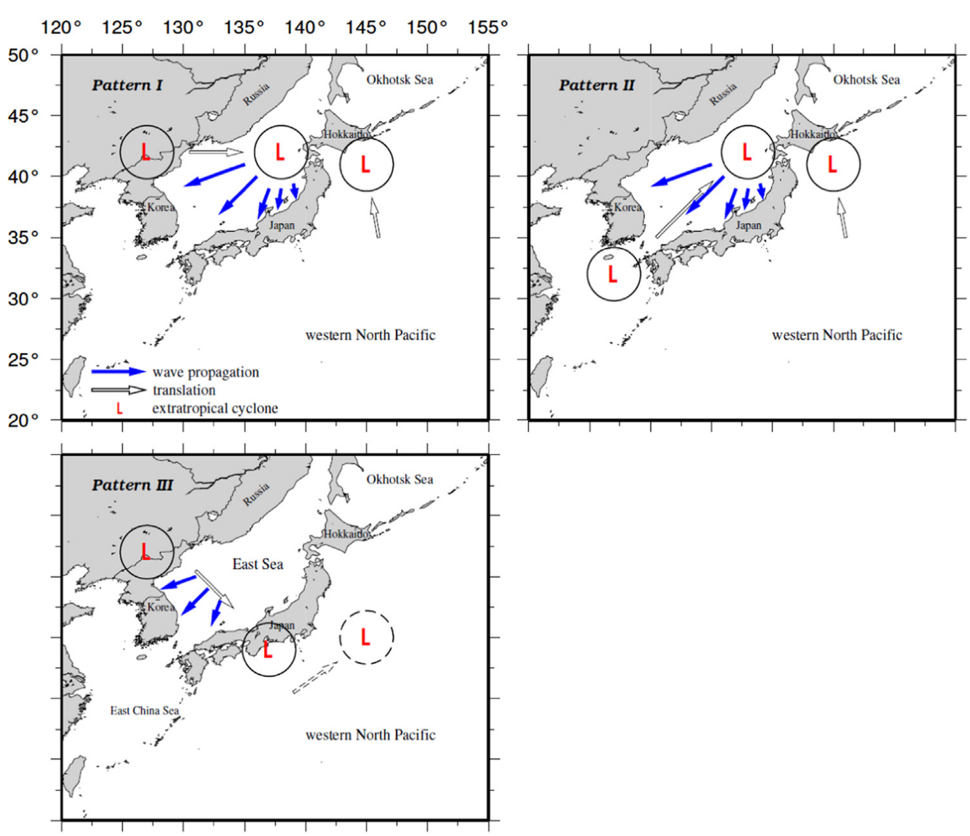

Fig. 1. Illustrations of the classified winter storm (extra-tropical cyclones) patterns responsible for the abnormal storm wave events in the East Sea.