Chapter

Surface Gravity Wave Modeling in Tropical Cyclones

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Abstract

Tropical cyclones are among the deadliest geophysical phenomena on earth. Tropical cyclone-generated wave fields are of interest both scientifically for understanding wind–wave-ocean interaction physics and operationally for predicting potentially hazardous conditions for ship navigation and coastal regions. This chapter briefly reviews the development of third generation wave models, the improvements of their input/dissipation source functions, and their applications in tropical cyclone generated surface wave predictions. Discussion on the status of coupled atmosphere-wave-ocean modeling in tropical cyclone predictions are given at the end of the chapter prompted by the growing scientific evidence on the importance of sea state on air-sea fluxes under extreme wind conditions.

Keywords: surface gravity wave, tropical cyclone, wave modeling, wave forecast, atmosphere–ocean-wave coupled models, tropical cyclone forecast

1. Introduction

Tropical cyclones, also popularly known as hurricanes or typhoons, are among the most spectacular and deadly geophysical phenomena. Not only the intense winds associated with the storms can create enormous waves, the ocean wave field generated by tropical cyclones are extremely complex with a combination of swell and wind sea due to the spatially inhomogeneous and directionally varying wind fields, and the directional distribution of the wind sea component is often skewed due to the rapid variation in the wind direction. Thus, the tropical cyclone-generated wave fields are of interest not only operationally for predicting potentially hazardous conditions for ship navigation and coastal regions, but also scientifically for understanding wind–wave-ocean interaction physics.

There have been considerable efforts made to understand the characteristics of tropical cyclone-generated surface waves through both measurements and numerical modeling. Several third generation wave models such as WAVEWATCH III [2], the Wave Model (WAM) [3], Simulating Waves Nearshore (SWAN) [4], University of Miami Wave Model (UMWM) [5], etc., have been used to study surface wave responses during hurricanes. The third generation wave models, as well as its predecessors (the first and second generation wave models), are all spectra models. Which means that the model solves the evolution of the surface wave energy spectral instead of the physical form of the surface wave itself, and thus it is also known as non-phase resolving wave model. Although phase resolving wave models have been actively developed during the past two decades, the spectral models are still the only approach capable of solving the temporal and spatial variations in the oceanic surface gravity wave fields. Thus, it will be the focus of this chapter. The readers interested in phase resolving wave modeling can read the chapter on "High-Resolution Numerical Simulation of Surface Wave Development under the Action of Wind" by Dr. Dmitry Chalikov. In this chapter, we will review the progress on the development of the third generation models, their applications to tropical cyclone wave forecasts, the improvements made to the input and dissipation source function in the model, and the challenges we face in advancing the wave forecast skills.

Since tropical cyclones are driven by enthalpy fluxes from the sea and limited mostly by surface drag, being able to accurately estimate the momentum and heat flux under these extreme wind conditions is critical for tropical cyclone predictions. During the past three decades, more and more scientific evidence has suggested that the air-sea fluxes is closely coupled to the sea state in the ocean [6–10]. With the continuous improvements in surface wave forecasts under tropical cyclone conditions, fully coupled atmosphere-wave-ocean model is suggested for accurate hurricane predictions as well as corresponding ocean responses [11–14]. However, the outcome from the coupled models are mixed, which we will discuss in more details at the end of the chapter.

2. Wave forecasts under tropical cyclones

2.1 Early developments in wave modeling

Ocean surface gravity waves are long regarded as a basic parameter of interest for marine engineering and navigation applications. Hence, it is necessary to develop the capability to forecast wave conditions over global and regional ocean domains to minimize loss of life and property. The basis for modern wave research was laid in the 1950s and 1960s. The first computer generated wave forecasts were made in 1956 by the Joint Numerical Weather Prediction Unit (JNWP) at Suitland, Maryland [15], which produced a single wave height and period at each grid point using a simple relationship between the local wind speed and duration and the wave height and period.

An important advance was the introduction of the concept of a wave spectrum by Pierson et al. [16], in which the random wave field is broken into a spectrum of many regular wave components which are distinguished by wavenumber vector (k), and relative or intrinsic frequency (σ). σ is also called angular frequency or radial frequency because it is measured in radian. Another popularly used frequency variable is f, which is measured in hertz (Hz) with $\sigma = 2\pi f$. Later on, an experimental milestone, the Joint North Sea Wave Project (JONSWAP) experiment [17], was conducted. In which, among other things, the fetch dependence of the spectral evolution was observed and the concept of self similarity of the spectral shape emerged. Following the success of the JONSWAP, rapid improvements were made in spectral wave modeling by solving the radiative transfer equation:

$$\frac{dN}{dt} = \frac{S_{in} + S_{nl} + S_{ds} + S_{bot} + \ldots}{\sigma} \tag{1}$$

where, $N(k,;,\theta,;,x,;,t) = F(k,;,\theta,;,x,;,t)/\sigma$ is the wave action density spectrum, $F(k,;,\theta,;,x,;,t)$ is the wave number-direction spectrum, θ is the wave direction, x is the vector represents the coordinate system in the geographical space, and t is time. The right side of the equation represents a combination of non-conservative sources and sinks of the wave energy with S_{in} represent the wind input source term, S_{ds} represent the dissipation due to wave breaking, S_{nl} represent the transfer of energy due to nonlinear interactions between the spectral wave components, and S_{bot} stands for dissipation due to bottom friction. Other source terms can be easily added such as surf breaking, bottom scattering or reflection by shoreline or iceberg. They are neglected in Eq. (1) here since they are not the focus of this chapter.

The classification of different spectral models is largely based on the treatment of the nonlinear interaction term (S_{nl}). In the so-called first generation models, S_{nl} is not modeled explicitly, so that all spectral components evolve independently. Dissipation for wind seas is generally modeled as an on–off mechanism, limiting the spectral evolution to some pre-described spectral shape. In second-generation models, simple approximations for nonlinear interactions are introduced, either treating the entire wind sea part of the spectrum using empirical growth relations and idealized spectral shapes (so-called hybrid models), or by modeling S_{nl} based on results for simplified spectral shapes (so-called discrete models).

After the Sea Wave Model Project (SWAMP) study in the mid-1980s, through community efforts, the Wave Model (WAM) was developed to solve Eq. (1) with explicit treatment the S_{nl} term, essentially replacing all previous models and marked the beginning of third-generation wave model era [18, 19]. The WAM was a major step forward in wave modeling, and it has been validated and applied to wave hindcast and Forecast over many seas of the world [20–22]. Since its development, the WAM model has been actively used by many wave research and forecast groups, including the European Center for Medium-range Weather Forecasts (ECMWF).

Despite the success of the WAM model, evaluations carried out at the National Centers for Environmental Prediction (NCEP) suggested that this model also left room for further improvement [23], such as the use of first-order numeric in the propagation terms that adversely influences swell propagations; the large fixed time steps used in source terms integrations can result in spectral shape errors in rapidly changing wave conditions, and extreme conditions were systematically underestimated due to an artifact of the physical parameterizations. WAVEWATCH III [24] was developed at NCEP in the spirit of the WAM. It is designed with more general governing transport equations that permit full coupling with ocean models, improved propagation schemes, improved physics integration scheme, and improved physics of wave growth and decay. It has been validated both over global-scale wave forecast and regional wave forecast [2, 25–27], and it was the first wave model validated for detailed wave spectra simulations under hurricane conditions.

For near-shore applications, Simulating Waves Nearshore (SWAN) model was developed at the Delft University of Technology [28]. Compare to WAM, it includes more flexible options on the parameters for processes such as non-linear wave–wave interactions, wind wave generation, energy dissipation by breaking, and friction and frequency shifting due to current and local topographical conditions. After being satisfactorily verified with field measurements [4, 29], it was the first model used to simulate tropical cyclone waves in the coastal waters of Taiwan Island.

The University of Miami Wave Model (UMWM) was developed [5] aimed at an efficient wave model to provide full atmosphere-wave-ocean coupling in hurricane forecasting systems [30]. Thus, the source functions that drive the space-time evolution of the energy spectra are developed in form based on theory and laboratory and field experiments under extreme wind conditions of tropical cyclones. The calibration factors (proportionality constants of the source functions) are determined from a comparison of modeled and observed significant height and mean period during Hurricane Bonnie (1998) and Hurricane Ike (2008). Although the modeled spectral shapes by UMWM in the four quadrants of Hurricane Bonnie (1998) match the Scanning Radar Altimeter measurements better than other spectral wave models, its overall performance against measurements from varies platforms shows less accuracy [31].

2.2 Wave predictions under tropical cyclones

The first wave modeling study under extreme tropical cyclone conditions was conducted by Ou et al. [32] using SWAN within the coastal waters of Taiwan. Model simulated significant wave height during the passages of four typhoons are compared with measurements at several wave stations near the island. The model results look reasonable on the east coast of the island while large discrepancies are found for the comparisons on the west coast of the island. The authors attribute the large errors to the simple wind field used to force the wave model, which is generated using a parametric model and did not account for the effect of the island's central mountains that partly damage the cyclonic structures of the passing-over typhoons.

While significant wave height is a useful information to have, it only gives a general idea of the total wave energy in the wave group. The directional wave spectrum contains information of the distribution of wave energy in wave number and direction space, and thus can be used to identify different contributions to local wave energy, e.g. swell from distant storms and locally wind-generated waves. The direction of propagation of wave energy and period ($1/f$ or $2\pi / \sigma$) of the most energetic waves are important for many practical applications, e.g. the design and operation of coastal and offshore structures and storm surge forecasts. Furthermore, the limited point measurements from a few moored buoy stations or oil platforms cannot reflect the spatial patterns of wave fields very well. Thus, considerable efforts have been made to measure the directional spectra of tropic cyclone generated surface waves and to investigate its spectral characteristics. Wyatt [33] described measurements of the directional spectra of storm waves using high frequency radar to explain the effect of fetch on the directional spectrum of Celtic Sea storm waves. Holt et al. [34] examined the capability of synthetic aperture radar imagery from ERS-1 satellite to track the wave fields emanating from an intense storm over a several day period. Wright et al. [35] and Walsh et al. [36] studied the spatial variation of hurricane directional wave spectra for both open ocean and landfall cases using the National Aeronautics and Space Administration (NASA) Scanning Radar Altimeter (SRA) for the first time through a joint effort between the NASA Goddard Space Flight Center and the National Oceanic and Atmospheric Administration (NOAA)/Hurricane Research Division (HRD). These measurements have provided detailed wave characteristics along the flight tracks of the NOAA aircraft carrying the SRA, and many SRA measurements have been carried out during hurricanes in the North Atlantic since.

To evaluate the ability of third generation wave models in prediction of directional wave spectra, Moon et al. [37] simulated Hurricane Bonnie (1998), a category 2–3 tropical cyclone on the Saffir-Simpson hurricane intensity scale (SSHS), when it approached the U.S. East Coast using WAVEWATCH III. Input and dissipation source function package ST2 was chosen for their simulation. Details about this source function package are given in Section 2.3. The results from their simulations are compared with buoy observations and NASA SRA data, which were obtained on 24 August 1998 in the open ocean and on 26 August when the storm was approaching the shore. While the model results yielded good agreement with observations of directional spectrum as well as significant wave height, dominant wavelength, and dominant wave direction (wavelength and direction at the peak frequency of the wave spectrum) excluding shallow areas near the shore, later studies found that WAVEATCH III overestimates the significant wave height under very high wind conditions in strong hurricanes [38–40]. These studies attribute this error to the overestimations of the drag coefficient (C_d) used in the wave model at very high winds.

Powell et al. [6] estimated C_d using a dataset from hundreds of global positioning system (GPS) sondes that were dropped in the vicinity of hurricane eyewalls, where the strongest wind occurs, in both the Atlantic basin and the eastern and central Pacific basins since 1997. This is among the first estimates of C_d in tropical cyclones under high wind speeds over 40 m/s. Their analysis found that surface momentum flux levels off as the wind speed increases above hurricane force, a behavior contradictory to surface flux parameterizations in a variety of modeling applications at the time. Inspired by their study, Donelan et al. [7] further studied the aerodynamic friction between air and sea under extreme winds in laboratory settings. They confirmed that the aerodynamic roughness approaches a limiting value in high winds, and a fluid mechanical explanation of this phenomenon was given based on their study. More comprehensive studies on the air-sea fluxes were carried out later on through the Coupled Boundary Layer Air-Sea Transfer experiment (CBLAST), a cooperative undertaking between the Office of Naval Research (ONR), NOAA's Oceanic and Atmospheric Research (OAR) lab, HRD, Aircraft Operations Center (AOC), including its US Weather Research Program (USWRP), and the U.S. Air Force Reserve Command's 53rd Weather Reconnaissance Squadron "Hurricane Hunters", which yielded an unprecedented dataset for exploring the coupled atmosphere and ocean boundary layers during an active hurricane [41]. Key results from the analysis effort to date have increased the range of air–sea flux measurements significantly, which have allowed drag and enthalpy exchange coefficients to be estimated in wind speeds to nearly hurricane force.

Fan et al. [12] investigated the effect of different drag coefficient parameterizations in WAVEWATCH III through a modification to the input/dissipation source package ST2 using a very strong tropical cyclone, Ivan (2004). Hurricane Ivan (SSHS category 4–5 in the Caribbean Sea and Gulf of Mexico) was one of the most intensively observed hurricane to date. Three sets of detailed SRA wave spectra measurements were collected as well as satellite measurements and National Data Buoy Center (NDBC) buoy time series, providing a nice temporal and spatial coverage along the passage of the hurricane. The illustration of the location of these measurements from their paper is given here in **Figure 1**.

The authors also utilized the NOAA/HRD real-time wind analysis (HWIND) as their model forcing. HWIND is an integrated tropical cyclone observing system in which wind measurements from a variety of observation platforms are used to develop an objective analysis of the distribution of wind speeds in a hurricane [42]. The spatial resolution of HWIND is about 6 km × 6 km and covers an area of about 8° × 8° in latitude–longitude around the hurricane's center. The wind field was usually provided near real time at intervals of every 3 or 6 hours. Although HWIND provides excellent spatial representation of the hurricane wind field, its coarse temporal resolution and small spatial coverage is not sufficient to force a numerical model, and was only used for theoretical wind field analysis after the product became publicly available since 1994.

To take advantage of this wind product, Fan et al. [12] introduced a normalized interpolation technique to interpolate the HWIND field in time and extrapolate it in space with minimum distortion of the hurricane wind field. Results from their wave simulation experiments suggested that the model with the original ST2 drag coefficient parameterization tends to overestimate the significant wave height and the dominant wavelength and produces a wave spectrum with narrower directional spreading. When an improved drag parameterization that considers the level off at

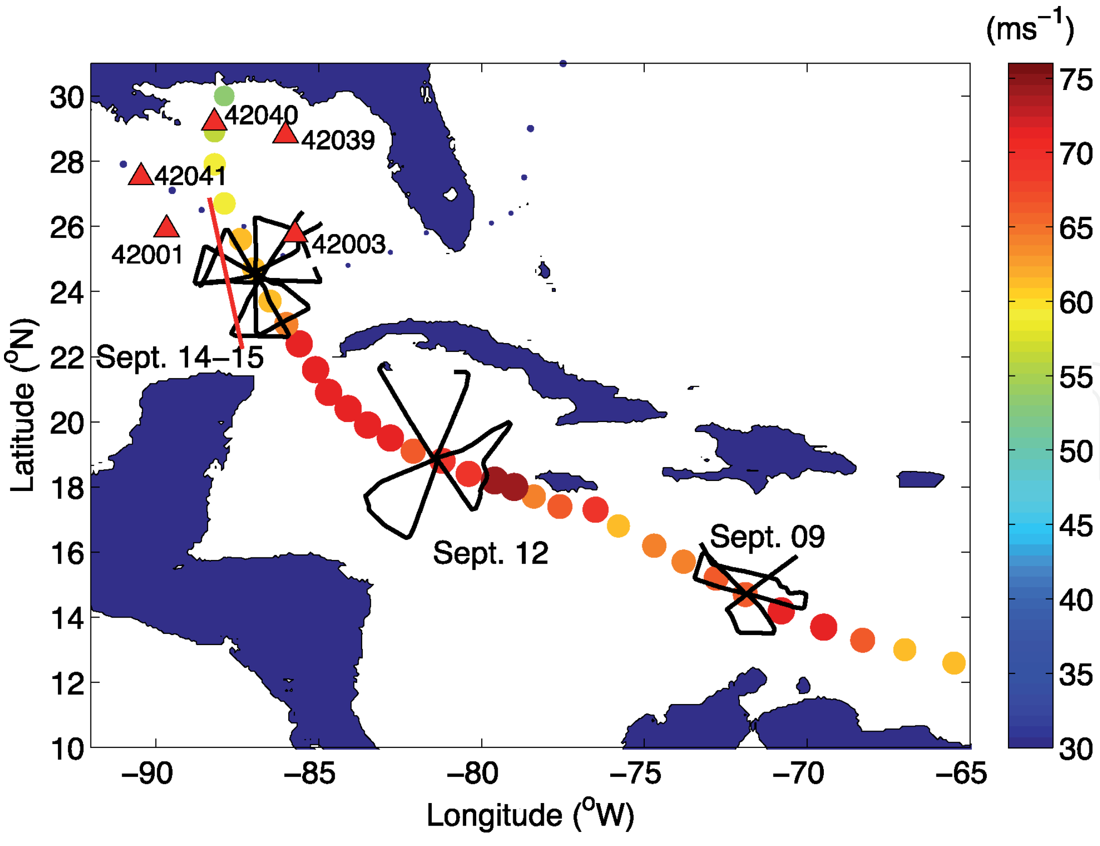

Figure 1.
Available measurements along Hurricane Ivan track. The color and size of the circle represents the maximum wind speed of the hurricane. The black lines in the vicinity of the hurricane track represent the aircraft storm relative flight tracks during the SRA measurements. The red line to the left of the hurricane track overlaps with the September 14–15 SRA measurements shows the satellite tracks of Envisat-1 and ERS-2. The red triangles in the Gulf of Mexico show National Data Buoy Center buoy locations along hurricane Ivan track.

high wind is introduced, the model yields an improved forecast of significant wave height when compared with SRA, satellite, and NDBC buoy measurements, but underestimates the dominant wavelength. The SRA model comparison on Sept 9 from their paper is given here in **Figure 2** as an example to illustrate the improvements in wave height simulations and the bias in wave length simulations. This bias was later on corrected with improved input and dissipation source functions as discussed in Section 2.3 below.

Most importantly, Fan et al. [12] investigated the effect of ocean current inputs on wave predictions in their study and found that the effect of wave-current interaction on hurricane wave predictions are even stronger than the improved C_d (**Figure 2**), especially when the hurricane moves over a preexisting mesoscale ocean feature, such as the Loop Current in the Gulf of Mexico or a warm- and cold-core ring, the current associated with the feature can accelerate or decelerate the wave propagation and significantly modulate the wave spectrum. Detailed idealized experiments conducted in Fan et al. [43] suggested that in the right-forward quadrant of the hurricane center where the currents are strong and roughly aligned with the dominant wave propagating direction, the advection effect of currents can introduce an absolution (relative) error in significant wave height as large as 2 m (~20%).

Since WAVEWATCH III was shown to perform better than SWAN under tropical cyclone conditions [44, 45], and was thus more popularly used by researchers and operational centers for surface wave simulations under extreme wind conditions, our discussion on wave modeling under tropical cyclone conditions will focus on WAVEWATCH III from hereafter.

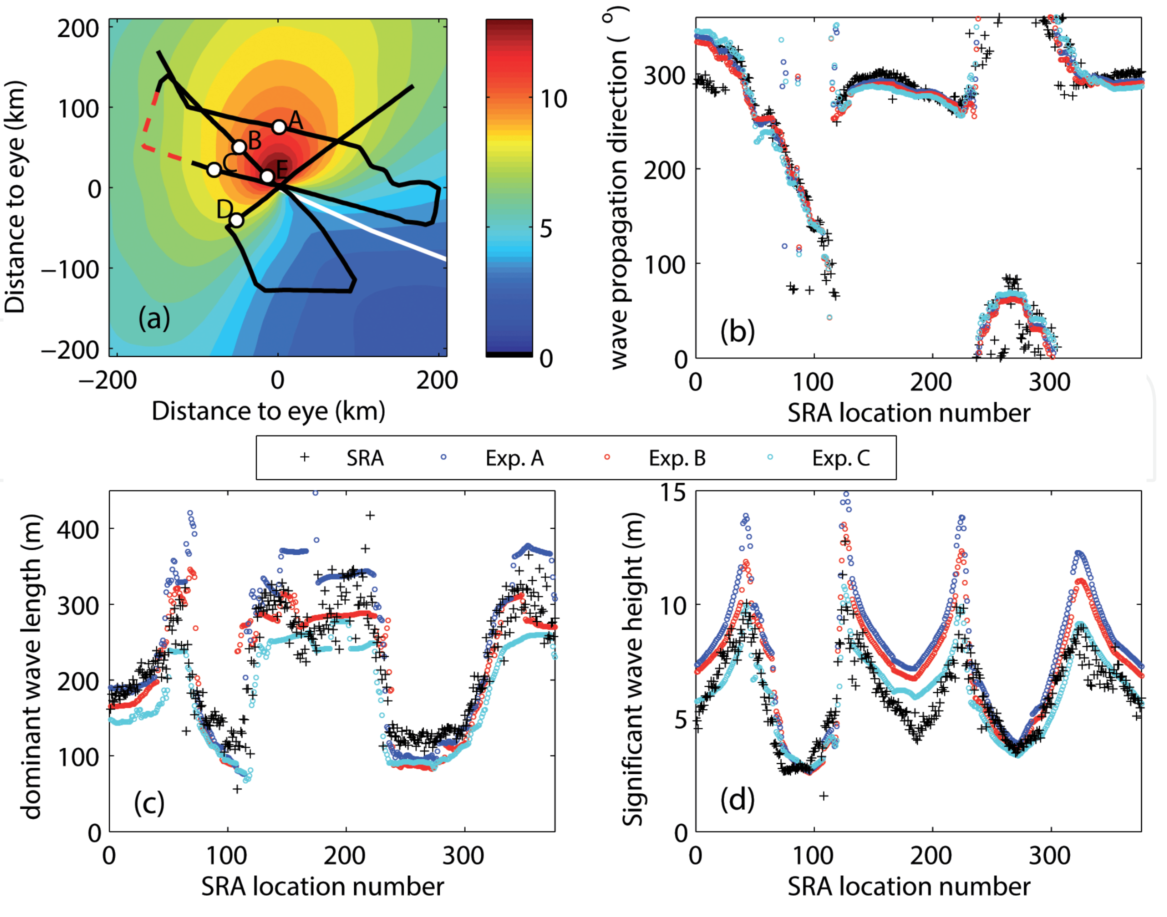

Figure 2.
(a) Significant wave height field (m, color) at 1800UTC on 9 September. The thick white line is the hurricane track and thick gray line is the flight track. The black arrow shows the start point and direction of the flight, and the black dots shows the SRA location in an increment of every 50 data points from the start. (b) Wave propagation direction relative to true north rotating clockwise, (c) dominant wavelength, and (d) significant wave height comparison between SRA measurements and model results in experiments A, B, and C corresponding to simulations using original c_d, modified c_d, and modified c_d plus wave-current interaction respectively.

2.3 Input and dissipation source functions

2.3.1 Developments of input and dissipation source functions in WAVEWATCH III

There are five different input/dissipation source term packages in WAVEWATCH III referred to as ST1, ST2, ST3, ST4, and ST6. Each model describes the wind generation and whitecapping dissipation differently. Generally, the term describing the wind input is determined as:

$$S_{in} = \beta(k,\theta)N(k,\theta)\sigma \tag{2}$$

where $\beta(k,\theta)$ is the dimensionless wind-wave growth rate parameter.

The $\beta(k,\theta)$ used in the first source package (ST1) is based on the source terms of WAM cycles 1 through 3 [46, 47]. It is an empirical formula as a function of the 10 m wind speed (U_{10}) and direction (θ_w) and the wave phase velocity (c_{ph}) and direction (θ). The drag coefficient C_d in this formulation is defined as a linear function of U_{10}, and a cap (2.5×10^{-3}) is applied to C_d for high winds based on previous findings for hurricane wave simulations.

Source package ST2 is initially developed by Tolman and Chalikov [48] and later on updated by Tolman [49]. It combines a wind input adjusted to the numerical model of airflow above waves by Chalikov and Belevich [50], in which $\beta(k,\theta)$ is a nondimensional wind-wave interaction parameter that varies with C_d and the dimensionless frequency of the spectral components. The wind input terms in ST2 can become negative for waves traveling at large angles with wind or faster than wind, and thus is a better representation of energy flow at the air-sea interface and a big improvement over the ST1 input source term.

Their dissipation term is also improved over ST1 by consisting of two separate terms for both the low frequency waves and the high-frequency tail of the spectrum, whose shape is adjusted to produce a roll-off of the wave spectrum proportional to f^{-5} at high frequencies, as proposed by Phillips [51].

Model results using ST2 has shown significant improvement over that using ST1 by being able to produce excellent growth behavior from extremely short fetches up to full development, giving smoother results and is less sensitive to numerical errors [48].

ST3 adapted the ECMWF WAM parameterization described by Bidlot [52]. This parameterization combines the wind input term originally based on the wave growth theory of Miles [53] with the feedback on the wind profile parameterized by Janssen [54], and the input source function is a function of the wave supported stress τ_w:

$$\tau_w = \left| \int_0^{k_{\max}} \int_0^{2\pi} \frac{S_{in}(k',\theta)}{C} (cos\theta, sin\theta) dk' d\theta + \tau_{hf}(u_*, \alpha)(\cos\theta_u, \sin\theta_u) \right| \quad (3)$$

where, k' and θ are the wave number and direction, C is the wave phase speed, θ_u is the wind directions, u_* is the friction velocity, and α is the Charnock coefficient. Eq. (3) for τ_w includes the resolved part of the spectrum, up to the maximum wave number $k_{\max}$, as well as the stress supported by shorter waves, τ_{hf}. Thus, to calculate the roughness parameter, the feedback of the wind-waves spectra is taken into account as well. So, in the considered parameterizations, the wind input is determined by the wind-wave interaction parameter as well as the friction velocity u_*.

This model added a linear swell dissipation component introduced by Janssen [55] to represent the shear stress variations in phase with the orbital velocity, and the mean frequency also occurs in the definition of the maximum frequency of prognostic integration of the source terms. A limitation of their dissipation source function is that it is too sensitive to swell. An increase in swell height typically reduces dissipation at the wind-sea peak, and increase dissipation at high frequencies.

Both ST4 and ST6 inherited the wind input source function from ST3, and focused on the improvement on the dissipation source function in the model.

The least understood aspect of the physics of wave evolution is the dissipation source function. Following Hasselmann's [56] idea that white capping is the main cause for the dissipation process and local in space, Phillips [57] argues that wave dissipation is rather local in wavenumber space. This is followed by Jenkins [58] who advocated the picture that breaking waves will generate ocean eddies (turbulence) that will damp the waves. During the next two to three decades, several dissipation source functions have been proposed and widely used in third generation wave models such as [47, 48]. However, these parameterizations were adjusted to close the wave energy balance instead of using the quantitative relationship with observed feathers. Following the pioneering work by Banner and Young [59], Banner et al. [60, 61] have analyzed breaking in relationship to the formation and related instabilities of groups. Babanin et al. [62], Babanin et al. [63], and Ardhuin et al. [64] worked on the physics of the process analyzing both laboratory and open-field data. These efforts led to new insights into the process of whitecapping, in a way making even more evident the limits associated with the various parameterizations in use. Ardhuin et al. [64] is the first to implement these findings into an operational wave model (WAVEWATCH III, ST4) through a dissipation function without any prescribed spectral shape but based on the empirical knowledge of the breaking of random waves from previous researches and the dissipation of swells over long distances due to air friction. Their work is immediately followed by Babanin [65] and Zieger et al. [66] who implemented the ST6 package in WAVEWATCH III that argues the swell attenuation is due to the interaction with ocean turbulence, and thus swells will transfer energy into the ocean when they dissipate rather than to the air.

2.3.2 Evaluation of different source functions in tropical cyclones

These input/dissipation source packages are evaluated in many studies and for different locations and scenarios. Using Hurricane Ivan (2004) as the test case, Liu et al. [31] conducted the first comprehensive evaluation of the relative strengths/weaknesses of all WAWEWATCH III source functions but ST1 under tropical cyclone conditions. Through the comparison of bulk wave parameters (i.e., significant wave height, mean wave direction and period) derived from SRA spectra measurements, satellite observations, and NDBC buoy data, the authors found that ST3, ST4, and ST6 have comparable skills on wave predictions under extreme wind conditions and significant outperformed the ST2 source package. Their comparisons with the SRA data are given in **Figure 3** for illustration. We can see that while ST2 has similar skills as other sources functions on wave direction predictions, it under predicts the significant wave height and mean wave period. One possible explanation for this is because the upper limiter on C_d adopted by ST2 (C_d, max = 2.5×10^{-3}) starts being active when U_{10} is far below the hurricane wind forcing ($U_{10} \sim 15$ ms^{-1}), which will influence the well-tuned wind wave growth behavior under low to moderate winds [48] and may influence the high wave predictions by ST2.

Another important feature to be noticed in **Figure 3** is the underprediction of wave period by ST2, a model bias reported by Fan et al. [12] as well (we can easily relate wave period to wave length through the dispersion relations), while good prediction skills on the wave period are found using ST3/4/6. This has suggested that more physical based new input/dissipation source functions were able to correct this bias efficiently.

Another wave model evaluated in Liu et al. [31] is the University of Miami Wave Model (UMWM) [5]. It was devised as an efficient wave model to provide full atmosphere-wave-ocean coupling in hurricane forecasting systems [30]. Thus, the physics-based but time-consuming nonlinear interaction source term S_{nl} (e.g., [67–69]) was treated parametrically in such a way that wave breaking was assumed to be the primary cause of the shift of energy to the longer waves. Based on the comparisons between model results and measurements from various platforms, such as the comparison with the SAR measurements in **Figure 3**, the authors concluded that UMWM shows less accuracy than WAVEWATCH III in specification of bulk wave parameters. This is possibly because (i) UMWM-estimated drag coefficient does not clearly show a saturation trend when wind

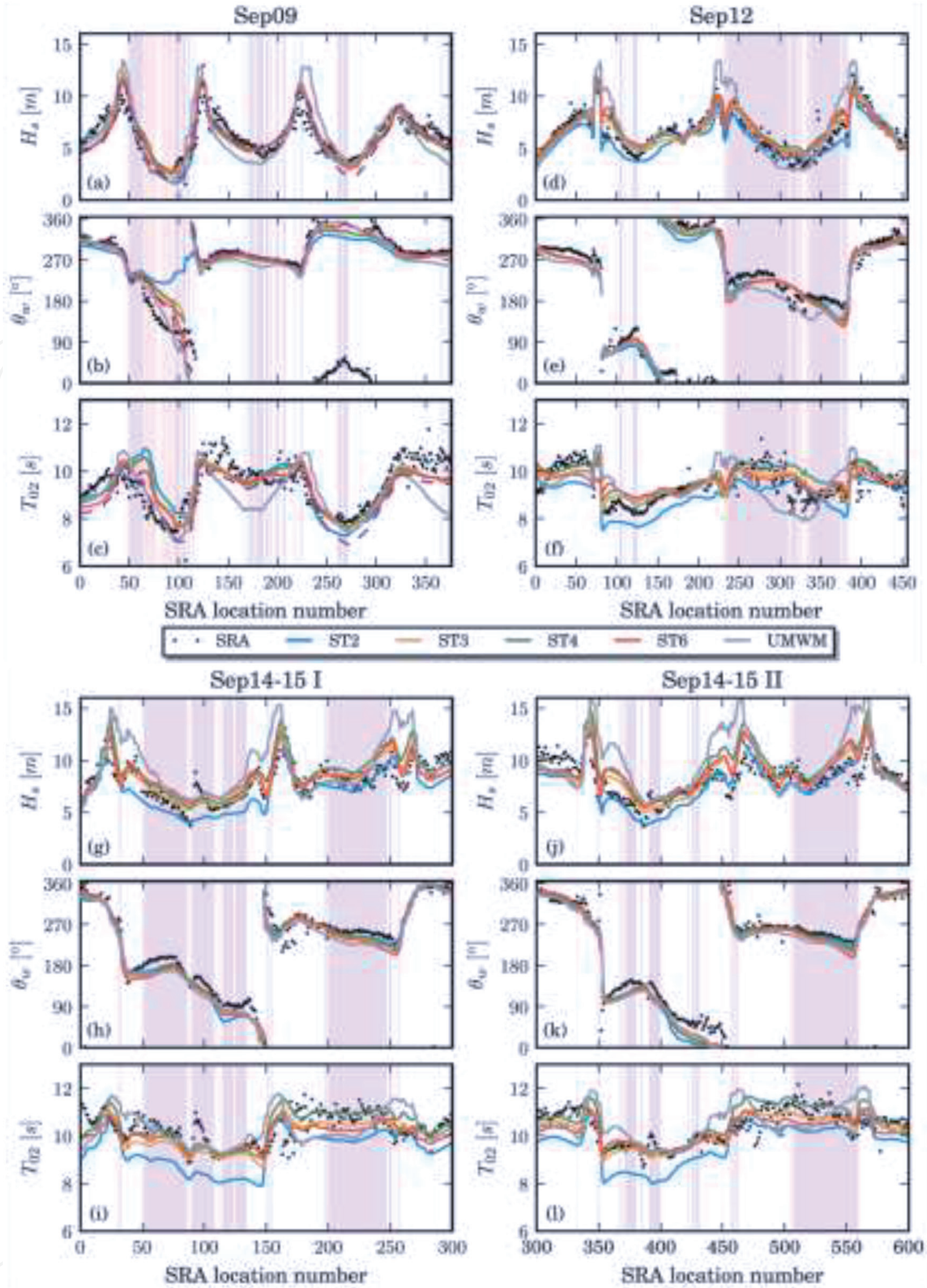

Figure 3.
Comparison of model results (colored lines: Blue for ST2, yellow for ST3, green for ST4, red for ST6 and gray for UMWM) and SRA observations (black dot •) acquired on September (a–c) 9, (d–f) 12 and (g–l) 14–15. For clarity, the SRA measurements on September 14–15 is divided into two parts. One (the first 300 records) is plotted in panels (g–i) and the other (the remaining 300 records) in panels (j–l). Three bulk parameters are taken into account: (a, d, g, j) significant wave height H_s*, (b, e, h, k) mean wave direction* θ_w *(oceanographic convention: the direction towards which waves are propagating, measured clockwise from geographic north) and (c, f, i, l) mean wave period* T_{02}*. The purple dashed lines in panel (a–c) represent the results from the ST6 + WRT experiment.*

speeds are beyond ~35 ms^{-1} and (ii) the four-wave interaction term of UMWM disagrees evidently with the full solution of the Boltzmann integral in detail.

3. Coupled models

As we all know, tropical cyclones are among the deadliest geophysical phenomena. Both the most lethal and the most expensive natural disasters in U.S. history were tropical cyclones [1]. However, being able to accurately predict the intensity and track of these storms is still a big challenge. While the primary driving source for the tropical cyclones are the heat transfer from the ocean through evaporation, the sea surface drag works to slow the storm down. There is little understanding of the behavior of these fluxes at very high wind speeds. Traditionally, due to technical limitations, direct measurements of the fluxes have only been made at wind speeds as large as 25 m/s. As a result, momentum transfer under extreme wind conditions has been extrapolated from these field measurements in a variety of modeling applications, including hurricane risk assessment and prediction of storm motion, intensity, waves and storm surges. However, drop sonde measurements by Powell et al. [6] and laboratory experiments by Donelan et al. [7] suggested that in those extreme circumstances the drag decreases with wind speed or saturates. Their work has opened a new chapter for tropical cyclone prediction models, but the understanding of the physics of such extreme events is only beginning.

Many studies following their pioneer work have suggested that the momentum flux at the air-sea interface is closely coupled with sea state in the ocean. Makin [8] argues that spray production may give rise to the reduction of drag coefficient, C_d, by suppressing the air turbulence for increasing wind speed during hurricanes. On the other hand, Andreas [9] has proposed that when spray returns to the water, short waves will be extinguished. This will no doubt reduce the drag considerably as the short waves carry most of the wave-induced stress [10]. Donelan et al. [7] also suggest that flow separation may be the reason for drag reduction since the outer airflow does not "see" the troughs of the waves during such events and thus unable to follow the wave surface, and skips from breaking crest to breaking crest. All these hypotheses are standing on one common ground – the momentum flux is closely coupled with the sea state in the ocean.

Given the success in wave modeling, there is keen desire in the modeling community to calculate momentum flux using the source function from the wave model and fully coupled Atmosphere-wave-ocean model is suggested for accurate hurricane predictions as well as corresponding ocean responses [12–14]. Although the newly developed fully coupled Atmosphere-wave-ocean models were shown to be able to improve model simulated surface wind and inflow angle in individual storms [14, 70, 71], no statistically significant improvements were observed in intensity forecasts by the Hurricane Forecast Improvement Program [72–75].

The wave energy spectrum computed by the wave models is from a balance between input and dissipation, and the wave parameters that are usually validated against observations are weighted by energy thus depend primarily on long waves around the peak. Since the momentum flux depends mainly on short wind waves, one may ask whether the model spectra represent real spectra well enough to provide reasonable momentum flux to atmosphere and ocean models in a coupled system for tropical cyclone predictions, or is there a stronger argument for using parameterized fluxes? To answer this question, Fan and Rogers [76] compared the drag coefficient computed using WAWEWATCH III simulated wave spectrum under Hurricane Ivan with that calculated using the SRA measured wave spectrum. The Donelan et al. [77] source function was used for these calculations because its stress calculation is based on the wave spectra and wind only, which is suitable for the SRA measurements. In order to quantify the uncertainties brought in by adding spectra tail to the SRA measurements, the model spectra were truncated at the SRA resolution and frequency range and added high frequency tail in the same way. The reconstructed model spectra were shown to give no noticeable difference in wave parameter and drag coefficient calculations from the original spectra.

From their study, the authors found that the drag coefficients disagree between the SRA and model spectra mainly in the right/left rear quadrant of the hurricane

(**Figure 4**) where the observed spectra appear to be bimodal while the model spectra are single peaked with more energy in the swell frequencies and less energy in the wind sea frequencies. The authors also found that the modeled wind sea part, which is essential for stress calculations, is more problematic than the swells. The reason for the large discrepancy in drag coefficients due to the spectra shape differences is because the surface waves are young and vary significantly with time and space in hurricanes, the momentum flux across the air-sea interface under such sea states depends mainly on short wind waves. Since the wind stress is a vector

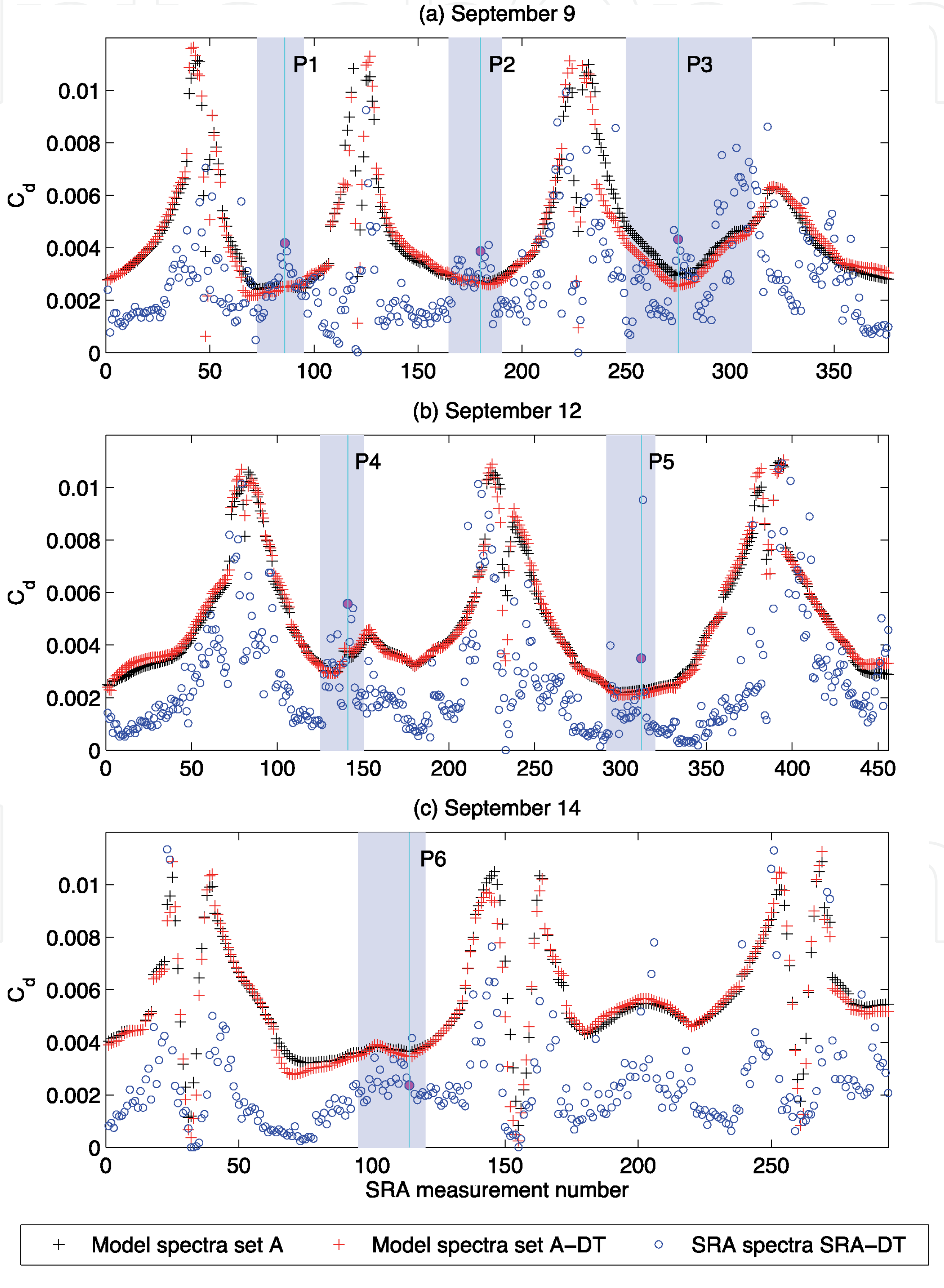

Figure 4.
Drag coefficient (C_d) calculated from original model spectra (set A, black cross), reconstructed model spectra (set A-DT, red cross), and constructed SRA spectra (SRA-DT, blue circle) using the Donelan et al. [77] source function along the flight track of (a) September 9, (b) September 12, and (c) September 14. The gray areas are corresponding to the part of flight track in the right/left rear quadrant of the hurricane.

sum of the momentum contributions in all frequencies and directions of the wave spectrum, the shape of the wave spectra will directly affect its magnitude.

The authors attributed the large discrepancies in the wave spectra simulations to the usage of HRD winds as the wave model forcing. Because the Hwinds are created through temporal and spatial interpolation/averaging of all available observations relative to the storm center, including land, sea, space, and air-borne platforms, the resulting wind field is smoother than real tropical cyclone winds and do not have the fine structures. However, although the wind field produced by the coupled atmosphere-ocean-wave models do have fine structures in the wind field, they failed to produce bimodal wave spectra as well. Which suggests that either the structure of the modeled wind fields is far from reality or there is some other physics missing in the wave model to capture the bimodal waves. For that, Fan and Rogers [76] commented on the dissipation terms in the wave model being developed with no any specific attention to the unique conditions of tropical cyclones. They may generate too little dissipation for the swells and too much dissipation for the wind sea under high wind conditions. This would result in modeled wind sea part of the spectra are continuous (unimodal) and narrower in frequency space compared to observations.

Since the Donelan et al. [77] wind input source functions used in their study was derived from measurements taken only under low to moderate wind conditions [46, 77], it may not be suitable for high wind conditions such as the hurricanes. Fan and Rogers [76] also conducted alternate drag calculations using Donelan et al. [5] source function that was developed for hurricane conditions. They found that although the magnitude of the drag coefficients is reduced, the discrepancy between the model and observed spectra calculations in the rear quadrants of the hurricane remains the same.

It is well established that the intensity of a tropical cyclone over an open ocean may be significantly affected by the cooling of sea surface temperature caused by air-sea interaction since the tropical cyclones are driven by enthalpy fluxes from the sea and limited mostly by surface drag [78]. While the strong wind of the hurricane leads to evaporation of warm water from the ocean surface that fuels the storm through condensation and latent heat release, as the storm continues to intensify, the increasing wind stress on the ocean's surface generates stronger turbulent mixing that deepens the mixed layer, reduces the sea surface temperature, and causes a reduction of sea surface heat and moisture flux and in turn decrease the intensity of the storm. Thus, the intensity of a tropical cyclone is highly sensitive to the magnitude and spatial distribution of C_d. The results in the Fan and Rogers [76] study have suggested that while the drag coefficients calculated using the wave spectra produced by WAVEWATCH III are comparable to the observations in some quadrants of hurricane, large discrepancies from the observations are found in other quadrants. Thus, the current wave model is not ready for the task of providing accurate drag calculations in the coupled forecast models.

4. Conclusions

This chapter has reviewed the progress in third generation wave models and their applications in tropical cyclone generated surface wave predictions. While we have demonstrated the significant improvements in third generation wave modeling under tropical cyclone condition during the past two decades with increasing accuracy in the model predicted integral properties of the sea (significant wave height, period and direction), the shape of their simulated wave spectra is far less impressive with the modeled wind sea part more problematic than the swells. Although the accuracy of the meteorological forcing is one important factor to blame for these model bias, the substantial degree of empiricism in our wave models based on physical assumptions in our wave theories are also accountable for these model deficiencies, especially for extreme weather conditions such as tropical cyclones.

The dissipation of wind waves in deep water is by far the source term we understand the least. There is hardly any agreement neither on the basic physics of the process nor on the best way, although empirical, to model it. Even though the experimental results exhibit some common features, they are often in serious disagreement with each other and thus does not provide much help in modeling this flux. Thus, given the limited level of knowledge we have on spectral dissipation, it has been used as the tuning knob in the numerical wave models through fittings with the observed wave integral properties (significant wave height, period, direction). However, such an approach of bending the model solutions to match observations may lead to unwanted diverge from the truth we wish to predict. The ultimate solution to this problem still lies within the fundamental improvements in the physical representations of this process.

The coupled atmosphere-ocean-wave models have not shown any convincing improvements in tropical cyclone forecasts, most likely due to the model bias in wave spectra simulations. This does not mean that we should refrain ourselves from this direction. The atmosphere interacts with the ocean through the surface gravity waves. This is how the nature works. Although there will be a long way to go before we can fully understand the dynamical processes that allow us to adequately simulate the wave spectra in the extreme wind regime, this is the right path to take if we aim at a better understanding and modeling of these extreme weather events.

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