Naval Research Laboratory

Washington, DC 20375-5320

NRL/MR/7322--20-10,164

Implementation of Two New Spectral Input Options in HOS-Ocean – Part I

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October 7, 2020

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
07-10-2020	NRL Memorandum Report	01 Oct 2016 - 30 Sep 2019

4. TITLE AND SUBTITLE

Implementation of Two New Spectral Input Options in HOS-Ocean – Part I"

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

Mark D. Orzech and Jie Yu

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER
6A51

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Naval Research Laboratory
1009 Balch Blvd
Stennis Space Center, MS 39529-5004

8. PERFORMING ORGANIZATION REPORT NUMBER

NRL/MR/7322--20-10,164

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Office of Naval Research
One Liberty Center
875 N. Randolph Street, Suite 1425
Arlington, VA 22203-1995

10. SPONSOR / MONITOR'S ACRONYM(S)

ONR

11. SPONSOR / MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT

DISTRIBUTION STATEMENT A: Approve for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

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15. SUBJECT TERMS

Higher-order spectral (HOS) model
HOS-ocean
Ocean surface waves
WAVEWATCH III
Frequency-directional spectra,
JONSWAP

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
					Mark D. Orzech
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**	Unclassified Unlimited	29	**19b. TELEPHONE NUMBER** *(include area code)*
Unclassified Unlimited	Unclassified Unlimited	Unclassified Unlimited			(228) 688-5974

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NRL MEMORANDUM REPORT

Implementation of two new spectral input options in HOS-ocean. Part I

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Abstract:

This report describes the implementation and testing of two new options in the higher-order spectral (HOS) model "HOS-ocean", each of which facilitates model initialization with two-dimensional (2D) frequency-directional wave spectra. The first option enables the user to generate a JONSWAP-based 2D spectrum with energy peaks at two different directions, specifying the principal directions, the directional spreads, and the JONSWAP parameters for the individual peaks. The second option facilitates model initialization using a frequency-directional spectral data file. The format of the data file is assumed to be that of the WAVEWATCH III (WW3) 2D spectral files, but the source of the data can be any. A library of bivariate interpolation of scattered data is installed, and used to transfer the input spectral data onto the HOS-ocean model grids in order to initialize the model fields. Results from preliminary test cases are presented and discussed here to evaluate the basic performance of the model utilizing the new features.

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1 INTRODUCTION

This report documents two additions that were made to the public-domain software package HOS-ocean (Ducrozet et al., 2007, 2016), each of which enables the model to initialize wave simulations with a two-dimensional (2D) frequency-directional spectrum. The first case facilitates initialization with a directionally bimodal spectrum (i.e., two wave peaks from different directions). Each peak is specified as a JONSWAP frequency spectrum, to which a cosine-power directional distribution is then applied. The second case facilitates model initialization using a frequency-directional spectrum data file. While the format of the input spectral data is assumed to be that of the output files from WAVEWATCH III (WW3DG, 2019), there is no assumption on the source of the data.

The HOS-Ocean model, developed at Ecole Centrale de Nantes (France), is based on the High-Order Spectral (HOS) method. It can efficiently simulate the propagation of highly nonlinear wave fields in three dimensions (assuming a constant or deep water depth). The HOS method is based on the potential flow theory, and recasts the Laplace Equation and boundary conditions into a system of fully nonlinear evolution equations for the free surface displacement and surface velocity potential. To solve the system, the vertical velocity at the free surface is needed, and obtained through a sequence of evaluations that involve eigenfunction expansion of the surface velocity potential in the wavenumber space (West et al., 1987; Dommermuth and Yue, 1987; among others). The transformation to and from the physical and wavenumber space is carried out by the Fast Fourier Transfer (FFT), which makes the HOS method numerically efficient.

When provided with a frequency directional spectrum, $S(\omega, \theta)$, the discrete HOS mode amplitudes are initialized as

Manuscript approved October 6, 2020.

$$\frac{|B_{mn}^{\eta}|^2}{2\Delta k_x \Delta k_y} = S_{HOS}(k_x, k_y) = \frac{\partial \omega}{\partial k}\frac{1}{k} S(\omega, \theta) \tag{1}$$

$$B_{mn}^{\tilde{\phi}} = \frac{-\mathrm{i}g}{\omega}\,\beta_{mn}^{\eta}$$

where B_{mn}^{η} and $B_{mn}^{\tilde{\phi}}$ are, respectively, for the free surface displacement η and the surface velocity potential $\tilde{\phi} \equiv \phi|_{z=\eta(x,t)}$, and $g = 9.81$ m/s^2 is the gravitational acceleration. A random phase is assumed for the complex amplitude B_{mn}^{η}. Note that $B_{mn}^{\tilde{\phi}}$ is initialized by relating to B_{mn}^{η} via the linearization (only at $t = 0$) of the dynamic free surface boundary condition (i.e. the Bernoulli equation at the free surface). Since B_{mn}^{η} is the mode amplitude in the wavenumber space (k_x, k_y), it is directly related to the spectrum $S(k_x, k_y)$ by definition. The latter is so related to $S(\omega, \theta)$ that the total energy represented by the two is the same.

The public-domain HOS-ocean model presently offers the capability to simulate waves based on a directionally spread, JONSWAP-based spectrum with a single peak centered at $\theta = 0°$ (i.e., waves entering domain perpendicular to left [x = 0] boundary). Users can modify the peak frequency, spectral steepness, and directional spread of this spectrum, but they cannot prescribe a different peak direction or multiple peaks. The first new capability described in this report adapts and extends the original JONSWAP option to allow the user to specify two different peaks (with individually defined energy levels, steepnesses, and spreads) that enter the model domain from different, user-specified peak directions. The second newly implemented capability fully enables the input of WW3-formatted spectra data. While this option apparently was listed in the current public-domain version of HOS-ocean (as of 2018), it is in fact erroneous. The main issue is caused by the 2D interpolation of the input spectral data onto the HOS-ocean model grids. In the 2018 release of the HOS-ocean model, the bilinear and bicubic interpolation are not properly coded. To address the issue, we install the library of bivariate interpolation of scattered data based on the quadratic Shepard method (Renka, 1988). Other adjustments have to apply (which, however, do not change the energy distribution described by the original spectral data), in order to make $S(\omega, \theta)$ consistent with the HOS-ocean formalism and suitable to be used in equation (1); see Section 2.2.

This paper details the modifications made to HOS-ocean in order to implement these new capabilities, and describes a number of tests conducted with the new software. The modifications themselves are outlined in Section 2. Following this, Section 3 introduces several basic test cases that were developed and run for each new capability. Further discussion and conclusions are provided in Section 4, and information on dissemination of this code is supplied in Section 5. Copies of the subroutines that are related to the implementation are included in the Appendix.

2 MODIFICATIONS TO HOS-OCEAN

The new software created for HOS-ocean was added by modifying existing files, rewriting or changing existing subroutines and adding new variables as needed. The list of FORTRAN90 source files has not been changed by these modifications. The primary file that was altered is `initial_condition.f90`, but minor additional modifications were also made to the files `variables_3D.f90`, `input_HOS.f90`, and `HOS-ocean.f90`. Some changes were also required in the model input file (`input_HOS.dat`), including the addition of 13 new lines providing for

user specification of parameters for each of the two new options described below. A sample copy of the new input file is also included in the Appendix.

2.1 Bimodal Spectra Based on JONSWAP Parameters

To facilitate an additional 2D spectral capability, we added routines allowing the user to specify a directionally bimodal input spectrum, featuring energy peaks at two separate directions. With this option, two JONSWAP-format spectra with user-specified shape, peak frequency, peak direction, and directional spreading are merged into a single frequency-directional spectrum.

The primary subroutine that has been added to enable this functionality is *initiate_cross_sea* (in HOS-ocean file `initial_condition.f90`). This subroutine is constructed from modified sections of the existing subroutine *initiate_irreg*, in which initialization of single-peak 2D spectra based on JONSWAP is done. In the new subroutine, two separate copies of the JONSWAP-building lines are utilized (with minor modifications) to generate the two separate peaks describing the crossing sea state (Gramstad et al., 2018).

The processing of the input file (`input_HOS.dat`) in Fortran file `input_HOS.f90` is modified to allow the user to specify a new case number (***icase*** = 33) along with input parameters for each of the two desired peaks (see Appendix for sample input file). The input specifications for wave height (***Hs_real***), peak period (***Tp_real***) and JONSWAP parameter (***gamma_J***) are the same for the new case as for the single-peak option (*icase* = 3), except that there are separate sets of values for each of the two peaks (i.e., ***Hsa***, ***Tpa***, ***gamma_a*** and ***Hsb***, ***Tpb***, ***gamma_b***). For this case, however, the directional spread of each peak is computed based on a cosine-power expression where the user specifies the power (i.e., $N = \boldsymbol{Na}$ and $N = \boldsymbol{Nb}$) instead of the value ***beta*** that is used for single-peak spectra.

$$D(k_x, k_y) = \cos^N(\theta_{x,y} - \theta_p) \tag{2}$$

$$S_{HOS}(k_x, k_y) = \frac{C_g}{|\vec{k}|} S_{HOS}(k_x, k_y) \cdot D(k_x, k_y) \tag{3}$$

Finally, the user must specify the peak direction associated with each of the peaks (***theta_pa***, ***theta_pb***) in degrees, corresponding to the principal directions toward which the two sets of waves are progressing when they enter the domain at the left ($k_x = 0$) boundary. It is recommended that these values remain between -90° and 90°.

2.2 Enabling Input of Frequency-Directional Spectra in WW3 Format

The public-domain HOS-ocean model is configured to read in a spectrum from single ASCII text file with a format similar to a standard WW3 output file. However, the model initialization in the public-domain version is not implemented correctly, as noted in Introduction. We have completely rewritten the subroutines *read_irreg_f* and *initiate_irreg_f* (both in the file `initial_condition.f90`)[1] to enable the simulation of waves using such fully 2D frequency-directional spectral data.

In the revised subroutine *read_irreg_f*, the following tasks are performed:

[1] The default input filename expected by the revised model is "WW3_spec_in.txt" (hard-coded in file `variables_3D.f90`).

(a) Read in the 2D spectrum from the input data file, assuming the WW3 format, and transform the data from the standard WW3 units of m^2/(Hz rad) to the HOS-ocean units of m^2/(rad/s rad), i.e.,

$$S(\omega,\theta) = S_{WW3}(f,\theta)/2\pi$$

(b) Preliminary calculations to determine the period T_p and direction of the maximum peak, and the total energy (which determines the energy-based significant wave height H_s). Note that HOS-ocean model runs in the non-dimensional space, and converts input quantities to dimensionless values before beginning the simulation. While the model input file (`input_HOS.dat`) requires the user to specify H_s and T_p for the normalization, those are over-written upon the preliminary calculations; i.e. in the case considered here, H_s and T_p given in `input_HOS.dat` are simply the placeholders to avoid run-time errors.

(c) Re-order the data so that the wave directions are in the ascending order. The sorting is necessary because the wave directions in the original WW3 data file are often not provided in a consistently increasing order, while those in HOS-ocean are ordered.

(d) Shift the axis of wave direction to re-locate the energy peaks in the range $-\pi/2 < \theta < \pi/2$. Currently, HOS-ocean model domain is limited to the upper half plane, and uses the above range for the wave directions. However, the WW3-formatted spectra are given in the range $0 < \theta < 2\pi$. A shift $\Delta\theta$ (user-specified) is applied to all wave angles, so that the major energy peaks of the input spectrum are contained in $-\pi/2 < \theta < \pi/2$. (Note that any waves from the original S_{WW3} that end up outside this angle range will be cut off and not represented in the HOS simulations. However, the energy lost due to the truncation is expected to be negligible since ocean waves are rarely so broad-banded.)

It should be mentioned that the procedures of re-ordering and shifting in (c) and (d) do not alter the energy distribution (i.e., the shape of the spectrum) described by the original input data. It is assumed that the user knows the overall distribution of energy densities in the original spectrum, and how much the spectral angles must be shifted in order to fit within the HOS-ocean domain as described above. (This may be determined, for example, simply by examining the input spectrum with a utility such as Matlab.) A new parameter (***ww3shft***) for specifying the spectral shift in degrees has been added to the `input_HOS.dat` file for use with ***icase***=31. (This ***icase*** value was already reserved in HOS-ocean for WW3-formatted input files, but the option did not work.) The additional line is highlighted in the sample input file provided in the Appendix. This line must be included to avoid a run-time error; for an input spectral file that already has the wave energy bins properly situated for the HOS-ocean domain, the ***ww3shft*** parameter may be set to 0.0.[2]

At present, several diagnostic files are still written as output by *read_irreg_f* in the current version of HOS-ocean maintained at NRL, to allow the user to confirm that the data are correctly processed and shifted before beginning a simulation. These files include `ww3_unsort_dimlss.dat` (original unsorted data, but converted to units of m^2/(rad/s rad) and then normalized), `ww3_sort_dimlss.dat` (sorted and normalized), `ww3_sorted_dim.dat`

[2] Note that, depending on the size that is defined for the HOS-ocean domain, some frequency bins of the input WW3 spectrum may also be excluded. This is dependent on parameters ***n1***, ***n2***, ***xlen***, and ***ylen*** specified by the user as detailed on the website https://github.com/LHEEA/HOS-ocean and in Ducrozet et al. (2016), and it is beyond the scope of the present work.

(sorted, units of m^2/(rad/s rad)), and `ww3_rctr_dimlss.dat` (recentered, units of m^2/(rad/s rad)).[3] Frequencies are normalized by the factor $\left(gk_p\right)^{-0.5}$, where g = 9.81 m/s^2 and k_p is the wavenumber corresponding the peak frequency ($f_p = 1/T_p$), while the spectrum is normalized by the factor $k_p^2 f_p$. Normalization and recentering should not change the shape of the spectrum. Consequently, when one plots these outputs in a utility such as Matlab, the graphs should look similar (other than the shifts in peak values and locations). Example plots of data from each of these files, initialized with a typical WW3 spectral file, are provided in Figure 1. The bottom two panels of the figure demonstrate how a user-specified shift of the spectrum can move peak energy closer to $\theta = 0$ and also allow a larger proportion of total spectral energy to be included in the HOS simulation.

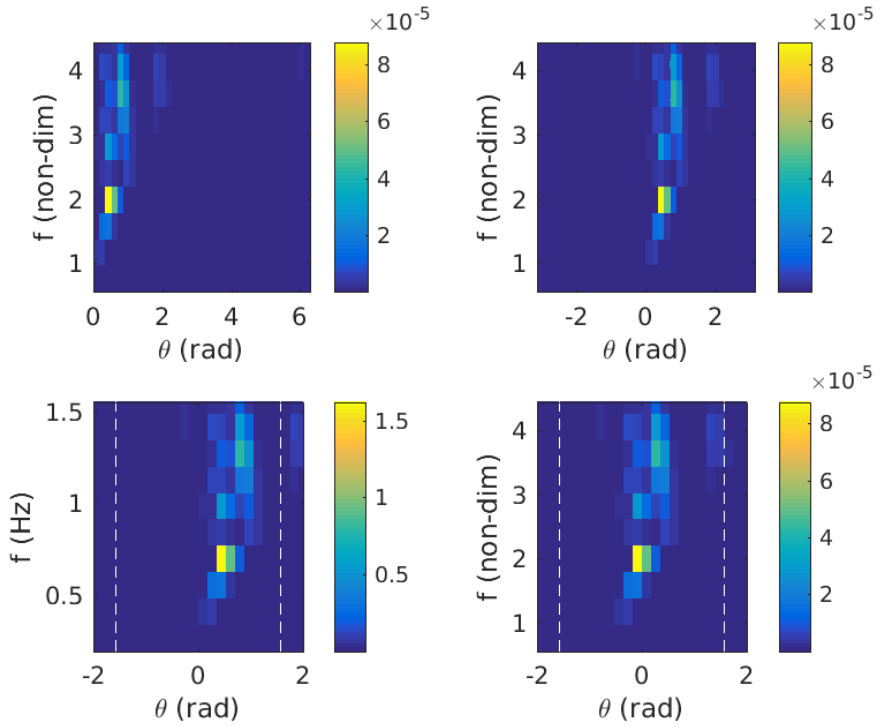

Figure 1. Spectral output of diagnostic test files generated at initiation of HOS-ocean simulation utilizing WW3 input spectrum that was shifted in direction using ***ww3shft*** = -30°. *Top left*: `ww3_unsort_dimlss.dat`; *Top right*: `ww3_sort_dimlss.dat`; *Bottom left*: `ww3_sorted_dim.dat`; *Bottom right*: `ww3_rctr_dimlss.dat`. Dashed lines in bottom two panels indicate directional limits of HOS-ocean domain, i.e., $-\pi/2 < \theta < \pi/2$.

In the revised subroutine *initiate_irreg_f*, there are two tasks:
(a) The spectral data in S_{HOS} (which have been processed by *read_irreg_f*) are interpolated onto the grid-points of the HOS-ocean domain. Here, a bivariate (quadratic) interpolation library is called for the scattered data (Renka, 1988). The algorithm of interpolation is based on the Shepard method which is an inverse distance-weighted least squares method. To call the library,

[3] Each of the diagnostic files is written in three-column format, with the columns containing frequency, direction, and spectral density respectively. Each column must be reshaped to a matrix of dimensions [# of directions] × [# of frequencies].

a user needs to declare the following parameters: *n*, the number of data points; *nq*, the number of points to be used in least squares fitting; *nw*, the number of data points within the radii of influence (hence determining the radii); *nr*, dividing the surface containing the data into *nr*-by-*nr* cells (which optimizes the search of relevant data points). In the current implementation, the declaration is done in *initiate_irreg_f* (with the recommended values). Note that the interpolation must be done in the (ω, θ) plan, since the coordinate-transformation from (ω, θ) to (k_x, k_y) is nonlinear.

(b) The interpolated spectrum $S_{HOS,intr}(\omega, \theta)$ is then used to initialize the mode amplitudes; see equation (1). Note that the dimensionless form of equation (1) is coded. The complex mode amplitudes for the free surface displacement have random phase angles.

Following this, subroutine *initiate_irreg_f* returns control to the main program, and the computation of evolving wave states begins (utilizing existing subroutines *fourier_2_space* and *space_2_fourier*). From this point, the simulation proceeds in the same manner as in the public-domain model.

3 TEST CASES

Several test cases for evaluating the new capabilities with idealized input spectra are described in this section. First, both new model features are applied to the simulation of a single, directionally broad wave spectrum in Section 3.1. Then, in Section 3.2, the system is tasked with simulating waves generated from a directionally bimodal spectrum. For all cases, HOS-ocean is configured to utilize 256 modes in both *x*- and *y*-directions (i.e., ***n1*** = ***n2*** = 256), the wave peak period is fixed at 4.0 sec, and the wave domain is set to fit 45 individual peak waves in the *x*- and *y*-directions (i.e., ***xlen*** = ***ylen*** = 45 in the `input_HOS.dat` file, resulting in a domain that is approximately 1124×1124 m^2). The generated wave state from the input spectrum (at t = 1 sec) is compared to that after a 100 sec simulation in each case, and the separate JONSWAP and WW3 cases are also compared. Possible sources of output differences between the two types of simulations are discussed.

3.1 Directionally Broad Single-Peak Spectrum

In this test set, two versions of an idealized spectrum with a single peak are first created with each of the two new input methods and configured to be nearly identical (Fig. 1), and then a third simulation is also run with a shifted version of the original spectrum. This case is primarily a test of the model's handling of a WW3-formatted input spectrum and how well the resulting simulation duplicates the wave state generated by the model's existing JONSWAP capability (which in this case did not require any code modifications). The boundary spectrum in both initial cases has a peak direction $\theta_p = 0°$ (i.e., peak waves enter normal to the *y*-axis boundary with $k_y = 0$). The spectrum in the third case is shifted so that peak waves enter the domain at a 25° angle, providing a test of the model's consistency if such a shift should be required.

3.1.1 JONSWAP-based spectrum

This case was set up and run as a "control" case for comparison with the newly implemented WW3-formatted spectral input. The boundary spectrum in this case makes use of HOS-ocean's existing capability to produce a wave state based on a directionally spread spectrum. This capability is initialized in the model with parameters from a somewhat modified JONSWAP spectral formulation (Ducrozet et al., 2016):

$$S_J(\omega,\theta) = C_J H_s^s \omega_*^2 \exp\left(-1.25\omega_*^4\right)\gamma^{\exp\left(-0.5(\omega_*-1)^2/\sigma^2\right)} \cdot (1/\beta)\cos^2\left(\pi\theta/2\beta\right) \quad (5)$$

where ω_* is wave frequency ω normalized by peak frequency ω_p, θ is wave direction in radians, γ is an adjustable parameter affecting the amplitude and narrowness of the spectral peak, and β is a directional spreading parameter developed by Dysthe (1979) with a functional range of roughly 0.10 (broad) to 0.30 (narrow). The (dimensionless) mode amplitudes for the free surface displacement coefficients of the wavenumber representation are computed from the spectrum as (Ducrozet et al., 2007)

$$|b_k| = \frac{g^2}{2\omega_k^4} S_J(\omega,\theta)\delta k_x \delta k_y \quad (6)$$

assuming random phases for the complex b_k. For the test, the model input file was configured with the options shown in Table 1.

Table 1. Input parameters for JONSWAP spectrum (single peak)

Parameter	Value
Duration of simulation (T_stop)	100 sec
Boundary wave format (icase)	3
Peak period (Tp_real)	4.0 sec
Peak direction	0° (default)
Sig wave height (Hs_real)	0.30 m
JONSWAP parameter (gamma_J)	3.3
Directionality (Dysthe beta)	0.30

For this case, the spectral representation of the wave state was saved at the beginning and end of the 100 sec simulation. A comparison of the two spectra indicate that HOS-ocean did a good job of maintaining the prescribed wave state (Figure 2, top panels). The total variance of the input and output spectra differs by only 0.16%.

3.1.2 WW3 formatted input spectrum

This case was set up using the newly implemented, rewritten option for WW3 spectral input. A single-peak WW3 spectrum file was constructed, based directly on the initial JONSWAP file used in Section 3.1.1 (see Table 2). The spectrum in this input file was confirmed to have the same shape and nearly the same total variance (0.88% difference) as the spectrum used in the JONSWAP test.

Table 2. Input parameters for WW3-formatted input spectrum (single peak)

Parameter	Value
Duration of simulation (T_stop)	100 sec
Boundary wave format (icase)	31
Peak period (Tp_real)	4.0 sec
Peak direction	0°
Sig wave height (from spectrum)	0.30 m

The spectral representation of the wave state was again saved at the beginning (t = 1 sec) and end (t = 100 sec) of the simulation. A comparison of these two spectra indicates that HOS-ocean

again did a very good job of maintaining the prescribed wave state (Figure 2, middle panels). The variance of the initial and final spectra differs by just 0.03%.

While the difference in total variance between the JONSWAP-formatted and WW3-formatted input spectra is somewhat larger at 0.88%, as noted earlier, the output spectra differ by a comparable, slightly lower 0.67% (Figure 2, bottom panels). As seen in the figure, however, there is a noticeable difference between the distributions of the variance in the corresponding JONSWAP and WW3 spectra, which was not apparent in the comparison of these spectra at the time they were read in. This is evidenced by the *absolute* differences between JONSWAP and WW3 in/out spectra, which are much larger at 14% / 25%, respectively.

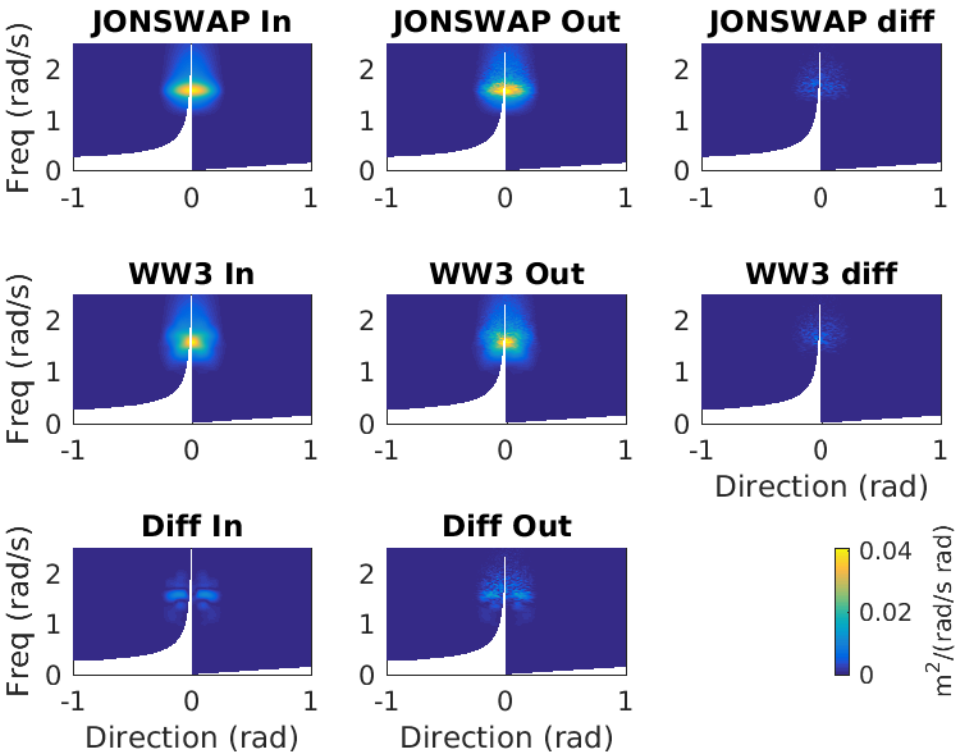

Figure 2. Comparison of initial and final spectral states, HOS-ocean simulation initialized with JONSWAP or WW3-formatted spectrum file. Difference spectra (right panels and bottom panels) show absolute differences on same scale as original spectra (lower right).

3.1.3 WW3 formatted input spectrum with direction shift

This case was set up using the same newly implemented WW3 spectral input format, with the spectral parameters shown in Table 3. A single-peak WW3 spectrum file was constructed in the same fashion as that in Section 3.1.2, except that now a shift of +25° was imposed on the spectrum before initiation of the simulation. In this case, the initial (t = 1 sec) spectrum had a somewhat narrower width and greater total variance (12% greater) in comparison to the spectrum used in the preceding section.

Table 3. Input parameters for *shifted* WW3-formatted input spectrum (single peak)

Parameter	Value
Duration of simulation (***T_stop***)	100 sec
Boundary wave format (***icase***)	31
Peak period (***Tp_real***)	4.0 sec
Original peak direction	0°
Shift in wave direction (***ww3shft***)	+25.0°
Sig wave height (from spectrum)	0.32 m

The spectral representation of the wave state was once again saved at the beginning and end of the simulation. A comparison of the two spectra indicate that, despite the generally skewed diagonal path of waves through the domain, HOS-ocean again did a very good job of

maintaining the prescribed wave state (Figure 3). The variance of the initial (t = 1 sec) and final (t = 100 sec) spectra in this case differs by just 0.13%.

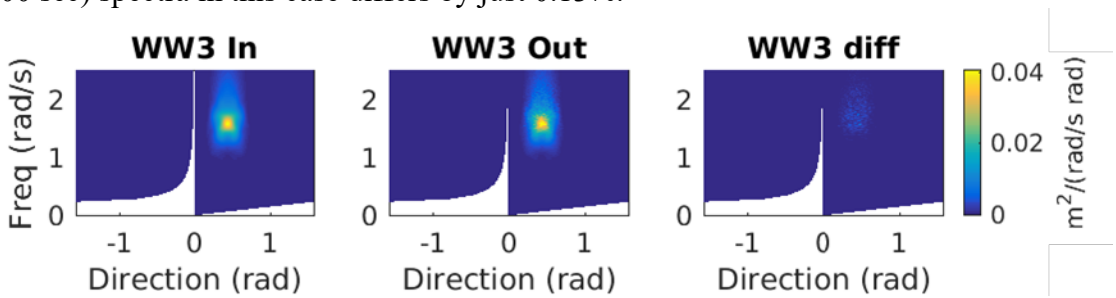

Figure 3. Beginning (*left*) and ending (*middle*) spectral states for 100 sec simulation with HOS-ocean, initialized by single peak spectrum shifted by ***ww3shft*** = +25°. Difference between beginning and end states is shown in right panel.

3.2 Directionally Bimodal (Two-Peak) Spectrum

In this set of tests, we evaluate the newly implemented capability to generate two-peak spectra based on JONSWAP parameters with an idealized test case, and a comparative simulation is run using a directionally bimodal WW3 input spectrum created from the original bimodal JONSWAP input. The same system settings (i.e., ***n1***, ***n2***, ***xlen***, ***ylen***) and simulation period (i.e., ***T_stop*** = 100 sec) are used as in Section 3.1, but in this case the two peaks are each configured to be directionally narrow (cosine power $N = 100$).

3.2.1 JONSWAP-based spectrum

This case was set up using the newly implemented bimodal JONSWAP spectral input format. Specifying the new "icase" value of 33 in the HOS-ocean input file, we also prescribed JONSWAP parameter values for each of two separate spectral peaks (labeled "a" and "b", as shown in Table 4). In this case, the JONSWAP peakedness parameter was set to a very large value (***gamma*** = 10.0) for each peak, and the cosine-power directional spreading was set to a very narrow value (***N*** = 100).

Table 4. Input parameters for directionally bimodal JONSWAP spectrum

Parameter	Value
Duration of simulation (T_stop)	100 sec
Boundary wave format (icase)	33
Peak period (Tpa, Tpb)	10 sec
Peak direction A (thet_pa)	+15°
Peak direction B (thet_pb)	-15°
Sig wave heights (Hsa, Hsb)	0.3 m
Sig wave height (total)	0.42 m
JONSWAP parameter (gamma_a,b)	10.0
Directional spread (Na, Nb)	100

Input and output spectra for the JONSWAP bimodal case are shown along with their absolute difference in the top three panels of Figure 4. A comparison of the two spectra indicate that HOS-ocean again did a reasonably good job of maintaining the prescribed wave state. The variance of the input and output spectra in this case differs by only 0.37%. Comparing the peaks

of this spectrum to the one generated with the parameters of Section 3.1.1, we find that these appear to be steeper (as expected from the larger ***gamma*** value) and to have a roughly similar directional spread. The similarity in spreads is not immediately anticipated, as two different methods ("Dysthe β" vs. "cosine power") vs were used to prescribe them. However, the result is at least somewhat foreseeable, as both the use of a value of ***beta*** = 0.30 in Section 3.1.1 and a cosine power ***N*** = 100 in this case are expected to produce directionally narrow spectral peaks.

3.2.2 WW3 formatted bimodal input spectrum

This case was set up using the newly implemented WW3 spectral input format (Table 5). A two-peak WW3 spectrum file was constructed, based directly on the initial directionally bimodal JONSWAP file used in Section 3.2.1. This input file was again confirmed to have the same shape and nearly the same total variance as the spectrum used in the bimodal JONSWAP test (Figure 4).

Table 5. Input parameters for bimodal WW3-formatted spectrum

Parameter	Value
Duration of simulation (***T_stop***)	100 sec
Boundary wave format (***icase***)	31
Shift in wave direction (***ww3shft***)	0.0°
Peak directions (from spectrum)	-15°, 15°
Sig wave height (from spectrum)	0.43 m

Spectra for the idealized WW3 bimodal case are shown at input (t = 1 sec) and output (t = 100 sec) time steps along with their absolute difference in Figure 4, middle panels. A comparison of the two spectra indicate that HOS-ocean maintained the prescribed wave state as well as in the preceding cases. The total variance of the input and output WW3 spectra in this case differs by just 0.02%. However, the absolute difference in variance was 11%, suggesting that the variation in phases and wave-wave interactions between the two directionally bimodal configurations caused the randomly phased waves to evolve in different ways that significantly shifted spectral energy levels during the simulation, although once again total energy was simultaneously conserved.

As in the single-peak tests, the initial (t = 1 sec) WW3 spectrum modeled on the JONSWAP spectrum in this case is very close to to the initial (t = 1 sec) JONSWAP spectrum. Total variance between WW3 and JONSWAP initial spectra differs by only 0.2%, and the absolute variance difference is just 0.6%. At the conclusion of the simulations (t = 100 sec), total variance of the WW3 and JONSWAP final spectra differs by less than 0.02%, but the absolute variance difference jumps to almost 19%. This may again reflect the differing pathways for nonlinear energy transfer among the randomly phased waves in the two separate simulations. While total energy in the domain is again well conserved in both simulations, interactions among different waves at different times seem to have produced considerable variations in the final spectral distributions (Figure 4, bottom panels).

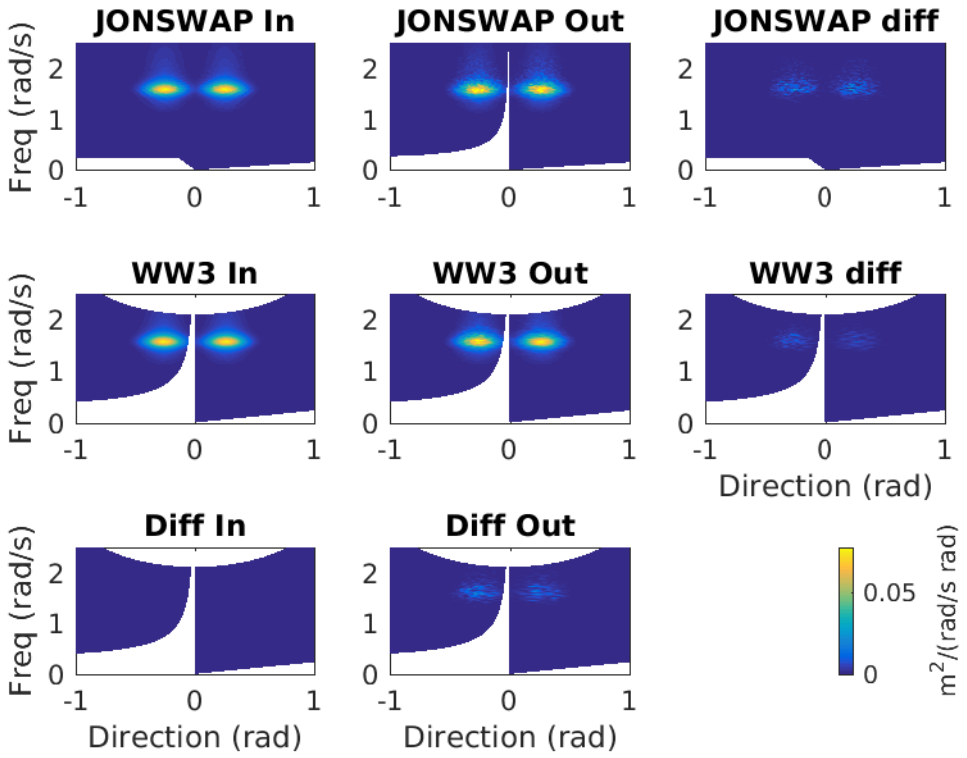

Figure 4. Comparison of initial and final spectral states, directionally bimodal HOS-ocean simulation initialized with JONSWAP or WW3-formatted spectrum file. Difference spectra (*right panels and bottom panels*) show absolute differences on same scale as original spectra (*lower right*).

3.2.3 WW3 formatted bimodal input spectrum with direction shift

This case was again set up using the newly implemented WW3 spectral input format, with parameters summarized in Table 6. A double-peak WW3 spectrum file was constructed in the same fashion as that in Section 3.2.2, except that now a shift of -75° was imposed on the spectrum before initiation of the simulation. Because of the extreme shift, a portion of one of the bimodal peaks was no longer in the angle range required for HOS-ocean (i.e., $\theta_{p,shift}$ = -15° - 75° = -90° or $-\pi/2$). The total variance in the shifted spectrum (Figure 5) is now 5.8% less than that of the original spectrum.

Table 6. Input parameters for *shifted* bimodal WW3-formatted spectrum

Parameter	Value
Duration of simulation (***T_stop***)	100 sec
Boundary wave format (***icase***)	31
Shift in wave direction (***ww3shft***)	-75.0°
Initial peak directions (from spectrum)	-15°, 15°
Sig wave height (from spectrum)	0.41 m

As with previous tests, the spectral representation of the wave state was again saved at the beginning (t = 1 sec) and end (t = 100 sec) of the simulation. A comparison of the two spectra indicate that HOS-ocean once again did a very good job of maintaining the prescribed wave state, based on the shifted spectrum which was partially cut off. The variances of the initial and

final spectra differ by 0.03%. Once again, the absolute difference is significantly larger, at 13%, indicating that energy levels were conserved but redistributed somewhat among wave frequencies and directions.

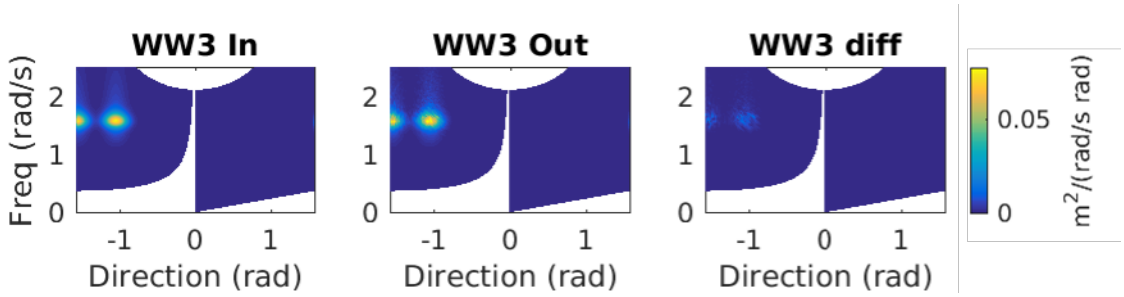

Figure 5. Beginning (t = 1 sec, *left*) and ending (t = 100 sec, *middle*) spectral states for simulation with HOS-ocean, initialized by originally symmetric bimodal spectrum shifted by ***ww3shft*** = -75°. Difference between beginning and end states is shown in right panel.

4 DISCUSSION AND CONCLUSIONS

We have implemented and tested two additional input options in the model HOS-ocean, which enable simulations to be initialized either with bimodal JONSWAP-based wave spectra or with more general frequency directional distributions in a WAVEWATCH III (WW3)-formatted input file. The bimodal JONSWAP-format spectra are generated using an adapted version of HOS-ocean's existing capability for creating directionally spread, single peak JONSWAP boundary spectra, with cosine power spreading utilized in the new capability instead of "Dysthe β". The WW3-formatted spectral input and initialization were implemented by re-writing the subroutines that properly process and interpolate the input data, in accordance with the HOS-ocean requirements. Both capabilities have been validated with simple test cases, producing the results as anticipated.

For initializing single-peak spectra, it was confirmed that simulations with the modified HOS-ocean were substantially identical, whether they were initialized with JONSWAP parameters or with a WW3-formatted spectrum file based on those parameters. Total variance values for the initial and final spectra were nearly the same between the two sets of simulations, although energy was redistributed among the frequency directional bins to some degree during the simulations. When a directional shift was applied to the single-peak WW3 spectrum (from a peak direction of 0° to a new peak of 25°), this resulted in a 12% increase in overall spectral variance, possibly because the model was unable to fully capture (in wavenumber space) the spectral energy of waves traveling near angle $\theta = 0°$ for the specific domain that was used. This could probably be remedied by specifying larger values of domain parameters ***n1***, ***n2***, ***xlen***, and ***ylen***.

For initializing double-peak spectra (i.e., energy peaks at two different directions), it was confirmed that simulations with the modified HOS-ocean were again substantially identical, whether they were initialized with JONSWAP parameters or with a JONSWAP-based, WW3-format spectrum file. Variance values of the initial spectra were again nearly the same between the two sets of simulations, and in this case the variances of final spectra again differed significantly (19%) between the JONSWAP and WW3-initialized cases. This may have been due to differences in the random phases of the two cases and their effects on nonlinear interactions among crossing waves from the bimodal wave state. In a third case, a large directional shift was applied to the double-peak WW3 spectrum (from a mean direction of 0° to a

new mean of -75°), this resulted in a 5.8% decrease in overall spectral variance, primarily because a portion of one bimodal peak was shifted outside of the HOS-ocean directional range (i.e., $-90° < \theta < 90°$) so that some if its waves were excluded from the resulting simulations. Despite the shift, HOS-ocean still maintained the overall variance of the waves throughout the simulation.

Additional tests are presently being conducted with this code to investigate the effects of bimodal wave spectra on the development of extreme (rogue) ocean waves. These extended investigations will be completed in early FY21 and will be detailed in Part II of this memorandum report series.

5 DISSEMINATION OF CODE

HOS-ocean is an open-source, "community" model, available in its public release version from the GitHub platform (https://github.com/LHEEA/HOS-ocean). The new features described herein will ultimately be included in a future public release version of the software, but at present the full set of modifications may be obtained by contacting one of the report authors.

6 REFERENCES

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7 APPENDIX – PRINTOUTS OF NEW CODE AND INPUT FILE

As noted earlier, the new code added to HOS-ocean was primarily contained in subroutines *initiate_cross_sea, read_irreg_f,* and *initiate_irreg_f*, all of which are included in the HOS-ocean file `initial_condition.f90`. Each of these new subroutines is printed out below. An example of a modified input file, `input_HOS.dat`, is also included following the code printouts.

```
SUBROUTINE initiate_cross_sea
!-------------------------------------------
! Written by Jie Yu, NRL, 2018-08-21
! -Initialisation of crossing sea state (case=33) that consists of more than
!  one wave systems such that the wave spectrum has multiple peaks with
!  different directions and frequencies
!
! -In this version, the crossing sea state is a random bimodal wave field
!  (Gramstad et al 2018), given by S(ome,dir)=Sa(ome,dir)+Sb(ome,dir), where
!  Sa abd Sb are two JONSWAP spectra with their own directional distributions
!  (cos(thet-thet_p))**N.
!
! -The parameters specifying the spectra,
!    Tpa, thet_pa, Hsa, gamma_a, Na, and  Tpb, thet_pb, Hsb, gamma_b, Nb
!  are given in input_HOS.dat
!
! -In this version, deep-water waves are assumed.
!-------------------------------------------
!
    implicit none

    integer  :: iseed, i1, i2
    real(rp) :: pioxlen, pioylen
    real(rp) :: angle, angle1, angle2

    real(rp) :: alp_a, alp_b, sigma, coeff_a, coeff_b
    real(rp) :: a, ome_dim, omega_pa, omega_pb
    real(rp) :: E_a, E_b, E_tot, Cg

    real(rp), dimension(m1o2p1,m2,2) :: rnd
    real(rp), dimension(m1o2p1,m2)   :: Sa, Sb, Da, Db, Sc
    real(rp), dimension(m1o2p1,m2)   :: thet_hos
    integer,  dimension(2)           :: indx


    pioxlen = TWOPI/xlen_star     !dkx
    pioylen = TWOPI/ylen_star     !dky

    omega_pa= TWOPI/Tpa
    omega_pb= TWOPI/Tpb

    thet_pa = thet_pa*PI/180.0_rp !change from deg to rad
    thet_pb = thet_pb*PI/180.0_rp

! Directional spreading  functions
    !Cal theta used in HOS. By definition, thet_hos = [-pi, pi]
    thet_hos(1,1) = 0.0_rp
    do i1=1,n1o2p1
      do i2=1,n2
        if (i1 /=1 .or. i2 /= 1) then
          thet_hos(i1,i2) = atan2(ky_n2(i2),kx(i1))
        endif
      enddo
    enddo
```

```
    !coefficients An in D(theta)
    coeff_a = gamma(Na/2.0_rp+1.0_rp)/gamma(Na/2.0_rp+0.5_rp)/sqrt(PI)
    coeff_b = gamma(Nb/2.0_rp+1.0_rp)/gamma(Nb/2.0_rp+0.5_rp)/sqrt(PI)

    !Da(theta), Db(theta)
    do i1=1,n1o2p1
      do i2=1,n2
        if (abs(thet_hos(i1,i2)-thet_pa) .le. PIO2) then
          Da(i1,i2)=coeff_a*(cos(thet_hos(i1,i2)-thet_pa))**Na
        else
          Da(i1,i2)=0.0_rp
        endif
        if (abs(thet_hos(i1,i2)-thet_pb) .le. PIO2) then
          Db(i1,i2)=coeff_b*(cos(thet_hos(i1,i2)-thet_pb))**Nb
        else
          Db(i1,i2)=0.0_rp
        endif
      enddo
    enddo

! Sa(omega) and Sb(omega)
! T = 1/omega_pa is used for normalization

    Sa(1,1)=0.0_rp
    Sb(1,1)=0.0_rp
    do i1=1,n1o2p1
      do i2=1,n2
        if (i1 /=1 .or. i2 /= 1) then
          ome_dim=omega_n2(i1,i2)/T
          if (ome_dim .lt. omega_pa) then
            sigma=0.07_rp
          else
            sigma=0.09_rp
          endif
          a=exp(-(ome_dim-omega_pa)**2/(2.0_rp*sigma**2*omega_pa**2))
          Sa(i1,i2)=omega_n2(i1,i2)**(-5)* &
            exp(-5.0_rp/4.0_rp*(ome_dim/omega_pa)**(-4))*gamma_a**a

          if (ome_dim .lt. omega_pb) then
            sigma=0.07_rp
          else
            sigma=0.09_rp
          endif
          a=exp(-(ome_dim-omega_pb)**2/(2.0_rp*sigma**2*omega_pb**2))
          Sb(i1,i2)=omega_n2(i1,i2)**(-5)* &
            exp(-5.0_rp/4.0_rp*(ome_dim/omega_pb)**(-4))*gamma_b**a

        endif
      enddo
    enddo
    if (iseven(n2)) then
      Sa(:,n2o2p1) = 0.0_rp
      Sb(:,n2o2p1) = 0.0_rp
    endif

    !Determine alp_a and alp_b, s.t. E_a=(Hsa/4)**2, E_b=(Hsb/4)**2
    E_a = 0.0_rp
    E_b = 0.0_rp
    do i1 = 1, n1o2p1
      do i2 = 1, n2
        if (i1 /= 1 .or. i2 /= 1) then
          Cg  = 0.5_rp*omega_n2(i1,i2)/k_abs(i1,i2)    !deep-water Cg
          E_a = E_a + Cg/k_abs(i1,i2)*Sa(i1,i2)*Da(i1,i2)*pioxlen*pioylen
          E_b = E_b + Cg/k_abs(i1,i2)*Sb(i1,i2)*Db(i1,i2)*pioxlen*pioylen
        endif
      enddo
```

```
    enddo
    alp_a = (Hsa/4.0_rp)**2/(grav**2*omega_pa**(-4))/E_a
    alp_b = (Hsb/4.0_rp)**2/(grav**2*omega_pa**(-4))/E_b
    !Recall that omega_pa is used for normalization
    write(*,*) 'In initiate_cross_sea(): alp_a, alp_b = ', alp_a, alp_b

    Sa = Sa*alp_a
    Sb = Sb*alp_b

! Amplitudes of the Fourier modes
    !random numbers used for the phases
    if (random_phases.eq.0) then
      !same random numbers for each run, given (n1,n2)
      call init_not_random_seed()
      call random_number(rnd)
    elseif (random_phases.eq.1) then
      !different random numbers for each run
      call init_random_seed()
      call random_number(rnd)
    else
      print*, 'Random number generation undefined'
      stop
    endif

    Sc    = 0.0_rp
    a_eta = 0.0_cp    !make sure a_eta(1,1)=0, a_phis(1,1)=0
    a_phis= 0.0_cp
    E_tot = 0.0_rp
    do i1 = 1, n1o2p1
      do i2 = 1, n2
        if (i1 /= 1 .or. i2 /= 1) then
          Cg  = 0.5_rp*omega_n2(i1,i2)/k_abs(i1,i2)    !deep-water Cg
          Sc(i1,i2) = Sa(i1,i2)*Da(i1,i2)+Sb(i1,i2)*Db(i1,i2)

          angle1 = rnd(i1,i2,1)*TWOPI
          angle2 = rnd(i1,i2,2)*TWOPI
          angle  = 0.0_rp

          a_eta(i1,i2)=(2.0_rp*Cg/k_abs(i1,i2)*Sc(i1,i2)*pioxlen*pioylen)**(0.5_rp) &
                       *exp(i*(angle1+angle2+angle))

          a_phis(i1,i2)=(-1.0_rp*i/omega_n2(i1,i2))*a_eta(i1,i2)

          E_tot=E_tot + 0.5_rp*abs(a_eta(i1,i2))**2
        endif
      enddo
    enddo
    E_tot = E_tot * g_star ! g_star=1 for deep-water wave
    indx=maxloc(Sc)
    i1=indx(1)
    i2=indx(2)
    write(*,*) 'In initiate_cross_sea,g_star,L_out,T_out=',g_star,L_out,T_out
    write(*,*) 'For Sc=Sa+Sb, Tp =',TWOPI/(omega_n2(i1,i2)/T),' thet_p = ', &
                thet_hos(i1,i2)*180.0_rp/PI
    write(*,*) 'E_tot =',E_tot,'Hs_ini =',4*SQRT(E_tot/g_star) * L_out

    open(99,file='cross_sea_spc.dat',status='unknown')
    do i1=1,n1o2p1
      do i2=1,n2
       write(99,*) omega_n2(i1,i2)/T,thet_hos(i1,i2), &
        Sc(i1,i2)*grav**2*omega_pa**(-5), Sa(i1,i2)*grav**2*omega_pa**(-5), &
        Sb(i1,i2)*grav**2*omega_pa**(-5), Da(i1,i2), Db(i1,i2)
      enddo
    enddo
    close(99)
```

```
end SUBROUTINE initiate_cross_sea

 ------------------------------------------------------------------------------------------------------------

SUBROUTINE read_irreg_f
!
!-----------------------------------------------------------------------
! Rewritten by Jie Yu, NRL. 2018-08-08
!  - Read in the spectrum given by a WAVEWATCH III simulation
!  - Recenter the spectrum along the direction-axis, so that the main peaks
!    are within the HOS angle range [-pi/2, pi/2]
!  - Calculate Tp_real and Hs_real
!  - In this version, deep-water waves are assumed.
!
! Note: If the input spectrum is already properly situated in [-pi/2,pi/2], skip
!       the steps of shifting and relocation.
!-----------------------------------------------------------------------
!
      IMPLICIT NONE

      REAL(RP) :: dthet, O_p_ww, k_p_ww, E_int_tot, variance
      INTEGER  :: i1,i2,ii,jj,ind_o_max
      !real(rp) :: Tp_real, L_out, T_out, HS_real

      !REAL(RP), DIMENSION(ifreq) :: phi_ww_int,E_int,df
      !REAL(RP), DIMENSION(7)     :: phi_temp

      !real(rp), dimension(ifreq,ithet) :: phi2
      !real(rp), dimension(ithet)       :: thet2
      !integer,  dimension(ithet)       :: indx
      !integer,  dimension(2)           :: temp

      !** Move the commented declarations to variables_3d.f90
      !REAL(RP), ALLOCATABLE :: freq_ww(:)
      !REAL(RP), ALLOCATABLE :: thet_ww(:)
      !REAL(RP), ALLOCATABLE :: phi_ww(:,:)
      !REAL(RP), ALLOCATABLE :: phi_ww_int,E_int,df
      REAL(RP), DIMENSION(7) :: phi_temp
      !real(rp), ALLOCATABLE :: phi2(:,:)
      !real(rp), ALLOCATABLE :: thet2(:)
      !integer,  ALLOCATABLE :: indx(:)
      integer,  dimension(2) :: temp
      integer nloc
      character*31 str1,str2

      integer  :: ind
      real(rp) :: shft,tmp1,tmp2

! shft is for relocating the spectral energy. Optimal value may be
! determined by visual inspection of the WW3 data (e.g., using matlab).
! User specifies it as input ww3shft in input_HOS.dat file.

      shft = ww3shft*PI/180.0_rp  ! Shift value specified by user (convert to radians)

! Read WW3 spectrum data file

      open (1002,file=ww3_filename,status='old')
      read(1002,*) str1,ifreq,ithet,nloc,str2

      npt = ifreq*ithet
      nr = floor(dsqrt(npt/3.0_rp))
      allocate(freq_ww(ifreq),thet_ww(ithet),phi_ww(ifreq,ithet))
      allocate(phi_ww_int(ifreq),E_int(ifreq),df(ifreq))
      allocate(phi2(ifreq,ithet))
      allocate(thet2(ithet),indx(ithet))
```

```
      DO ii=1,FLOOR(ifreq/8.0)
        READ(1002,*) freq_ww(8*(ii-1)+1:8*ii)
      ENDDO

      if (8*FLOOR(ifreq/8.0).lt.ifreq) then
        ii=8*floor(ifreq/8.0)+1
        read(1002,*) freq_ww(ii:ifreq)
      endif

      DO ii=1,FLOOR(ithet/7.0)
        READ(1002,*) thet_ww(7*(ii-1)+1:7*ii)
      ENDDO

      if (7*FLOOR(ithet/7.0).lt.ithet) then
        ii=7*floor(ithet/7.0)+1
        read(1002,*) thet_ww(ii:ithet)
      endif

      dthet=abs(thet_ww(2)-thet_ww(1))

      !df as define in plot_ww3_2dspec.m
      df(1)=freq_ww(2)-freq_ww(1);
      df(ifreq)=freq_ww(ifreq)-freq_ww(ifreq-1);
      do ii=2,ifreq-1
        df(ii)=(freq_ww(ii+1)-freq_ww(ii-1))/2.0_rp;
      enddo

      READ(1002,*)
      READ(1002,*)
      DO i1=1,FLOOR(ithet * ifreq / 7.0)
        READ(1002,*) phi_temp(1:7)
        DO i2 = 1,7
          jj=FLOOR(((i1-1)*7+i2-1)/REAL(ifreq,RP))+1
          ii=(i1-1)*7+i2 - (jj-1)*ifreq
          phi_ww(ii,jj)=phi_temp(i2)      !phi_ww(freq,dir)
        ENDDO
      ENDDO

      READ(1002,*) phi_ww(ifreq-(ithet *ifreq-7*FLOOR(ithet*ifreq/7.0))+1:ifreq,ithet)
      CLOSE(1002)
!
! Preliminary calculations

      temp=MAXLOC(phi_ww)
      write(*,*) 'In read_irreg_f, T_p =',1.0/freq_ww(temp(1)), &
                 ' peak dir =',360.0/TWOPI*thet_ww(temp(2))

      E_int     = 0.0_rp
      E_int_tot = 0.0_rp
      variance  = 0.0_rp
      DO jj=1,ithet
        DO ii = 1,ifreq
          E_int(ii) = E_int(ii) + phi_ww(ii,jj) * dthet
          variance  = variance + phi_ww(ii,jj) * dthet * df(ii)
        ENDDO
      ENDDO
      DO ii = 1,ifreq-1
        E_int_tot = E_int_tot + &
           0.5_rp*(E_int(ii)+E_int(ii+1))*(freq_ww(ii+1)-freq_ww(ii))
      ENDDO
      write(*,*) 'In read_irreg_f, 4sqrt(variance)  =',4.0_rp*sqrt(variance)
      write(*,*) 'In read_irreg_f, 4sqrt(E_int_tot) =',4.0_rp*sqrt(E_int_tot)

! Transform frequency to omega, and S(f,dir) to S(omega,dir)
```

```
      freq_ww=freq_ww * TWOPI       !omega=2*pi*freq
      phi_ww=phi_ww / TWOPI         !S(omega)=S(f)/2pi

! ************
! Adim the variables (preliminary)
! ************
      DO ii=1,ifreq
        phi_ww_int(ii)=SUM(phi_ww(ii,:)) * dthet
      ENDDO
! Locate the peak freq
      ind_o_max= MAXLOC(phi_ww_int,1)
      O_p_ww   = freq_ww(ind_o_max)
      k_p_ww   = O_p_ww**2 / grav      !assuming deep-water waves
      Tp_real  = TWOPI / O_p_ww
      L_out    = 1/k_p_ww
      T_out    = 1/O_p_ww
      Hs_real  = 4.0_rp * sqrt(E_int_tot)
      tmp1     = sqrt(grav*k_p_ww)
      tmp2     = k_p_ww **2 * O_p_ww
      write(*,*) 'From WW3 file, Hs_real,Tp_real =', Hs_real, Tp_real
      write(*,*) 'From WW3 file, o_p_ww, sqrt(grav*k_p_ww),k_p_ww^2*o_p_ww =',&
         O_p_ww, tmp1, tmp2

!In the original WW3 file, the wave directions are not ordered ('messed up')
!Sort phi_ww in ascending angle
      open(77,file='ww3_unsort_dimlss.dat',status='unknown')
      open(78,file='ww3_sort_dimlss.dat',status='unknown')
      open(79,file='ww3_sort_dim.dat',status='unknown')
      open(80,file='ww3_rctr_dimlss.dat',status='unknown')

      ind=minloc(thet_ww,1)
      thet2(1)=thet_ww(ind)
      indx(1) = ind
      do ii=2,ithet
        ind=minloc(thet_ww,1,mask=thet_ww.gt.thet2(ii-1))
        thet2(ii)=thet_ww(ind)
        indx(ii) =ind
      enddo
      do ii=1,ifreq
        do jj=1,ithet
          phi2(ii,jj) = phi_ww(ii,indx(jj))
        enddo
      enddo
      do ii=1,ifreq
        do jj=1,ithet
          write(77,*) freq_ww(ii)/tmp1, thet_ww(jj), phi_ww(ii,jj)*tmp2
          write(78,*) freq_ww(ii)/tmp1, thet2(jj),   phi2(ii,jj)*tmp2
          write(79,*) freq_ww(ii),      thet2(jj),   phi2(ii,jj)
        enddo
      enddo
      close(77)
      close(78)
      close(79)

      phi_ww=phi2
      thet_ww=thet2
      temp=maxloc(phi_ww)
      !Sorting should not change the peak freq and dir
      write(*,*) 'After sorting, T_p =',TWOPI/freq_ww(temp(1)), &
                           ' peak dir =',360.0/TWOPI*thet_ww(temp(2))
! Relocate the peaks
      do ii=1,ithet
        thet_ww(ii) = thet_ww(ii)+shft
        if(thet_ww(ii) .ge. TWOPI) thet_ww(ii) = thet_ww(ii)-TWOPI
      enddo
      ind=minloc(thet_ww,1)
```

```
      thet2(1)=thet_ww(ind)
      indx(1) = ind
      do ii=2,ithet
        ind=minloc(thet_ww,1,mask=thet_ww.gt.thet2(ii-1))
        thet2(ii)=thet_ww(ind)
        indx(ii) =ind
      enddo
      do ii=1,ifreq
        do jj=1,ithet
          phi2(ii,jj) = phi_ww(ii,indx(jj))
        enddo
      enddo

      phi_ww=phi2
      thet_ww=thet2
      temp=maxloc(phi_ww)
      !Tp_real should not be changed
      write(*,*) 'After recentering, T_p =',TWOPI/freq_ww(temp(1)), &
                       ' peak dir =',360.0/TWOPI*thet_ww(temp(2))

! Admin variables (after sorting and relocation)
      !Check the peaks and total energy
      do ii=1,ifreq
        phi_ww_int(ii)=SUM(phi_ww(ii,:)) * dthet
      enddo
      !Locate the peak freq
      ind_o_max= MAXLOC(phi_ww_int,1)
      O_p_ww   = freq_ww(ind_o_max)
      k_p_ww   = O_p_ww**2 / grav        !deep water
      Tp_real  = TWOPI / O_p_ww
      L_out    = 1/k_p_ww
      T_out    = 1/O_p_ww
      Hs_real  = 4.0_rp * sqrt(E_int_tot)
      tmp1     = sqrt(grav*k_p_ww)
      tmp2     = k_p_ww **2 * O_p_ww
      write(*,*) 'After relocation, Hs_real,Tp_real =', Hs_real, Tp_real

      do ii=1,ifreq
        do jj=1,ithet
          write(80,*) freq_ww(ii)/tmp1,thet_ww(jj), phi_ww(ii,jj)*tmp2
        enddo
      enddo
      close(80)

 100  continue

      !Normalization. Prepare for initiate_irreg_f
      freq_ww = freq_ww/tmp1
      phi_ww  = phi_ww*tmp2

END SUBROUTINE read_irreg_f

-------------------------------------------------------------------------------------------------------------------


SUBROUTINE initiate_irreg_f
!
!-----------------------------------------
! Rewritten by Jie Yu, NRL, 2018-08-08
! Initialisation of irregular multi-directional sea state (linear)
!   - From spectrum file from WAVEWATCH III
!   - Bivariate interpolation onto model grid points.
! Note:
!   Make sure that the WW3 spectrum peaks are in the range [-pi/2, pi/2],
!   which is currently the HOS setup. The modification is done in read_irreg_f().
!   It can also be pre-processed using matlab.
```

```
!-----------------------------------------
!
IMPLICIT NONE

INTEGER  :: iseed,i1,i2
REAL(RP) :: theta, E, pioxlen, pioylen
REAL(RP) :: angle, angle1, angle2

REAL(RP), DIMENSION(m1o2p1,m2,2) :: rnd
REAL(RP), DIMENSION(m1o2p1,m2)   :: phi_E
INTEGER,  DIMENSION(m1o2p1,m2)   :: ind_o_ww,ind_t_ww

! For interpolation
!   n = number of data points
!   nq= number of points to be used in least square fit.
!       5 <nq< min(40, n-1). nq=13 is highly recommended.
!   nw= number of data points within (hence determining) the radii of influence R(k).
!       1 <nw< min(40,n-1).  nw=19 is recommended for large data set
!   nr: dividing the surface containing the data into nr x nr cells.
!       nr = sqrt(n/3) is recommended.
!
  !* Move to variables_3d:  integer (kind=4), parameter :: npt= ifreq*ithet
  integer (kind=4), parameter :: nq = 13
  !* Move to variables_3d: integer(kind=4),parameter :: nr = floor(dsqrt(npt/3.0_rp))
  integer (kind=4), parameter :: nw = 19

  integer (kind=4), dimension(nr,nr) :: lcell
  integer (kind=4), dimension(npt)   :: lnext
  real (kind=8),    dimension(npt)   :: rsq
  real (kind=8),    dimension(npt)   :: xd,yd,zd
  real (kind=8),    dimension(5,npt) :: coeff

  real (kind=8),    dimension(n1o2p1,n2) :: thet_hos

  integer (kind=4) :: ier
  real (kind=8)    :: px,py,q,dx,dy,xmin,ymin,rmax
  real (kind=8)    :: qx,qy   !needed if qs2grd() is used

  real (kind=8)    :: phi_max,cutoff
  integer (kind=4) :: temp(2)

  pioxlen = TWOPI/xlen_star     !dkx
  pioylen = TWOPI/ylen_star     !dky

  do i1=1,ifreq
    do i2=1,ithet
      xd((i1-1)*ithet + i2) = freq_ww(i1)
      yd((i1-1)*ithet + i2) = thet_ww(i2)
      zd((i1-1)*ithet + i2) = phi_ww(i1,i2)
    enddo
  enddo

! Rescale to make zd_max=1.0, to avoid small numbers in interpolation cal.

  phi_max = maxval(phi_ww)
  zd = zd/phi_max
  cutoff = 0.05_rp

! Call QSHEP2 to define the interpolant Q to this data.
!
  call qshep2(npt,xd,yd,zd,nq,nw,nr,lcell,lnext,xmin,ymin,&
              dx,dy,rmax,rsq,coeff,ier)
  if (ier /= 0) then
    write (*,'(a,i8)') '  Error in qshep2, ier = ', ier
    stop
  end if
```

```
  !Calculate theta used in HOS
  thet_hos(1,1) = 0.0_rp
  i2=1
  do i1=2,n1o2p1
    thet_hos(i1,i2) = atan2(ky_n2(i2),kx(i1))
  enddo
  i1=1
  do i2=2,n2
    thet_hos(i1,i2) = atan2(ky_n2(i2),kx(i1))
  enddo
  do i1=2,n1o2p1
    do i2=2,n2
      thet_hos(i1,i2) = atan2(ky_n2(i2),kx(i1))
    enddo
  enddo

  phi_E = 0.0_rp
  do i1=1,n1o2p1
    do i2=1,n2
      px=omega_n2(i1,i2)
      if(px .ge. freq_ww(1) .and. px .le. freq_ww(ifreq)) then
        py=thet_hos(i1,i2)
        if (py .ge. thet_ww(1) .and. py .le. thet_ww(ithet)) then
          !Do the interpolation.
          q=qs2val(px,py,npt,xd,yd,zd,nr,lcell,lnext, &
                   xmin,ymin,dx,dy,rmax,rsq,coeff)

          !If gradient at (px,py) is also needed use qs2grd
          !!call qs2grd(px,py,npt,xd,yd,zd,nr,lcell,lnext,xmin, &
          !!             ymin,dx,dy,rmax,rsq,coeff,q,qx,qy,ier)

          if (q .lt. 0.0) then
            if (abs(q) .le. cutoff) then
              q = 0.0_rp
            else
              write(*,'(a,3e14.6)') 'At (px,qx), negative q : ', px,py,q
              !stop
            endif
          endif
          phi_E(i1,i2) = q
        else
          phi_E(i1,i2) = 0.0_rp  !Outside the range of directions
        endif
      else
        phi_E(i1,i2) = 0.0_rp    !Outside the range of frequencies
      endif
    enddo
  enddo
  if (iseven(n2)) phi_E(:,n2o2p1) = 0.0_rp

  phi_E = phi_E*phi_max !scale back

  write(*,*) 'max phi_E =', maxval(phi_E)
  write(*,*) 'n1o2p1, n2 = ', n1o2p1, n2
  open(99,file='ww3_intpl.dat',status='unknown')
  do i1=1,n1o2p1
    do i2=1,n2
      px=omega_n2(i1,i2)
      py=thet_hos(i1,i2)
      write(99,*) px,py,phi_E(i1,i2)
    enddo
  enddo
  close(99)

! Compute the random numbers used for phases
```

```
  IF (random_phases.EQ.0) THEN
    ! Same random numbers for each run, given (n1,n2)
    CALL init_not_random_seed()
    CALL RANDOM_NUMBER(rnd)
  ELSEIF (random_phases.EQ.1) THEN
    ! Different random numbers for each run
    CALL init_random_seed()
    CALL RANDOM_NUMBER(rnd)
  ELSE
    PRINT*, 'Random number generation undefined'
    STOP
  ENDIF

! -Initialize the amplitudes of the Fourier modes for surface elevation \eta
!  and surface velocity potential.
!    a_eta = 2*(Cg/k)*S(omega, theta)*dkx*dky
!    a_phis= (-i*g/omega)*a_eta (linearized Beroulli eq at z=0, with p_atm=0)
! -In the following implementation, deep-water waves are assumed.
! -Under the normalization used by HOS-ocean,
!    2*(Cg/k)=1/omega*^3, -i*g/omega = -i/omega*,
!  where omega* = omega/omega_p is the dimensionless frequency.

  a_eta=0.0_cp    !make sure a_eta(1,1)=0, a_phis(1,1)=0
  a_phis=0.0_cp
  E=0.0_rp
  do i1 = 1, n1o2p1
    do i2 = 1, n2
      if (phi_E(i1,i2) .gt. tiny) then
        !phi_E should be non-negative after the interpolation calculations.
        !for small phi_E, a_eta = 0
        if (i1 /= 1 .or. i2 /= 1) then

          angle1 = rnd(i1,i2,1)*TWOPI
          angle2 = rnd(i1,i2,2)*TWOPI
          angle = 0.0_rp

          a_eta(i1,i2)=(phi_E(i1,i2)*pioxlen*pioylen)**(0.5_rp) &
                       *(1.0_rp/omega_n2(i1,i2)**3)**(0.5_rp) &
                       *exp(i*(angle1+angle2+angle))

          a_phis(i1,i2)=(-1.0_rp*i/omega_n2(i1,i2))*a_eta(i1,i2)

          E=E + 0.5_rp*abs(a_eta(i1,i2))**2

        endif
      endif
    enddo
  enddo

  E_tot = E * g_star ! g_star=1 for deep-water wave
  write(*,*) 'In initiate irreg_f, g_star,L_out,T_out=',g_star,L_out,T_out  !jyu
  write(*,*) 'E =',E,'Hs_ini =',4*SQRT(E/g_star) * L_out, 'Tp_ini =',Tp_real

END SUBROUTINE initiate_irreg_f
```

Modified `input_HOS.dat` (new options highlighted in **bold blue** font):

```
Restart previous computation :: i_restart        :: 0
Choice of computed case      :: i_case           :: 33
--- Geometry of the horizontal domain
Length in x-direction        :: xlen             :: 70.0
Length in y-direction        :: ylen             :: 18.0
```

```
--- Time stuff (dimensionless)
Duration of the simulation   :: T_stop           :: 7200.0
Sampling frequency (output)  :: f_out            :: 2.0
Tolerance of RK scheme       :: toler            :: 1.0e-7
Dommermuth initialisation    :: n                :: 4
Dommermuth initialisation    :: Ta               :: 10.0
--- Physical dimensional parameters
Gravity                      :: grav             :: 9.81
Water depth                  :: depth            :: -50.
--- Irregular waves (i_case=3)
Peak period in s             :: Tp_real          :: 10.0
Significant wave height in m :: Hs_real          :: 1.4142
JONSWAP Spectrum             :: gamma_J          :: 1.0
Directionality (Dysthe)      :: beta             :: 0.302
Random phases generation     :: random_phases    :: 1
--- WW3 input spectrum (i_case=31)
Shift of WW3 spectrum deg    :: ww3shft          :: 30.0
--- Crossing sea (i_case=33)
Peak period in s             :: Tpa              :: 4.0
Peak direction deg           :: thet_pa          :: 15.0
Significant wave height in m :: Hsa              :: 0.3
JONSWAP Spectrum             :: gamma_a          :: 10.0
Direction spreading          :: Na               :: 100
Peak period in s             :: Tpb              :: 4.0
Peak direction deg           :: thet_pb          :: -15.0
Significant wave height in m :: Hsb              :: 0.3
JONSWAP Spectrum             :: gamma_b          :: 10.0
Direction spreading          :: Nb               :: 100
--- Output files
Tecplot version              :: tecplot          :: 11
Output: 1-dim. ; 0-nondim.   :: i_out_dim        :: 1
3d free surface quantities   :: i_3d             :: 1
3d modes                     :: i_a_3d           :: 0
2d free surface, center line :: i_2d             :: 0
Wave probes in domain        :: i_prob           :: 0
Swense output 1='yes',0='no' :: i_sw             :: 0
```
