

MIKE 21 Spectral Waves FM

Spectral Wave Module

User Guide





PLEASE NOTE

COPYRIGHT

This document refers to proprietary computer software which is protected by copyright. All rights are reserved. Copying or other reproduction of this manual or the related programs is prohibited without prior written consent of DHI. For details please refer to your 'DHI Software Licence Agreement'.

LIMITED LIABILITY

The liability of DHI is limited as specified in Section III of your 'DHI Software Licence Agreement':

'IN NO EVENT SHALL DHI OR ITS REPRESENTATIVES (AGENTS AND SUPPLIERS) BE LIABLE FOR ANY DAMAGES WHATSOEVER INCLUDING, WITHOUT LIMITATION, SPECIAL, INDIRECT, INCIDENTAL OR CONSEQUENTIAL DAMAGES OR DAMAGES FOR LOSS OF BUSINESS PROFITS OR SAVINGS, BUSINESS INTERRUPTION, LOSS OF BUSINESS INFORMATION OR OTHER PECUNIARY LOSS ARISING OUT OF THE USE OF OR THE INABILITY TO USE THIS DHI SOFTWARE PRODUCT, EVEN IF DHI HAS BEEN ADVISED OF THE POSSIBILITY OF SUCH DAMAGES. THIS LIMITATION SHALL APPLY TO CLAIMS OF PERSONAL INJURY TO THE EXTENT PERMITTED BY LAW. SOME COUNTRIES OR STATES DO NOT ALLOW THE EXCLUSION OR LIMITATION OF LIABILITY FOR CONSEQUENTIAL, SPECIAL, INDIRECT, INCIDENTAL DAMAGES AND, ACCORDINGLY, SOME PORTIONS OF THESE LIMITATIONS MAY NOT APPLY TO YOU. BY YOUR OPENING OF THIS SEALED PACKAGE OR INSTALLING OR USING THE SOFTWARE, YOU HAVE ACCEPTED THAT THE ABOVE LIMITATIONS OR THE MAXIMUM LEGALLY APPLICABLE SUBSET OF THESE LIMITATIONS APPLY TO YOUR PURCHASE OF THIS SOFTWARE.'





CONTENTS

1	ABOUT THIS GUIDE	9
1.1	Purpose	9
1.2	Assumed User Background	9
1.3	General Editor Layout	10
1.3.1	Navigation tree	10
1.3.2	Editor window	10
1.3.3	Validation window	10
1.4	Online Help	11
2	INTRODUCTION	13
2.1	Short Description	13
2.2	Application Areas	14
2.3	Computational Features	16
3	GETTING STARTED	19
3.1	General	19
3.2	Defining and Limiting the Wave Problem	19
3.2.1	Identify the wave problem	19
3.2.2	Check MIKE 21 SW capabilities	20
3.2.3	Selecting model formulation	20
3.2.4	Define computational domain	20
3.2.5	Check computer resources	21
3.3	Collecting Data	21
3.4	Setting up the Model	21
3.4.1	What does it mean	21
3.4.2	Mesh and bathymetry	22
3.4.3	Boundary conditions	22
3.4.4	Bottom friction coefficients	22
3.4.5	Wind field	22
3.5	Calibrating and Verifying the Model	23
3.5.1	Purpose	23
3.5.2	Calibration and verification situations	23
3.5.3	Calibration factors	23
3.6	Running the Production Simulations	24
3.7	Presenting the Results	25
4	EXAMPLES	27
4.1	General	27
4.2	Fetch-limited Wave Growth in a Lake	27



4.2.1	Purpose of example	27
4.2.2	Defining and limiting the wave problem	27
4.2.3	Presenting the results	29
4.2.4	List of data and specification files	32
4.3	North Sea and West-coast Wave Conditions	33
4.3.1	Purpose of the test	33
4.3.2	Defining and limiting the wave problem	33
4.3.3	Presenting the results	36
4.3.4	List of data and specification files	39
4.4	Wave Transformation on a Barred Beach	39
4.4.1	Purpose of example	39
4.4.2	Defining and limiting the wave problem	40
4.4.3	Presenting the results	43
4.4.4	List of data and specification files	44
4.5	Wave Transformation Around an Island	45
4.5.1	Purpose of example	45
4.5.2	Defining and limiting the wave problem	45
4.5.3	Presenting the results	47
4.5.4	List of data and specification files	50
5	BASIC PARAMETERS	53
5.1	Domain	53
5.1.1	Mesh and bathymetry	53
5.1.2	Domain Specification	53
5.1.3	Boundary Names	54
5.2	Time	55
6	SPECTRAL WAVE MODULE	57
6.1	Basic equations	57
6.1.1	Spectral formulation	57
6.1.2	Time formulation	57
6.1.3	Remarks and hints	58
6.2	Time Parameters	58
6.3	Spectral discretization	58
6.3.1	Frequency discretisation (fully spectral formulation only)	59
6.3.2	Directional discretisation	59
6.3.3	Separation of Wind-sea and Swell	59
6.3.4	Remarks and hints	60
6.4	Solution technique	60
6.4.1	Instationary formulation	60
6.4.2	Quasi-stationary formulation	62
6.4.3	Output of convergence information	64
6.4.4	CFL Number	65
6.5	Water level conditions	65
6.5.1	Remarks and hints	66
6.6	Current conditions	66
6.6.1	Remarks and hints	68
6.7	Wind forcing	68



6.7.1	General description	70
6.7.2	Remarks and hints	71
6.8	Ice coverage	71
6.9	Diffraction	72
6.9.1	Remarks and hints	72
6.10	Energy transfer	73
6.10.1	Remarks and hints	73
6.11	Wave breaking	74
6.11.1	General description	75
6.11.2	Remarks and hints	76
6.12	Bottom friction	76
6.12.1	General description	78
6.12.2	Remarks and hints	78
6.13	White capping	79
6.13.1	General description	80
6.13.2	Remarks and hints	81
6.14	Structures	82
6.14.1	Point structures	82
6.14.2	Line structures	84
6.15	Initial conditions	87
6.15.1	Remarks and hints	88
6.16	Boundary conditions	88
6.16.1	Boundary specification	88
6.16.2	Remarks and hints	95
6.17	Outputs	96
6.17.1	Geographic View	96
6.17.2	Output specification	96
6.17.3	Integral wave parameters	101
6.17.4	Input parameters	103
6.17.5	Model parameters	104
6.17.6	Spectral parameters	105
7	SCIENTIFIC DOCUMENTATION	107
8	LIST OF REFERENCES	109





1 ABOUT THIS GUIDE

1.1 Purpose

The main purpose of this User Guide is to enable you to use, MIKE 21 Spectral Wave Model FM (MIKE 21 SW), for applications involving the assessment of wave climates in offshore and coastal areas. The User Guide is complemented by the On-line Help.

The following section, Section 2, INTRODUCTION, gives you a short description of the module MIKE 21 SW and the type of applications it can be used for.

Section 3, GETTING STARTED, contains a step-by-step procedure which can be followed when working on an application or when writing a proposal. It is the intention that by following this procedure, and by using the SPECTRAL WAVE MODULE (Section 6), you should be able to get good and reliable results from MIKE 21 SW although a formal procedure is no substitute for common sense.

Section 4, EXAMPLES, includes a number of simple and more complicated MIKE 21 SW applications. These are chosen to cover typical application areas of MIKE 21 SW. The emphasis in these examples is on how the parameters are selected and how the results are presented.

Section 5, BASIC PARAMETERS, describes the necessary spatial and temporal information of your model setup. Section 6, SPECTRAL WAVE MODULE, describes the parameters in the MIKE 21 SW dialogs. It provides more details on specific aspects of the operation of MIKE 21 SW and is what you will normally refer to for assistance if you are an experienced user. The contents of section 5 and 6 is the same as found in the On-line Help.

In Section 7, SCIENTIFIC DOCUMENTATION, you can find information on the scientific background for MIKE 21 SW.

In Section 8, LIST OF REFERENCES, you can find a reference list.

An INDEX is found at the end of this MIKE 21 SW User Guide.

1.2 Assumed User Background

Although MIKE 21 SW has been designed carefully with emphasis on a logical and user-friendly interface, and although the User Guide contains modeling procedures and a large amount of reference material, common sense is always needed in any practical application.

In this case, “common sense” means a background in wave mechanics which is sufficient for you to be able to check whether the results from MIKE 21 SW



are reasonable or not. This User Guide is not intended as a substitute for - and it cannot replace - a basic knowledge of the area in which you are working: mathematical modelling of wave problems.

It is assumed that you are familiar with the basic elements of MIKE 21: file types and file editors, the Plot Composer, the MIKE Zero Toolbox, the Data Viewer and the Mesh Generator. The documentation for these can be found by the MIKE Zero Documentation Index.

1.3 General Editor Layout

The MIKE Zero setup editor consists of three separate panes.

1.3.1 Navigation tree

To the left is a navigation tree, that shows the structure of the model setup file, and is used to navigate through the separate sections of the file. By selecting an item in this tree, the corresponding editor is shown in the central pane of the setup editor.

1.3.2 Editor window

The editor for the selected section is shown in the central pane. The content of this editor is specific for the selected section, and might contain several property pages.

For sections containing spatial data - e.g. sources, boundaries and output - a geographic view showing the location of the relevant items will be available. The current navigation mode is selected in the bottom of this view, it can be zoom in, zoom out or recenter. A context menu is available from which the user can select to show the bathymetry or the mesh, to show the optional GIS background layer and to show the legend. From this context menu it is also possible to navigate to the previous and next zoom extent and to zoom to full extent.

If the context menu is opened on an item - e.g. a source - it is also possible to jump to this item's editor.

Further options may be available in the context menu depending on the section being edited.

1.3.3 Validation window

The bottom pane of the editor shows possible validation errors, and is dynamically updated to reflect the current status of the setup specifications.

By double-clicking on an error in this window, the editor in which this error occurs will be selected.



1.4 Online Help

The On-line Help can be activated in several ways, depending on the user's requirement:

- **F1-key seeking help on a specific activated dialog:**
To access the help associated with a specific dialog page, press the F1-key on the keyboard after opening the editor and activating the specific property page.
- **Open the On-line Help system for browsing manually after a specific help page:**
Open the On-line Help system by selecting “Help Topics” in the main menu bar.





2 INTRODUCTION

2.1 Short Description

MIKE 21 SW includes a new generation spectral wind-wave model based on unstructured meshes. The model simulates the growth, decay and transformation of wind-generated waves and swell in offshore and coastal areas.



Figure 2.1 MIKE 21 SW is a state-of-the-art numerical tool for prediction and analysis of wave climates in offshore and coastal areas

MIKE 21 SW includes two different formulations:

- Directional decoupled parametric formulation
- Fully spectral formulation

The directional decoupled parametric formulation is based on a parameterization of the wave action conservation equation. The parameterization is made in the frequency domain by introducing the zeroth and first moment of the wave action spectrum as dependent variables following Holthuijsen (1989). A similar approximation is used in MIKE 21 NSW Nearshore Spectral Wind-Wave Module.

The fully spectral formulation is based on the wave action conservation equation, as described in e.g. Komen et al. (1994) and Young (1999), where the directional-frequency wave action spectrum is the dependent variable.

The basic conservation equations are formulated in either Cartesian co-ordinates for small-scale applications and polar spherical co-ordinates for large-scale applications.



MIKE 21 SW includes the following physical phenomena:

- Wave growth by action of wind
- Non-linear wave-wave interaction
- Dissipation due to white-capping
- Dissipation due to bottom friction
- Dissipation due to depth-induced wave breaking
- Refraction and shoaling due to depth variations
- Wave-current interaction
- Effect of time-varying water depth and flooding and drying

The discretization of the governing equation in geographical and spectral space is performed using cell-centered finite volume method. In the geographical domain, an unstructured mesh technique is used. The time integration is performed using a fractional step approach where a multi-sequence explicit method is applied for the propagation of wave action.

2.2 Application Areas

MIKE 21 SW is used for the assessment of wave climates in offshore and coastal areas - in hindcast and forecast mode.

A major application area is the design of offshore, coastal and port structures where accurate assessment of wave loads is of utmost importance to the safe and economic design of these structures. Measured data is often not available during periods long enough to allow for the establishment of sufficiently accurate estimates of extreme sea states. In this case, the measured data can then be supplemented with hindcast data through the simulation of wave conditions during historical storms using MIKE 21 SW.

MIKE 21 SW is particularly applicable for simultaneous wave prediction and analysis on regional scale (like the North Sea, see Figure 2.2) and local scale (west coast of Jutland, Denmark, see Figure 2.4). Coarse spatial and temporal resolution is used for the regional part of the mesh and a high-resolution boundary- and depth-adaptive mesh is describing the shallow water environment at the coastline.

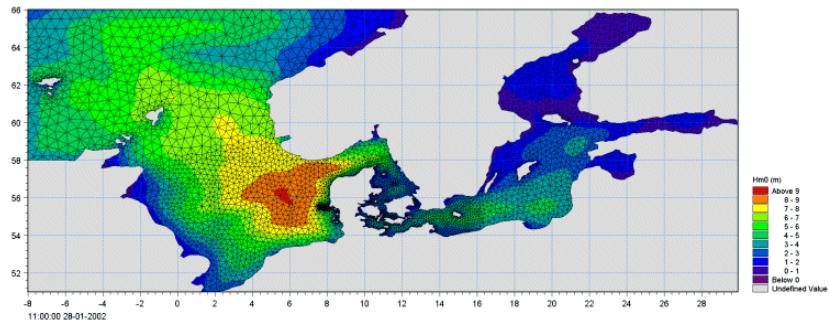


Figure 2.2 A MIKE 21 SW forecast application in the North Sea and Baltic Sea. The chart shows a wave field illustrated by the significant wave height in top of the computational mesh. See <http://www.waterforecast.com>

MIKE 21 SW is also used in connection with the calculation of the sediment transport, which for a large part is determined by wave conditions and associated wave-induced currents. The wave-induced current is generated by the gradients in radiation stresses that occur in the surf zone. MIKE 21 SW can be used to calculate the wave conditions and associated radiation stresses. Subsequently the wave-induced flow is calculated using MIKE 21 Flow Model FM.

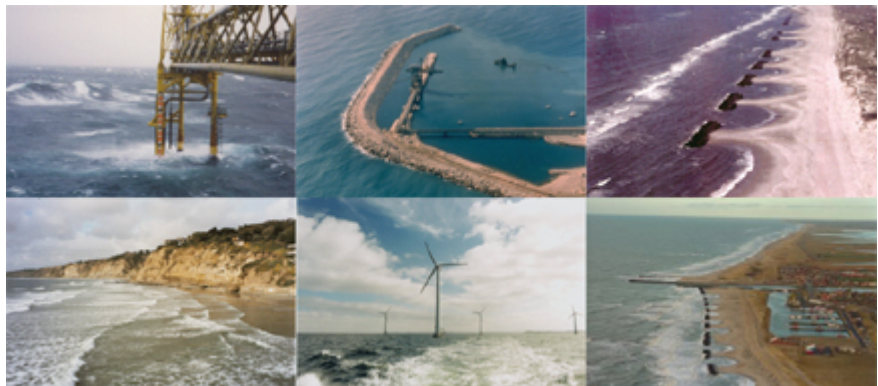


Figure 2.3 Illustration of typical application areas

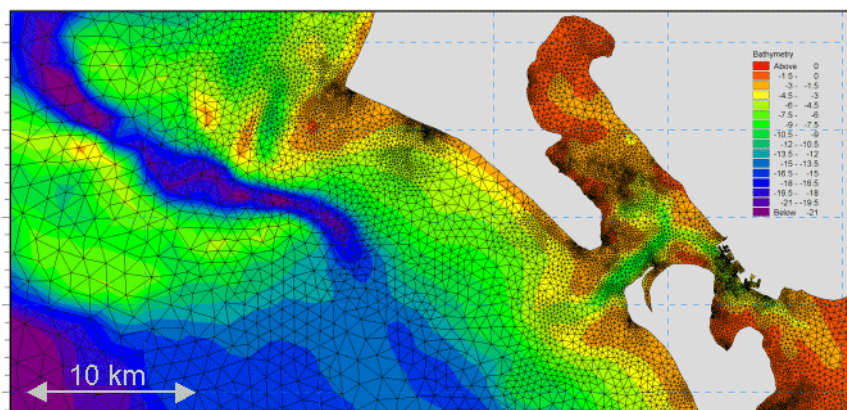


Figure 2.4 Example of a computational mesh used for transformation of offshore wave statistics using the directionally decoupled parametric formulation

MIKE 21 SW is also applied on global scale as illustrated in Figure 2.5.

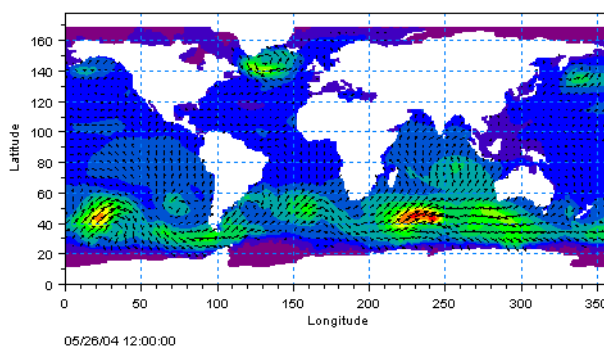


Figure 2.5 Example of a global application of MIKE 21 SW. Results from such a model can be used as boundary conditions for regional scale forecast or hindcast models. See <http://www.waterforecast.com>

2.3 Computational Features

The main features of MIKE 21 SW are as follows:

- Fully spectral and directionally decoupled parametric formulations
- Source functions based on state-of-the-art 3rd generation formulations
- Instationary and quasi-stationary solutions
- Optimal degree of flexibility in describing bathymetry and ambient flow conditions using depth-adaptive and boundary-fitted unstructured mesh
- Effects of ice coverage



- Coupling with hydrodynamic flow model for modelling of wave-current interaction and time-varying water depth
- Flooding and drying in connection with varying water levels
- Cell-centered finite volume technique
- Time integration using a fractional step approach and an efficient multi-sequence method
- Extensive range of model output parameters (wave, swell, air-sea interaction parameters, radiation stress tensor, spectra, etc.)





3 GETTING STARTED

3.1 General

The purpose of this chapter is to give you a general check list which you can use when modelling situations involving the growth, decay and transformation of wind-generated waves and swell in offshore and coastal areas using the new generation spectral wind-wave models included in MIKE 21 SW.

The work will normally consist of the six tasks listed below:

- defining and limiting the wave problem
- collecting data
- setting up the model
- calibrating and verifying the model
- running the production simulations
- presenting the results

Each of these six tasks are described for a “general wave study” in the following sections. For your particular study only some of the tasks might be relevant.



Please note that whenever a word is written in *italics* it is included as an entry in the *On-line Help* and in the *Reference Guide*.

3.2 Defining and Limiting the Wave Problem

3.2.1 Identify the wave problem

When preparing to do a study you have to assess the following before you start to set up the model:

- what are the “important wave phenomena”? The following phenomena should be taken into consideration:
 - Shoaling
 - Refraction
 - Diffraction
 - Reflection
 - Bottom dissipation
 - Wave breaking
 - Wind-wave generation
 - Frequency spreading
 - Directional spreading
 - Wave-wave interaction
 - Wave-current interaction



The MIKE 21 SW module can handle these phenomena with the exception of diffraction and reflection.

- what is the “area of influence” of the wave phenomena?

3.2.2 Check MIKE 21 SW capabilities

Next, check if the MIKE 21 SW module is able to solve your problem. This you can do by turning to Section 2, which gives a short description of MIKE 21 SW and an overview of the type of applications for which MIKE 21 SW can be used, and by consulting the Scientific Documentation.

3.2.3 Selecting model formulation

For the assessment of wave conditions in nearshore and coastal areas which most often involves transformation of known offshore wave statistics (derived from e.g. measurement, regional/global models, remote sensing data, etc.) you will typically use the directionally decoupled parametric formulation. It is important you notice that the wind-wave generation process is presently not included in this formulation. If this process is important you have to use the fully spectral formulation, which is more computational demanding, but of course also more accurate.

The fully spectral model is often used for simultaneous wave prediction and analysis on large and local scale. Coarse spatial and temporal resolution is used for the regional (or large) scale part of the computational domain and a high-resolution boundary- and depth-adaptive mesh is describing the shallow water environment at the coastline. An example is presented in Section 4 EXAMPLES (p. 27).

3.2.4 Define computational domain

Draw up your model domain on a sea chart showing the area of interest and the area of influence. This is normally an iterative process as on one hand you should keep the model domain as small as possible, while on the other hand you have to include the total area of influence. You also have to consider the *Boundary Conditions* (6.16 Boundary conditions (p. 88)).

The choice of the discrete resolution in the geographic and spectral space depends on the wave conditions for which simulations are to be performed and on the bathymetry and forcing fields (wind, current, water level):

- discrete resolution in the geographical space must be selected to provide adequate resolution of the bathymetry and the forcing fields.
- discrete resolution in the geographical space and the discrete representation of the frequency and directions must be selected to provide adequate resolution at the wave field under consideration.



In order to provide an accurate description of the transport of wave action the CFL number based on the group velocity should be less than 1 in all computational nodes. Please notice that the *CFL number* can be saved as a model output parameter.

3.2.5 Check computer resources

Finally, before you start to set up the model, you should check that you are not requesting unrealistic computer resources:

- the CPU time required should be estimated.
- the Disk Space required should be estimated.

It is recommended to run the MIKE 21 SW examples included in the installation for assessment of the computational speed on your PC and to assess the disk space consumption.

3.3 Collecting Data

This task may take a long time if, for example, you have to initiate a monitoring program. Alternatively it may be carried out very quickly if you are able to use existing data which are immediately available. In all cases the following data should be collected:

- bathymetric data such as sea charts from local surveys or, for example, from the Hydrographic Office, UK, or MIKE C-MAP.
- wind data; there might be synoptic weather charts, collected cyclone data, measurement of the wind conditions in selected locations, etc.
- current and water level data; if wave-current interaction and/or varying water level is important for your MIKE 21 SW application you often have to setup and run a MIKE 21 Flow Model FM simulation prior to the execution of the wave simulation.
- information on sea bed characteristics for assessment of the influence of bottom dissipation.
- calibration and validation data; these might be measured wave parameters at selected locations, e.g. significant wave height, peak wave period and mean wave direction.

3.4 Setting up the Model

3.4.1 What does it mean

“Setting up the model” is actually another way of saying transforming real world events and data into a format which can be understood by the numeri-



cal model. Thus generally speaking, all the data collected have to be resolved on the domain selected.

3.4.2 Mesh and bathymetry

Providing MIKE 21 SW with a suitable mesh and bathymetry is essential for obtaining reliable results from your model. Setting up the mesh includes the appropriate selection of the area to be modelled, adequate resolution of the bathymetry, wave, wind and flow fields under consideration and definition of codes for essential and land boundaries. Furthermore, the resolution in the geographical space must also be selected with respect to stability considerations.

Describing the water depth in your defined model domain is one of the most important tasks in the modelling process. A few hours less spent in generating the mesh covering the bathymetry may later on mean extra days spent in the calibration process.

The mesh file including your bathymetry is always generated by MIKE Zero Mesh Generator, which is a tool for the generation and handling of unstructured meshes, including the definition and editing of boundaries. The MIKE Zero Bathymetry Editor can not be used for creating of flexible meshes.

3.4.3 Boundary conditions

An offshore boundary where no wave information is available is most often treated as an absorbing (land) boundary. No waves can enter the model domain from this type of boundary and waves propagating out of the domain are fully absorbed.

If offshore wave data is available (e.g. wave measurements or data derived from a MIKE 21 SW simulation) an essential boundary can be chosen. The boundary conditions can be described through either a parameterized formulation (H_{m0} , T_p , etc.) or a wave spectrum. The wave boundary conditions can be variable in time and space.

3.4.4 Bottom friction coefficients

The bottom friction can be specified as a dissipation coefficient, as a Nikuradse roughness parameter or as the sand grain size (see section 6.12 Bottom friction (*p. 76*)).

3.4.5 Wind field

Successful wave hindcast and forecast depend on accurate wind fields deduced from meteorological models and analysis. As the wind field is the



main driving force, the largest gain in MIKE 21 SW is to specify accurate and representative wind fields.

The wind field can be specified as constant in space/time or variable in space/time.



Please notice that the wind-wave generation in this release is only possible using the fully spectral formulation.

3.5 Calibrating and Verifying the Model

3.5.1 Purpose

Having completed all tasks listed above you are ready to do the first wave simulation and to start on the calibration and verification of the model.

The purpose of the calibration is to tune the model in order to reproduce known/measured conditions for a particular situation.

The calibrated/tuned model is then verified by running one or more simulations for which measurements are available without changing any tuning parameters. This should ensure that simulations can be made for any situation similar to the calibration and verification situations with satisfactory results. However, you should never use simulation results, whether verified or not, without checking if they are reasonable or not.

3.5.2 Calibration and verification situations

The situations which you select for calibration and verification of the model should cover the range of situations you wish to investigate in the production runs. However, as you must have some measurements/observations against which to calibrate and, as the measurements are often only available for short periods, you may only have a few situations from which to choose.

3.5.3 Calibration factors

When you run your calibration run the first time and compare the simulation results to your measurements you will in many cases see differences between the two. The purpose of the calibration is then to tune the model so that these differences become negligible. The most important factor in the calibration is the accuracy of the data. Hence, in order to reduce the differences, you may have to change the basic model specifications listed in Section 3.4.

The calibration parameters available in MIKE 21 SW are:

- Resolution in geographical and spectral space



- Bottom friction
 - An increase of the bottom friction coefficient in shallow water depths usually leads to increased energy dissipation and thus decreased wave heights and increased wave periods. The converse is also the case. In deep water the effect of bottom friction will be negligible, since the waves will not feel the bottom.
- Breaking parameters
 - The breaking wave parameters can also be used as calibration factors in some cases. However, you should be careful in tuning these parameters. The parameter α controls the rate of energy dissipation after breaking while γ (depth-induced) controls the amount of depth related breaking. An increase in α increases the rate of energy dissipation. Increasing γ reduces the amount of depth-related wave breaking.
 - In the directionally decoupled parametric formulation you can also use the steepness-induced wave breaking parameter to calibrate your model. By increasing this value the dissipation can be reduced resulting in increased wave height and wave period.
- White capping (fully spectral formulation only)
 - In most applications you will apply the default values of the two free parameters controlling the rate of white-cap (or steepness induced) dissipation; C_{ds} and δ . The default values ($C_{ds} = 4.5$ and $\delta = 0.5$) are identical to the recommendations made in Komen et al. (1994).

If you for instance find difficulties in calibrating an offshore model (in deep water), where the simulated wave heights/wave periods are generally to small compared to measurements you may reduce the coefficient C_{ds} to improve your model performance. This has been the case for the North Sea application discussed in section 4.3 North Sea and West-coast Wave Conditions (p. 33).
- Wind data
 - The accuracy of the MIKE 21 SW is closely related to the accuracy of the wind field specification. Typically an error of 10% in the wind speed will lead to an error of 20% in the corresponding wave height.
- Current and water level data
 - For particularly shallow water applications accurate information on current and water level variations can be important for the simulated results.
- Boundary data

3.6 Running the Production Simulations

As you have calibrated and verified the model you can get on to the “real” work, that is doing your actual investigation. This will, in some cases, only include a few runs, while in others several storm events will have to be hind-casted.



3.7 Presenting the Results

Throughout a modelling study you are working with large amounts of data and the best way of checking them is therefore to look at them graphically. Only in a few cases, such as when you check your mesh/bathymetry along a boundary or you want to compare simulation results to measurements in selected locations, should you look at the individual numbers. Much emphasis has therefore been placed on the capabilities for graphical presentation in MIKE 21 and it is an area which will be expanded and focused on even further in future versions.

Essentially, one plot gives more information than scores of tables and if you can present it in colours, your message will be even more easily understood.

A good way of presenting the model results is using contour plots of the calculated wave parameters, e.g. the significant wave heights and the mean wave periods, and in form of vector plots showing the mean wave directions.

Plotting in MIKE Zero is done by using the Grid Editor, the Plot Composer tool and the Data Viewer.

Table 6.2 List of tools for viewing, editing and plotting results. (p. 97) provides you with an overview of the various plotting/viewing tools available in MIKE Zero.





4 EXAMPLES

4.1 General

One of the best ways of learning how to use a modelling system like MIKE 21 is through practice. Therefore we have included a number of applications, which you can go through yourself and which you can modify, if you like, in order to see what happens if this or that parameter is changed.

The specification data files for the examples are included with the installation of MIKE 21. For each example a folder is provided. The folder names are as follows:

- Fetch-limited wave growth in a lake
.\Examples\MIKE_21\SW\Lake
- North Sea and West-coast wave conditions
.\Examples\MIKE_21\SW\NorthSea
- Wave transformation on a barred beach
.\Examples\MIKE_21\SW\Fjaltring
- Wave transformation around an island
.\Examples\MIKE_21\SW\Island

4.2 Fetch-limited Wave Growth in a Lake

4.2.1 Purpose of example

The purpose of this simple application is to study fetch-limited wind-wave growth in a 40 km long and 40 km wide lake having a constant water depth of 15 m. The fully spectral formulation is used. The results can readily be compared to well-known fetch-limited growth relationships in the literature.

4.2.2 Defining and limiting the wave problem

Mesh and bathymetry

The model domain is 40 km x 40 km with a constant water depth of 15 m. All boundaries are closed (absorbing) land boundaries. The mesh is shown in Figure 4.1. You can generate this mesh by loading the “Lake_Mesh_Generation_15m.mdf” file into the MIKE Zero Mesh Generator and triangulate the area. The structured mesh includes 289 nodes and 512 elements. The mesh size is 2500 m and the element area is $3.125 \times 10^6 \text{ m}^2$. As the boundaries are considered as absorbing (land) boundaries the arc attributes (including start/end nodes) are all set to 1. By interpolation (using the file “water_15m.xyz”) the bathymetry is generated as shown in Figure 4.2.

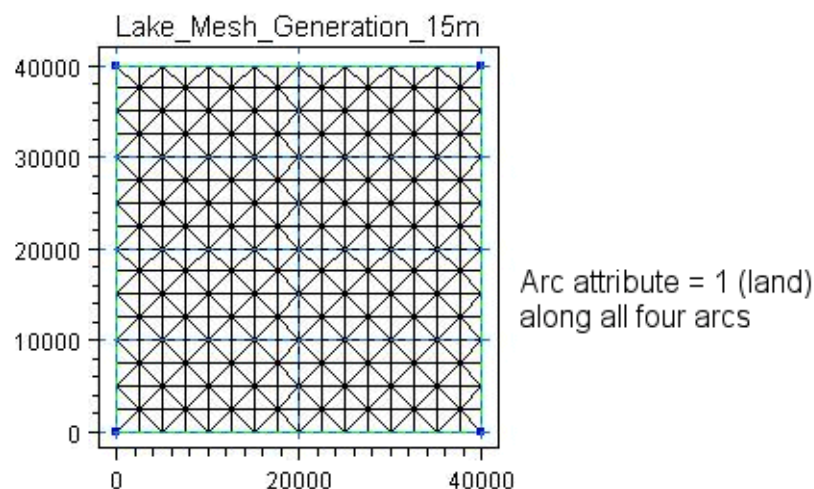


Figure 4.1 Computational mesh

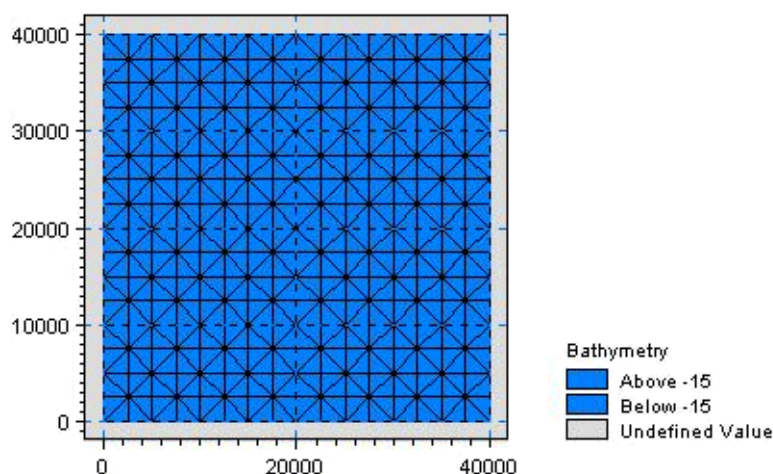


Figure 4.2 Bathymetry

Wind forcing

The wind is blowing from West (270 °N) in 6 hours. Then the wind direction turns to a south direction (180 °N) from where it blows for 8 hours. The wind speed is constant $U_{10} = 13$ m/s. The wind time series is shown in Figure 4.3.

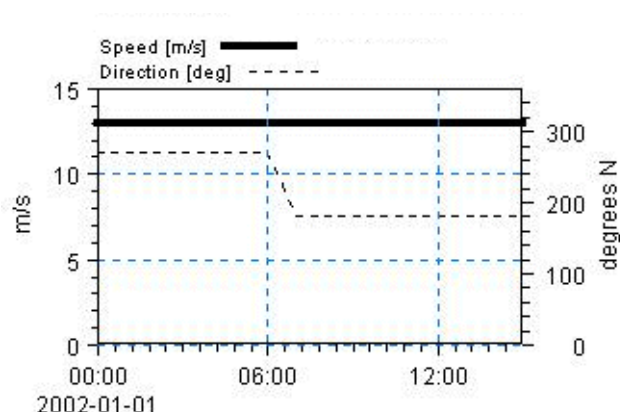


Figure 4.3 Wind conditions

Spectral discretization

The minimum frequency is 0.055 Hz, the frequency ratio is 1.1 and there are 25 discrete frequencies in this case. Hence the frequency spectrum is resolved within the frequency range [0.055; 0.6] Hz.

The 360° rose is resolved with 16 discrete directions.

Time integration

The time step is 120 s and the simulation period covers 15 hours.

4.2.3 Presenting the results

In Figure 4.4 wave growth curves are shown for the significant wave height and peak wave period (west boundary is to the left). The growth curve at 06:00 hours predicts at fetch 40 km a significant wave height of 1.55 m and a corresponding spectral peak period of 4.8 s. This prediction is in very good agreement with Shore Protection Manual (1984) shallow water growth curves ($H_{m0} = 1.49$ m and $T_p = 4.6$ s) and the growth curves suggested by Kahma and Calkoen (in Komen et al., 1994, p. 175-176) ($H_{m0} = 1.62$ m and $T_p = 4.9$ s).

The maps shown in Figure 4.5 clearly illustrate the influence of the absorbing boundaries on the wave field. The graphics are created by the MIKE Zero Data Viewer.

Figure 4.6 shows how the directional spectrum change during the turn of the wind direction. The graphics are created by the Polar Plot in MIKE Zero Data Viewer.

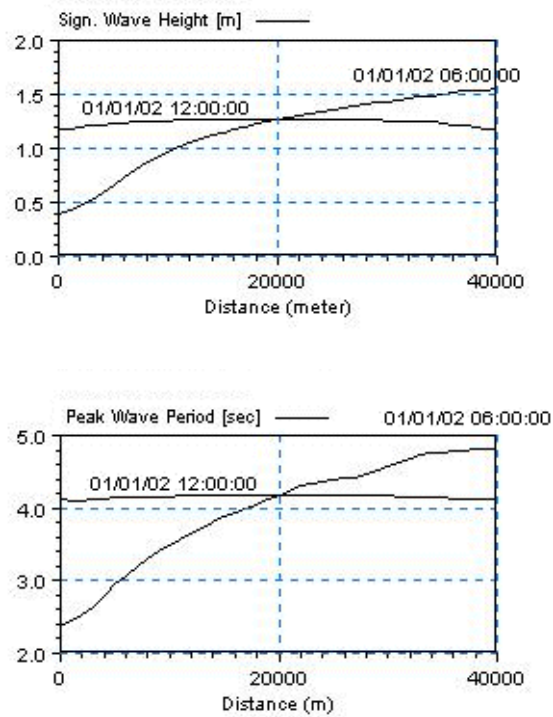


Figure 4.4 Spatial variation of the significant wave height and peak wave period at two different instances. The results are extracted from the result file "Wave_line.dfs1"

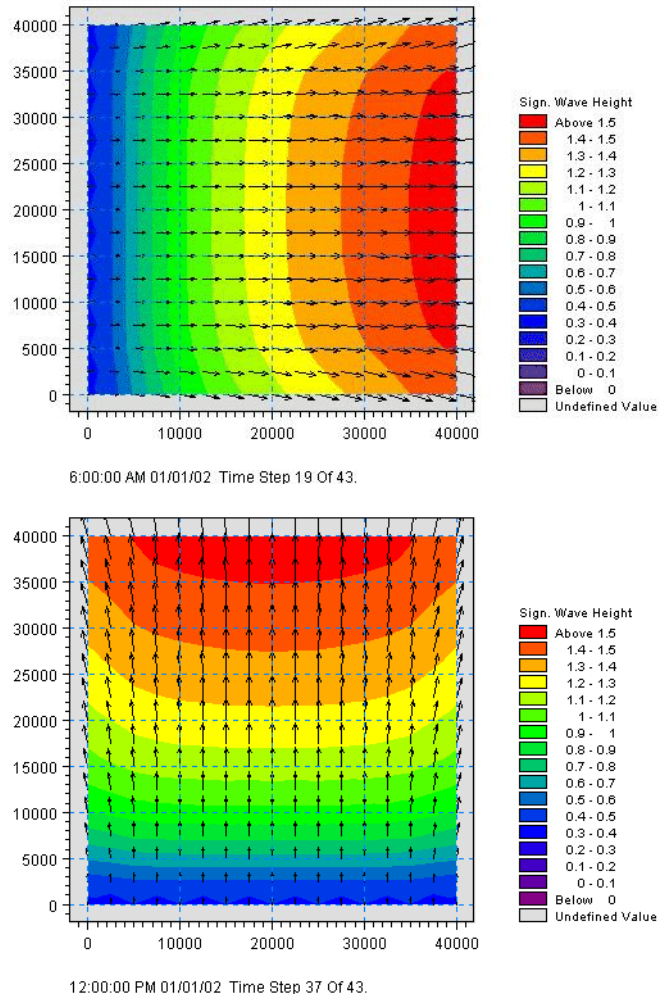


Figure 4.5 Maps of the significant wave height at two different instances

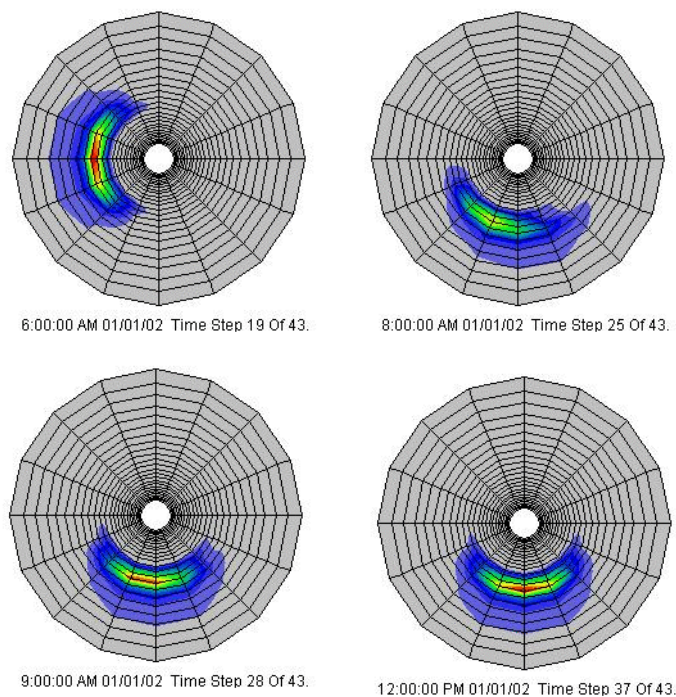


Figure 4.6 Evolution of the directional spectrum during a 90° turn of the wind direction. The plots are made in the Data Viewer. Polar plots can also be made in the MIKE Zero Plot Composer (Polar Plot control)

4.2.4 List of data and specification files

The following data files (included in the \sw\Lake folder) are supplied with MIKE 21 SW:

File name:	Lake_Mesh_Generation_15m.mdf
Description:	MeshEdit document for generation of the Lake_Mesh.mesh file including the computational mesh and bathymetry
File name:	water_15m.xyz
Description:	xyz-file including the bathymetry information
File name:	Lake_Mesh.mesh
Description:	Mesh-file including the mesh and bathymetry
File name:	Wind.dfs0
Description:	Time series of wind speed and direction
File name:	Lake.sw
Description:	MIKE 21 Spectral Wave Setup Document

4.3 North Sea and West-coast Wave Conditions

4.3.1 Purpose of the test

Accurate predictions of extreme values of waves are essential when determining design data for marine structures. The safety of structures, as well as the possibility of developing an economic design, relies above all on the reliability and accuracy of the underlying design data.

DHI has carried out a large number of design studies covering various locations in the U.K., Norwegian and Danish sectors of the North Sea. These studies were conducted for Dansk Olie og Naturgas A/S (Denmark), Mærsk Olie and Gas A/S (Denmark), Hamilton Brothers Oil & Gas Ltd. (U.K.), British Petroleum (U.K.), Phillips Petroleum Company (Norway) and many others.

Recently, DHI has implemented a forecast model for Eltra A/S (Denmark) for short and long term wave prediction in connection with planning of installation and maintenance of an new offshore wind farm located at Horns Rev at the Danish West-coast. An extensive validation has been carried out for the MIKE 21 SW model. The present example shows a simulation for the period 5-12 November 2000, where comparison with offshore data (Ekofisk) and onshore data (Horns Rev) is available.



Figure 4.7 Offshore wind farm

4.3.2 Defining and limiting the wave problem

Mesh and bathymetry

The model domain is about 1000 km x 2000 km with a maximum water depth of approximately 4000 m. All boundaries are closed (i.e. absorbing land

boundaries). The overall computational mesh is shown in Figure 4.8. A local refinement with higher spatial resolution has been made at the wind farm site. A close-up of the mesh in this area is shown in Figure 4.9. The spatial resolution is about 40 km in the North Sea and about 2 km at the site.

Please notice that the bathymetry used in this example and shown in Figure 4.8 and Figure 4.9 is a modified version of the bathymetry used in the forecast model.

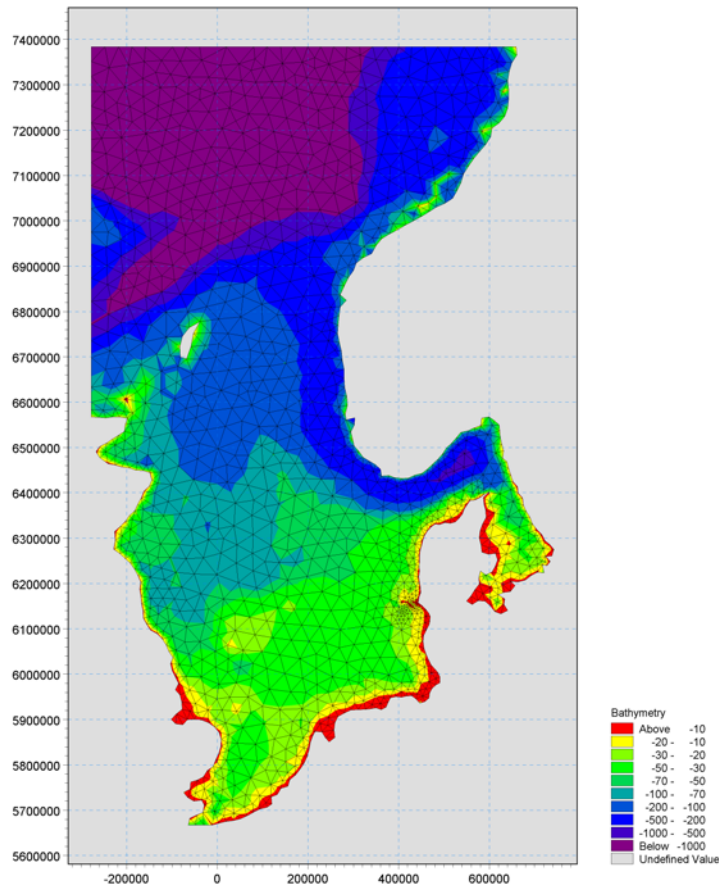


Figure 4.8 Computational mesh and bathymetry

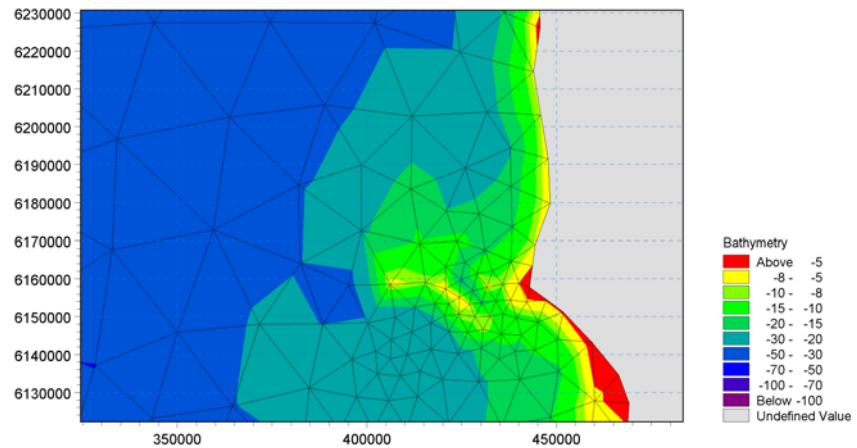


Figure 4.9 Local refinement of the mesh at Horns Rev

Wind forcing

During the peak of the storm (7 November 2000 00:00) the wind is blowing from easterly directions with a wind speed of about 20 m/s in central North Sea and about 10 m/s at the West-coast of Jutland, Denmark. An example of a wind field is shown Figure 4.10.

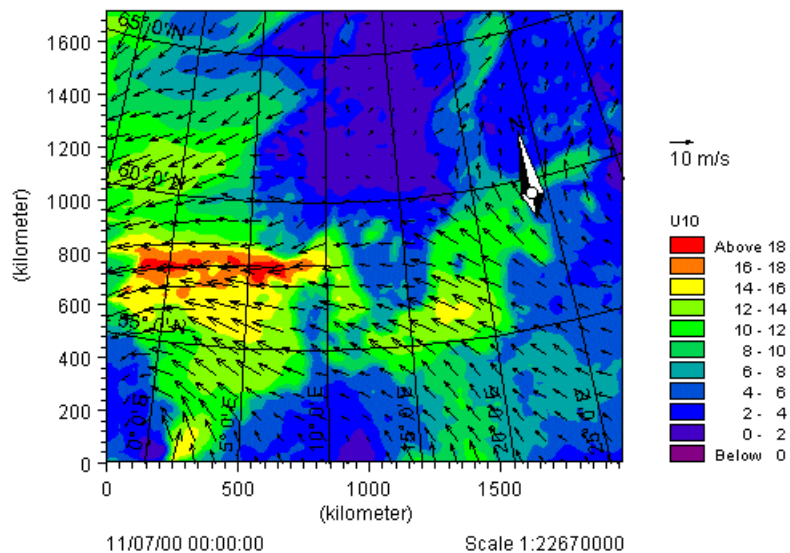


Figure 4.10 Wind field during the peak for the storm

Spectral discretization

The minimum frequency is 0.055 Hz, the frequency ratio is 1.1 and there are 25 discrete frequencies in this case. Hence the frequency spectrum is resolved within the frequency range [0.055; 0.6] Hz.

The 360° rose is resolved with 16 discrete directions.

Time integration

The time step is 900 s (or 15 minutes) and the number of time steps is 672. This corresponds to a one-week period simulation time.

4.3.3 Presenting the results

Figure 4.11 shows a map of the significant wave height for the entire domain, while Figure 4.12 and Figure 4.13 shows time series of the wave height, spectral peak wave period and mean wave period at the two measurement stations. The comparison between model and measured data is seen to be very good.

Figure 4.14 shows examples of simulated directional wave spectra at Horns Rev (created by Polar Plot in the MIKE Zero Plot Composer).

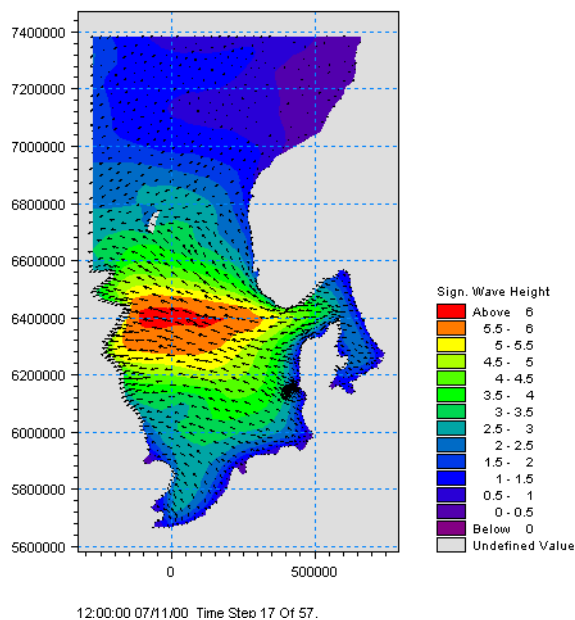


Figure 4.11 Maps of the significant wave height at the peak of the storm

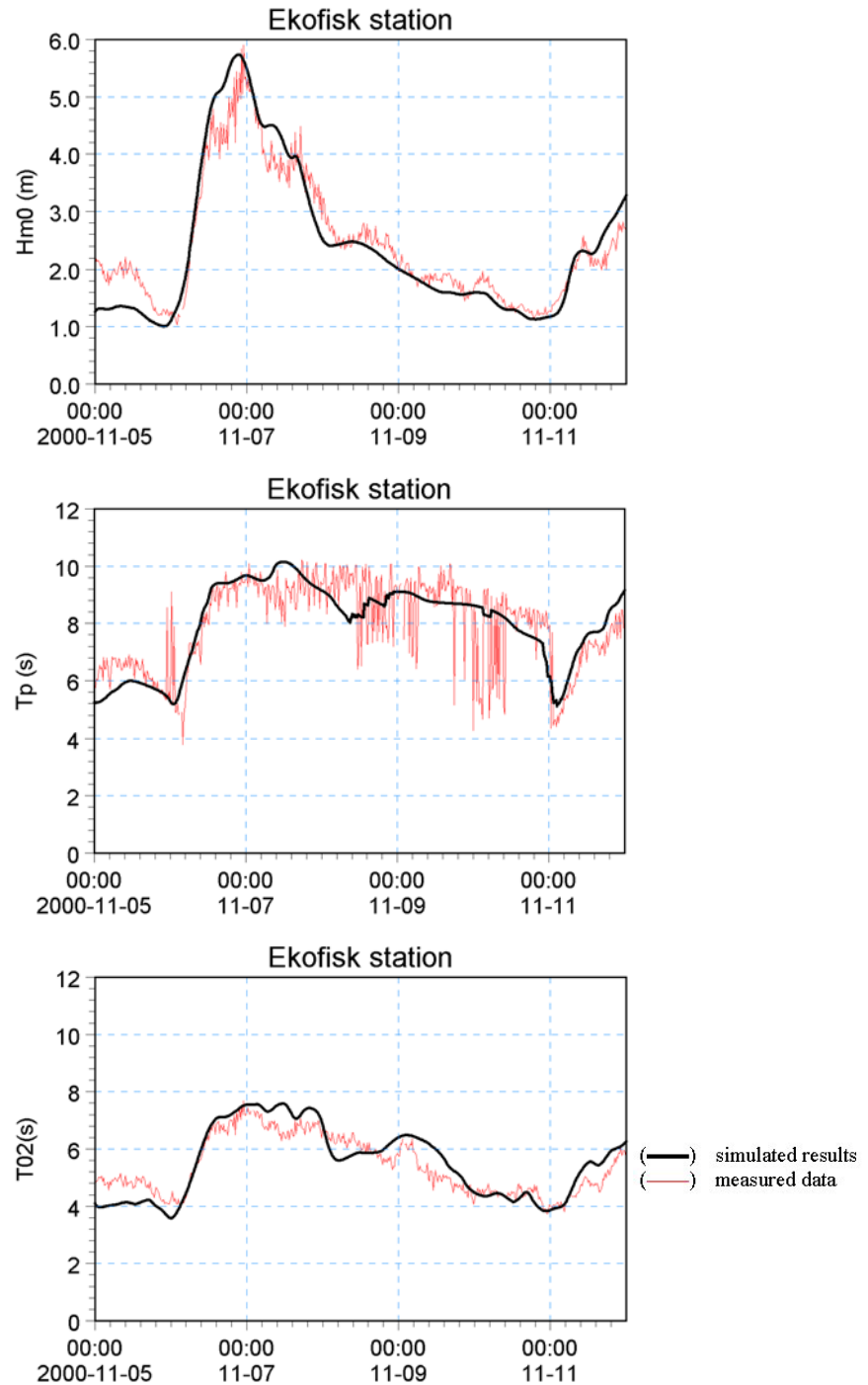


Figure 4.12 Time series of significant wave height (upper), spectral peak wave period (middle) and mean wave period (lower) at the offshore buoy (Ekofisk)

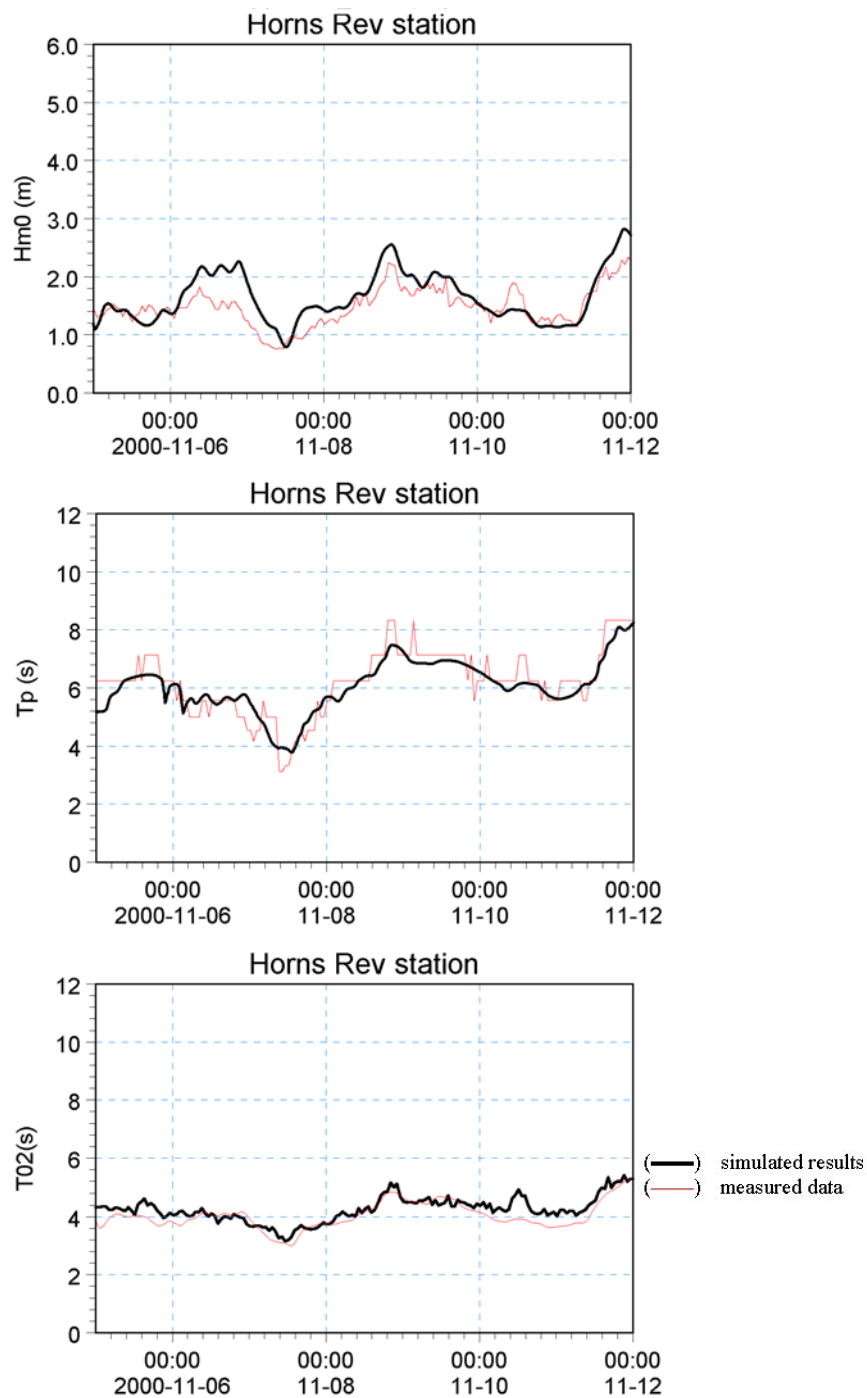


Figure 4.13 Time series of significant wave height, spectral peak wave period and mean wave period at onshore buoy (Horns Rev)

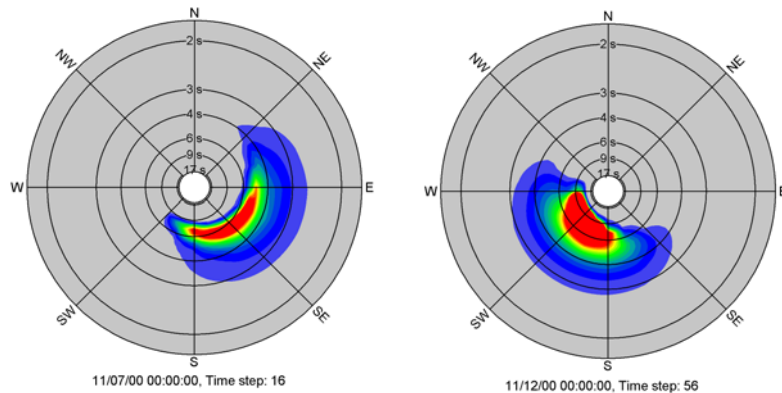


Figure 4.14 Simulated directional spectra at Horns Rev. The plots are made using the Polar plot control in the MIKE Zero plot composer

4.3.4 List of data and specification files

The following data files (included in the \sw\NorthSea folder) are supplied with MIKE 21 SW:

File name:	bathy.mesh
Description:	Mesh-file including the mesh and bathymetry
File name:	wind.dfs2
Description:	2D time series of wind velocity components
File name:	setup.sw
Description:	MIKE 21 Spectral Wave Setup Document

4.4 Wave Transformation on a Barred Beach

4.4.1 Purpose of example

The purpose of this example is to study the wave transformation on a barred beach using the directional decoupled parametric formulation. The site is located north of Torsminde at the Danish West-Coast facing the North Sea. The photograph in Figure 4.15 shows the location of the beach. From this photograph it is possible to identify the breaking waves on an offshore bar as well along the shoreline. Measured wave data is available at an offshore station (Fjaltring, directional Waverider buoy, UTM co-ordinate easting: 441895 and northing: 6259258, water depth 17.5 m MSL) and onshore (Fjaltring, S4, UTM co-ordinate easting: 445677 and northing: 6257941, water depth 4.5 m MSL).



Figure 4.15 Location of site

4.4.2 Defining and limiting the wave problem

Mesh and bathymetry

The model domain is 4 km x 9 km with a maximum water depth of about 20 m. The south, west and north boundaries are open where the offshore wave condition is specified. The overall computational mesh is shown in Figure 4.16. A local refinement with very high spatial resolution has been made to the bar system in the northern part of the domain. A close-up of the mesh in this area is shown in Figure 4.17. The spatial resolution is about 200 m offshore and 5-10 m at the bar.

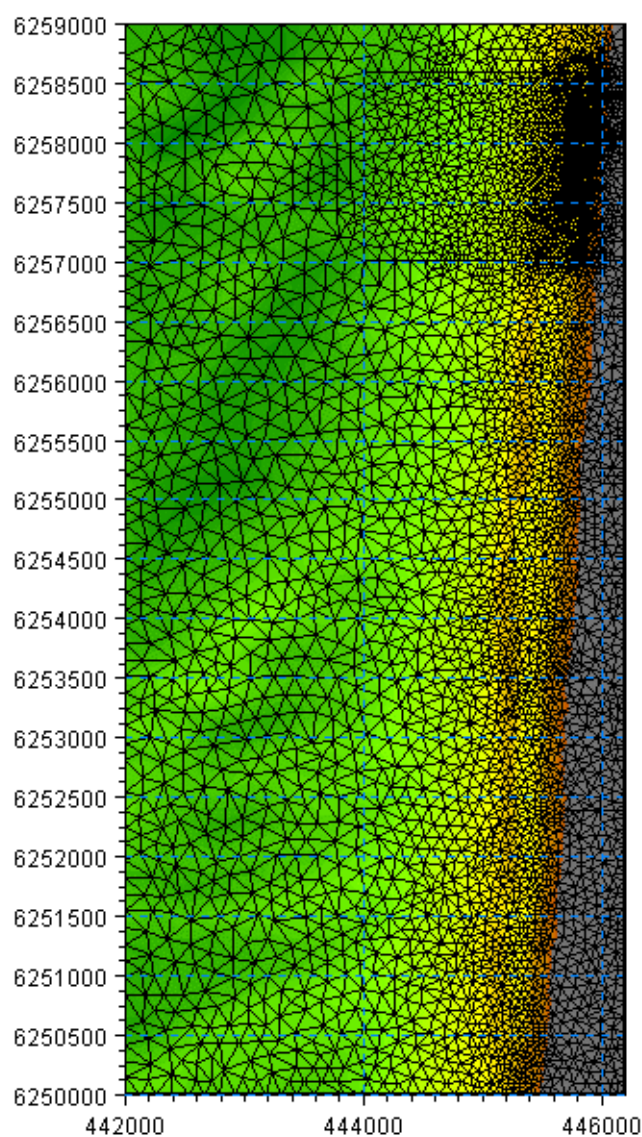


Figure 4.16 Computational mesh and bathymetry

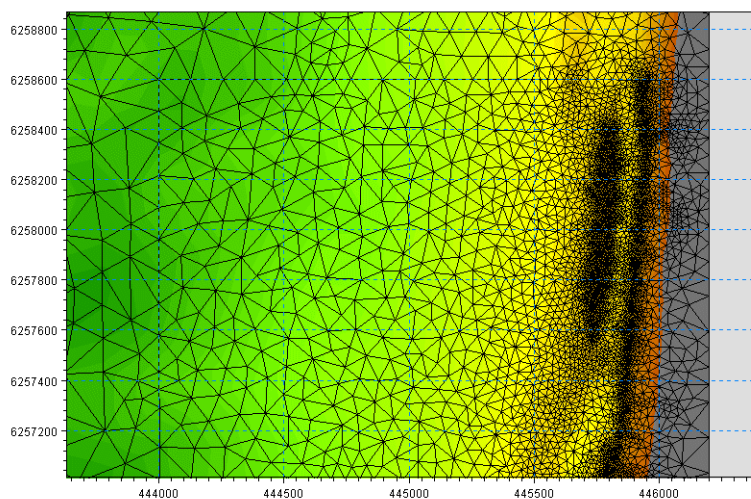


Figure 4.17 Local depth-adaptive refinement of the mesh

Basic Equations

For this case we want to calculate a stationary solution using the directionally decoupled parametric formulation. Hence, you should select 'Quasi-stationary formulation' and 'Directionally decoupled parametric formulation'.

Boundary conditions

The offshore wave condition is $H_{m0} = 2.84$ m, $T_p = 9.1$ s, MWD = 271°N and directional spreading index $n = 7$. This condition is applied along the offshore (west) boundary. A lateral boundary condition is used along the northern and southern boundary. This type of boundary condition is a good approximation when the boundary line is almost straight and when the depth contours are almost perpendicular to the line. This event corresponds to a situation occurred 28 February 1999 18:00. The corresponding water level is +0.64 m MSL.

Spectral discretization

The directional sector 240°-300°N is resolved with 13 directions. This results in a 5° directional resolution.

Solution Technique

The default parameters for the iterative method can be used for this case. However, you may choose to save information of the iterative procedure.



4.4.3 Presenting the results

Figure 4.18 shows a map of the significant wave height for the entire domain. The convergence of the iterative algorithm is shown in Figure 4.19.

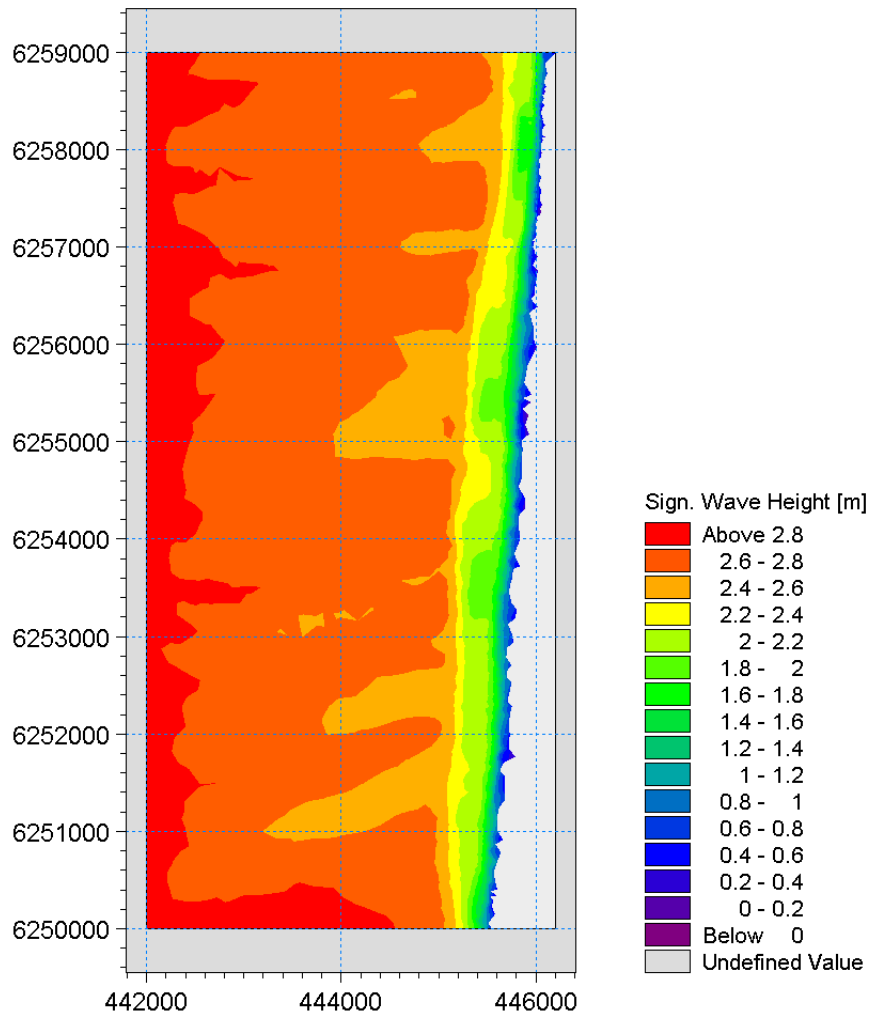


Figure 4.18 Map of the significant wave height

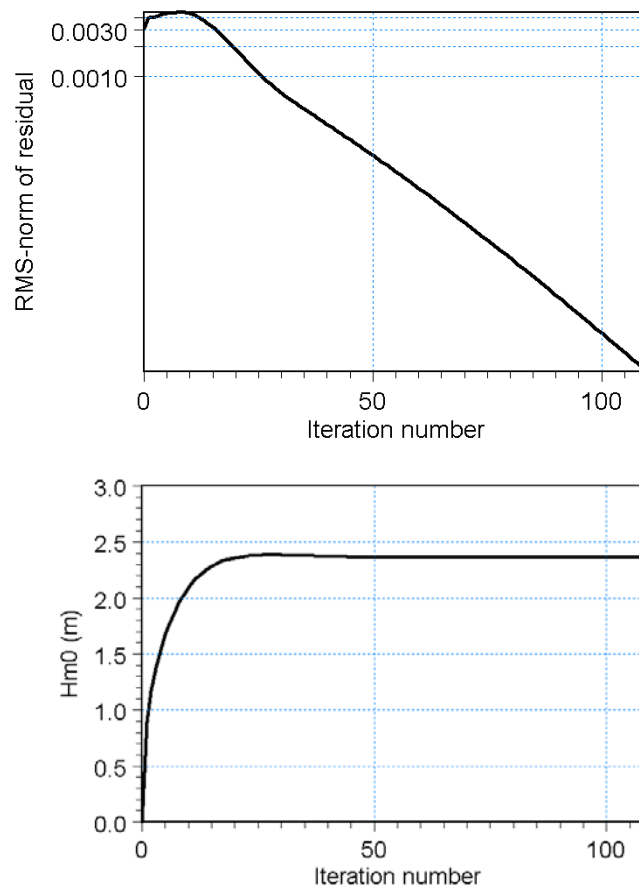


Figure 4.19 Convergence of
a) RMS-norm of the residual as function of the iteration number and
b) significant wave height at the onshore boundary buoy as function of the iteration number.

4.4.4 List of data and specification files

The following data files (included in the \sw\Fjaltring folder) are supplied with MIKE 21 SW:

File name:	Nourtec_Mesh.mesh
Description:	Mesh-file including the mesh and bathymetry
File name:	Model_setup.sw
Description:	MIKE 21 Spectral Wave Setup Document



4.5 Wave Transformation Around an Island

4.5.1 Purpose of example

The overall objective of this example is to study the wave transformation around an island where flooding and drying occurs due to a varying still water level. The directional decoupled parametric formulation is used. The results are compared to model results obtained with the phase-resolving MIKE 21 BW 2DH Boussinesq Wave Module including wave breaking and moving shoreline.

4.5.2 Defining and limiting the wave problem

Mesh and bathymetry

The model domain is 1 km x 1 km. The bathymetry is an elliptic paraboloid having an elevation of approximately +0.2 m (above the still water level) at the top point and decreasing to a constant depth of 16 m offshore. The mesh and bathymetry are shown in Figure 4.20.

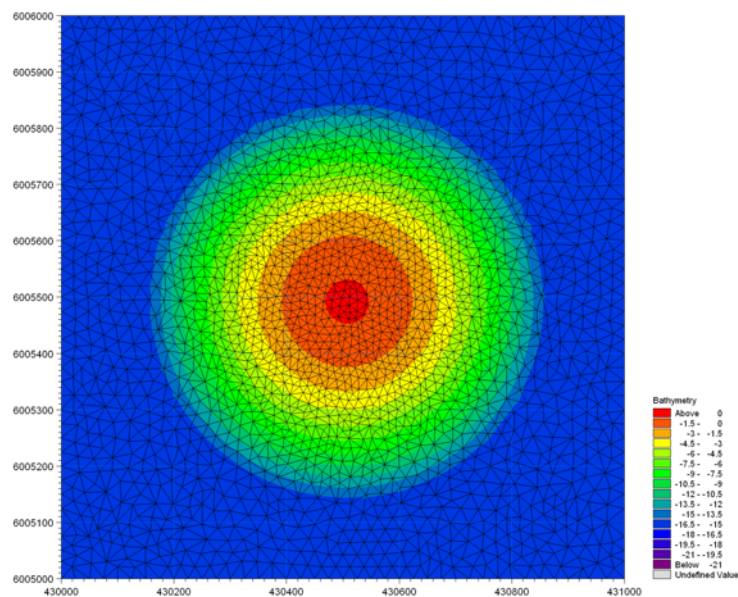
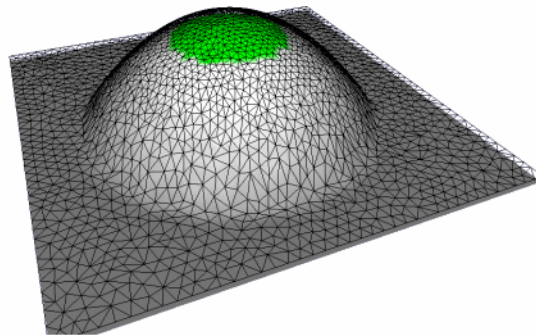


Figure 4.20 Computational mesh and bathymetry

The unstructured mesh includes 4646 elements. The spatial resolution is 20-30 m at 16 m depth and 10-15 m at the initial dry points on the island.

Boundary conditions

The offshore wave conditions is $H_{m0} = 2.0$ m, $T_p = 8$ s, MWD = 270° N and directional spreading index $n = 8$ (Type 1 boundary formulation). This condition is applied at the west, north and south boundaries. The east boundary is a fully absorbing land boundary.



Water level conditions

A time varying water level is used in this example to illustrate the handling of flooding and drying in the model. The initial and final water level is 4 m below the still water level. Figure 4.21 shows the time series of the water level.

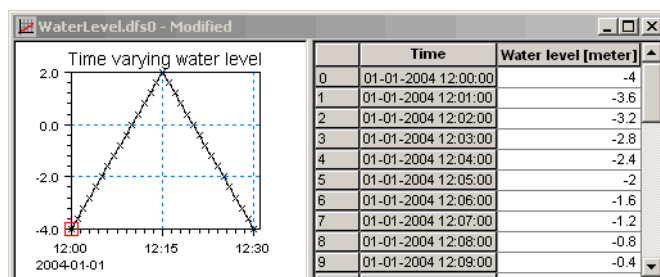


Figure 4.21 Time varying water level

Spectral discretization

The 360° directional space is resolved by 18 directions.

Time integration

The time step is 2 s and the number of time steps is 900 corresponding to a 30-minute simulation time. An instationary time formulation is used in this case in order to keep the simulation time low. This approach is sufficient for illustration of the handling of flooding and drying.

4.5.3 Presenting the results

Figure 4.22 shows maps of the significant wave height at water level -4 m MSL (time 12:30) and $+2$ m MSL (time 12:15). In the last case, the significant wave height is approximately 1.1 m at the top of the island. This is in excellent agreement with the experience of $H_{m0} \sim 0.5 \cdot h \sim 1.1$ m ($h = 2.2$ m is the water depth) in the breaking zone.

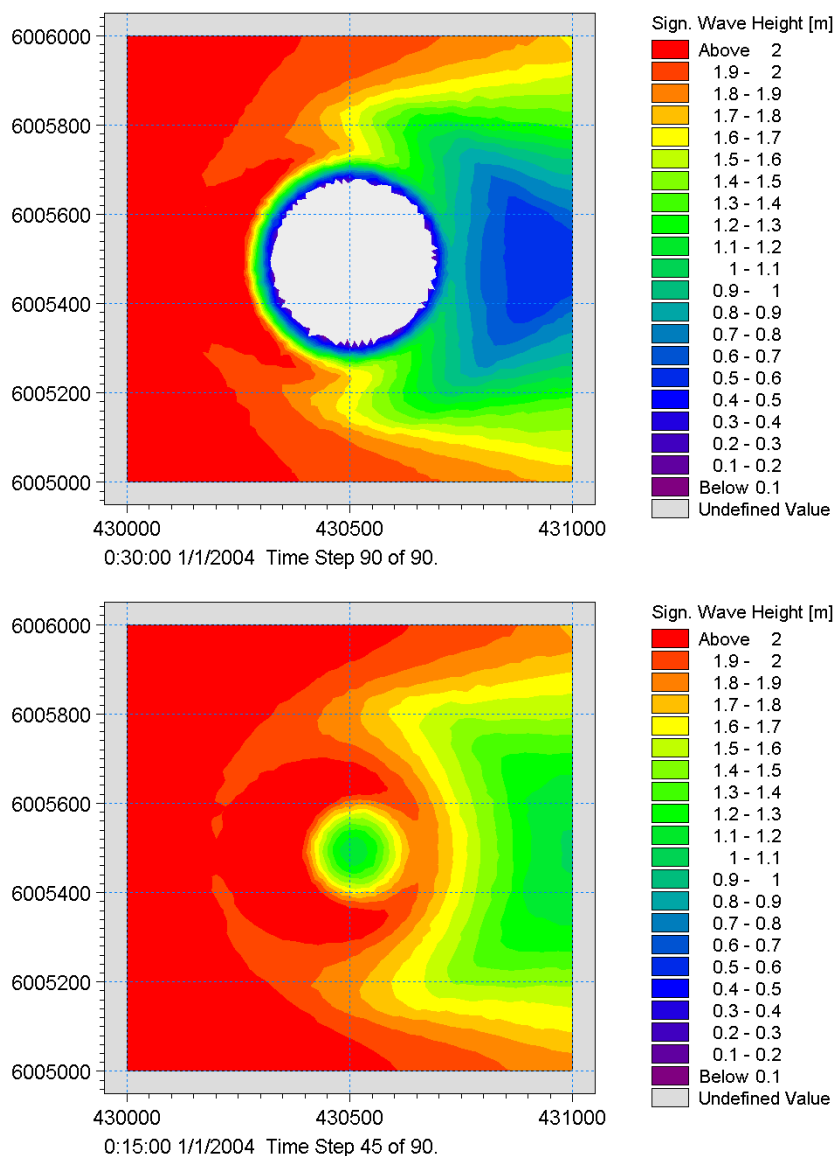


Figure 4.22 Maps of the significant wave height at two different instances (upper at water level -4 m MSL and lower at water level $+2$ m MSL)

Results from a MIKE 21 SW simulation using a constant water level of 0 m MSL have been compared to results from MIKE 21 BW including wave breaking and moving shoreline⁽¹⁾. Figure 4.23 shows maps of significant wave heights and wave directions.

¹ The model setup used for MIKE 21 BW is included in the installation, please see `.\Examples\MIKE_21\BW\Island`

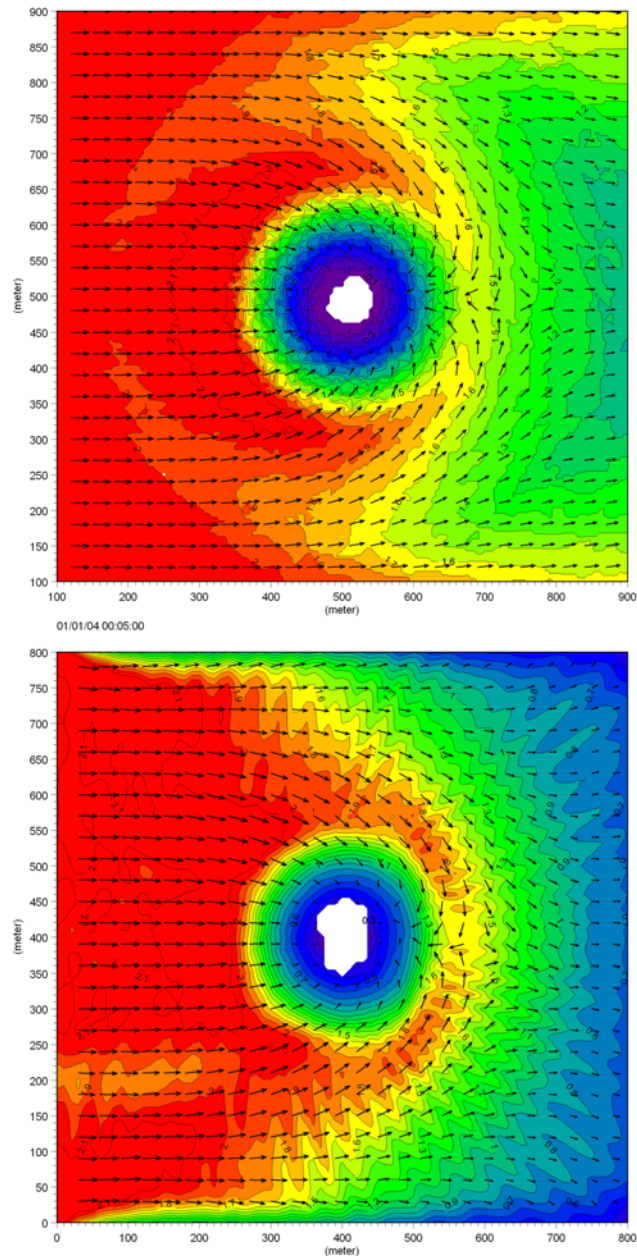


Figure 4.23 Maps of the significant wave height and mean wave direction. Upper panel shows MIKE 21 SW results and lower panel shows results from a MIKE 21 BW simulation. The directional analysis of the Boussinesq model results is made by using the WSWAT Directional Wave Analysis tool available in MIKE Zero

In Figure 4.24 a comparison is made between the two models prediction of the significant wave height along two cross-sections. An excellent agreement



is seen in the wave breaking zone ($x = 300\text{--}500$ m, upper panel). MIKE 21 BW predicts slightly higher waves immediately before breaking, which is due to nonlinear shoaling. The observed oscillations offshore the breaking point are caused by reflection from the island bathymetry.



Please note the wave height is reduced to zero at the boundaries as fully absorbing boundaries (sponge layers) were used in the MIKE 21 BW simulation. Behind the island the phase-resolving model (MIKE 21 BW) results in larger waves than the phase-averaged model (MIKE 21 SW), which is caused by effects of diffraction, reflection and nonlinearities.

4.5.4 List of data and specification files

The following data files (included in the \SW\Island folder) are supplied with MIKE 21 SW:

File name:	Island.mesh
Description:	Mesh-file including the mesh and bathymetry
File name:	Setup.sw
Description:	MIKE 21 Spectral Wave Setup Document
File name:	Waterlevel.dfs0
Description:	Water level variation in time

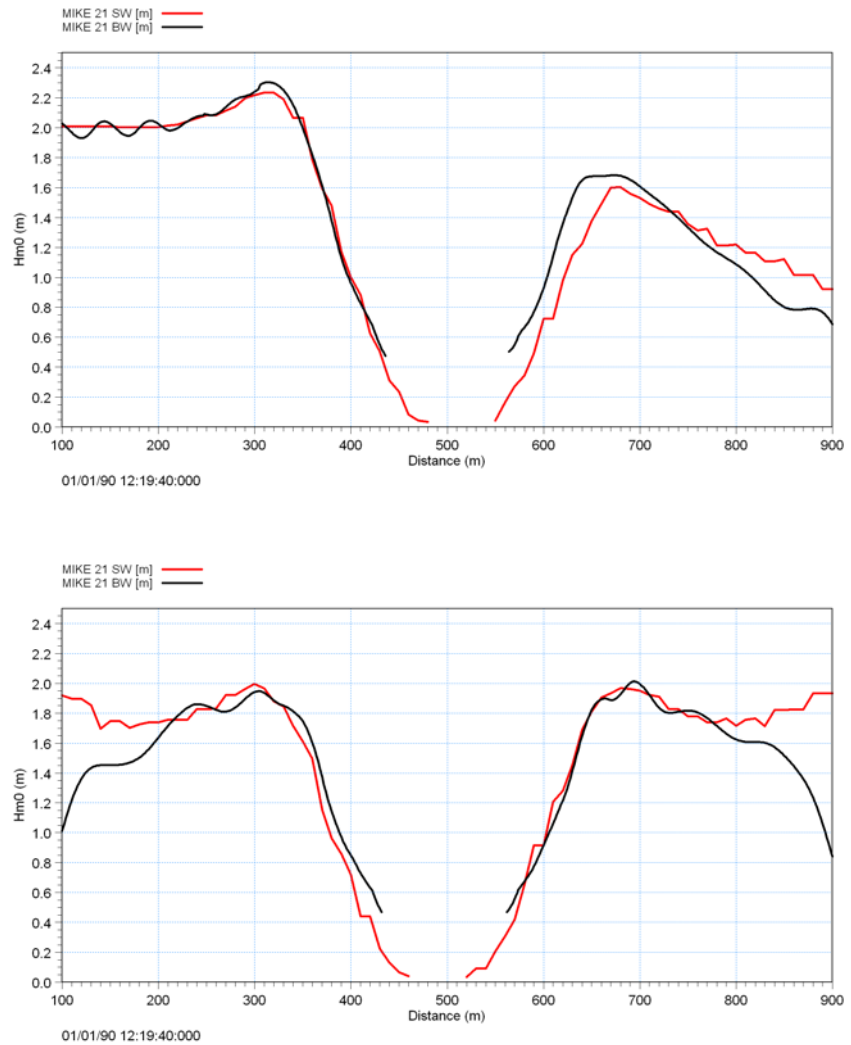


Figure 4.24 Comparison between modelled significant wave height using a phase-averaged model (MIKE 21 SW) and a phase-resolving model (MIKE 21 BW). Upper panel shows a comparison along $y=500$ m (west-east direction) and lower panel shows a comparison along $x=500$ m (south-north direction)





5 BASIC PARAMETERS

5.1 Domain

Providing MIKE 21 SW with a suitable mesh is essential for obtaining reliable results from your model. Setting up the mesh includes selection of the appropriate area to be modelled, adequate resolution of the bathymetry, wave, wind and flow fields under consideration and definition of codes for open and land boundaries. Furthermore, the resolution in the geographical space must also be selected with respect to stability considerations.

The MIKE 21 SW is based on flexible mesh approach.

5.1.1 Mesh and bathymetry

You have to generate your mesh file in the MIKE Zero Mesh Generator, which is a tool for the generation and handling of unstructured meshes, including the definition and editing of boundaries.

The mesh file is an ASCII file including information of the geographical position and bathymetry for each node point in the mesh. The file also includes information of the node-connectivity in the triangular element mesh.

5.1.2 Domain Specification

Map projection

If the mesh is generated by the MIKE Zero Mesh Generator, the map projection is defined in the mesh file and is only shown for reference. If the map projection is not defined in the mesh file, you have to select the correct map projection corresponding to the data in the mesh file.

Minimum depth cutoff

Computations made on water depth less than the minimum depth cutoff are performed using the minimum depth cutoff value. Please note that depths are negative as they are in the mesh file.

If you also apply a datum shift - the depth cutoff is relative to the corrected depths.

For instance - you have a mesh file with values between +2 and -20 meters. You then shift these to a different datum with a shift of +1 meters. Your corrected bathymetry now ranges between +1 and -21 m. You then cutoff all depths above -2m, leaving the bathymetry used in the model to range between -2 and -21 m.

Datum shift

You can use any convenient datum for setting up the mesh of your model. This can be Chart Datum (CD), Lowest Astronomical Tide (LAT) or Mean Sea Level (MSL). The actual datum is unimportant. What is important is, that for each simulation, you must provide the model with the correct height of the model reference level relative to the datum used in the set up of your bathymetry. Specifying the datum shift does this. In this way it is possible to carry out simulations using a range of different water levels without having to alter the mesh file.

If you do not plan to apply different water levels in different simulations it is recommended that you set up your bathymetry with the datum that you plan use in the simulations, thus having a datum shift of 0 m.



A datum shift of e.g. 2 m (-2 m) means the water depth is increased (reduced) by 2 m in all node points.

Mesh decomposition

To improve the performance of the numerical scheme it is possible to include reordering of the mesh (renumbering of the element and node numbers). This can significantly speed up the computational time by optimizing the memory access.



Note: When reordering is applied the numbering of the nodes and elements in the output files has been changed compared to the information in the mesh file. The information in the log file corresponds to the new ordering.

To improve the performance of the numerical scheme a domain decomposition technique is applied. You can specify the number of subdomain. If reordering is included the reordering is applied at subdomain level.

5.1.3 Boundary Names

When you generate your mesh using the MIKE Zero Mesh Generator you already have defined a code value for open water boundaries. Figure 5.1 shows the definition of codes in a simple application.

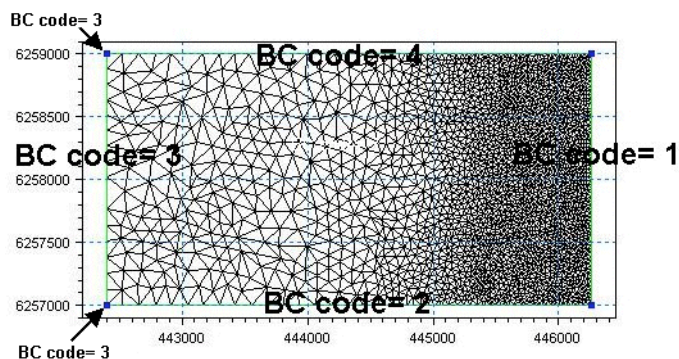


Figure 5.1 The definition of boundary codes in a mesh is made in the Mesh Generator

In this case three open boundaries have been detected from the mesh file specified in the domain parameters; code 2, code 3 and code 4. In the main Boundary Conditions dialog you can re-name the code values to more appropriate names, see Figure 5.2.

Boundary	Name	→	Boundary	Name
Code 3	Code 3		Code 3	West BC
Code 2	Code 2		Code 2	South BC
Code 4	Code 4		Code 4	North BC

Figure 5.2 Change of default code names (from the mesh file) to more appropriate names

5.2 Time

The period to be covered by the simulation is specified in this dialog. You have to specify the simulation start date, the overall number of time steps and the overall time step interval (in seconds).

Using the Instationary formulation (see section 6.4.1) the overall discrete time steps specified on this page are only used to determine the frequency for which output can be obtained. The time step used in the calculation is determined dynamically during the simulation.

Using the Quasi-stationary formulation (see section 6.4.2) the overall discrete time steps are used to determine the time steps for which a stationary solution is calculated and thereby the overall frequency for which output can be obtained.

The simulation always starts with time step number 0 and the simulation start date is the historical data and time corresponding to time step 0. The simulation end date is presented for reference.





6 SPECTRAL WAVE MODULE

The spectral wave module simulates the growth, decay and transformation of wind-generated waves and swell in offshore and coastal areas.

6.1 Basic equations

The spectral wave module is based on the wave action balance equation where the wave field is represented by the wave action density spectrum $N(\sigma, \theta)$. The independent phase parameters (fully spectral formulation only) have been chosen as the relative (intrinsic) angular frequency, $\sigma = 2\pi f$ and the direction of wave propagation, θ .

The relation between the wave energy density spectrum $E(\sigma, \theta)$ and the wave action density spectrum is given by

$$N = \frac{E}{\sigma} \quad (6.1)$$

6.1.1 Spectral formulation

The spectral wave module includes two different formulations

- Directionally decoupled parametric formulation
- Fully spectral formulation

The directionally decoupled parametric formulation is based on a parameterization of the wave action conservation equation. Following Holthuijsen et al. (1989) the parameterization is made in the frequency domain by introducing the zeroth and first moment of the wave action spectrum as dependent variables.

The fully spectral formulation is based on the wave action conservation equation as described in e.g. Komen et al. (1994) and Young (1999), where the directional-frequency wave action spectrum is the dependent variable.

6.1.2 Time formulation

The spectral wave module includes two time formulations

- Quasi-stationary formulation
- Instationary formulation

In the quasi-stationary mode, the time is removed as an independent variable and a steady state solution is calculated at each time step.



6.1.3 Remarks and hints

As the fully spectral formulation simulates the evolution of the directional-frequency wave action spectrum this model is several times slower than the directionally decoupled parametric formulation.

Which model formulation to use?

The fully spectral formulation can in principle be used in wave studies involving wave growth, decay and transformation of wind-generated waves and swell in offshore and coastal areas. However, the computationally less demanding directionally decoupled parametric formulation is sufficient in a number of situations. Examples of such cases are:

- small scale wave transformation applications, say, spatial scale is less than ~10-50 km
- applications where fully developed seas are dominating
- applications where swell and combined sea/swell is not important

Note, that forcing due to the wind can not be included using the instationary directionally decoupled parametric formulation.

Which time formulation to use?

The quasi stationary formulation is sufficient in a number of situations and is in general less computationally demanding than the instationary formulation. Examples are:

- when the forcing (eg. wind) is slowly varying in space and time
- fetch limited wind-wave growth
- when individual wave events can be considered as independent

6.2 Time Parameters

The spectral wave calculation is activated at a start time step relative to the start of the simulation specified on the Time dialog.



Note: the start time step can only be specified using the MIKE 21/3 Coupled Model FM.

6.3 Spectral discretization

The dependent variable in the spectral mode is the directional-frequency wave action spectrum in each node point. In this dialog you specify the discrete frequencies and directions used to resolve the wave action spectrum in the computations.



6.3.1 Frequency discretisation (fully spectral formulation only)

Two types of discretisation are available; logarithmic and equidistant distribution. It is recommended to always use the logarithmic distribution of frequencies, which is given by

$$f_j = f_0 c^j, \quad j = 0, 1, \dots, n-1$$

where f_j is the frequency, f_0 minimum frequency, c the frequency factor ($= 1.1$ as default) and n is the number of frequencies. The upper & lower bound of each frequency bin is defined by $f_j = f_0 c^{j+0.5}$ & $f_j = f_0 c^{j-0.5}$, respectively.

The frequency range should cover wave frequencies expected to occur in the computational domain. For typical offshore applications wave periods from 4 s to 25 s (i.e. frequencies from 0.25 Hz to 0.04 Hz) are found. In enclosed waters wave periods of 2-3 s (i.e. frequencies from 0.33 Hz to 0.5 Hz) may also be of interest and should be resolved.

6.3.2 Directional discretisation

Two types of discretisation are available; 360 degree rose and directional sector. The 360 degrees compass rose is typically chosen for varying wind/wave/swell directions. However, if the expected wind/wave/swell directions fall within a predefined range of directions, the choice of a directional sector type of discretisation is recommended as it reduce the computational time.

The number of discrete directions should be large enough to resolve the directional variation of the waves. For swell with a relative narrow directional distribution of the wave action/energy a relatively small directional resolution is needed, $\Delta\theta < 2^\circ$ - 10° (the first number (2°) corresponds to coastal areas and the last number (10°) to offshore areas. For wind waves with a wider directional distribution of the action/energy a resolution of about $\Delta\theta < 10^\circ$ - 30° is usually sufficient.

6.3.3 Separation of Wind-sea and Swell

The separation of wind-sea and swell can be used both in connection with determination of the maximum prognostic frequency and white capping. As standard the mean frequency, used in the determination of the maximum prognostic frequency, is also calculated based on the whole spectrum. For swell dominated wave conditions this can result in a too low cut-off frequency and thereby an underestimation of the local generated wind waves. The predictions can be improved by calculation the mean frequency based on only the wind-sea part of the spectrum.



For whitecapping the separation of wind-sea and swell can be used to improve the results in case of strong swell. For more detail see Wave parameters (p. 80).

The separation of wind-sea and swell can be specified in three ways

- No separation
- Constant threshold frequency
- Dynamic threshold frequency

Selecting "Constant threshold frequency" you have to specify the threshold frequency and selecting "Dynamic threshold frequency" you have to specify the maximum threshold frequency.

For details regarding the distinction of wind-sea and swell, see the scientific documentation (section 5.1 Field Type). The "Dynamic threshold frequency" used here corresponds to the "Dynamic threshold frequency (version 1)" described in the scientific documentation.

6.3.4 Remarks and hints

The recommended minimum number of discrete directions is 16.

6.4 Solution technique

The discretisation in geographical and spectral space is performed using a cell-centered finite volume method. In the geographical domain, an unstructured mesh is used. The spatial domain is discretized by subdivision of the continuum into non-overlapping elements. The convective fluxes are calculated using a first-order upwinding scheme.

6.4.1 Instationary formulation

The integration in time is based on a fractional step approach. Firstly, a propagation step is performed calculating an approximate solution at the new time level by solving the basic conservation equations without the source functions. Secondly, a source function step is performed calculating the new solution from the estimated solution taking into account only the effect of the source functions.

Algorithms for discretization in geographical and spectral domain

The simulation time and accuracy can be controlled by specifying the order of the numerical schemes which are used in the numerical calculations. The schemes for discretization in the geographical domain and the spectral domain can be specified. You can select either a lower order scheme (first order) or a higher order scheme. The lower order scheme is faster, but less



accurate. For more details on the numerical solution techniques, see the Scientific documentation.

Propagation step

The propagation step is carried out by an explicit Euler scheme. To overcome the severe stability restriction using an explicit scheme, a multi-sequence integration scheme is employed following the idea by Vilsmeier and Hänel (1995). Here, the maximum time step is increased by locally employing a sequence of integration steps, where the number of levels (steps) may vary from element to element.

The maximum number of levels (or time steps) in the propagation (transport) calculation is 32.

Source function step

The source integration step is carried out using the method of Komen et al. (1994) and Hersbach (1998). It is recommended setting the number of time steps in the source calculation to 1.

Time step interval

A variable time step interval is used in the time integration of the governing equations. The time step is determined so that the CFL Number is less than the critical CFL number (typically 1, see section 6.4.4). If an element is close to the critical CFL number, the number of levels (and thereby the local time step) is maximised up to the number specified in the user input so that the local CFL number is less than 1. The number of layers in the time step factor cannot be greater than 32 and increases in multiples of 2. To control the time step it is also possible for the user to specify a minimum time step and a maximum time step.

Remarks and hints

The total number of time steps in the calculation and the maximum and minimum time interval during the calculation are printed in the log-file for the simulation. Both the CFL Number and the number of levels (time step factor) can be saved in an output file. Elements with a high CFL and high time step factor determine the minimum time step and therefore control the speed of the computation.



In applications with strong wave breaking you should limit the number of time step levels, say, less than 8 or less. If the maximum number of time step levels is 32 in the breaking zone (information extracted from an initial run) you should reduce the maximum time step and/or the maximum number of levels.

6.4.2 Quasi-stationary formulation

The steady state solution at each time step in the quasi-stationary time integration can be solved using the following two methods

- Modified Newton_Raphson iteration
- Iteration in the time domain

Algorithms for discretization in geographical and spectral domain

The simulation time and accuracy can be controlled by specifying the order of the numerical schemes which are used in the numerical calculations. The schemes for discretization in the geographical domain and the spectral domain can be specified. You can select either a lower order scheme (first order) or a higher order scheme. The lower order scheme is faster, but less accurate. For more details on the numerical solution techniques, see the Scientific documentation.

Modified Newton_Raphson iteration

The steady state equations are solved using a modified Newton-Raphson iteration. Solving the set of non-linear equations

$$\bar{F}(\bar{x}) = \bar{0} \quad (6.2)$$

where $\bar{x} = \{x_1, x_2, \dots, x_N\}$ and $\bar{F} = \{F_1(\bar{x}), F_2(\bar{x}), \dots, F_N(\bar{x})\}$

the iteration procedure is given by the following algorithm

For $k = 0, 1, 2 \dots$ until convergence do:

$$\text{Solve } \bar{\bar{A}} \Delta \bar{x}^{k+1} = -\bar{F}(\bar{x}^k)$$

$$\text{Set } \bar{x}^{k+1} = \bar{x}^k + \alpha \Delta \bar{x}^{k+1}$$

where α is a relaxation factor and $\bar{\bar{A}}$ is an approximation to the Jacobian ($J_{ij} = \partial F_i / \partial x_j$) of the operator \bar{F} with respect to the dependent variables \bar{x} . The relaxation factor must be in the range from 0 to 1. The matrix $\bar{\bar{A}}$ is obtained taken into account the convective terms in geographic space and the diagonal part in the functional derivative of the source term due to bottom friction, wave breaking and non-linear transfer (fully spectral formulation).

The iteration procedure is stopped when a maximum number of iterations is performed or when the root-mean-square (RMS) norm of a residual vector and the max-norm of the vector containing the increment of the significant wave height between two iteration steps are smaller than a two user-specified tolerances

$$\|\bar{F}(\bar{x}^{k+1})\|_{RMS} < TOL_1 \quad \text{and} \quad \|\bar{H}_{m0}^{k+1} - \bar{H}_{m0}^k\|_{max} < TOL_2 \quad (6.3)$$



The RMS-norm and the max-norm is defined by

$$\begin{aligned} \text{Root-mean-square norm: } \|\bar{x}\|_{RMS} &= \left[\frac{\sum_{i=1}^N x_i^2}{N} \right]^{1/2} \\ \text{Max norm: } \|\bar{x}\|_{MAX} &= \max(x_i), i = 1, N \end{aligned} \quad (6.4)$$

Iteration in the time domain

The steady state solution is obtained as the steady state solution solving the instationary basic equations with steady boundary conditions and forcing. The same time integration procedure as used in the instationary mode is applied. However, the time step used in this iteration procedure is determined automatically to satisfy the stability restriction.

The iteration procedure is stopped when a maximum number of iterations is performed or when the root-mean-square norm of a vector, containing the increment of the significant wave height between to iteration steps, is smaller than a user-specified tolerance

$$\|\bar{H}_{m0}^{k+1} - \bar{H}_{m0}^k\|_{RMS} < TOL_1 \quad (6.5)$$

Recommended Values

The maximum number of iterations has a default value of 500.

Using the modified Newton-Raphson method the default value for the relaxation factor is 0.1. In general a high factor will give a fast convergence, however the iteration sequence may diverge. Hence, to ensure convergence a small value must be used.

Using the method based on iteration in the time domain the maximum number of iteration must normally be very high to ensure convergence and the tolerance must be very small. The maximum number of iteration times the time step used in the algorithm must be larger than the time it takes for the waves to propagate through the computational domain. If the tolerance is too high the algorithm may stop before the steady state solution is obtained. Note that in case the increment rate of spectral energy in time becomes too large (e.g. for very high wind speeds), the model will automatically limit the spectral energy in order to ensure stability in the numerical solution. You can read more about this in the section *Time Integration* in the scientific documentation.

It is strongly recommended to use the modified Newton-Raphson method.



6.4.3 Output of convergence information

For monitoring the convergence of the iteration procedure used in the quasi-stationary formulation it is possible to write output of the overall convergence information and the domain convergence information.

Overall

For the output of overall convergence information you can select the following three options

- No output
- Standard output
- Standard output and point output

For the standard output the following items for each iteration step is written to a dfs0-file

- The time step
- The iteration number
- The RMS-norm of the change in significant wave height between two iterations steps
- The Max-norm of the change in significant wave height between two iterations steps
- The RMS-norm of the residual (only method 1)
- The time step (only method 2)

If "Standard output and point output" is selected the significant wave height in a number of user-specified points is also written to the dfs0.

You must specify the name of the output file and if you choose "Standard output and point output" you must also specify the location of the points. You must select the map projection (Long/Lat, UTM-32 etc.) in which you want to specify the horizontal location of the points. The geographical coordinates are either taken from the dialog or from a file. The file format is an ascii file with four space separated items for each point on separate lines. The first two items must be floats (real numbers) for the x- and y-coordinate. The third item is unused (but must be specified). The last item (the remaining of the line) is the name specification for each point. The point values in the output file are determined by piecewise linear interpolation. Hence, the point values are the discrete values for the element in which the specified point is located.

Domain

For the output of domain convergence information you can select the following three options



- No output
- Output after end calculation
- Intermediate output

If domain output is selected the following items is written to a dfsu-file

- The significant wave height
- The mean wave period
- The mean wave direction
- The change in significant wave height between two iterations steps
- The RMS-norm of the local residual (spectral domain)

You must specify the name of the output file and if you choose "Intermediate output" and you must also specify the frequency by which information should be stored.

6.4.4 CFL Number

For the fully spectral formulation and Cartesian co-ordinates, the CFL number is defined as

$$CFL = \left| c_x \frac{\Delta t}{\Delta x} \right| + \left| c_y \frac{\Delta t}{\Delta y} \right| + \left| c_\sigma \frac{\Delta t}{\Delta \sigma} \right| + \left| c_\theta \frac{\Delta t}{\Delta \theta} \right| \quad (6.6)$$

where c_x , c_y , c_s and c_q is the is the propagation velocity of a wave group in the four-dimensional phase space x , y , σ and θ . Δx and Δy are characteristic length scale in the x - and y -direction for an element, $\Delta \sigma$ and $\Delta \theta$ is discrete interval in the direction and frequency space and Δt is the time step interval.

6.5 Water level conditions

For wave simulations in tidal areas, it is important that the correct water level is used in the wave simulation. This will ensure that the changes in wave conditions due to varying water depths resulting from the tides are properly modelled. The water level condition can be specified in three different ways

- No water level variation
- Specified water level variation
- Water level variation from HD simulation

Selecting the Specified water level variation option you must specify the water level in m. Note, that the last option is only possible using the MIKE 21/3 Coupled Model FM and only if the Hydrodynamic simulation is included.



Water level data

The format of the water level data can be specified in three different ways

- Constant (in domain and time)
- Varying in time, constant in domain
- Varying in time and domain

For the case with water level varying in time but constant in domain you have to prepare a data file containing the water level before you set up the spectral wave simulation. The data file must be a time series file (dfs0). The data must cover the complete simulation period. The time step of the input data file does not, however, have to be the same as the time step of the spectral wave simulation. A linear interpolation will be applied if the time steps differ.

For the case with water level varying both in time and domain you have to prepare a data file containing the water level before you set up the spectral wave simulation. The file must be a 2D unstructured data file (dfs1) or a 2D grid data file (dfs2). The area in the data file must cover the model area. If a dfs1-file is used piecewise constant interpolation is used to map the data, while if a dfs2-file is used bilinear interpolation is used. The data must cover the complete simulation period. The time step of the input data file does not, however, have to be the same as the time step of the spectral wave simulation. A linear interpolation will be applied if the time steps differ.

Soft start interval

The soft start interval is the time interval over which the forcing functions are gradually increased from zero to 100% of their true value.

6.5.1 Remarks and hints

A dfs1 data file including spatial and temporary varying water level is obtained by running a MIKE 21 Flow Model FM simulation a priori to the wave simulation.

6.6 Current conditions

In the presence of a current field the wave action and not the wave energy is conserved. The main effect of the current on the waves is that the current velocity has to be taken into consideration in calculating the propagation speed of the wave action. Furthermore, the effect of the current on the source functions is also taken into account. The current condition can be specified in three different ways

- No current
- Specified current variation



- Current variation from HD simulation

Selecting the specified current variation option you must specify the velocity components in m/s. Note, that the last option is only possible using the MIKE 21/3 Coupled Model FM and only if the Hydrodynamic module is included.

Blocking factor

For cases with strong apposing current blocking may occur. For wave blocking conditions the wave heights can be overestimated. Therefore the wave action density is set to zero, when the current become to strong, that is when the following criterion is satisfied

$$(C_g + (u \cos(\theta) + v \sin(\theta))) / C_g < f \quad (6.7)$$

where C_g is the group velocity, (u, v) is the current velocity components, θ is the discrete directions of wave propagation and f is the blocking factor. The default value of the blocking factor is 0.1.

Current data

The format of the current data can be specified in three different ways

- Constant (in domain)
- Varying in time, constant in domain
- Varying in time and domain

For the case with current field varying in time but constant in domain you have to prepare a data file containing the two velocity components before you set up the spectral wave simulation. The data file must be a time series file (dfs0). The data must cover the complete simulation period. The time step of the input data file does not, however, have to be the same as the time step of the spectral wave simulation. A linear interpolation will be applied if the time steps differ.

For the case with current field varying both in time and domain you have to prepare a data file containing the velocity components before you set up the spectral wave simulation. The file must be a 2D unstructured data file (dfs1) or a 2D grid data file (dfs2). The area in the data file must cover the model area. If a dfs1-file is used piecewise constant interpolation is used to map the data, while if a dfs2-file is used bilinear interpolation is used. The data must cover the complete simulation period. The time step of the input data file does not, however, have to be the same as the time step of the spectral wave simulation. A linear interpolation will be applied if the time steps differ.

Note, that the two velocity components are interpolated as scalar items.

Soft start interval

The soft start interval is the time interval over which the forcing functions are gradually increased from zero to 100% of their true value.

6.6.1 Remarks and hints

A dfsu data file including spatial and temporary varying current is obtained by running a MIKE 21 Flow Model FM simulation a priori to the wave simulation.

Wave blocking is not included in the Spectral Wave Module. When an opposing current is too strong for the waves to exist the propagation speed is set to zero.

6.7 Wind forcing

Successful wave hindcast and forecast depend on accurate wind fields deduced from meteorological models and analysis. As the wind field is the driving force, the largest gain in the Spectral Wave Module is to specify accurate and representative wind fields.



Please note that wind forcing using the directionally decoupled parametric formulation is only possible for the quasi-stationary time formulation.

The wind forcing can be specified in three different ways

- No wind
- Wind, speed and direction
- Wind, velocity components

Wind data

When the speed and direction option is selected the format of the wind data can be specified in three different ways

- Constant (in domain and time)
- Varying in time, constant in domain
- Varying in time and domain

For the case with wind field varying in time but constant in domain you have to prepare a data file containing the wind speed and direction (in degrees from true North) before you set up the spectral wave simulation. The data file must be a time series file (dfs0). The data must cover the complete simulation period. The time step of the input data file does not, however, have to be the same as the time step of the spectral wave simulation. A linear interpolation will be applied if the time steps differ.



For the case with wind field varying both in time and domain you have to prepare a data file containing the wind speed and direction (in degrees from true North) before you set up the spectral wave simulation. The file must be a 2D unstructured data file (dfs_u) or a 2D grid data file (dfs2). The area in the data file must cover the model area. If a dfs_u-file is used piecewise constant interpolation is used to map the data, while if a dfs2-file is used bilinear interpolation is used. The data must cover the complete simulation period. The time step of the input data file does not, however, have to be the same as the time step of the spectral wave simulation. A linear interpolation will be applied if the time steps differ.

When the velocity components option is selected the format of the wind data must be specified as varying in time and domain. You have to prepare a data file containing the two velocity components before you set up the spectral wave simulation. The file must be a 2D unstructured data file (dfs_u) or a 2D grid data file (dfs2). The area in the data file must cover the model area. If a dfs_u-file is used piecewise constant interpolation is used to map the data, while if a dfs2-file is used bilinear interpolation is used. The data must cover the complete simulation period. The time step of the input data file does not, however, have to be the same as the time step of the spectral wave simulation. A linear interpolation will be applied if the time steps differ.

Soft start interval

The soft start interval is the time interval over which the forcing functions are gradually increased from zero to 100% of their true value.

Type of air-sea interaction (fully spectral formulation)

Wind-wave generation is the process by which the wind transfers energy into the water body for generating waves. You can choose between two types of wind input.



- A “coupled” formulation means the momentum transfer from the wind to the waves or drag depends not only on the wind but also on the waves according to the formulation in Komen et al. (1994). Thus, the “coupled” formulation is a sea-state dependent roughness similar to the community WAM Cycle 4 wave model, WAMDIG Group (1988). The default value of the background roughness Charnock parameter is 0.01. It is recommended not to change this parameter.
- An “uncoupled” formulation means the momentum transfer from the wind to the waves solely depends on the wind speed, and consists on a sea state independent roughness description. You can specify either a Charnock constant (version 1) or wind drag coefficient (version 2). For open oceans a Charnock parameter of 0.01 is typically used while a value of 0.0185 has been suggested for coastal areas. The default drag law is taken from Smith and Banke (1975).



For large scale applications (say, spatial scale $> \sim 100$ km) it is recommended to use the coupled formulation with default values. For small scale applications (say, spatial scale $< \sim 10$ -100 km) the use of the coupled formulation may result in an overestimation of the sea surface roughness and thus an overestimation of the significant wave height, see eg, Johnson and Kofoed-Hansen (2000) and Kofoed-Hansen et al (2000). The overestimation has mainly been observed for relatively strong winds, say, $U_{10} > 13$ m/s. Improved model results have been obtained using an uncoupled formulation of the air-sea interaction, eg. the drag law proposed by Smith and Banke (1975). This is default in MIKE 21 SW is the coupled formulation.

Wind generation formula (parametric spectral formulation only)

The formulation of the wave generation by wind (Directional decoupled parametric formulation) is based on empirical relationships. It is assumed that

- the directional spreading of the energy from the wind follows a $\cos^2\theta$ -distribution
- the average frequency is independent of the direction.

The Spectral Wave Module includes the following five wind formulations, see Johnson (1998) for a thorough description and validation:

SPM73/HBH

Based on expressions derived from the Shore Protection Manual (1973) formulation for the wave growth for fetch-limited sea states in deep water with coefficients as fitted by Holthuijsen, Booij and Herbers (1989).

SPM84

Based on expressions derived from the Shore Protection Manual (1984) formulation for the wave growth for fetch-limited sea states in deep water using a power fit for the growth equations.

Kahma and Calkoen

Based on the Kahma and Calkoen (1994) formulation for fetch-limited wave growth in deep water using a power fit for the growth equations.

SPM73

Based on the Shore Protection Manual (1973) using a power fit for the growth equations instead of tuning as done for SPM73/HBH.

JONSWAP

Same as SPM84, but using U_{10} instead of U_a . U_a is the adjusted wind speed as defined in the Shore Protection Manual.

6.7.1 General description

For the fully spectral formulation the wind input source term is parameterized following Janssen's formulation and implemented as in WAM cycle 4, see



Komen et al. (1994). For a given wind speed and direction, the growth rate of waves of a given frequency and direction depends on the friction velocity, u_* , and sea roughness z_0 . In principle, if the sea roughness is known or assumed (e.g. the Charnock parameter $z_{ch} = g \cdot z_0 / u_*^2$, may be assumed), the wind friction speed can be estimated using the logarithmic wind profile. Thus, the growth rate of waves due to wind input can be calculated. Assuming a dimensionless sea roughness ($z_{ch} = g \cdot z_0 / u_*^2$) of 0.0144, this formulation was shown in Komen et al. (1994) to fit the observations compiled by Plant (1982). Note that the use of a constant Charnock parameter implies that sea roughness is not coupled with the wave spectrum in the comparison with observations shown in Komen et al.

In addition to the parameterization of the wind input source term, Janssen (1991) parameterized the sea roughness in terms of wave induced stress, τ_w which depends on the wave spectrum.

6.7.2 Remarks and hints

The wind direction is defined with respect to true North (coming from). Wind speeds should be given as U_{10} (wind speed taken 10 m above the Mean Sea Level).

6.8 Ice coverage

It is possible to take into account the effects of ice coverage on the wave field. Ice covered sea is considered as 'land' assuming zero wave energy and boundary conditions at the ice edges are identical to boundary conditions at shorelines.

Mesh points are taken out of the calculations if the ice concentration (defined as the fraction of sea covered with ice) becomes larger than a user-defined concentration (default 0.33). If the ice concentration drops below this value, the corresponding mesh point is 're-activated'. The spectrum is then initialised with a PM spectrum based on a local wind direction with a peak frequency corresponding to the second highest discrete frequency.

The treatment of ice coverage follows the discontinuous approach described in e.g. Tolman (2003).

Maps of ice concentration are issued by e.g. meteorological institutes.

Ice data

You have to prepare a data file containing the ice concentration before you set up the spectral wave simulation. The file must be a 2D unstructured data file (dfs1) or a 2D grid data file (dfs2). The area in the data file must cover the model area. If a dfs1-file is used piecewise constant interpolation is used to map the data, while if a dfs2-file is used bilinear interpolation is used. The

data must cover the complete simulation period. The time step of the input data file does not, however, have to be the same as the time step of the spectral wave simulation. A linear interpolation will be applied if the time steps differ.

6.9 Diffraction

Diffraction is included using the phase-decoupled refraction-diffraction approximation proposed by Holthuijsen et al. (2003). For more details see the scientific manual.

The approximation is based on the mild-slope equation for refraction and diffraction, omitting phase information. It does therefore not permit coherent wave fields in the computational domain as in deterministic phase-resolving models such as Boussinesq type models.

For instationary calculations the inclusion of diffraction can cause oscillations in the numerical solution in areas with very fine resolution and/or large ratio between element sizes. For quasi-stationary calculations the inclusion of diffraction can cause convergence problems. To reduce these problems a smoothing is introduced for the discrete values of the square root of the directional spectral energy density, $A_{i,l} = A(x_i, y_i, \sigma_l)$, which is used in the calculation of the diffraction parameter. This smoothing is done according to

$$A_{i,l}^k = (1 - \alpha)A_{i,l}^{k-1} + \alpha(A_{i,l}^{k-1})^* \quad k = 1, \text{nsteps} \quad (6.8)$$

Here k is the number of smoothing steps and α is the smoothing factor. The smooth approximation, A^* , is calculated by first calculating the vertex values using the pseudo-Laplacian procedure proposed by Holmes and Connell (1989) and then calculating the cell-centred values by averaging the vertex values corresponding to each element. By default one filtering step is performed with a smoothing factor of $\alpha = 1$. Note, the smoothing is only used in the calculation of the diffraction parameter. Increasing the smoothing (increasing the number of smoothing steps) will reduce the oscillation/convergence problem, but will also have the effect that the diffraction effect will be reduced.

6.9.1 Remarks and hints

Holthuijsen et al. (2003) suggest that the phase-decoupled refraction–diffraction approximation can be used in most situations, including situations near absorbing or reflecting coastlines of oceans, seas, bays, lagoons and fjords with an occasional obstacle such as islands, breakwaters, or headlands.

It cannot be used in harbours with standing waves or near well-defined cliff walls. Note that the coastline may be fully reflecting as long as the reflection is incoherent (e.g., irregular blocks, rocks or reefs that are small compared to



the wave length) because incoherent reflection can be accounted for using a reflective boundary condition. A harbour with reflective quays that would induce coherent wave fields in the harbours (seen as standing or partial standing wave patterns) cannot be accommodated.

6.10 Energy transfer

The nonlinear energy transfer amongst the different wave components of a directional-frequency spectrum plays a crucial role for the temporal and spatial evolution of a wave field.

Quadruplet-wave interaction

The quadruplet-wave interaction controls

- the shape-stabilisation of the high-frequency part of the spectrum
- the downshift of energy to lower frequencies
- frequency-dependent redistribution of directional distribution functions

The quadruplet-wave interaction in the spectral wave module is described by the accepted approximate Discrete Interaction Approximate (DIA), Komen et al. (1994). The DIA has been found quite successful in describing the essential features of a developing wave spectrum.

Triad-wave interaction

In shallow water triad-wave interaction becomes important. Nonlinear transformation of irregular waves in shallow water involves the generation of bound sub- and super-harmonics and near-resonant triad interactions, where substantial cross-spectral energy transfer can take place in relatively short distance. The process of triad interactions exchanges energy between three interacting wave modes. The triad-wave interaction is modeled using the simplified approach proposed by Eldeberky and Battjes (1995, 1996).

Transfer coefficient

You can specify the transfer coefficient for triad-wave interaction. This coefficient controls the magnitude of the interaction. The default value is 0.25.

6.10.1 Remarks and hints

The computation of the DIA quadruplet-wave interaction source function is computational time consuming. You may exclude this source function in wave transformation calculations for very small domains (say, extensions less than 5 km).

In very shallow water (say, water depth less than 5 m) triad-wave interactions may result in the development of secondary peaks at harmonics of the spec-



tral peak frequency as well as the generation of spectral energy within the infragravity wave frequency band. For further reading reference is made to Kofoed-Hansen and Rasmussen (1998, 2000).

The inclusion of triad-wave interaction in combination with quadruplet-wave interaction can give cause to instability and unphysical solution.

6.11 Wave breaking

Depth-induced wave breaking is the process by which waves dissipate energy when the waves are too high to be supported by the water depth, i.e. reach a limiting wave height/depth-ratio.

The formulation used in the spectral wave module is based on the formulation of Battjes and Janssen (1978). This model has been used successfully in the past in fully spectral models as well as in parameterized versions.

If wave breaking is included you have to specify the Gamma parameter used in the breaking formulation. The Gamma parameter can be specified in three ways

- Specified Gamma
- Functional form (Ruessink et. al. 2003)
- Functional form (Nelson (1987, 1994))

Gamma data

For the case with specified gamma, the Gamma parameter can be specified in two ways

- Constant (in domain)
- Varying in domain

For the case with values varying in domain you have to prepare a data file containing the Gamma parameter before you set up the spectral wave simulation. The file must be a 2D unstructured data file (dfs2) or a 2D grid data file (dfs2). The area in the data file must cover the model area. If a dfs2-file is used piecewise constant interpolation is used to map the data, while if a dfs2-file is used bilinear interpolation is used.

Alpha

The alpha controls the rate of dissipation and is a proportional factor on the wave breaking source function. The default value is 1.



Gamma (wave steepness)

This gamma value controls the wave steepness condition and is used in the directionally decoupled parametric formulation only. The default value is 1.

Effect on mean wave frequency

The effect of wave breaking on the mean wave frequency can be included in the directionally coupled parametric formulation. Here, the assumption is that the dissipation of energy due to wave breaking is concentrated on the low frequencies. Hence, the wave breaking has the effect that the mean wave period is reduced. By default the effect on the mean wave frequency is excluded.

6.11.1 General description

Depth-induced breaking occurs when waves propagate into very shallow areas, and the wave height can no longer be supported by the water depth. The formulation of wave breaking is based on the breaking model by Battjes and Janssen (1978). Eldeberky and Battjes (1995) proposed a spectral version of the breaking model, where the spectral shape was not influenced by breaking.

The source term due to depth-induced breaking can be written

$$S_{surf}(\sigma, \theta) = -\frac{\alpha Q_b \bar{\sigma} H_m^2}{8\pi} \frac{E(\sigma, \theta)}{E_{tot}} \quad (6.9)$$

where $\alpha \approx 1.0$ is a calibration constant, Q_b is the fraction of breaking waves, $\bar{\sigma}$ is the mean relative frequency, E_{tot} is the total wave energy and $H_m = \gamma d$ is the maximum wave height. Here γ is the free breaking parameter (a wave height - to depth ratio).

Based on laboratory data and field data it has been shown that the breaking parameter γ varies significantly depending on the wave conditions and the bathymetry. Kaminsky and Kraus (1993) found that γ values in the range between 0.6 and 1.59 with an average of 0.79. A number of expressions for determination of the breaking parameter γ have been proposed in literature. Battjes and Stive (1985) found that γ depends weakly on the deep water wave steepness. They proposed the following expression

$$\gamma = 0.5 + 0.4 \tanh(33 s_0) \quad (6.10)$$

Here $s_0 = H_0/L_0$ is the deep water steepness, where H_0 and L_0 is the wave height and the wave length, respectively, in deep water. This formulation can not be used in the present spectral wave model, because the value of γ is not determined based on local parameters. Nelson (1987, 1994) found that γ can



be determined as a function of the local bottom slope, $\partial d / \partial s$, in the mean wave direction. Nelson suggested the following expression

$$\begin{aligned} \gamma &= 0,55 + 0,88 \exp\left(-0,012 \cotan\left(\frac{\partial d}{\partial s}\right)\right) & d \leq 100 \\ \gamma &= 0,55 & d > 100 \end{aligned} \quad (6.11)$$

Recently, Ruessink et al. (2003) have presented a new empirical form for γ , where γ is determined as a function of the product of the local wave number k and the water depth d

$$\gamma = 0,76kh + 0,29 \quad (6.12)$$

Ruessink et al. showed that using this formulation for the breaking parameter the prediction of the wave heights in the breaking zone can be improved for barred beaches. However, the new formulation is also applicable to planar beaches.

6.11.2 Remarks and hints

By increasing the gamma and/or alpha parameter the dissipation can be reduced. In the calibration process it is recommended to first consider the influence of changing/varying the gamma value controlling the depth-induced wave breaking.

The default value of 1 for the gamma value controlling the dissipation due to wave steepness can in some cases give a too strong dissipation. Especially, when the wind is included. In this case a larger value (2-5) can be used.



Experience has shown that in general the best results are obtained if the effect of breaking on the mean wave period is excluded.

6.12 Bottom friction

As waves propagate into shallow water, the orbital wave velocities penetrate the water depth, and the source function due to wave-bottom interaction become important. The dissipation source function used in the spectral wave module is based on the quadratic friction law and linear wave kinematic theory. The dissipation (proportional) coefficient proportional depends on the hydrodynamic and sediment conditions as described in Johnson and Kofoed-Hansen (2000).

The bottom friction can be specified in five different ways

- No bottom friction
- Friction coefficient, C_{fw}



- default value is 0.0077 m/s
 - the dissipation coefficient does not depend on the wave hydrodynamic/sediment conditions
- Friction factor, f_w
 - default value is 0.0212
 - the dissipation coefficient does not depend on the wave hydrodynamic/sediment conditions
- Nikuradse roughness, k_N
 - default value is 0.04 m (this value is often used for offshore applications using the fully spectral formulation, but is usually too high for nearshore applications)
 - the dissipation coefficient depends on wave hydrodynamic conditions
- Sand grain size, d_{50}
 - default value is 0.00025 m (median sediment grain size)
 - the dissipation coefficient depends on wave hydrodynamic and sediment conditions

Bottom friction data

The bottom friction parameter (the friction coefficient, the friction factor, the Nikuradse roughness or sand grain size) can be specified in two ways

- Constant (in domain)
- Varying in domain

For the case with values varying in domain you have to prepare a data file containing the bottom friction parameter before you set up the spectral wave simulation. The file must be a 2D unstructured data file (dfsu) or a 2D grid data file (dfs2). The area in the data file must cover the model area. If a dfsu-file is used piecewise constant interpolation is used to map the data, while if a dfs2-file is used bilinear interpolation is used.

Current friction factor

When wave current interaction is studied in shallow water you also have to specify a current friction factor. The default value is zero.

Effect on mean wave frequency

The effect of bottom dissipation on the mean wave frequency can also be included in the directionally decoupled parametric formulation. Here the assumption is that the dissipation of energy due to bottom friction is concentrated on the low frequencies of the spectrum. Hence, the bottom dissipation has the effect that the mean wave period is reduced. By default the effect on the mean wave frequency is included.

6.12.1 General description

As waves propagate into shallow water, the orbital wave velocities penetrate the water depth and the source terms due to wave-bottom interaction become important. Furthermore, the deep-water source terms are modified because of depth effects. A review of the different wave-bottom interaction processes is given by Shemdin et al. (1978), who consider dissipation due to friction in the turbulent boundary layer, percolation into a porous bottom, motion of a soft bottom and scattering on bottom irregularities. According to Shemdin et al. (1978) bottom friction is generally dominant when the sediment is composed of fine sand, $d_{50} = 0.1\text{-}0.4$ mm or when sand ripples are present. In this case, the low permeability prohibits percolation and granular friction prevents viscous flow behaviour (Shemdin et al., 1978). In many practical cases, the bed is composed of fine sand or wave-generated ripples are present (e.g. Dinger and Inman (1976) found this to be true on many continental shelves).

For the fully spectral formulation the bottom dissipation source function is based on linear theory and can be generalised into Eq. (6.13) below, Weber (1991)

$$S_{bot}(\sigma, \theta) = -C_f \frac{k}{\sinh 2kh} E(\sigma, \theta) \quad (6.13)$$

where C_f is a dissipation coefficient ($= f_w U_{bm}$), which depends on the hydrodynamic and sediment conditions. Here f_w is the wave friction factor and U_{bm} is the maximum near-bed particle velocity given by

$$U_{bm} = \left[\iint 4 \frac{gk}{\sinh 2kh} N(\sigma, \theta) d\sigma d\theta \right]^{1/2} \quad (6.14)$$

Further details are described in Johnson and Kofoed-Hansen (2000).

6.12.2 Remarks and hints

By reducing the roughness of the bottom the dissipation can be reduced. In the calibration process it is recommended to use the default model (Nikuradse roughness) and evaluate the influence of changing/varying the roughness height.

The bottom friction in areas dominated by sand depends on the grain size of the sediment and the presence of bed forms. For the case where there is no bed form, the Nikuradse roughness parameter k_N can be estimated by $k_N = 2d_{50}$, where d_{50} is the median grain size. In the presence of ripples k_N can be much larger than this value and should be estimated including the ripple characteristics. The bed roughness can be further increased due to the presence



of vegetation. In general, it is quite difficult to assess this parameter; thus it is used as a calibration factor.

If a variable bottom friction value is used (dfs2/dfsu data file) the spectral wave module utilises a linear interpolation to obtain the bottom friction values at the node points.



Experience has shown that in general the best results are obtained if the effect of bottom dissipation on the mean wave period is included.

6.13 White capping

White capping is primarily controlled by the steepness of the waves. It is important that white capping is included in your model simulation. By excluding the white capping you may, however, evaluate its impact on the establishment of an equilibrium sea state.

The breaking wave dissipation source function is detailed described in the Komen et al. (1994) and includes two free parameters; C_{dis} and Δ_{dis} .

If white capping is included you have to specify the two dissipation coefficients, C_{dis} and Δ_{dis} . The C_{dis} coefficient is a proportional factor on the white capping dissipation source function and thus control the overall dissipation rate. The Δ_{dis} coefficient is controlling the weight of dissipation in the energy/action spectrum.

Dissipation coefficient C_{dis}

The dissipation coefficient, C_{dis} , can be specified in two ways

- Constant (in domain)
- Varying in domain

For the case with values varying in domain you have to prepare a data file containing the dissipation coefficient, C_{dis} , before you set up the spectral wave simulation. The file must be a 2D unstructured data file (dfsu) or a 2D grid data file (dfs2). If a dfsu-file is used the mesh in the data file must match exactly the mesh in the simulation. If a dfs2-file is used the area in the data file must cover the model area. Bilinear interpolation is used to map the data.

Dissipation coefficient Δ_{dis}

The dissipation coefficient, Δ_{dis} , can be specified in two ways

- Constant (in domain)
- Varying in domain

For the case with values varying in domain you have to prepare a data file containing the dissipation coefficient, Δ_{dis} , before you set up the spec-



tral wave simulation. The file must be a 2D unstructured data file (dfs_u) or a 2D grid data file (dfs2). The area in the data file must cover the model area. If a dfs_u-file is used piecewise constant interpolation is used to map the data, while if a dfs2-file is used bilinear interpolation is used.

Wave parameters

The values for the mean frequency power and mean wave number power must be specified as well. The two parameters are used in the definition of the mean angular frequency and the mean wave number (See General description below).

The type of spectrum can be specified in two ways:

- Whole spectrum
- Wind sea part

The formulation of the source term due to whitecapping is as standard applied over the entire spectrum and the integral wave parameters used in the formulation is calculated based on the whole energy spectrum. For wave conditions with a combination of wind-sea and swell this may result in too strong decay of energy on the swell components. Hence, when "Separation of Wind-sea and Swell" is specified on the Spectral discretization page (see p.58), the predictions for these cases can be improved by only including the dissipation on the wind sea part of the spectrum and by calculating the wave parameters, used in the formulation of whitecapping, from the wind-sea part of the spectrum.

6.13.1 General description

The source function describing the dissipation due to white-capping is based on the theory of Hasselmann (1974). With the introduction of Janssens (1989) description of wind input, it was realized that the dissipation source function needs to be adjusted in order to obtain a proper balance between the wind input and the dissipation at high frequencies.

For the fully spectral formulation the source function is given by

$$S_{ds}(\sigma, \theta) = -C_{ds}(\bar{k}^2 m_0)^2 \left\{ (1 - \delta) \frac{k}{\bar{k}} + \delta \left(\frac{k}{\bar{k}} \right)^2 \right\} \bar{\sigma} N(\sigma, \theta) \quad (6.15)$$



where C_{ds} (Cdis) and δ (DELTA_{dis}) are two dispersion coefficients. The mean angular frequency, $\bar{\sigma}$, and the mean wave number, \bar{k} , are calculated as follows

$$\bar{\sigma} = 2\pi\bar{f} = 2\pi \frac{\int_0^{2\pi\infty} \int_0^{2\pi\infty} E(f, \theta) f_{\sigma}^p df d\theta}{\int_0^{2\pi\infty} \int_0^{2\pi\infty} E(f, \theta) df d\theta}^{p_{\sigma}} \quad (6.16)$$

$$\sqrt{\bar{k}} = \frac{\int_0^{2\pi\infty} \int_0^{2\pi\infty} E(f, \theta) (\sqrt{k})^{p_k} df d\theta}{\int_0^{2\pi\infty} \int_0^{2\pi\infty} E(f, \theta) df d\theta}^{p_k} \quad (6.17)$$

where p_{σ} and p_k are mean angular frequency power and the mean wave number power. Janssen (See Komen et. al (1994)) proposed to use the following values: $C_{ds} = 4.5$, $\delta = 0.5$ and $p_{\sigma} = p_k = -1$.

To improve the the whitecapping for wave conditions with a combination of wind-sea and swell Bidlot et. al 2007 proposed a revised formulation of whitecapping. Here eq. (6.15) is still applied but the mean relative angular frequency and the mean wave number are calculated using $p_{\sigma} = p_k = 1$ and the default values for C_{ds} and δ are changed to 2.1 and 0.6, respectively.

6.13.2 Remarks and hints

Please notice that the white capping dissipation is only relevant for the fully spectral formulation.

By reducing the Cdis coefficient the overall white capping dissipation can be reduced resulting in larger waves.

Please notice that the DELTA_{dis} value should be larger than zero and smaller than one.

A DELTA_{dis} coefficient less than 0.5 correspond to increase the weight of dissipation on lower frequencies resulting in smaller wave periods. A DELTA_{dis} coefficient larger than 0.5 correspond to increase the weight of dissipation on higher frequencies resulting in larger wave periods.



6.14 Structures

The horizontal dimension of structures such as piers, offshore wind turbines, breakwaters, dams and caissons is usually much smaller than the resolution used in the computational grid. Therefore, the presence of these structures must be modeled by a subgrid scaling technique. Two different types of structures can be included in the simulations:

- Point structures
- Line structures

6.14.1 Point structures

Two approaches have been developed for taking into account the effect of point structures:

- Source term approach
- Convective flux approach

The source term approach takes the effects of the structures into account by introducing a decay term to reduce the wave energy behind the structure. This formulation is only accurate when the energy decay is limited and the reflection of the wave energy is not taken into account. The convective flux approach is based on a correction of the convective flux term in geographical space.

Depending on the choice of property page you can either specify detailed information for the structures or see a geographic view.

Structure data

The geographical coordinates of the structures are either taken from the dialog or from a file. The file format is an ASCII file with two space separated items for each point on separate lines. The two items must be floats (real numbers) for the x- and y-coordinate. For each structure you must specify the type of structure. You can select either "Circular pier" or "User-specified structure". If "Circular pier" is selected you must also specify the diameter of the pier. If "User-specified structures" is selected you must enter the file name for the file containing the reflection factor table. This table should contain the reflection factor as function of the discrete values of the depth and the mean wave period. For the description of the format of the file see below. Note that the format of the table is the same whether you apply a source term approach or a convective flux approach.

You must also select the map projection (Long/Lat, UTM-32 etc.) in which you want to specify the horizontal location of the points.



ASCII format for the reflection factor table

This is a general format which can be generated by most spread sheets or text editors. The first part of the ASCII file must contains the header Information. The header information consists of two lines each with three space separated items. The first line contains the number of discrete depth, nd , the minimum depth, d_{min} , and the maximum depth, d_{max} . The second line contains the number of discrete mean wave periods, nt , the minimum mean wave period, T_{min} , and the maximum mean wave period, T_{max} . Data follows after the header information. The data consist of the reflection factor, $c_{i,j}$, as function of discrete value of the depth and mean wave periods

$$d_i = d_{min} + (i-1) \frac{d_{max} - d_{min}}{(nd-1)}, \quad i = 1, nd \quad (6.18)$$

$$T_j = T_{min} + (j-1) \frac{T_{max} - T_{min}}{(nt-1)}, \quad j = 1, nt \quad (6.19)$$

The format of a reflection factor table is shown below:

```

nd d_min d_max
nt T_min T_max
c1,1 c1,2 c1,3 ... c1,nt
c2,1 c2,2 c2,3 ... c2,nt
...
...
cnd,1 cnd,2 cnd,3 ... cnd,nt

```

General description

Source term approach

The source term due to the effect of a structure can be written

$$s = -\frac{c}{A} c_g E(\sigma, \theta) \quad (6.20)$$

where A is the area of the cell/element in the mesh in which the structure is located, c is the reflection factor, c_g is the group celerity and $E(\sigma, \theta)$ is the energy density.

Convective flux approach

The contribution from the convective transport to the time-derivative wave action density due to the effect of a structure can be written

$$-\frac{1}{A} \sum (F_n \cdot \Delta l) \quad (6.21)$$



where A is the area of the cell/element in the mesh in which the structure is located and the normal flux through the element edge, F_n , is multiplied with the length Δl and summed over the number of edges.

6.14.2 Line structures

Depending on the choice of property page you can see a Geographic View or a List View of the Line structures.

There are two different methods for specification of the line structure.

In the List View you can create a new line structure clicking on the "New line" button. By selecting a Line structure in the Line list and clicking on the "Delete line" button you can remove this line structure. For each line structure you can specify the name of the line structure and whether the line structure should be active or not. The specification of detailed information for each line structure is made subsequently. From the List View page you can navigate to the dialog for specification by clicking on the "Go to ..".

In the Geographic View it is also possible to create a new line structure by selecting "Add New line" from the context menu. Click once to add a point and twice to add the end point of the line structure. You may edit the individual line structure by selecting and moving the specified points (point, click and drag) or using the functionalities from the context menu (point, right-click). The additional information for the line structure is entered subsequently.

Line structure specification

The data for the line structure and the location and geometry of the line structure must be specified.

Data

The type of transmission can be specified as

- Constant transmission coefficient
- Goda's formula

When **Constant transmission coefficient** is selected you have to specify the value of the transmission coefficient, K_t . When **Goda's formula** is selected you have to specify the two parameters α and β in the formula (see General description p. 86) and the minimum and maximum transmission coefficient.

The type of reflection can be specified as

- Constant reflection coefficient
- Full reflection



When "Constant reflection coefficient" is selected you have to specify the value of the reflection coefficient, K_r . When "Full reflection" is specified the reflection coefficient is determined as

$$K_r = 1 - K_t \quad (6.22)$$

Location and geometry

The location in the horizontal domain of a structure may be given by a number of geo-referenced points which together make up a polyline. A minimum of two points is required. The polyline is composed of a sequence of line segments. The line segments are straight lines between two successive points. The polyline (cross section) in the numerical calculations is defined as a section of element faces. The face is included in the section when the line between the two element centers of the faces crosses one of the line segments.

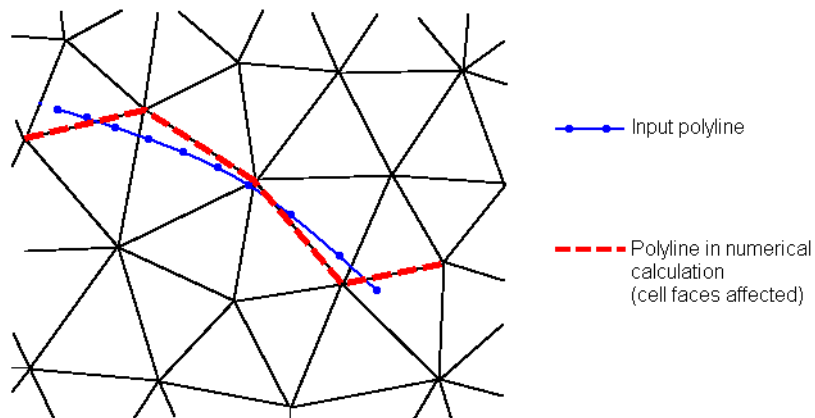


Figure 6.1 The location of a line structure. Note the affected cell faces.

The crest level of the structure has to be specified when "Goda's formula" is selected for the "Transmission type". This crest level can be specified as

- Constant
- Varying in domain

When Constant is specified you have to specify the constant crest level. The geographical coordinates and the crest level, when "Varying in domain" is selected for the crest level, are taken from the dialog or from an ASCII file. The file format is three space separated floats (real numbers) for the x- and y-coordinate and the crest level on separate lines for each of the points. The faces defining the line section are listed in the log-file.

You must also select the map projection (Longitude/Latitude, UTM etc.) in which you want to specify the location of the line section for the structure.

Crest level correction

When "Goda's formula" is selected for the "Transmission type" it is also possible to specify a correction of the crest level. The format for the crest level correction can be specified as

- Constant
- Constant in time and varying along line
- Varying in time and varying along line

When "Constant in time and varying along line" and "Varying in time and varying along line" is specified you have to prepare a data file containing crest level correction before you set up the wave simulation. The file must be a dfs1 file, where the number of grid points corresponds to the number of points, which is used to define the input polyline. The data must cover the complete simulation period when "Varying in time and varying along line" is specified for the format. The time step of the input data file does not, however, have to be the same as the time step of the hydrodynamic simulation. A linear interpolation will be applied if the time steps differ.

General description

The energy balance equation for the physical process of a wave encountering a structure can be stated as

$$K_t^2 + K_r^2 + K_l^2 = 1 \quad (6.23)$$

where K_t is the transmission coefficient, K_r is the reflection coefficient and K_l is the loss coefficient. The transmission coefficient, K_t , describes the intensity of a transmitted wave height relative to an incident wave height. The corresponding transmission of the wave energy for each individual spectral bin is taken as K_t^2 . The reflection coefficient, K_r , describes the intensity of a reflected wave height relative to an incident wave height. The corresponding reflection of the wave energy for each individual spectral bin is taken as K_r^2 .

Using Goda's formula the transmission coefficient is given by

$$\begin{aligned} K_t &= K_{t, \max} & \frac{f}{H_i} < \left(\frac{f}{H_r} \right)_{\min} \\ K_t &= \frac{1}{2} \left(1 - \sin \left(\frac{\pi \frac{f}{H_i} + \beta}{2 \alpha} \right) \right) & \left(\frac{f}{H_r} \right)_{\min} \leq \frac{f}{H_i} \leq \left(\frac{f}{H_r} \right)_{\max} \\ K_t &= K_{t, \min} & \frac{f}{H_i} > \left(\frac{f}{H_r} \right)_{\max} \end{aligned} \quad (6.24)$$



where a and b are two fitting coefficients and $K_{t,min}$ and $K_{t,max}$ are the minimum and maximum transmission coefficients. H_i is the incoming wave height and f is the freeboard which is determined as the crest level minus the surface elevation. The minimum and maximum relative freeboard is given by

$$\left(\frac{f}{H_i}\right)_{min} = 2\frac{\alpha}{\pi}\text{asin}(1 - 2K_{t,max}) - \beta \quad (6.25)$$

$$\left(\frac{f}{H_i}\right)_{max} = 2\frac{\alpha}{\pi}\text{asin}(1 - 2K_{t,min}) - \beta \quad (6.26)$$

Goda's formula can be used to estimate the transmission of waves over breakwaters, dams and caissons. Both submerged and emergent or subaerial structures can be taken into account. Using Goda's formula the transmission coefficient is calculated based on the freeboard and the incoming significant wave height and the transmission coefficient is independent of the wave direction. For a vertical wall breakwater $\alpha=2.2$ and β in the range 0.1 to 0.8 with a mean value of 0.4. For more detail on the values of the two fitting coefficients see Goda et. al. (1967) and Goda (1969).

6.15 Initial conditions

You can choose between following three different types of initial conditions:

- Zero spectra
 - the wave action is set to zero in all node points
- Spectra from empirical formulations
 - three different types of formula are available:
 - JONSWAP fetch growth expression
 - SPM 1973 deep water fetch growth expression
 - SPM 1973 shallow water fetch growth expression
 - the description of the empirical formulations can be found in Komen et al. (1994) and the Shore Protection Manual (1973, 1984)
- Spectra from a dfsu data file
 - this type can be used if e.g. you want to hotstart from a previous simulation using MIKE 21 SW
 - using the fully spectral formulation, the input spectrum is the normal wave action spectrum N , e.g expressed by $[m^2s^2/rad]$

- using the directionally decoupled parametric formulation two items must be specified: the zeroth moment m_0 , e.g. expressed by $[m^2/\text{rad}]$, of the normal wave action spectrum and the first moment m_1 , e.g. expressed by $[m^2s/\text{rad}]$, of the normal wave action spectrum.

When the quasi-stationary formulation is used the specified type of initial condition is used as the initial guess for the iterative procedure for the first time step only. For subsequent time steps the initial guess for the iterative procedure is based on the solution obtained from the previous time step. However, you have the option to apply the initial conditions as starting guess for the iterative procedure for all time steps. This is recommendable if you model a time series of representative independent waves.

6.15.1 Remarks and hints



It is recommend using the default type of initial conditions.

Please notice that presently no interpolation in geographical or spectral space is performed. Hence, the data file containing the spectral information must be obtained from a simulation using the same geographical mesh and spectral discretization.

If the simulation includes wind effect an initial condition based on a formulation accounting for fetch length may be a better starting point than a Zero spectra.

6.16 Boundary conditions

Initially, the set-up editor scans the mesh file for boundary codes (sections), and displays the recognized codes and suggest a default name for each. You can re-name these names to more meaningful names in the Domain dialog (see Boundary Names (p. 54)).

Depending on the choice of property page you can get a geographic view or a list view of the boundaries.

The specification of boundary information for each code (section) is made subsequently. From the list view you can go to the dialog for specification by clicking on the “Go to..” button.

6.16.1 Boundary specification

You can choose between the following nine different types of boundary conditions

- Closed boundary



- Wave parameters (Version 1)
- Wave parameters (version 2)
- Wind-sea and swell parameters (Version 1)
- Wind-sea and swell parameters (Version 2)
- Wave action spectrum
- Wave energy spectrum
- Lateral boundary
- Reflective boundary

Closed boundary

Specifying a closed boundary corresponds to having land along the boundary, i.e. no waves enter the model domain through this boundary and the outgoing waves are fully absorbed. This type of boundary is utilized if no wave data is available.

Wave parameters (Version 1 and 2)

Selecting one of the two wave parameters options a parametric representation of the spectral distribution is used. You must specify the following wave parameters at the boundary

- Significant wave height, $Hm0$
- Spectral peak period, Tp
- Mean wave direction, MWD
- Directional spreading index, n (Version 1) or
- Directional standard deviation, DSD (Version 2)

In Version 1 the directional spreading index n is specified, while in Version 2 the directional standard deviation is specified.

For the fully spectral formulation the distribution in the frequency domain is a JONSWAP spectrum with standard shape parameters ($\gamma=3.3$, $\sigma_a=0.07$ and $\sigma_b=0.09$).

Using the directional decoupled parametric formulation the calculations is based on the action-averaged angular wave frequency, ω_0 . Hence, using this formulation a relation between the action-averaged angular wave frequency and the peak period is needed. In the model the following relationships are used. For the JONSWAP spectrum with standard shape parameters the relationship between the action-averaged angular wave frequency, Ω_0 , and the energy-averaged angular wave frequency, ω_0 , is given by $\omega_0/\Omega_0=0.92$ and the relationship between the peak period, T_p , and the energy-averaged angular wave frequency, Ω_0 , is given by $\Omega_0=2\pi/T_p/0.83$.

For the directional distribution a $\cos n(\theta-\theta_m)$ distribution is used, where n is the directional spreading index and θ_m is the mean wave direction (MWD).



The mean wave direction is defined with respect to true North (coming from). When the directional standard deviation, DSD, is specified (Version 2) an equivalent directional spreading index is determined.

The directional standard deviation DSD is defined by

$$DSD = \sqrt{2(1 - \sqrt{a^2 + b^2})}$$

where

$$a = \frac{1}{m_0} \int_0^{2\pi} \int_0^n \cos(\theta) E(\sigma, \theta) d\sigma d\theta$$

$$b = \frac{1}{m_0} \int_0^{2\pi} \int_0^n \sin(\theta) E(\sigma, \theta) d\sigma d\theta$$



The relationship between the directional spreading index and the directional standard deviation is presented in Table 6.1 below.

Table 6.1 The relationship between the directional spreading index and the directional standard deviating

Directional spreading index	Directional standard deviation (deg)
1	39.15
2	32.52
3	28.36
4	25.45
5	23.28
6	21.58
7	20.20
8	19.05
9	18.08
10	17.24
11	16.52
12	15.87
13	15.30
14	14.78
15	14.31
16	13.88
17	13.49
18	13.13
19	12.80
20	12.49
40	8.94
60	7.33
80	6.36
100	5.70

The energy spectrum at the boundary is scaled so that the energy in the discrete part of the spectrum corresponds to the specified energy at the boundary.

Wind-sea and swell parameters (Version 1 and 2)

Selecting one of the two wind-sea and swell parameters options the energy spectrum at the boundary is determined as the superposition of the energy spectra determined from the wave parameters for wind-sea and the wave parameters swell. Both spectra are determined as described in the previous section "Wave parameters (Version 1 and 2)". For the wind-sea part of the



spectrum the standard shape parameters for a JONSWAP spectrum are used and for the swell part the peakedness parameter is changed to $\gamma=5.0$.

Note, that this type of boundary conditions can only be used for the fully spectral formulation.

Wave action spectrum

Selecting the wave action spectrum option you must specify the following parameters

- using the directionally decoupled parametric formulation two items must be specified: the zero-th moment $m_0(q)$, e.g. expressed by $[m^2/\text{rad}]$, of the normal wave action spectrum and the first-order moment $m_1(q)$, e.g. expressed by $[m^2\text{s}/\text{rad}]$, of the normal wave action spectrum. Here q is the wave direction.
- using the fully spectral formulation, the input spectrum is the normal wave action spectrum $N(s,q)$, e.g. expressed by $[m^2\text{s}^2/\text{rad}]$. Here s is the relative angular frequency and q is the wave direction.

Wave energy spectrum

Selecting the wave energy spectrum you must specify normal energy spectrum $E(f,q)$, e.g. expressed by $[m^2\text{s}/\text{rad}]$. Here f is the relative frequency and q is the wave direction.

Lateral boundary

For this type of boundary condition a one-dimensional calculation of the basic equations is solved along the boundary line. The information of the incoming waves in the start point and the end point of the line are obtained from the connected boundary lines.

This type of boundary conditions is a good approximation when the boundary line is almost straight and when the depth contours is almost perpendicular to the line.

Reflective boundary

When specifying a reflective boundary no waves can enter the model domain through this boundary, and the outgoing waves are reflected from the boundary. The amount of wave reflection is controlled by the specified reflection coefficient, R . When the value is 0 the outgoing waves are fully absorbed, and when the value is 1 outgoing waves are fully reflected. In between the waves are partial reflected.

The specified reflection coefficient, R , describes the intensity of a reflected wave height relative to an incident wave height. The corresponding reflection of the wave energy for each individual spectral bin is taken as R^2 . Hence it does therefore not permit coherent wave fields in the computational domain (eg. harbours with standing-wave patterns are excluded).



Boundary Data

Wave parameters (Version 1 and 2) data

The wave parameters can be specified in three different ways

- Constant (in time and along line)
- Varying in time, constant along line
- Varying in time and along line

For the case with waves varying in time but constant in along the boundary you have to prepare a data file containing the boundary values before you set up the wave simulation. The data file must be a time series file (dfs0). The data must cover the complete simulation period. The time step of the input data file does not, however, have to be the same as the time step of the hydrodynamic simulation. You can choose between different type of interpolation (see Interpolation type below).

For the case with waves varying both in time and along the boundary you have to prepare a data file containing the boundary values before you set up the wave simulation. The file must be a profile file (dfs1). The mapping from the input data file to the boundary section is described in Interpolation Type. The data must cover the complete simulation period. The time step of the input data file does not, however, have to be the same as the time step of the wave simulation. You can choose between different type of interpolation (see Interpolation type below).

Wind-sea and swell parameters (Version 1 and 2) data

The wind-sea and swell parameters can be specified in three different ways

- Constant (in time and along line)
- Varying in time, constant along line
- Varying in time and along line

For the case with waves varying in time but constant in along the boundary you have to prepare a data file containing the boundary values before you set up the wave simulation. The data file must be a time series file (dfs0). The data must cover the complete simulation period. The time step of the input data file does not, however, have to be the same as the time step of the hydrodynamic simulation. You can choose between different type of interpolation (see Interpolation type below).

For the case with waves varying both in time and along the boundary you have to prepare a data file containing the boundary values before you set up the wave simulation. The file must be a profile file (dfs1). The mapping from the input data file to the boundary section is described in Interpolation Type. The data must cover the complete simulation period. The time step of the input data file does not, however, have to be the same as the time step of the



wave simulation. You can choose between different type of interpolation (see Interpolation type below).

Wave action spectrum data

The wave action spectrum parameters can be specified in two different ways

- Varying in time, constant along line
- Varying in time and along line

In both cases you have to prepare a data file containing the boundary values before you set up the wave simulation. Using the directionally decoupled parametric formulation the file must contain the zero-th moment $m_0(q)$, e.g. expressed by $[m^2/\text{rad}]$, of the normal wave action spectrum and the first-order moment $m_1(q)$, e.g. expressed by $[m^2\text{s}/\text{rad}]$, of the normal wave action spectrum. Using the fully spectral formulation, the file must contain the normal wave action spectrum $N(s,q)$, e.g. expressed by $[m^2\text{s}^2/\text{rad}]$.

For the case "Varying in time, constant along line" the file must be a dfsu file or a dfs1 or a dfs2 file, respectively, for the two different formulations. For the case "Varying in time and along line" the file must be a dsu file containing line information of the spectral parameters. The data file can be obtained from a previous spectral wave simulation when you have saved spectral information in a selected point or along a line. Using the directionally decoupled parametric formulation linear interpolation is used to map the data in the directional domain. Using the fully spectral formulation bilinear interpolation is used to map the data in the frequency-directional domain. The mapping in the geographical domain for the case "Varying in time and along line" is described in Interpolation Type.

The data must cover the complete simulation period. The time step of the input data file does not, however, have to be the same as the time step of the hydrodynamic simulation. A linear interpolation will be applied if the time steps differ.

Wave energy spectrum data

The wave energy spectrum parameters can be specified in two different ways

- Varying in time, constant along line
- Varying in time and along line

You have to prepare a data file containing the energy spectrum $E(f,q)$, e.g. expressed by $[m^2\text{s}/\text{rad}]$, before you set up the wave simulation.

For the case "Varying in time, constant along line" the file must be a dfsu file or a dfs2 file. For the case "Varying in time and along line" the file must be a dsu file containing line information of the energy spectrum. The data file can be obtained from a previous simulation using the fully spectral formulation when you have saved the energy spectrum in a selected point or along a line.



The mapping in the geographical domain for the case "Varying in time and along line" is described in Interpolation Type.

Using the directionally decoupled parametric formulation the zero-th and first-order moment of the action density directional spectrum is obtained from the specified energy spectrum by integration in the frequency domain. Linear interpolation is used to map the data in the directional domain. Using the fully spectral formulation bilinear interpolation is used to map the data in the frequency-directional domain. The data must cover the complete simulation period. The time step of the input data file does not, however, have to be the same as the time step of the hydrodynamic simulation. A linear interpolation will be applied if the time steps differ.

Soft start

The soft start time interval is time over which the forcing functions are gradually increased from the reference significant wave height to 100% of the true value. The increase can either be linear or follow a sinusoidal curve.

When the Wind-sea and swell parameters (Version 1 and 2) is selected the wind-sea part is soft started using the specified reference value for the significant wave height, while the swell part always is soft started using a reference value of 0 for the significant wave height.

Interpolation type

For the two cases with values varying in time two types of time interpolation can be selected:

- linear
- piecewise cubic

In the case with values varying along the boundary two methods of mapping from the input data file to the boundary section are available:

- normal
- reverse order

Using normal interpolation the first and last point of the line are mapped to the first and the last node along the boundary section and the intermediate boundary values are found by linear interpolation. Using reverse order interpolation the last and first point of the line are mapped to the first and the last node along the boundary section and the intermediate boundary values is found by linear interpolation.

6.16.2 Remarks and hints

The directional spreading index is typically within the interval 2-8 for wind waves and larger than 10 for swell.



6.17 Outputs

Standard data files with computed results from the simulation can be specified here. Because result files tend to become large, it is normally not possible to save the computed discrete data in the whole area and at all time steps. In practice, sub areas and subsets must be selected.

In the main Outputs dialog you can add a new output file by clicking on the "New output" button. By selecting a file in the Output list and clicking on the "Delete output" you can remove this file. For each output file you can specify the name (title) of the file and whether the output file should be included or not. The specification of the individual output files is made subsequently. You can go to the dialog for specification by clicking on the "Go to .." button. Finally, you can view the results using the relevant MIKE 21 viewing/editing tools on the "View" button during and after the simulation.

6.17.1 Geographic View

This dialog shows the geographical position of the output data.

6.17.2 Output specification

For each selected output file the field type, the output format, the treatment of flood and dry, the output file (name and location), and time step must be specified. Depending on the output format the geographical extend of the output data must also be specified.

Field type

You can choose between the following types of data

- Parameters
 - Integral wave parameters
 - Input parameters
 - Model parameters
- Spectral parameter (direction)
 - The direction energy/action spectrum is obtained by integration over the discretized frequencies
- Spectral parameter (frequency)
 - The frequency energy/action spectrum is obtained by integration over the discretized directions
- Spectral parameter (direction - frequency)



Output format

You can choose between following types of output formats

- Point series. Selected field data in geographical defined points
- Line series. Selected field data in geographical defined lines
- Area series. Selected field data in geographical defined area

The file type depends on the field type as described in Table 6.2.

Table 6.2 List of tools for viewing, editing and plotting results.

Output format		Field type			
		Parameters	Direction spectrum	Frequency spectrum	Direction-frequency spectrum
Point series	File type	dfs0	dfs1/dfsu	dfs1	dfsu/dfs2
	Viewing/ editing tools	Time Series Editor	Profile Series Editor	Profile Series Editor	Data Viewer /Grid Series Editor
	Plotting tools	Plot Composer (Time Series Plot)	Plot Composer (Line Series Plot, dfs1 files only)	Plot Composer (Line Series Plot)	Data Viewer (dfsu files only) Plot Composer (Polar Plot, dfs2 files only)
Line series	File format	dfs1	dfsu	dfsu	dfsu



Output format		Field type			
		Parameters	Direction spectrum	Frequency spectrum	Direction-frequency spectrum
	Viewing/ editing tools	Profile Series Editor	-	-	-
	Plotting tools	Plot Composer (Line Series Plot)	-	-	-
Area series	File format	dfsu	dfsu	dfsu	dfsu
	Viewing/ editing tools	Data Viewer/ Data Manager	-	-	-
	Plotting tools	Data Viewer/ Plot Composer (dfsu Plot)	-	-	-

Output file

A name and location of the output file must be specified along with the type of data (file type)

Treatment of flood and dry

The flood and dry can be treated in three different ways

- Whole area
- Only wet area
- Only real wet area

Selecting the Only wet area option the output file will contain delete values for land points. The land points are defined as the points where the water depth is less than a drying depth. The drying depth is by default set to zero. When the spectral wave module is dynamic coupled with the hydrodynamic module and flood and dry is included in the hydrodynamic simulation the drying depth for the spectral wave module is set equal to the drying depth in the hydrodynamic module. Selecting the Only real wet area option the output file will contain delete values not only on land but also in points covered by ice and



points for which the water depth is smaller than the minimum water depth for which calculations are performed. The minimum depth is 0.01 m.

Time step

The temporal range refers to the overall time steps specified under Simulation period in the Time dialog.

Point series

If "Parameters" is selected for the field type you must specify the type of interpolation. You can select discrete values or interpolated values. If "Spectral parameters" is selected for the field type the interpolation type is always set to discrete values.

The geographical coordinates of the points are either taken from the dialog or from a file. The file format is an ascii file with four space separated items for each point on separate lines. The first two items must be floats (real numbers) for the x- and y-coordinate. For 3D field data the third item must be an integer for the layer number if discrete values are selected and a float (real number) for the z-coordinate if interpolated values are selected. For 2D field data the third item is unused (but must be specified). The last item (the remaining of the line) is the name specification for each point.

You must also select the map projection (Long/Lat, UTM-32 etc.) in which you want to specify the horizontal location of the points.

If "discrete values" is selected for the type of interpolation, the point values are the discrete values for the elements in which the points are located. The element number and the coordinates of the center of the element are listed in the log-file.

If "interpolated values" is selected for the type of interpolation, the point values are determined by 2nd order interpolation. The element in which the point is located is determined and the point value is obtained by linear interpolation using the vertex (node) values for the actual element. The vertex values are calculated using the pseudo-Laplacian procedure proposed by Holmes and Connell (1989). The element number and the coordinates are listed in the log-file.

Line series

You must specify the first and the last point on the line and the number of discrete points on the line. The geographical coordinates are taken from the dialog or from a file. The file format is an ascii file with three space separated items for each of the two points on separate lines. The first two items must be floats (real numbers) for the x- and y-coordinate. For 3D field data the third item must be a float (real number) for the z-coordinate. For 2D field data the third item is unused (but must be specified). If the file contains information for



more than two points (more than two lines) the information for the first two points will be used.

You must also select the map projection (Long/Lat, UTM-32 etc.) in which you want to specify the horizontal location of the points.

If "Parameters" is selected for the field type the values for the points on the line are determined by 2nd order interpolation. The element in which the point is located is determined and the point value is obtained by linear interpolation using the vertex (node) values for the actual element. The vertex values are calculated using the pseudo-Laplacian procedure proposed by Holmes and Connell (1989). The element number and the coordinates are listed in the log-file.

If "Spectral parameters" is selected for the field type values for the points on the line are determined by piecewise linear interpolation. Hence, the point values are the discrete values for the elements in which the specified points are located. The element number and the horizontal coordinates of the center of the element and z-coordinate are listed in the log file.

Area series

The discrete field data within a polygon can be selected. The closed region is bounded by a number of line segments. You must specify the coordinates of the vertex points of the polygon. Two successive points are the endpoints of a line that is a side of the polygon. The first and final point is joined by a line segment that closes the polygon. The geographical coordinates of the polygon points are taken from the dialog or from a file. The file format is an ascii file with three space separated items for each of the two points on separate lines. The first two items must be floats (real numbers) for the x- and y-coordinate. For 3D field data the third item must be a float (real number) for the z-coordinate. For 2D field data the third item is unused (but must be specified).

You must also select the map projection (Long/Lat, UTM-32 etc.) in which you want to specify the horizontal location of the points.



6.17.3 Integral wave parameters

The available parameters are defined in the table below.

Name	Symbol	SI unit	Notes
Significant wave height	H_{m0}	meter	
Maximum wave height	H_{max}	meter	
Peak wave period	T_p	seconds	
Mean wave period	T_{01}	seconds	
Zero-crossing wave period	T_{02}	seconds	$T_{02} \sim T_z$, where T_z is mean crossing period
Wave energy wave period	T_{-10}	seconds	
Peak wave direction	PWD	degrees true N	
Mean wave direction	MWD	degrees true N	
Directional standard deviation	DSD	degrees	
Wave height with direction	$H_{m0} \cdot \cos(MWD + \Delta_{conv})$ $H_{m0} \cdot \sin(MWD + \Delta_{conv})$	meter	
Radiation stresses	S_{xx}, S_{xy}, S_{xy}	m^3/s^2	
Particle velocities	$U_{max}(z=-d),$ $U_{max}(z=0),$ $W_{max}(z=0),$ $U_{max}(z=z_0),$ $W_{max}(z=z_0)$	m/s	
Wave power	$P_{energy},$ $P_{energy,x},$ $P_{energy,y}$	kW/m	

Δ_{conv} is the angle from true North to projection North (positive clockwise).

Using the fully spectral formulation the integral parameters can be determined for the total spectral, the wind sea part or the swell part.



Type of Spectrum

The type of spectrum can be defined in four different ways:

- Whole spectrum
- Frequency range
- Directional range
- Frequency and directional range

You have to make sure the frequency range is within the selected discrete frequencies. A frequency range is often relevant when simulated results are compared with measured data.

Separation of wind sea and swell waves

The distinction between wind sea and swell can be calculated in one of three ways:

- Constant threshold frequency
- Dynamic threshold frequency, version 1
- Dynamic threshold frequency, version 2

Constant threshold frequency

A constant threshold frequency of e.g. 0.125 Hz corresponds to a separation between waves and swell at wave period 8 s.

Dynamic threshold frequency, version 1

The dynamic threshold frequency is defined by

$$f_{threshold} = \alpha f_{p,PM} \left(\frac{E_{PM}}{E_{Model}} \right)^{\beta}$$

where

$$\alpha = 0.7$$

$$\beta = 0.31$$

$$f_{p,PM} = 0.14 \frac{g}{U_{10}} \quad (6.27)$$

(peak frequency for a fully developed wind-sea described by a Pierson-Moskowitz spectrum (PM), see also Young (1999) p. 92)

$$E_{PM} = \left(\frac{U_{10}}{1.4g} \right)^4 \quad (6.28)$$



(total wave energy in a fully developed wind-sea described by a Pierson-Moskowitz spectrum (PM))

E_{Model} = calculated total wave energy in MIKE 21 SW at each node point.

Thus, for a fully developed sea state the threshold frequency is 70% of the peak frequency for the wind-sea.

Dynamic threshold frequency, version 2

Swell wave components are defined as those components fulfilling the following wave-age based criterion

$$\frac{U_{10}}{c} \cos(\theta - \theta_w) < 0.83 \quad (6.29)$$

where U_{10} is the wind speed, c the phase speed and θ and θ_w is the wave propagation and wind direction, respectively.

Remarks and hints

It is recommended to use a Constant threshold frequency for distinction between wind, sea and swell.

6.17.4 Input parameters

The available parameters are defined in the table below.

Name	Symbol	SI unit	Notes
Water level	S	meter	
Water depth	D	meter	
Current velocity	U	m/s	
Wind speed	U_{10}	m/s	
Wind direction	θ_w	degrees true N	Wind coming from
Ice concentration	c	-	

The input parameters are identical to the forcing used in the wave model.

Remarks and hints

Usually it is not necessary to save the input parameters.



6.17.5 Model parameters

The available parameters are defined in the table below

Name	Symbol	SI unit	Notes
Friction coefficient	C_{fw}	-	Related to bottom friction dissipation
Breaking parameter	γ	-	Gamma for depth-induced breaking
Breaking index	Q_b		Fraction of breaking waves
CFL number	CFL	-	
Time step factor	α	-	In the range 1 to 32
Convergence angle	Δ_{conv}	degrees	
Length	l	m	Characteristic mesh length
Area	a	m ²	Characteristic mesh area
Threshold period	$T_{threshold}$	seconds	
Wind friction speed	u^*	m/s	Related to air-sea interaction
Roughness length	z_0	meter	Related to air-sea interaction
Drag coefficient	C_D	-	Related to air-sea interaction
Charnock coefficient	z_{ch}		Related to air-sea interaction

The first three parameters are related to bottom friction and wave breaking, respectively. The Courant number and time step factor is related to the integration of the wave action balance equation. The length and area are related to the mesh used. The last four parameters are all typically used in connection with detailed studies of air-sea interaction processes.

Δ_{conv} is the angle from true North to projection North (positive clockwise).

Remarks and hints

Except for the time step factor and the CFL number usually it is not necessary to save the other model parameters.



6.17.6 Spectral parameters

Using the fully spectral formulation the wave energy can be determined for the total spectral, the wind sea part or the swell part.

Spectral parameter (frequency)

Using the fully spectral formulation you can save the directional integrated frequency spectrum $E(f_r)$ or the directional integrated frequency spectrum $A(f_r)$. Here f_r is the relative wave frequency (=absolute wave frequency in case of no ambient current).

Spectral parameter (direction)

Using the full spectral formulation you can save the distribution of wave energy $E(\theta)$ with discrete directions or the distribution of wave action $A(\theta)$ with discrete directions.

Using the directional decoupled parametric formulation you can save the distribution of wave energy $E(\theta)$ with discrete directions as well the directional distribution of zero-th $m_0(\theta)$ and first-order moment $m_1(\theta)$ of wave action.

The discrete directions are defined positive clockwise from projection North (coming from).

Spectral parameter (direction - frequency)

Using the full spectral formulation you can either save the normal⁽¹⁾ wave energy spectrum $E(\sigma, \theta)$ or the normal wave action spectrum $N(\sigma, \theta)$. You can also save the wind sea part and the swell sea part of the normal⁽¹⁾ wave energy spectrum $E(\sigma, \theta)$.

The discrete directions are defined positive clockwise from projection North (coming from).



Please notice that the output file extension may be either .dfsu or .dfs2:

- Using .dfsu (default) the underlying mesh visualise the spectral discretisation (σ, θ) and each element contains the related computed value.
- Using .dfs2 the data will be structured in 2D with the axis defining σ and θ , respectively. This file can be visualised using Polar plot in Plot Composer.

¹ See MIKE 21 SW Scientific Documentation





7 SCIENTIFIC DOCUMENTATION

Scientific documentation for MIKE 21 SW can be accessed from the MIKE 21 Documentation Index. The documentation here is in the form of ready-to-read-and-print Adobe Acrobat Document (.PDF file).





8 LIST OF REFERENCES

The references listed below provide you with more basic information applicable to spectral wave modelling in deep water as well in shallow water.

Battjes, J.A. and J.P.F.M., 1978: Energy loss and set-up due to breaking of random waves, in Proc. 16th Int. Conf. On Coastal Eng., ASCE, NY, 569-587.

Battjes, J.A. and M.J.F. Stive, 1985: Calibration and verification of a dispersion model for random breaking waves, *Geophys. Res.*, 90, 9159-9167.

Bidlot, J., P. Janssen, and S. Abdalla, 2007: A revised formulation of ocean wave dissipation and its model impact. Technical Report Memorandum 509, ECMWF, Reading, U. K.

Bouws, E. and G.J. Komen, 1983: On the balance between growth and dissipation in an extreme, depth-limited wind-sea in the southern North Sea. *J. Phys. Oceanogr.*, 13, 1653-1658.

Booij, N., R.C. Ris and L.H. Holthuijsen, 1999: A third-generation wave model for coastal regions. 1. Model description and validation. *J. Geophys. Res.*, 104, 7649-7666.

Charnock, H., 1955: Wind Stress on a water surface. *Quart. J. Roy. Meteorol. Soc.*, 81, 639-640.

Collins, J.I., 1972: Prediction of shallow water spectra. *J. Geophys. Res.*, 77, 2693-2707.

Dingler, J. R., 1974: Wave formed ripples in nearshore sands. PhD. Thesis, Univ. of California, San Diego, CA, 136pp.

Dingler, J. R., and D. L. Inman, 1976: Wave formed ripples in nearshore sands. Proc. 15th International Conference on Coastal Engineering, Honolulu, Hawaii, ASCE, 2109-2126.

Donelan, M. A., J. Hamilton and W. H. Hui, 1985: Directional Spectra of Wind-Generated Waves. *Phil. Trans. R. Soc. Lond.*, A 315, 509-562.

Donelan, M.A., 1990: Air-Sea Interaction. *The Sea*, B. LeMehaute and D. Hanes (Eds.), John Wiley and Sons, 239-292.

Donelan, M.A., F.W. Dobson, S.D. Smith and R.J. Anderson, 1993: On the dependence of sea surface roughness on wave development. *J. Phys. Oceanogr.*, 23, 2143-2149.

Donelan, M.A., W.M. Drennan, and K. B. Katsaros, 1997: The air-sea momentum flux in conditions of wind sea and swell. *J. Phys. Oceanogr.*, 15, 2087-2099.



- Eldeberky, Y. and Battjes, J.A., 1995: Parameterization of triad interaction in wave energy models, Proc. Coastal Dynamics Conf. '95, Gdansk, Poland, 140-148.
- Eldeberky, Y. and Battjes, J.A., 1996: Spectral modelling of wave breaking: Application to Boussinesq equations, J. Geophys. Res., 101, No. C1, 1253-1264.
- Geernaert, G.L., S.E. Larsen, and F. Hansen, 1987: Measurements of the wind stress, heat flux and turbulence intensity during storm conditions over the North Sea. J. Geophys. Res., 92C, 13,127 - 13,139.
- Geernaert, G.L., K.B. Katsaros and K. Richter, 1986: Variation of the drag coefficient and its dependency on sea state. J. Geophys. Res., 91C, 6, 7667-7669.
- Garratt, J.R., 1977: Review of drag coefficients over oceans and continents, Monthly Weather Review, 105, 915.
- Goda Y., 1969, Re-analysis of laboratory of data on wave transmission over breakwaters, Rep. Port and Harbour Res. Inst., Vol. 8, No. 3, pp 3-18.
- Goda, Y, H. Takeda and Y. Moriya, 1967, Laboratory investigation of wave transmission over breakwaters, Rep. port and Harbour Res. Inst., No. 13, 38 pp.
- Günther, H., S. Hasselmann and P.A.E.M. Janssen, 1992: The WAM model cycle 4. DKRZ Technical Report No 4, Hamburg.
- Gulev, S.K. and L. Hasse, 1998: North Atlantic wind waves and wind stress fields from voluntary observing ship data. J. Phys. Oceanogr., 28, 1107-1130.
- Hasselmann, K., T.P. Barnett, E. Bouws, H. Carlson, D.E. Cartwright, K. Enke, J.A. Wing, H. Gienapp, D.E. Hasselmann, P. Kruseman, A. Meerburg, P. Müller, D.J. Olbers, K. Richter, W. Sell and H. Walden, 1973: Measurements of wind-wave growth and swell decay during the Joint North Sea Wave Project (JONSWAP). Dtsch. Hydrogr. Z. Suppl. A (12), 95 pp.
- Hasselmann, K., 1962: On the nonlinear energy transfer in a gravity-wave spectrum, Part 1, General theory. J. Fluid Mech., 12, 481-500.
- Hasselmann, S., and K. Hasselmann, 1985: Computation and parameterizations of Non-linear Energy Transfer in a Gravity-wave Spectrum, Part 1: A New Method for Efficient Computations of the exact Non-linear Transfer Integral, J. Phys. Oceanogr., 15, 1369-1377.
- Hasselmann, S., and K. Hasselmann, (1985), Computation and parameterizations of Non-linear Energy Transfer in a Gravity-wave Spectrum, Part 2: Parameterisations of non-linear energy transfer for applications in wave models, J. Phys. Oceanogr., 15, 1378-1391.



Hersbach, H. and P.A.E.M. Janssen 1999: 'Improvement of the short-fetch behaviour in the Wave Ocean Model (WAM). J. Atmos. & Ocean Tech., 16, 884-892.

Holmes, D. G. and Connell, S. D. (1989), Solution of the 2D Navier-Stokes on unstructured adaptive grids, AIAA Pap. 89-1932 in Proc. AIAA 9th CFD Conference.

Holthuijsen, L.H., N. Booij, and T.H.T Herbers, 1989, A prediction model for stationary, short crested waves in shallow water with ambient currents. Coastal Eng., 13, 23-54.

Holthuijsen L.H., Herman A., Booij N. and Cieslikiewicz W., 2002, Diffraction in SWAN, Proceedings 28th International Conference Coastal Engineering, Cardiff, 405-412.

Janssen, J.A.M., 1997: Does wind stress depend on sea-state or not? – A statistical error analysis of HEXMAX data. Boundary-Layer Meteorology, 83, 479-503.

Janssen, P.A.E.M., 1989: Wave induced stress and the drag of airflow over sea waves. J. Phys. Oceanogr., 19, 745-754.

Janssen, P.A.E.M., 1991: Quasi-linear theory of wind wave generation applied to wave forecasting. J. Phys. Oceanogr., 21, 1631-1642.

Janssen, P.A.E.M., 1992: Experimental evidence of the effect of surface waves on the airflow. J. Phys. Oceanogr., 22, 1600-1604.

Johnson, H.K., 1998: On modeling wind-waves in shallow and fetch limited areas using the method of Holthuijsen, Booij and Herbers. J. Coastal Research, 14, 3, 917-932.

Janssen, P.A.E.M., 1998: On the effect of ocean waves on the kinetic energy balance and consequences for the initial dissipation technique. J. Phys. Oceanogr., 30, 1743-1756.

Johnson, H.K. and H. Kofoed-Hansen, 2000: Influence of Bottom Friction on Sea Surface Roughness and Its Impact on Shallow Water Wind Wave Modeling. J. Phys. Oceanogr., 30, 1743-1756.

Johnson, H.K., J. Højstrup, H.J. Vested and S.E. Larsen, 1998: On the Dependence of Sea Surface Roughness on Wind Waves. J. Phys. Oceanogr., 28, 1702-1716.

Johnson, H.K., H.J. Vested, H. Hersbach, J. Højstrup, and S.E. Larsen, 1999: On the coupling between wind and waves in the WAM model, To appear in Journal of Atmospheric and Oceanic Technology.



- Kahma, K.K. and C.J. Calkoen, 1994: Growth curve observations, In *Dynamics and Modelling of Ocean Waves* by Komen et al., Cambridge University Press, 174-182,
- Kaminsky, G.M. and Kraus, N.C. 1993: Evaluation of depth-limited wave breaking criteria, *Proc. Of 2nd Int. Symposium on Ocean Wave Measurement and Analysis*, New Orleans, 180-193.
- Katsaros, K. B, M.A. Donelan and W.M. Drennan, 1993: Flux measurements from a SWATH ship in SWADE. *J. Mar. Sys.*, 4, 117-132.
- Kitaigorodskii, S.A., 1970: *The physics of air-sea interaction*. Translated for Russian by A. Baruch, Israel Program for Scientific Translations, Jerusalem, 237pp.
- Kitaigorodskii, S.A., 1998: The dissipation subrange in wind wave spectra. *Geophysical*, 34 (3), 179-207.
- Kofoed-Hansen, H; and J.H. Rasmussen, 1998: Modelling of non-linear shoaling based on stochastic evolution equations. *Coastal Engineering*, 33, 203-232.
- Komen, G.J., P.A.E.M. Janssen, V. Makin, K. Mastenbroek and W. Oost, 1998: Review: On the sea state dependence of the Charnock parameter, *J. Glob Atmos. Ocean System*, 5, 367-388.
- Komen, G.J., Cavaleri, L., Doneland, M., Hasselmann, K., Hasselmann S. and Janssen, P.A.E.M. (1994) *Dynamics and modelling of ocean waves*. Cambridge University Press, UK, 560pp.
- Kudryatsev, V.N. and V.K. Makin (1996): Transformation of wind in the coastal zone. KNMI, Scientific Report WR 96-04.
- Large, W.G. and S. Pond, 1981: Open ocean momentum flux measurements in moderate to strong winds. *J. Phys. Oceanogr.*, 14, 464-482.
- Makin V.K. and V.N. Kudryatsev, 1999: Coupled sea surface-atmosphere model. 1. Wind over waves coupling. *J. Geophys. Res.*, 104C, 7613-7623.
- Makin V.K., V.N. Kudryatsev and C. Mastenbroek, 1995: Drag of the sea surface. *Boundary-Layer Meteorol.*, 73, 159-182.
- Mastenbroek, C., G.J.H. Burgers, P.A.E.M. Janssen, 1993: The dynamical coupling of a wave model and a storm surge model through the atmospheric boundary layer. *J. Phys. Oceanogr.*, 23, 1856-1866.
- Merzi, N. and W.H. Graf, 1985: Evaluation of the drag coefficient considering the effects of mobility of the roughness elements. *Ann. Geophys.*, 3, 473-478.



- Monbaliu, J., 1994: On the use of the Donelan wave spectral parameter as a measure for the measure for the roughness of wind waves. *Boundary-Layer Meteorol*, 67, 277-291.
- Nelson, R.C., 1987: Design wave heights on very mild slopes: An experimental study, *Civil. Eng. Trans., Inst. Eng., Aust.*, 29, 157-161.
- Nelson, R.C., 1994: Depth limited wave heights in very flat regions, *Coastal Eng.*, 23, 43-59.
- Nielsen, P., 1979: Some basic concepts of wave sediment transport. Series paper 20 Institute of Hydrodynamic and Hydraulic Engineering, Technical University of Denmark, 160pp.
- Nordeng, T.E., 1991: On the wave age dependent drag coefficient and roughness length at sea. *J. Geophys. Res.*, 96, 7167-7174.
- Oost, W.A., 1998: The Knmi HEXMAX stress data – a reanalysis. *Boundary-Layer Meteorology*, 86, 447-468.
- Perrie, W. and B. Toulany 1990: Fetch relations for wind-generated waves as a function of wind-stress scaling, *J. Phys. Oceanogr.*, 20, 1666-1681.
- Phillips, O.M., 1960: On the dynamics of unsteady gravity waves of finite amplitude, Part 1. *J. Fluid Mech.*, 9, 193-217.
- Phillips, O.M., 1981: The structure of short gravity waves on the ocean surface. In: *Spaceborn Synthetic Aperture Radars for Oceanography*, the Johns Hopkins Press.
- Plant, W. J. (1982): A relationship between wind stress and wave slope, *J. Geophys. Res.*, 87(C3), 1961–1967.
- Rasmussen, J.H. (1999): Deterministic and stochastic modelling of surface gravity waves in finite water depth. Ph.D. thesis, Department of Hydrodynamic and Water Resources (ISVA), Technical University of Denmark.
- Resio, D.T., B. Tracy, C.L. Vincent, and J.H. Rasmussen (1999): Non-linear energy fluxes and the finite-depth equilibrium range in wave spectra. Submitted to *J. Phys. Oceanogr.*
- Ris, R.C. 1997: Spectral modelling of wind waves in coastal areas, PhD. thesis, Delft 1997.
- Ris, R.C., L.H. Holthuijsen and N. Booij, 1999: A third-generation wave model for coastal regions. 2. Verification. *J. Geophys. Res.*, 104C, 7667-7681.
- Ruessink, B.G., Walstra, D.J.R. and Southgate, H.N. 2003: Calibration and verification of a parametric wave model on barred beaches, *Coastal Eng.*, 48, 139-149.



- Shemdin, O., K. Hasselmann, S. V. Hsiao and K. Heterich, 1978: Nonlinear and linear bottom interaction effects in shallow water. Turbulent Fluxes through the sea surface, Wave Dynamics and Prediction. NATO Conf. Ser. V, 1, 347-365.
- Smith, S.D., 1988: Coefficients for sea surface wind stress, heat flux and wind profiles as function of wind speed and temperature. J. Geophys. Res., 93C, 15,467 - 15,472.
- Smith, S.D. and E.G. Banke, 1975: Variation of the sea surface drag coefficient with wind speed. Quart. J. Roy. Meteor. Soc, 101, 665-673.
- Smith, S.D. 1980: Wind stress and heat flux over the open ocean in gale force winds. J. Phys. Oceanogr., 10, 709-726.
- Smith, S.D., R.J. Anderson, W.A. Oost, C. Kraan, N. Maat, J. DeCosmo, K.B. Katsaros, K.L. Davidson, K. Bumke, L. Hasse, and H.M. Chadwick, 1992: 'Sea surface wind stress and drag coefficients: The HEXOS results. Boundary-Layer Meteorology, 60, 109-142.
- Smith, S.D., Katsaros, K.B., Oost, W.A. and Mestayer, P., 1996: The impact of the HEXOS Programme. Boundary-Layer Meteorol., 78, 109-142.
- Schneggenburger, C., 1998: Spectral wave modelling with nonlinear dissipation. Phd. dissertation, GKSS-Forschungszentrum Geesthacht GmbH. 117pp.
- Sørensen, O.R., M. Rugbjerg, L.S. Sørensen and H. Kofoed-Hansen, 2004: A third-generation spectral wind-wave model using an unstructured finite volume technique. Manuscript in preparation.
- Taylor, P.A. and R.J. Lee, 1984: Simple guidelines for estimating wind speed variations due to small-scale topographic features, Climatol Bull, 18, 3-32.
- Toba, Y., N. Iida, H. Kawamura, N. Ebuchi and I.S.F. Jones, 1990: Wave dependence on sea-surface wind stress. J. Phys. Oceanogr., 20, 705-721.
- Tolman, H. L., 2003: Treatment of unresolved islands and ice in wind wave models. Ocean Modelling, 4, 219-231.
- Tolman, H.L. 2002: Limiters in third-generation wind wave models. Global Atmos. and Ocean. System, 8, 67-83.
- Tolman, H. L., 2002: Alleviating the Garden Sprinkler Effect in wind wave models. Ocean Modelling, 4, 269-289.
- Tolman, H.L. and D. Chalikov, 1996: Source terms in a third-generation wind wave model. J. Phys. Oceanogr., 26, 2497-2518.
- Troen, I. and E.L. Petersen, 1989: European Wind Atlas, Risø National Laboratory. 656pp.



Vledder, G. van, 1999: Source term investigation in SWAN. Report prepared for Rijkswaterstaat, the Netherlands, by Alkyon, the Netherlands. Report A162.

WAMDI-group, The: S. Hasselmann, K. Hasselmann, E. Bauer, P.A.E.M. Janssen, G.J. Komen, L. Bertotti, P. Lionello, A. Guillaume, V.C. Cardone, J.A. Greenwood, M. Reistad, L. Zambresky and J.A. Ewing, 1988: 'The WAM model - a third generation ocean wave prediction model', J. Phys. Oceanogr., 18, 1775-1810.

Weber, S.L., 1991: Bottom friction for wind sea and swell in extreme depth-limited situations, J. Phys. Oceanogr., 21, 149-172.

Weber, S.L., 1988: The energy balance of finite depth gravity waves. J. Geophys. Res. 93, C4, 3601-3607.

Wu, J., 1980: Wind stress coefficients over sea surface near neutral conditions. A revisit, J. Phys. Oceanogr., 10, 727-740.

Yelland, M. and P.T. Taylor, 1996: Wind stress measurements from the open ocean. J. Phys. Oceanogr., 26, 1712-1733.

Yelland, M., B.I. Moat, P.K. Taylor, R.W. Pascal, J. Hutchings and V.C. Cornell, 1998: Wind stress measurements from the open ocean corrected for air-flow distortion by the ship. J. Phys. Oceanogr., 28, 1511-1526.

Taylor, P.K. and M.J. Yelland, 1999: The dependence of sea surface roughness on the height and steepness of the waves. Manuscript submitted to. J. Phys. Oceanography, July 1999.

U S Army Corps of Engineers, Coastal Engineering Research Center (1973, 1984), Shore Protection Manual.

Young, I. and L.A. Verhagen, 1996: 'The growth of fetch-limited waves in water of finite depth. Part I and II.', Coastal Engineering, 29 pp.47-99.

Young, I. and R.M. Gorman, 1995: 'Measurements of the evolution of ocean wave spectra due to bottom friction', J. Geophys. Res, 100, C6, pp.10987-11004.

Young, I.R., 1999: Wind generated ocean waves, in Elsevier Ocean Engineering Book Series, Volume 2, Eds. R. Bhattacharyya and M.E. McCormick, Elsevier.





INDEX



A	
About this guide	9
Alpha data	74
Ambient flow	16
Application areas	9
Assessment of wave climates	9
B	
Background roughness Charnock parameter	69
Basic equations	57
Boundary-fitted unstructured mesh	16
Breaking parameters	24
C	
Calibration and verification	23
Calibration factors	23
CFL number	21, 65, 104
Charnock constant	69
Check list	19
Computational features	16
Computer resources	21
Convergence angle	104
Coordinate type	53
Coupled formulation	69
Coupling	17
Courant number	104
Cyclone generated waves	39
D	
Datum shift	54
Depth-adaptive	20
depth-adaptive	14
Design	9
Directional decoupled parametric formulation	13
Directional discretisation	59
Directional resolution	59
Directional spectra	39
Directional spectrum	29, 32
Directionally decoupled parametric formulation	20, 57
Directionally decoupled parametric formulations	16
Discrete Interaction Approximate (DIA)	73
Domain parameters	55
E	
Ekofisk	33, 37
Energy transfer	73
Examples	27
Extreme sea states	14
F	
Fetch-limited wave growth in a lake	27
Fetch-limited wave growth test	27
Fjaltring	39
Flooding and drying	45
Frequency discretisation	59
Frequency range	59
Fully spectral formulation	13, 20, 57
G	
Gamma data	75
Getting started	19
Global models	20
Global scale	16
H	
Horns Rev	33
I	
Ice coverage	71
Ice data	71
Input parameters	103
Integral parameters	101
Island	45
L	
Local depth-adaptive refinement of mesh	42
Local depth-adaptive refinement of the mesh	42
M	
Mesh decomposition	54
Mesh file	53
MIKE Zero Mesh	53
Minimum depth cutoff	53
Model formulation	20
Model parameters	104
N	
North Sea	14, 33
wave conditions	33
North Sea and West-coast wave conditions	



33	
North Sea and west-coast wave conditions	
33	

O

Offshore buoy	37
Offshore wind farm	33
Offshore wind turbine	82
On-line help	9
Onshore buoy	38
Output format	97

P

Presenting the results	19, 25
Production simulations	24
Propagation step	61

Q

Quadruplet wave-wave interaction	73
Quadruplet-wave interaction	73

R

Regional scale	14
Reordering	54

S

Sediment transport	15
Setting up the model	21
Soft start interval	66
Solution technique	60
Spectral discretization	58
Spectral parameters	105
Swell	17, 19, 102, 103

T

Time parameters	55
Torsminde	39
Triad-wave interaction	73
Type of air-sea interaction	69

U

Uncoupled formulation	69
Unstructured meshes	13
User background	9

W

WAM Cycle 4	69
Water level conditions	65
Water level data	66

Wave action conservation equation	13
Wave breaking	74
Wave breaking source function	74
Wave phenomena	19
wave phenomena	19
Wave-induced currents	15
Wind data	68
Wind field	22, 35
Wind forcing	28
Wind sea	102
Wind-generated waves	19
Wind-wave generation	20, 23

