MIKE 21 Spectral Waves FM

Spectral Wave Module

User Guide

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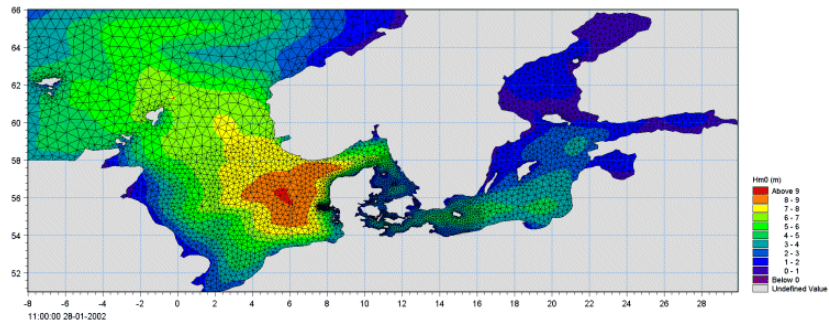
Figure 2.2   A MIKE 21 SW forecast application in the North Sea and Baltic Sea. The chart shows a wave field illustrated by the significant wave height in top of the computational mesh. See http://www.waterforecast.com

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.
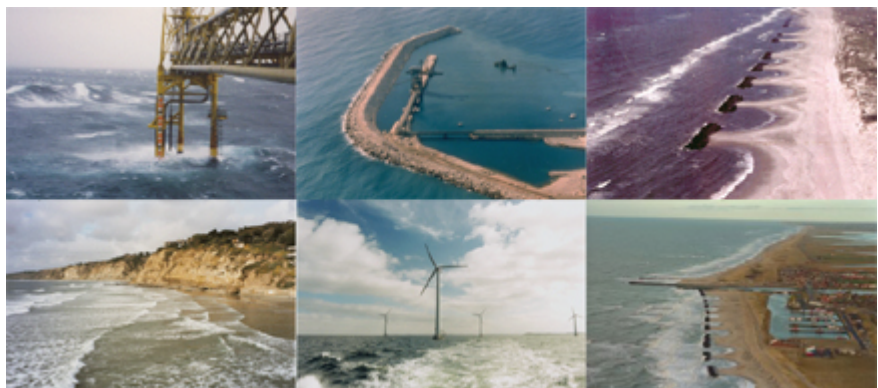
Figure 2.3   Illustration of typical application areas
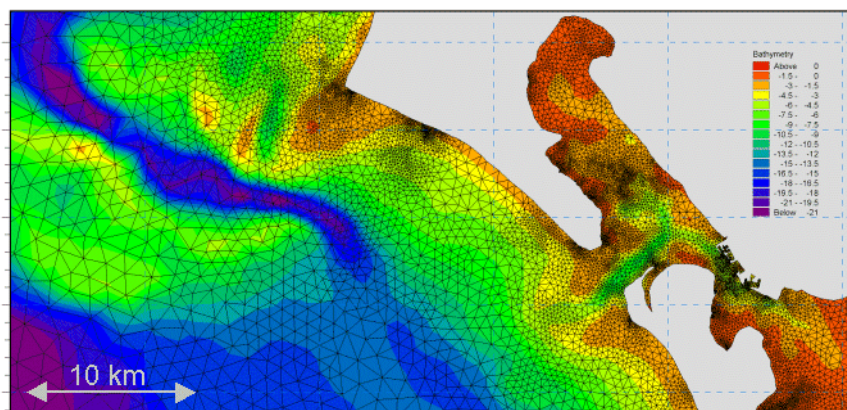
Figure 2.4   Example of a computational mesh used for transformation of offshore wave statistics using the directionally decoupled parametric formulation

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

05/26/04 12:00:00
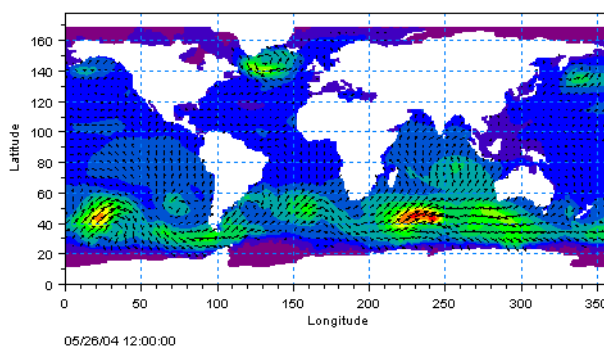
Figure 2.5   Example of a global application of MIKE 21 SW. Results from such a model can be used as boundary conditions for regional scale forecast or hindcast models. See http://www.waterforecast.com

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 all these phenomena. Note however that diffraction is modelled using the approximation by Holthuijsen et. Al. (2003) and that reflection can only be accounted for on the boundaries of the computational domain and for point and line structures.

- 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* (6.20 Boundary conditions *(p. 101)*).

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 numerical 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 6.14 Bottom friction *(p. 83)*).

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.

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 δ= 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 6.3 List of tools for viewing, editing and plotting results *(p. 110)* 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 generated 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 3.125×10^6 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.
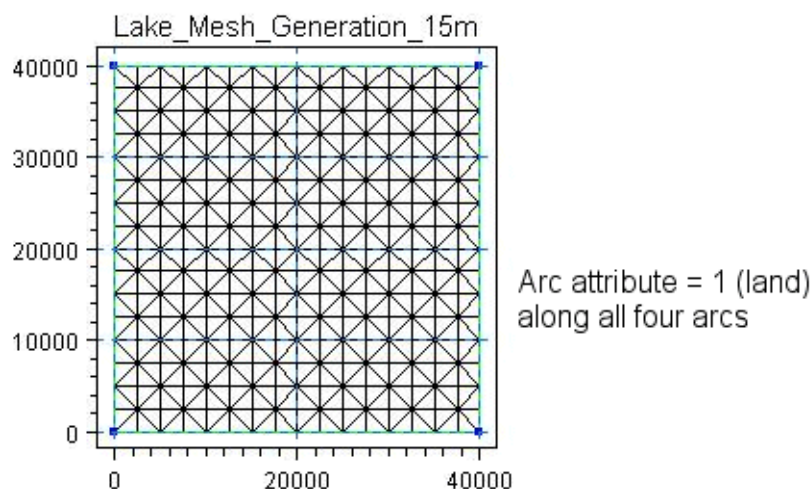
Figure 4.1   Computational mesh
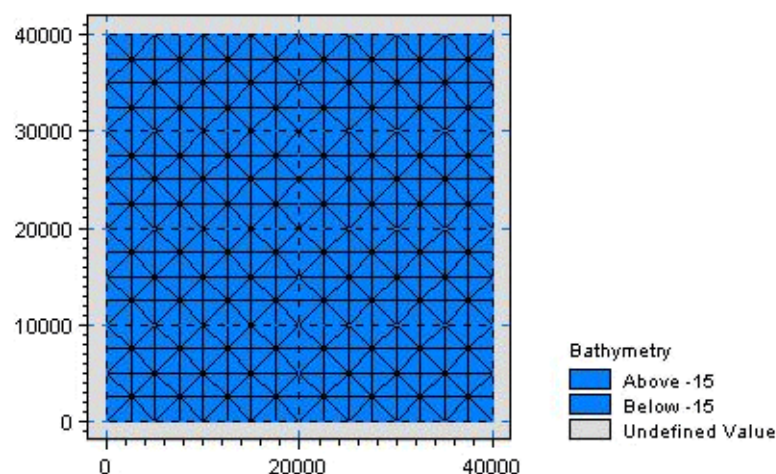
Figure 4.2   Bathymetry

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.
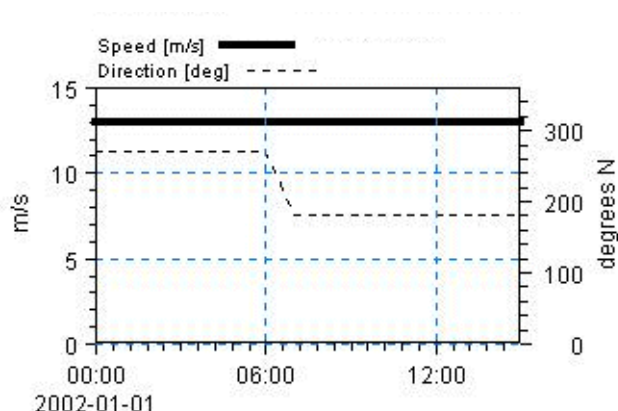
Figure 4.3   Wind conditions

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.
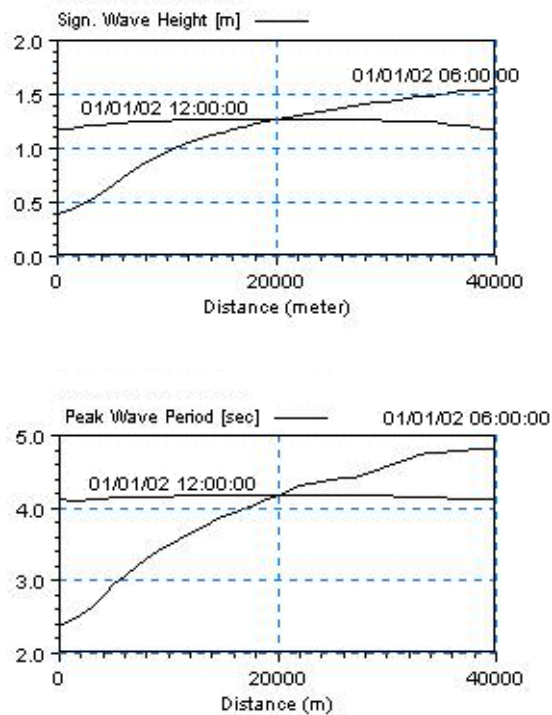
Figure 4.4   Spatial variation of the significant wave height and peak wave period at two different instances. The results are extracted from the result file "Wave_line.dfs1"
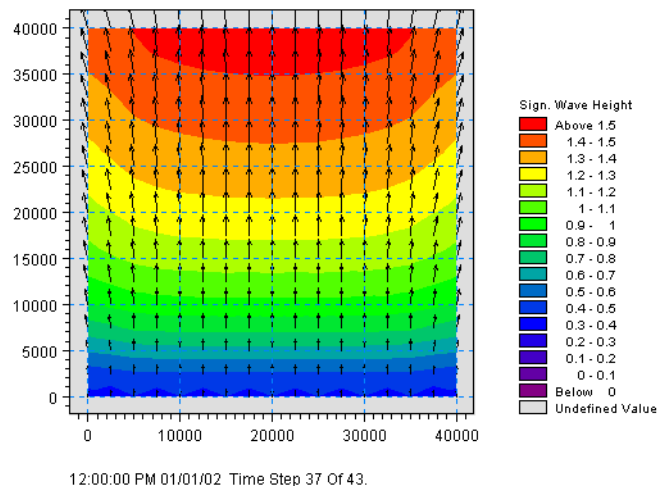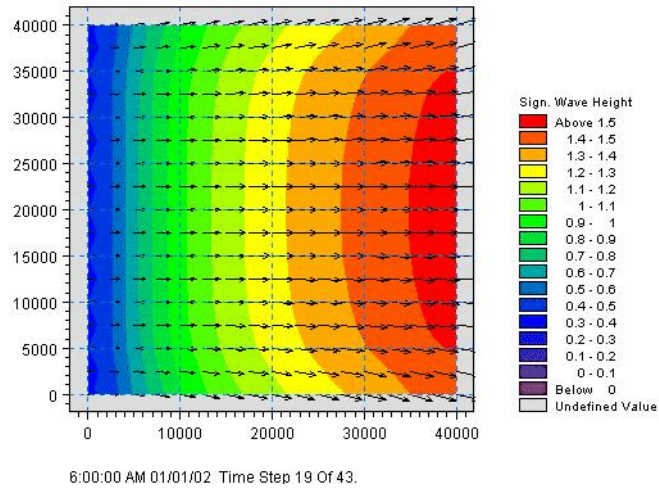
Figure 4.5   Maps of the significant wave height at two different instances

6:00:00 AM 01/01/02 Time Step 19 Of 43.

8:00:00 AM 01/01/02 Time Step 25 Of 43.

9:00:00 AM 01/01/02 Time Step 28 Of 43.

12:00:00 PM 01/01/02 Time Step 37 Of 43.
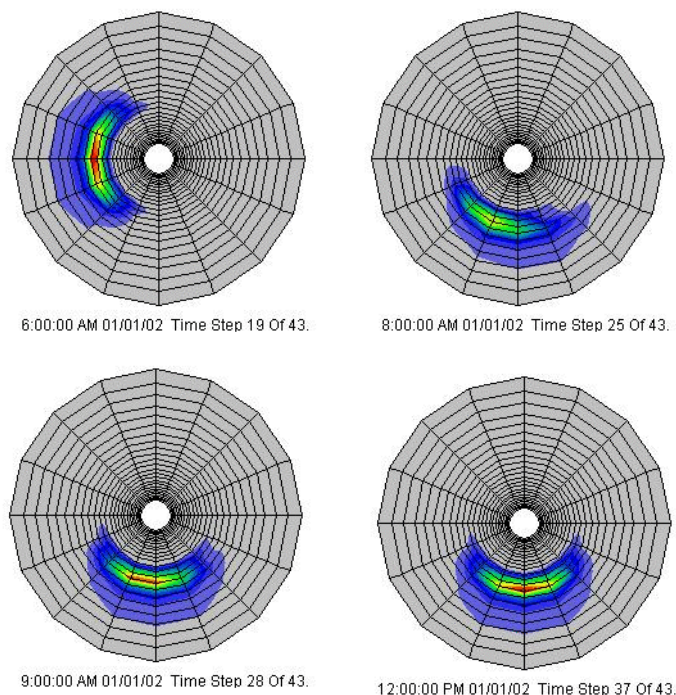
Figure 4.6   Evolution of the directional spectrum during a 90° turn of the wind direction. The plots are made in the Data Viewer. Polar plots can also be made in the MIKE Zero Plot Composer (Polar Plot control)

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.

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.
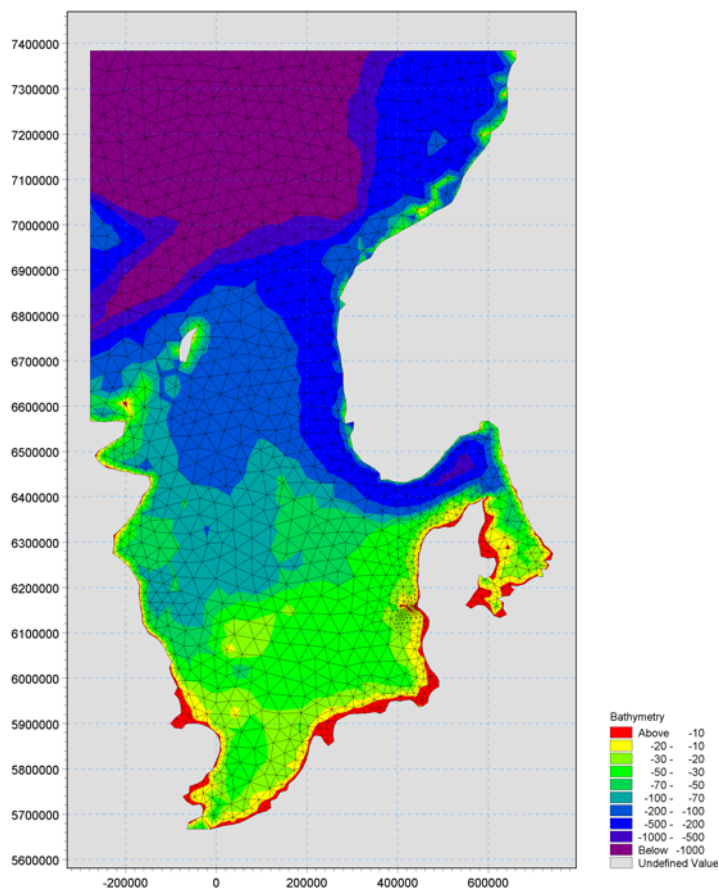
Figure 4.8   Computational mesh and bathymetry
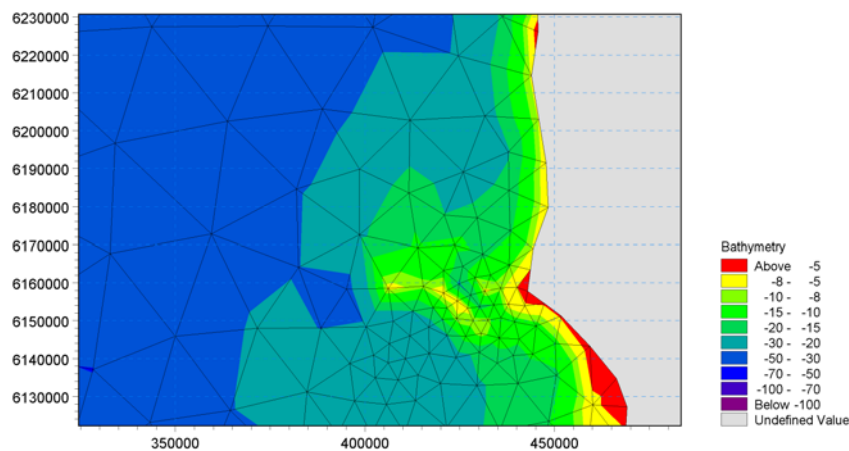
Figure 4.9   Local refinement of the mesh at Horns Rev

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.
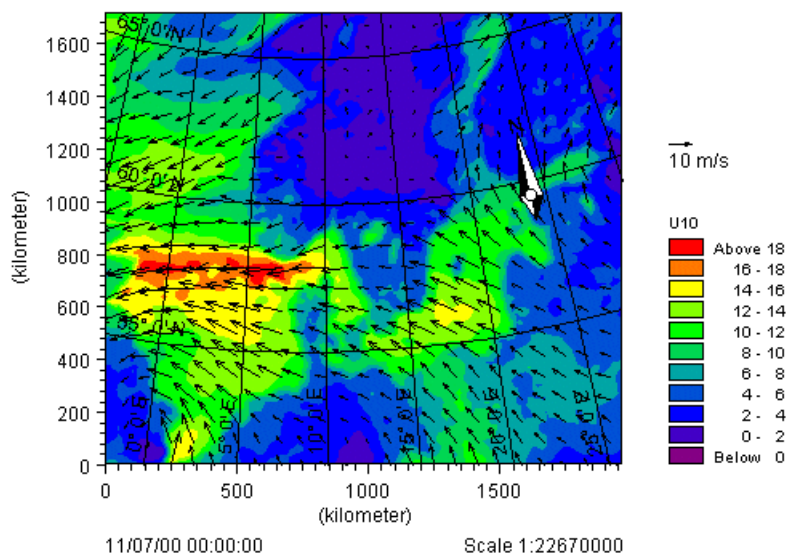
Figure 4.10   Wind field during the peak for the storm

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.

Parametrization of the source terms

Simulations are performed using both the "Modified WAM Cycle 4" parametrization (settings=1) and the "Ardhuin et al." parametrization (settings=2). For the "Modified WAM Cycle 4" parametrization default values for the wind forcing and whitecapping parameters are applied. The coupled air-sea interaction formulation is used and the values for the growth parameter, the wave age tuning parameter and the background Charnock parameter are 1.2, 0.008 and 0.006, respectively. The values for the two dissipation coefficients, Cdis, and , DELTAdis, are 1.33 and 0.5, respectively. For the "Ardhuin et al." parametrization the values for the growth parameter, the wave age tuning parameter and the background Charnock parameter are 1.42, 0.008 and 0.0062, respectively.

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).

12:00:00 07/11/00 Time Step 17 Of 57.
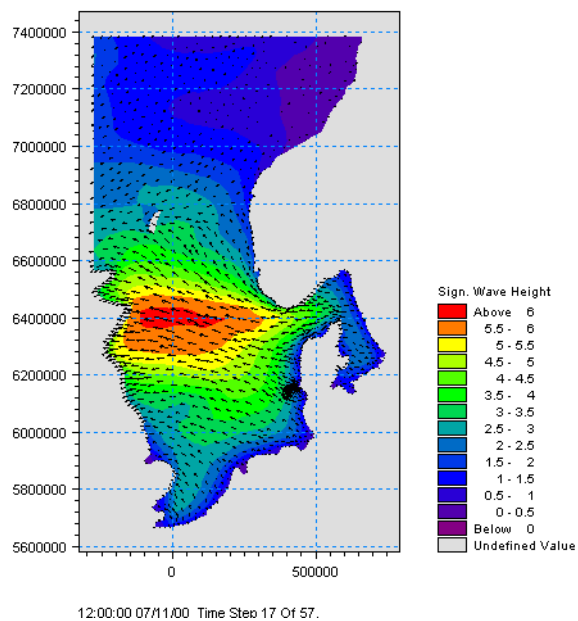
Figure 4.11   Maps of the significant wave height at the peak of the storm
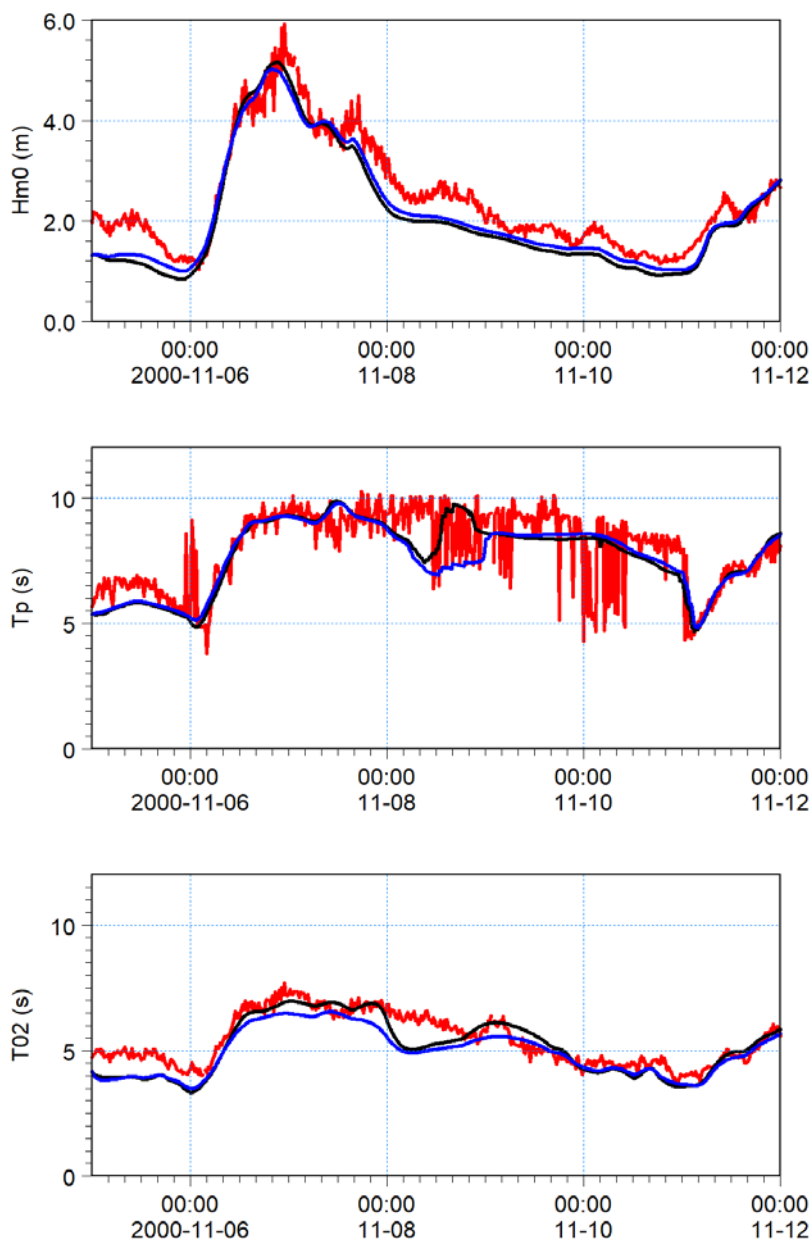
Figure 4.12   Time series of significant wave height (upper), spectral peak wave period (middle) and mean wave period (lower) at the offshore buoy (Ekofisk). Red curve: Measurements; Black curve: Settings=1; Blue curve: Settings=2.
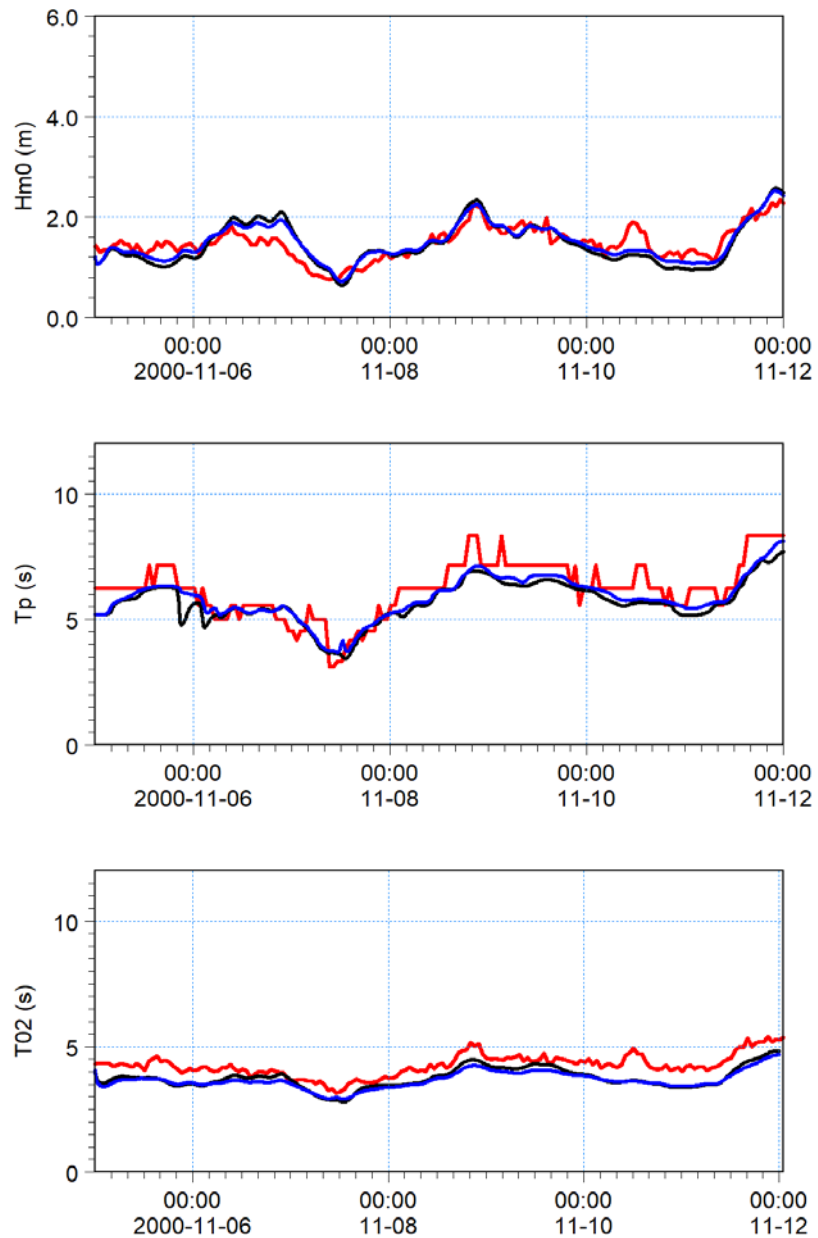
Figure 4.13   Time series of significant wave height, spectral peak wave period and mean wave period at onshore buoy (Horns Rev). Red curve: Measurements; Black curve: Settings=1; Blue curve: Settings=2.
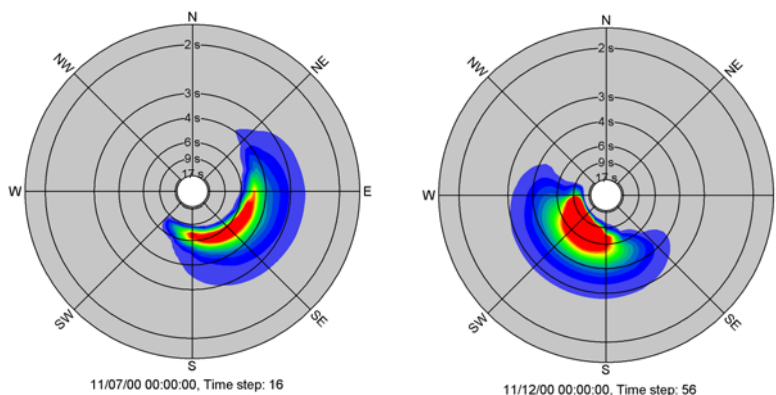
Figure 4.14   Simulated directional spectra at Horns Rev. The plots are made using the Polar plot control in the MIKE Zero plot composer

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:	setup1.sw
Description:	MIKE 21 Spectral Wave Setup Document (settings=1)

File name:	setup2.sw
Description:	MIKE 21 Spectral Wave Setup Document (settings=2)

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 sta-

tion (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.
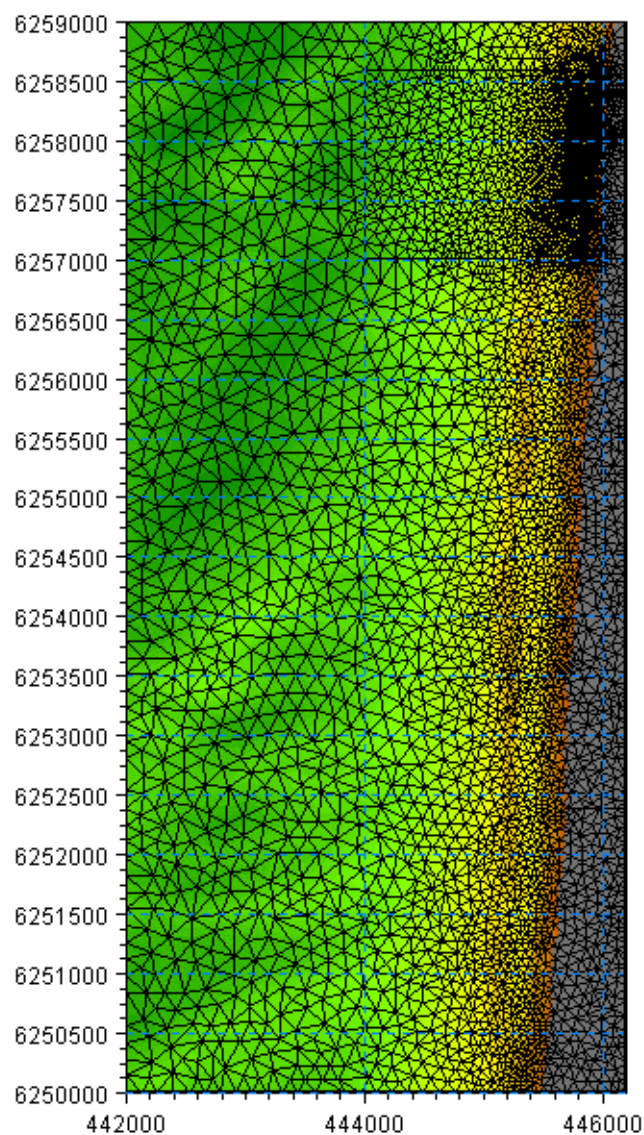
Figure 4.16   Computational mesh and bathymetry
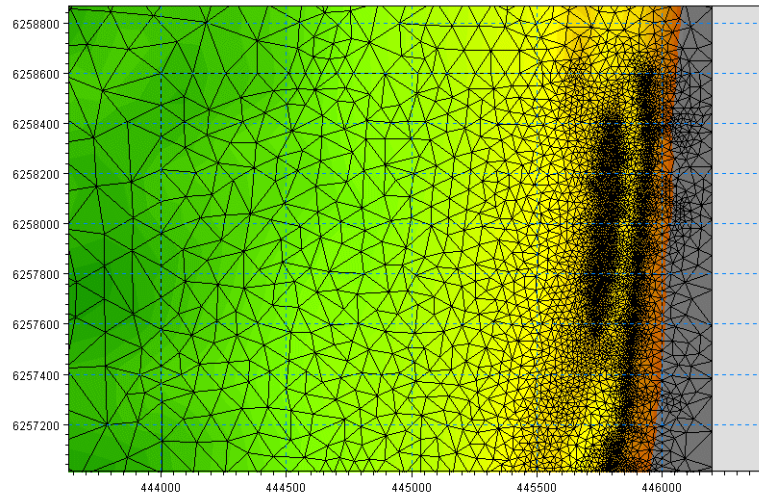
Figure 4.17   Local depth-adaptive refinement of the mesh

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.
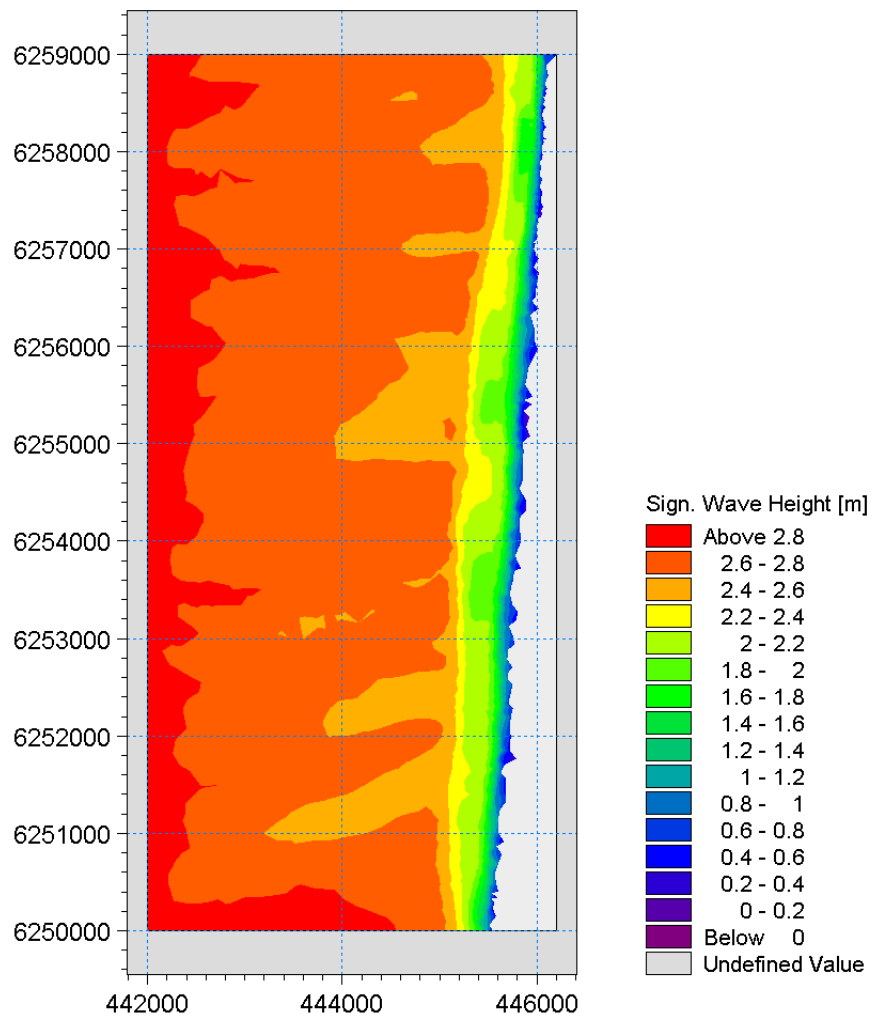
Figure 4.18   Map of the significant wave height
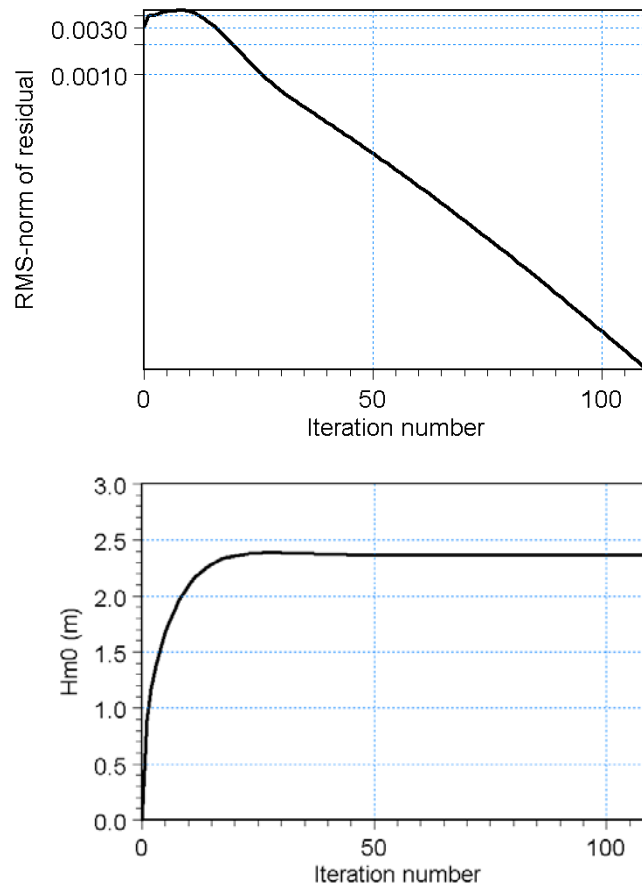
Figure 4.19   Convergence of
a) RMS-norm of the residual as function of the iteration number and
b) significant wave height at the onshore boundary buoy as function of
the iteration number.

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.
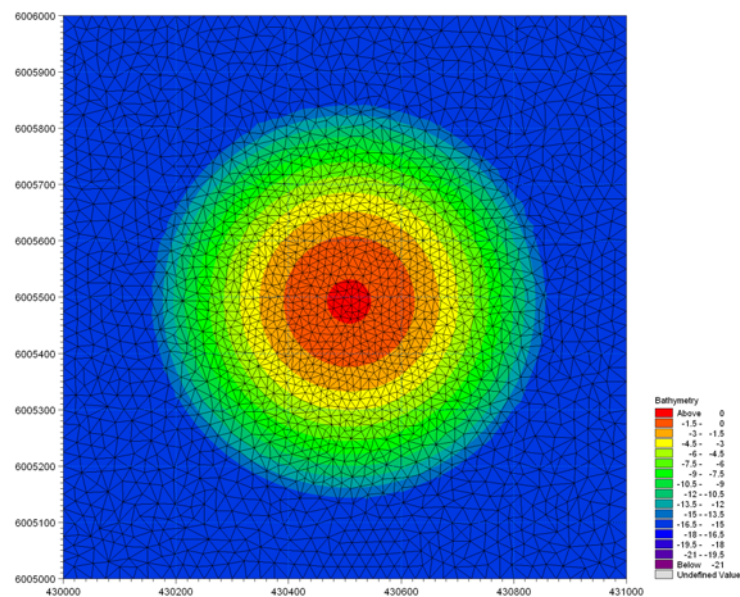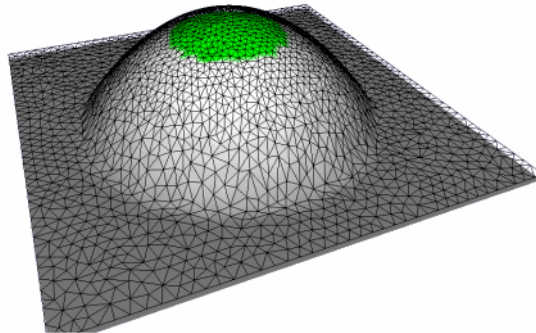
Figure 4.20   Computational mesh and bathymetry

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.
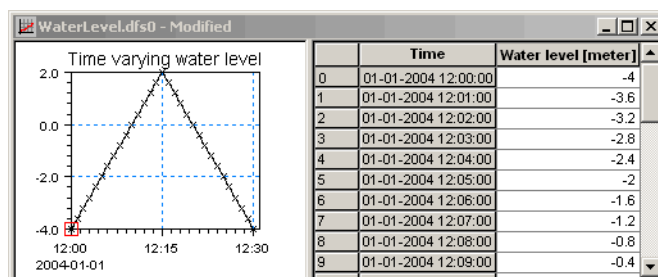
Figure 4.21   Time varying water level

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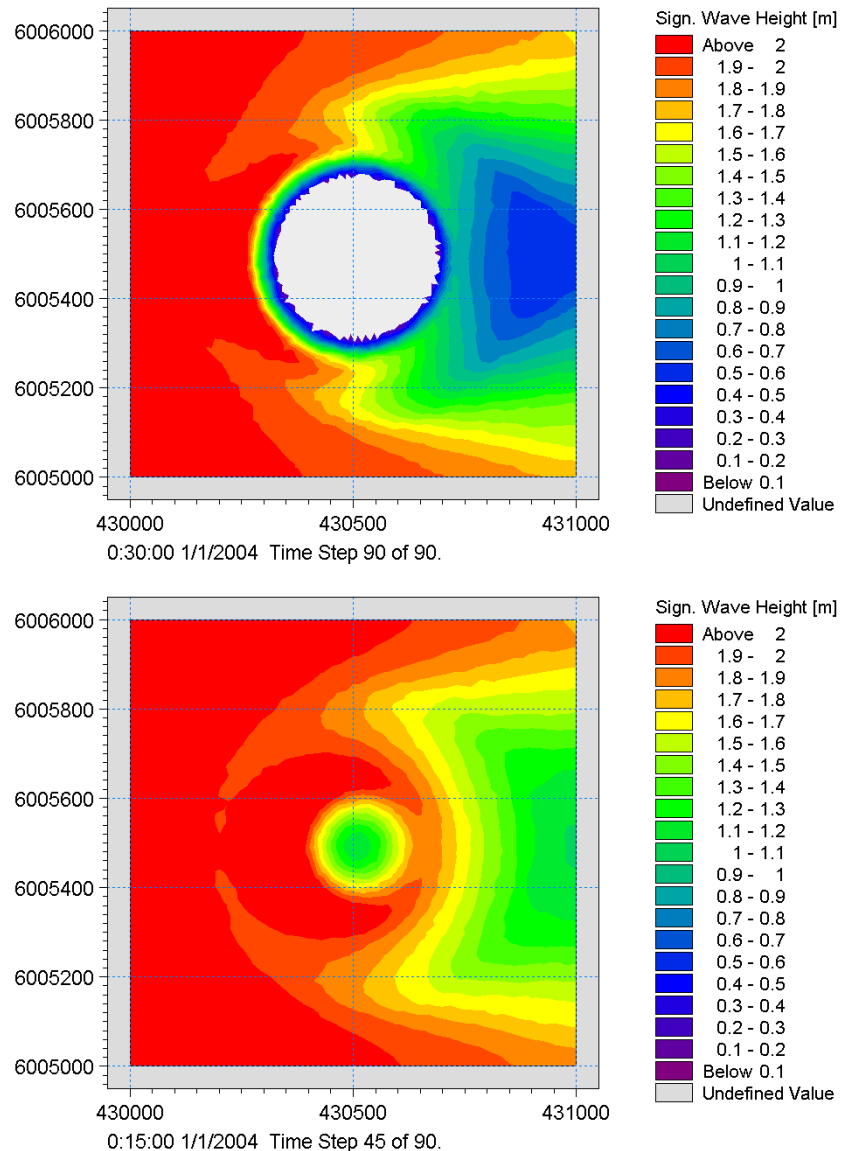
Figure 4.22   Maps of the significant wave height at two different instances (upper at water level –4 m MSL and lower at water level +2 m MSL)

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.

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1   The model setup used for MIKE 21 BW is included in the installation, please see .\Examples\MIKE_21\BW\Island
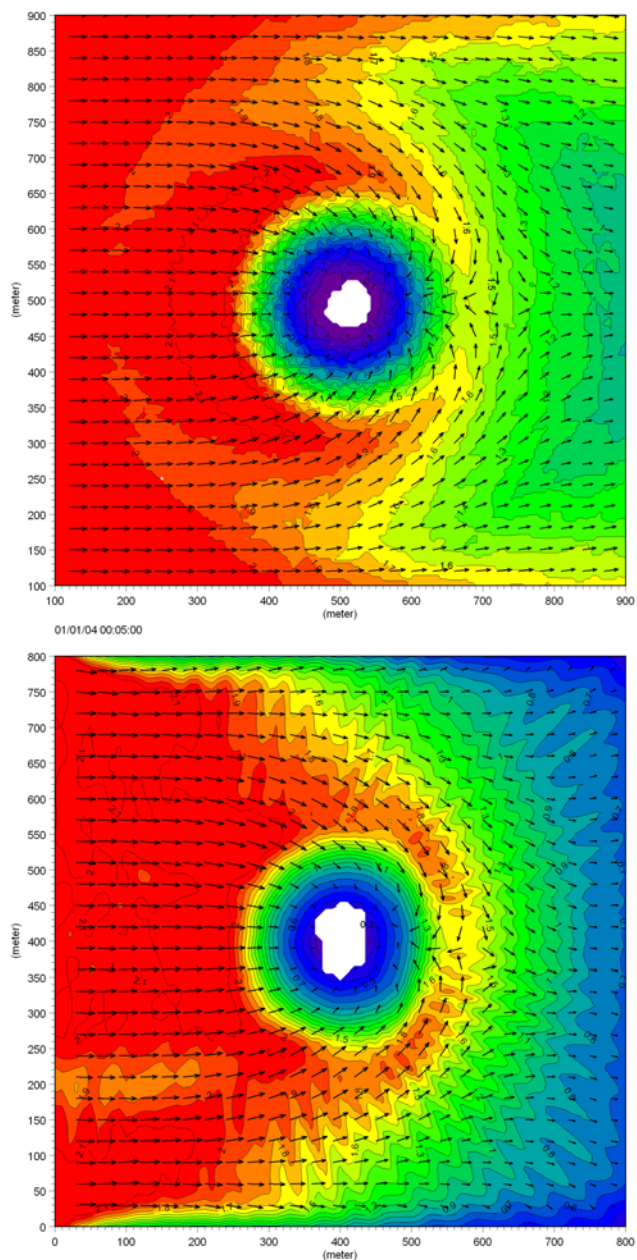
Figure 4.23   Maps of the significant wave height and mean wave direction. Upper panel shows MIKE 21 SW results and lower panel shows results from a MIKE 21 BW simulation. The directional analysis of the Boussinesq model results is made by using the WSWAT Directional Wave Analysis tool available in MIKE 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= 300-500 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
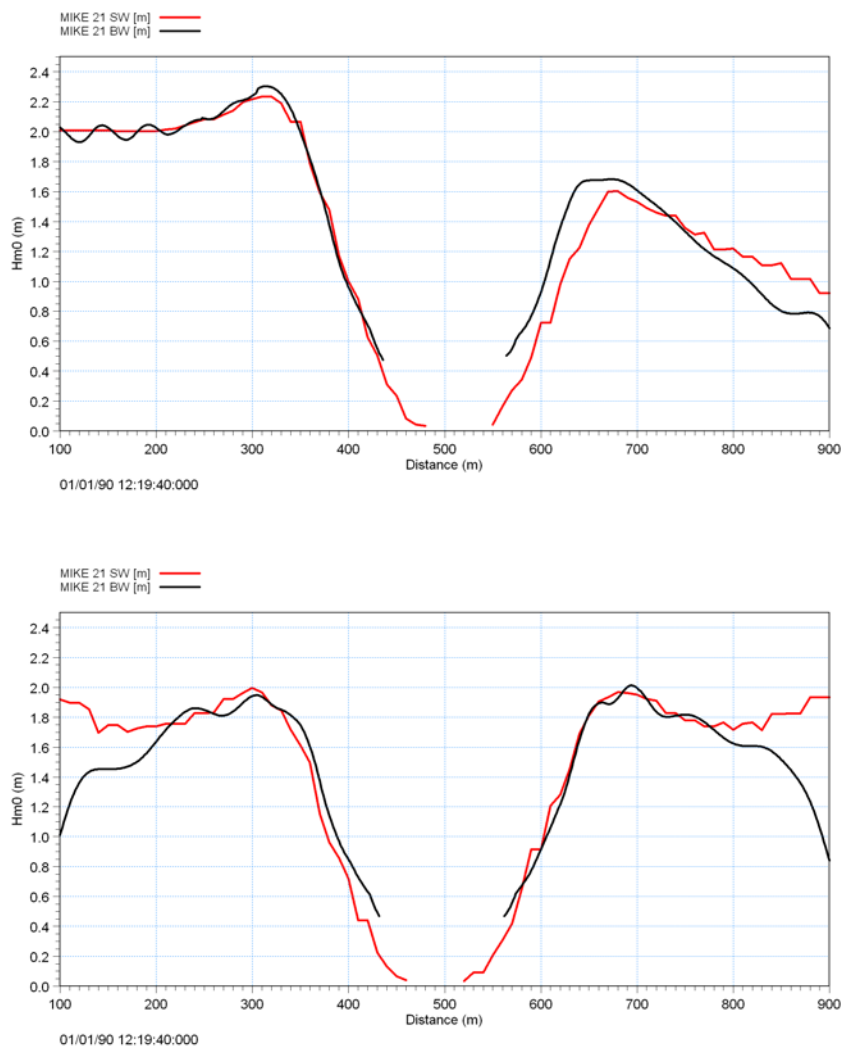
Figure 4.24   Comparison between modelled significant wave height using a phase-averaged model (MIKE 21 SW) and a phase-resolving model (MIKE 21 BW). Upper panel shows a comparison along y= 500 m (west-east direction) and lower panel shows a comparison along x= 500 m (south-north direction)

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

The mesh and bathymetry can be specified either using a mesh file or a bathymetry data file.

Mesh file

You 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 map projection and of the geographical position and bathymetry (Bed elevation) for each node point in the mesh. The file also includes information of the node-connectivity in the mesh.

Bathymetry data file

You generate your bathymetry data file in the MIKE Zero Bathymetry Editor, which is a tool for the generation of structured meshes. An example with a step-by-step description of how to use the Bathymetry Editor for creating a bathymetry data file is included with the installation. Please find this example in your installation folder under Examples\MIKEZero\BatEdit.

The bathymetry data file is a dfs2 file which contains the bathymetry (Bed elevation) and the following geographical information of the computational domain

- The map projection
- The geographical position of the grid origin
- The grid orientation.

The grid orientation is defined as the angle between true north and the y-axis of the model measured clockwise. A mnemonic way of remembering this definition is by thinking of NYC, which normally means **N**ew **Y**ork **C**ity, but which for our purpose means "from **N**orth to the **Y**-axis **C**lockwise", see Figure 5.1.

True north

Orient

Model north
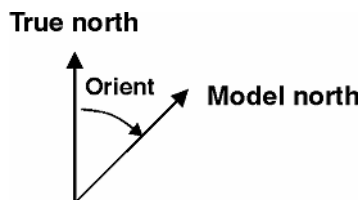
Figure 5.1   Definition of model orientation

The bathymetry data file also contains information of the true land value. True land value is the minimum value you have specified for land points when you prepared the bathymetry. All grid points with a depth value equal to or greater than the value you specify will be excluded from the computational domain. The value representing land is the forth element in the custom block called M21_Misc which consists of 7 elements of type float. The computational mesh is shown in the graphical view.

The bathymetry data file does not contain any information of the boundaries. Therefore starting at the grid origin and going counter-clockwise a boundary code (2, 3, 4 …) is set for each open boundary section of the grid. The boundary codes can be seen by clicking on the graphical view and select "Show mesh".

The bathymetry data file can also be converted to a mesh file using the MIKE Zero Mesh Converter Tool. This will allow you to edit the boundary codes using the MIKE Zero Data Viewer. Note, that a simulation using a mesh file will give different result than using the bathymetry data file directly due to the difference in the determination of the bed elevation in the cell center (see Bed elevation).

Bed elevation

Using a mesh file for specification of the mesh and bathymetry, the bed elevation is given at the nodes (vertices) of the elements. The governing equations are solved using a cell-centred finite volume approach. Here the bed level is required at the cell center. This bed level is determined as the mean value of the node values.

Using a bathymetry data file for specification of the mesh and bathymetry, the bed elevation at the cell center of the elements is determined as the bed elevation specified in the input data file. The bed elevation at the nodes is determined as the area-weighted mean values of the bed elevation in the elements connected to the node and the weight factors are the areas of the connected elements.

5.1.2 Domain Specification

Map projection

When the mesh is specified using a mesh file generated by the MIKE Zero Mesh Generator or the mesh is specified using a bathymetry data file generated by the MIKE Zero Bathymetry Editor the map projection is defined in the input data file and is only shown for reference in the user interface. 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

If the bathymetry level in an element is above the minimum depth cutoff value then the minimum depth cutoff value is replacing the actual bathymetry value in the computations. Please note that the minimum depth cutoff value may be negative as the bathymetry levels is often so 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 can 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, however, 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.

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

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.

5.1.3 Boundary Names

When the mesh is specified using a mesh file generated by the MIKE Zero Mesh Generator you have already defined a code value for the boundaries. Figure 5.2 shows the definition of codes in a simple application. In this case the three open boundaries have been detected from the mesh file specified in the domain dialog.
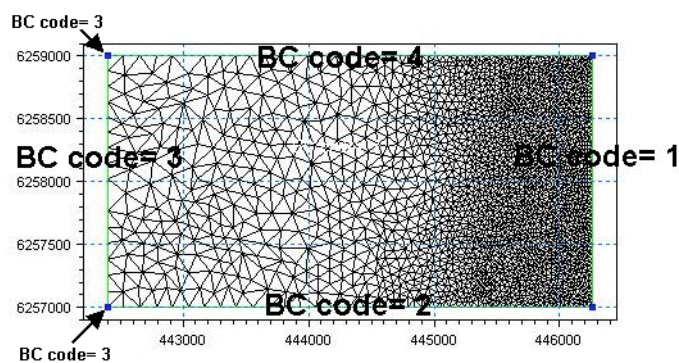
Figure 5.2   The definition of boundary codes in a mesh is made in the Mesh Generator

When the mesh is specified using a bathymetry data file generated by MIKE Zero Bathymetry Editor the boundary codes is defined as described on the Domain dialog.

In the main Boundary Conditions dialog you can re-name the code values to more appropriate names, see Figure 5.3.

Figure 5.3   Change of default code names (from the mesh file) to more appropriate names

5.1.4 Material

The domain can be divided into different material zones. The zone information can be used to represent areas with different type of vegetation.

Three types of file format can be used for defining the material zones

- dfs file
- xyz file
- shape file

For the dfs file, the zones are defined by a map identifying the location of the different zones. Each zone is identified by an integer number larger than zero. If no zone is specified, the value should be zero. For the xyz file and the shape file, the zones are defined as the closed region within a number of polygons. If an element belongs to more than one polygon in the xyz file or the shape file, the information from the last polygon read from the file is applied.

In the material tab you can rename the zone names to more appropriate names.

Data

dfs file
You must prepare a data file containing an item with the zone numbers. 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. For both a dfsu-file and a dfs2 file piecewise constant interpolation is used to map the data. The input data file must contain only a single time step.

xyz file
The data in the file must be formatted as ASCII text in five columns with the two first columns giving the x-and y-coordinates of the points. The third column represents connectivity. The connectivity column is used to define arcs. All points along an arc - except the last point - shall have a connectivity value of 1 and the last point shall have a connectivity value of 0. The fourth column contains the z-value at the point. Finally, the fifth column contains the zone number. The z-coordinates are not used when the xyz file is used to define material zones.

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

shape file

The shape file format is a geospatial vector data format for geographic information system (GIS) software. To use a shape file to define zones, the shape type must be either Polygon, PolygonZ or PolygonM. The zone numbers must be written as a field in the dbf-file. The zone numbers must be integers larger than 0 for each polygon.

In the shape file selector, you specify the map projection in which the data is given when you click on "Conversion". If a .prj file is included in the shape file data, the projection is obtained from this file. If there is no .prj file available, you need to specify the map projection.

5.2   Time

The period to be covered by the simulation is specified in this dialog. You can specify the simulation period in two ways:

- No. of time steps, time step interval and simulation start date
- Time step interval, simulation start date and simulation end date

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. When "No. of time steps, step interval and simulation start date" is selected the simulation end date is presented for reference. When "time step interval, simulation start date and simulation end date" is selected the number of time steps is calculated as the smallest integer (a whole number), which is larger than the duration time divided by the time step interval, and the simulation end data is corrected accordingly.

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.

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

$$N = \frac{E}{\sigma} \tag{6.1}$$

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 Settings

For the fully spectral formulation two different parametrizations for the source terms for wind input and dissipation terms (swell dissipation and whitecapping) are available.

- Modified WAM Cycle 4
- Ardhuin et al.

The first option is a modified version of the parametrization used in WAM Cycle 4. The second option is the parameterization proposed by Ardhuin et al. (2010). The main difference between the two parametrizations are the parametrizations of the dissipation terms. The parametrization of the wind input is based on the same basic parametrization, but there are some differences in the implementation and the values for the parameters used (see Parameter values for Wind Forcing). The "Modified WAM Cycle 4" option correspond to the parametrization used in the previous version of MIKE 21 Spectra Wave Model FM. However, a new swell dissipation term has been included. For more details see the scientific documentation.

6.1.4 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 then the instationary formulation. Examples are:

- when the forcing (eg. wind) is slowing 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

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

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 $f_j = f_0 \cdot c^{j+0.5}$ & $f_j = f_0 \cdot c^{j-0.5}$, 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, $\Delta\theta < 2°\text{-}10°$ (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 $\Delta\theta < 10°\text{-}30°$ 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. 92).

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

- No separation
- Constant frequency
- Constant frequency and wind dir.
- Dynamic frequency
- Dynamic frequency and wind dir.
- Wave-age approach

Selecting "Constant frequency" or "Constant frequency and wind dir." you have to specify the threshold frequency. Selecting "Dynamic frequency" or "Dynamic frequency and wind dir." you have to specify the maximum threshold frequency. Finally, selecting "Wave-age approach" you must specify two additional parameters, "Coefficient" and "Power". The default values are 0.83 and 1.0, respectively.

For details regarding the distinction of wind-sea and swell, see the scientific documentation (section 5.1 Field Type).

Note: In older versions the options "Constant threshold frequency" and "Dynamic threshold frequency" were available. These correspond to "Constant frequency and wind dir." and "Dynamic frequency and wind dir.", respectively.

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.

Algorithm for discretization in geographical domain

The simulation time and accuracy can be controlled by specifying the order of the numerical scheme which is used in the numerical calculations. The scheme for discretization in the geographical 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 recommend 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

Algorithm for discretization in geographical domain

The simulation time and accuracy can be controlled by specifying the order of the numerical scheme which is used in the numerical calculations. The schemes for discretization in the geographical 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

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

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

the iteration procedure is given by the following algorithm

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

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

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

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 $\bar{A}$ 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

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

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

Root-mean-square norm: $\quad \|\bar{x}\|_{RMS} = \left[\dfrac{\sum\limits_{i}^{N} x_i^2}{N} \right]^{1/2}$ (6.4)

Max norm: $\quad \|\bar{x}\|_{MAX} = \max(x_i), i = 1, N$

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

$$\left\| \bar{H}_{m0}^{\ k+1} - \bar{H}_{m0}^{\ k} \right\|_{RMS} < TOL_1 \tag{6.5}$$

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 that 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

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

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 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 (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. 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 dfsu 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

$$(C_g + (u\cos(\theta) + v\sin(\theta)))/C_g < \text{ f} \tag{6.7}$$

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 (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. 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

The wind direction is defined with respect to true North (coming from). Wind speeds should be given as U10 (wind speed taken 10m above the Mean Sea Level (MSL)). The formulation used for air-sea momentum transfer is valid for a 10m wind speed corresponding to a neutrally stratified lower atmosphere. The actual wind conditions at 10m are generally influenced by stable or unstable conditions in the atmospheric boundary layer. To conform with the air-sea momentum formulation then for the fully spectral formulation, it is possible to calculate the neutral wind speed at 10 m based on the actual wind speed at 10m and additional input data layers required to characterize the stratification of the atmospheric boundary layer.

For calculation of the neutral 10m wind speed information of the 10m wind speed, the water properties (sea surface temperature, and salinity) and the air properties (surface pressure, air temperature and relative humidity) are required. The air temperature and the relative humidity should be obtained at level 2m above MSL. In general, the atmospheric boundary condition is unstable when heated from below by the sea and stable when cooled. The atmospheric mixing associated with strong wind speeds will increasingly cause the boundary layer to become more and more neutral, in which case the correction to neutral winds becomes small. Since very light wind speeds excites small waves, then the main effect of using neutral wind conditions will be for modest to intermediate wind speeds.

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 (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. 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 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 (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. 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 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.

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 U10 instead of Ua. Ua is the adjusted wind speed as defined in the Shore Protection Manual.

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. 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 the wind input source term, you have to specify the growth parameter and the wave age tuning parameter.

You can choose between two types of air-sea interaction

- Uncoupled
- Coupled

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 coefficients (version 2). The default drag law is taken from Smith and Banke (1975).

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 user can specify the background roughness Charnock parameter.

For large scale applications (say, spatial scale > ~100 km) it is recommended to use the coupled formulation with default values. For small scale applications (say, spatial scale < ~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 e.g, Johnson and Kofoed-Hansen (2000) and Kofoed-Hansen et al (2000). The overestimation has mainly been observed for relatively strong winds, say, U10 > 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). The default in MIKE 21 SW is the coupled formulation.

Parameter values (fully spectral formulation)

For the fully spectral formulation the balance between the different source terms is essential for obtaining accurate results. The values for the parameters for the wind input therefore depend on the type of settings and the type of air-sea interaction.

It is recommended only to use the uncoupled formulation for the air-sea interaction in combination with the "Modified WAM Cycle 4" settings. For open oceans a Charnock parameter of 0.01 is typically used while a value of 0.0185 has been suggested for coastal areas

Using the "Modified WAM Cycle 4" settings, the default values for the growth parameter, the wave age tuning parameter and the background Charnock parameter are 1.2, 0.008 and 0.006, respectively. These parameter settings are used in the ECWAM model Cycle 46R1 (iphys=0). In the previous version of MIKE 21 Spectral Wave model the values 1.2 and 0.011 were used for the growth parameter and the wave age tuning parameter. The default value for the background Charnock parameter was 0.01. These values correspond to the values used in WAM Cycle 4.

Using the "Ardhuin et al." settings, the default values for the growth parameter, the wave age tuning parameter and the background Charnock parameter are 1.42, 0.008 and 0.0062, respectively. These parameter settings are used in the ECWAM model Cycle 46R1 (iphys=1).

When an existing MIKE 21 SW setup file based on the previous version of MIKE 21 Spectral Wave model is opened in the MIKE Zero user interface, then the growth parameter and the wave age tuning parameter is set to 1.2 and 0.011, respectively, to give results that are very similar to those produced by previous versions of MIKE 21 SW.

Correction of friction velocity (fully spectral formulation)

For extreme wind conditions (e.g. hurricanes, tropical cyclones) the wind drag becomes very high resulting in unrealistic high wave growth rates. Therefore, a simple limit (cap) on the ratio between the friction velocity, U_*, and wind

speed, U_{10}, at 10m level can be applied. This approach was proposed by Jensen et al. (2006). The friction velocity is then calculated as

$$u_* = \min(u_*, fU_{10}) \tag{6.8}$$

The default cap value is $f = 0.06$.

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.

6.8 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 (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. 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 Water properties

For the fully spectral formulation the ratio of air density and water density is used in the calculation of the wind input. The water density, the sea surface temperature and the salinity are also used in calculation of the neutral stratification mean wind speed.

Density

The water density can be specified in two ways

- Specified density
- Function of temperature and salinity

When "Function of temperature and salinity" is selected you must specify the water temperature and salinity. The density is calculated using UNESCO's standard equation of state for sea water. These relations are applicable for temperatures ranging from -2.1 ºC to 40.0 ºC and salinities in the range from 0 to 45 PSU (Practical Salinity Unit).

When calculation of neutral wind speed is included, it is recommended to calculate the density as a function of temperature and salinity.

Temperature

If you specify water density as "Function of temperature and salinity" or neutral wind calculation is included in the simulation, you must specify the water temperature.

Salinity

If you specify water density as "Function of temperature and salinity" or neutral wind calculation is included in the simulation, you must specify the salinity of the water.

Data

The format of the data for water property calculation can be specified as:

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

For the case with data varying in time but constant in domain you have to prepare a data file containing the relevant variable 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 wave simulation. A linear interpolation will be applied if the time steps differ.

For the case with data varying in domain you have to prepare a data file containing the relevant variable before you set up the 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. If a dfs2-file is used, bilinear interpolation is used to map the data. For the case with varying in both time and domain the data must also 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. A linear interpolation will be applied if the time steps differ.

6.10 Air properties

For the fully spectral formulation the ratio of air density and water density is used in the calculation of the wind input. The air density, the surface pressure, the air temperature and the humidity are also used in calculation of the neutral wind speed.

Density

The air density can be specified in two ways

- Specified density
- Function of pressure, temperature and humidity

When "Function of pressure, temperature and humidity" is selected you must specify the air pressure, air temperature and the relative humidity. For the calculation of the air density see the scientific documentation.

When calculation of neutral wind speed is included it is recommended to calculate the density as function of pressure, temperature and relative humidity.

Pressure

If you specify air density as "Function of pressure, temperature and humidity" or neutral wind calculation is included in the simulation, you must specify the air pressure at Mean Sea Level.

Temperature

If you specify air density as "Function of pressure, temperature and humidity" or neutral wind calculation is included in the simulation, you must specify the air temperature 2m above the Mean Sea Level.

Humidity

If you specify air density as "Function of pressure, temperature and humidity" or neutral wind calculation is included in the simulation, you must specify the relative humidity 2m above the Mean Sea Level.

Data

The format of the data for air property calculation can be specified as:

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

For the case with data varying in time but constant in domain you have to prepare a data file containing the relevant variable 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 wave simulation. A linear interpolation will be applied if the time steps differ.

For the case with data varying in domain you have to prepare a data file containing the relevant variable before you set up the 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. If a dfs2-file is used, bilinear interpolation is used to map the data. For the case with varying in both time and domain the data must also 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. A linear interpolation will be applied if the time steps differ.

6.11   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

$$A_{i,l}^k = (1-\alpha)A_{i,l}^{k-1} + \alpha(A_{i,l}^{k-1})^* \qquad k = 1, \text{nsteps} \qquad (6.9)$$

Here k is the number of smoothing steps and a 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) with reduce the oscillation/convergence problem, but will also has the effect that the diffraction effect will be reduced.

6.11.1   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.

6.12   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.

6.12.1   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 results in the development of secondary peaks at harmonics of the spectral 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.

6.13 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 (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.

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.

6.13.1 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 no influenced by breaking.

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

$$S_{surf}(\sigma,\theta) = -\frac{\alpha Q_b \bar{\sigma} H_m^2}{8\pi} \frac{E(\sigma,\theta)}{E_{tot}} \tag{6.10}$$

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

$$\gamma = 0,5 + 0,4\tanh(33 s_0) \tag{6.11}$$

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

$$\gamma = 0,55 + 0,88\exp\left(-0,012\cotan\left(\frac{\partial d}{\partial s}\right)\right) \quad d \le 100$$
$$\gamma = 0,55 \qquad\qquad\qquad\qquad\qquad d > 100 \tag{6.12}$$

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

$$\gamma = 0{,}76kh + 0{,}29 \tag{6.13}$$

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.

6.13.2 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.

6.14 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.

6.14.1 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} = 0.1-0.4 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. Dingler 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. (6.14) below, Weber (1991)

$$S_{bot}(\sigma,\theta) = -C_f \frac{k}{\sinh 2kh} E(\sigma,\theta) \tag{6.14}$$

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

$$U_{bm} = \left[\iint 4 \frac{gk}{\sinh 2kh} N(\sigma,\theta) d\sigma \; d\theta \right]^{1/2} \tag{6.15}$$

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

6.14.2 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.

6.15 Vegetation

The spatial variability of the vegetation is modelled using the zone concept. The computational domain is divided into a number of zones and for each zone constant vegetation data can be specified.

6.15.1 Zone data

The vegetation zones can be defined in two ways

- Zone map from input file
- Zone map from material tab

When "Zone map from input file" is selected, the user must supply a map identifying the location of the different vegetation zones. Each zone is identified by an integer number larger than zero. In areas where there is no vegetation the values should be set to zero. "Zone map from material tap" can only be selected when "Include material zones" is selected on the "Material" tab on the "Domain" page.

The vegetation zones are shown in the zone list view. Here you can rename the zone names to more appropriate names. For each zone you can also specify whether the zone should be active or not.

Data

When "Zone map from input file" is selected, the user has to prepare a data file containing the zone map before you set up the simulation. The file must be a 2D unstructured data file (dfsu) or a 2D grid data file (dfs2). If a dfsu-file is used piecewise constant interpolation is used to map the data. If a dfs2-file is used bilinear interpolation is used to map the data. The area in the data file must cover the model area.

6.15.2 Vegetation data

The vegetation data for each zone can be specified in the corresponding zone tab.

For modelling of dissipation due to vegetation an explicit approach can be used. Two models can be used

- Suzuki et al.
- Jacobsen et al.

Here the model by Suzuki et al. is using a layered approach, while the model by Jacobsen et al. is only using one layer. Both models have been implemented for the fully spectral formulation while only the Suzuki et al. model has been implemented for the directionally decoupled parametric formulation.

The vegetation is modelled as rigid stems (cylinders), and the flexibility and the properties of the vegetation are taken into account through the drag coefficient. To take into account vertical variation in the vegetation a layered concept is used, where the basic parameters for the vegetation are specified for each layer. Hence, you need to specify the number of vertical layers.

It is also possible to choose between three formulations for the drag coefficient

- Constant
- Variable (Sanchez-Gorzalez et al.)
- Variable (Mendez and Losada)

The three basic vegetation parameters are the height of the vegetation, the stem diameter and the vegetation density (the number of plants per square meter) for each vertical vegetation section. You must specify the input format for these parameters as either

- Constant
- Time varying

If "Constant" is selected, the vegetation parameters must be specified in the grid. If "Time varying" is selected, you must prepare a data file containing the information before you set up the spectral wave simulation. The data file must be a time series data file (dfs0). The data must cover the complete simulation period. The time step interval 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 step interval differs.

Note, that if you change the number of layers and "Time varying" is selected for the input format you must load in the input file again.

You must also specify the drag coefficient for each layer in the grid, when "Constant" is selected for the formulation of the drag coefficient. When the formulation by Sanchez-Gorzalez et al. is used, then you must specify the two parameters alpha_Cd and Beta_Cd and the valid range for the expression: the minimum and maximum Keulegan-Carpenter number, KC_{min} and KC_{max}.

6.15.3 General description

Model by Suzuki et al. (2012)

For the fully spectral formulation the model by Suzuki et al. (2012) can be used for the dissipation term due to vegetation, S_{veg}. Here the dissipation term is given by

$$S_{veg}(f, \theta) = -\sqrt{\frac{2}{\pi}} g^2 C_D d_s N_v \left(\frac{\bar{k}}{2\pi \bar{f}}\right)^3 \frac{(\sinh \bar{k} h_v^*)^3 + 3\sinh \bar{k} h_v^*}{3\bar{k}(\cos \bar{k} d)^3} \sqrt{E_{tot}} E(f, \theta) \qquad (6.16)$$

where g is the gravitational acceleration, C_D is the drag coefficient, d_s is the stem diameter, N_v is the vegetation density, d is the water depth, $\bar{k}$ is the mean wave number, $\bar{f}$ is the mean frequency, E_{tot} is the total energy and $E(f,\theta)$ is the energy density as function of the frequency, f, and the wave direction, θ. h_v^* is given as $h_v^* = min(h_v, d)$, where h_v is the vegetation height. The vegetation density is the number of plants per unit area.

To take into account the vertical variation of the vegetation a layered approach is used. The drag coefficient, $C_{D,i}$, the stem diameter, $d_{s,i}$, the vegetation density, $N_{v,i}$, and the vegetation height, $h_{v,i}$, is then specified for each vertical layer, i. The vegetation height for each layer is the distance from the bed to the top of the vegetation layer. The dissipation term due to vegetation is then determined as

$$S_{veg}(f, \theta) = \sum_{i=1}^{nlayers} S_{veg,i}(f, \theta) \qquad (6.17)$$

where

$$S_{veg,i}(f, \theta) = -\sqrt{\frac{2}{\pi}} g^2 C_{D,i} d_{s,i} N_{v,i} \left(\frac{\bar{k}}{2\pi \bar{f}}\right)^3 \cdot$$
$$\frac{((\sinh \bar{k} h_{v,i}^*)^3 - (\sinh \bar{k} h_{v,i-1}^*)^3) + 3(\sinh \bar{k} h_{v,i}^* - \sinh \bar{k} h_{v,i-1}^*)}{3\bar{k}(\cos \bar{k} d)^3} \sqrt{E_{tot}} E(f, \theta) \qquad (6.18)$$

For the directionally decoupled parametric formulation the same approach is used. Here the dissipation term in the equation for the zeroth moment of the wave action spectrum is given by

$$S_{veg}(\theta) = -\sqrt{\frac{2}{\pi}} g^2 C_D d_s N_v \left(\frac{\bar{k}}{2\pi \bar{f}}\right)^3 \frac{(\sinh \bar{k} h_v^*)^3 + 3\sinh \bar{k} h_v^*}{3\bar{k}(\cos \bar{k} d)^3} \sqrt{E_{tot}} E(f, \theta) \qquad (6.19)$$

It is assumed that the dissipation due to vegetation have no effect on the mean frequency.

Model by Jacobsen et al. (2019)

For the fully spectral formulation the model by Jacobsen et al. (2019) can also be used for the dissipation term due to vegetation, S_{veg}. Here the dissipation term is given by

$$S_{veg}(f, \theta) = -\frac{1}{g}\sqrt{\frac{2}{\pi}}\alpha^3 C_D d_s N_v \cdot$$
$$\left(\int_{-d}^{-d+h_v} \sqrt{m_{u,0}}\left(\frac{2\pi f \cosh k(z+d)}{\sinh(kd)}\right)^2 dz\right) E(f, \theta) \tag{6.20}$$

where α is a velocity reduction factor, $m_{u,0}$ is the zeroth moment of the velocity spectrum s_u and k is the wave number. The velocity spectrum is given by

$$s_u = \left(\frac{2\pi f \cosh k(z+d)}{\sinh(kd)}\right)^2 E(f, \theta) \tag{6.21}$$

Following Jacobsen et al. (2019), the numerical integration of the vertical integration term is performed using Simpson´s rule with 21 integration points.

Drag coefficient

The drag coefficient, C_D, can be a constant or determined from an empirical expression as function of the Keulegan-Carpenter number. The Keulegan-Carpenter number is defined as

$$KC = u_b T_p / d_v \tag{6.22}$$

where u_b is the maximum orbital velocity near the bed and T_p is the peak period. Sánchez-Ganzález et al. (2011) proposed to use the following expression

$$C_D = \alpha KC^\beta \qquad KC_{min} \le KC \le KC_{max} \tag{6.23}$$

where α=22.9, β =1.09, KC_{min}=15 and KC_{max}=425. Mendez and Losada (2004) proposed the following expression

$$C_D = \frac{\exp(-0{,}0138 Q)}{Q^{0{,}3}} \qquad 7 \le Q \le 172 \tag{6.24}$$

where Q is the modified Keulegan-Carpenter number

$$Q = \frac{KC}{\left(\dfrac{h_v}{d}\right)^{0{,}76}} \tag{6.25}$$

6.16   Mud

In coastal areas, the presence of a fluid mud layer can have a significant effect on the wave condition. The energy dissipation by fluid mud can be taken into account by introducing an additional source term.

The mud can be specified in three different ways

- No mud
- Specified mud properties
- Mud properties from MT simulation

Selecting the specified mud properties option, you must specify the thickness of the mud layer and the dry mud density. Note, that the last option is only possible using the MIKE 21/3 Coupled Model FM and only if the Mud Transport module is included. Here, the fluid mud layer thickness and the dry density is defined as the thickness and density of the active layer in the MT simulation. The active layer is the first layer where the layer thickness is larger than zero.

You must also specify the kinematic viscosity of the mud. The wave damping is quite sensitive to the value of the viscosity, so the viscosity is an important parameter in the calibration. When "Specified mud properties" is selected, you must also specify the sediment density. When "Mud properties from MT simulation is selected, then the sediment density defined in the MT specifications is applied. The sediment density is required to calculate the bulk density (see General description). Finally, you must also specify the scaling factor. This is a factor which can be used to calibrate the dissipation of waves due to the fluid mud.

Note: Mud-induced wave damping can only be taken into account for the fully spectral formulation.

6.16.1   Mud Data

The format of the data for the thickness of the mud layer and the dry density of the mud layer can be specified as:

- Constant (in both time and domain)
- Constant in time and varying in domain
- Varying in time and domain

For the case with data varying in domain you must prepare a data file containing the relevant variable before you set up the hydrodynamic 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, piece-wise constant interpolation is used to map the data. If a dfs2-file is used, bilin-

ear interpolation is used to map the data. For the case with varying in both time and domain the data must also cover the complete simulation period. The time step of the input data file does not, however, must be the same as the time step of the hydrodynamic simulation. A linear interpolation will be applied if the time steps differ.

6.16.2 General description

The description of the mud-induced wave damping is based on the two-layer model approach. At the bottom there is a layer consisting of fluid mud and at the top a water layer. The energy dissipation term proposed by Kranenburg et al. (2011) is applied. For determination of the complex wave number the dispersion relation proposed by De Wit (1995) is used. Here the Newton-Raphson method is used to find the roots of this nonlinear function. For more details see the scientific documentations. The density used in the dispersion relation is the bulk (or wet) density. The bulk density is calculated as

$$\rho_{bulk} = \rho_{dry} + \left(1 - \frac{\rho_{dry}}{\rho_{sediment}}\right)\rho_{water} \qquad (6.26)$$

Here ρ_{dry} is the dry density, $\rho_{sediment}$ is the sediment density and ρ_{water} is the density of water.

6.17 White capping

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

When the "Modified WAM Cycle 4" setting is applied (see Basic equations) the source function describing the dissipation due to white capping is based on the theory of Hasselmann (1974). The breaking wave dissipation source function is detailed described in the Komen et al. (1994) and includes two free parameters; Cdis and DELTAdis. If white capping is included you must specify the two dissipation coefficients, Cdis and DELTAdis. The Cdis coefficient is a proportional factor on the white capping dissipation source function and thus control the overall dissipation rate. The DELTAdis coefficient is controlling the weight of dissipation in the energy/action spectrum.

When the "Ardhuin et al." setting is applied the white cap dissipation of Ardhuin et al. (2010) is used. For more details, see the scientific documentation.

Dissipation coefficient Cdis

The dissipation coefficient, Cdis, 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, Cdis, 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 DELTAdis

The dissipation coefficient, DELTAdis, 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, DELTAdis, 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.

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

It is only possible to specify the type of spectrum, when "Separation of Wind-sea and Swell" is specified on the Spectral discretization page. If "No separation" is specified, the mean angular frequency and the mean wave number is calculated using the whole spectrum.

Parameter values

Janssen (See Komen et al. (1994)) proposed to use the following values: Cds= 4.5, δ= 0.5 and $p_\sigma = p_k$ = -1. The formulation of the source term due to white capping is 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 results in too strong decay of energy on the swell components. The pre-

dictions 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 white capping, from the wind-sea part of the spectrum.

To improve the white capping for wave conditions with a combination of wind-sea and swell Bidlot et al. (2007) proposed a revised formulation of white capping. Here eq. (6.27) 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 Cds and δ are changed to 2.1 and 0.6, respectively. The whole spectrum was used in the calculation of the mean angular frequency and the mean wave number. More recently the values have been retuned in connection with the tuning of the parameter for the wind input. The values used in ECWAM model Cycle 46R1 (iphys=0) are Cds= 1.33, δ= 0.5 and p_σ = p_k = 1.

By reducing the Cdis coefficient the overall white capping dissipation can be reduced resulting in larger waves. DELTAdis coefficient less than 0.5 corresponds to increasing the weight of the dissipation on lower frequencies resulting in smaller wave periods. A DELTAdis coefficient lager than 0.5 corresponds to increasing the weight of the dissipation on higher frequencies resulting in larger wave periods. The DELTAdis value should be larger than zero and smaller than one.

6.17.1 General description

Using the "Modified WAM Cycle 4" setting 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

$$S_{ds}(\sigma,\theta) = -C_{ds}(\bar{k}^2 m_0)^2 \left\{ (1-\delta)\frac{k}{\bar{k}} + \delta\left(\frac{k}{\bar{k}}\right)^2 \right\} \bar{\sigma} N(\sigma,\theta) \tag{6.27}$$

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

$$\bar{\sigma} = 2\pi\bar{f} = 2\pi\left(\frac{\int_0^{2\pi}\int_0^\infty E(f,\theta)f_\sigma^p\,dfd\theta}{\int_0^{2\pi}\int_0^\infty E(f,\theta)\,dfd\theta}\right)^{p_\sigma} \tag{6.28}$$

$$\sqrt{\bar{k}} = \left(\frac{\int_0^{2\pi}\int_0^\infty E(f,\theta)(\sqrt{k})^{p_k}\,dfd\theta}{\int_0^{2\pi}\int_0^\infty E(f,\theta)\,dfd\theta}\right)^{p_k} \tag{6.29}$$

where p_σ and pk are mean angular frequency power and the mean wave number power.

6.18 Structures

The horizontal dimension of structures such as piers, offshore wind turbines, breakwaters, dams and caisons 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

6.18.1 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

$$d_i = d_{min} + (i-1)\frac{d_{max} - d_{min}}{(nd - 1)}, \quad i = 1, nd \tag{6.30}$$

$$T_j = T_{min} + (j-1)\frac{T_{max} - T_{min}}{(nt - 1)}, \quad j = 1, nt \tag{6.31}$$

The format of a reflection factor table is shown below:

```
nd dmin dmax
nt Tmin Tmax
c1,1 c1,2 c1,3 ... c1,nt
c2,1 c2,2 c2,3 ... c2,nt
```

...
...
$c_{nd,1}$ $c_{nd,2}$ $c_{nd,3}$ ... $c_{nd,nt}$

General description

Source term approach

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

$$s = -\frac{c}{A}c_g E(\sigma, \theta) \tag{6.32}$$

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-deriative wave action density due to the effect of a structure can be written

$$-\frac{1}{A}\sum(F_n \cdot \Delta l) \tag{6.33}$$

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.

6.18.2 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. 99) 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

$$K_r = \sqrt{1 - K_t^2} \qquad (6.34)$$

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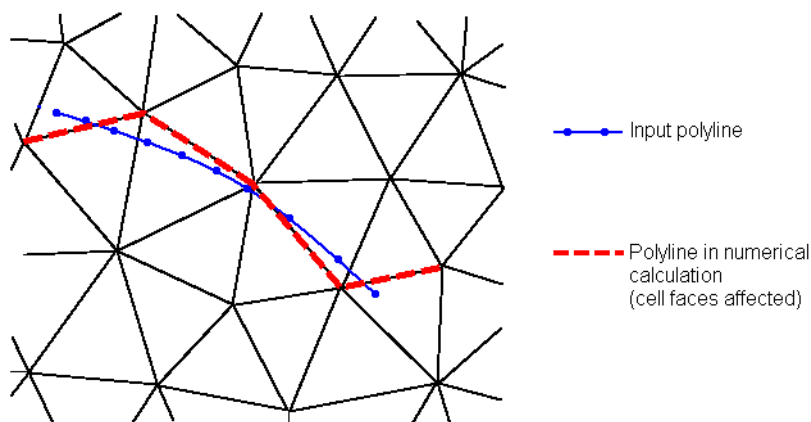
Figure 6.1   The location of a line structure. Note the affected cell faces.

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, how-

ever, 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

$$K_t^2 + K_r^2 + K_l^2 = 1 \tag{6.35}$$

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

$$
\begin{cases}
K_t = K_{t,max} & \dfrac{f}{H_i} < \left(\dfrac{f}{H_i}\right)_{min} \\[2ex]
K_t = \dfrac{1}{2}\left(1 - \sin\left(\dfrac{\pi}{2}\dfrac{\dfrac{f}{H_i} + \beta}{\alpha}\right)\right) & \left(\dfrac{f}{H_i}\right)_{min} \le \dfrac{f}{H_i} \le \left(\dfrac{f}{H_i}\right)_{max} \\[2ex]
K_t = K_{t,min} & \dfrac{f}{H_i} > \left(\dfrac{f}{H_i}\right)_{max}
\end{cases}
\tag{6.36}
$$

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

$$\left(\frac{f}{H_i}\right)_{min} = 2\frac{\alpha}{\pi}\operatorname{asin}(1 - 2K_{t,max}) - \beta \tag{6.37}$$

$$\left(\frac{f}{H_i}\right)_{max} = 2\frac{\alpha}{\pi}\operatorname{asin}(1 - 2K_{t,min}) - \beta \tag{6.38}$$

Goda's formula can be used to estimate the transmission of waves over breakwaters, dams and caisons. 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 α=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).

6.19 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 [m²s²/rad]
    – using the directionally decoupled parametric formulation two items must be specified: the zeroth moment m_0, e.g. expressed by [m²/rad], of the normal wave action spectrum and the first moment m_1, e.g. expressed by [m²s/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.

6.19.1 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. However note that the empirical formulation is not resolved fully in the full domain for MPI simulations where several sub-domains are used.

6.20 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. 56)*).

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.

6.20.1 Boundary specification

You can choose between the following ten 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
- Cyclic 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 (γ=3.3, σ_a=0.07 and σ_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 ω_0/Ω_0=0.92 and the relationship between the peak period, T_p, and the energy-averaged angular wave frequency, Ω_0, is given by Ω_0=$2\pi/T_p$/0.83.

For the directional distribution a cos*n*(θ-θm) distribution is used, where *n* is the directional spreading index and θm 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 precious 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 [m²/rad], of the normal wave action spectrum and the first-order moment $m_1(q)$, e.g. expressed by [m²s/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 [m²s²/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 [m²s/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).

Cyclic boundary

For a cyclic (periodic) boundary condition two boundaries are connected so that the wave propagation out of one boundary will propagate in through the other boundary. For each of the two connected boundaries you must specify the boundary, which the actual boundary is connected to. The two connected boundaries must have the same number of boundary faces and the length of the faces must be the same.

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/rad], of the normal wave action spectrum and the first-order moment $m_1(q)$, e.g. expressed by [m^{2}s/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}s^2/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}s/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.

6.20.2 Remarks and hints

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

6.21 Outputs

Standard data files with computed results from the simulation can be specified here. Because result files tend to become large, it is nomally 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.

6.21.1 Geographic View

This dialog shows the geographical position of the output data.

6.21.2 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

Data type

You must specify the data type. You can select discrete values or interpolated values. For point series and area series both options are available. For line series only interpolated values is available. See also Table 6.2.

If "discrete values" is selected for the data type, the values written in the data file are the cell-averaged values.

If "interpolated values" is selected for the data type, the values written in the data file 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 from on the cell-averaged values using the pseudo-Laplacian procedure proposed by Holmes and Connell (1989).

Note, that all adjacent elements, including dry elements, are considered in the interpolation calculation.

Output file

A name and location of the output file must be specified along with the file type. The file type depends on the Output format and the Data type as shown in Table 6.2.

Vectors components and tensors components in a 2D dfsu file are given in the projection coordinate system. In a dfs2 file the vector and tensor components are given in the local coordinate system.

Table 6.2   List of file types for the output files

Output format	Data type	File type
Point series	Discrete values	dfs0
	Interpolated values	dfs0
Line series	Interpolated values	dfs1
Area series	Discrete values	dfsu, dfs2*
	Interpolated values	dfsu**, dfs2
Cross-section	Not relevant	dfs0
Domain series	Not relevant	dfs0

* For area series with discrete values selected for the data type the file type dfs2 can only be specified when the Mesh and bathymetry is specified using a bathymetry data file.

** For area series with interpolated values selected for the data type the file type dfsu can only be specified for spectral output. Note, that here only a simple piecewise constant interpolation is used to map the data.

Table 6.3   List of tools for viewing, editing and plotting results

File type	Viewing/editing tools	Plotting tools
dfs0	Time Series Editor	Plot Composer
dfs1	Profile Series Editor	Plot Composer Result Viewer
dfs2	Grid Series Editor Data Viewer	Plot Composer Result Viewer Data Viewer
dfsu	Data Viewer Data Manager	Data Viewer Result Viewer Plot Composer (2D)

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 then the minimum water depth for which calculations is 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.

If checking the "Use simulation end time" check box, then the simulation end time specified in the Time dialog will automatically be used as last output time step. Hence, the last output time step will be automatically updated if the simulation period is changed.

Point series

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 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 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.

Line series

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

The line is defined by defining a polyline in the horizontal domain. The polyline is given by a number of geo-referenced points. 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 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 points on separate lines. The first two items must be floats (real numbers) for the x- and y-

coordinate (Easting and Northing or Longitude and Latitude). The third item is unused (but must be specified).

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 centre of the element and z-coordinate are listed in the log file.

Area series

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

If discrete values is selected for the data type 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. The third item is unused (but must be specified).

If interpolated values is selected for the data type the values is calculated on a structured grid (overlay). For each direction you should specify

- The origin
- The grid spacing
- The number of grid points

Furthermore, the orientation of the grid at the origin must be specified. This is defined as the angle between y-axis in the selected projection and the y-axis of the grid measured clockwise.

6.21.3 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	Wave coming from
Mean wave direction	MWD	degrees true N	Wave coming from
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	
Surface Stokes drift	U_{st}	m/s	

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 five ways:

- Constant frequency
- Constant frequency and wind dir.
- Dynamic frequency
- Dynamic frequency and wind dir.
- Wave-age approach

Selecting "Constant frequency" or "Constant frequency and wind dir." you have to specify the threshold frequency. Selecting "Dynamic frequency" or "Dynamic frequency and wind dir." you have to specify the maximum threshold frequency. Finally, selecting "Wave-age approach" you must specify two additional parameters, "Coefficient" and "Power". The default values are 0.83 and 1.0, respectively.

For details regarding the distinction of wind sea and swell, see the scientific documentation (section 5.1 Field type).

Note: In older versions the options "Constant threshold frequency" and "Dynamic threshold frequency" were available. These correspond to "Constant frequency and wind dir." and "Dynamic frequency and wind dir.", respectively.

Remarks and hints

It is recommended to use a Constant frequency option or the wave-age approach for distinction between wind, sea and swell.

When model results of wave parameters for wind sea and swell are compared with measurements it is very important that the same approach is used for distinction of wind sea and swell.

6.21.4   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	-	
Water density	ρ_{water}	kg/m^3	
Air density	ρ_{air}	kg/m^3	
Fluid mud thickness	H_{mud}	m	
Mud bulk density	ρ_{bulk}	kg/m^3	
Mud dry density	ρ_{dry}	kg/m^3	

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

6.21.5   Model parameters

The available parameters are defined in the table below

Name	Symbol	SI unit	Notes
Neutral wind speed	U_N	m/s	Neutral wind speed at 10m height
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	

Name	Symbol	SI unit	Notes
Length	l	m	Characteristic mesh length
Area	a	m^2	Characteristic mesh area
Threshold period	$T_{treshold}$	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).

6.21.6 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.

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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

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