

Process-based coastal modelling Regional models

Wave modelling using Delft3D-WAVE

Johan Reyns

Goal of today's lectures

- **Show the potential of (regional) wave models for coastal engineering applications**
- **Give an overview of the wave processes they include, to guide their correct use**

Contents

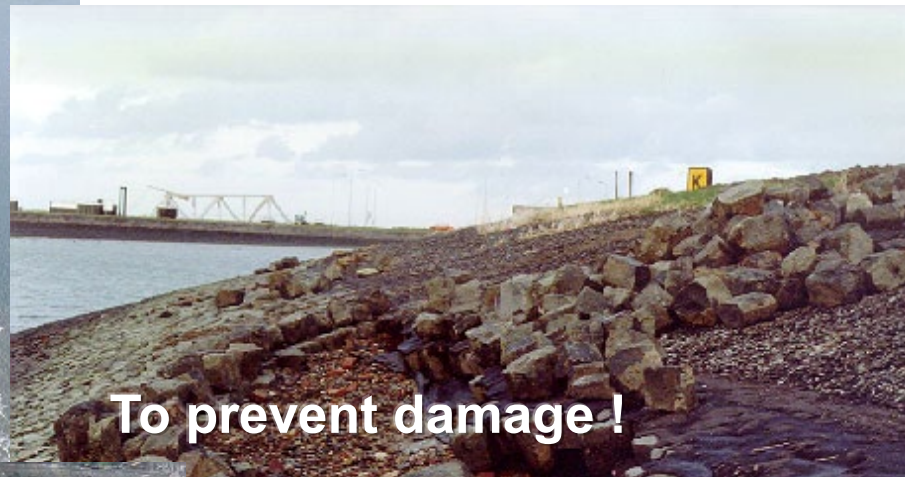
- Wave predictions for coastal engineering
- Wave fields and wave parameters
- SWAN wave model used in Delft3D-WAVE
- Real world applications

- Setting up a wave computation in Delft3D-WAVE
- Exercises

Why wave predictions in coastal areas ?



Wave conditions near shore



To prevent damage !



Extreme events !



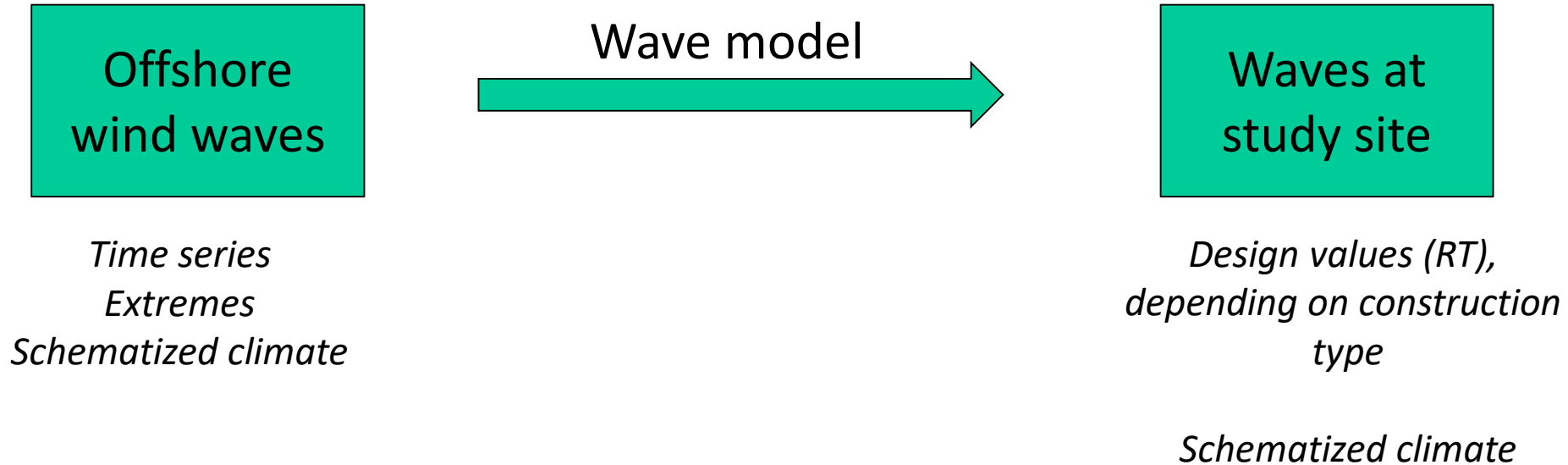
Wave conditions off-shore

Why wave predictions in coastal areas ?

- **Wave conditions (among others) are needed as input for coastal engineering design:**
 - ✓ **Dike and dam freeboard and revetments**
 - ✓ **Breakwater dimensions and geometry**
 - ✓ **Constructions**
 - ✓ **But also: dune volumes!**
- **Typical derived quantities are wave runup, wave overtopping discharges, wave impact loads.**
- **Usually the focus is on short (wind generated) waves, but infragravity waves get more and more attention (ie seiching in harbours, see wave penetration lectures)**



Why wave predictions in coastal areas ?



Sources can be satellites, NWP models, bigger wave models

Why wave predictions in coastal areas ?

Monthly distribution of wave height (m)

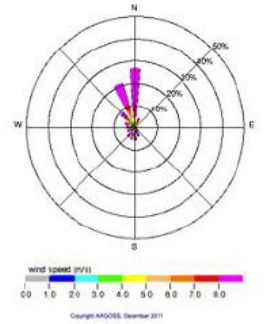
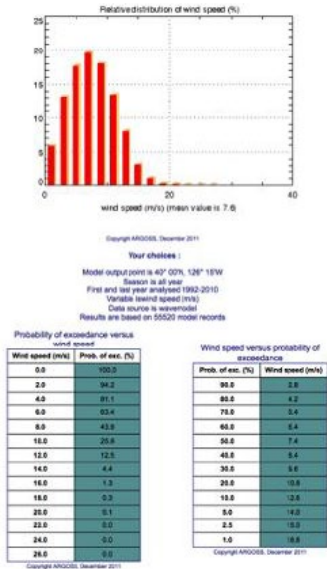
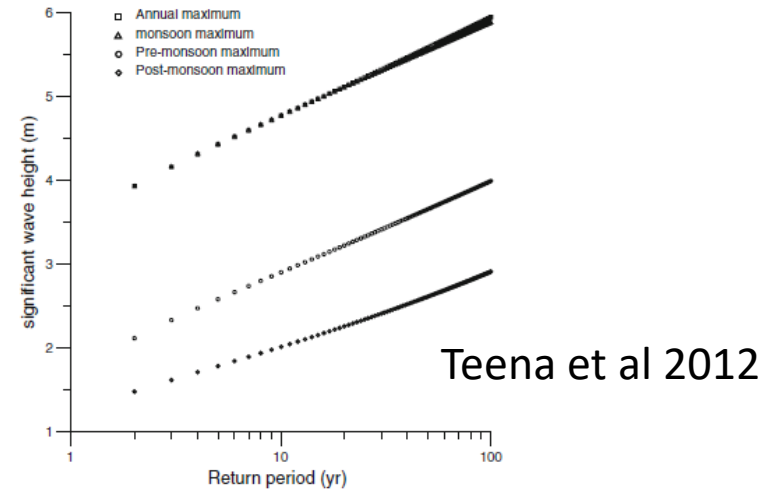
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0.5	1.0	0.2	0	0	0.25	0	0.4	1.1	1.4	1.9	1.7	0.6	0.4	0
1.0	1.5	2.0	1.4	2.4	4.7	15.9	17.1	24.5	20.7	8.4	4.3	4.3	4.3	
1.5	2.0	7.7	5.5	15.9	18.9	20.5	21	20.7	20.7	19.1	12.5	6.9	6.9	
2.0	2.5	15.8	13.1	16.4	19.1	20.1	23.2	19.5	18.9	17.8	14.7	8.9	8.9	
2.5	3.0	16.9	17.3	18.4	19.2	19.1	22.8	19.3	18.1	21.9	16.7	14.3	14.3	
3.0	3.4	14.1	16.3	14.9	14.4	14.1	14.1	14.4	14.1	14.4	14.3	14.3	14.3	
3.5	4.0	10.8	13.1	12.1	8.3	4.9	3.7	3.7	3.2	4.7	7.2	11.6	14.3	
4.0	4.5	11.0	8.8	8.7	9.2	2.9	0.9	0.9	0.1	1.3	3.4	7.9	12.6	
4.5	5.0	9.8	8.4	8.3	2.4	0.8	0.4	0.2	0	0.2	2.4	4.5	6.1	
5.0	5.5	9.4	5.1	3.5	1.3	0.2	0.1	0	0	0	1.3	3.6	4.3	
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6.0	6.5	1.4	1.7	0.9	0.3	0	0	0	0	0	0.4	1.1	2.1	
6.5	7.0	1.7	1.0	0.9	0.2	0	0	0	0	0	0.3	0.9	1.2	
7.0	7.5	0.9	0.7	0.5	0.2	0	0	0	0	0	0.2	0.5	0.9	
7.5	8.0	0.4	0.4	0.2	0.2	0	0	0	0	0	0	0.2	0.4	
8.0	8.5	0.2	0.1	0.2	0	0	0	0	0	0	0.1	0.1	0.1	
8.5	9.0	0.1	0.1	0	0	0	0	0	0	0	0	0.1	0.1	
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10.5	11.0	0	0	0	0	0	0	0	0	0	0	0	0	
11.0	11.5	0	0	0	0	0	0	0	0	0	0	0	0	
total		100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	

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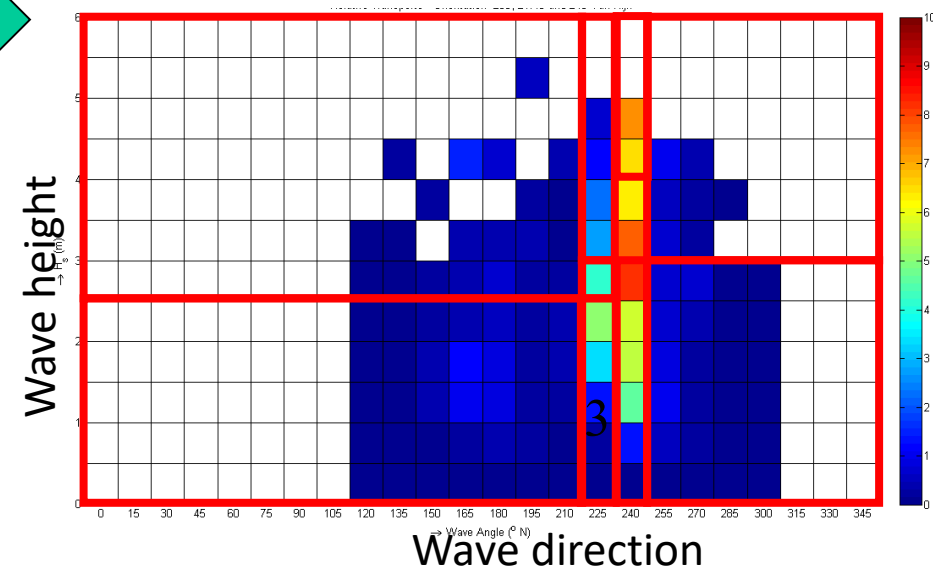
Percentage of occurrence of wave height (m) in rows versus zero-crossing wave period (s) in columns

lower	upper	02	03	04	05	06	07	08	09	10	11	12	13	14	15	total
0.0	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0
0.5	1.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0
1.0	1.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0
1.5	2.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0
2.0	2.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0
2.5	3.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0
3.0	3.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0
3.5	4.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0
4.0	4.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0
4.5	5.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0
5.0	5.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0
5.5	6.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0
6.0	6.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0
6.5	7.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0
7.0	7.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0
7.5	8.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0
8.0	8.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0
8.5	9.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0
9.0	9.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0
9.5	10.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0
10.0	10.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0
10.5	11.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0
11.0	11.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0
total		0.0	0.0	1.8	21.4	28.6	21.8	15.1	7.3	1.8	0.9	0.3	0.1	0.0	0.0	100.0

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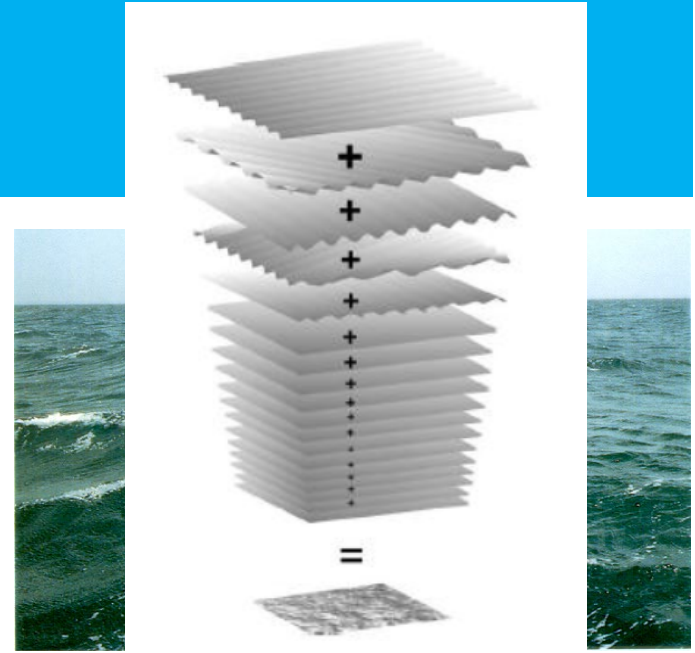


Van Vledder, 2012

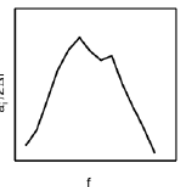
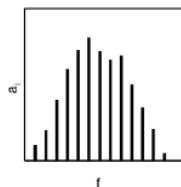
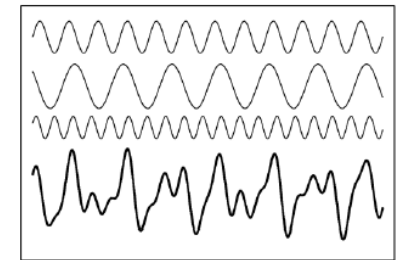
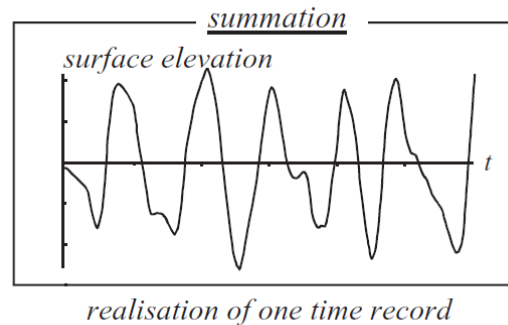
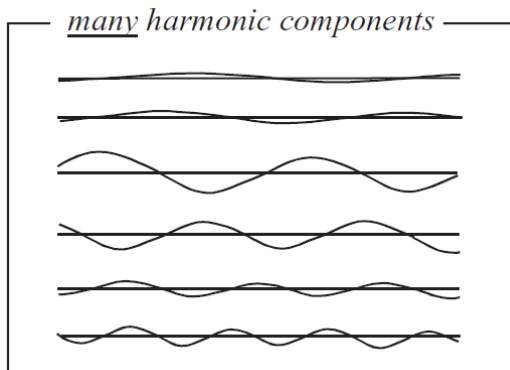


Wind generated waves

- Wave field is result of superposition of different harmonic wave components:
 - ✓ Amplitude
 - ✓ Direction
 - ✓ Period
 - ✓ **Phase is random**



$$\eta(x, y, t) = \sum_{i=1}^N a_i \cos(k_{x,i}x + k_{y,i}y + 2\pi f_i t + \bar{\varphi}_i)$$



Wind generated waves

- Wave spectra describe the distribution of the variance of the water surface displacements over frequencies and directions
- From $E(f)$, you can calculate distribution moments:

$$m_n = \int_0^{\infty} f^n E(f) df$$

- From these moments, you can calculate:
 - ✓ Wave height H_{m0}

$$H_s = H_{m0} = 4 \sqrt{\int_0^{\infty} E(f) df} = 4 \sqrt{m_0}$$

- ✓ Period measures T_{m01} ; T_{m02} ; $T_{m-1,0}$

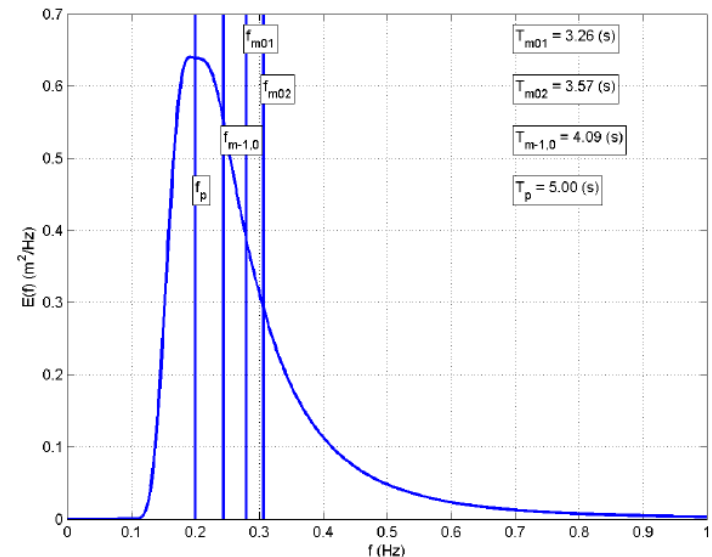
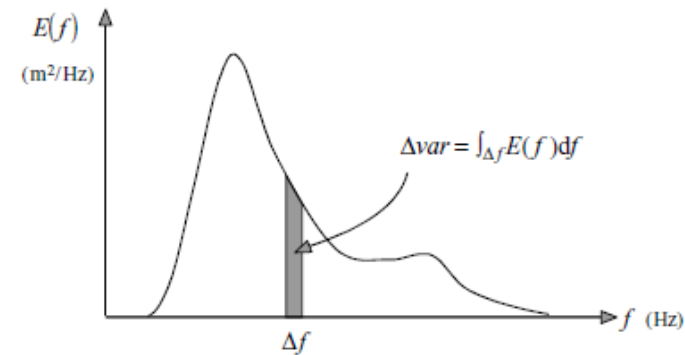
$$T_{m01} = m_0 / m_1$$

$$T_{m02} = \sqrt{m_0 / m_2}$$

$$T_{m-1,0} = m_{-1} / m_0$$

$$T_z = T_{m02}$$

$$T_p = 1.1 * T_{m-1,0}$$



Why use wave models?

- Waves have changing characteristics as they move onshore, and deep water (linear) relations do not hold any more
 - ✓ Refraction
 - ✓ Diffraction
 - ✓ Energy gain by local wind forcing
 - ✓ Energy dissipation through breaking, whitecapping and bottom friction (and others: vegetation, reefs, muddy bottoms,...)
 - ✓ Non-linear wave interactions cause energy shifts between frequencies
- ✓ Reflection off structures
- ✓ Transmission through structures
- ✓ Overtopping

Type of wave models

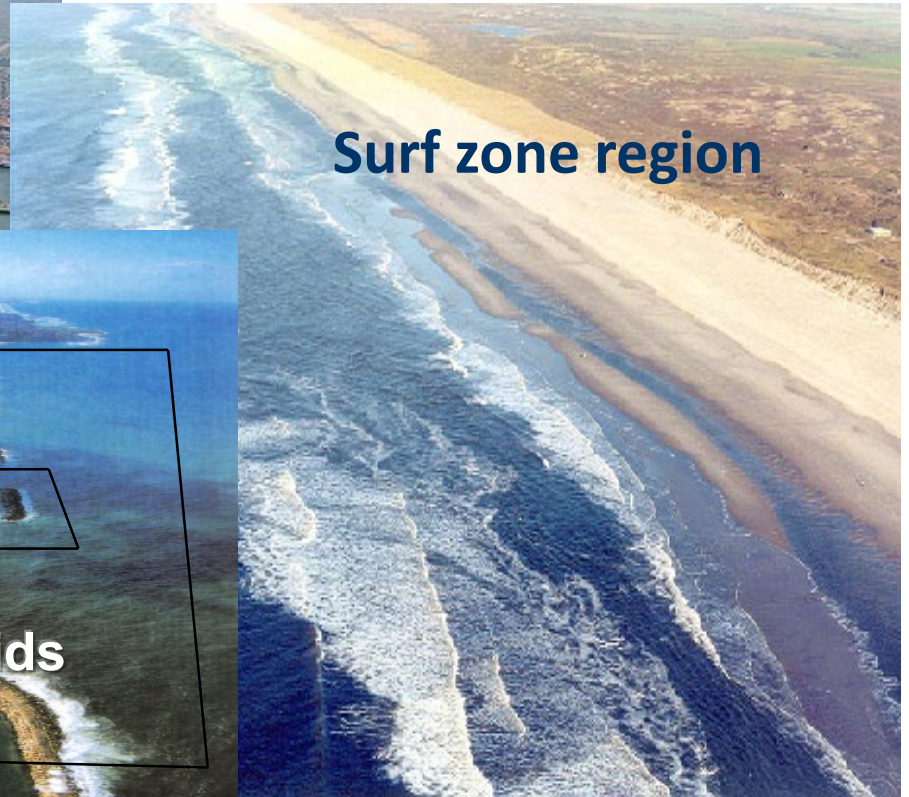
- **Phase-resolving**
 - ✓ Solve the water level, not the wave statistics
 - ✓ High resolution required (minimum $O(10)$ points/wave length)
 - ✓ Diffraction / reflections naturally incorporated
 - ✓ but: no wind generation/ breaking limited requires numerical treatment
- **Phase-averaged**
 - ✓ Solve the propagation and transformation of wave action over f and θ
 - ✓ Large(r) scale applications
 - ✓ Wind as a source possible, breaking parameterized
 - ✓ But: no accurate diffraction
 - ✓ Interpretation of spectra in shallow water difficult, bulk statistics often reasonable

Delft3D-WAVE: phase-averaged type

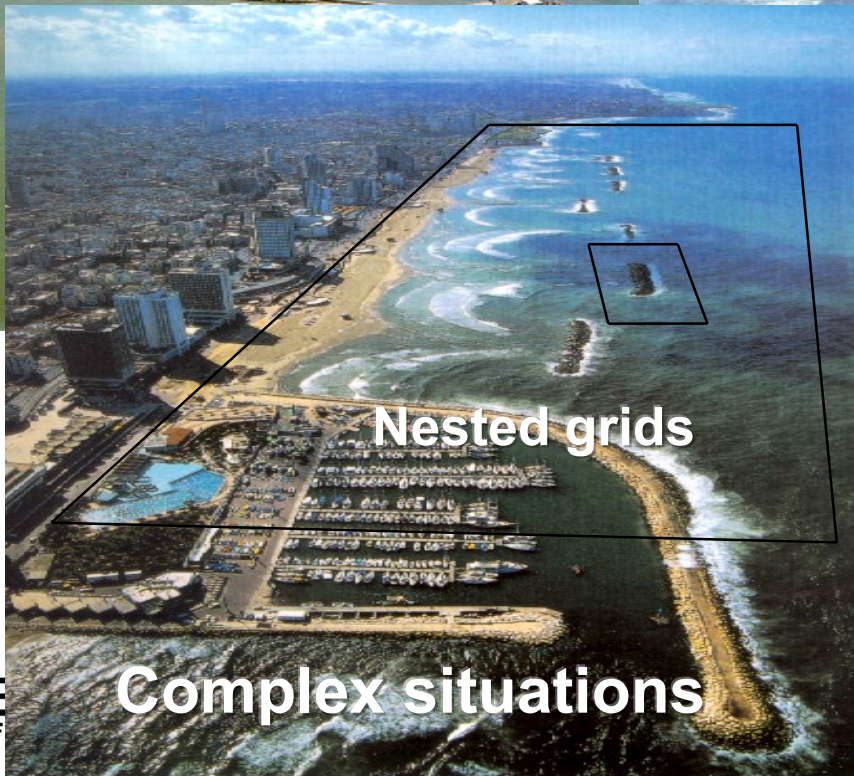
Shoreface region



Surf zone region



Nested grids

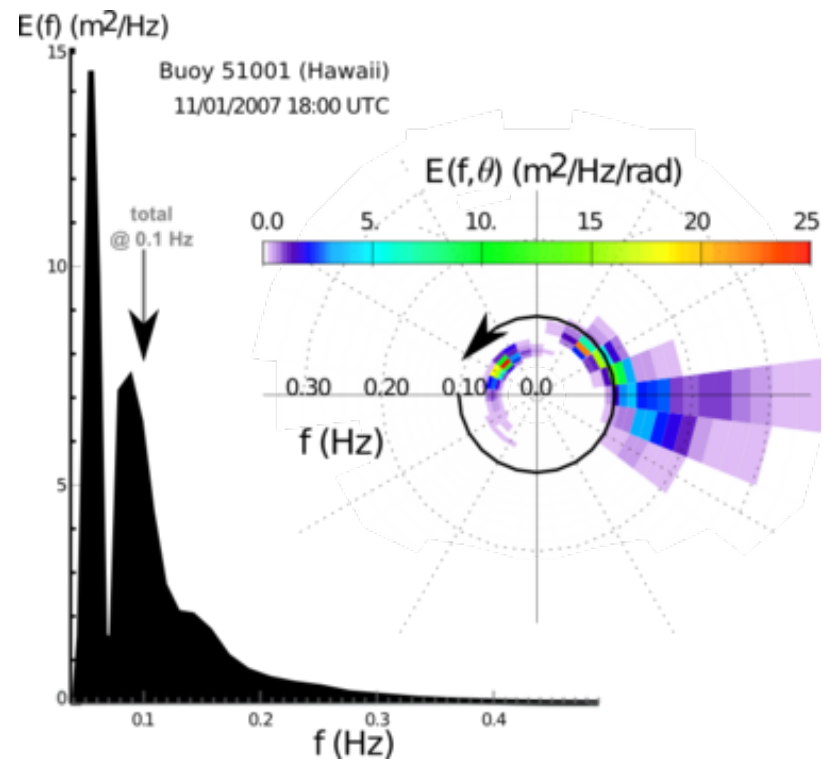


Complex situations

+ laboratory
(but not harbours)

The computational engine: SWAN

- Introduction
- Physics
- Numerics
- Validation
- Conclusions



Introduction SWAN (Booij et al 1999)

Simulating WAVes Nearshore

Describes the evolution of 2D wave spectra, based on solving the wave action balance equation:

$$\begin{aligned} \frac{\partial}{\partial t} N(\sigma, \theta) + \frac{\partial}{\partial x} C_x N(\sigma, \theta) + \frac{\partial}{\partial y} C_y N(\sigma, \theta) + \frac{\partial}{\partial \theta} C_\theta N(\sigma, \theta) + \dots \\ \dots + \frac{\partial}{\partial \sigma} C_\sigma N(\sigma, \theta) = S(\sigma, \theta) \end{aligned}$$

where: • $N = N(x, y, \sigma, \theta) = E / \sigma$

• $S = S_{wind} + S_{whitecapping} + S_{quad} + S_{breaking} + S_{triad} + S_{bott} + S_{veg}$

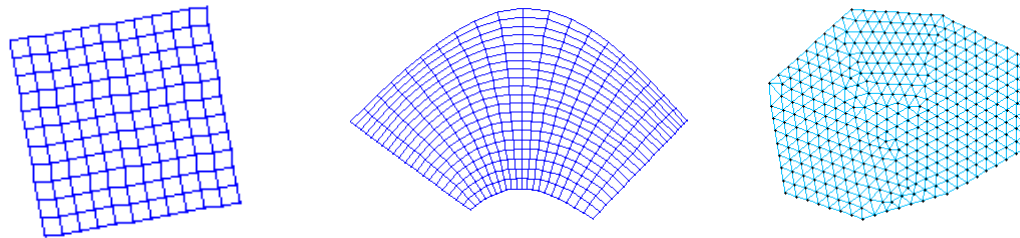
• $C =$ propagation velocities in x, y, σ, θ

Action N is conserved under the presence of currents!

Introduction SWAN (Booij et al 1999)

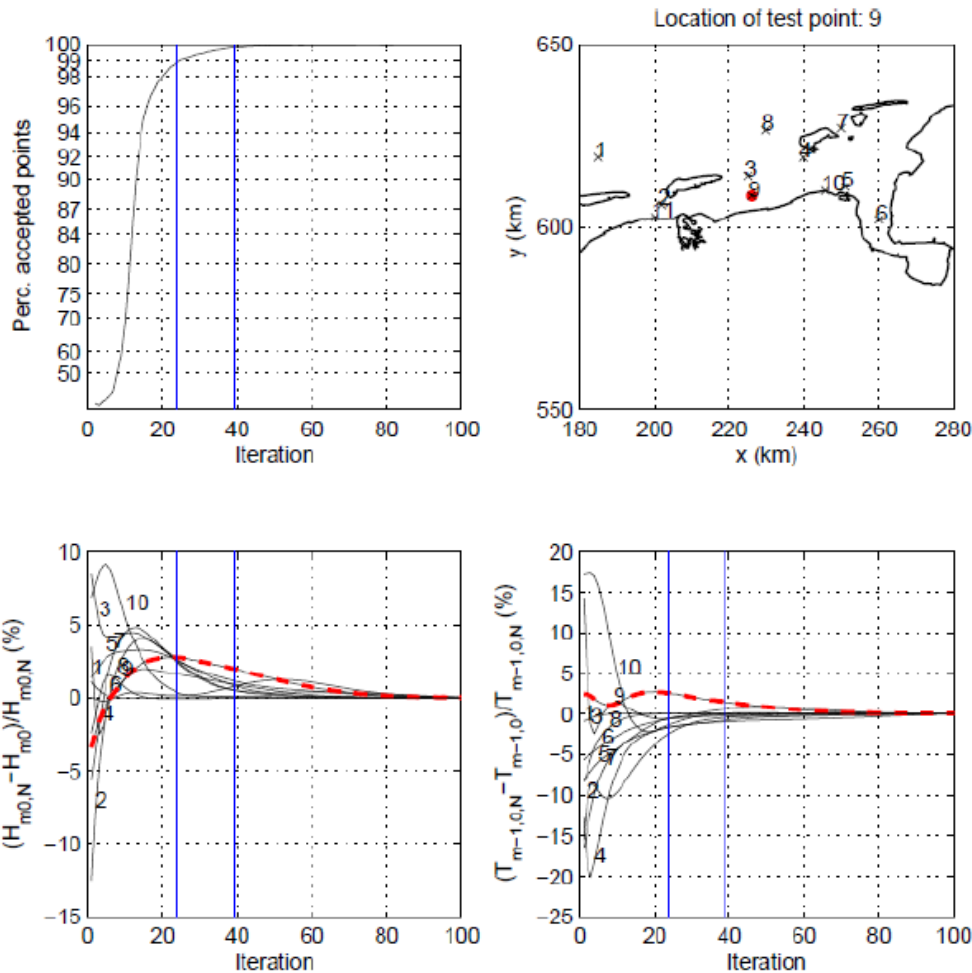
Simulating WAVes Nearshore

- Action balance equation is solved on **rectangular**, **curvilinear** or **unstructured** grids (triangles only)



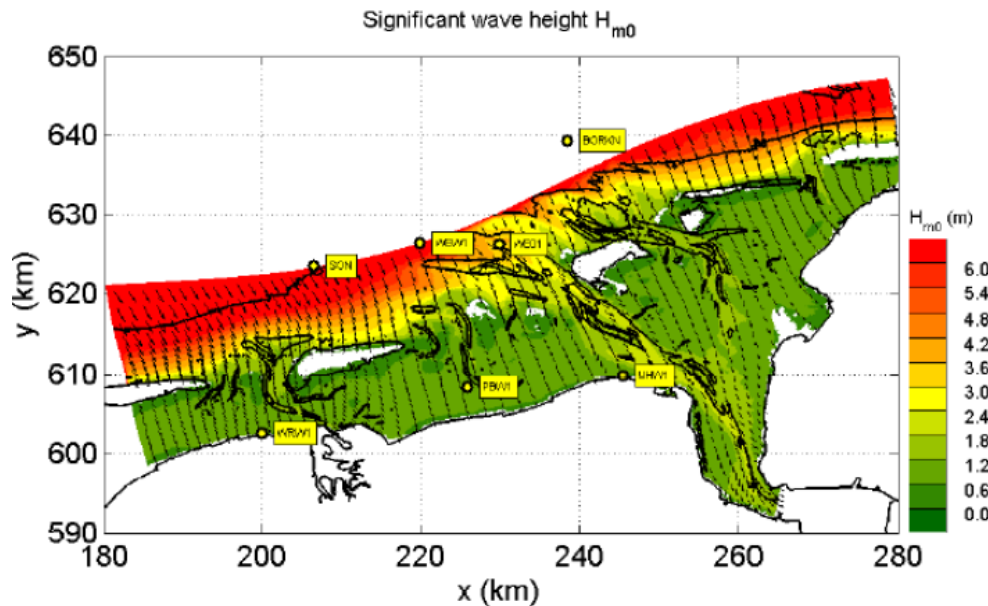
- Wave spectra are propagated for **swell and wind waves** (no IG)
- Forced by wave boundaries and/or wind fields
- Can be **coupled** to a hydrodynamic model for water levels and currents
- Iterative solver, using a sweeping algorithm with 4 quadrants to solve **implicit scheme**

SWAN numerics - Convergence



- Sweeping algorithm needs **iterations** to converge to solution
- True solution not known, so convergence assessed by change between iterations
- Stationary runs: large no (>10)
Non-stationary: 1-2, and small dt
- Check with test points covering the different parts of the domain

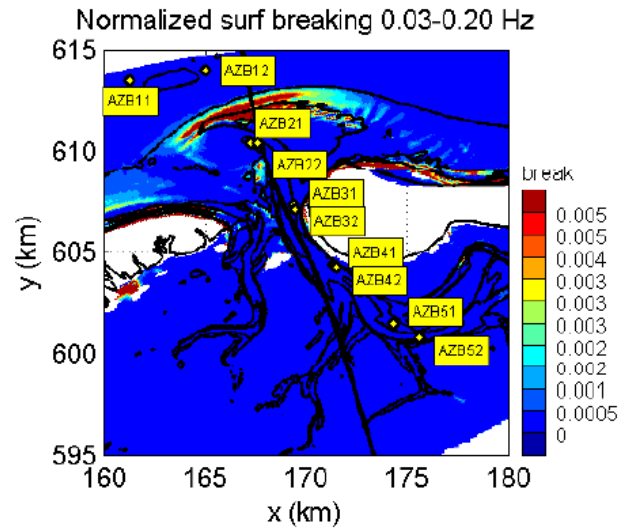
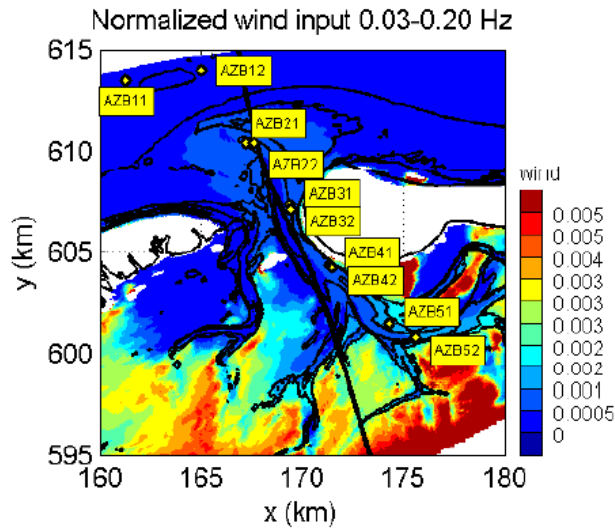
Applications of SWAN – Wind growth in the Wadden Sea



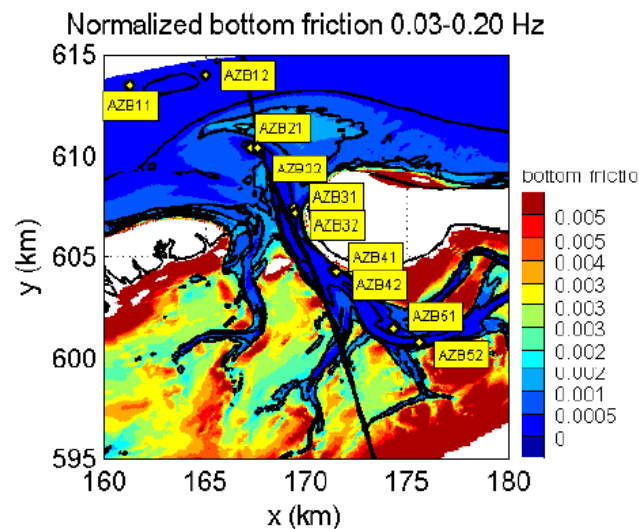
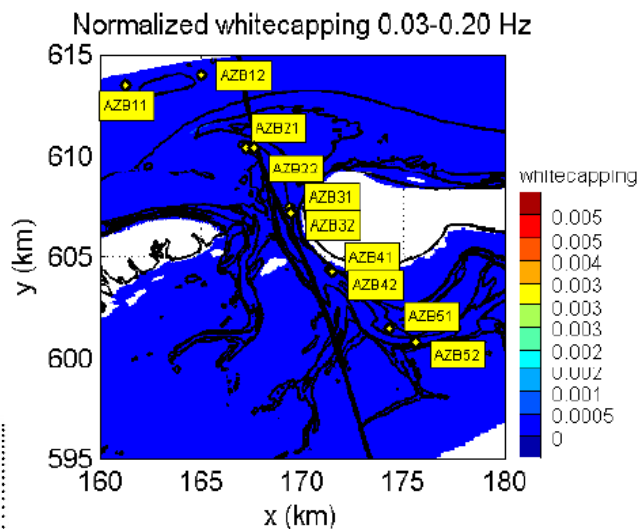
- Very little offshore wave penetration through tidal inlets
- Local wind wave growth important
- Setup at the shoreline determined by wind surge and wave setup

Van Vledder 2012

Applications of SWAN – Wind growth in the Wadden Sea



*Storm Nov 2005
Ameland*



Alkyon A2085

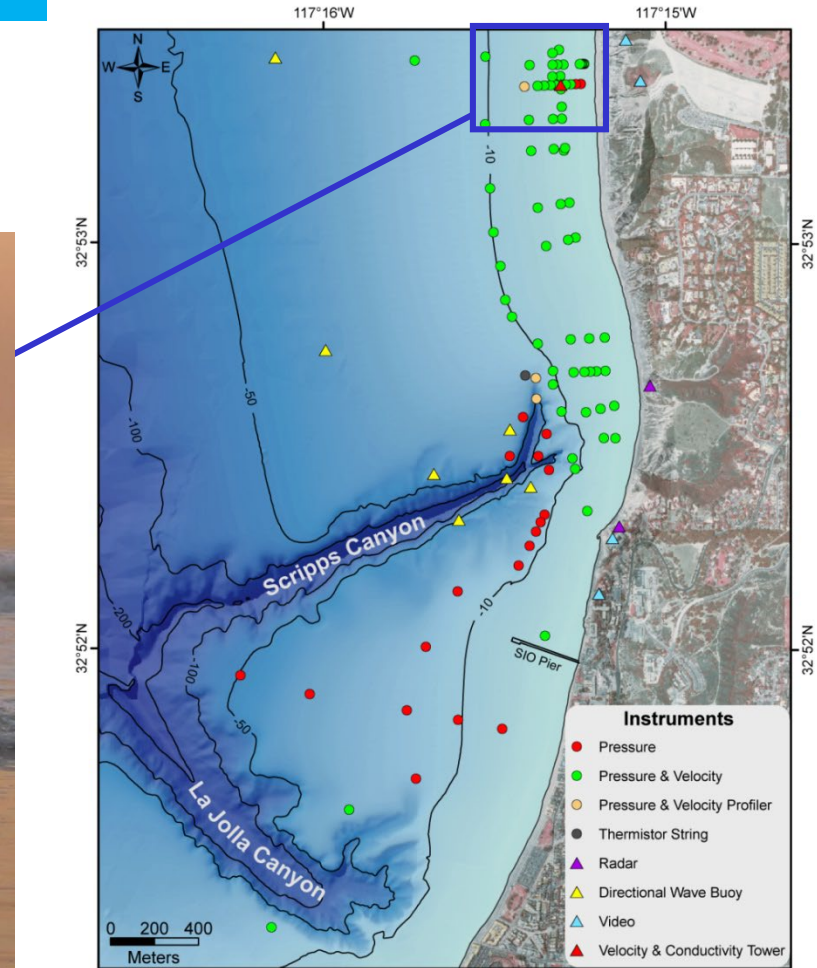


Applications of SWAN - NCEX



Photo by Britt Raubenheimer

X (m)



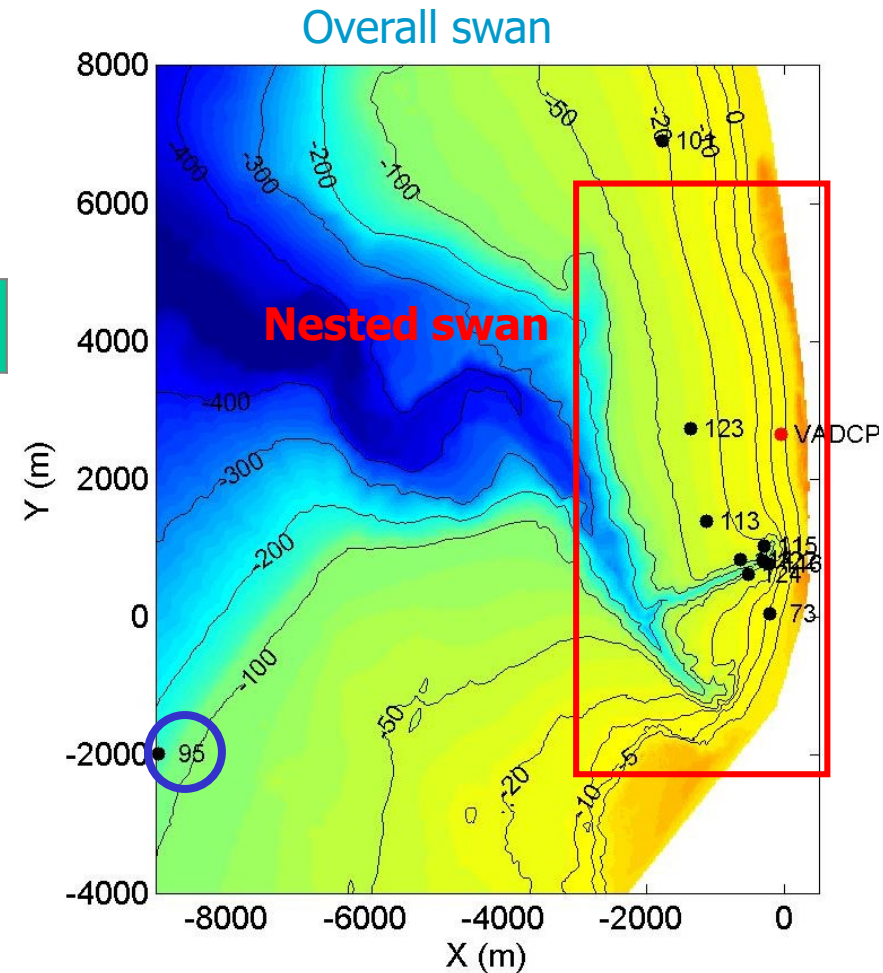
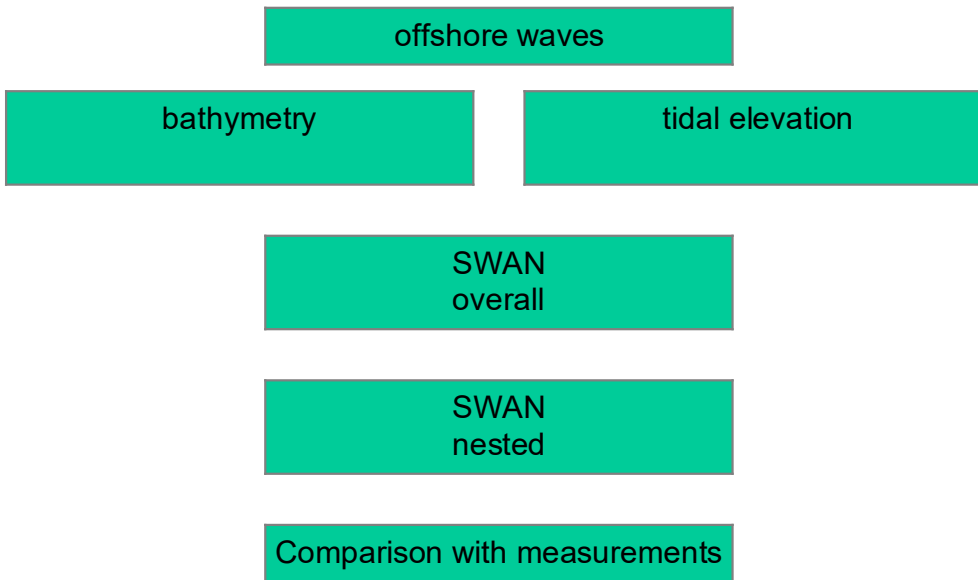
NCEX Nearshore Canyon
EXperiment - Fall 2003



Courtesy of Steve Elgar

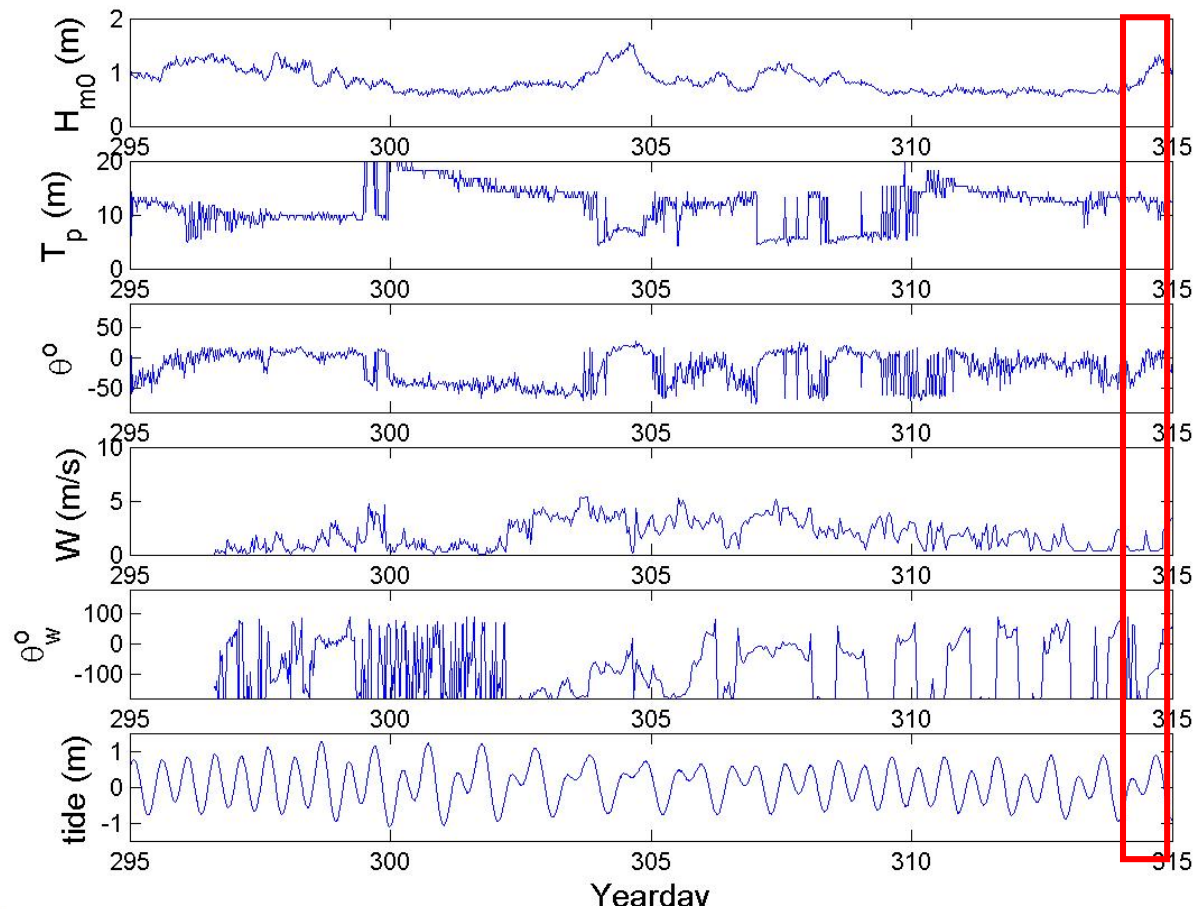
Applications of SWAN - NCEX

Modeling approach



Applications of SWAN - NCEX

- Wave Climate (B95 CDIP <http://cdip.ucsd.edu/ncex/>)



Applications of SWAN - NCEX

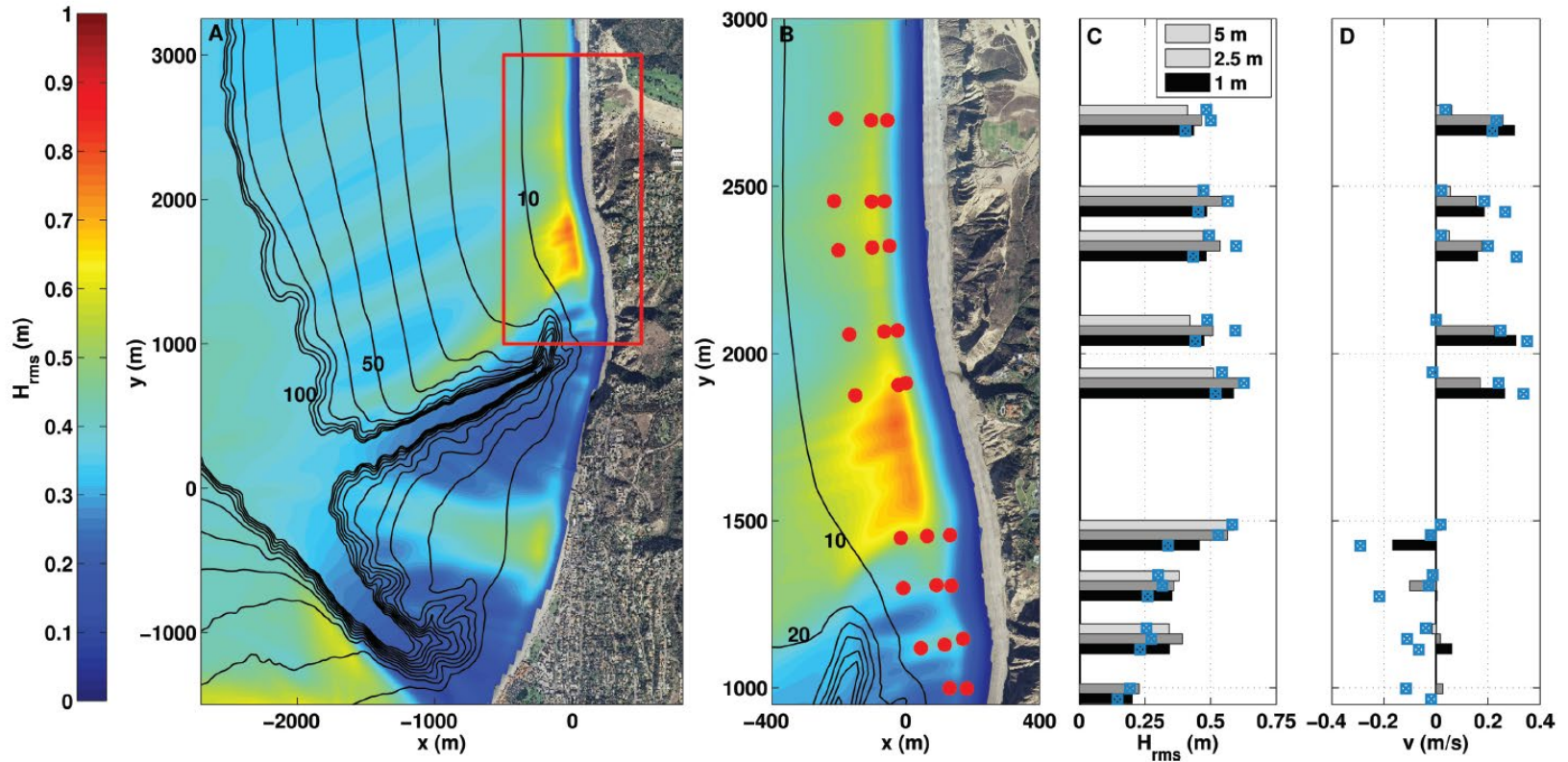
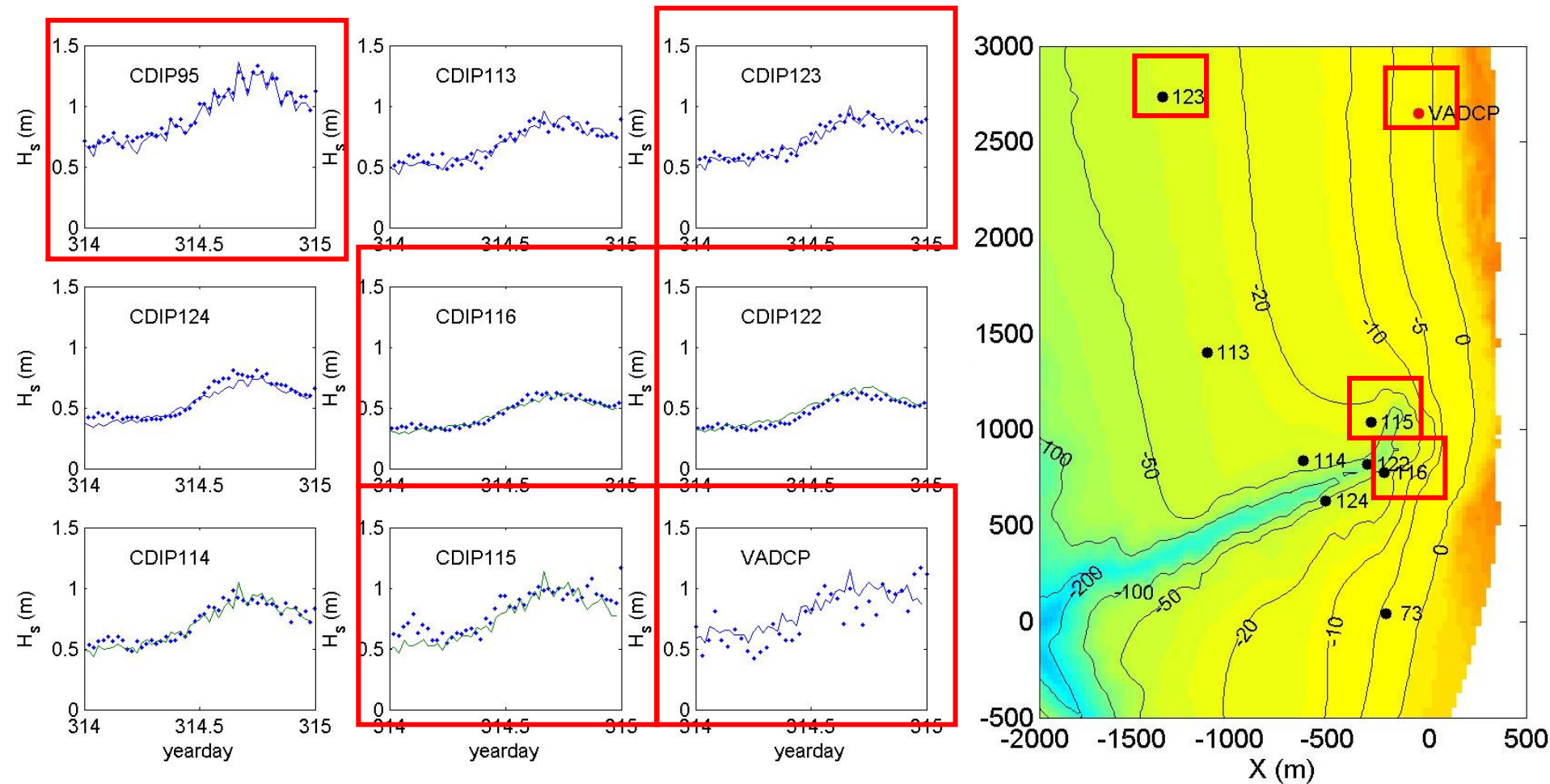
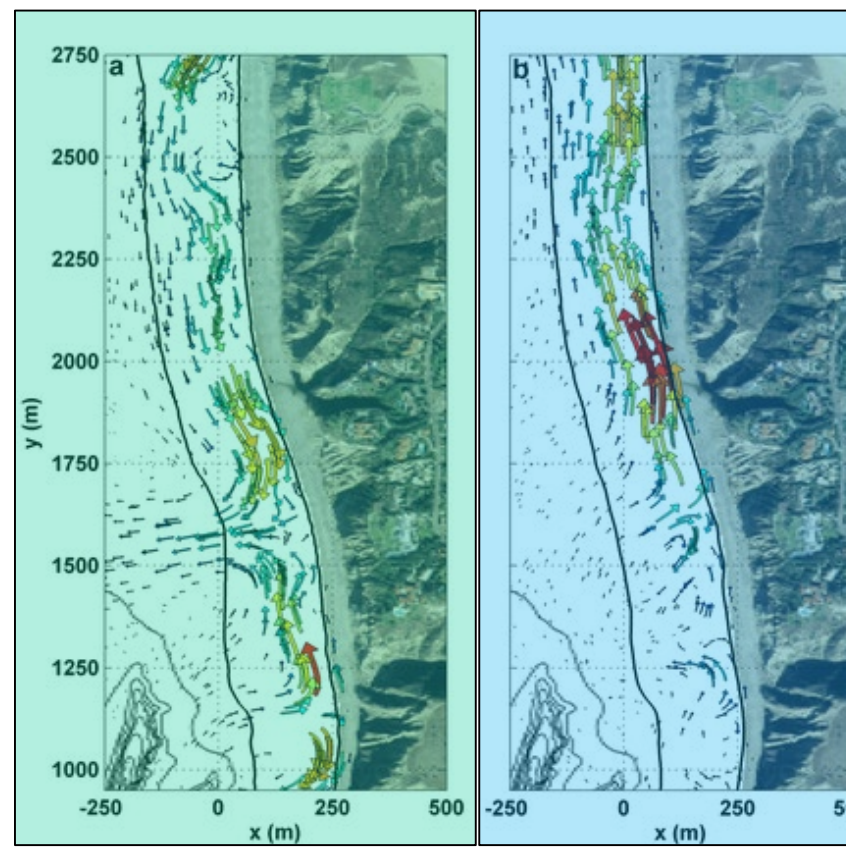
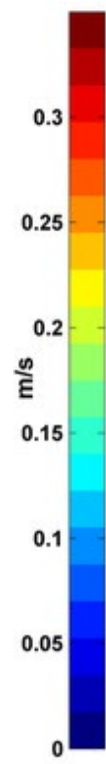
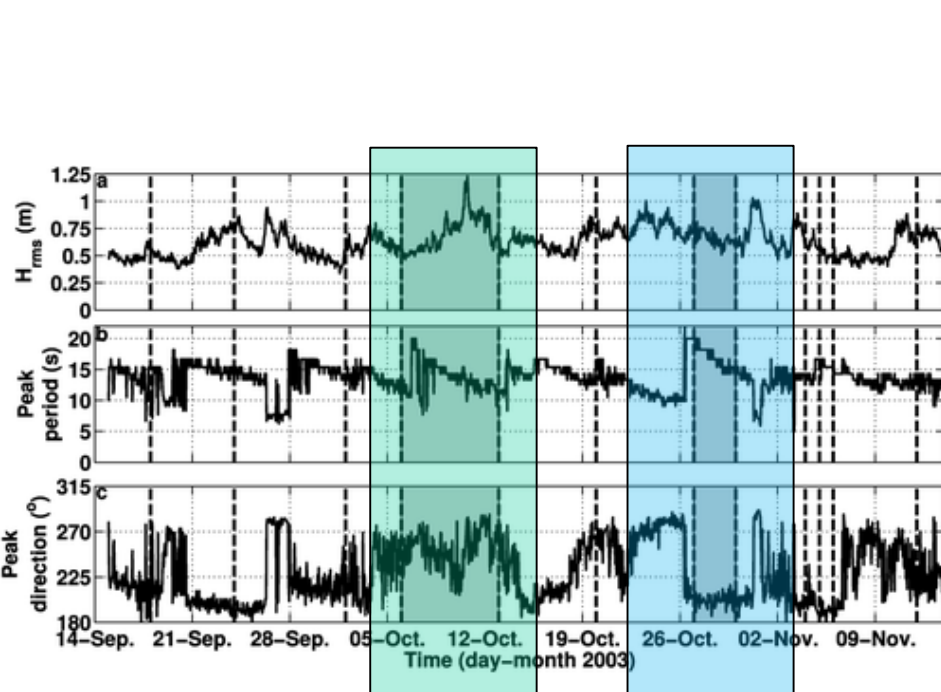


Figure 4. Regional (a) and experiment area (b, note different y scale) 24 h mean predicted wave heights (color contours, scale on left) and 24 h mean predicted (bars) and observed (blue squares) wave heights (c) and alongshore velocities (d) at the 26 instrument sites (red circles in Figure 4b) on 27 October 2003. Black curves in Figures 4a and 4b are depth contours every 10 m from 10 to 100 m, and the red rectangle in Figure 4a indicates the experiment area shown in Figure 4b.

Applications of SWAN - NCEX



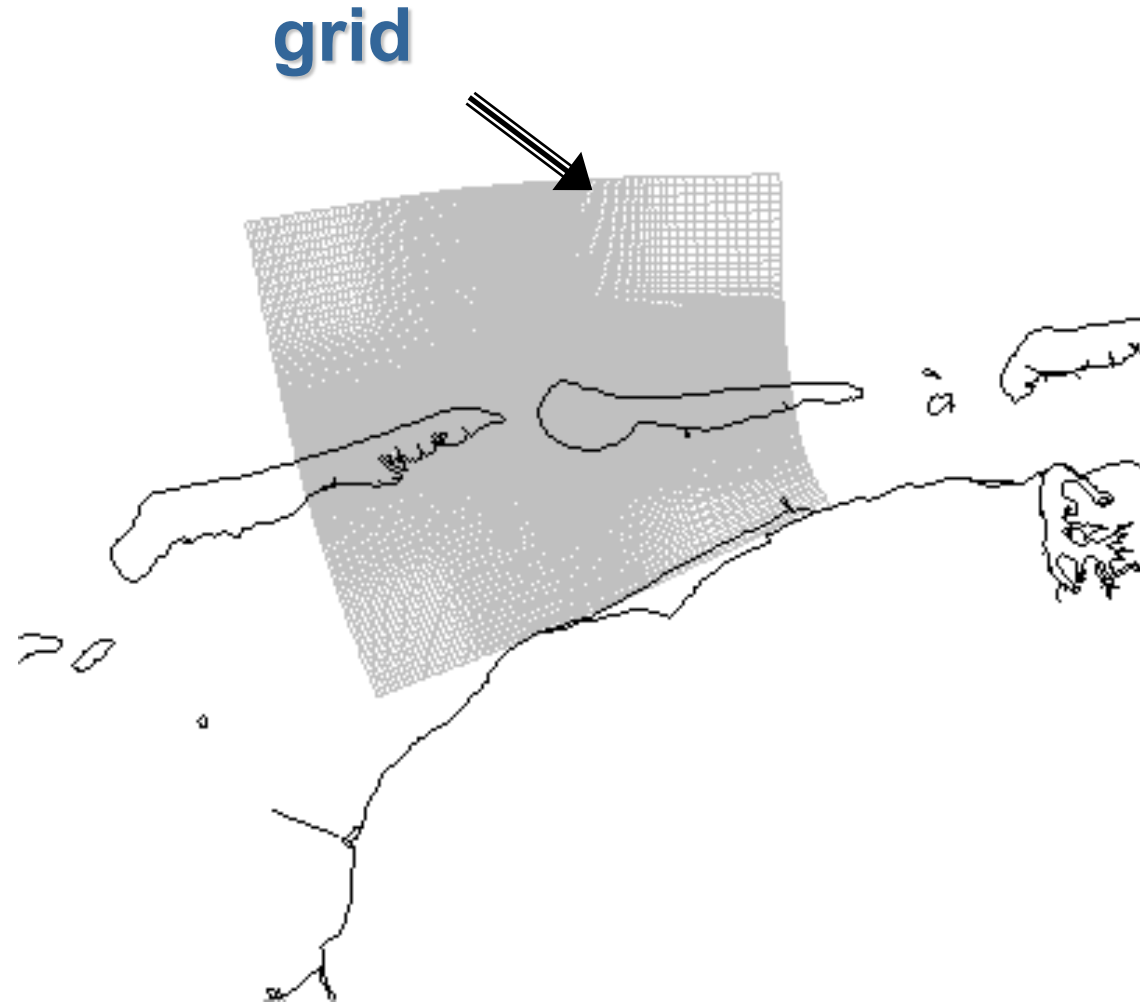
Applications of SWAN - NCEX



Hansen et al 2017 JGR
Apotsos et al 2008 JGR

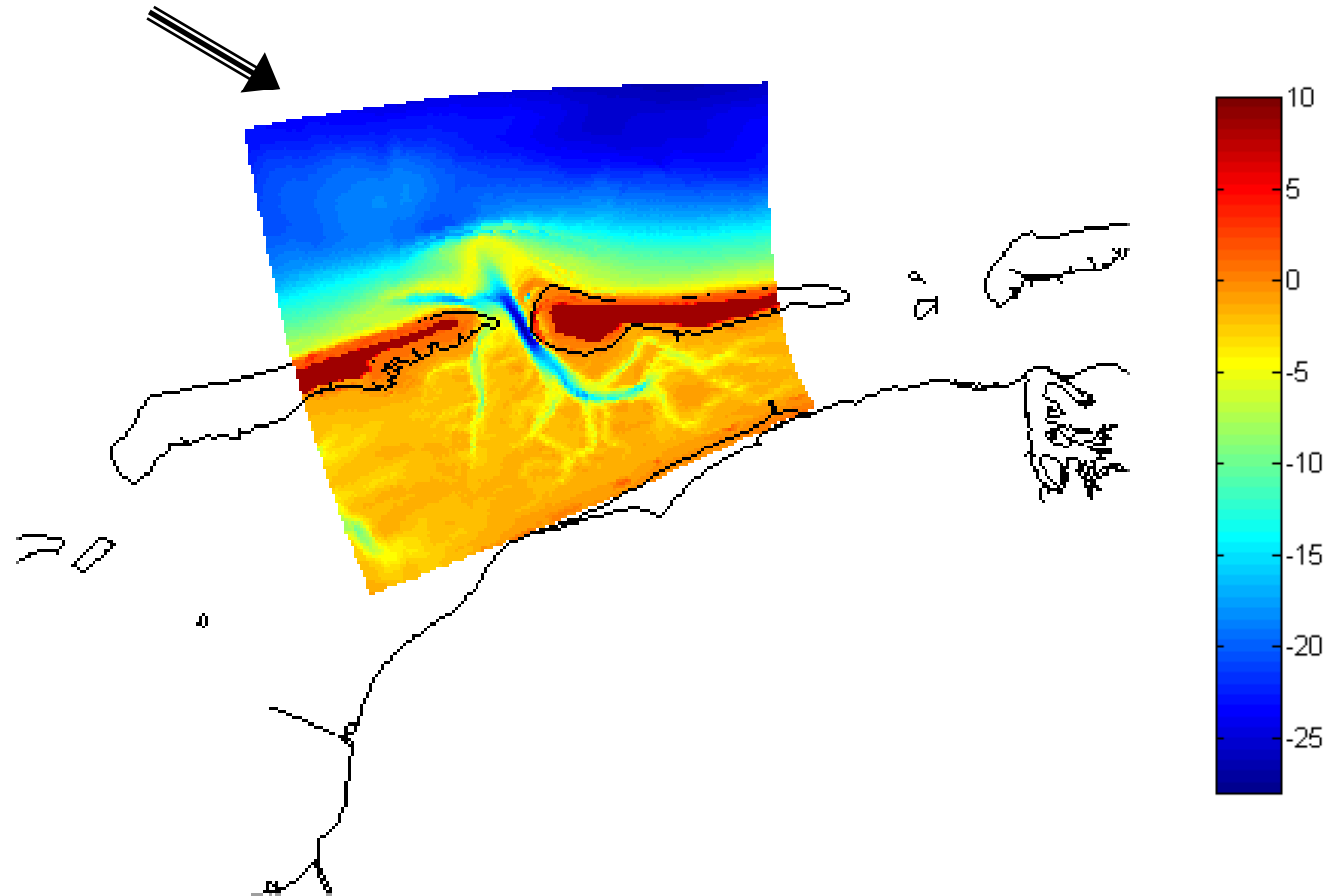
Setting up a Delft3D-WAVE model

Wave simulation with Delft3D-WAVE

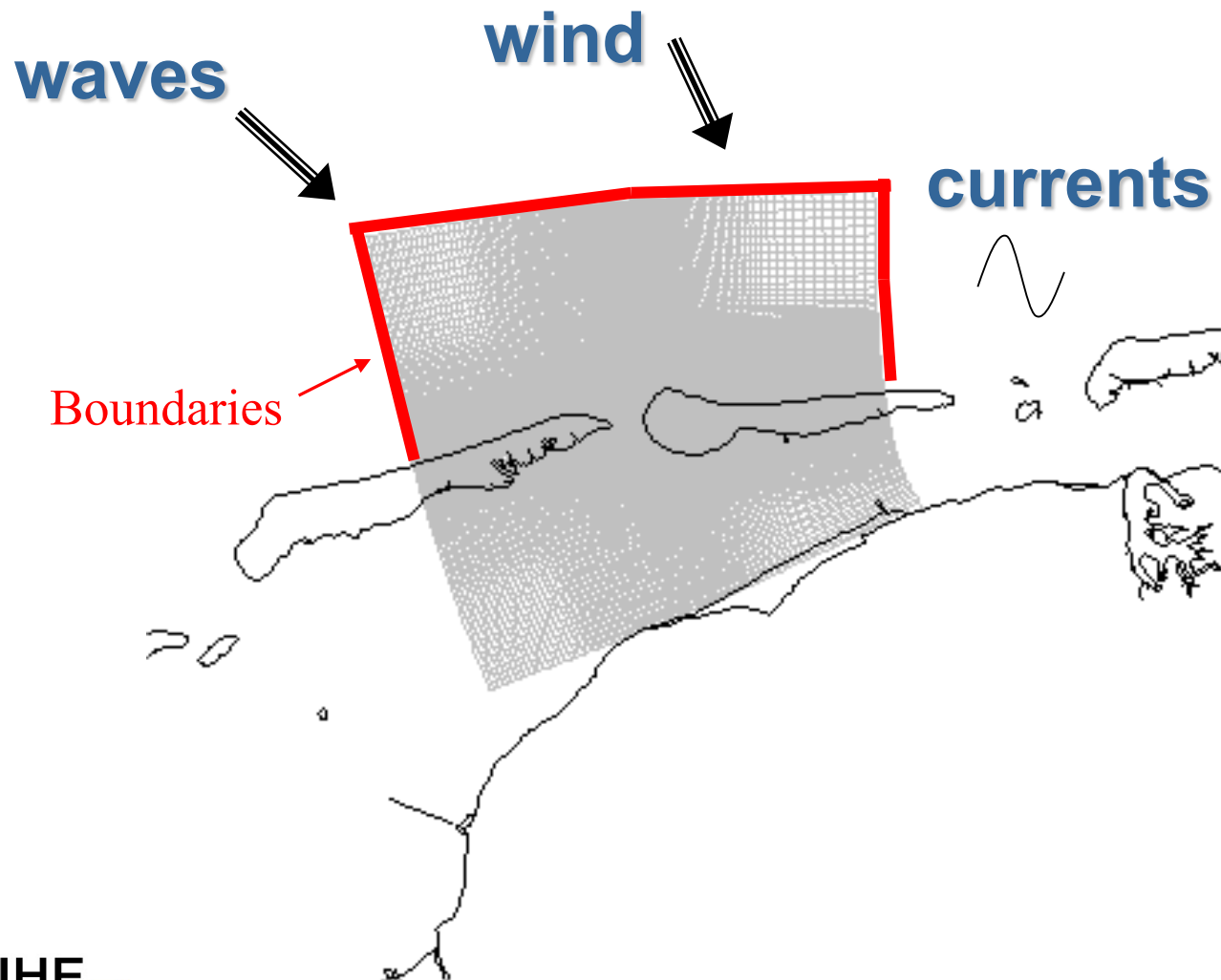


Wave simulation with Delft3D-WAVE

bathymetry

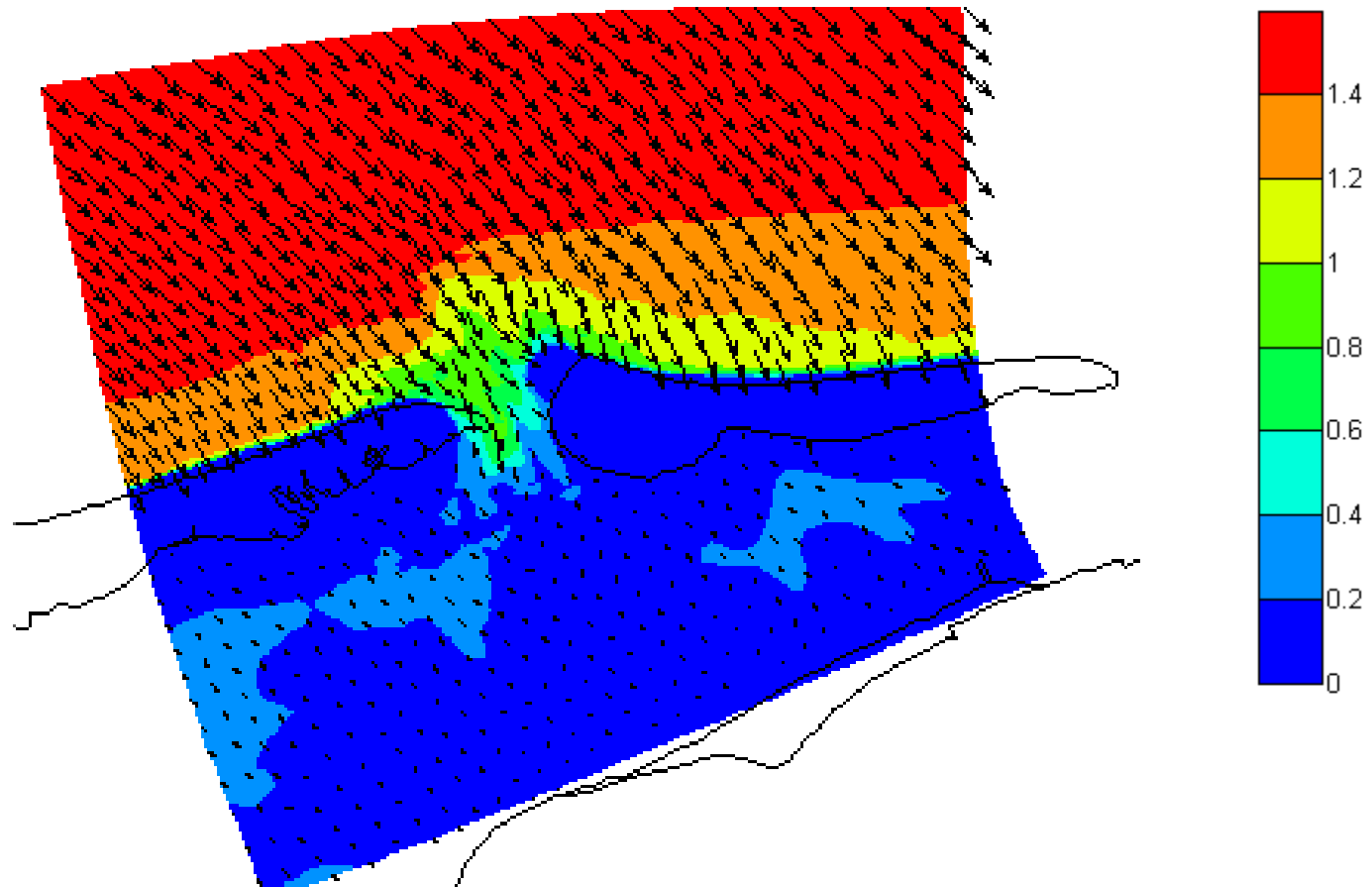


Wave simulation with Delft3D-WAVE



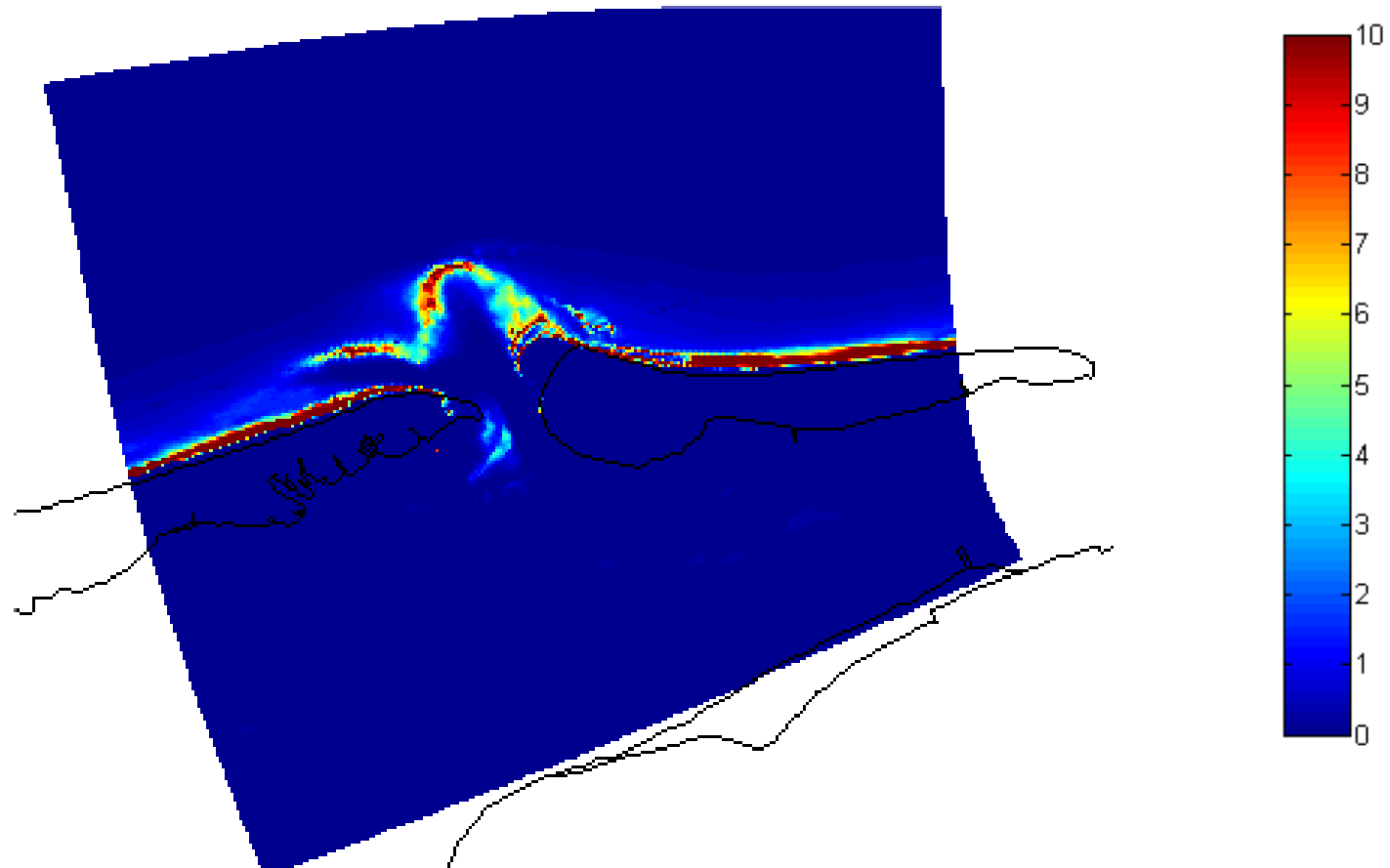
Wave simulation results

Wave height and direction



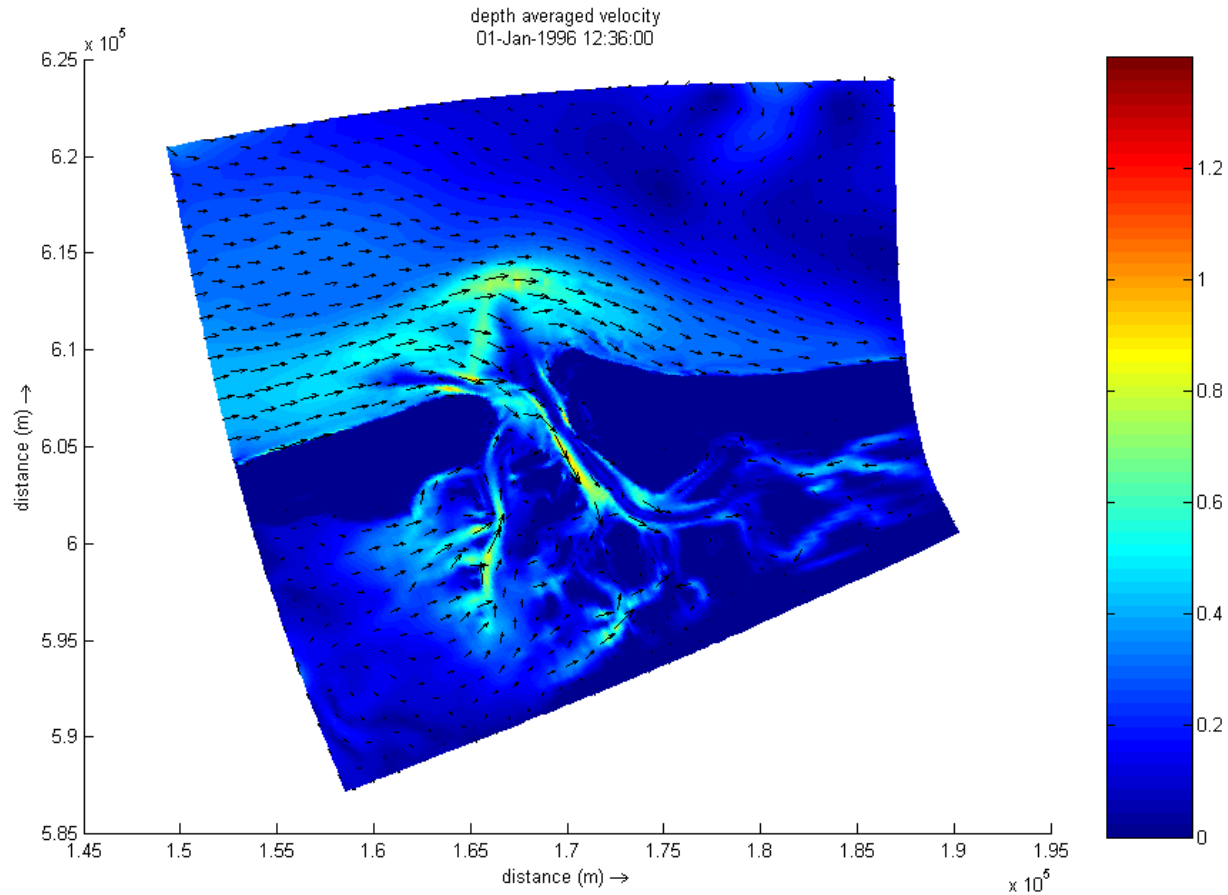
Wave simulation results

Wave breaker dissipation



Coupled WAVE-FLOW simulation results

Currents



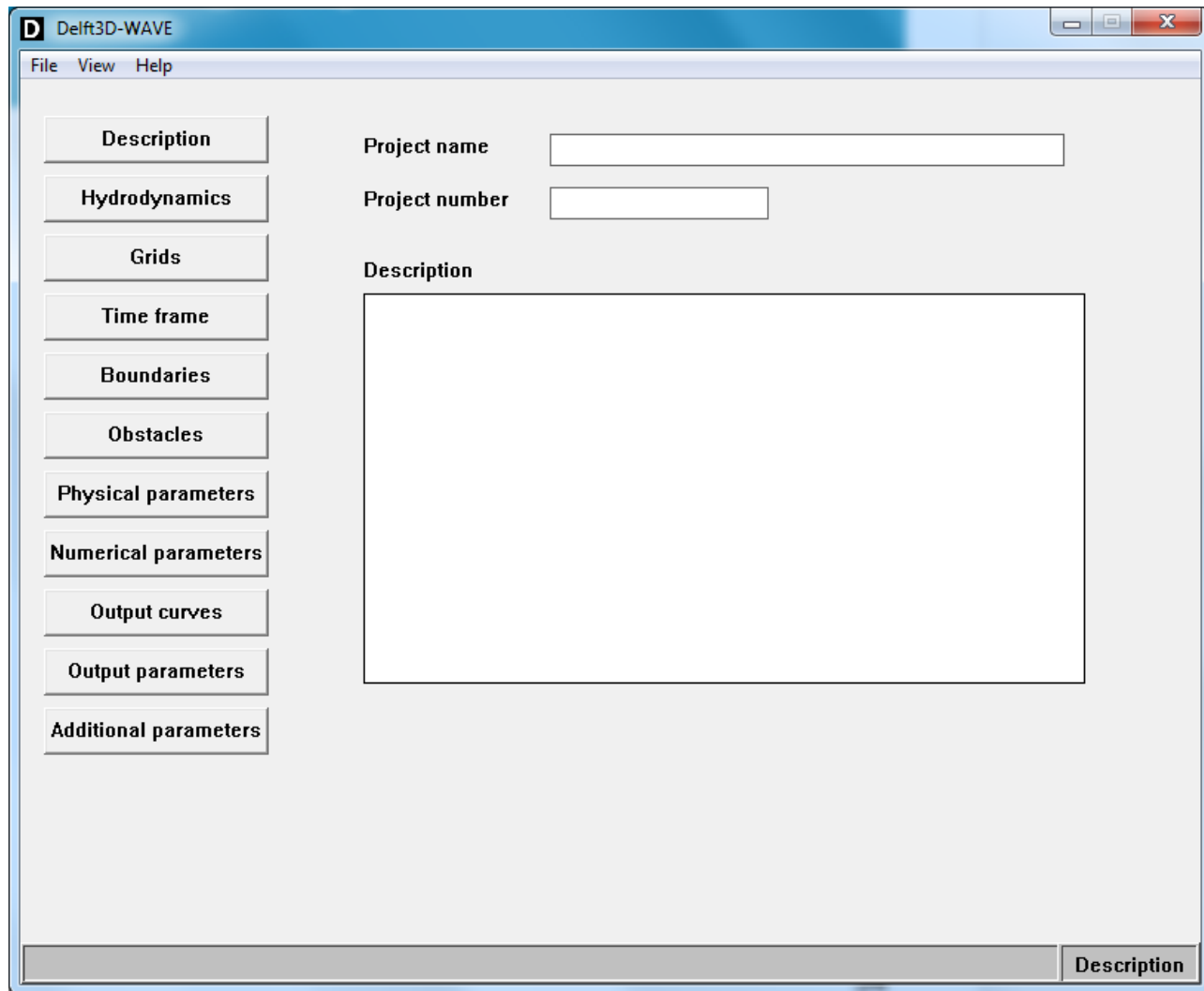
Modelling aspects

- Pick your area of interest (x, y, σ, θ)
- Define the boundary conditions you want to propagate
- Consider a good choice of resolutions ($\Delta x, \Delta y, \Delta \sigma, \Delta \theta$)
- Do a sensitivity study of numerical parameters
 - Lateral boundary effect in SWAN important!
 - Model convergence (eg quadruplets very expensive)
- Do a sensitivity study of the physics
- Calibration & verification of the model

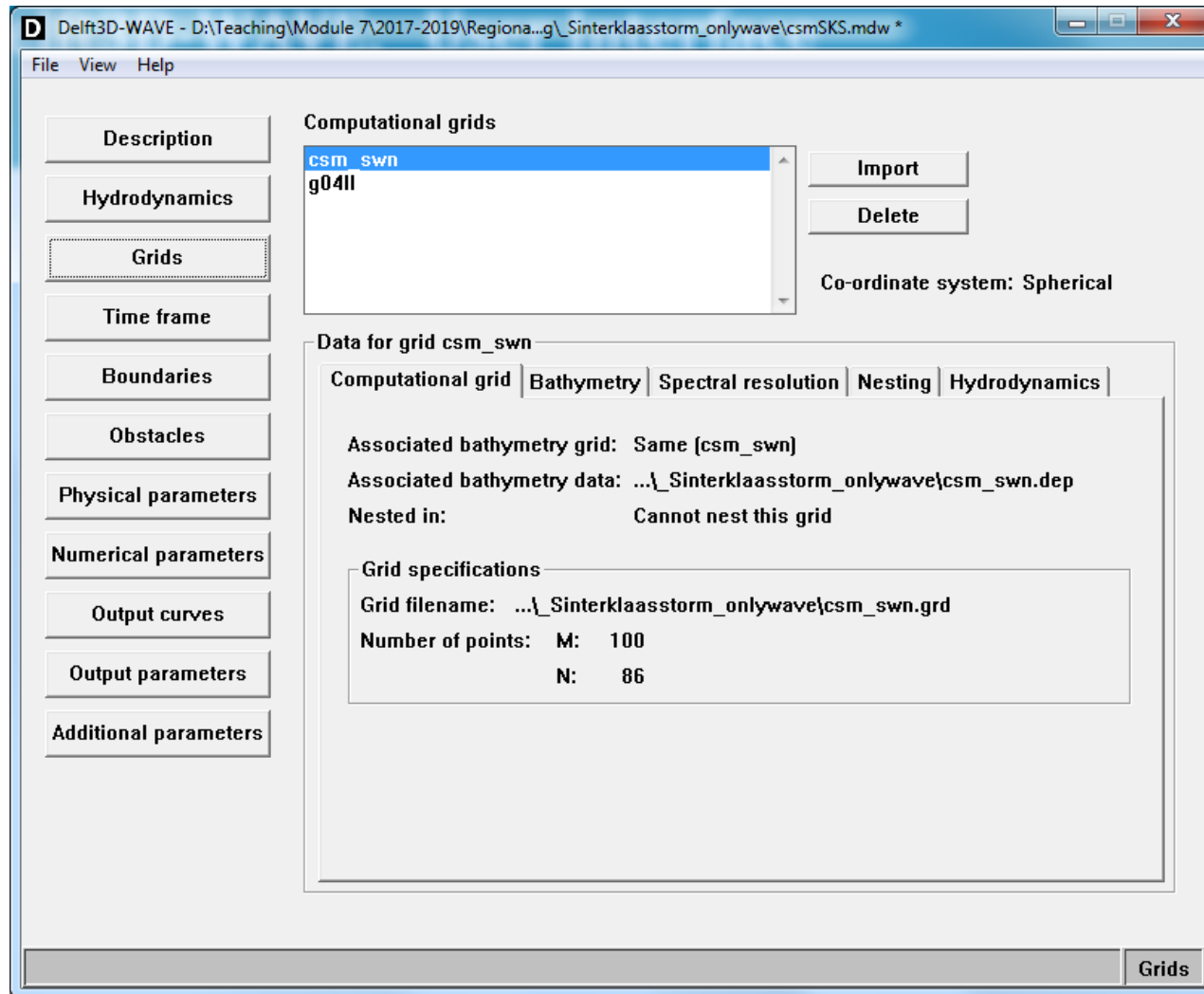
Modelling aspects

- Accuracy of the SWAN output depends on:
 - ✓ Quality of the model input, of which **bathymetry** is most important
 - ✓ Quality of the boundary conditions (waves, wind, tides,...)
 - ✓ Is all the **relevant physics** included
- Numerical schemes can have a huge impact on the accuracy of your result

Delft3D-WAVE - GUI



Delft3D-WAVE: Spatial grids

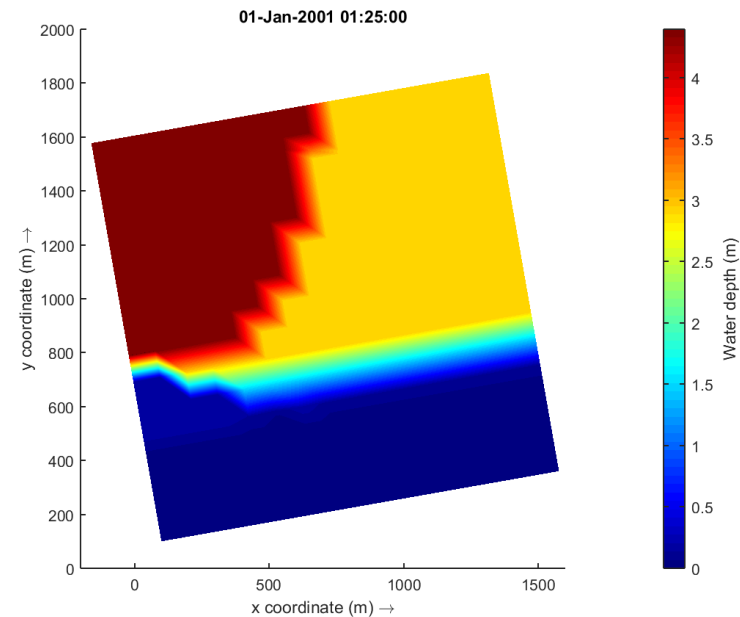
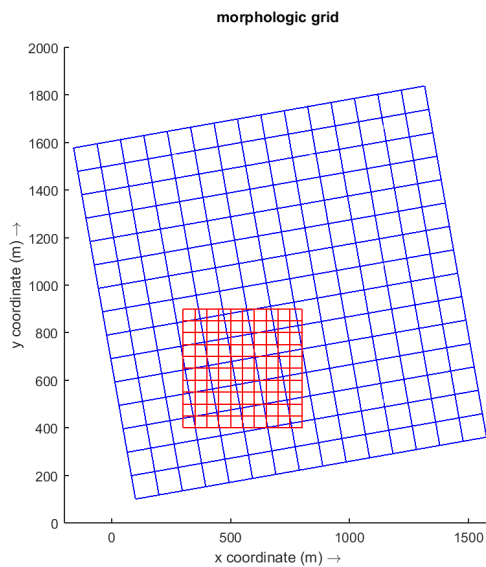


Delft3D-WAVE: Spatial grids

- **Bottom grids**

- ✓ bathymetry: resolve relevant spatial details
- ✓ resolution: bottom grid ~ computational grid

- **Interpolations**



d

Delft3D-WAVE: Spectral grid (σ, θ)

The screenshot shows the Delft3D-WAVE software interface. The window title is "Delft3D-WAVE - D:\Teaching\Module 7\2017-2019\Regiona...g_Sinterklasstorm_onlywave\csmSKS.mdw *". The menu bar includes "File", "View", and "Help".

On the left side, there is a vertical navigation pane with buttons for: "Description", "Hydrodynamics", "Grids" (highlighted), "Time frame", "Boundaries", "Obstacles", "Physical parameters", "Numerical parameters", "Output curves", "Output parameters", and "Additional parameters".

The main area is titled "Computational grids" and contains a list box with "csm_swn" (selected) and "g04II". To the right of the list box are "Import" and "Delete" buttons. Below the list box, it says "Co-ordinate system: Spherical".

Below the "Computational grids" section is the "Data for grid csm_swn" section. It has several tabs: "Computational grid" (selected), "Bathymetry", "Spectral resolution", "Nesting", and "Hydrodynamics".

Under the "Computational grid" tab, there are two sections:

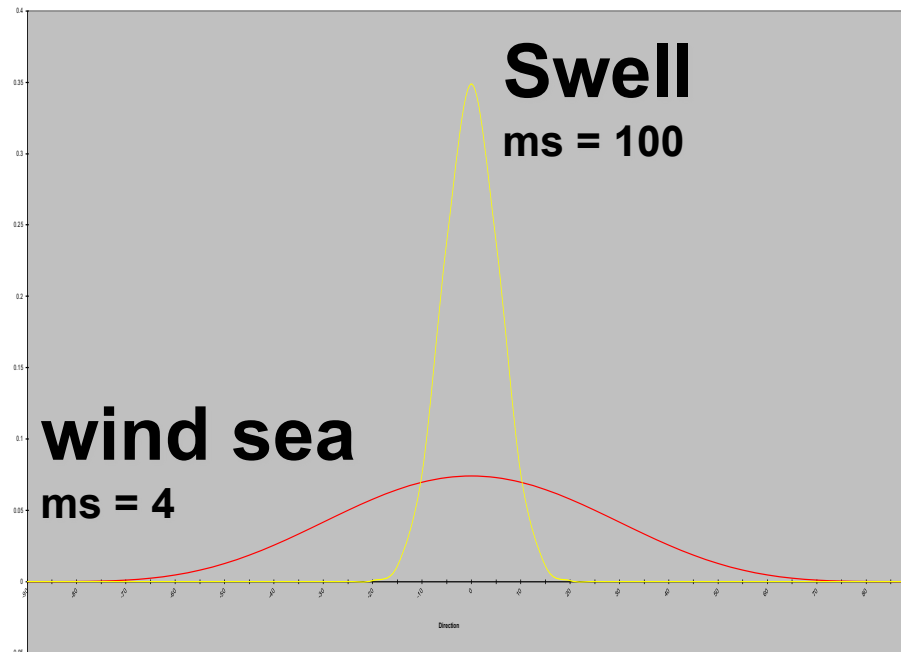
- Directional space:** Includes radio buttons for "Circle" (selected) and "Sector". Below them are input fields for "Start direction: 0 [deg] (counter clockwise)" and "End direction: 0 [deg] (counter clockwise)". A "Number of directions:" field is set to "36".
- Frequency space:** Includes input fields for "Lowest frequency: 0.05 [Hz]", "Highest frequency: 1 [Hz]", and "Number of frequency bins: 24".

At the bottom right of the window, there is a "Grids" button.

Delft3D-WAVE: Spectral grid (σ, θ)

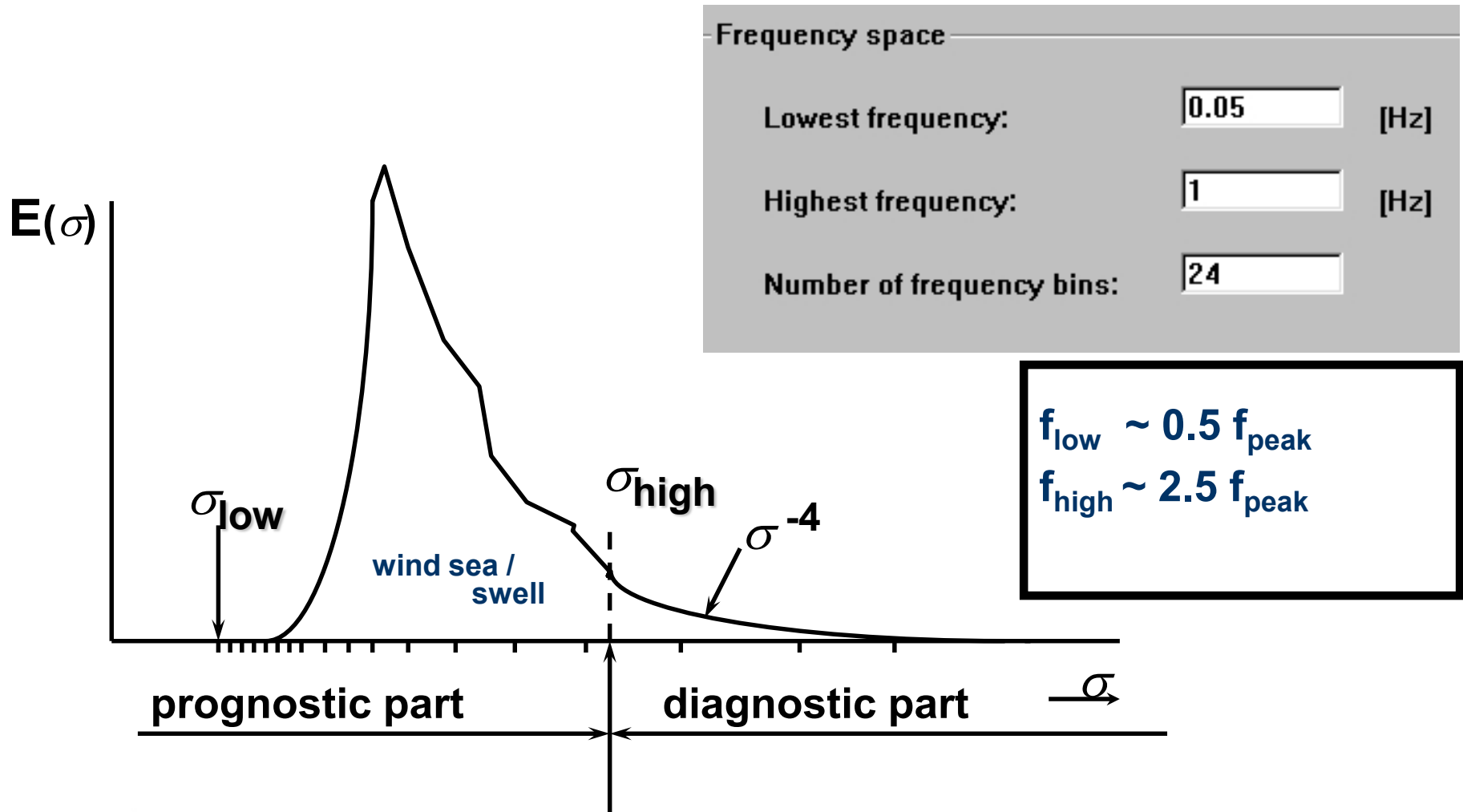
Directional spreading

- The value of $\Delta\theta$ is chosen regarding the nature of the wave field



Delft3D-WAVE: Spectral grid (σ, θ)

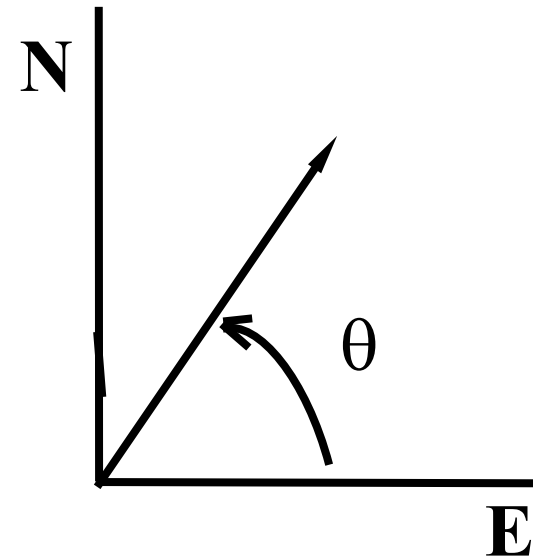
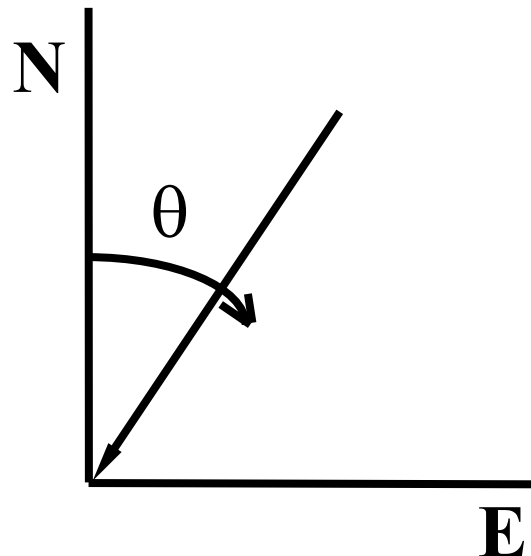
Resolution σ -space



Delft3D-WAVE: Spectral grid (σ, θ)

Directions WIND and WAVES

Nautical Convention or **Cartesian convention**



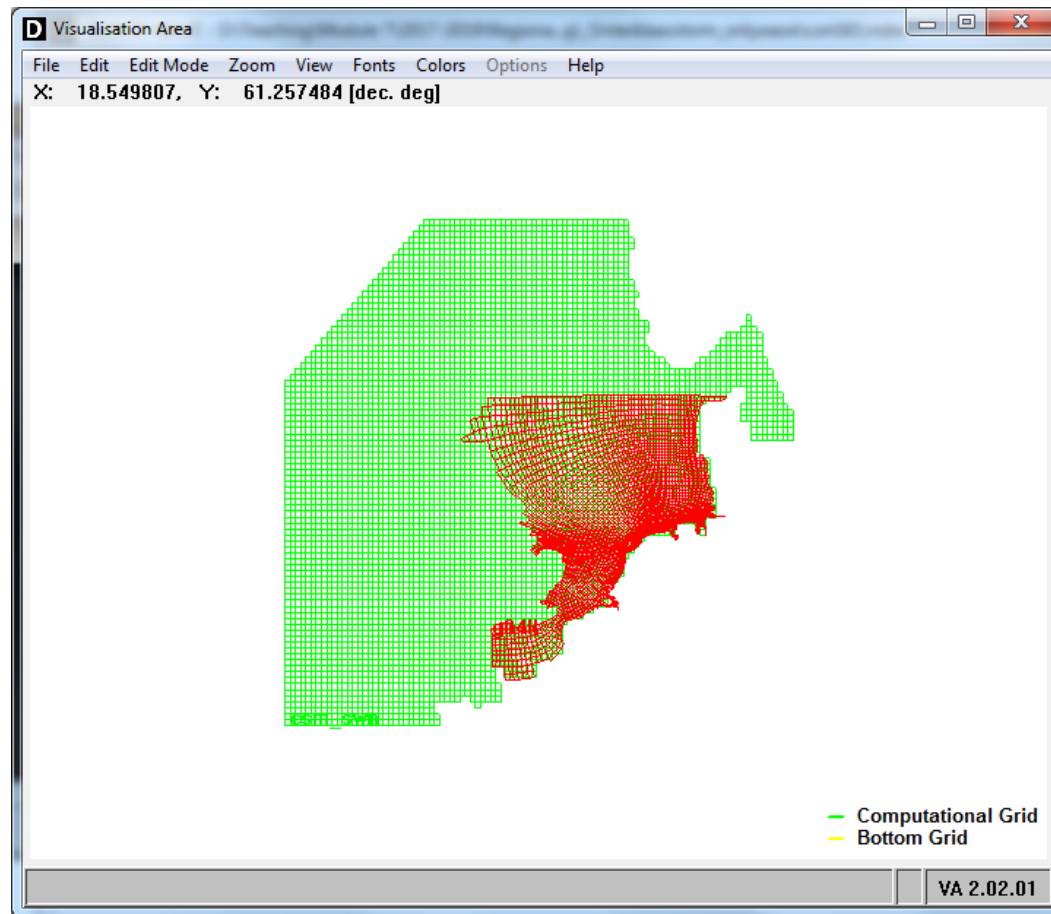
Delft3D-WAVE: Nesting

The screenshot shows the Delft3D-WAVE software interface. The window title is "Delft3D-WAVE - D:\Teaching\Module 7\2017-2019\Regiona...g_Sinterklaasstorm_onlywave\csmSKS.mdw *". The menu bar includes "File", "View", and "Help". On the left, there is a vertical sidebar with buttons for "Description", "Hydrodynamics", "Grids", "Time frame", "Boundaries", "Obstacles", "Physical parameters", "Numerical parameters", "Output curves", "Output parameters", and "Additional parameters". The main area is titled "Computational grids" and contains a list with "csm_swn" and "g04II" (selected). To the right of the list are "Import" and "Delete" buttons, and below them, "Co-ordinate system: Spherical". Below the grid list is a section titled "Data for grid g04II" with tabs for "Computational grid", "Bathymetry", "Spectral resolution", "Nesting", and "Hydrodynamics". The "Nesting" tab is active, showing "Grid g04II is nested in" with a dropdown menu set to "csm_swn". Below this is a box titled "Specifications for grid csm_swn" containing the following information:

Grid filename:	..._Sinterklaasstorm_onlywave\csm_swn.grd		
Associated bathymetry grid:	Same (csm_swn)		
Associated bathymetry data:	..._Sinterklaasstorm_onlywave\csm_swn.dep		
Nested in:	Not nested		
X, Y origin:	-11.937	48.0415	[m]
Number of points M, N:	100	86	

At the bottom right of the main area is a "Grids" button.

Delft3D-WAVE: Nesting



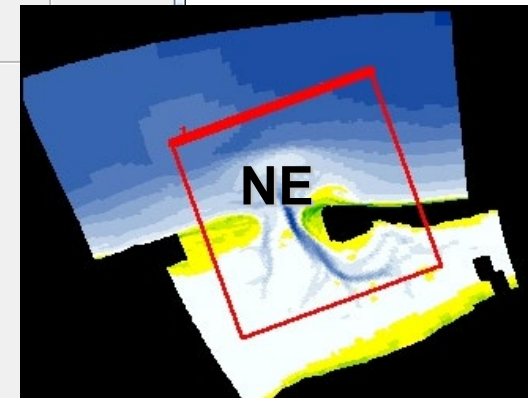
SWAN boundary conditions

The screenshot shows the 'Boundaries' panel in the Delft3D-WAVE software. The 'Boundaries' list contains 'Boundary 1' and 'Boundary 2'. The 'Data for selected boundary' section is configured as follows:

- Boundary name: Boundary 2
- Define boundary by: Orientation
- Boundary orientation: North
- Boundary start: [] [m]
- Boundary end: [] [m]
- Boundary conditions:
 - Conditions along boundary: Uniform, Space-varying
 - Specification of spectra: Parametric, From file

Buttons for 'Add', 'Delete', 'Edit conditions', and 'Edit spectral space' are visible.

Boundaries at each side



- parametric
- 1D or 2D spectra

SWAN boundary conditions

Parametric:

H_s , T_p (or T_{m01}), θ , ms (or σ_θ), g

Uniform boundary conditions

Significant wave height: [m]

Peak period T_p : [s]

Direction (nautical): [deg]

Directional spreading: [H]

Spectral Space

Shape: JONSWAP Peak enh. fact.:

Pierson-Moskowitz

Gauss Spreading:

Period: Peak

Mean

Directional spreading:

Cosine power

Degrees (standard deviation)

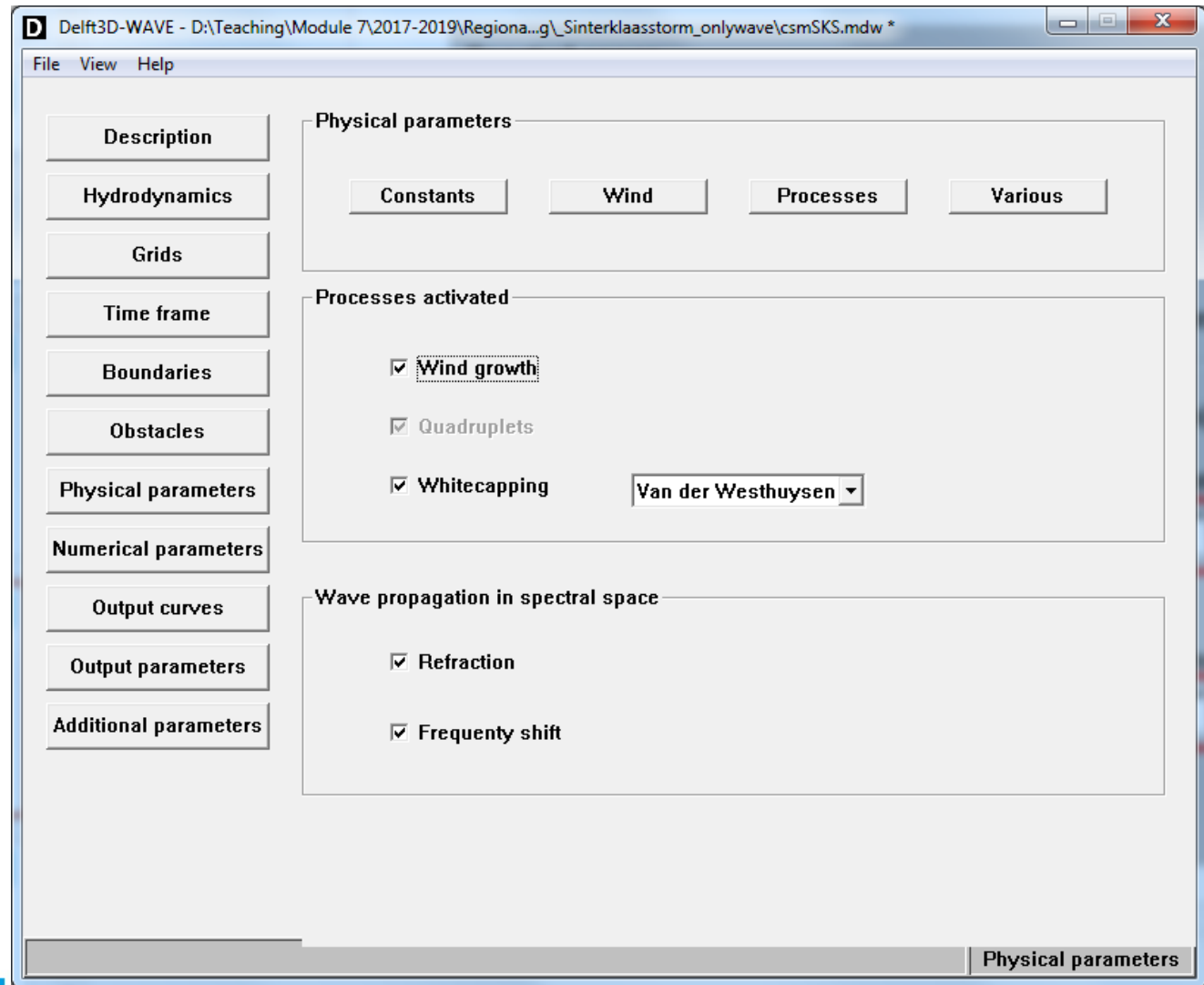
SWAN physics

The screenshot shows the 'Physical parameters' window in the Delft3D-WAVE software. The window title is 'Delft3D-WAVE - D:\Teaching\Module 7\2017-2019\Regiona...g_Sinterklaasstorm_onlywave\csmSKS.mdw *'. The interface includes a menu bar (File, View, Help) and a sidebar with buttons for 'Description', 'Hydrodynamics', 'Grids', 'Time frame', 'Boundaries', 'Obstacles', 'Physical parameters', 'Numerical parameters', 'Output curves', 'Output parameters', and 'Additional parameters'. The 'Physical parameters' section contains sub-sections: 'Constants', 'Wind', 'Processes', and 'Various'. The 'Processes' sub-section is active, showing the following settings:

- Generation mode for physics:** 3-rd generation (dropdown menu with options: none, 1-st generation, 2-nd generation, 3-rd generation)
- Depth-induced breaking (B&J model):**
 - Alpha: [text box]
 - Gamma: [text box]
- Non-linear triad interactions (LTA):**
 - Alpha: 0.1 [text box] [H]
 - Beta: 2.2 [text box] [H]
- Bottom friction:**
 - Type: JONSWAP (dropdown menu)
 - Coefficient: 0.067 [text box] [m2s-3]
- Diffraction:**
 - Smoothing coef.: 0.2 [text box] [H]
 - Smoothing steps: 5 [text box] [H]
- Adapt propagation**

The status bar at the bottom right of the window displays 'Physical parameters'.

SWAN physics



SWAN numerics

Spectral space

Directional space (CDD): [-] (0.0-1.0)

Frequency space (CSS): [-] (0.0-1.0)

CDD and CSS determine the numerical scheme: 0 = central, 1 = upwind

Accuracy criteria (to terminate the iterative computations)

Relative change

Hs-Tm01: [-]

Percentage of wet grid points

[%]

Relative change w.r.t. mean value

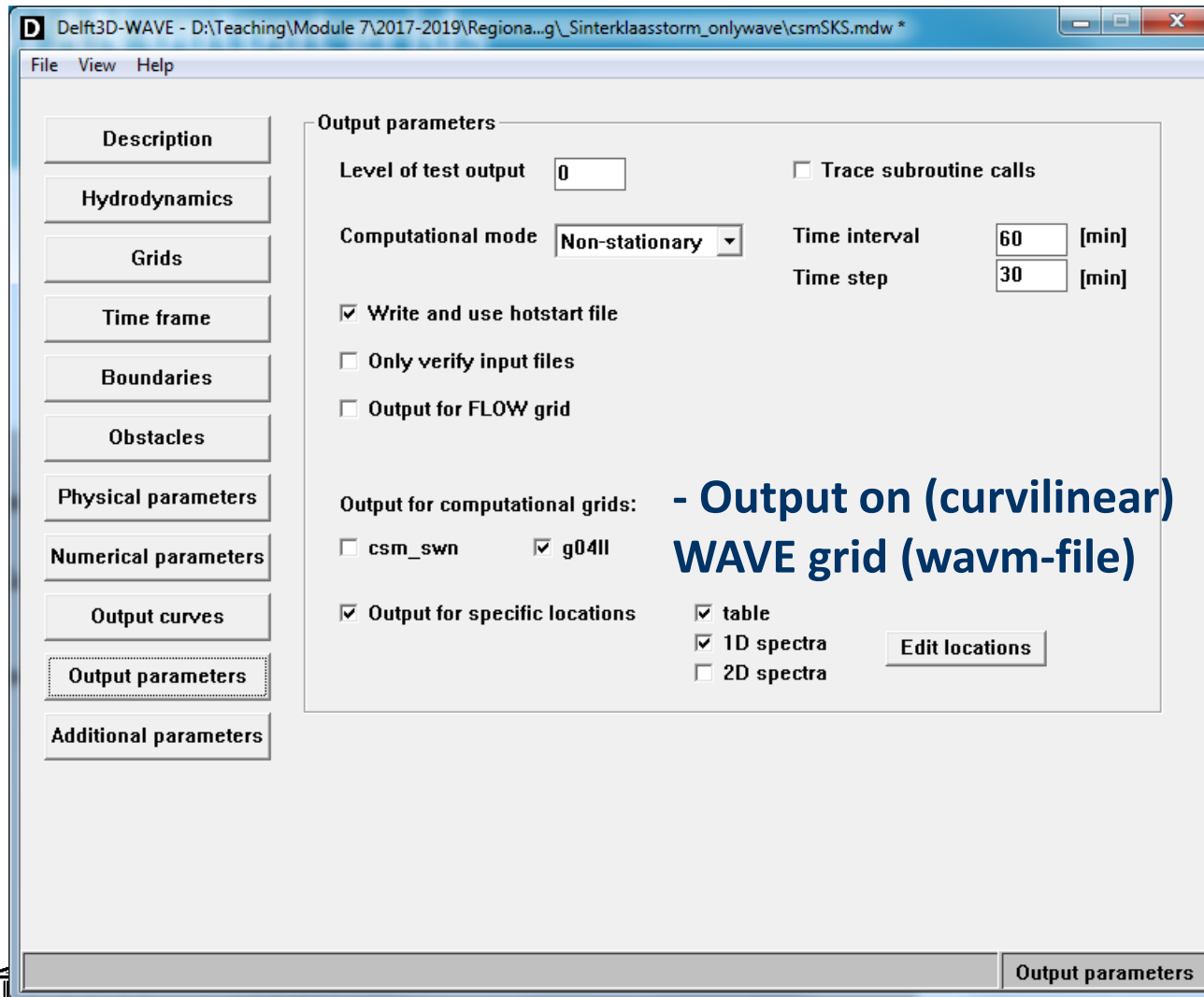
Hs: [-]

Tm01: [-]

Max. number of iterations

Criteria to terminate the iterative computation

SWAN output grids



Structures in Delft3D-WAVE

Attention: dry points and thin dams in a FLOW model do **NOT block waves in coupled models!**

- **Apply obstacles**

or, to effectuate dry points:

- **Apply bottom grid with 'dry values' e.g. -20m in the WAVE and FLOW grids when coupling with bathymetry exchange.**

Time to practice.....

Exercise North Sea model - Goals

After completing this exercise, you will be able to:

- Set up a SWAN wave model forced with stationary and instationary boundary conditions
- Nest two SWAN models
- Visualize and interpret time series and spectral wave output

Make a separate, new directory each time you change model settings!!!

Exercise North Sea model

1. Create a SWAN model using the g04ll grid and dep file in the directory *SWAN_exercise_modelsetup*. *Make a new directory and copy the files before starting*
2. Investigate the effect of imposing a 5m Hm0 wave height, 10s Tp peak period from North, at the northern boundary, using **stationary mode**; put output points for wave parameters and spectra and generate output on the SWAN grid.
3. Next, **in a new directory**, make a new model, and put a 15 m/s uniform wind from the North on the domain
4. Make another new model in a separate directory, and apply both boundary forcing and a wind field at the same time
5. Plot the results of the three models in 3 observation stations, and evaluate the difference in the end results. Can you explain what happens?

Exercise North Sea model (2)

6. We are now going to force the southern North Sea model we made in the previous exercise with a larger scale wind forced model. Copy the contents of *_Sinterklaasstorm_onlywave_windforced* to a new directory
7. Open *csmSKS.mdw*
8. Add two grids and bathymetries: first *csm*, then *g04ll*. Choose to nest *g04ll* in *csm*.
9. Add a 5m H_{m0} wave height, 10s T_p peak period from North, at all the boundaries, and make the run non-stationary, with a timestep of 15 minutes, and a time interval of 3h. Switch on output for the inner domain only.
10. Let it run. See how the small model gets its bc from the large one.

Exercise North Sea model (3)

11. Copy the contents of *_Sinterklaasstorm_onlywave_windforced* to a new directory
12. Open *csmSKS.mdw*
13. Add two grids and bathymetries: first *csm*, then *g04ll*. Choose to nest *g04ll* in *csm*.
14. Make the run non-stationary, with a timestep of 15 minutes and a time interval of 3h.
15. Switch on output for the domain, and 1D spectrum output in the observation points.
16. Switch on Quadruplets and Wind Growth manually in the *mdw* file using a text editor, as the GUI switches them off.
17. Finally, add spatially varying wind fields, using keyword *MeteoFile* under the [General] block of the *mdw* file.

Keyword	Value
MeteoFile	sinterklaasstorm.amu
MeteoFile	sinterklaasstorm.amv

Exercise North Sea model (4)

18. Load the wave measurements from `_Sinterklaasstorm_data/matroosZuno_sks_20131201-20131207.mat` in Matlab. The locations are in variables 'datahs.lon' and 'datahs.lat'.
19. Plot the 9 wave measurement stations in Google Earth using KMLscatter.
20. Eye-ball a transect from north to south across the North Sea, and select stations along that line. In Quickplot, plot the 1D (.sp1) spectra of the different stations for (a) Dec 2nd 12h; (b) Dec 4th 12h; (c) Dec 5th 12h; (d) Dec 5th 24h; (e) Dec 6 18h. Explain the change in shape of the spectrum. You can add the sp1 filetype under File - Preferences - File filter in Quickplot.
21. Compare the model generated time series with the measurements. What is missing to get correct wave heights in the coastal observation points? This will be the focus of the next bullet.
22. **Watch the video on creating a coupled FLOW-WAVE setup, and apply this to the present model**
23. Plot and compare the results in the transect with the run without FLOW coupling