Prepared for:
Rijkswaterstaat/RIKZ

Nonstationary SWAN simulation in the Wadden Sea

Report
April 2008
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Andre van der Westhuysen

Report

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**Client:** Rijkswaterstaat/RIKZ

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**Abstract:**
The spectral wind wave model SWAN plays a key role in the estimation of the Hydraulic Boundary Conditions (HBC) for the primary sea defences of the Netherlands. Since some uncertainty remains with respect to the reliability of SWAN for application to the geographically complex area of the Wadden Sea, a number of activities have been initiated under project H4918 ‘Uitvoering Plan van Aanpak SBW-RVW Waddenzee’ (Plan of Action on the Boundary Conditions for the Wadden Sea) to devise a strategy for the improvement of the model. In this context, a number of hindcast studies have been carried out with SWAN for the Amelander Zeegat in the Wadden Sea. In all of these studies, the stationary simulation mode of SWAN was applied, since this is the approach currently followed in the computation of the HBC. Although the Wadden Sea interior is relatively small – typically making stationary simulation appropriate - the wave boundary conditions and the local wind and current forcings vary relatively rapidly, so that stationary simulation may become inaccurate. Furthermore, if the model domain would be extended offshore to compute the HBC for the entire Wadden Sea, nonstationary simulation could become necessary. The aim of the present study is to compare the results of nonstationary and stationary hindcasts with SWAN in the Wadden Sea, for typical W to NW storm conditions. In addition, the effect of including morphological changes in the computations is considered. This study has shown that, when simulating over a large spatial domain that includes the entire Dutch coast and a portion of the North Sea, a notable difference between the results of these two simulation modes is the absence of a phase lag between offshore and the nearshore wave conditions in the case of stationary simulation. Over these relatively large spatial scales, both the nonstationary and stationary modes of SWAN strongly underestimate energy at the spectral peak nearshore of the barrier islands. When simulating on the scale of the Wadden Sea, notable differences between the results of nonstationary and stationary simulations are found in the Amelander Zeegat tidal inlet. However, along the Frisian coast, differences between the two simulation modes are relatively small. In nonstationary simulations on the scale of the Amelander Zeegat, the inclusion of morphological changes has little effect on the wave conditions at the Frisian coast. Based on the results of this study, it is recommended to continue the use of the stationary mode of SWAN for simulations on the scale of the Amelander Zeegat.

**References:**
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Contents

List of Tables
List of Figures
List of Symbols

1 Introduction......................................................................................................1–1
   1.1 Problem statement..................................................................................1–1
   1.2 Aim .......................................................................................................1–1
   1.3 Method ..................................................................................................1–2
   1.4 Project team ...........................................................................................1–3
   1.5 Report structure .....................................................................................1–3

2 Large-scale model: Storm conditions and schematisation...............................2–1
   2.1 Storm conditions ....................................................................................2–1
      2.1.1 Water levels...............................................................................2–2
      2.1.2 Wind and pressure conditions ....................................................2–2
      2.1.3 Wave conditions ........................................................................2–2
   2.2 Coupled flow and wave modelling .........................................................2–3
   2.3 Hydrodynamic model setup....................................................................2–4
      2.3.1 Grid and bathymetry..................................................................2–4
      2.3.2 Boundary conditions and model settings ....................................2–4
   2.4 Wave model setup ..................................................................................2–4
      2.4.1 Grid and bathymetry..................................................................2–4
      2.4.2 Boundary conditions..................................................................2–5
      2.4.3 Model settings ...........................................................................2–5
      2.4.4 Communication with hydrodynamic model................................2–7

3 Large-scale model: Results...............................................................................3–1
   3.1 Flow model results and wind fields ........................................................3–1
   3.2 Wave model results ................................................................................3–2
      3.2.1 Iteration behaviour and convergence..........................................3–2
      3.2.2 Comparison with observations ...................................................3–3
      3.2.3 Differences between nonstationary and stationary model
         results........................................................................................3–5
      3.2.4 Conclusion ................................................................................3–6

4 Amelander Zeegat model: Storm conditions and schematisation ...................4–1
   4.1 Storm conditions ....................................................................................4–1
      4.1.1 Water levels ...............................................................................4–2
      4.1.2 Wind and pressure conditions ....................................................4–2
4.1.3 Wave conditions ......................................................... 4–2
4.2 Coupled flow and wave modelling ........................................... 4–3
4.3 Hydrodynamic model setup ...................................................... 4–3
  4.3.1 Grid and bathymetry ....................................................... 4–3
  4.3.2 Boundary conditions ..................................................... 4–3
  4.3.3 Model settings .......................................................... 4–4
4.4 Wave model setup ............................................................... 4–4
  4.4.1 Boundary conditions ....................................................... 4–4
  4.4.2 Model settings .......................................................... 4–5
  4.4.3 Communication with hydrodynamic model ....................... 4–5
4.5 Morphological model .......................................................... 4–6
  4.5.1 Sediment transport formulae ............................................ 4–6
  4.5.2 Sediment characteristics and bed updating ....................... 4–6
5 Amelander Zeegat model: Results ........................................... 5–1
  5.1 Flow model results .......................................................... 5–1
  5.2 Wave model results .......................................................... 5–1
    5.2.1 Iteration behaviour and convergence .............................. 5–1
    5.2.2 Comparison with observations ........................................ 5–3
    5.2.3 Differences between nonstationary and stationary results .... 5–5
    5.2.4 Impact of morphological changes ................................... 5–8
6 Conclusions .............................................................................. 6–1
7 Recommendations ..................................................................... 7–1
8 References .............................................................................. 8–1

Appendices
A Appendix: SWAN input for large-scale model ......................... A–1
B Appendix: SWAN input for Amelander Zeegat model ................ B–1
# List of Tables

2.1 Location of observations stations for the large-scale simulation

4.2 Location of observations stations for the Amelander Zeegat simulation
List of Figures

1.1 Location of the Amelander Zeegat in the Dutch Wadden Sea

2.1 Amelander Zeegat storm of 7–9 February 2004. Locations of various observation stations
2.2 Amelander Zeegat storm of 7–9 February 2004. Observed water levels at three nearshore stations
2.3 Wind fields at various time points during the storm of 7–9 February 2004
2.4 Amelander Zeegat storm of 7–9 February 2004. Observed wind time series at three stations
2.5 Amelander Zeegat storm of 7–9 February 2004. Time series comparison of HIRLAM wind and observations at three stations
2.6 Amelander Zeegat storm of 7–9 February 2004. Scatterplot comparison of HIRLAM wind and observations at three stations
2.7 Amelander Zeegat storm of 7–9 February 2004. Observed significant wave heights
2.8 Amelander Zeegat storm of 7–9 February 2004. ZUNO model grid used for flow computations and outline of wave model grid
2.9 Bathymetry of the ZUNO model
2.11 Bathymetry of the SWAN model

3.1 Amelander Zeegat storm of 7–9 February 2004. Measured versus computed water levels at three nearshore stations
3.2 Amelander Zeegat storm of 7–9 February 2004. Computed water levels at various instants during the storm
3.3 Amelander Zeegat storm of 7–9 February 2004. Simulated current fields at six instants during the storm
3.4 Amelander Zeegat storm of 7–9 February 2004. HIRLAM wind fields at six instants during the storm
3.6 Amelander Zeegat storm of 7–9 February 2004. Iteration behaviour of $H_{m0}$ during nonstationary simulation.
3.7 Amelander Zeegat storm of 7–9 February 2004. Iteration behaviour of $T_{m0}$ during nonstationary simulation.
3.8 Amelander Zeegat storm of 7–9 February 2004. Iteration behaviour of $H_{m0}$ during stationary simulation.
3.9 Amelander Zeegat storm of 7–9 February 2004. Iteration behaviour of $T_{m0}$ during stationary simulation.
3.10 Amelander Zeegat storm of 7–9 February 2004. Significant wave height at six instants during the storm
3.11 Amelander Zeegat storm of 7–9 February 2004. Mean wave period at six instants during the storm
3.12 Amelander Zeegat storm of 7–9 February 2004. Directional spreading at six instants during the storm
List of Figures

3.13 Amelander Zeegat storm of 7–9 February 2004. Measured versus computed significant wave heights
3.14 Amelander Zeegat storm of 7–9 February 2004. Measured versus computed mean period Tm–1.0
3.15 Amelander Zeegat storm of 7–9 February 2004. Measured versus computed mean direction
3.18 Amelander Zeegat storm of 7–9 February 2004. Difference in wave height at four instants: $\left( H_{m0,\text{instat}} - H_{m0,\text{stat}} \right) / H_{m0,\text{stat}}$
3.19 Amelander Zeegat storm of 7–9 February 2004. Difference in mean period at four instants: $\left( T_{m-1.0,\text{instat}} - T_{m-1.0,\text{stat}} \right) / T_{m-1.0,\text{stat}}$
3.20 Amelander Zeegat storm of 7–9 February 2004. Difference in mean direction at four instants: $\text{Dir}_{\text{instat}} - \text{Dir}_{\text{stat}}$
3.21 Amelander Zeegat storm of 7–9 February 2004. Difference in directional spreading at four instants: $\text{Dspr}_{\text{instat}} - \text{Dspr}_{\text{stat}}$

4.1 Amelander Zeegat storm of 1–3 January 2005. Bathymetry of the Amelander Zeegat and location of observation stations
4.2 Amelander Zeegat storm of 1–3 January 2005. Observed water levels at Terschelling Noordzee and Nes
4.3 Wind fields at various time points during the storm of 1–3 January 2005
4.4 Amelander Zeegat storm of 1–3 January 2005. Observed wind time series at three stations
4.5 Amelander Zeegat storm of 1–3 January 2005. Observed wave data time series at various buoys
4.6 Amelander Zeegat storm of 1–3 January 2005. Grids for flow (top) and wave (bottom) computations. Every second cell shown.

5.1 Amelander Zeegat storm of 1–3 January 2005. Measured versus computed water levels at Terschelling Noordzee and Nes
5.2 Amelander Zeegat storm of 1–3 January 2005. Computed water levels (in m) at various instants during the storm
5.3a Amelander Zeegat storm of 1–3 January 2005. Current fields at 2005/01/02 at 10:00 (top) and 12:00 (bottom)
5.3b Amelander Zeegat storm of 1–3 January 2005. Current field at 2005/01/02 at 17:00
5.5 Amelander Zeegat storm of 1–3 January 2005. Iteration behaviour of $H_{m0}$ during nonstationary simulation.
5.6 Amelander Zeegat storm of 1–3 January 2005. Iteration behaviour of $T_{m01}$ during nonstationary simulation.
5.7 Amelander Zeegat storm of 1–3 January 2005. Iteration behaviour of $H_{m0}$ during stationary simulation.
5.8 Amelander Zeegat storm of 1–3 January 2005. Iteration behaviour of $T_{m01}$ during stationary simulation.
5.9 Amelander Zeegat storm of 1–3 January 2005. Significant wave height at six instants during the storm
5.10 Amelander Zeegat storm of 1–3 January 2005. Mean wave period $T_{m-1,0}$ at six instants during the storm
5.11 Amelander Zeegat storm of 1–3 January 2005. Directional spreading at three instants during the storm
5.12 Amelander Zeegat storm of 1–3 January 2005. Measured versus computed significant wave heights
5.13 Amelander Zeegat storm of 1–3 January 2005. Measured versus computed mean period $T_m - 1,0$
5.14 Amelander Zeegat storm of 1–3 January 2005. Measured versus computed mean direction
5.15 Amelander Zeegat storm of 1–3 January 2005. Measured versus computed directional spreading
5.16 Amelander Zeegat storm of 1–3 January 2005. Computed and observed spectra on 02/01/2005 at 10:00
5.17 Amelander Zeegat storm of 1–3 January 2005. Computed and observed spectra on 02/01/2005 at 12:00
5.18 Amelander Zeegat storm of 1–3 January 2005. Computed and observed spectra on 02/01/2005 at 17:00
5.19a Amelander Zeegat storm of 1–3 January 2005. Difference in Significant wave height: $(H_{m0,nstat} - H_{m0,stat})/H_{m0,stat}$
5.19b Amelander Zeegat storm of 1–3 January 2005. Difference in Significant wave height: $(H_{m0,nstat} - H_{m0,stat})/H_{m0,stat}$
5.20a Amelander Zeegat storm of 1–3 January 2005. Difference in mean period: $(T_{m-1,0,nstat} - T_{m-1,0,stat})/T_{m-1,0,stat}$
5.20b Amelander Zeegat storm of 1–3 January 2005. Difference in mean period: $(T_{m-1,0,nstat} - T_{m-1,0,stat})/T_{m-1,0,stat}$
5.21a Amelander Zeegat storm of 1–3 January 2005. Difference in mean direction: $\text{Dir}_{nstat} - \text{Dir}_{stat}$
5.21b Amelander Zeegat storm of 1–3 January 2005. Difference in mean direction: $\text{Dir}_{nstat} - \text{Dir}_{stat}$
5.22a Amelander Zeegat storm of 1–3 January 2005. Difference in directional spreading: $D_{snp,nstat} - D_{snp,stat}$
5.22b Amelander Zeegat storm of 1–3 January 2005. Difference in directional spreading: $D_{snp,nstat} - D_{snp,stat}$
5.23 Amelander Zeegat storm of 02/01/2005 at 10:00. Nonstationary vs. stationary results along Transect A
5.24 Amelander Zeegat storm of 02/01/2005 at 12:00. Nonstationary vs. stationary results along Transect A
5.25 Amelander Zeegat storm of 02/01/2005 at 17:00. Nonstationary vs. stationary results along Transect A
5.26a Amelander Zeegat storm of 1–3 January 2005. Difference in bed level: Levelmorph – Levelno morph
5.26b Amelander Zeegat storm of 1–3 January 2005. Difference in bed level: Levelmorph – Levelno morph
5.27a Amelander Zeegat storm of 2005/01/02 at 17:00. Difference in wave height and period: $(P_{morph} - P_{no morph})/P_{no morph}$
5.27b Amelander Zeegat storm of 2005/01/02 at 17:00. Difference in mean direction and directional spreading: Par$_{\text{morph}}$ – Par$_{\text{no morph}}$
## List of Symbols

<table>
<thead>
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1 Introduction

1.1 Problem statement

The spectral wind wave model SWAN (Booij et al. 1999) plays a key role in the estimation of the Hydraulic Boundary Conditions (HBC) for the primary sea defences of the Netherlands. Since some uncertainty remains with respect to the reliability of SWAN for application to the geographically complex area of the Wadden Sea, a number of activities have been initiated under project H4918 ‘Uitvoering Plan van Aanpak SBW-RVW Waddenzee’ (Plan of Action on the Boundary Conditions for the Wadden Sea) to devise a strategy for the improvement of the model. This activity is carried out in parallel with a measurement campaign that is being undertaken in the Wadden Sea to assist in the establishment of the boundary conditions (‘SBW-Veldmetingen’). In this context, a number of hindcast studies have been carried out with SWAN for the Amelander Zeegat in the Wadden Sea, depicted in Figure 1.1 (WL 2006b; Royal Haskoning 2006; WL & Alkyon 2007; Royal Haskoning 2007). In all of these studies, the stationary simulation mode of SWAN was applied, since this is the approach currently followed in the computation of the HBC.

Stationary simulation is considered to be justified when the residence time of the simulated waves – the time that waves require to travel through the model domain – is small relative to the time scale of changes in the wave boundary conditions and forcings (e.g. wind and current fields). As the model domain and hence the residence time of the waves increases, nonstationary simulation becomes more appropriate, and stationary simulation becomes inaccurate. Nonetheless, Rogers et al. (2007) show that stationary simulation may even yield acceptable results on large scale (order >100 km) shelf sea applications. Although the Wadden Sea interior is relatively small, and therefore the residence time is small, the wave boundary conditions and the local wind and current forcings vary relatively rapidly, so that stationary simulation may become inaccurate. Furthermore, as suggested by WL (2006a), if the model domain would be extended offshore to compute the HBC for the entire Wadden Sea, nonstationary simulation could become necessary. For the accurate estimation of waves in the Wadden Sea, it is therefore necessary to determine whether the stationary mode of simulation is justified and, if not, where differences with respect to full nonstationary simulations occur. The investigation of these differences is the main subject of this study. A secondary aim of this investigation is to determine whether the inclusion of morphological changes in fully nonstationary simulations in the Wadden Sea has any additional significant effects on the model outcomes.

1.2 Aim

The aim of the present study is to compare the results of nonstationary and stationary SWAN hindcasts in the Wadden Sea with each other, and with observations, for typical W to NW storm conditions. This is to be done both on a larger scale, starting 100 km offshore of the barrier islands, and on a small scale, including the barrier islands, the Wadden Sea interior and the mainland coast. In addition, the effect of including morphological changes in the simulations is considered.
1.3 Method

In this study, we consider two simulation modes of SWAN, namely the nonstationary and the stationary modes. In nonstationary simulation, the time variation of the action density $\partial N_{ww}/\partial t$ is considered in the action balance equation (see Booij et al. 1999), whereas in stationary mode this time derivative is absent. Nonetheless, the time evolution of a wave field can be modelled in stationary mode by performing stationary simulations at regular time steps, with time-varying boundaries and forcings. This method of simulation is typically applied in coupled wave and hydrodynamic simulations, and is often called quasi-nonstationary simulation. This method of simulation provides a stationary SWAN result at every time step, as if a stationary hindcast had been performed for that storm instant. This quasi-nonstationary method of simulation, henceforth referred to compactly as stationary simulation, will be applied in this study in the comparison with fully nonstationary simulation.

In order to determine the differences between nonstationary and stationary simulation to model results in the Amelander Zeegat and the Frisian coast, two series of simulations were conducted over different spatial scales. In the first series of tests, the influence of nonstationary simulation is considered on a large geographical scale, including the entire Dutch coast and a portion of the North Sea. Here the focus is on the transformation of offshore wave conditions to conditions immediately outside the Amelander Zeegat ebb tidal delta. Both nonstationary simulations and sequential stationary simulations are conducted with SWAN for a selected NW storm. These simulations were conducted using the Delft3D model suite, with which a two-way coupling was obtained between the computation of the wave field and the computation of tidal, wind- and wave-induced currents and water levels. The results of the nonstationary and stationary SWAN simulations were subsequently compared in terms of time series results and, for selected storm instants, in terms of wave spectra and spatial plots.

In the second series of tests, nonstationary versus stationary simulation was considered on the scale of the Amelander Zeegat, to investigate the impacts on computed wave conditions along the Frisian coast. These tests are based on a recent study by WL (2007), in which coupled wave-current-morphology modelling was investigated for a westerly storm in the Amelander Zeegat. In these tests, the model boundary is positioned just offshore of the Amelander Zeegat, and nonstationary and stationary simulations are conducted through the tidal inlet, over the Wadden Sea interior, and up to the Frisian coast. As in the larger scale tests, these simulations were conducted using the Delft3D model suite. The results of these simulations were compared in terms of time series results and, for selected storm instants, in terms of wave spectra and spatial plots. The model outcomes were also compared over a transect running along the Frisian coast. In addition, a sensitivity test was performed in which morphological changes, computed in Delft3D, were also included in the nonstationary simulations. Using these results, it was determined whether morphological changes occurring within a single storm have an impact on the comparison between stationary and nonstationary model results.
1.4  Project team

This study has been carried out by André van der Westhuysen, with the assistance of Arjen Luijendijk and Jan-Joost Schouten. The internal quality assurance has been conducted by Jacco Groeneweg. The external review was done by W. Erick Rogers (Naval Research Laboratory, USA).

1.5  Report structure

This report is structured as follows: Section 2 presents the storm conditions and model setup considered for the simulations on the large-scale spatial domain. The results of these tests are presented in Section 3. Section 4 presents the environmental conditions and model setup considered for the simulations on the Amelander Zeegat spatial scale. The results of these smaller-scale tests are presented in Section 5. Sections 6 and 7 close this report with conclusions and recommendations.
Large-scale model: Storm conditions and schematisation

This section and Section 3 present the large-scale nonstationary and stationary SWAN simulations on the scale of the entire Dutch coast and a portion of the North Sea. Section 2.1 presents the storm conditions considered in this study, namely a NW storm recorded during 7-9 February 2004. Section 2.2 presents the general concept of coupled flow and wave modelling followed in this study. Subsequently, Sections 2.3 and 2.4 describe the setup of the hydrodynamic model and the wave model respectively.

2.1 Storm conditions

For the hindcast on the scale of the entire Dutch coast and a portion of the North Sea, a NW storm occurring during 7-9 February 2004 was selected. This storm has the following characteristics: A southeastward-bound low-pressure system passed over the Dutch coast, resulting in NW winds of up to 17 m/s in the southwestern North Sea and 15 m/s above the Wadden Sea. The peak of the storm was in the afternoon of 8 February, at which time a significant wave height of around 6 m was measured at station K13-Alpha (for its location, see Figure 2.1). The northwesterly winds caused a large storm surge in the northern coastal areas, with a maximum additional water level of 0.7 m at station Terschelling Noordzee, and 1.0 m at Wierumergronden, which coincided with high tide at these locations.

For this hindcast, conditions over the North Sea and up to the barrier islands of the Wadden Sea (in particular the Amelander Zeegat tidal inlet) are of interest. Measured water levels, and wind and wave conditions are available for this storm period, observed at several locations. These stations are depicted in Figure 2.1, and their coordinates are given in Table 2.1. In addition, computed spatially varying wind and pressure fields are available. Details of these various sources of data are given in the sections below.

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<th>X (m RD)</th>
<th>Y (m RD)</th>
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<th>Freq. range (Hz)</th>
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<td>583 217</td>
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<td>779 998</td>
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Table 2.1: Location of observations stations for the large-scale simulation, in Rijksdriehoek (RD) coordinates. Depths given relative to the Dutch national levelling datum NAP, DW denotes directional wave information,
2.1.1 Water levels

Water levels were measured at a number of stations offshore of the Wadden Sea. Here we consider the observations made at three stations, namely Texel Noordzee, Terschelling Noordzee, and Wierumergronden (see Figure 2.1). The measured water levels at these three locations are presented in Figure 2.2. The tidal ranges at these three stations are comparable, with a time lag of 2.5 hours between Texel Noordzee and Wierumergronden. It can be seen that an additional water level increase of between 0.5 and 1.0 m was experienced at these three locations during the storm period of 7-9 February.

2.1.2 Wind and pressure conditions

Spatially varying HIRLAM wind fields, as provided by RIKZ, were used in the flow and wave modelling. The HIRLAM data was computed on an 11 km grid, with a time interval of 6 hours. Figure 2.3 shows the spatial variation of the wind speed and direction of the HIRLAM wind fields for 7-9 February 2004. It can be seen that during 8 February, the day of the peak of the storm, the wind direction over the Dutch coast turned from WSW to NW. As the low-pressure system passed, the highest wind velocities are first found over the western half of the North Sea, and then over the eastern half. Figure 2.4 shows the observed wind speeds and directions of the wind at K13-Alpha, Texelhors and Hoorn (Terschelling) during the storm. This data is courtesy of the Royal Netherlands Meteorological Institute. See Figure 2.1 for the location of these stations along the Dutch coast. These observations show that the wind direction progressed from $250^\circ$ N to $325^\circ$ N during the storm period. The highest winds were recorded at the offshore station K13-Alpha, and decreased moving landward (Texelhors) and to the east (Hoorn).

Figures 2.5 and 2.6 present a comparison between the computed HIRLAM winds and the observations at the three observation stations, for the duration of the storm. Figure 2.5 shows the time series of the 6-hourly HIRLAM data and the hourly observations. Although the resolution in time of the HIRLAM data is much lower than that of the observation, the comparison at the offshore station K13-Alpha suggests an underestimation by HIRLAM at the peaks of the storm, particularly on 8 February 2004 at 22:20. At the coastal station Texelhors the observations appear to be equally underestimated by HIRLAM. By comparison, at station Hoorn (on the lee side of Terschelling) the model results fit the observations well, tending towards an overprediction. Figure 2.6 present scatter plots of the time series data, in which the HIRLAM results have been interpolated at intervals of 1 hour. The scatter plots illustrate that at stations K13-Alpha the higher observed values of appear to be underestimated by HIRLAM. This underprediction at the storm peaks could possibly have negative impacts on the wave and hydrodynamic model results.

2.1.3 Wave conditions

Five wave measurement stations were located in the area of interest during the storm period. These are the K13-Alpha platform, the German NSB2 wave buoy, the wave monitoring station ELD, and the buoys AZB11 and AZB12 (Figure 2.1). Since the buoys AZB11 and AZB12 positioned outside the Amelander Zeegat tidal inlet were co-located, data from
AZB12 was not considered here. The locations of the four considered wave observation stations and the corresponding depths at those locations are given in Table 2.1.

Directional wave spectra are available for the stations NSB2 and AZB11. We note that here and in the remainder of the study, the spectral mean direction in both the observations and SWAN has been computed according to Kuik et al. (1988), namely the weighted mean over both the directional and frequency dimensions. At the AZB11 buoy, this information is available every 10 minutes, and is recorded over the frequency range 0.01-0.5 Hz, at linearly-distributed frequencies of 0.01 Hz. At the NSB2 buoy, of which the spectra served as a boundary condition, wave information was recorded more infrequently, with time intervals ranging between 1 and 5.5 hours. For this buoy, the frequency range and discretization varied with the peak frequency of the wave condition. At the peak of the storm, the high-frequency cut-off was as low as 0.2 Hz. For the model input, these spectra were interpolated onto the frequency range 0.025-0.5 Hz, with the spectral density allowed to linearly decrease to zero at 0.635 Hz. The mean direction and directional spreading were assumed constant beyond the measured cut-off. It is noted that within SWAN the spectra tail assumes an \( f^{-4} \) decay within a few grid cells inside the model domain. At the locations K13-Alpha and ELD, hourly information is available, but only in terms of the wave parameters \( H_{m0} \), \( T_{m02} \) and the spectral mean direction (Dir). At station K13-Alpha, of which the wave information served as a boundary condition, a JONSWAP spectral shape was assumed. The observed spectral mean direction was assigned to all frequencies. Since information on the directional spreading was not available at K13-Alpha, the spectral mean directional spreading observed at NSB2 was applied here. This mean directional spreading was assigned to all frequencies.

Figure 2.7 presents the measured significant wave heights at these four locations during the storm period of 7-9 February 2004. At the offshore station K13-Alpha, the wave height increased up to a maximum value of \( H_{m0} = 6.1 \) m on 8 February 2004 at 22:30. At NSB2, the other offshore station, the maximum significant wave height of similar magnitude was reached on 9 February 2004 at 01:20, around which time the wind field over the southern North Sea reached a maximum velocity here. At the stations ELD and AZB11 closer to the barrier inlands, maximum significant wave heights of approximately \( H_{m0} = 5.5 \) m were reached, on 8 February at around 20:00 and 21:00 respectively.

### 2.2 Coupled flow and wave modelling

To simulate the hydrodynamic and morphodynamic processes the process-based numerical model Delft3D has been used. Two modules of Delft3D are used in this study: Delft3D-FLOW and Delft3D-WAVE. Delft3D-FLOW provides the hydrodynamic basis for all the other modules of Delft3D. In this module the hydrodynamic flow, sediment transport and bottom changes (morphology) are computed simultaneously. Delft3D-WAVE is the interface through which the model SWAN is run, which simulates the evolution of wind-generated waves.

These two modules are coupled with a pre-defined frequency when information is communicated in two directions. Therefore Delft3D-FLOW is able to include wave forces in the hydrodynamics and sediment transport and conversely Delft3D-WAVE is able to use the hydrodynamics and calculated bathymetry of the Delft3D-FLOW model. In this study, the
imbedded SWAN simulation is run either in full nonstationary mode, or in stationary mode at each time step (i.e. quasi-nonstationary mode, see Section 1.3). The model schematization of the hydrodynamic model and the wave model (SWAN) are presented below. In Sections 4 and 5, in which the smaller-scale application of the Amelander Zeegat is considered, the morphological model will also be described and applied.

2.3 Hydrodynamic model setup

2.3.1 Grid and bathymetry

The flow modelling for this storm was performed using the ZUNO model (Roelvink et al. 2001), a well-calibrated hydrodynamic model of the southern North Sea. Figure 2.8 shows the computational grid of the ZUNO model, which spans from the English Channel to the northern tips of Scotland and the Jutland Peninsula. The resolution of this grid ranges from 15 km by 10 km on the North Sea interior to 200 m (cross-shore) by 3000 m (longshore) along the Wadden Sea barrier islands. Also shown are the outlines if the wave modelling grid used, which can be seen to cover the southwestern part of the ZUNO grid. Details on the wave model grid follow in Section 2.4.1.

Figure 2.9 presents the bathymetry of the ZUNO model. In the southern part of the North Sea, offshore of The Netherlands, water depths of 30-40 m are found. To the north of the ZUNO model domain the water depths increase to an average of about 130 m.

2.3.2 Boundary conditions and model settings

Details of the boundary conditions, setup and calibration of the ZUNO model can be found in Roelvink et al. (2001). The hydrodynamic model was run in depth-averaged mode, and the time step was set at 1 minute. Along all the land boundaries, water level boundaries were imposed, using astronomical components. The bed roughness was prescribed with the Manning formula, using a spatially varying roughness coefficient. The ZUNO model has not been specifically calibrated for the storm under consideration.

2.4 Wave model setup

2.4.1 Grid and bathymetry

Figure 2.10 presents the computational grid used for the SWAN simulations. This grid is based on a cut section of the ZUNO-fine model grid. The grid has subsequently been altered along its NW edge to form a straight model boundary connecting the two offshore stations K13-Alpha and NSB2, and to also be perpendicular to the NW storm direction. In addition, this adapted ZUNO-fine grid has been refined in both grid dimensions. The resolution ranges from 1000 m (cross-shore) by 2000 m (longshore) along the offshore model boundary to 100 m (cross-shore) by 1400 m (longshore) along the barrier islands and outside the Amelander Zeegat tidal inlet.
Figure 2.11 presents the bathymetry used in the SWAN model grid, which was taken from the ZUNO-fine model. It can be seen that along the northwesterly edge of the considered domain, where the K13-Alpha and NSB2 stations are located, water depths of -50 m NAP are found. Moving toward the coast, the seabed gradually rises, up to a level of -19 m NAP at the AZB11 location. In the Wadden Sea interior the water depths are considerably less, but this region is not considered in the present large-scale simulation.

### 2.4.2 Boundary conditions

The observed wave conditions at the offshore stations K13-Alpha and NSB2 were used as boundary conditions for the wave model. As described in Section 2.1.3, at the NSB2 location, directional wave spectra were available as model input. At K13-Alpha, a JONSWAP spectral shape was imposed, using observed integral wave parameters. The K13-Alpha station provided wave information every hour during the storm period, and the NSB2 buoy at intervals between 1 hour and 5.5 hours. The wave information of the K13-Alpha station was applied on the NW-facing (offshore) boundary over the segment to the southwest of the station, and also along the SW-facing lateral boundary. These segments are indicated with a thick blue line in Figure 2.10. Over the segment of the offshore boundary between K13-Alpha and NSB2, SWAN interpolates the components of these two spectra linearly (green line). Along the NE-facing lateral boundary (yellow line), the spectra from the NSB2 buoy were applied uniformly.

### 2.4.3 Model settings

The wave computations were performed using the most recent SWAN model version 40.51AB. For wind-wave generation, the setting WESTH was used, which features the combination of wind input and saturation-based whitecapping proposed by Van der Westhuysen (2007). We note that this model version contains improvements over the version 40.51A with respect to whitecapping dissipation over large geographical scales. In particular, the excessive dissipation of low-frequency energy displayed by the Van der Westhuysen et al. (2007) whitecapping formulation has been corrected with version 40.51AB. Quadruplet interactions are modelled using the Discrete Interaction Approximation of Hasselmann et al. (1985). For the sake of reducing the computational effort, the setting IQUAD = 8 has been used for computing the quadruplet interactions. With this setting, interaction contributions are not interpolated over the four surrounding spectral bins, but assigned to the nearest bin. The shallow water source terms include triad interaction according to Eldeberky (1996) using $D_{EB} = 0.05$ and $CUTFR = 2.5$, surf breaking according to Battjes and Janssen (1978) using $\alpha_{BJ} = 1$ and $\gamma_{BJ} = 0.73$. Bottom friction is modelled according to the JONSWAP formulation with $C_{JON} = 0.067$ (Hasselmann et al. 1973). These settings are activated by the following user commands:

```plaintext
GEN3 WESTH
QUAD IQUAD = 8
BREAKING 1.0 0.73
FRICTION JONSWAP 0.067
TRIAD 0.05 2.5
```
Using these settings for model physics as basis, two sets of SWAN simulations were conducted in a coupled mode with the hydrodynamic model, namely nonstationary and stationary simulations. In the discussion below, we will distinguish between a simulation (meaning one application of the model executable with one command file) and a computation (of which there may be several inside a command file). The nonstationary SWAN simulation was activated using the command MODE NONSTAT. For comparable spatial scales as considered here, WL (2006a) and Caires et al. (2006) found that the BSBT numerical scheme (integrated backwards in both space and time), with a computational time step of 10 min, proved to be sufficient to accurately propagate energy through the model domain, and to capture the changing (wind, water level and current) model forcings. In order to ensure numerical accuracy, SWAN performs a number of iterations per time step until convergence is reached. Fraza (1998) demonstrated that under conditions of strong wave growth, three iterations are required per time step to achieve well-converged solutions. Therefore, to assure good convergence, a mandatory three iterations per time step was imposed. This was achieved with the following setting for the default gradient-based convergence criteria:

```
NUM ACCUR 0.010 0.010 0.010 [npnts] = 101.000 NONSTAT [mxitns] = 3
```

It is noted that although this setting deactivates the convergence criterion, the criterion still provides valuable information about the convergence level. With this setting, convergence is tested against a criterion of relative changes in $H_{m0}$ and $T_{m01}$ of 1%.

The stationary (quasi-nonstationary) SWAN simulations were activated using the command MODE STAT, and were performed at intervals of 20 minutes. As in the nonstationary simulation, convergence criteria were applied in the iterative procedure. A number of studies have shown that in stationary simulation the default convergence criteria of SWAN yield insufficiently converged solutions (e.g. Zijlema and van der Westhuysen (2005); Van der Westhuysen et al. 2005; Alkyon 2007a,b), a situation which is improved on by using the curvature-based criteria proposed by Zijlema and Van der Westhuysen (2005). Hence, to ensure a high level of convergence, these latter convergence criteria were applied in the stationary simulations. Based on the recommendation of Alkyon (2007a,b), the following convergence settings were applied:

```
NUM STOPC 0.000 0.010 0.001 [npnts] = 99.50 [mxitst] = 20 [alfa] = 0.001
```

These criteria deviate from the recommendation of Alkyon (2007a,b) in one aspect, namely that a lower maximum number of iterations was applied ([mxitst] = 20). This reduction in number of iterations was made possible by using hotfiles to link successive stationary simulations – the converged stationary model results at a particular time step were stored in a hotfile and used as the initial state for the stationary simulation at the next time step. In this way, the number of iteration required to reach convergence was significantly reduced, so that an upper limit of 20 proved to be sufficient. The effectiveness of these criteria, and also those applied for the nonstationary simulations, will be demonstrated in Section 3.1.

Finally, trial simulations revealed that the stationary model results displayed some small-amplitude oscillation. To reduce this negative iteration behaviour, a small amount of underrelaxation was applied ([alfa] = 0.001). This has the effect of slightly reducing the
spectral updates made from one iteration to the next, thereby enhancing the stability of the simulation. An example of the SWAN input file used can be found in Appendix A.

### 2.4.4 Communication with hydrodynamic model

For the communication between the hydrodynamic and wave model, an interval of 20 minutes has been chosen. This means that SWAN is activated every 20 minutes, and then performs either a nonstationary computation of 20 minutes (with a 10 min time step) or an entire stationary simulation, using the corresponding measured wave spectra as boundary conditions.

Besides the imposed wave spectra, SWAN uses the water levels, currents and bed levels, provided and computed by the hydrodynamic model for that specific time. After the SWAN stationary simulation for one time step, or nonstationary computation for two time steps, the wave results are provided to the hydrodynamic model in order to compute the wave-driven currents, setup and sediment transports. After a 20 minute hydrodynamic computation, the recomputed water levels, currents and bed levels are provided to SWAN again. This exchange frequency of information is kept constant throughout the hydrodynamic simulation.

In order to create a continuous nonstationary SWAN simulation despite the frequent interaction with the hydrodynamic module, the time-dependent wave state is transferred from one 20 minute nonstationary computation period to the next (bridging the communication interval) using a hotfile. At the end of a SWAN computation, wave spectra at every computational grid point (representing the active wave state) are written to a hotfile. However, the variance density at each spectral bin is stored in the hotfile using only four significant numbers, and hence introduce a small rounding error each time a hotfile is used. When applying hotfiles as frequently during the simulation as once in every 20 minutes, the cumulative rounding error can become significant, affecting the higher spectral frequencies in particular. Hence, for the purpose of this study, the accuracy with which the variance density is stored in the hotfile has been increased to six significant numbers. This was achieved with the following alteration in the SWAN source code file swmod2.f. In the module OUTP_DATA, the lines

```fortran
CHARACTER (LEN=40) :: FIX_SPEC  = '(200(1X,I4))'   ! spectral output
INTEGER :: DEC_SPEC  =  4       ! number of decimals for spectral output
```

were replaced by the lines

```fortran
CHARACTER (LEN=40) :: FIX_SPEC  = '(200(1X,I6))'   ! spectral output
INTEGER :: DEC_SPEC  =  6       ! number of decimals for spectral output
```

We note, however, that although the above-mentioned alteration was required for the present study, the use of greater numerical accuracy in the hotfile storage increases the file size of the latter by about 50%.
3 Large-scale model: Results

This section presents the simulation results of the investigation into the large-scale nonstationary simulation with SWAN for the NW storm of 7-9 February 2004, which is considered over a portion of the North Sea and up to the Amelander Zeegat. Section 3.1 presents the results of the flow modelling with the ZUNO model over the southern North Sea. Section 3.2 describes the results of the wave modelling using SWAN, focusing first on the comparison with observations (Section 3.2.2), and thereafter on the differences between the results of nonstationary and stationary simulation (Section 3.2.3).

3.1 Flow model results and wind fields

Figures 3.1-3.3 present the results of the hydrodynamic module of Delft3D obtained in the coupled SWAN-Delft3D model, with SWAN run in nonstationary mode. Figure 3.1 compares the measured and computed water levels at the observation stations Texel Noordzee, Terschelling Noordzee and Wierumergronden (see Figure 2.1). As presented above, the tidal signals at the three stations show a similar tidal variation, with a phase lag of about 2.5 hours between stations Texel Noordzee and Wierumergronden. During the storm period of 7-9 February 2004, a storm surge of 0.5 to 1 m was experienced at these stations. The simulation results of the ZUNO model, which has not been specifically calibrated for the present storm condition, show a good general agreement with the observations (apart from the first 12 hours of spin-up time). In particular, the high simulated water level at the peak of the storm (8 February 2004 at 22:30) shows very good agreement with the observations. These results are therefore considered to be of sufficient accuracy for the present investigation.

Figure 3.2 presents the geographical distribution of the simulated water levels every 6 hours during the storm period. At the storm instants presented, it was consecutively high and low tide at the Wadden Sea, due to the passing of the tidal wave. This figure also shows the high water level in this region at the peak of the storm (8 February 2004 at 22:20), due to the combination of high tide and the storm surge from the NW wind. Figure 3.3 presents the computed current velocity fields at these six storm instants, interpolated onto the wave model grid. Since at the selected storm instants it was either high or low tide in the Wadden Sea, the current velocities are rather low over the wave model domain at these times – maximums of around 1 m/s at Zeeland (southern part of The Netherlands), but only about 0.5 m/s offshore of the Amelander Zeegat.

Figure 3.4 presents the imposed HIRLAM wind field, as interpolated onto the wave model grid. As was seen in Figure 2.3, during the course of the storm, the wind direction turned from SW (7 February 2004 at 22:20) to NW (9 February 2004 at 04:20). Over this period, the strongest wind speeds are initially found over the southwestern part of the wave model domain, but shift towards the northwestern part of the domain as the low-pressure system passes over the Wadden Sea.
3.2 Wave model results

3.2.1 Iteration behaviour and convergence

Figures 3.5 to 3.9 present the convergence behaviour of the nonstationary and stationary models for the computed storm event. Figure 3.5 presents the level of convergence reached during the course of the storm, in terms of the percentage of converged points, given the convergence criteria applied. The four vertical lines included in these figures indicate instants during the storm that will be analysed in more detail below. As presented in Section 2.4.3, the convergence criteria applied for the nonstationary and stationary models differ. For the nonstationary model the gradient-based convergence criteria were applied, whereas for the stationary model the optional (and stricter) curvature-based criteria have been applied. The upper panel of Figure 3.5 shows that the nonstationary model, using three (imposed) iterations per time step, achieved a high level of convergence throughout the simulation period. Except for the start-up phase of the simulation, the convergence criteria were generally met at over 99.5% of the wet computational grid points during the simulation, occasionally dropping to 99%. These periods of somewhat poorer convergence can be correlated with strong changes in the wind forcing (e.g. 8 February 2004 around 06:00) or in the wave boundary condition (e.g. 8 February 2004 around 18:00). In addition, it can be seen that at every second time step the degree of convergence appears to be somewhat lower than at neighbouring instants. These instants of lower convergence correlate with the communication intervals with the hydrodynamic model, when the time step in SWAN is simulated with an updated water level field. The lower panel of Figure 3.5 shows that in the stationary simulation the strict curvature-based criterion was met at over 99.5% of wet grid points during almost the entire modelled period, suggesting a high level of convergence of all the stationary runs.

An alternative way to evaluate the convergence of the simulations is to directly consider the changes in the integral parameters during the iteration process (iteration curves). Figures 3.6 and 3.7 present, for the nonstationary simulation, the iteration behaviour of the significant wave height $H_{m0}$ and mean period $T_{m01}$ as a function of the iteration level at the four wave buoy locations during the storm. These curves present a surface, with on the x-axis the time during the storm period, the y-axis the iteration level and the z-axis the value of the integral parameter, normalised with its value at the last iteration ($H_{m0,i}/H_{m0,i=end}$ and $T_{m01,i}/T_{m01,i=end}$), which in this case was always three. For each instant during the storm along the x-axis, the iteration behaviour can be followed by reading the graph along in the y direction. Figure 3.6 shows that at the start of the simulation the value of the significant wave height varies strongly during the iteration process (white regions denote values of $H_{m0,i}/H_{m0,i=end} < 0.95$). After the first four hours, however, the difference between the iterates after respectively 2 and 3 iterations becomes small, indicating that the parameters values are well-converged after three iterations. Likewise, Figure 3.7 shows that the values of the mean period $T_{m01}$ are also well-converged during almost the entire storm simulation.

Figures 3.8 and 3.9 present the iteration behaviour of $H_{m0}$ and $T_{m01}$ at the four buoy locations for the stationary simulation, using the same presentation as above. In this simulation, a maximum of 20 iterations was set. Figures 3.8 and 3.9 show that at each time step between 10 and 20 iterations were required to fulfil the convergence criteria. Time instants where the values of $H_{m0}$ and $T_{m01}$ vary strongly with the iteration level, and where
more iterations are required for convergence, can again be correlated with strong changes in the wind forcing or in the wave boundary condition. Nonetheless, from the small variation in the integral wave parameters at the end of each iteration process, it can be seen that convergence is reached at almost all time instants during the simulated storm.

### 3.2.2 Comparison with observations

**Spatial results**

Figures 3.10 to 3.12 present the geographical distribution of the nonstationary SWAN results at six instants during the storm. Figure 3.10 shows the spatial distribution of the significant wave height $H_{m0}$ and the mean wave direction (indicated by vector arrows). The distribution of these model results can be seen to reflect the input from the HIRLAM wind fields. The simulated mean wave direction turns from W to NW at the peak of the storm on 8 February 2004 at 22:20. The significant wave heights steadily increase over the model domain during the course of the storm. These are initially the highest over the SW part of the model domain, where K13-Alpha is located, but become higher over the NE part of the domain (at NSB2) towards the end of the storm. Moving toward the northern coastlines of the barrier islands, the significant wave height gradually decreases. As a result, up to the peak of the storm, the computed significant wave heights are consistently somewhat higher at station ELD than at AZB11 at the Amelander Zeegat.

Figure 3.11 presents the mean wave period $T_{m-1,0}$ and the mean direction (arrows) at the same six instants during the storm. Along the NW offshore boundary, the mean periods increase from $T_{m-1,0} = 6-8$ s to 8-11 s during the course of the storm, reaching a peak value of $T_{m-1,0} = 11$ s at the NSB2 station at 9 February 2004 at 04:20. The spatial distribution of the mean wave period during the simulation period can be seen to resemble that of the significant wave height. Moving from the offshore boundary toward the barrier island coast and the nearshore stations ELD and AZB11, the simulated mean periods decrease somewhat, to values that vary between $T_{m-1,0} = 6$ and 9 s during the course of the storm.

Figure 3.12 presents the computed directional spreading and the mean direction (arrows) at the six selected instants during the storm. During the storm, directional spreading values of between 25° and 35° are found offshore of the Wadden Sea. In the offshore, initially high values of the directional spreading (35°) reduce to about 25° towards the end of the storm. Considering the spatial distribution of the directional spreading, higher values of this parameter are found at the offshore stations K13-Alpha and NSB2, and lower values, of about 25°-30°, are found along the barrier islands at ELD and AZB11.

It is noted that in this simulation typical CFL values ranging from 5 at the offshore boundary to high values of 50 along the Wadden Islands were found. However, since the spatial propagation was calculated using the BSBT numerical scheme in SWAN, and since the curvature ($\frac{\partial^2 N}{\partial x^2}$) in the computed wave field is low, these high CFL values are not expected to adversely affect model accuracy.

**Time series and wave spectra**

Figures 3.13 to 3.16 present a comparison between the simulated and observed time series of the main wave field parameters, computed from the wave spectra over the frequency
The four vertical dotted lines in these figures denote storm instant where the differences between the nonstationary and stationary model results will be investigated in detail (see Section 3.2.3 below). Figure 3.13 compares the significant wave height results of the nonstationary and stationary simulation modes of SWAN with the observations at the stations K13-Alpha, NSB2, ELD and AZB11. The former two stations were used as boundary values, so that the model results match them closely. It can be seen that the significant wave heights at the nearshore stations ELD and AZB11 are generally underestimated by both the nonstationary and stationary modes of SWAN. At the peak of the storm, SWAN underestimates the observed $H_{m0}$ at stations ELD and AZB11 by about 1 m out of 5 m. This strong underestimation may be related to the finding that the computed HIRLAM winds underestimates observed wind speeds at the storm peak (Section 2.1.2). It may also point to inaccuracies in the model physics. Another salient feature of this comparison is that the stationary model generally produces similar levels of significant wave height as the nonstationary model, but that it does not reproduce the observed phase lag between storm peak at respectively the offshore stations K13-Alpha and NSB2, and the nearshore stations ELD and AZB11. In the stationary model, the storm peak occurs simultaneously at K13-Alpha, ELD and AZB11. As a result, the stationary model produces larger significant wave heights than the nonstationary model over the period leading up to the observed storm peak at AZB11, and smaller values than the nonstationary model after the observed storm peak. We note that this result agrees with those of WL (2006a) and Rogers et al. (2007), found for other shelf sea applications.

Figure 3.14 compares mean period ($T_{m-1,0}$) results of the nonstationary and stationary simulation modes of SWAN with the observations. For both simulation modes SWAN reproduces the spectra at the buoys K13-Alpha and NSB2 well, indicating that the wave boundary values are properly imposed in terms of mean period. It can be seen that at the AZB11 buoy both the nonstationary and the stationary models underestimate the observed mean period at the peak of the storm (8 February 2004 at 22:20). The underestimation by both the nonstationary and stationary models is of the order 1.0-1.5 s. No information of the mean wave period $T_{m-1,0}$ is available for ELD.

Figure 3.15 compares mean direction computed by the nonstationary and stationary simulation modes of SWAN with the observations. The computed mean direction at the offshore stations K13-Alpha and NSB2 correspond well with the observations, indicating that the boundaries are properly imposed. At the nearshore stations ELD and AZB11, the results of the nonstationary and stationary simulations are quite similar. They both agree well with the observations, which show a gradual change of the mean wave direction from SW to NNW during the storm.

Figure 3.16 compares the directional spreading produced by the nonstationary and stationary simulation modes of SWAN with the observations. As described in Section 2.1.3, the directional spreading observed at the NSB2 station was imposed as model input both here and at the offshore station K13-Alpha. These observed values decrease from about 35º at the start of the storm period to about 25º beyond the peak of the storm. In Figure 3.16 it can be seen that the results of both the nonstationary and stationary models match these observed quite well, indicating that the offshore model boundary is properly imposed. Moving to the nearshore, the directional spreading was only recorded at the AZB11 buoy at the Amelander Zeegat. Here directional spreading values of around 40º were observed during the entire storm. It can be seen that at this location the results of the nonstationary and stationary
models are similar, but that they both consistently underestimate the observed directional spreading by 10-15°.

Figure 3.17 compares the simulated and observed wave spectra at the stations NSB2 and AZB11, at three instants around the peak of the storm. The observations of the NSB2 buoy are plotted up to the frequency at which these were recorded, which was between 0.2 and 0.25 Hz at the peak of the storm. For this buoy, the results of the nonstationary and the stationary simulation modes are similar, and both agree well with those of the observations up to 0.25 Hz. At the buoy AZB11, off the Amelander Zeegat, it can be seen that variance density levels at the spectral peak are underestimated by both the nonstationary and stationary modes of simulation (especially at 8 February 2004 at 22:30). This corresponds to the underestimation in significant wave height and mean period seen in Figures 3.14 and 3.15 above. Considering the mean direction and the directional spreading at AZB11, the results of the nonstationary and stationary simulations are again similar, and both agree well with the observations.

3.2.3 Differences between nonstationary and stationary model results

Figures 3.18 to 3.21 present the spatial difference plots between the results of the nonstationary and stationary simulation results of SWAN at four instants around the peak of the storm. These four storm instants correspond to the times denoted by vertical lines in Figures 3.13 to 3.16 above. Figure 3.18 presents the difference plot between the significant wave height results produced by the nonstationary and stationary simulation modes. It can be seen that ahead of the storm peak, on 8 February 2004 at 10:20, the nonstationary model produced about 4% higher significant wave heights than the stationary model in the region offshore of the Wadden Sea. Six hours before the storm peak (at 16:20), however, the significant wave heights produced by the nonstationary model are about 12% lower than those of the stationary model. As described in Section 3.2.2 above, this difference can be ascribed to the result that the stationary model does not reproduce the time lag between wave conditions offshore and nearshore. In addition, the wave model also generates energy internally from the imposed wind field. The stationary model instantaneously reaches the fetch-limited (infinite duration) state, so that in growing seas, it will tend to respond too rapidly to changes in the wind, showing more energy than the nonstationary model. At the peak of the storm (at 22:20), the differences between the nonstationary and stationary results have reduced to about 4% in the region of the Amelander Zeegat. At this time, the nonstationary model produced 14% lower \( H_{\text{m0}} \) values than the stationary model over the German Wadden Sea, where a new storm peak was growing. Beyond the peak of the storm, on 9 February 2004 at 04:20, the differences between the nonstationary and stationary models decrease again to around 5%.

Figure 3.19 presents the corresponding difference plots for the mean period at the four storm instants. It can be seen that, in general, the differences in the mean period produced by the nonstationary and stationary simulation modes display the same pattern as that of the significant wave height presented above. At the start of the storm, the mean period results of the nonstationary and stationary models are comparable. However, as with the significant wave height, it can be seen that just ahead of the storm the nonstationary model produces lower mean periods than the stationary model. At the peak of the storm, the largest differences between the mean periods are found over the German Wadden Sea. At the time
instant 9 February 2004 at 04:20, after the peak of the storm, the results of the nonstationary and stationary models become comparable again.

Figure 3.20 presents the difference in the mean direction results produced by the nonstationary and stationary models. From this figure it can be seen that the spatial distributions of mean direction produced by the nonstationary and stationary models are comparable, differing by up to 10° only in isolated regions. Figure 3.21 presents the differences in directional spreading produced by the nonstationary and stationary models. As with the mean direction, it can be seen that the differences between the results of directional spreading between the two simulation modes are minimal.

### 3.2.4 Conclusion

From the results presented in this section, it can be concluded that when simulating on the scale of the entire Dutch coast and a portion of the North Sea, the simulation results of the nonstationary and stationary modes are generally rather similar. A notable difference between the results of these two simulation modes is the absence of a phase lag between offshore and the nearshore wave conditions in the case of stationary simulation (particularly evident in the significant wave height). However, a salient feature of the results of both the nonstationary and the stationary model results is an apparent strong underprediction of the significant wave height at the nearshore buoy locations ELD and AZB11, and an underestimation of the mean wave period at AZB11. These errors may be related either to the sub-optimal quality of the computed wind fields used in the simulation, or to underlying inaccuracies in SWAN.
This section and Section 5 considers nonstationary simulation on the scale of the Amelander Zeegat, and is based on a recent coupled hydrodynamic, wave and morphology study by WL (2007), of which the basic model set-up was re-used. The study of WL (2007) was conducted for a different storm event than that considered in Sections 2 and 3 above, namely a W storm recorded during 1-3 January 2005. Section 4.1 presents the environmental conditions for this storm event. Sections 4.2 to 4.4 describe the setup of the hydrodynamic model and the setup of the wave model. Finally, Section 4.5 presents the morphological model used to compute bottom changes.

### 4.1 Storm conditions

For the hindcast on the scale of the Amelander Zeegat, the W storm of 1-3 January 2005 was selected. This storm has the following characteristics: Around New Years Eve a cold front passed the Dutch coast, after which a western wind developed of 8 Bft in the southern North Sea and 9 Bft above the Wadden Sea. During 2 January, the wind remained stormy and started to decrease to 6 Bft in the morning of the 3rd January. The westerly storm caused significant increase of the water levels in the northern coastal areas, with a maximum additional water level of 1.54 m at Harlingen. Measured water levels, and wind and wave conditions are available for this storm period, as well as computed spatially varying wind and pressure fields. Details of these various sources of data are given in the sections below. The locations of these various stations are presented in Figure 4.1, and details of their coordinates are given in Table 4.1.

<table>
<thead>
<tr>
<th>Observations station</th>
<th>Type of observation</th>
<th>X (m RD)</th>
<th>Y (m RD)</th>
<th>Depth (m NAP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AZB11</td>
<td>Waves</td>
<td>161 250</td>
<td>613 500</td>
<td>-19</td>
</tr>
<tr>
<td>AZB12</td>
<td>Waves</td>
<td>164 990</td>
<td>614 010</td>
<td>-19.5</td>
</tr>
<tr>
<td>AZB21</td>
<td>Waves</td>
<td>167 200</td>
<td>610 400</td>
<td>-11</td>
</tr>
<tr>
<td>AZB22</td>
<td>Waves</td>
<td>167 610</td>
<td>610 400</td>
<td>-11.3</td>
</tr>
<tr>
<td>AZB31</td>
<td>Waves</td>
<td>169 380</td>
<td>607 320</td>
<td>-9.2</td>
</tr>
<tr>
<td>AZB32</td>
<td>Waves</td>
<td>169 450</td>
<td>607 110</td>
<td>-9.1</td>
</tr>
<tr>
<td>AZB41</td>
<td>Waves</td>
<td>171 340</td>
<td>604 400</td>
<td>-16.7</td>
</tr>
<tr>
<td>AZB42</td>
<td>Waves</td>
<td>171500</td>
<td>604250</td>
<td>-17.6</td>
</tr>
<tr>
<td>AZB51</td>
<td>Waves</td>
<td>174 290</td>
<td>601 500</td>
<td>-6.9</td>
</tr>
<tr>
<td>AZB52</td>
<td>Waves</td>
<td>175 600</td>
<td>600 820</td>
<td>-13.4</td>
</tr>
<tr>
<td>Terschelling Noordzee</td>
<td>Water level</td>
<td>151 400</td>
<td>606 250</td>
<td>-</td>
</tr>
<tr>
<td>Nes</td>
<td>Water level</td>
<td>179 810</td>
<td>604 920</td>
<td>-</td>
</tr>
<tr>
<td>Vlieland</td>
<td>Wind</td>
<td>123 800</td>
<td>583 850</td>
<td>-</td>
</tr>
<tr>
<td>Lauwersooog</td>
<td>Wind</td>
<td>208 850</td>
<td>602 790</td>
<td>-</td>
</tr>
<tr>
<td>Huibertgat</td>
<td>Wind</td>
<td>221 990</td>
<td>621 330</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 4.1: Location of observations stations for the Amelander Zeegat simulation
4.1.1 Water levels

Water levels were measured at two stations in the study area: Terschelling Noordzee and Nes (see Figure 4.1). The exact coordinates are given in Table 4.1. The measured water level elevations at both locations are presented in Figure 4.2. It is evident that the tidal range inside the tidal basin (Nes) is comparable to that at Terschelling Noordzee, with a phase lag of about 1.5 hours. However, due to the greater storm surge, the total water level at Nes reaches higher than at Terschelling Noordzee.

4.1.2 Wind and pressure conditions

Spatially varying HIRLAM wind fields, provided by RIKZ, were used in the flow and wave modelling. The HIRLAM data was computed on an 11 km grid, with a time interval of 6 hours. Figure 4.3 shows the spatial variation of the wind speed and direction of the HIRLAM wind fields for 1-3 January 2005.

Figure 4.4 shows the wind speeds and directions of the wind at Huibertgat, Lauwersoog and Vlieland during the storm. See Figure 1.1 for the orientation of these stations in relation to the Amelander Zeegat. The direction during the storm period varies between 190 and 290 degrees (nautical). For all locations it holds that the wind speed increases during January 1 from about 3m/s up to the maximum occurring wind speed during the storm. This maximum differs for each location. For Vlieland, located west of the inlet, wind velocities of 22 m/s during the peak of the storm were measured. The maximum occurring wind velocity for the stations east of the Amelander Zeegat was around 20 m/s.

4.1.3 Wave conditions

Ten wave buoys were located in the area of interest, of which two (AZB21 and AZB22) did not collect any relevant data. The locations of the wave buoys are shown in the lower panel of Figure 4.1, and their coordinates and corresponding depths are summarised in Table 4.1. The measured wave heights at the eight operational locations are presented in Figure 4.4 for the period between 1 and 5 January 2005.

Four of the remaining eight wave buoys (AZB11, AZB12, AZB31 and AZB41) were directional wave riders, which provide a directional variance density spectrum as well as a mean direction and directional spreading per frequency bin at every ten minutes. The remaining four wave buoys (AZB32, AZB42, AZB51 and AZB52) are non-directional wave riders. The measured spectra are provided as energy density, mean wave direction and directional spreading as function of frequency. These frequencies are linearly distributed between 0.01 Hz and 0.5 Hz with a resolution of 0.01 Hz.

The measured values of $H_{m0}$ are presented in Figure 4.5 for each of the eight wave buoys separately. The maximum occurring wave height of 6.3 m is measured at buoy AZB11. Along the propagation of this wave towards the inlet the wave height decreases to 2.3 m at AZB31. Further inside the inlet (AZB51) the wave heights decrease to 1 m during the peak of the storm. At the shallower locations, the wave height clearly follows the tidal cycle.
4.2 Coupled flow and wave modelling

For the investigated model domain, the coupling between the hydrodynamic and wave modelling were conducted with the same coupled system as described in Section 2, using the Delft3D modelling suite. The setup of the hydrodynamic and wave models for the Amelander Zeegat model domain, which is based on that used by WL (2007), is described in Sections 4.3 and 4.4 below. In addition to flow and wave modelling, morphological changes were also considered for this model domain. The schematization of the morphological model is presented in Section 4.5.

4.3 Hydrodynamic model setup

4.3.1 Grid and bathymetry

The computational grid of the hydrodynamic model is shown in Figure 4.6 and is based on Roelvink and Steijn (1999). The grid in the Wadden Sea covers the area up to the two watersheds (west and east) and is extended in nearshore direction towards the Frisian dikes.

The topography of the Amelander Zeegat is rather complex due to the presence of several channels and flats. The main channel is the Borndiep, which is sheltered by a large ebb delta (the Bornrif, see Figure 4.1). The channels and flats in the Amelander inlet are constantly moving. There is a cyclic pattern visible in the inlet, with a morphologic period of about 50 to 60 years. The cyclic patterns develop from a one-channel system in a two-channel system and back into a one-channel system. The bathymetry used in the simulations was composed from various available data sets, as described in WL (2007).

4.3.2 Boundary conditions

Three open boundaries are located outside the Amelander inlet, offshore of Terschelling and Ameland. The remaining boundaries are set as closed boundaries for flow as well as for sediment. From the three boundaries, the offshore boundary is prescribed as a water level type of boundary condition. The water level is forced with astronomical components. The two lateral boundaries are prescribed as Neumann boundaries, meaning that instead of a pre-defined water level, alongshore water level gradients are imposed at the lateral boundaries. The alongshore gradient is assumed to be the same over the entire length of the lateral boundary, since with a limited cross-shore extent the gradient will not vary much in cross-shore direction. Additionally to the tidal components prescribed at the alongshore boundary, the measured surge levels at station Terschelling Noordzee are added uniformly along the boundaries. This enables Delft3D-FLOW to include a surge level in the results without using an overall larger scale model to provide wind setup at the boundary conditions.

The wind and pressure fields applied in the model are derived from the HIRLAM fields. This data, delivered by RIKZ, has a frequency of six hours. As the time step of the hydrodynamic computation is a fraction of the six hours time step of the HIRLAM fields, the data is interpolated in between.
We note that Alkyon (2007c) has recently shown that during strong westerly storms in the Wadden Sea, winds can generate large-scale northeasterly-directed flow through the Wadden Sea, which dominates over the flow pattern obtained by astronomical forcing. The modelling approach followed in the present study, in which the flow remains within the watersheds of the tidal basin (based on flow patterns under astronomical forcing), may therefore produce unreliable estimates of current flow in the tidal inlet.

### 4.3.3 Model settings

The hydrodynamic time step is set at 15 seconds which fulfils the Courant number criteria for free surface waves. Furthermore, the hydrodynamic model is run in depth averaged mode. The bed roughness is prescribed with a Chézy coefficient of $63 \text{ m}^{1/2}/\text{s}$ for the hydrodynamic simulations. For the morphodynamic simulations, the bed roughness predictor model has been activated which results in a time- and space-varying roughness field.

### 4.4 Wave model setup

#### 4.4.1 Boundary conditions

For the simulations on the scale of the Amelander Zeegat (storm of 1-3 January 2005), the observed wave spectra at the two most offshore wave buoys (AZB11 and AZB12) were used as boundary conditions for the wave model. These wave buoys provided wave energy density spectra at every ten minutes during the storm period considered. However, since this wave data consists of frequent relatively large differences in wave heights from one measurement to the next, a three-point running average was applied to the wave data, so that 20 minute-averaged spectra were used as input. Along the northern (offshore) boundary of the domain west of AZB11 the measured spectra of AZB11 have been imposed uniformly. East of AZB12 the measured spectra of AZB11 have been applied. For the area between the buoys of AZB11 and AZB12, SWAN interpolates the components of the spectra linearly. Along the western and eastern cross-shore boundaries (at sea), the spectra of AZB11 and AZB12, respectively, are imposed uniformly.

Along the open lateral boundaries in the Wadden Sea interior, located along the shallow watersheds (Dutch: ‘wantij’), no wave boundary values are imposed. This is considered a reasonable approximation for two reasons. Firstly, due to the limited water depth over these watersheds, little wave energy can penetrate over them. Secondly, as will be shown in the simulation results, the boundaries are placed sufficiently far away from the locations of interest, and the local depth-limited wave growth in the model domain sufficiently dominant, as to not affect the model comparisons.
4.4.2 Model settings

The wave simulations on this domain were performed using SWAN version 40.51A, since this version has been applied in a number of recent (stationary) hindcast studies in the Amelander Zeegat (e.g. Royal Haskoning 2007; WL & Alkyon 2007). The computational grids for the SWAN simulation are shown in Figure 4.6. For wind-wave generation, the setting WESTH was used, which features the combination of wind input and saturation-based whitecapping proposed by Van der Westhuysen et al. (2007). For this relatively small model domain, the differences in physical formulations between versions 40.51A and 40.51AB are negligible. The remaining settings for model physics are identical to those described in Section 2.4.3 above.

As was done for the simulations over the large-scale domain presented in Sections 2 and 3, two sets of simulations were conducted, namely nonstationary and stationary simulations. The numerical settings used for these two sets of simulations are based on those described in Section 2. The same time steps as used above are applied in both the nonstationary (time step = 10 min) and stationary (time interval = 20 min) models, but the convergence criteria and numerical updating have been altered. For the nonstationary simulation mode, the number of imposed iterations per time step was doubled to six. This alteration has been made since it was found that, particularly in the shallower regions in the Wadden Sea, more than three iterations are required for convergence (see Section 5.2.1 below). Therefore, the following setting of the convergence criteria was used:

```
NUM ACCUR  0.010  0.010  0.010  [npnts] = 101.000  NONSTAT  [mxitns] = 6
```

For the stationary simulation mode, the same convergence criteria as described in Section 2 have been used. However, for this model domain and forcings, initial simulation results did not suggest the need to apply underrelaxation (see p. 2-6). Therefore, the following numerical settings were applied:

```
NUM STOPC  0.000  0.010  0.001   [npnts] = 99.50   [mxitst] = 20
```

As was done in Section 2, the maximum number of iterations was limited to 20, which was again made possible by using hotfiles to link successive stationary simulations. As will be shown in Section 5.2.1 below, this mode of operation ensured a high level of convergence during most of the simulation period. However, the strict curvature-based convergence criteria were not met for this complex geographical region. Therefore, at the three instants during the storm that were used for the detailed comparison with the nonstationary mode, the simulation was continued up to a maximum of 50 iterations. An example of the SWAN input file used can be found in Appendix B.

4.4.3 Communication with hydrodynamic model

The communication between the SWAN simulations and the hydrodynamical model were set up similarly to the coupling described in Section 2.4.4, including the use of the increased precision hotfiles. As above, the information exchange between the wave and hydrodynamical modules occurred every 20 minutes.
4.5 Morphological model

4.5.1 Sediment transport formulae

In order to compute bed level changes during the storm period, the sediment transports need to be calculated. In this study, the state-of-the-art formulation of Van Rijn, called TR2004, has been applied (van Rijn, 2004).

This formulation categorizes sediment transport not only into bed load and suspended load transport, but also distinguishes current-related transport and wave-related transport. TR2004 uses the advection-diffusion equation to calculate the current-related transport. The depth-averaged concentration in this advection-diffusion equation is determined using the method of Galappatti. Van Rijn developed a bed load transport formula in which both the wave-related and current-related bed load transports are included. The influence of waves is included in this formula by modifying the bed shear stress based on a new approach. TR2004 also accounts for suspended transport due to wave-asymmetry. This transport component can be significant in the shallow areas. The wave-related suspended transport is added as an extra component to the bed load transport.

An additional feature in TR2004 is a bed roughness predictor. By applying this predictor, the bed roughness does not have to be pre-defined, but is calculated at every time step. Van Rijn relates the roughness to the grain size in case of small-scale ripples and to the form roughness in case of mega-scale ripples and dunes. The mobility parameter is also considered in the approach to predict the ripple dimensions. On the basis of the mobility parameter the prevailing wave-flow regime is determined.

4.5.2 Sediment characteristics and bed updating

Available data indicates that the sediment diameter (D50) varies from 220-260μm on the intertidal beach to 150-160μm in the lower shoreface (Guillen and Hoekstra, 1996). In the model the sediment diameter is prescribed uniformly at 200μm.
5 Amelander Zeegat model: Results

This section presents the simulation results of the investigation into the use of nonstationary simulation in the Wadden Sea. Section 5.1 presents the results of the flow modelling in the Amelander Zeegat. Section 5.2 describes the results of the wave modelling using SWAN, focusing first on the comparison with observations (Section 5.2.2), and thereafter on the differences between the results of nonstationary and stationary simulation (Section 5.2.3).

5.1 Flow model results

Figures 5.1-5.3 present the results of the hydrodynamic module of Delft3D obtained in the coupled SWAN-Delft3D model. Figure 5.1 compares the measured and computed water levels at the observation stations Terschelling Noordzee and Nes. The observed water level signals show a clear tidal variation and a storm surge over the storm period under consideration. Since the station Terschelling Noordzee is close to the offshore boundary where the tidal signal and surge level are imposed, the computed signal match the observations closely here. The agreement between model results and observations is somewhat poorer at the station Nes, situated behind Ameland, with underestimations of up to 25 cm. These results are however considered to be of sufficient accuracy for the present investigation.

Figure 5.2 presents the geographical distribution of the water level during the storm. Over the period 01/01/2005 at 06:00 to 02/01/2005 at 06:00, a strong increase in the mean water level in the Wadden Sea as a result of the storm can be seen. Figure 5.2 also gives details of the tidal cycle of 06:00 to 18:00 on 02/01/2005. Firstly the storm instant 10:00 is shown, which feature high water levels offshore of the barrier islands, resulting in flooding of the Wadden Sea. At 12:00, the tidal high is reached, with comparable water levels inside and offshore of the Wadden Sea. At 17:00, the third storm instant considered, water levels in the Wadden Sea exceed those offshore, leading to ebb conditions.

Figure 5.3 presents the current velocity fields corresponding to the three storm instants discussed above. The storm instant of 10:00 on 02/01/2005 results in a strong flood current through the Amelander Zeegat towards the Wadden Sea, reaching a maximum of 1.7 m/s. At slack tide (12:00), current velocities in the inlet are reduced to about 0.5 m/s. At 17:00, a strong offshore-directed ebb current is found, reaching a maximum of about 1.7 m/s.

5.2 Wave model results

5.2.1 Iteration behaviour and convergence

Figures 5.4 to 5.8 present the iteration behaviour and the degree of convergence of the nonstationary and stationary simulation modes of SWAN for the storm event in the Amelander Zeegat under consideration. Figure 5.4 presents the level of convergence of the two simulation modes in terms of the number of converged wet points, given the selected iteration criteria. The three vertical dotted lines in these figures denote storm instant where
the differences between the nonstationary and stationary model results will be investigated in detail (see Section 5.2.3 below). In the top panel of Figure 5.4 it can be seen that, according to the gradient-based convergence criteria applied, high levels of convergence are reached in the nonstationary simulation. During the most energetic part of the storm (after 02/01/2005 at 00:00), a general level of more than 99.5% converged points are maintained. As found in Section 3.2.1 above, the percentage of converged points in the nonstationary simulation can be seen to drop somewhat at distinct times during the storm. For this model domain, these instants can be correlated with times of strongly changing wind forcing (e.g. 01/01/2005 at 22:00, see also Figure 4.4), but in particularly - in this shallow water region - with the tidal variation. Comparison with Figure 4.2 reveals that these intervals of reduced convergence agree with periods of rising tide during the simulated period, when the wave condition is adapting to the greater water depth. Apart from these larger-scale corrections of the wave field, the degree of convergence can also be seen to vary on a short time scale of every second time step. As found in Section 3.2.1 above, this phenomenon is due to the update of the water level from the hydrodynamic model at every second time step.

The lower panel of Figure 5.4 presents the number of converged points during the stationary simulation. It can be seen that in part due to the stricter convergence criteria applied in the stationary simulation, the number of grid points considered to be converged are generally lower than in the nonstationary simulation. Up to 02/01/2005 at 00:00, the percentage of converged points is rather low (down to 75%). Over the energetic part of the storm (02/01/2005 to 03/01/2005), the percentage of converged points is consistently greater than 97%, although never reaching the 99.5% specified by the convergence criteria.

To obtain a more equal comparison between the degree of convergence of the nonstationary and stationary models, the normalised iteration behaviour of the significant wave height and mean period are considered. Figures 5.5 to 5.8 present surfaces of iteration curves in time relative to the 6th iteration, similar to those presented in Section 3.2.1 above. Figures 5.5 and 5.6 present the iteration behaviour of the nonstationary simulation, for four buoy locations in the Amelander Zeegat (AZB1, 31, 41 and 51), and at a location in front of the Frisian coast (on Transect A, see Figure 5.19a). From the flat iteration curves at the buoy locations in Figures 5.5 and 5.6, it can be seen that, at these locations, the nonstationary model is generally converged after the first or second iteration. However, at Transect A, in the shallow region along the Frisian coast, the iterations curves are periodically steep, indicating that many iterations are required to reach convergence. As mentioned above, these episodes can be correlated to variations in water level. Comparison with Figure 4.2 shows that over periods of ebb (falling water level) the significant wave height decreases from a high initial value to a lower converged value. The opposite is found during periods of flood. These events are repeated with intervals of about 12 hours. The mean period (Figure 5.6) displays similar iteration patterns at Transect A, although less pronounced than the significant wave height. Six iterations per time step appear to sufficient to allow for this convergence process.

Figures 5.7 and 5.8 present the iteration behaviour for the stationary simulation mode. It can be seen that throughout the simulation the upper limit of 20 iterations are used, since the convergence criteria are never quite met (compare Figure 5.4, lower panel). Figure 5.7 shows that strong iteration activity in the significant wave height is found at the offshore buoy AZB11 (where the model in adjusting to the boundary values) and at Transect A along the Frisian coast. Similar patterns can be seen in the iteration behaviour of the mean period
(Figure 5.8). However, it can be concluded that at the locations considered the model is sufficiently converged after 20 iterations during almost the entire simulation period.

### 5.2.2 Comparison with observations

#### Spatial results

Figures 5.9 to 5.11 present spatial plots of the nonstationary model results for the significant wave height, mean period, mean direction and directional spreading at various instances during the storm of 1-3 January 2005. Figure 5.9 shows that, on the North Sea side of the barrier islands, the significant wave height increased from $H_{\text{m0}} = 1$ m to 6 m during the course of the storm. This increase in wave energy occurred simultaneously with a shift in the mean wave direction (indicated by vector arrows, with lengths scaled with the significant wave height) from W to NW, which reflects the change in wind direction during the storm from SSW to W, taking into account refraction on the shallow regions offshore. Throughout the storm, the wave energy arriving from the North Sea is strongly reduced over the ebb tidal delta. As a result, wave conditions in the Wadden Sea interior are dominated by local wind wave growth.

Figure 5.10 presents the progression of the mean wave period $T_{m-1,0}$ and mean direction (arrows) during the course of the storm. It can be seen that on the North Sea side of the barrier islands, the mean wave period $T_{m-1,0}$ increases from 4 s to about 9 s at the peak of the storm. In the Wadden Sea interior, where the wave conditions are locally generated, the mean wave period $T_{m-1,0}$ increases from less than 1 s to around 4 s at the buoy locations at the peak of the storm. Figure 5.11 presents spatial plots of the directional spreading and mean direction (arrows) over the storm period. It can be seen that, offshore of the barrier islands, the simulated directional spreading is initially greater than 40° (up to 01/01/2005 at 18:00), reduces to about 20° at the peak of the storm (01/02/2005 at 06:00), and increases again to 30° by 01/02/2005 at 17:00. The initially high values for the directional spreading can be related to the strong change in the wind direction and hence the wave direction at the start of the storm period. In the lee of the barrier islands and downwind (to the east) of the ebb tidal delta, the directional spreading is large, presumably due to the mixed sea states (low frequency waves from NW and younger waves from SW) found here.

In this simulation, typical CFL values of 50-70 were found in the model domain. Since, particularly in the region of the tidal gap, the curvature ($\partial^2 N/\partial x^2$) in the computed wave field is high, these high CFL could suggest some diffusion of the solution locally. However, in the Wadden Sea interior and along the Frisian coast negligible diffusion is expected to occur, because of the low overall gradients there.

#### Time series results

Figures 5.12 to 5.15 compare the time series plots of the computed nonstationary and stationary model results and observations at the buoy stations AZB11, AZB31, AZB41 and AZB52. Figure 5.12 shows that at AZB11 the results of the nonstationary and stationary model runs fit the observations well, indicating that in terms of total energy the wave boundary values are properly imposed. Moving into the tidal inlet, at station AZB31, the observed wave heights reduce strongly, they also become modulated with a period of about 12 hours. Comparison with Figure 5.1 reveals that for this depth-limited location the
modulation originates from the tidal variation, with the highest values found at high tide. At the AZB31 buoy, the results of both the nonstationary and stationary model runs agree rather well with the observations. Moving further into the inlet, at stations AZB41 and AZB52, the agreement between the model results and the observations deteriorates. Both the model results and observations remain modulated, but the $H_{m0}$ values of both the nonstationary and stationary simulations lie about 0.5 m above the observations during the simulated period. By contrast, the differences between the nonstationary and stationary results at these two stations are quite small by comparison. However, particularly at high tide, the stationary model results are higher than those of the nonstationary model.

Figure 5.13 presents a comparison between the time series results of the simulated and observed mean period $T_{m1,0}$ at the stations AZB11, AZB31, AZB41 and AZB52. At the station AZB11, both the nonstationary and stationary model results closely follow observed $T_{m1,0}$ values, indicating that the boundary values are adequately imposed in terms of mean period. Moving into the tidal inlet and the Wadden Sea interior, however, the correspondence between the model results and the observations reduces. At station AZB31, the nonstationary and stationary model results both underestimate the observed values by about 1.5 s. At station AZB41 in the Wadden Sea interior, both sets of model results display a strong (overestimated) modulation about the observed values. At AZB52, an equally underestimated modulation is found in the computed mean periods, but also a general overprediction of the observations. At both AZB41 and AZB52, the modulation in the results of the nonstationary model is marginally less than that produced by the stationary model. As found above, this modulation in the mean period is correlated with the tidal current through the inlet.

Figure 5.14 compares the time series results of the simulated and observed mean direction at the four buoy locations. At the offshore buoy AZB11, the agreement between the nonstationary and stationary model results and the observations is again very good over the duration of the storm, from 02/01/2005 onwards, indicating adequate boundary conditions with respect to wave direction. At the inshore stations AZB31, AZB41, the agreement between the model results and observations are less good, with differences up to about 30°. With reference to Section 4.3.2, we note that these inaccuracies may, in part, be due to inaccuracies in the flow field modelling. No directional information was measured at AZB52. By comparison, the differences between the nonstationary and stationary model results are small. As in the model results of the significant wave height and mean period, the model results of mean direction show a modulation that is related to the tidal current. A similar modulation is found in the observations at AZB41. Figure 5.15 presents the time series results of the simulated and observed directional spreading at the four buoy locations considered. At the offshore buoy location AZB11, the nonstationary and stationary model results closely follow the observations, which vary between 50° and 20°. The agreement between the model results and the observations gradually deteriorates moving into the Wadden Sea (see stations AZB31 and AZB41). At station AZB31, the agreement between model results and observations are good, although the model results again display an exaggerated current-induced modulation about the observed values. At the station AZB41, both the nonstationary and stationary model results underestimate the observations. By contrast, the differences between the results of the nonstationary and stationary models are small by comparison.
Wave spectra

Figures 5.16 to 5.18 compare the observed and simulated frequency spectra of all the buoy locations at three instants (flood, slack and ebb) at the peak of the storm. At four of the buoy locations, directional information is also available. The top rows of Figures 5.16 to 5.18 show good agreement between the model results and the observations at the locations AZB11 and AZB12 near the model boundary. The remaining panels of Figures 5.16 to 5.18 present the model results of frequency spectra in the tidal channel. Figure 5.16 shows, for the flood condition, that at the stations AZB21 and AZB22 the nonstationary model yields somewhat higher levels of energy density, whereas at the stations AZB31, AZB32, AZB41 and AZB42 the nonstationary model results are somewhat below those of the stationary model. For the buoys AZB31, AZB32, AZB41 and AZB42, the agreement between the model results and the observations is generally good in terms of energy levels. However, at these stations the low frequency peak tends to be underestimated, which at station AZB41 is coupled with a significant underestimation of the (very large) observed directional spreading at these low frequencies. It has been noted by one of our reviewers that buoys often register such large values of the directional spreading at low frequencies. These values may be due to noise in the directional data, which is common when the signal is low. In addition, as was seen in the time series results, the prediction of the mean direction is rather poor. At stations AZB51 and AZB52, both the nonstationary and the stationary models overestimate wave growth in the following current.

Figure 5.17 shows that for the slack tide storm instant the agreement between the model results and the observations is generally good. For this instant, the energy levels of the spectra at AZB41, AZB42, AZB51 and AZB52 produced by the stationary simulation are higher than those of the nonstationary simulation, so that here the stationary model results agree better with the observations. Figure 5.18 shows that at ebb tide the results of the nonstationary and stationary models at AZB31 and AZB32 are quite comparable and that fair agreement with observations is found (apart from the low-frequency spectral peak, which is again underestimated, and some inaccuracy in the directional characteristics). However, at the buoys AZB41, AZB42, AZB51 and AZB52 wave growth is strongly overestimated in the opposing ebb current. This agrees with the results of previous stationary hindcast studies (WL & Alkyon 2007, Royal Haskoning 2007). At these buoys, the energy levels produced by the nonstationary model is consistently lower than those of the stationary model, which reduces the large difference with the observations somewhat.

5.2.3 Differences between nonstationary and stationary results

In the previous section, the results of the nonstationary and stationary model simulations were compared with observations with respect to temporal variation of integral parameters and also directional and frequency spectra. This comparison showed, with a few notable exceptions, a generally good comparison between the results of these models and observations, giving confidence in the results of these models. The present section undertakes a more detailed comparison of the results produced by the nonstationary and stationary modes of operation, by considering spatial difference plots and results along an output transect, defined along the Frisian coast.
Figures 5.19 to 5.21 show spatial difference plots of the wave parameters of significant wave height, mean period, mean direction and directional spreading for the three storm instants (flood, slack and ebb) considered in detail. These instants all occurred around the peak of the storm, with maximum significant wave heights offshore at station AZB11. These plots show a number of differences between the results of nonstationary and stationary simulation. Figure 5.19 presents the difference plots for the significant wave height for the three instants during the storm. In the offshore, significant wave heights produced by the nonstationary model differ little (up to 3% higher) from those of the stationary model. On the ebb tidal delta, the nonstationary simulation produces values of significant wave height that are locally up to 10% higher than those of the stationary model. A salient difference between the results of the two modes of simulation is found in the tidal channel. During flood tide (01/02/2005 at 10:00), at which time the waves in the tidal channel experience following current, the nonstationary simulation produces significant wave heights in the tidal channel that are locally up to 10% higher than those of the stationary model. By contrast, on the eastern bank of the main tidal channel, significant wave heights produced by the nonstationary model are lower (up to about 5%) than those of the stationary model. At the slack tide instant (01/02/2005 at 12:00), where the current velocities in the channel are low, the differences in model results in the tidal channel decrease. During ebb tide (01/02/2005 at 17:00), when waves in the tidal channel experience opposing currents, the nonstationary model produces significant wave heights that are generally lower (by up to 10%) than the stationary model. These notable differences between the results of the nonstationary and stationary simulation modes in this region can be ascribed to the fact that the time-variation in the tidal currents is properly accounted for in the nonstationary wave simulation, but only approximated in the stationary simulation. In the Wadden Sea interior, outside of the tidal channel, the differences between nonstationary and stationary simulation can be seen to be generally small. During the flood (01/02/2005 at 10:00) and ebb (01/02/2005 at 12:00) instants, the significant wave heights produced by the nonstationary model are somewhat lower (up to 2-3%) than those of the stationary model. During the ebb instant (01/02/2005 at 17:00), the significant wave height results of the two simulation modes are comparable.

Figure 5.20 presents the spatial difference plots for the mean period for the three instants during the storm considered above. Offshore of the barrier islands the results produced by the nonstationary and stationary simulations are similar. In general, the similarity between the simulation modes is also extended to the region of the ebb tidal delta. However, at the ebb instant (01/02/2005 at 17:00), the nonstationary model produces mean periods over the ebb tidal delta that are locally up to 10% higher than those produced by the stationary model. In the tidal gap between the barrier islands of Terschelling and Ameland, the nonstationary model produces higher mean periods (up to 5%) than the stationary model during all three considered storm instants. As was seen in Figure 5.19 above, in the tidal channel region, distinct differences are found between the results of the mean wave period produced by the nonstationary and stationary models. During the flood instant (01/02/2005 at 10:00), the nonstationary simulation produces locally higher mean wave periods (about 5%) than the stationary simulation. During the ebb instant (01/02/2005 at 17:00) the opposite occurs, with the mean periods in the tidal channel produced by the nonstationary run being lower (by about 5%) than those of the stationary run. During the slack instant (01/02/2005 at 12:00), no clear differences between the results of the stationary and
nonstationary runs due to the tidal currents in the channel can be seen. In the Wadden Sea interior, outside of the tidal channel, the differences between nonstationary and stationary simulation results are generally small, with the former producing only slightly lower mean periods.

Figure 5.21 presents the spatial difference plots of the mean direction produced by the nonstationary and stationary simulations for the three considered instants during the storm. As found above, offshore of the islands the mean direction produced by the nonstationary and stationary models are comparable. However, in the tidal inlet and the Wadden Sea interior differences between the results of the nonstationary and stationary simulations can be seen. The mean wave direction in the Wadden Sea interior produced by the nonstationary simulation is initially (on 01/02/2005 at 10:00) somewhat more northerly than that of the stationary simulation. It is noted that in Figure 5.21 isolated regions of very large differences are found (e.g. two white patches south of Terschelling on 01/02/2005 at 10:00). These large differences are considered to be due to local non-convergence of the simulated mean direction in these regions. As above, some current-related differences are found in the tidal channel. During flood, the mean directions in the tidal channel produced by the nonstationary simulation are more northerly (by up to 5°) than those by the stationary model. During ebb, the mean directions by the nonstationary model are somewhat more westerly.

Figure 5.22 presents the spatial difference plots for the directional spreading produced by the nonstationary and stationary simulations for the three instants during the storm. It can be seen that the directional spreading results produced by the nonstationary and stationary simulations are generally comparable over the entire model domain, including the offshore region, the tidal channel and the Wadden Sea interior. An exception to this general result is found immediately down-wind of the island of Terschelling, where the nonstationary simulation produces directional spreading that is locally up to 10° higher than that of the stationary model. As stated above, it is noted that isolated regions of very large differences (white patches, found on 01/02/2005 at 10:00) are considered to be due to local non-convergence of the simulated directional parameters.

Results along mainland coast

The spatial difference plots presented in Figures 5.19 to 5.22 each include a transect (indicated by ‘A’), running along the 0 m NAP contour along the mainland coast. This Transect A is 25 km long, and each 5 km interval is demarcated with a plus sign. In this section, the impact of nonstationary as opposed to stationary simulation on wave conditions along the mainland coast is quantified by considering the model results along this transect.

Figure 5.23 compares the integral parameter results of the nonstationary and stationary simulations along transect A for the storm instant of 01/02/2005 at 10:00 (flood). It can be seen that for this storm instant, the nonstationary simulation computes lower significant wave heights (-1 to -5%) and lower mean periods (0 to -5%) than the stationary simulation along the mainland coast. The differences in the mean wave directions along this transect vary from 0° to 4°, with the results of the nonstationary simulation being generally more northerly than those of the stationary simulation, and hence closer to shore-normal. The directional spreading along transect A produced by the two simulation modes are comparable, with mean differences between -1° and 1°.
Figure 5.24 compares the results of the nonstationary and stationary simulations along transect A for the storm instant of 01/02/2005 at 12:00 (slack). For this storm instant, the significant wave heights and mean periods along transect A produced by the two simulation modes differ by -2 to -5% and by -1 to -4% respectively. By contrast, the respective nonstationary and stationary simulation results for the mean direction and directional spreading are quite similar. The mean directions produced by the nonstationary model are somewhat more northerly than those of the stationary model (0° to 0.7°), and the directional spreading somewhat smaller (0° to -1°).

Finally, Figure 5.25 compares the integral parameter results of the nonstationary and stationary simulations for the storm instant of 01/02/2005 at 17:00 (ebb). In general, the significant wave heights and mean periods produced by the nonstationary simulation are comparable (differences between -0.5 and 1%) and somewhat larger (differences -1 to 3%) respectively than those produced by the stationary simulation. The mean direction results produced by the nonstationary model are somewhat more westerly (0° to -2°) than those produced by the stationary simulation. Similarly, the directional spreading results produced by the two simulation modes are comparable, differing by between -1° and 1°.

It can be concluded that the differences in the results of the nonstationary and stationary simulation modes along the Frisian coast are generally smaller than those found in the tidal channel and over the ebb tidal delta (as was seen in Figures 5.19-5.22). On average, the differences in mean direction and directional spreading can be considered to be negligible. The differences in significant wave height and mean period are larger, and for these the nonstationary simulation mode generally produces lower values.

5.2.4 Impact of morphological changes

This section presents the results of nonstationary simulations with SWAN on the scale of the Amelander Zeegat in which the simulation of morphological changes were included in the coupled wave and hydrodynamics simulations. This investigation is comparable to that conducted by WL (2007), but differs in that the wave modelling with SWAN was performed in full nonstationary mode.

Figure 5.26 presents the computed bed level changes at three instants during the storm of 1-3 January 2005. It can be seen that the morphological changes are limited to the beaches on the north side of the barrier islands, the ebb tidal delta and the tidal channel. The largest changes are found on the ebb tidal delta and the banks of the tidal channel, where bed level changes of up to approximately 0.8 m are found.

Figure 5.27 presents the impact of the computed bed level changes on the simulated integral wave parameters. It can be seen that the changes in these parameters are confined to the regions where the morphological changes have occurred, and that the changes do not reach the Frisian coast. The largest differences in the integral wave parameters are found at the ebb tidal delta and in the tidal channel. In these regions, the significant wave height and mean period $T_{m,10}$ are locally increased by up to 10%. Maximum differences in the mean direction of 4° are found on the ebb tidal delta, and 10° down-wind of the eastern tip of
Terschelling. The directional spreading is little affected by the morphological changes, with differences generally below $3^\circ$. 
6 Conclusions

This study investigated the application of the wind wave model SWAN in nonstationary simulation mode to hindcasts in the Wadden Sea. The aim of the study was to determine the differences between the results of the nonstationary and stationary simulation modes of SWAN over two spatial scales: firstly over a large scale that covers the entire Dutch coast and a portion of the North Sea, and secondly over a smaller scale, that covers the Amelander Zeegat in the Wadden Sea. These hindcasts were conducted for one NW storm (7-9 February 2004) and one W storm (1-3 January 2005). The simulations were conducted using coupled hydrodynamic and wave modelling within the Delft3D suite of models. Based on the findings of this investigation, the following conclusions can be drawn:

- Comparison between the results of the nonstationary and stationary modes of SWAN over the larger geographical domain have shown that the results of significant wave height at the stations ELD and AZB11 can differ by up to 14%. However, in the stationary model the observed phase lag between conditions in the offshore and in the nearshore is absent. Therefore, preceding the storm peak, the stationary model produces higher values of significant wave height than the nonstationary model. Beyond the storm peak, the higher values are produced by the nonstationary model. This result generally agrees with findings of WL (2006a) and Rogers et al. (2007). These results suggest that over the large spatial domain the nonstationary model provides the better basis for simulation.

- Simulating over the larger geographical domain, the nonstationary and stationary models produce generally similar results for the mean direction and directional spreading at the nearshore stations ELD and AZB11 over the entire storm duration.

- Simulating over the Amelander Zeegat domain, the nonstationary and stationary models differ markedly over the ebb tidal delta and in the tidal channel. Considering three instants around the peak of the storm, the time variation of the current in the tidal channel leads to differences between the nonstationary and stationary simulation results of up to 10% in $H_{\text{avg}}$, 5% in $T_{\text{m-1,0}}$, and 5° in the mean direction. However, in the Wadden Sea interior outside of the tidal channel, the differences between nonstationary and stationary simulation are generally small.

- In nonstationary simulations on the scale of the Amelander Zeegat, the inclusion of morphological changes has little effect on the wave conditions at the Frisian coast.

- From these results, the general conclusion can be drawn that in the Wadden Sea interior, and in particular along the Frisian coast, the differences between the results of these two modelling modes are of such a small magnitude that they do not provide sufficient basis on which to prefer nonstationary simulation over the stationary simulation.

In addition, from the comparison between the nonstationary SWAN model results and observations, the following can be concluded in terms of the general model accuracy for the cases considered:
• Comparison between SWAN results and observations over the larger geographical domain have shown that the significant wave height $H_{m0}$ at the nearshore stations ELD and AZB11 are generally underestimated by about 1 m out of 5 m at the peak of the storm. At the storm peak, the observed mean wave period $T_{m-1.0}$ at station AZB11 is underestimated by approximately 1.0-1.5 s. The mean direction at ELD and AZB11 is predicted well, whereas the simulated directional spreading is consistently underestimated by 10-15°. These errors may be related either to the sub-optimal quality of the computed wind fields used in the simulation, or to underlying inaccuracies in SWAN.

• Comparison between the results of the nonstationary model and observations over the Amelander Zeegat domain have shown that in the tidal channel, where the observation stations are located, significant wave heights are generally overestimated and are strongly modulated in time by the ambient current. A similar modulation is found in the mean period and the directional characteristics.

• Finally, in this study it was found that when using *hotfiles* to link successive nonstationary SWAN simulations, the number of decimal places presently used to store the directional spectra in the *hotfiles*, namely 4, is insufficient. The rounding-off error that is made during the production of each *hotfile* can accumulate to significant errors in model results during a simulated storm period.
7 Recommendations

Based on the results of this study, and the conclusions drawn in Section 6, the following recommendations are made:

- Based on the results of this study, it is recommended to continue the use of the stationary mode of SWAN for simulations on the scale of the Amelander Zeegat. Over the larger spatial domain investigated here, however, the nonstationary model provides the better basis for simulation.

- This study has shown that, when simulating over a large spatial domain that includes the entire Dutch coast and a portion of the North Sea, SWAN strongly underestimates spectral energy levels at the barrier island coastline at the peak of the wave. This inaccuracy is produced by both the nonstationary and stationary simulation modes, although it appears to be more pronounced in the former. It is recommended to investigate and correct the source of this underestimation.

- In the simulations on the scale of the Amelander Zeegat, both the nonstationary and the stationary simulation results have shown that SWAN inaccurately predicts the wave field in the tidal inlet where strong tidal currents are found. This inaccuracy may be due to both the quality of the input current fields (the hydrodynamic modelling) and the model physics of SWAN. Therefore, it is firstly recommended to improve the hydrodynamic modelling by applying a larger model domain. Secondly, it is recommended to improve the modelling of wave-current interaction in SWAN.

- This study has shown that when using hotfiles to link successive nonstationary SWAN simulations, the number of decimal places presently used to store the directional spectra in the hotfiles is insufficient. It is recommended to increase the number of decimal characters with which the spectra are written away from 4 to 6.
8 References


A Appendix: SWAN input for large-scale model

In this section, examples are given of the SWAN input files used for the large-scale simulations described in Section 2. The first example the input file used in the nonstationary simulation for the storm of 7-9 February 2004:

```plaintext
$***************************** HEADING *********************************
$PROJECT 'SBW             '  '4918'
                     'H4918.74 SBW
                                       
$***************************** MODEL INPUT ****************************
$SET   LEVEL =   0.00  NOR =  90.00    DEPMIN =   0.05
       MAXMES = 1000   MAXERR = 2
       GRAV =    9.81  RHO =  1025.00  INRHOG =      1
       NAUT
$MODE NONST
CGRID CURV  348  380          EXCEPT  0.0    0.0         
                      CIR                        36       0.03       1.00   37
$READ COOR 1. 'TMP_grid2swan01' 
            4   0   1 FREE
$INPGRID _
BOTTOM CURV 0. 0.  348  380
READINP BOTTOM 1.0 'BOTNOW' 4 0 FREE
INPGRID _
CURREN CURV 0. 0.  348  380
READ CUR FAC= 1.    
'CURNOW' IDLA=4 FREE
$INPGRID _
WIND CURV 0. 0.    348  380
READ WIN FAC= 1.    
'WNDNOW' IDLA=4 FREE
$INPGRID _
BOUN SHAPE JONSWAP   3.30 MEAN DSPR DEGR
BOUN SEGM IJ 0       0   205  0
               CON FILE 'k13_total.spl' 1
BOUN SHAPE JONSWAP   3.30 MEAN DSPR DEGR
BOUN SEGM IJ 0       0  223  0
               CON FILE 'k13_total_a.spl' 1
BOUN SHAPE JONSWAP   3.30 MEAN DSPR DEGR
BOUN SEGM IJ 0  223  0   380
               VAR FILE 0.00 'k13_total_b.spl' 1
28500.00 'nsb_total.spl' 1
BOUN SHAPE JONSWAP   3.30 MEAN DSPR DEGR
BOUN SEGM IJ 0  380   281  380
               CON FILE 'nsb_total_a.spl' 1
INIT HOTS 'hot298'
$GEN3 WESTH
QUAD IQUAD=8
BREAK CON          1.00  0.73
FRIC JON 0.0670
TRIAD 0.0500 2.5000  0.2  0.01
```
Secondly, an example the input file used in the stationary simulation for the storm of 7-9 February 2004 is given below. Note that this input file differs from the one given above mainly in terms of the mode of simulation applied (MODE STAT instead of MODE NONSTAT) and in terms of the convergence criteria.

```plaintext
$***************************** HEADING *********************************
```
$ PROJECT 'SBW' '4918'
   'H4918.74 SBW'
   
$***************************** MODEL INPUT **********************************
$ SET   LEVEL =  0.00 NOR =  90.00 DEPMIN =  0.05 _
       MAXMES = 1000 MAXERR = 2 _
       GRAV =  9.81 RHO = 1025.00 INRHOG =  1 _
NAUT
$ MODE STAT
CGRID CURV  348  380 EXCEPT  0.0  0.0 _
       CIR   36  0.03  1.00  37
$ READ COOR 1. 'TMP_grid2swan01' _
       4  0  1 FREE
$ INPGRID _
BOTTOM CURV 0. 0.  348  380 READINP BOTTOM 1.0 'BOTNOW' 4 0 FREE
INPGRID _
CURREN CURV 0. 0.  348  380 READ CUR FAC= 1. _
       'CURNOW' IDLA=4 FREE
$ INPGRID _
WIND CURV 0. 0.  348  380 READ WIN FAC= 1. _
       'WNDNOW' IDLA=4 FREE
$ POINTS 'rrrpnt' FILE 'stations_k13_nsb.loc'
$ INIT HOTS 'hot101'
$ BOUN SHAPE JONSWAP 3.30 MEAN DSPR DEGR
BOUN SEG M 0 0 205 0 _
       CON FILE 'k13_397.sp1'  1
$ BOUN SHAPE JONSWAP 3.30 MEAN DSPR DEGR
BOUN SEG M 0 0 223 _
       CON FILE 'k13_397a.sp1'  1
$ BOUN SHAPE JONSWAP 3.30 MEAN DSPR DEGR
BOUN SEG M 0 223 0 380 _
       VAR FILE 0.00 'k13_397b.sp1'  1 _
       285000.00 'nsb_397.sp1'  1
$ BOUN SEG M 0 380 281 380 _
       CON FILE 'nsb_397a.sp1'  1
SPEC 'rrrpnt' SPECID 'rrrt397.sp1'
$ GEN3 WESTH
QUAD IQUAD=8
BREAK CON 1.00 0.73
FRIC JON 0.0670
TRIAD 0.0500 2.5000 0.2 0.01
LIM 0.1 1
NUM DIR cdd= 0.50 SIGIM css= 0.50
NUM STOPC 0.000 0.010 0.001 99.500 20 alfa=0.001
PROP BSBT
$***************************** OUTPUT REQUEST **************************
TABLE 'COMPGRID' NOHEAD 'SWANOUT'
HSIGN  DIR  TM01  DEPTH  VELOC  TRANSP
DSPR  DISSIP  LEAK  QB  XP  YP
DIST  UB0T  TMM10  WLENGTH  FORCES  RTP
POIR  WIND

TEST  ITEST=  0  ITRACE=  0  POINTS  XY
0.1612200E+06  0.6135200E+06
0.1612600E+06  0.6135200E+06
0.1612400E+06  0.6135400E+06
0.1612400E+06  0.6135000E+06
0.1649700E+06  0.6140100E+06
0.1650100E+06  0.6140100E+06
0.1649900E+06  0.6140100E+06
0.1649900E+06  0.6143900E+06
0.1649900E+06  0.6140300E+06
0.1671800E+06  0.6104000E+06
0.1672200E+06  0.6104000E+06
0.1672000E+06  0.6104000E+06
0.1672000E+06  0.6103800E+06
0.1672000E+06  0.6104200E+06
0.1675900E+06  0.6104000E+06
0.1676300E+06  0.6104000E+06
0.1676100E+06  0.6104000E+06
0.1676100E+06  0.6103800E+06
0.1676100E+06  0.6104200E+06
0.2154841E+06  0.7799982E+06
0.9929081E+04  0.5832174E+06
0.1065122E+06  0.5879543E+06
0.2065252E+06  0.6234839E+06

PAR 'rif5t397.itr'
COMPUTE
HOTF 'hot101'
STOP
Appendix: SWAN input for Amelander Zeegat model

In this section, examples are given of the SWAN input files used for the small-scale simulations described in Section 4. The first example the input file used in the nonstationary simulation on the scale of the Amelander Zeegat, for the storm of 1-3 January 2005:

```
$***************************** HEADING *********************************
$ PROJECT 'SBW             '  '4918'  'H4918.46 SBW                                                            '
$******************************************************************************
$***************************** MODEL INPUT ****************************
$ SET   LEVEL =   0.00  NOR =  90.00    DEPMIN =   0.05  
    MAXMES = 1000   MAXERR = 2   
    GRAV =    9.81  RHO =  1025.00  INRHOG =      1 
    NAUT
$ MODE NONST
CGRID CURV 439 424   
    EXCEPT 0.0    0.0         
    CIR                         36       0.03       1.00   37
$ READ COOR 1. 'TMP_grid2swan01' _
4   0   1 FREE
$ INPGRID _
BOTTOM CURV 0. 0.  439 424
READINP BOTTOM 1.0 'BOTNOW' 4 0 FREE
INPGRID _
CURREN CURV 0. 0.  439 424
READ CUR FAC= 1.    _ 
'CURNOW' IDLA=4 FREE
$ INPGRID _
WIND CURV 0. 0.    439 424
READ WIN FAC= 1. _
'WNDNOW' IDLA=4 FREE
$ INPGRID _
BOUN SHAPE JONSWAP   3.30 PEAK DSPR POWER
BOUN SEGM IJ 0 0   0  0    110 &
    CON FILE 'total.sp1' 1
BOUN SHAPE JONSWAP   3.30 PEAK DSPR POWER
BOUN SEGM IJ 0 110   0  165 &
    VAR FILE 0.00 'total_a.sp1' 1 &
    3806.00 'total_azb12.a.sp1' 1
BOUN SHAPE JONSWAP   3.30 PEAK DSPR POWER
BOUN SEGM IJ 0 165   0  424 &
    CON FILE 'total_azb12.a.sp1' 1
BOUN SHAPE JONSWAP   3.30 PEAK DSPR POWER
BOUN SEGM IJ 0 0   0  180 &
    CON FILE 'total_b.sp1' 1
INIT HOTS 'hot286'
$ GEN3 WESTH
QUAD IQUAD=8
```
Secondly, an example of the input file used in the stationary simulation on the scale of the Amelander Zeegat (storm of 1-3 January 2005) is given below. Note that this input file differs from the one given above mainly in terms of the mode of simulation applied (MODE STAT instead of MODE NONSTAT) and in terms of the convergence criteria.

Secondly, an example of the input file used in the stationary simulation on the scale of the Amelander Zeegat (storm of 1-3 January 2005) is given below. Note that this input file differs from the one given above mainly in terms of the mode of simulation applied (MODE STAT instead of MODE NONSTAT) and in terms of the convergence criteria.
PROJECT 'SBW' '4918'

'H4918.46 SBW'

$***************************** MODEL INPUT *****************************$

$SET   LEVEL = 0.00  NOR = 90.00  DEPMIN = 0.05 _$

$GRAV = 9.81  RHO = 1025.00  INRHOG = 1 _$

$NAUT$

$MODE STAT$

$CGRID CURV 439 424  EXCEPT 0.0 0.0 _$

$CIR 36 0.03 1.00 37$

$READ COOR 1. 'TMP_grid2swan01' _$

$4 0 1$

$INPGRID _

$BOTTOM CURV 0. 0. 439 424$

$READINP BOTTOM 1.0 'BOTNOW' 4 0 FREE$

$INPGRID _

$CURRENT CURV 0. 0. 439 424$

$READ CUR FAC=1. _$

'CURNOW' IDLA=4 FREE$

$INPGRID _

$WIND CURV 0. 0. 439 424$

$READ WIN FAC=1. _$

'WNDNOW' IDLA=4 FREE$

$INPGRID _

$POINTS 'rrrpnt' FILE 'stations.loc'$

$INIT HOTS 'hot101'$

$BOUN SHAPE JONSWAP 3.30 PEAK DSPR POWER$

$BOUN SEGM IJ 0 0 0 110 _$

$CON FILE 't397.sp1' 1$

$BOUN SEGM IJ 0 110 0 165 _$

$VAR FILE 0.00 't397a.sp1' 1 _$

$3806.00 't397b.sp1' 3$

$BOUN SEGM IJ 0 165 0 424 _$

$CON FILE 't397c.sp1' 3$

$GEN3 WESTH$

$QUAD IQUAD=8$

$BREAK CON 1.00 0.73$

$FRIC JON 0.0670$

$TRIAD 0.0500 2.5000 0.2 0.01$

$LIM 0.1 1$

$NUM DIR cdd= 0.50 SIGIM css= 0.50$

$NUM STOPC 0.000 0.010 0.001 99.500 20$

$***************************** OUTPUT REQUEST *****************************$

$TABLE 'COMPGRID' NOHEAD 'SWANOUT' _$

$HSIGN DIR TM01 DEPTH VELOC TRANSP _
DSPR   DISSIP  LEAK    QB    XP    YP    _
DIST   UBOT    TMM10  WLENGTH  FORCES  RTP    _
POIR   WIND
$
$
TEST  ITEST=  0  ITRACE=  0  POINTS XY  161240  613520  _
164990  614010  _
167200  610400  _
167610  610400  _
169380  607320  _
169450  607110  _
171340  604400  _
171500  604250  _
174290  601500  _
175600  600820  _
169103  591928  _
174381  594995  _
179342  597099  _
182397  598374  _
186845  600545  _
190451  601357  _

PAR 'rif5t397.itr'
COMPUTE
HOTF 'hot101'
STOP
Figures
Location of the Amelander Zeegat in the Dutch Wadden Sea

The Netherlands

Easting [m, Paris]
Northing [m, Paris]

Amelander Zeegat
Terschelling
Ameland
Friesland

SWAN nonstationary
WL | DELFT HYDRAULICS
H4918.46  Fig. 1.1
Amelander Zeegat storm of 7–9 February 2004
Locations of various observation stations

Fig. 2.1

Wave stations
Water level stations
Wind stations
Amelander Zeegat storm of 7–9 February 2004
Observed water levels at three nearshore stations

SWAN nonstationary

WL | DELFT HYDRAULICS

H4918.46  Fig. 2.2
Wind fields at various time points during the storm of 7–9 February 2004

Fig. 2.3

Wind fields at various time points during the storm of 7–9 February 2004

SWAN nonstationary

WL | DELFT HYDRAULICS

H4918.46 Fig. 2.3
Amelander Zeegat storm of 7–9 February 2004
Observed wind time series at three stations

SWAN nonstationary

Fig. 2.4
Amelander Zeegat storm of 7–9 February 2004
Time series comparison of HIRLAM wind and observations at three stations

Station K13–A

Station Texelhors

Station Hoorn (Terschelling)

SWAN nonstationary

WL | DELFT HYDRAULICS

H4918.46
Fig. 2.5
Amelander Zeegat storm of 7–9 February 2004
Scatterplot comparison of HIRLAM wind and observations at three stations

Station K13–A

Station Texelhors

Station Hoorn (Terschelling)

Observed pot. wind speed at 10 m elev. (m/s) vs. HIRLAM $U_{10}$ (m/s) for various stations.
Amelander Zeegat storm of 7–9 February 2004
Observed significant wave heights

SWAN nonstationary
Amelander Zeegat storm of 7–9 February 2004
ZUNO model grid used for flow computations and outline of wave model grid

SWAN nonstationary

WL | DELFT HYDRAULICS

H4918.46  Fig. 2.8
Fig. 2.9

Bathymetry of the ZUNO model

Northing [m, Paris]

Easting [m, Paris]

Depth (m NAP)

-180 -170 -160 -150 -140 -130 -120 -110 -100 -90 -80 -70 -60 -50 -40 -30 -20 -10 0

SWAN nonstationary

WL | DELFT HYDRAULICS

H4918.46  Fig. 2.9
Amelander Zeegat storm of 7–9 February 2004
Grid used for wave computations. Every second cell shown.

SWAN nonstationary

WL | DELFT HYDRAULICS

H4918.46 Fig. 2.10
Bathymetry of the SWAN model

SWAN nonstationary

WL | DELFT HYDRAULICS

H4918.46 Fig. 2.11
Amelander Zeegat storm of 7–9 February 2004
Measured versus computed water levels at three nearshore stations

SWAN nonstationary

Fig. 3.1
Amelander Zeegat storm of 7–9 February 2004
Computed water levels at various instants during the storm

SWAN nonstationary

WL | DELFT HYDRAULICS
H4918.46  Fig. 3.2
Amelander Zeegat storm of 7–9 February 2004
Simulated current fields at six instants during the storm

Fig. 3.3
Amelander Zeegat storm of 7–9 February 2004
HIRLAM wind fields at six instants during the storm

SWAN nonstationary

Fig. 3.4
Amelander Zeegat storm of 7–9 February 2004
Percentage converged grid points in nonstationary and stationary simulations

Nonstationary: NUM ACCUR 0.01 0.01 0.01 101.00 NONSTAT 3

Stationary: NUM STOPC 0.000 0.010 0.001 99.50 20 ALFA=0.001
Amelander Zeeaget storm of 7–9 February 2004
Iteration behaviour of $H_{m0}$ during nonstationary simulation

SWAN nonstationary

WL | DELFT HYDRAULICS

H4918.46

Fig. 3.6
Amelander Zeegat storm of 7–9 February 2004
Iteration behaviour of $T_{m01}$ during nonstationary simulation

Location K13–A
$T_{m01,it}/T_{m01,it=end}$

Location NSB2
$T_{m01,it}/T_{m01,it=end}$

Location ELD
$T_{m01,it}/T_{m01,it=end}$

Location AZB11
$T_{m01,it}/T_{m01,it=end}$
Fig. 3.8

Amelander Zeegat storm of 7–9 February 2004
Iteration behaviour of $H_{m0}$ during stationary simulation

SWAN nonstationary

WL | DELFT HYDRAULICS

H4918.46  Fig. 3.8
Amelander Zeegat storm of 7–9 February 2004
Iteration behaviour of $T_{\text{m01}}$ during stationary simulation

SWAN nonstationary

Fig. 3.9
Amelander Zeegat storm of 7–9 February 2004
Significant wave height at six instants during the storm

SWAN nonstationary

Fig. 3.10
Amelander Zeegat storm of 7–9 February 2004
Mean wave period at six instants during the storm

SWAN nonstationary

Fig. 3.11
Amelander Zeegat storm of 7–9 February 2004
Directional spreading at six instants during the storm

SWAN nonstationary

WL | DELFT HYDRAULICS

H4918.46  Fig. 3.12
Amelander Zeegat storm of 7–9 February 2004
Measured versus computed significant wave heights

SWAN nonstationary

07/02/2004 08/02/2004 09/02/2004

Date

Hₘ₀ (m)

Location K13–A

Location NSB2

Location ELD

Location AZB11

Observed
SWAN Nonstat
SWAN Stat
Amelander Zeegat storm of 7–9 February 2004
Measured versus computed mean period $T_{m-1,0}$

Location K13–A

Location NSB2

Location ELD

Location AZB11

Date

SWAN nonstationary

WL | DELFT HYDRAULICS
H4918.46  Fig. 3.14
Amelander Zeegat storm of 7–9 February 2004
Measured versus computed mean direction

SWAN nonstationary

WL | DELFT HYDRAULICS
Amelander Zeegat storm of 7–9 February 2004
Measured versus computed directional spreading

Location K13–A

Location NSB

Location ELD

Location AZB11

SWAN nonstationary

WL | DELFT HYDRAULICS

H4918.46  Fig. 3.16
Amelander Zeegat storm of 7–9 February 2004
Measured versus computed frequency spectra

Fig. 3.17

SWAN nonstationary

WL | DELFT HYDRAULICS

H4918.46  Fig. 3.17
Amelander Zeegat storm of 7–9 February 2004
Difference in wave height at four instants: \( \frac{H_{m0, nstat} - H_{m0, stat}}{H_{m0, stat}} \)
Amelander Zeeag storm of 7–9 February 2004
Difference in mean period at four instants: \((T_{m-1,0,\text{stat}} - T_{m-1,0,\text{stat}})/T_{m-1,0,\text{stat}}\)

**SWAN nonstationary**

H4918.46  Fig. 3.19
Amelander Zeegat storm of 7–9 February 2004
Difference in mean direction at four instants: \( \text{Dir}_{\text{rstat}} - \text{Dir}_{\text{stat}} \)

SWAN nonstationary

WL | DELFT HYDRAULICS

H4918.46  Fig. 3.20
Amelander Zeegat storm of 7–9 February 2004
Difference in directional spreading at four instants: $D_{spr nstat} - D_{spr stat}$

SWAN nonstationary

WL | DELFT HYDRAULICS

H4918.46  Fig. 3.21
Bathymetry of the Amelander Zeegat
and location of observation stations

SWAN nonstationary

Fig. 4.1

Easting [m, Paris]
Northing [m, Paris]

Water level stations
Wind stations

Depth (m NAP)

-26
-25
-24
-23
-22
-21
-20
-19
-18
-17
-16
-15
-14
-13
-12
-11
-10
-9
-8
-7
-6
-5
-4
-3
-2
-1
0

Easting [m, Paris]
Northing [m, Paris]
Amelander Zeegat storm of 1–3 January 2005
Observed water levels at Terschelling Noordzee and Nes

Water level at Terschelling Noordzee

Water level at Nes
Wind fields at various time points during the storm of 1–3 January 2005

Wind fields at various time points during the storm of 1–3 January 2005

SWAN nonstationary

WL | DELFT HYDRAULICS

H4918.46

Fig. 4.3
Amelander Zeegat storm of 1–3 January 2005
Observed wind time series at three stations

Huibertgat

Wind speed (m/s)

01/01/2005 02/01/2005 03/01/2005 04/01/2005 05/01/2005

0 10 20

Wind direction (°)

01/01/2005 02/01/2005 03/01/2005 04/01/2005 05/01/2005

0 10 20

Lauwersoog

Wind speed (m/s)

01/01/2005 02/01/2005 03/01/2005 04/01/2005 05/01/2005

0 200 400

Wind direction (°)

01/01/2005 02/01/2005 03/01/2005 04/01/2005 05/01/2005

0 200 400

Vlieland

Wind speed (m/s)

01/01/2005 02/01/2005 03/01/2005 04/01/2005 05/01/2005

0 150 300

Wind direction (°)

01/01/2005 02/01/2005 03/01/2005 04/01/2005 05/01/2005

0 150 300
Amelander Zeegat storm of 1–3 January 2005
Observed wave data time series at various buoys

SWAN nonstationary

WL | DELFT HYDRAULICS

H4918.46  Fig. 4.5
Amelander Zeegat storm of 1–3 January 2005
Grids for flow (top) and wave (bottom) computations. Every second cell shown.

SWAN nonstationary

WL | DELFT HYDRAULICS

H4918.46  Fig. 4.6
Water level at Terschelling Noordzee

Water level at Nes

Measured versus computed water levels at Terschelling Noordzee and Nes
Amelander Zeegat storm of 1–3 January 2005
Computed water levels at various instants during the storm

SWAN nonstationary

WL | DELFT HYDRAULICS
H4918.46  Fig. 5.2
Amelander Zeegat storm of 1−3 January 2005
Current fields at 2005/01/02 at 10:00 (top) and 12:00 (bottom)

SWAN nonstationary

WL | DELFT HYDRAULICS

H4918.46  Fig. 5.3a
Amelander Zeegat storm of 1–3 January 2005
Current field at 2005/01/02 at 17:00

SWAN nonstationary

2 January 2005 17:00

Current speed (m/s)

0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9

x 10^5

Northing [m, Paris]

Easting [m, Paris]

x 10^5

WL | DELFT HYDRAULICS

H4918.74 Fig. 5.3b
Amelander Zeegat storm of 1−3 January 2005
Iteration behaviour in nonstationary (top) and stationary (bottom) simulations

Nonstationary: NUM ACCUR 0.01 0.01 0.01 101.00 NONSTAT 6

Stationary: NUM STOPC 0.000 0.010 0.001 99.50 20

SWAN nonstationary
Amelander Zeegat storm of 1–3 January 2005
Iteration behaviour of $H_{m0}$ during nonstationary simulation

SWAN nonstationary

WL | DELFT HYdraulics

H4918.46  Fig. 5.5
Amelander Zeegat storm of 1–3 January 2005
Iteration behaviour of $T_{m01}$ during nonstationary simulation

SWAN nonstationary

WL | DELFT HYDRAULICS

H4918.46 Fig. 5.6
Amelander Zeegat storm of 1–3 January 2005
Iteration behaviour of $H_{m0}$ during stationary simulation

SWAN nonstationary

WL | DELFT HYDRAULICS

H4918.46  Fig. 5.7
Amelander Zeegat storm of 1–3 January 2005
Iteration behaviour of $T_{m01}$ during stationary simulation

SWAN nonstationary

WL | DELFT HYDRAULICS

H4918.46  Fig. 5.8
Amelander Zeegat storm of 1–3 January 2005
Significant wave height at six instants during the storm

SWAN nonstationary

H4918.46
Fig. 5.9
Amelander Zeegat storm of 1–3 January 2005
Mean wave period $T_{m^{-1},0}$ at six instants during the storm

SWAN nonstationary

WL | DELFT HYDRAULICS

H4918.46 | Fig. 5.10
Amelander Zeegat storm of 1–3 January 2005
Directional spreading at three instants during the storm

SWAN nonstationary

WL | DELFT HYDRAULICS

Fig. 5.11
Amelander Zeegat storm of 1–3 January 2005
Measured versus computed significant wave heights

SWAN nonstationary
Amelander Zeegat storm of 1–3 January 2005
Measured versus computed mean period $T_{m-1,0}$

SWAN nonstationary

Fig. 5.13
Amelander Zeegat storm of 1–3 January 2005
Measured versus computed mean direction

SWAN nonstationary
Amelander Zeegat storm of 1–3 January 2005
Measured versus computed directional spreading

SWAN nonstationary

WL | DELFT HYDRAULICS
H4918.46  Fig. 5.15
Amelander Zeegat storm of 1–3 January 2005
Computed and observed spectra on 02/01/2005 at 10:00

SWAN nonstationary
Amelander Zeegat storm of 1–3 January 2005
Computed and observed spectra on 02/01/2005 at 12:00

SWAN nonstationary

WL | DELFT HYdraulics
Amelander Zeegat storm of 1–3 January 2005
Computed and observed spectra on 02/01/2005 at 17:00

SWAN nonstationary

WL | DELFT HYDRAULICS

H4918.46 | Fig. 5.18
The Amelander Zeegat storm of 1–3 January 2005 is analyzed in this document. The difference in significant wave height, denoted as $\Delta H_m0$, is given by the formula $\Delta H_m0 = (H_{m0,stat} - H_{m0,nstat}) / H_{m0,stat}$. The graphs illustrate the significant wave height changes over time, with color bars indicating the percentage change from nonstationary conditions to stationary conditions. The station data and the Easting and Northing coordinates are provided for reference.
Amelander Zeegat storm of 1−3 January 2005
Difference in Significant wave height: \( \frac{H_{m0,\text{stat}} - H_{m0,\text{stat}}}{H_{m0,\text{stat}}} \)

Fig. 5.19b
Amelander Zeegat storm of 1–3 January 2005

Difference in mean period: \( \frac{(T_{m-1,0,nstat} - T_{m-1,0,stat})}{T_{m-1,0,stat}} \)

SWAN nonstationary

WL | DELFT HYDRAULICS

H4918.46 Fig. 5.20a
Amelander Zeegat storm of 1–3 January 2005
Difference in mean period: $(T_{m-1,0,nstat} - T_{m-1,0,stat}) / T_{m-1,0,stat}$

SWAN nonstationary

WL | DELFT HYDRAULICS

H4918.46 Fig. 5.20b
Amelander Zeegat storm of 1–3 January 2005
Difference in mean direction: \( \text{Dir}_{\text{natat}} - \text{Dir}_{\text{stat}} \)

\[ \text{SWAN nonstationary} \]

WL | DELFT HYDRAULICS

H4918.46  Fig. 5.21a
Amelander Zeegat storm of 1–3 January 2005
Difference in mean direction: $\text{Dir}_{\text{nstat}} - \text{Dir}_{\text{stat}}$

SWAN nonstationary

WL | DELFT HYDRAULICS

H4918.46  Fig. 5.21b
Amelander Zeegat storm of 1–3 January 2005
Difference in directional spreading: $\Delta\text{Dspr}_{\text{nonstat}} - \Delta\text{Dspr}_{\text{stat}}$

SWAN nonstationary

WL | DELFT HYDRAULICS

H4918.46 Fig. 5.22a
Amelander Zeegat storm of 1–3 January 2005
Difference in directional spreading: $D_{\text{spr}}^{\text{nonstat}} - D_{\text{spr}}^{\text{stat}}$

SWAN nonstationary

WL | DELFT HYDRAULICS

H4918.46 Fig. 5.22b
Amelander Zeegat storm of 02/01/2005 at 10:00
Nonstationary vs. stationary results along Transect A

SWAN nonstationary

WL | DELFT HYDRAULICS
H4918.46  Fig. 5.23
Amelander Zeegat storm of 02/01/2005 at 12:00
Nonstationary vs. stationary results along Transect A

SWAN nonstationary

Fig. 5.24
Amelander Zeegat storm of 02/01/2005 at 17:00
Nonstationary vs. stationary results along Transect A

SWAN nonstationary

H4918.46  Fig. 5.25
Amelander Zeegat storm of 1–3 January 2005
Difference in bed level: $L_{\text{morph}} - L_{\text{no morph}}$

SWAN nonstationary

WL | DELFT HYDRAULICS

H4918.46 Fig. 5.26a
Amelander Zeeqat storm of 1−3 January 2005
Difference in bed level: Level$_{\text{morph}}$ − Level$_{\text{no\,morph}}$

SWAN nonstationary

WL | DELFT HYDRAULICS

H4918.46 Fig. 5.26b
Amelander Zeegat storm of 2005/01/02 at 17:00
Difference in wave height and period: \( \frac{\text{Par}_{\text{morph}} - \text{Par}_{\text{no morph}}}{\text{Par}_{\text{no morph}}} \)

SWAN nonstationary

WL | DELFT HYDRAULICS

H4918.46 Fig. 5.27a
Amelander Zeevat storm of 2005/01/02 at 17:00
Difference in mean direction and directional spreading:
Par\_morph - Par\_no morph

SWAN nonstationary

WL | DELFT HYDRAULICS

H4918.46  Fig. 5.27b