Horns Rev 2
Offshore Wind Farm

Coastal Impact Assessment

Energi E2 A/S

Final Report
May 2006

DHI WATER & ENVIRONMENT

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Offshore Wind Farm

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Agern Allé 5
DK-2970 Hørsholm, Denmark

Tel: +45 4516 9200
Fax: +45 4516 9292
Dept. fax: +45 4516 8952
e-mail: dhi@dhigroup.com
Web: www.dhigroup.com

Client	Client's representative
Energi E2 A/S	Steffen Andersen

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Authors	Date
Karsten Mangor	18 May 2006
	Approved by: Ida Brøker

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0 INTRODUCTION

0.1 Background

This Draft Report describes the work carried out under the project: "Horns Rev 2 Offshore Wind Farm - Coastal Impact Assessment". The work is carried out by DHI Water & Environment (hereafter referenced as DHI) for ENERGI E2 A/S (hereafter referenced to as E2) according to the work order No 3068184 from E2 dated 17 November 2005.

The scope of work is described in the DHI letter: "Tilbud på metocean studium og vurdering af kystmorfologi i forbindelse med Horns Rev 2 Havmøllepark" dated 27 October 2005. This proposal overrules the description of coastal impact studies described in DHI's original proposal: "Horns Rev 2, Metocean Design Basis and Coastal Impact" of 17 October 2005.

The scope of work thus includes:

- Desk study of the expected effect of the two Offshore Wind Farms - the existing Horns Rev 1 and the planned Horns Rev 2 - on waves and currents in the area

- Evaluation of the possible impact of the two Offshore Wind Farms on the coastal morphology and littoral transport in the area.

0.2 Method

The present assessment of the impact of the two Offshore Wind Farms Horns Rev 1 and Horns Rev 2 will be performed on basis of previous and ongoing studies for Offshore Wind Farms and basic investigation on geology and sediment transport in the area as described in the following.

The present assessment of hydraulic and coastal impacts is run in parallel to the Metocean study and the data from the latter is utilized in the assessment of the impacts. This data includes model computations of waves and currents from the area.

Furthermore, the assessments are based on a number of investigations carried out prior to this study. The most important are listed in the following:

- Basic investigations: Ref. /1/, /4/ and /5/

- Specific investigations carried out for the Horns Rev 1 project: Refs. /2/ and /3/.

The present impact assessment report contains the following sections:

- Section 2 Description of the project
- Section 3 Baseline description of the area
- Section 4 Baseline description of the wave conditions in the area
- Section 5 Baseline description of the current conditions in the area
- Section 6 Assessment of impacts on waves, currents and coastal morphology

1 RESUMÉ AND CONCLUSION

1.1 In English

An assessment of the impact caused by the Offshore Wind Farms Horns Rev 1 and 2 on waves, currents, coastal morphology and sediment transport has been carried out.

The Horns Rev 1 Wind Farm was constructed in 2002. It consists of 80 2 MW wind turbines installed on monopiles with a diameter of D = 4 m. It is located in the SE-ern part of the outer Horns Rev, between Vyl and Munk.

The Horns Rev 2 Wind Farm is being planned with 95 2.3 MW wind turbines installed on monopiles with a diameter of D = 4.2 m. It is located in the NW-ern part of the outer Horns Rev, immediately north to northwest of Vovov. There are two alternative layouts: Horns Rev 2 North and Horns Rev 2 South.

Horns Rev is located west of the westernmost point of Denmark, Blåvands Huk. Horns Rev can be divided in the outer Horns Rev and the inner Horns Rev, which are separated by the deep channel named Slugen. Both the outer and the inner Horns Rev are shallow reefs. The outer Horns Rev consists primarily of pebbles, gravel and sand. Geomorphologically it can be described as a terminal moraine ridge formed of glaciofluvial material deposited in front of the icecap during a retreating state of the Saale glaciation. The glacier in an advancing state then pushed up the deposited material. The inner Horns Rev consists primarily of marine deposits. It had been formed due to the shelter provided by the outer Horns Rev.

The outer Horns Rev is considered a stable form, which has kept its present position since its formation. The area around Blåvands Huk and the inner Horns Rev is constantly adjusting to the changes in the adjacent coastline and to minor changes in hydrography and sea level. However, Blåvands Huk and the inner Horns Rev are considered being overall stable on the long term.

The wave climate in the North Sea is rough both during summer and winter. Based on a conservative assumption it is rendered probable that the wave height just leeward of the wind farm areas will be reduced by 2 to 4% on the average dependent of the configuration. The nearshore wave climate will be practically unaffected by the presence of the wind farms. The reduction in currents downstream of the wind farm areas is insignificant and considered without importance for the environment and for sediment transport and coastal morphology. However, local scour has not been addressed in the present report.

It is therefore concluded that the presence of the two wind farms Horns Rev 1 and Horns Rev 2 will cause only negligible impact on the environment with respect to hydrography, sediment transport and coastal morphology.

Possible hydraulic impacts during construction are not covered by the present evaluation; however, based on the investigations made in connection with the Horns Rev 1 Wind Farm project, refer Ref. /3/, it is evaluated that such impacts will be negligible.

1.2 Resumé og konklusion

En evaluering af virkningerne på bølge- og strømforhold, sedimenttransport og kystmorfologi af de to offshore vindmølleparker Horns Rev 1 og Horns Rev 2 er foretaget som et skrivebordsstudium.

Horns Rev 1 vindmølleparken blev bygget i 2002. Den består af 80 stk. 2 MW vindmøller installeret på monopæle med en diameter på D = 4 m. Horns Rev 1 vindmølleparken er placeret i den sydøstlige del af Horns Rev området imellem Vyl og Munk.

Horns Rev 2 vindmølleparken er under planlægning. Den kommer til at består af 95 stk. 2,3 MW vindmøller samt tre større forsøgsmøller. Møllerne vil blive installeret på monopæle med en diameter på ca. D = 4,2 m. Horns Rev 2 vindmølleparken vil blive placeret i den nordvestlige del af Horns Rev området, umiddelbart nord til nordvest for Vovov.

Horns Rev ligger vest for Danmarks vestligste punkt, Blåvands Huk. Horns Rev består af to dele, ydre Horns Rev og indre Horns Rev. De to dele er adskilt af den dybe rende Slugen. Begge dele af Horns Rev er lavvandede. Det ydre Horns Rev består hovedsageligt af ral, grus og sand. Geomorfologisk set er Horns Rev en terminalmoræne. Den sandsynlige dannelse af revet er, at glacio-fluvialt sediment aflejret foran isen under Saale istiden er blevet skubbet op på et tidspunkt, hvor isen avancerede mod syd. Revet består derfor ikke af det typiske blandede sediment fra en moræne (grus, sand, silt og ler), men af relativt velsorterede sedimenter i form af sten, ral, grus og sand. Denne dannelseshypotese underbygges af, at man flere steder på det jyske fastland f.eks. ved Kjelst, beliggende kun ca. 12 km øst for Blåvands Huk, finder mægtige (tykkelse) aflejringer af denne type. Dette vidner om, at området har været beliggende foran en afsmeltende isfront i en længere periode. Det indre Horns Rev består af marine aflejringer som er aflejret grundet lævirkningen fra det ydre Horns Rev.

Det ydre Horns Rev betragtes derfor som en stabil formation, som har bibeholdt sin placering siden sin dannelse. I modsætning hertil er det indre Horns Rev og Blåvands Huk forholdsvis mobile formationer, som konstant er under omlejring og tilpasser sig de til enhver tid fremherskende vind og bølgeforhold. Deres overordnede form vurderes imidlertid at være stabil.

Bølgeklimaet i Nordsøen er barskt både sommer og vinter. Det vurderes på baggrund af konservative estimater, at bølgehøjden i læ af vindmølleparken vil blive reduceret med 2 til 4% i gennemsnit afhængigt af de alternative udformninger. De kystnære bølger vil derfor praktisk taget være upåvirkede af tilstedeværelsen af de to vindmølleparker. Reduceringen i strømhastigheden gennem mølleparken vurderes ligeledes at være ubetydelig og vil følgelig ikke have betydning for sedimenttransporten og kystmorfologien i området. Helt lokale forhold tæt på pælene i form af eventuelt scour er ikke adresseret i nærværende rapport

Det konkluderes derfor, at opførelsen af de to vindmølleparker Horns Rev 1 og Horns Rev 2 kun vil have ubetydelig indflydelse på hydrografi, sedimenttransport og kystmorfologi.

Påvirkninger i konstruktionsfasen er ikke dækket i nærværende undersøgelser, men baseret på de undersøgelser som blev udført i forbindelse med Horns Rev 1 projektet, jævnfør Ref. /3/, skønnes det, at de hydrauliske virkninger på miljøet under byggefasen vil være ubetydelige.

2 DESCRIPTION OF PROJECT

2.1 Horns Rev 2

The Horns Rev 2 Offshore Wind Farm area is located at the NW-ern part of Horns Rev. Two alternative installation areas are under consideration, referred to as North and South, respectively, see Figure 2.1. The North area has the highest priority. However, it has not been finally decided yet which installation area will be used.

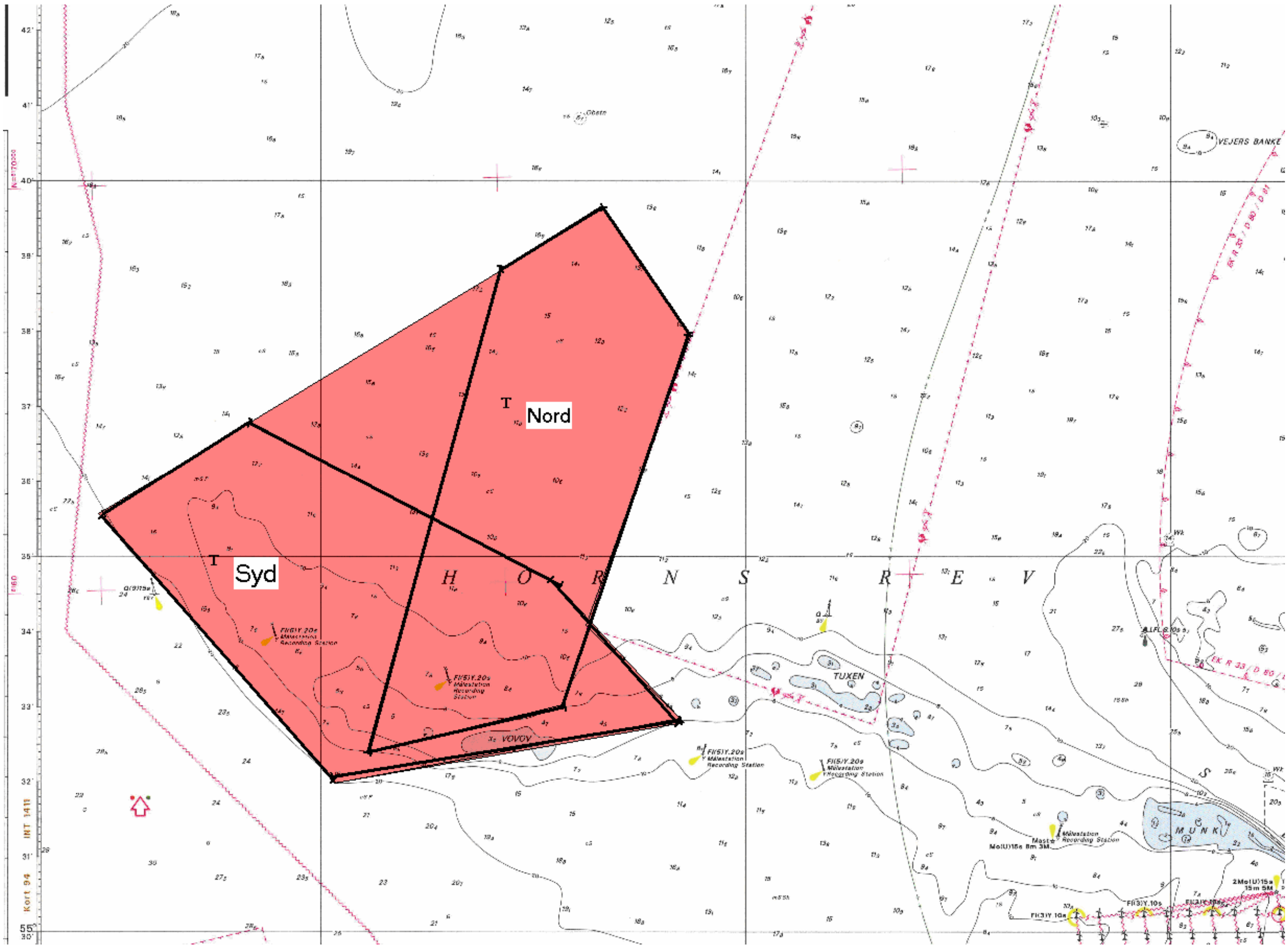

Figure 2.1 The two alternative installation areas North and South.

The Horns Rev 2 Offshore Wind Farm will consist of max. 95 wind turbines including 3 larger test turbines plus one transformer as shown in Figure 2.2 and Figure 2.3 for alternative North and South, respectively. The wind turbines will be mounted on monopiles with a diameter of D = 4.2 m.

Details of the configuration of foundations and scour protection are not known at present. The wind mills have been taken simply as 4.2 m diameter monopiles. Extensive scour protections or large foundation structures above the natural sea bed may modify the assessed impact of the wind mill parks on the waves and current, but not so drastically that the main conclusions are to be changed.

It is seen that the wind turbines for alternative North are located from the Vovov area towards NNE in 14 rows in a fan-shaped configuration. There are up to 7 wind turbines in each row. The southernmost row has an approximate orientation of W by S and the northernmost row an approximate orientation of NW by N. The distances between the rows are on the average. 850 m. The distances between the turbines in the rows are approximately 540 m.

The depths in the North area vary between 4 and 14 m.

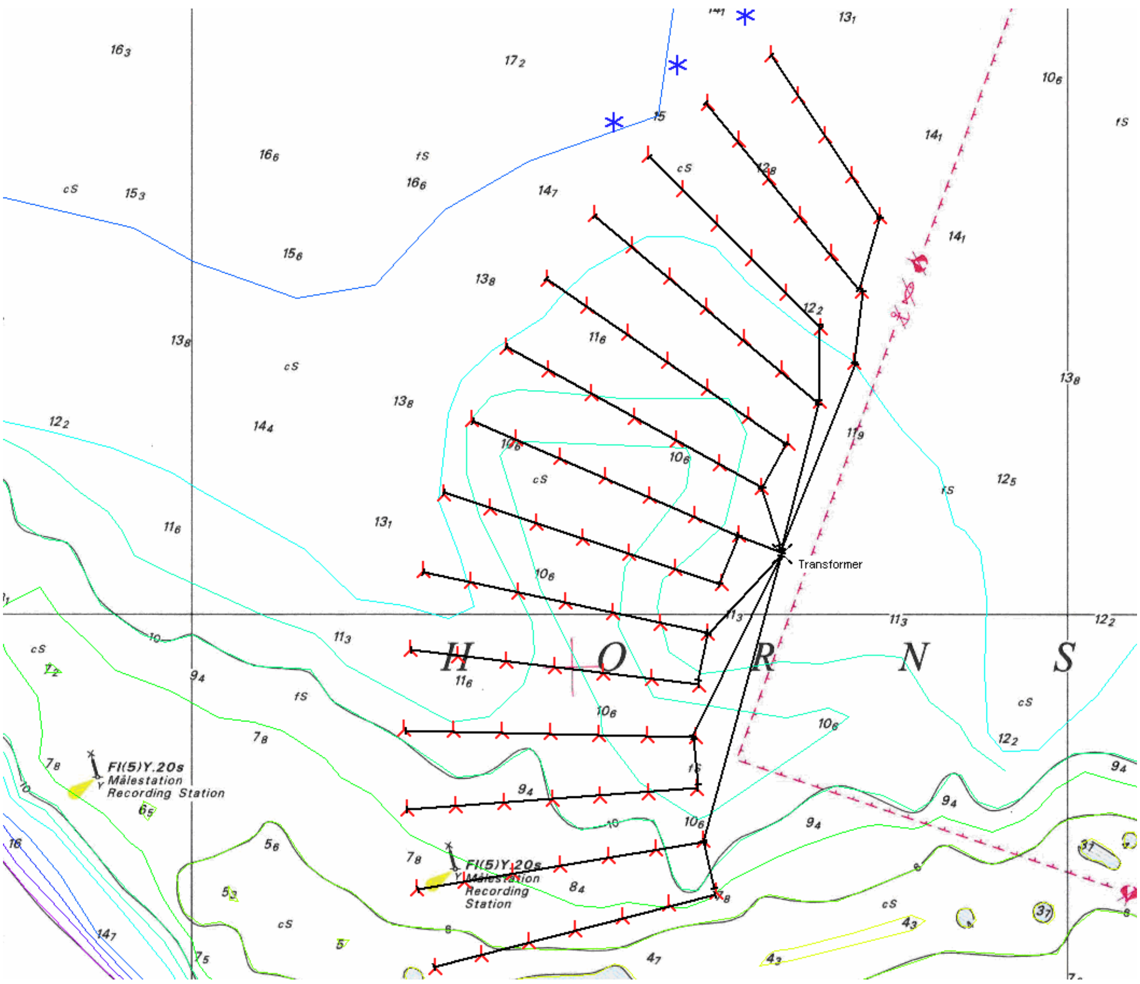

Figure 2.2 Positioning sketch plan for Horns Rev 2 North Offshore Wind Farm showing 95 2.3 MW turbines, 3 test turbines and the transformer.

It is seen that the wind turbines for alternative South are located on the northern part of the westernmost tip of Horns Rev in 14 rows in a fan-shaped configuration. There are up to 7 wind turbines in each row. The easternmost row has an approximate orientation of SSE and the westernmost row an approximate orientation of W by S. The distances between the rows are on the average 850 m. The distances between the turbines in the rows are approximately 540 m.

The depths in the South area vary also between 4 and 14 m. However, the South area is on the average on more shallow water than the North area.

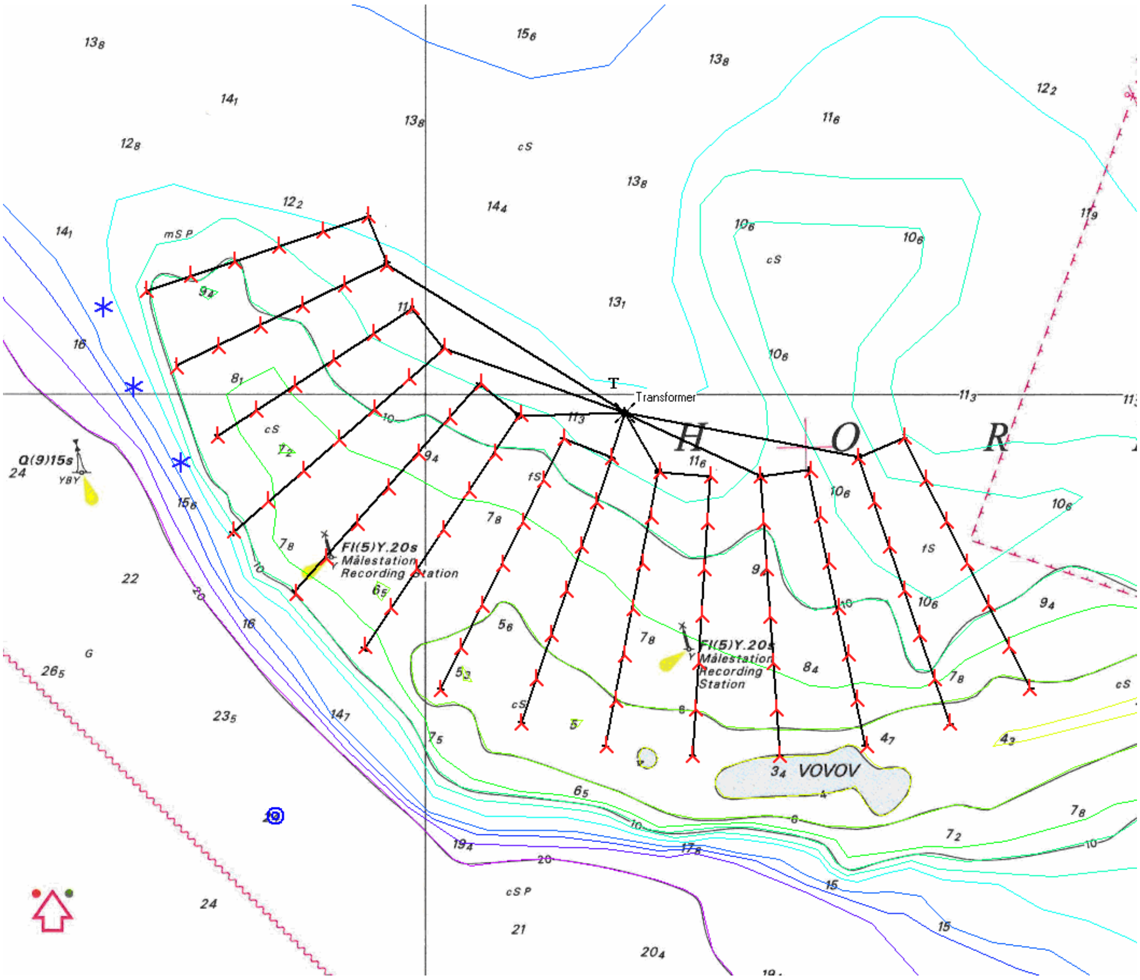

Figure 2.3 Positioning sketch plan for Horns Rev 2 South Offshore Wind Farm showing 95 2.3 MW turbines, 3 test turbines and the transformer.

2.2 Horns Rev 1

The Horns Rev 1 Offshore Wind Farm is described in the following as the purpose of the present project is to describe the combined impact of the Horns Rev 1 and the Horns Rev 2 Offshore Wind Farms.

The Horns Rev 1 Farm is located south of the inner part of Horns Rev, see location map in Figure 2.4 and detailed location map in Figure 2.5.

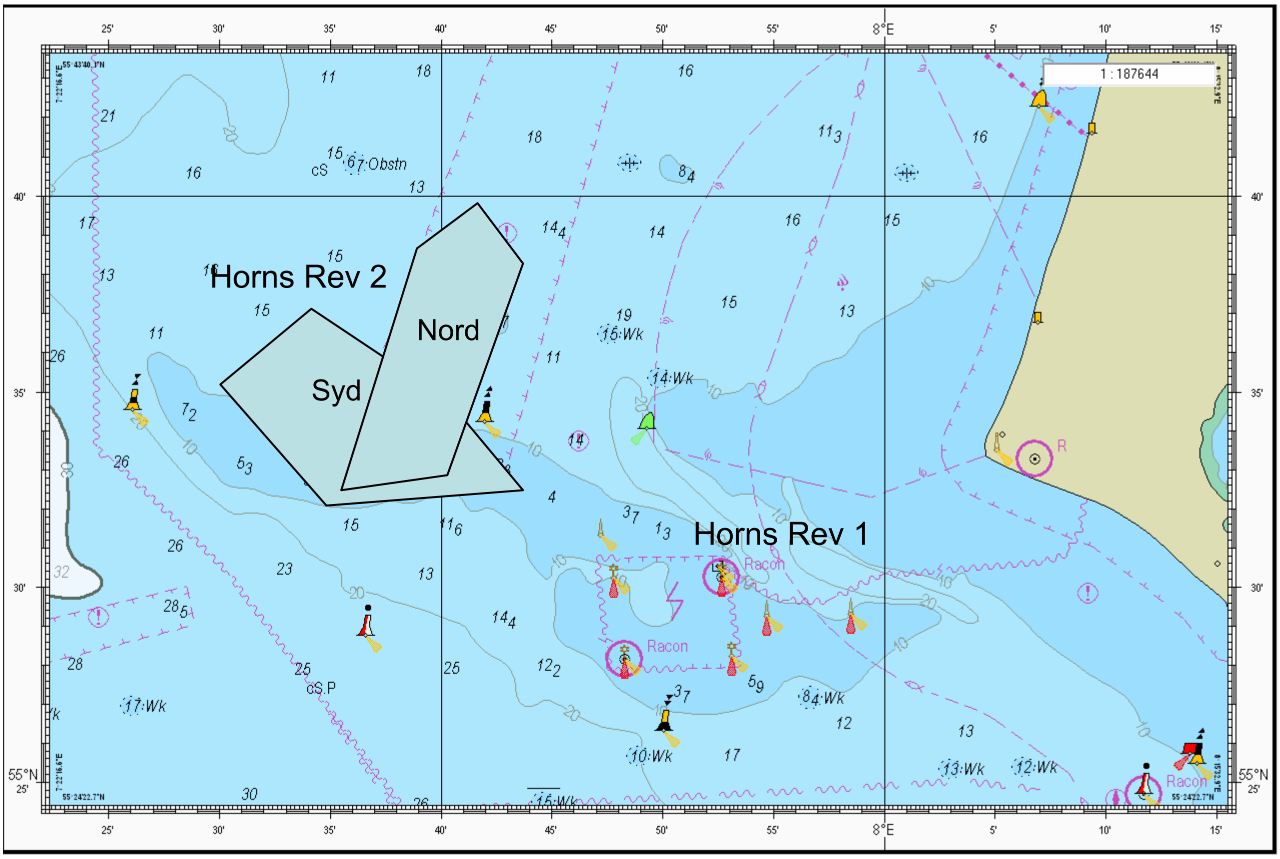

Figure 2.4 Upper: Location map for Horns Rev 1 and 2. Lower: Detailed location map showing location of the Horns Rev 1.

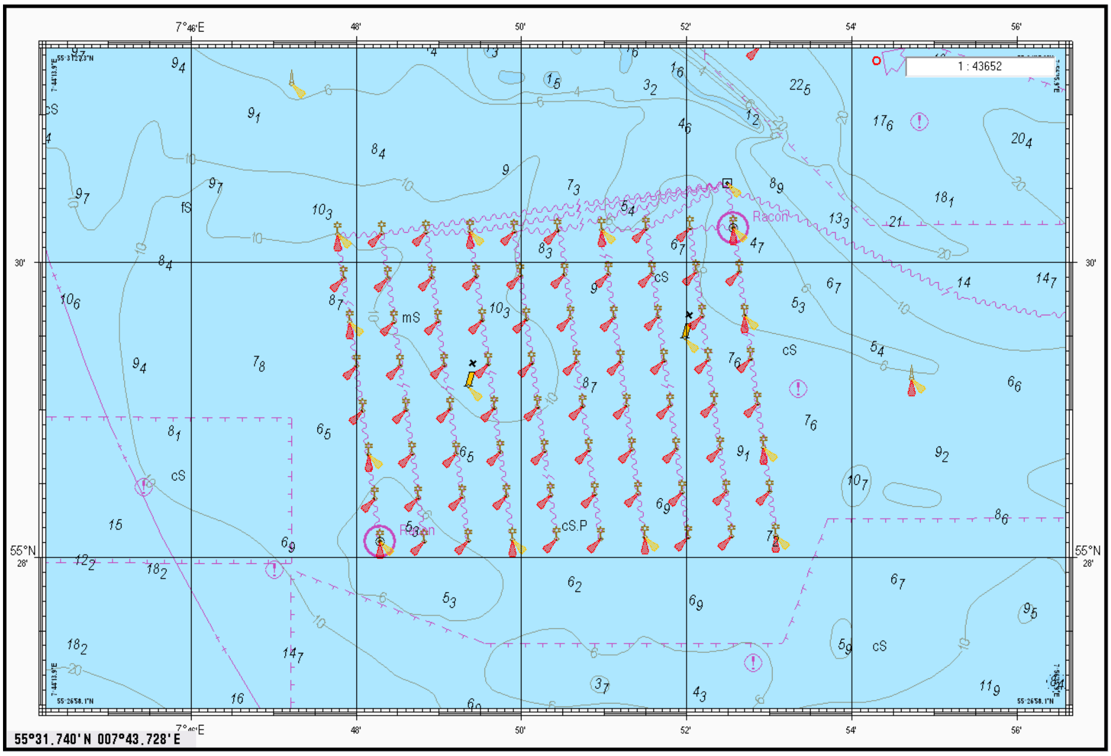

Figure 2.5 Upper: Location map for Horns Rev 1 and 2. Lower: Detailed location map showing location of the Horns Rev 1.

3 BASELINE DESCRIPTION OF THE AREA

3.1 Background

DHI has in 1999 carried out specific investigations in the area for the Horns Rev 1 Wind Farm, Refs. /2/ and /3/, and in a detailed investigation in 2001 of the sediment transport and morphology in the area, Ref. /4/. Researchers from the Geographical Institute at Copenhagen University have made a description of the area in 1995, Ref. /1/ and GEUS has made the most recent description in 2003, Ref. /5/.

The Ref. /4/ study is a detailed investigation performed on basis of advanced numerical modelling of hydrodynamics, waves and sediment transport and on basis of updated, but scarce information on seabed sediments in the area. The Ref. /5/ study is a geological investigation based on the newest geological information available in the area. The Ref. /5/ included information from Ref. /4/ and there is in general fair agreement between the two studies. However, it should be noted that the geological and the sediment transport processes in the area are very complicated and the available data area scarce. Consequently:

- The geological study of the area suffers from lack of detailed geological data from the Horns Reef proper

- The interpretation of the numerical modelling suffers from a great variability in the surface sediments and from a very complicated bathymetry in the area.

Furthermore, there are contradicting descriptions of the area from fishermen, who have been fishing on the reef.

The baseline descriptions in the following are summaries of the above described references /1/ to /5/.

3.2 Geographic Setting

Blåvands Huk is the westernmost point in Denmark. Geomorphologically, Blåvands Huk is a cuspate foreland stabilised by the shallow reef, Horns Rev, situated to the west of Blåvands Huk and extending approximately 40 km to the west into the North Sea (Figure 3.1).

In the Horns Rev area there are the following major features:

- Blåvands Huk
- The Inner Horns Rev stretching 16 km westward of Blåvands Huk
- Slugen, which is a deep channel separating the Inner Horns Rev and the Outer Horns Rev
- The Outer Horns Rev (this is officially called Horns Rev).

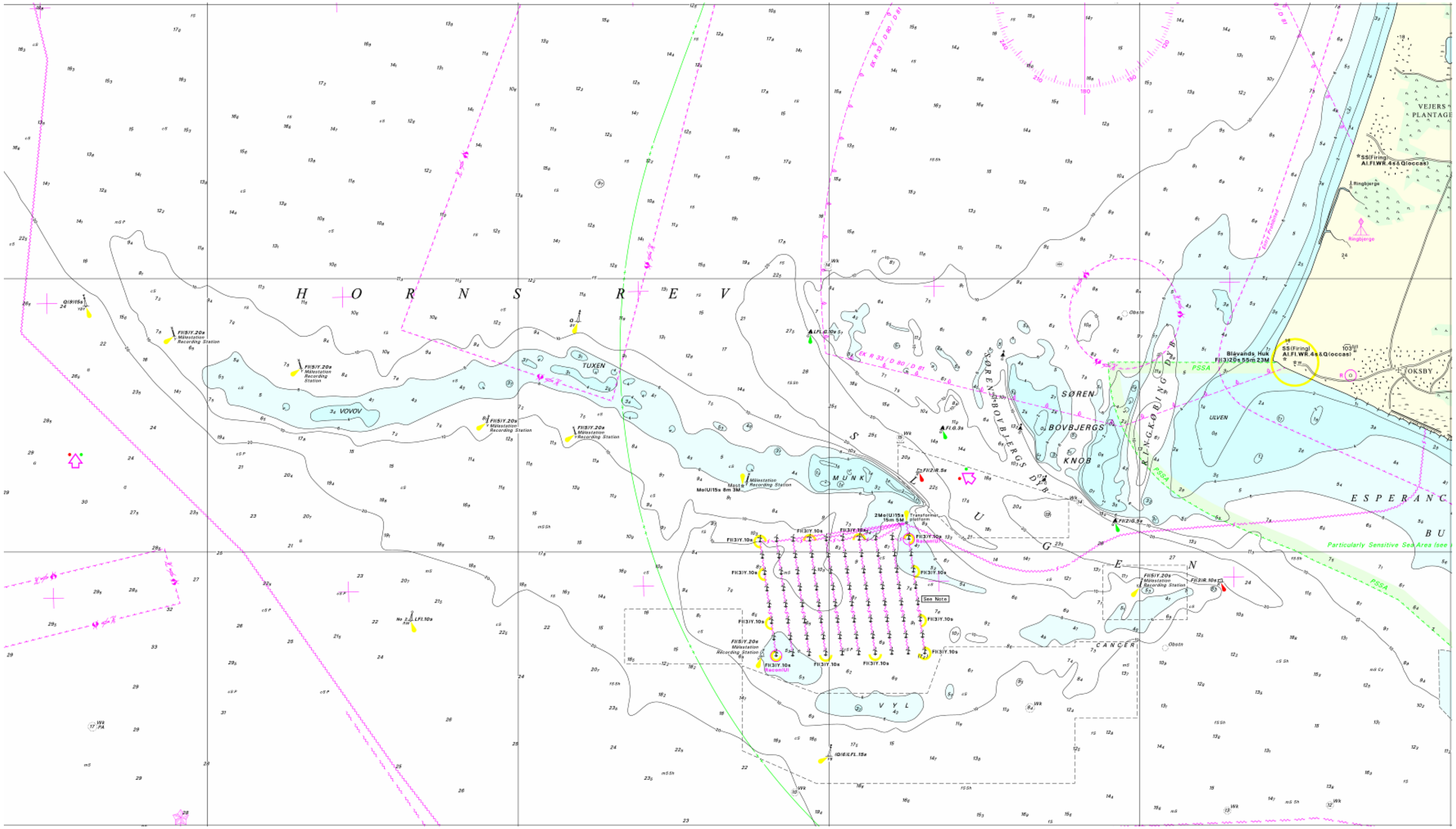

Figure 3.1 Bathymetric map of the Horns Rev area, extract of Sea Chart 61. Locations of Horns Rev 1 and 2 are indicated. Copyright: Kort & Matrikelstyrelsen.

In the following these major features are described in detail.

Blåvands Huk
Blåvands Huk is a cuspate foreland, which is formed as a result of trapping of the southward littoral transport along the coast north of Blåvands Huk, which presently is in the order of 1.2 mill. m^3/year, Ref. /4/.

The Inner Horns Rev
The depth conditions in the area off Blåvands Huk are very complicated. In the alignment of the coast north of Blåvands Huk towards SSW there is a shallow shoal called Ulven. A complicated system of shoals and channels stretches to the west of Ulven to a distance of 16 km westward form the Huk. These formations are referred to as the Inner Horns Rev and consist of the following shoals and channels from east to west:

- Shoal: Ulven
- Channel: Ringkøbing Dyb
- Shoal: Søren Bovbjergs Knob
- Channel: Søren Bovbjergs Dyb
- Shoal: Westernmost part of Inner Horns Reef, no official name
- Channel: Slugen (West Slugen or Nordmands Dyb), which separated the Inner Horns Rev and the Outer Horns Rev.

Slugen
Slugen is a deep channel separating the inner Horns Rev and the outer Horns Rev. Slugen has a curved shape and consists of two parts:

- The eastern Slugen, which has depths up to 27 m, has a direction ESE – WNW
- The Western Slugen or Nordmands Dyb, which has depths up to 28 m, has a direction SE – NW
- A sill with depths of around 18 m separates the eastern and the western parts of Slugen.

The outer Horns Rev
The outer Horns Rev, which is normally referred to as Horns Rev, consists of two rows of shallow shoals, the SE-ern part and the NW-ern part. Horns Rev has a total length of approximately 35 km. The two parts of Horns Rev consist of the following shoals:

The SE-ern part of Horns Rev consists of two shoals:

- Eastern shoal: Cancer, with depths less than 5 m

- Western shoal: Vyl, with depths less than 4 m.

The total length of the SE-ern part of Horns Rev is approximately 15 km; the direction is ENE - WSW. The width of the SE-ern part of Horns Rev, between the 6 m contours, is approximately 1 km.

The NW-ern part of Horns Rev consists of 3 shoals:

- Eastern shoal: Munk, with depths less than 2 m

- The middle shoal: Tuxen, with depths less than 3 m

- Western shoal: Vovov, with depths less than 4 m.

The total length of the NW-ern part of Horns Rev is approximately 30 km, the direction is SE - NW between Munk and Tuxen and E – W between Tuxen and Vovov. The width of the NW-ern part of Horns Rev, between the 6 m contours, is approximately 1.5 km.

Horns Rev 1 is located between Vyl and Munk. Horns Rev 2 North is located N of Vovov and Horns Rev 2 South is located W of Vovov.

The NW-ern part of Horns Rev can be characterised as a huge detached natural groyne, which is probably responsible for the formation of the other features in the area, namely: the SE-ern part of Horns Rev, Slugen, the Inner Horns Rev and Blåvands Huk. The geological conditions of the area are discussed in the following.

3.3 Tidal Amphidromy

The North Sea is a complex resonant tidal system caused by the rectangular form of the basin. The Atlantic tides send a wave southward into the North Sea, which is reflected and which moves back northwards taking three tidal periods to return to the entrance (Figure 3.2).

Three amphidromic systems are present in the North Sea and the tidal range at the coast is partly due to the distance from the amphidromic centre point (Ref. /7/). The tidal range has a great influence on the geomorphology of the coast. The tidal amphidromy along the Danish West Coast is anti-clockwise. The hydrographic effect of Horns Rev is a dampening of the northward travelling tidal wave, which has a drastic effect on the tidal ranges in the area as presented in Table 3.1.

Table 3.1 Spring Tidal Ranges in the Horns Rev area, from Admiralty Tidal Tables (Ref. /6/).

Location	Lat. N	Long. E	MHWS	MLWS	Spring Tidal Range
Hvide Sande	56 00	8 07	0.8	0.0	0.8 m
Blåvands Huk	55 33	8 05	1.8	0.0	1.8 m
Grådyb Bar	55 26	8 15	1.5	0.0	1.5 m
Esbjerg Port	55 28	8 27	1.9	0.1	1.8 m

It is seen that the Horns Rev has a shoaling effect on the tidal wave, which is expressed in the increased tidal range at Blåvands Huk (1.8 m) as compared to the area further southward at Grådyb Bar (1.5 m). North of the Horns Rev the tidal range is drastically reduced to 0.8 m at Hvide Sande.

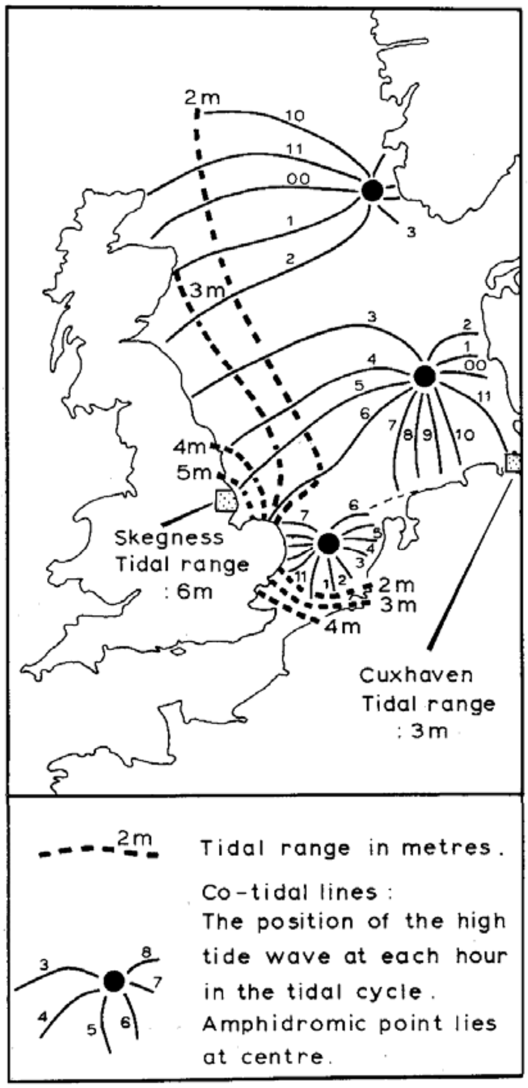

Figure 3.2 The tidal system of the North Sea (from Ref. /7/).

3.4 Geology

The geology of the west coast of Jutland is dominated by landscapes created during the second last glaciation period, the Saale period, which terminated approx. 100,000 years ago. These formations are the so-called “bakkeøer”. The west edge of these are clearly seen close to the coast approx. 10 km north of Blåvands Huk at Grærup and further north. The front of these formations turns towards SE at Grærup. They are seen as the coastal cliff out to Ho Bugt south of Varde Å, see Figure 3.3 (section of Figure 2 from Ref. /5/).

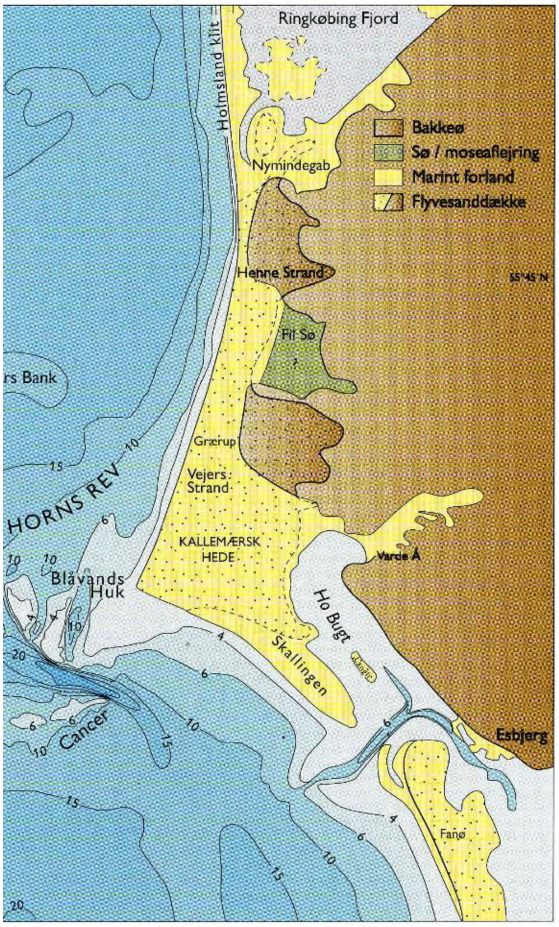

Figure 3.3 The glacial formations “bakkeøer” from the Saale period.

Since the last glaciation period, during the Holocene period, the sheltering effect caused by the outer Horns Rev has caused trapping of the southward littoral transport in the area around Blåvands Huk and the inner Horns Rev. This trapping of sand has caused the westernmost part of Denmark to move 10 km southward and 3 km westward (From Grærup to the Huk) and has caused trapping of all the material in the inner Horns Rev. This has mainly occurred during the last 7500 years, during which period the water level has been fairly constant. Before that period the water level was much lover.

The Skallingen is partly built by the sand coming from the north. As explained above, however, only a small fraction of it could pass the sheltered area around Blåvands Huk, and partly by sand being pushed landwards from the shallow area of Eem meltwater deposits, which are located offshore of Skallingen. Consequently, Skallingen is mainly a barrier island formation.

Geological investigations show that there are low laying moraine deposits in the outer area of Horns Rev in the form of boulder clay/till deposits, the so-called "Vovov bakkeø", which has a top level of around -15 m. This formation is from the Saale Ice Age or older. However, investigations indicate that the upper layers of the outer Horns Rev do not consist of till deposits but of an accumulation of sand, gravel and pebble. These relative coarse layers are at many locations, probably mainly on the slopes of the reef, covered by several metres of fine and medium marine sand.

Geomorphologically, the Horns Rev formation consists of the remnants of a terminal moraine ridge. It is most likely formed from glacio-fluvial sediments deposited in front of the icecap during the Saale glaciation (200,000 to 130,000 years BP) in a retreating state; the glacier in an advancing state then pushed up the frozen deposited material, which now forms the NW-ern outer Horns Rev. This is the explanation as to why this part of Horns Rev does not primarily consist of till (gravel, sand, silt and clay), but of relatively well-sorted sediments: mainly cobble, gravel and sand. This geomorphologic interpretation is additionally supported by the fact that deposits of this type are seen at several locations on the Jutland peninsula; e.g. at Kjelst, 12 km east of Blåvands Huk, where thick layers are exposed in gravel pits. These findings point to the conclusion that the area was situated in front of a retreating glacier for a longer period (Ref. /8/).

The above discussion does not exclude the speculations that Horns Rev during the Eem interglacial period formed an island or peninsula in a transgressing Eem Sea (Ref. /9/). It should be noted that the above interpretation is not in 100% agreement with the interpretation presented in Ref. /5/. More precise geophysical data from the outer Horns Rev is needed for a full clarification of the geological and geotechnical condition in the area.

When the latest glaciation (Weichsel) ended (12,000 BP), the sea level was significantly lower than today, allowing extensive out-wash plains to form in Southwest Jutland. Sand and gravel were transported by the melt-water from the ice-cover in a westward direction out to the sea on a very mild slope (~ 1 ‰) depositing its material at, for example, Horns Rev. During this period (Fastlandstiden), before the onset of the transgression, eolian sand, silt and gytje were deposited in the area south of Horns Rev. These deposits may also be found on the actual reef except for the north-western part, where glacio-fluvial deposits are seen on the seabed.

During the Holocene transgression, the formation at Horns Rev was subject to wave erosion forming a wave-cut platform extending to the east and south (Ref. /10/). Investigations have pointed to the conclusion that the hydrography in the area changed, when the transgression reached level -11m; from then on the marine accumulations of sand in the areas of Blåvands Huk and the inner Horns Rev began.

Today, the NW-ern part of the outer Horns Rev appears as a reef with water depths between 2 and 6 m, which is responsible for the formation of the large lee-side formation (Tombolo or Cuspate Spit) east of the area in the form of the Inner Horns Rev and Blåvands Huk. Although Blåvands Huk is constantly subject to changes adjusting to variations in hydrography and sea level changes, it is considered a quasi-stable formation that will continue to adjust to minor changes in the local conditions, including the possible influence from the planned wind power plant.

Also the SW-ern part of the outer Horns Rev is considered part of the morphological response from the NW-ern outer Horns Rev, as described in Section 3.6.

Figure 3.4 shows the shoreline change from north of Blåvands Huk to the south spit of Skallingen, showing the westernmost point to have moved up to 500 m within 200 years. This local change in shoreline location is not considered to have any effect on the installation area.

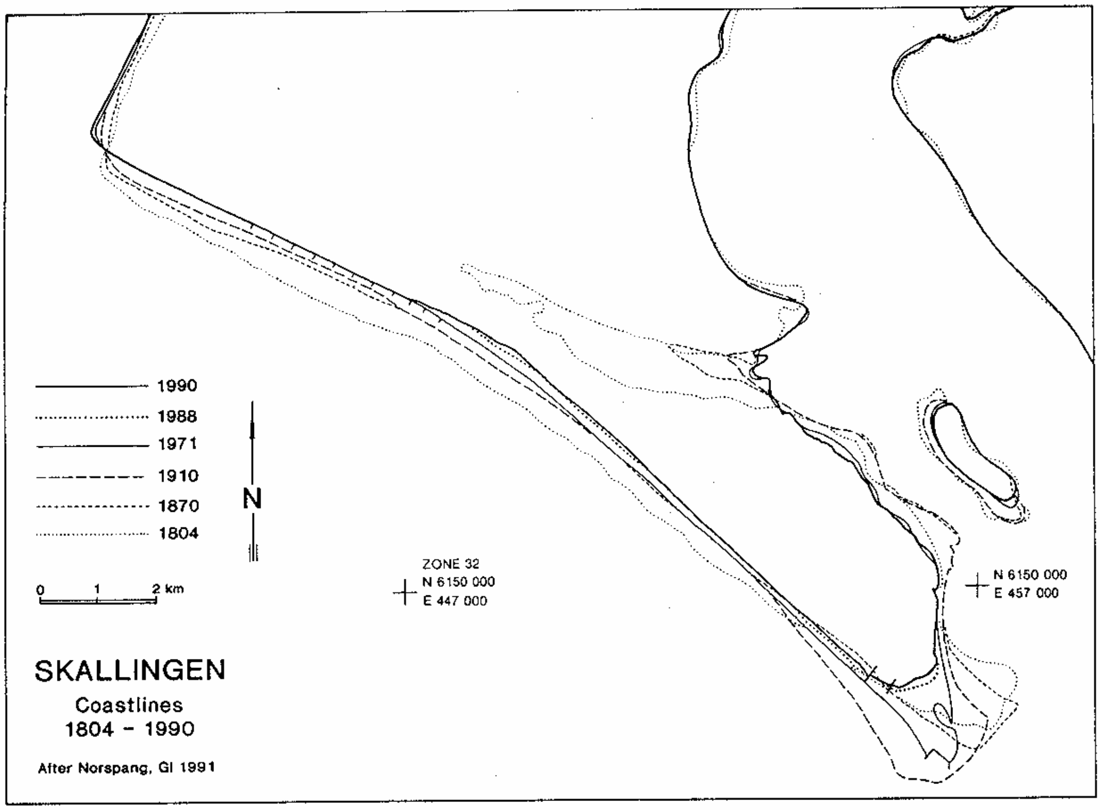

Figure 3.4 Shoreline changes at Horns Rev and Skallingen 1804-1990 (Ref. /1/).

3.5 Sea Bed Sediments

The seabed sediments at Horns Rev include Holocene beach ridges of coarse sand, gravel and stones, coarse glacial residual sediments, postglacial fine and medium sand and silty or clayey fine sand.

Major areas with exposed coarse beach ridge formations are found in the area from east of Vovov towards the southeast. Coarse residual glacigene sediments are seen on the northern part of the NE-ern outer Horns Rev and southwest of Horns Rev. Finer material, post-glacial fine and medium sands and clayey and silty sands are seen east of the reef e.g. at Slugen (Ref. /10/), see Figure 3.5.

Dunes and mega-ribbles are seen in the channels Normandsdyb and Slugen. Tidal currents create dunes and ribbles, showing evidence of transport directions both to the north and the south. Asymmetrical sand ridges are seen on the reef between Tuxen and Munk. All structures in the area apart from those in the tidal channels indicate a prevailing transport direction towards the south and southeast (see Figure 3.5).

The Horns Rev Wind Farm areas Horns Rev 1 and Horns Rev 2 (North and South) are indicated on the figure. It is seen that the bed sediments in the area of Horns Rev 2 vary between coarse sand/gravel with cobble and fine to medium sand.

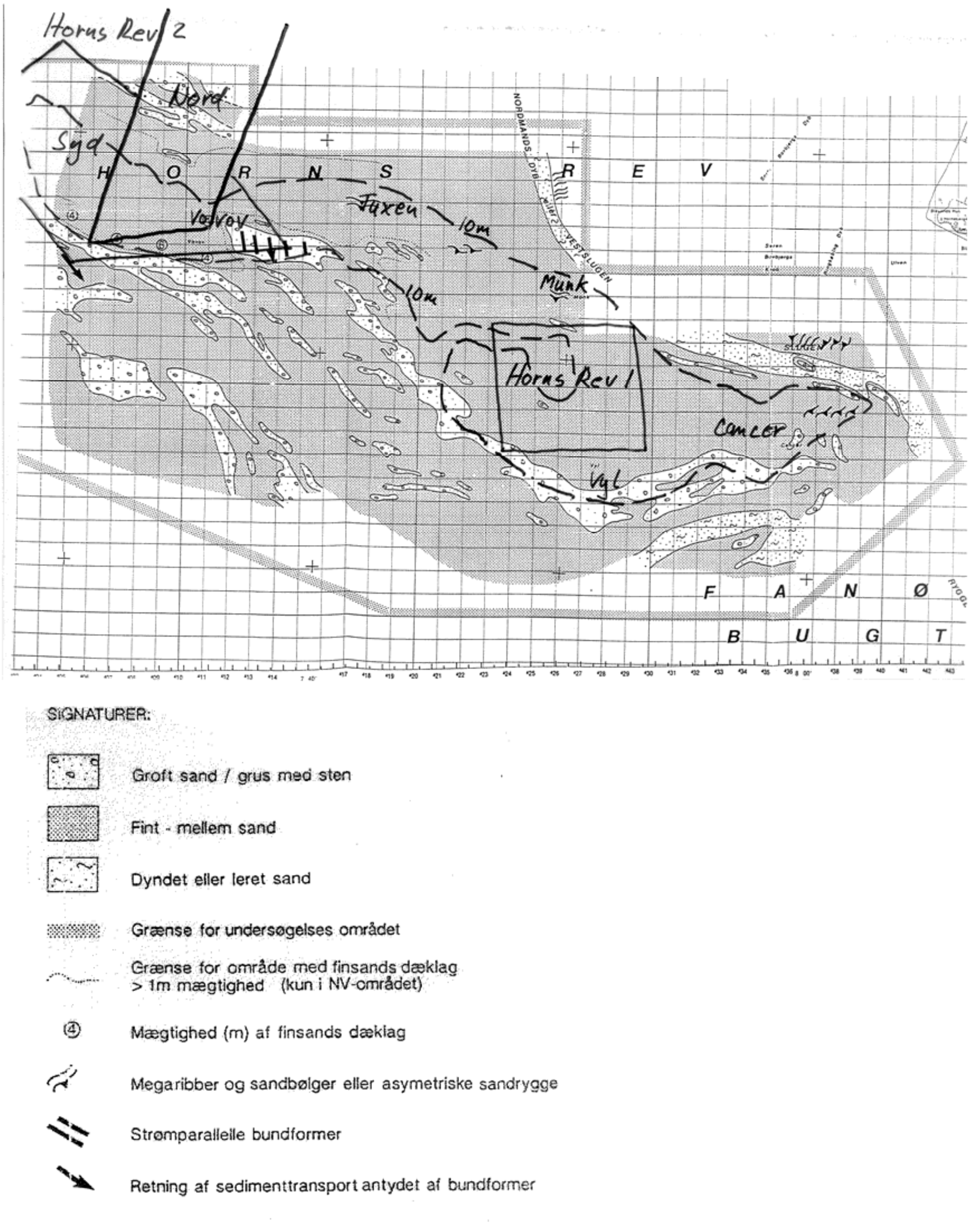

Figure 3.5 Overview of surface sediments at Horns Rev, from Ref. /10/.

3.6 Sediment Transport and Morphology

DHI has performed at major study of sediment transport in the area of Horns Rev and Blåvands Huk, Ref. /1/. The study was performed by application of 2D numerical models for waves, hydrodynamics and sediment transport. One of the major difficulties in the study was to define a representative distribution of seabed characteristics. The used grain size distribution, as defined by the Coastal Authority, is presented in Figure 3.6.

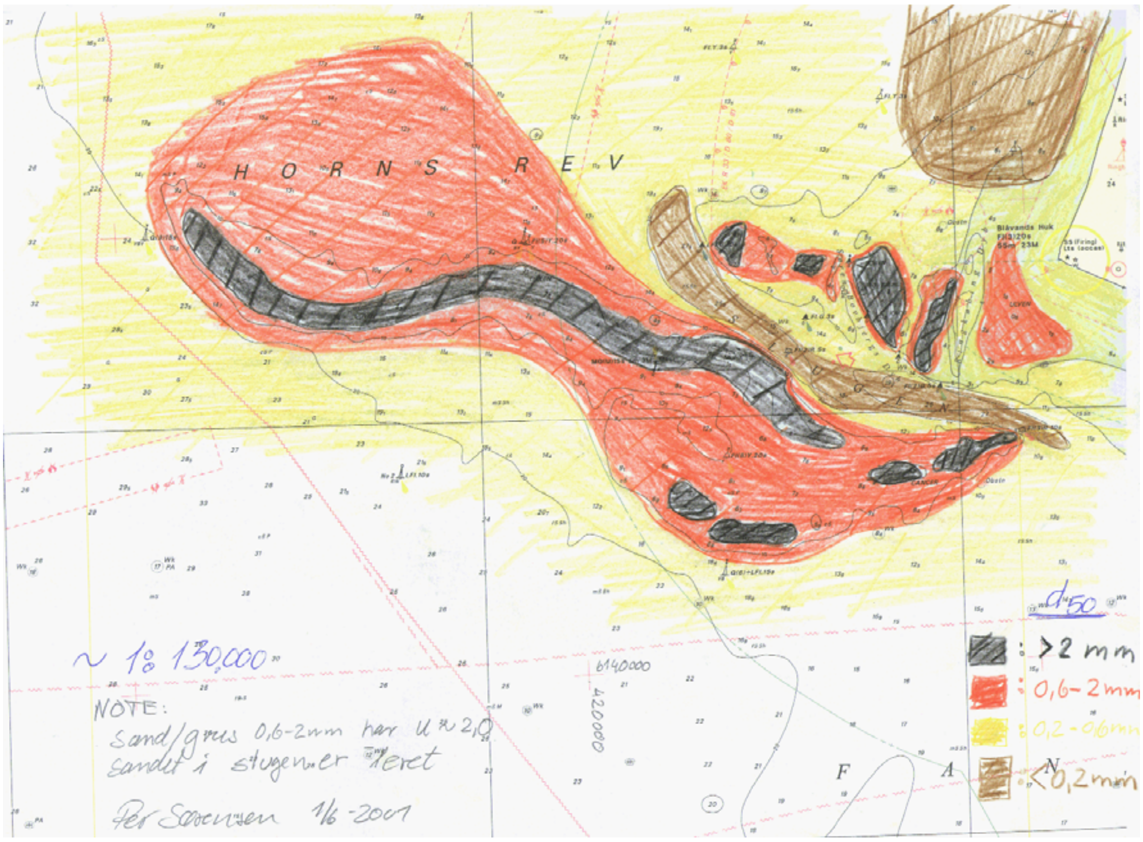

Figure 3.6 Distribution of mean grain diameter at Horns Rev, from Ref. /4/.

The complete summary of Ref. /4/ is presented in Appendix A (in Danish). The most important findings are summarised in the following.

The area is characterized by its complex bathymetry and variable seabed conditions as already described in the previous sub-sections. Consequently a detailed model complex for simulation of waves, hydrodynamics and sediment transport was applied in the study. The sediment transport is simulated under the influence of tides, storm surges and wave drive currents.

The littoral transport along the coast north of Blåvands Huk has been calculated. The net southward transport near Nymindegab is in the order of magnitude of 1 mill. m^3/year. The transport is decreasing towards Blåvands Huk indicating that this section of the coast is accreting, which is confirmed by the historical development as documented in Figure 3.4. This gradient in the transport is caused by the sheltering effect of outer Horns Rev. The shoreline south of Blåvands Huk is receding, as also seen in Figure 3.4. These two shoreline movements result in a northward movement of Blåvands Huk.

Transport fields for selected characteristic storms are presented in Figure 3.7 and Figure 3.8 in order to illustrate the characteristic processes, which form the background for the average transport field as presented in Figure 3.9. All the presented transport fields have been computed taking into consideration the distribution of grain size characteristics as presented in Figure 3.6.

The characteristic transport fields are the following:

- 4 - 7 February 1999. Characterized by waves from WNW to NW, Hs up to 6 m

- 29 Oct. to 2 Nov. 2000. Characterized by waves from WSW to SW, Hs up to 6 m.

The characteristics of the February 1999 storm and the October 2000 storm are described in the following.

The February 1999 southward transport characteristics
The NW-erly waves of the February 1999 storm give rise to the following transport characteristics:

- Southward littoral transport along the shore North of Blåvands Huk

- No littoral transport along the shore SW of Blåvands Huk

- Southward transport on the inner Horns Rev

- Southward transport on the outer NW-ern Horns Rev

- Small SW-ward transport on Vyl and Cancer

- No transport in Slugen

It is noted that possible changes in the transport conditions in the area of the Horns Rev 2 Offshore Wind Farm will have no impact on the transport conditions close to the coast.

The October 2000 northward transport characteristics
The SW-erly waves of the October 2000 storm give rise to the following transport characteristics:

- No littoral transport along the shore North of Blåvands Huk

- No littoral transport along the shore SW of Blåvands Huk

- Northward transport on the inner Horns Rev

- N-NNE-ward transport on the outer NW-ern Horns Rev

- Very large NW-ward (turning North) transport in the deep area immediately west of the tip of the reef
- Small Northward transport on Vyl and Cancer
- No transport in Slugen

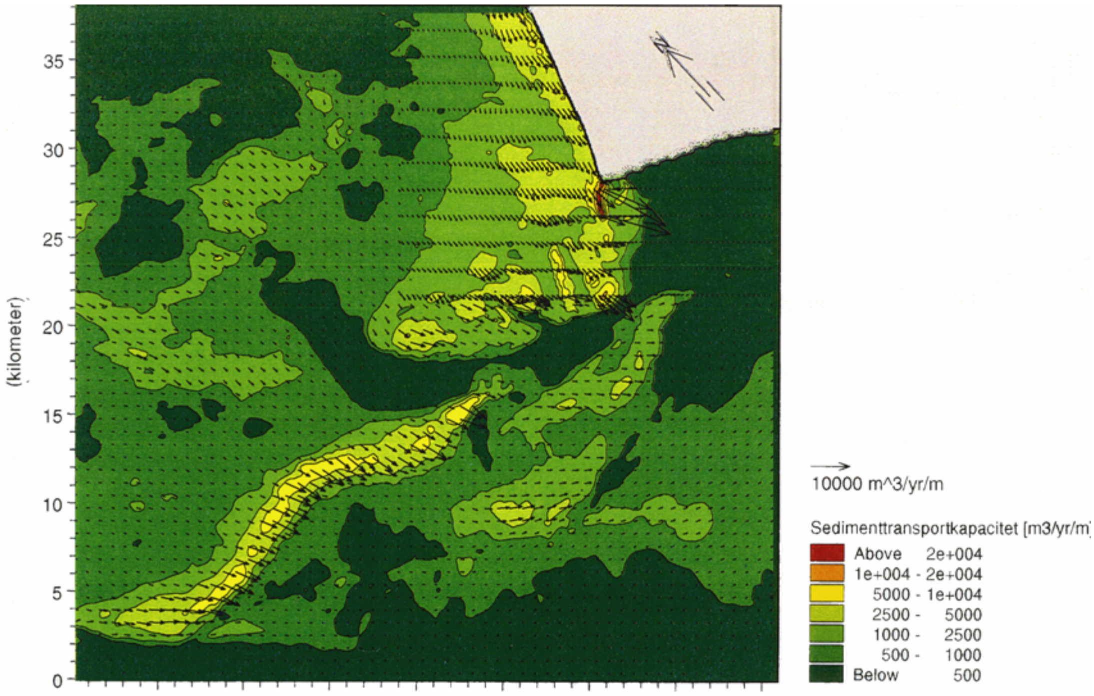

Figure 3.7 Transport conditions for the February 1999 storm, which was dominated by waves from WNW to NW, Ref. /4/.

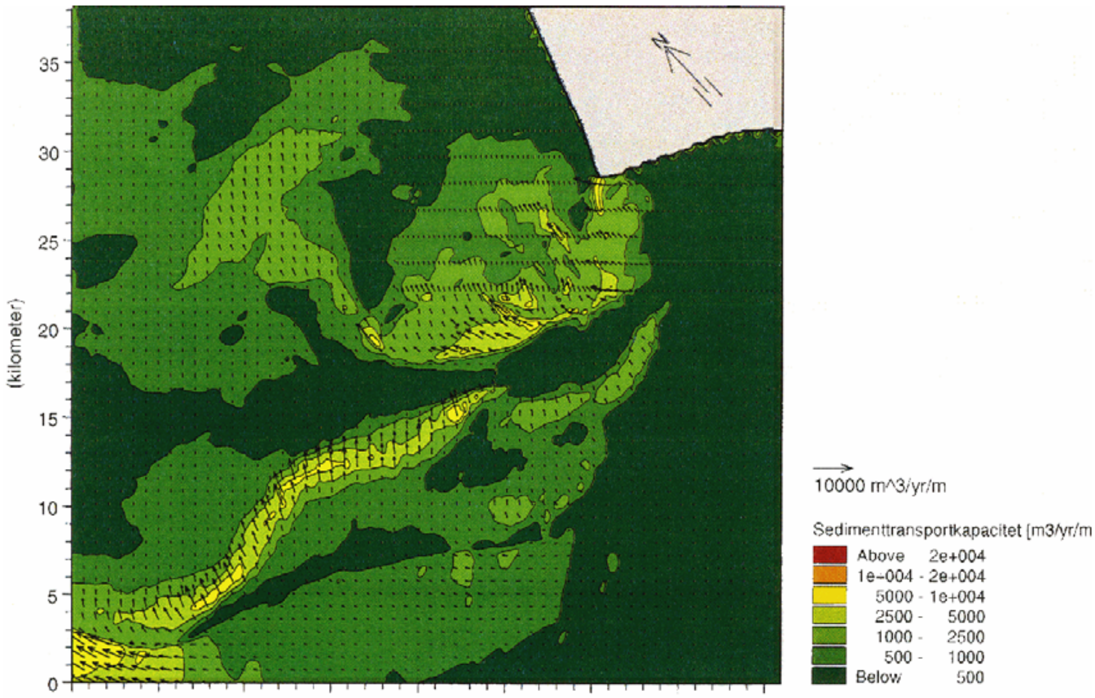

Figure 3.8 Transport conditions for the October 2000 storm, which was dominated by waves from WSW to SW, Ref. /4/.

The average yearly transport rates over the Horns Rev are presented in Figure 3.9.

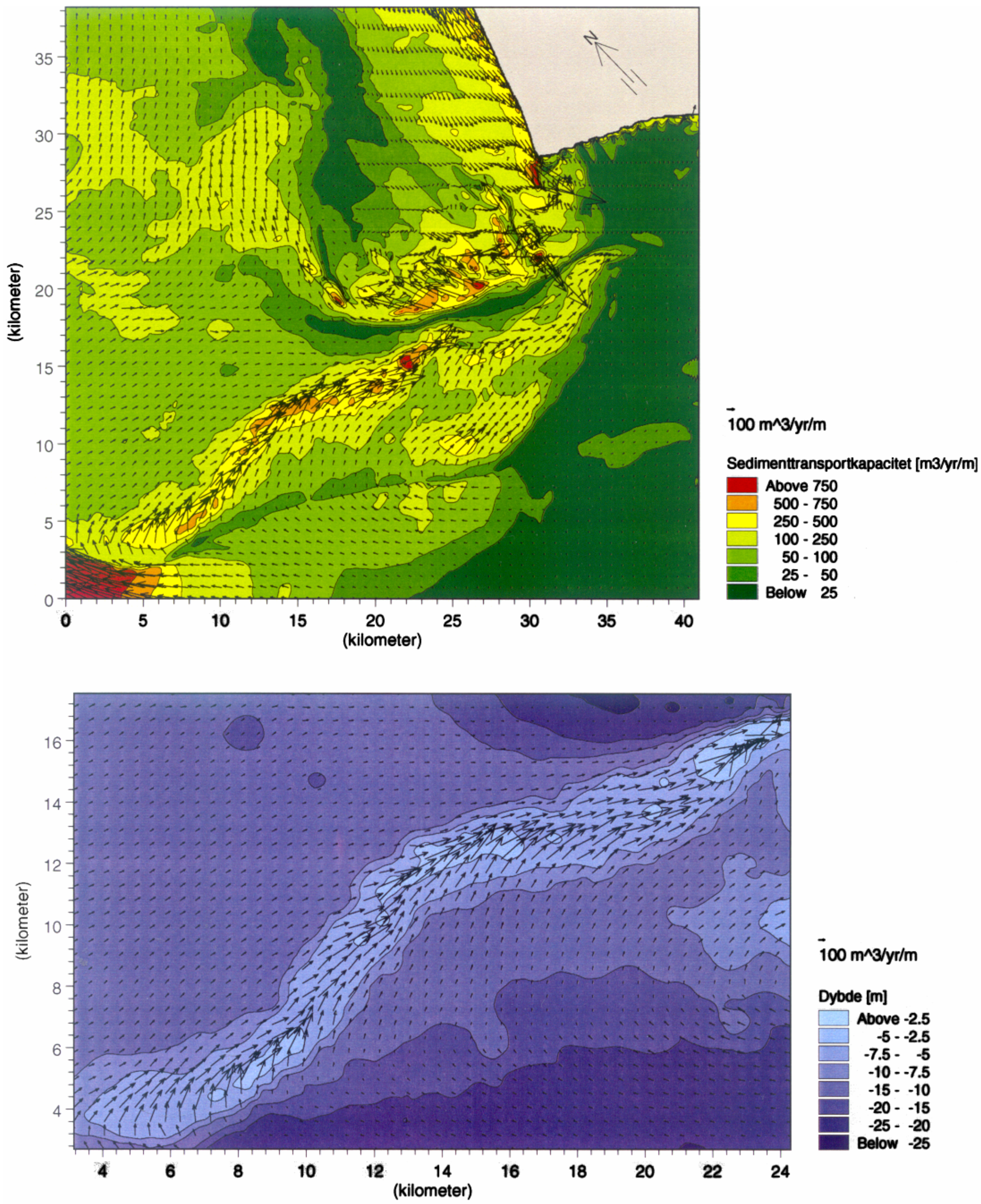

Figure 3.9 *Simulated yearly transport field in the entire area and on Horns Rev proper. The former with underlying contours of sediment transport capacity and the latter with depth contours.*

The transport pattern presented in Figure 3.9 is the average yearly transport field, which has been calculated as a weighted average of the series of storm events which were simulated in the Ref. /4/ study. This field is thus not a physical situation actually occurring, for which reason it can be difficult to understand. The transport fields presented in Figure 3.7 to Figure 3.9 provide, despite the shortcomings in the modelling approach and the difficulties in the interpretation, important information on the transport processes in the Horns Rev area. These are described in the following.

Outer Horns Rev
It is seen that there is a transport towards the reef from both sides and that there are very high transport rates along the reef in E-ward direction. The E-ward component is due to the fact that all wave situations from the predominant direction interval between SW and NW has an E-ward component and the South and North components balance each other. It should be noted that the computations are made with relatively coarse sediments on the top of the reef, refer to Figure 3.6, and despite that the transports are highest on the reef. It should also be noted that it is very difficult to interpret this kind of transport computations, as the computations show the theoretical transport at all locations assuming that the material, which is found on the bed, is being transported. However, this is only part of the truth, as also e.g. finer material transported to an area is transported through the area. The calculated transport field for Horns Rev can be interpreted in the following way. The transport field shows high transport rates on top of the reef, which would indicate that the reef would erode away, if the assumed transport pattern was a correct representation of the average conditions. This leads to the conclusion that the reef must consist of much coarser material than what has been used in the computations, otherwise the reef would not be there today. The transport fields also indicate that no sand can stay on top of the reef, at least only in local depressions in the coarser material. There is probably a tendency to erosion in the extreme western part of the reef and a tendency to accretion of the eastern tip of the reef. The transport fields for specific storms, as shown in Figure 3.7 and Figure 3.8, indicate that large amounts of sand are transported from one side of the reef to the other side.

Immediately west of the tip of the outer Horns Rev
There is a very high NW- and to N-ward transport in this area, which is due to the strong current in this area under situations with northward current. This is due to the considerable hydraulic resistance provided by Horns Rev, which generates contracting flow around the tip of the reef. This has caused deepening of the area south of the reef and deposition north of this area. This is clearly seen in the bathymetry over the area.

The offshore area north of the outer Horns Rev
This area shows primarily NE- and N-ward transport. This is caused by the "Jyllandsstrømmen", which is a general counter-clockwise circulation in the North Sea, caused by the tidal and the Coriolis power.

Along the coast North of Blåvands Huk
There is a clear net southward littoral transport along this coastal section, which is because this area is nearly totally sheltered for waves from SW by Horns Rev. Therefore there is only waves from NW, which drive the S-ward littoral transport. This transport feeds into the area called Ulven, whereas only a small fraction continues along the coast SW of the Huk.

The inner Horns Rev
The transport conditions in this area are very complicated. During situations with NW-erly waves sand is supplied from the littoral transport along the coast to this area, where it is deposited on the southern slopes of the shoals in this area. During situations with SW-erly waves this sand is transported towards north. The resulting transport pattern is thus a return of the S-ward littoral transport to the areas north of the inner Horns Rev. However, there is also shifting transport patterns within very short distances, which is reflected in the shift between shoals and channels in this area. These formations are gradually shifting NW-ward, which are evidenced by historical comparison as described in Ref. /2/. This indicates that the inner Horns Rev is a morphological active formation in contrast to the outer Horns Rev, which is most probably stable due to its composition of mainly very coarse material. This, however, remains to be physically confirmed.

4 BASELINE DESCRIPTION OF WAVE CONDITIONS IN THE AREA

Wave conditions have been modelled in the area in order to provide design conditions for the offshore wind turbines.The offshore wind turbines were not included in the modelling. The wave modelling study is reported in a separate report, Ref. /11/.

There are two main factors of importance in the evaluation of the impact of the Horns Rev Wind Farms on the wave condition:

1. The wave conditions in the area before the construction of the wind farm

2. The attenuation of the waves by the monopile foundation for the turbines.

Item 1 is discussed in the following subchapters whereas item 2 is discussed in Section 6.

4.1 Description of General Wave Conditions in the Area

Results of the wave simulations have been extracted with the purpose of illustrating the overall wave conditions in the area. Wave conditions corresponding to the offshore wind directions: 330°, 310°, 290°, 270°, 250°, 230° and 210°, for wind speeds of 15 m/s, were modelled. These wave patterns are presented in Figure 4.1 through Figure 4.4.

Wave height direction distributions have also been extracted in the central part of the Horns Rev 2 area as well as along the coastal sections North and SW of Blåvands Huk, in Points 1 - 3 and 4 – 6, respectively. The points 1 through 3 have been extracted at a distance of about 5 km from the coast at water depths of 10 to 15 m whereas the points 4 through 6 have been extracted at a distance of about 3 km from the coast at water depths of about 5 m. The location of the extraction points are presented in Figure 4.5 and the wave roses are presented in Figure 4.6.

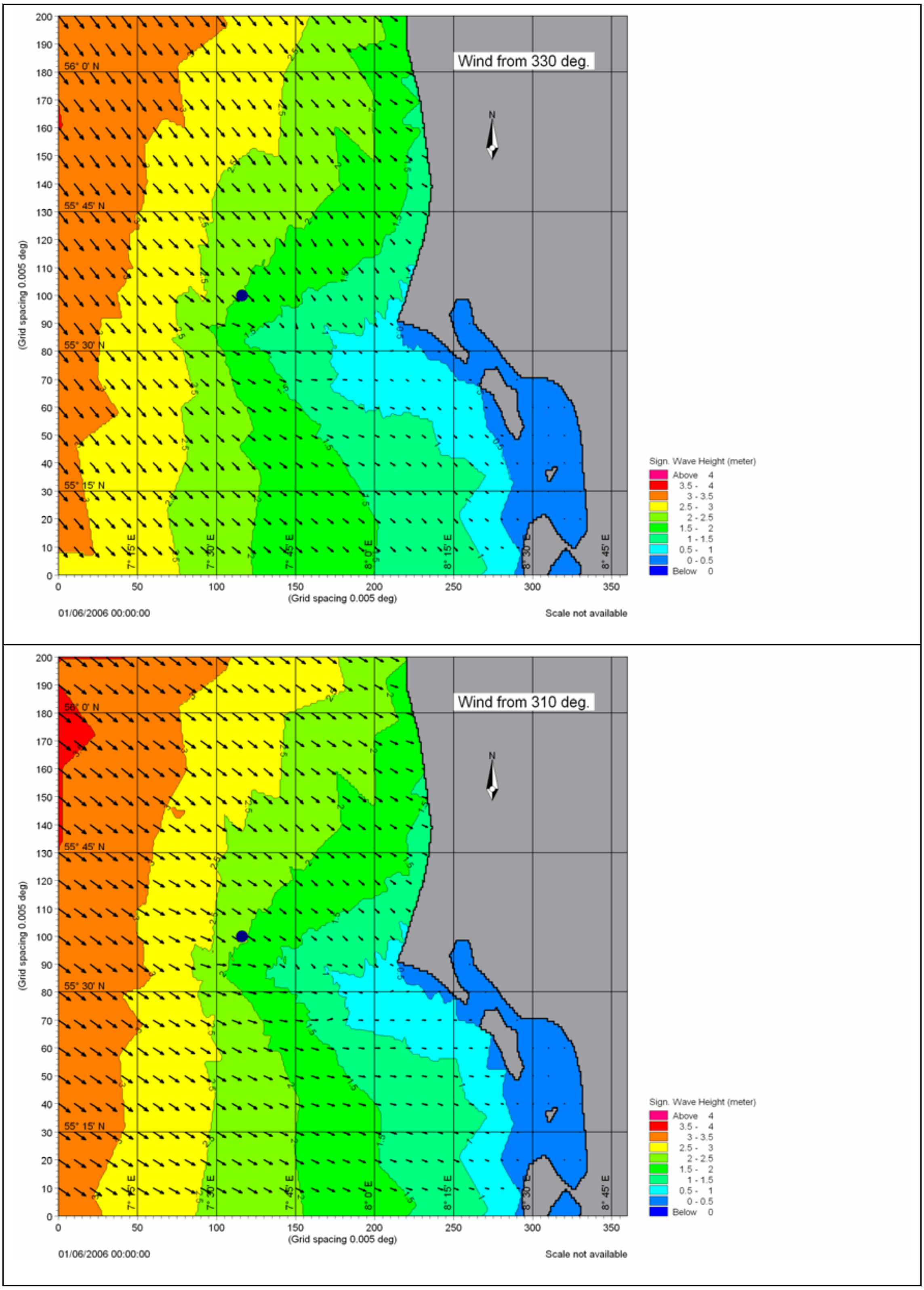

Figure 4.1 Wave patterns over Horns Rev area for constant wind speed of 15 m/s for wind directions 330° and 310°.

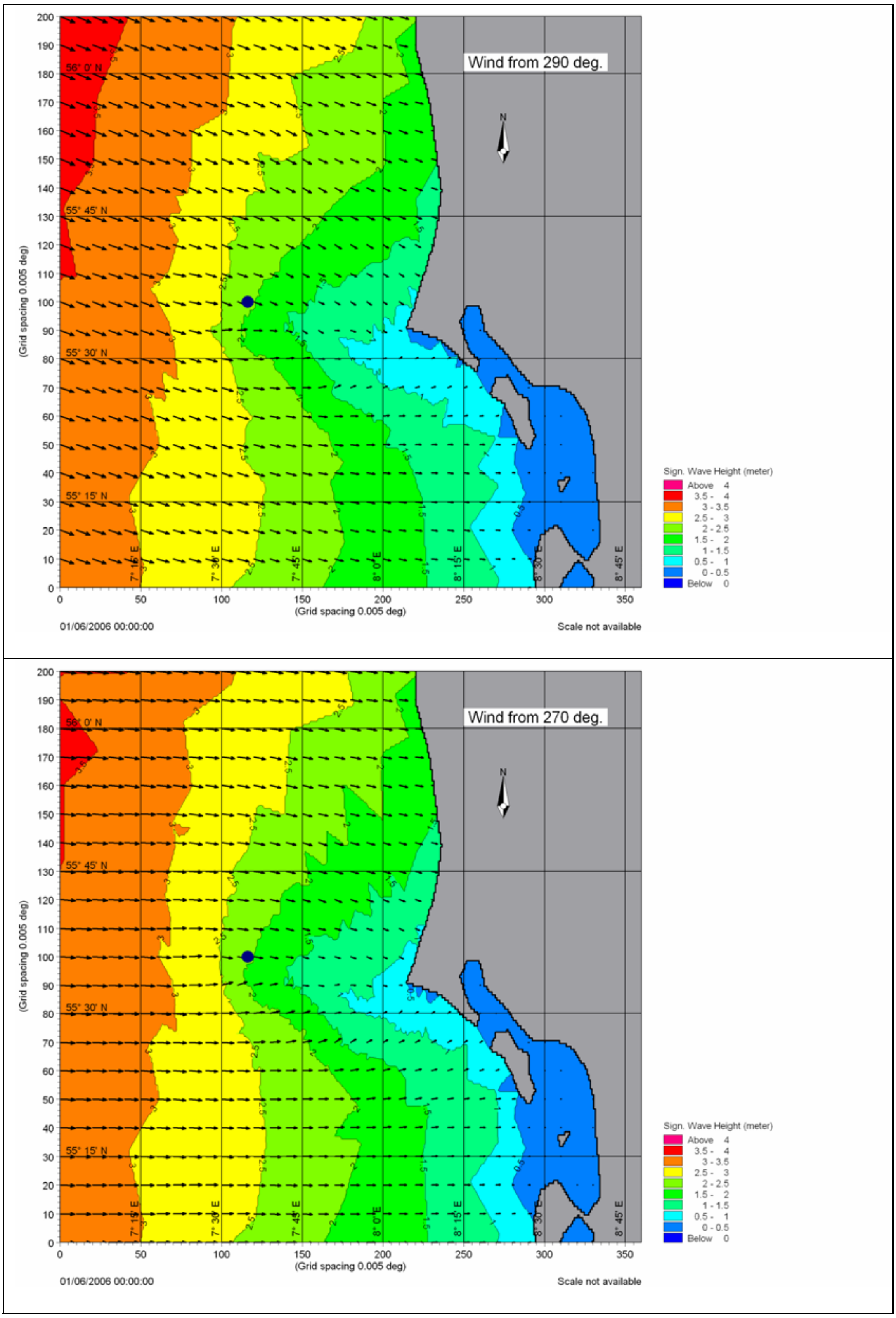

Figure 4.2 Wave patterns over Horns Rev area for constant wind speed of 15 m/s for wind directions 290° and 270°.

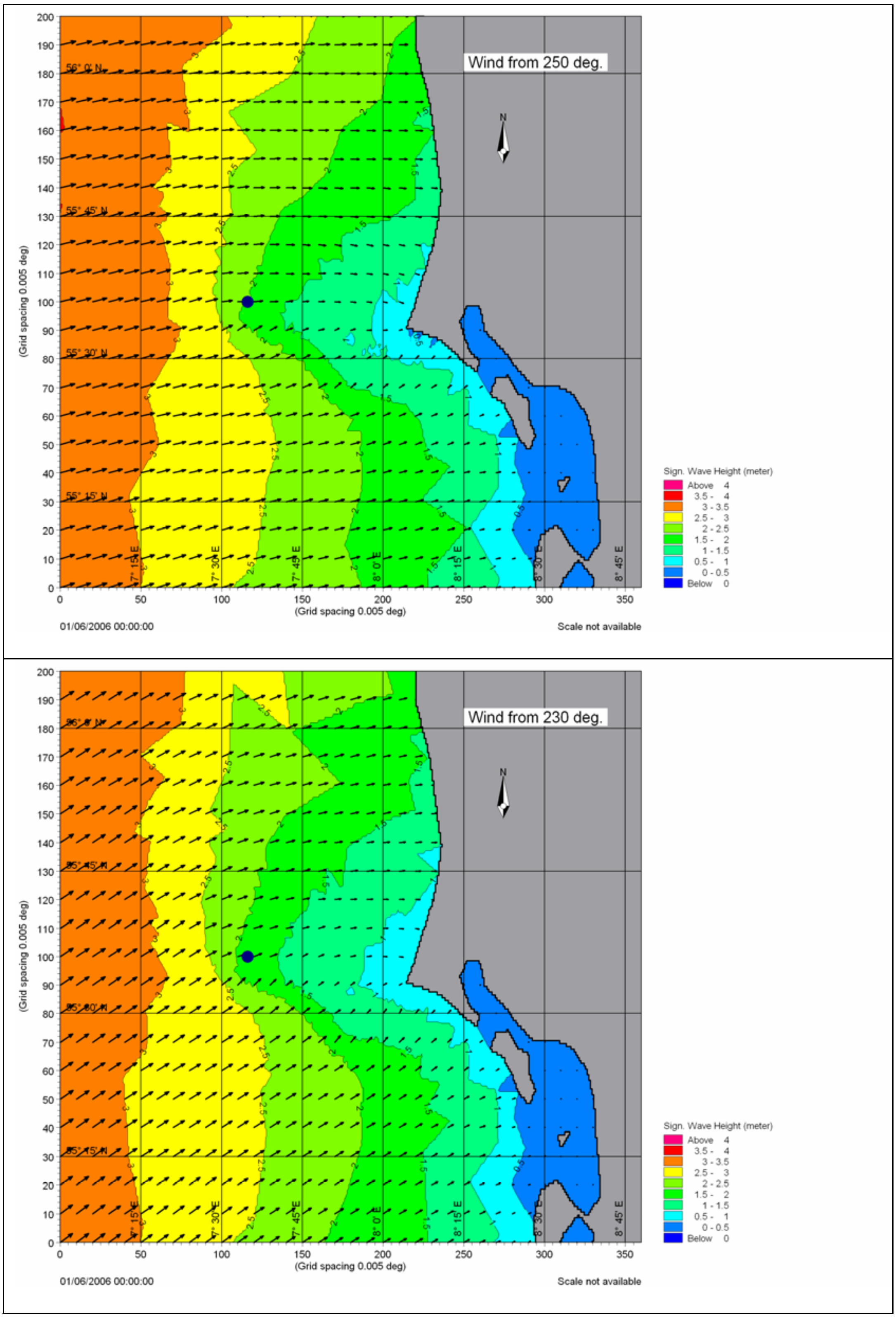

Figure 4.3 Wave patterns over Horns Rev area for constant wind speed of 15 m/s for wind directions 250° and 230°.

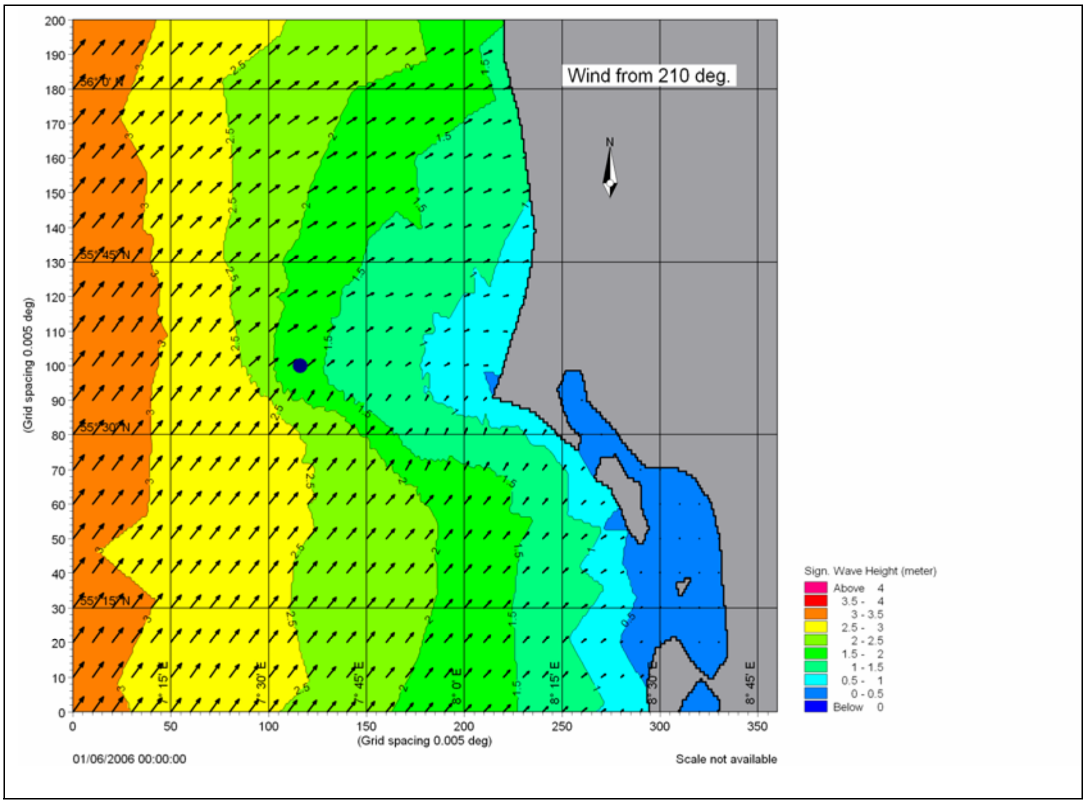

Figure 4.4 Wave pattern over Horns Rev area for constant wind speed of 15 m/s for wind direction 210°.

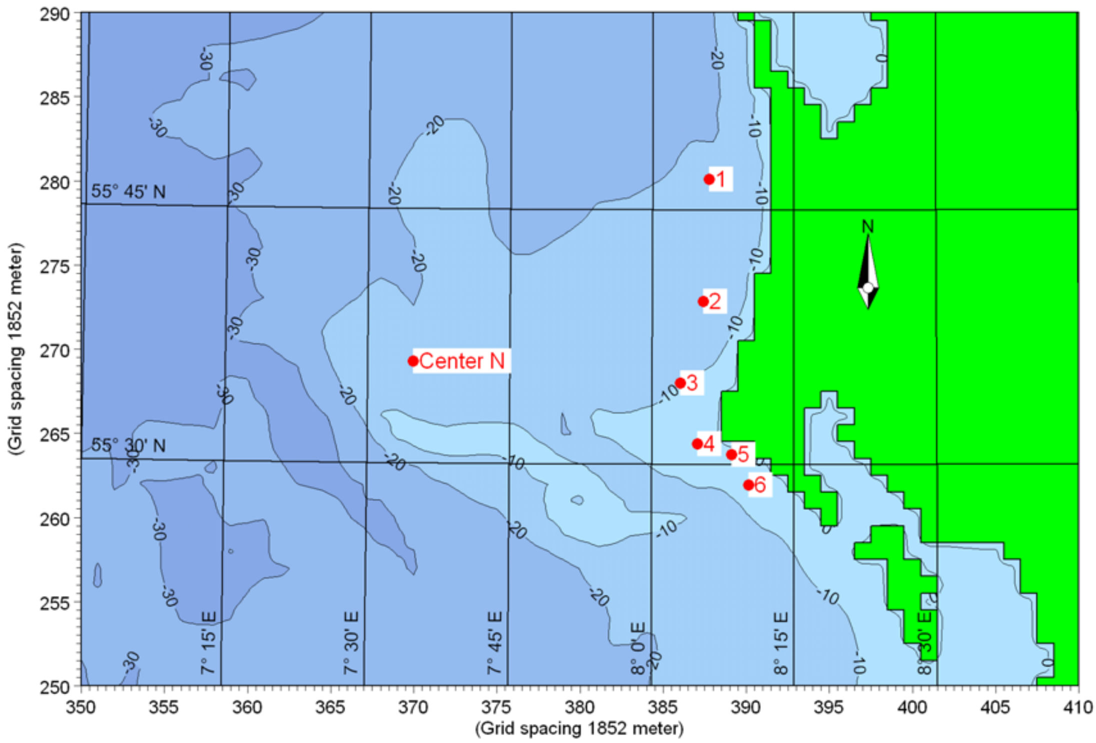

Figure 4.5 Location map showing the extraction points for the wave roses which are presented in Figure 4.6.

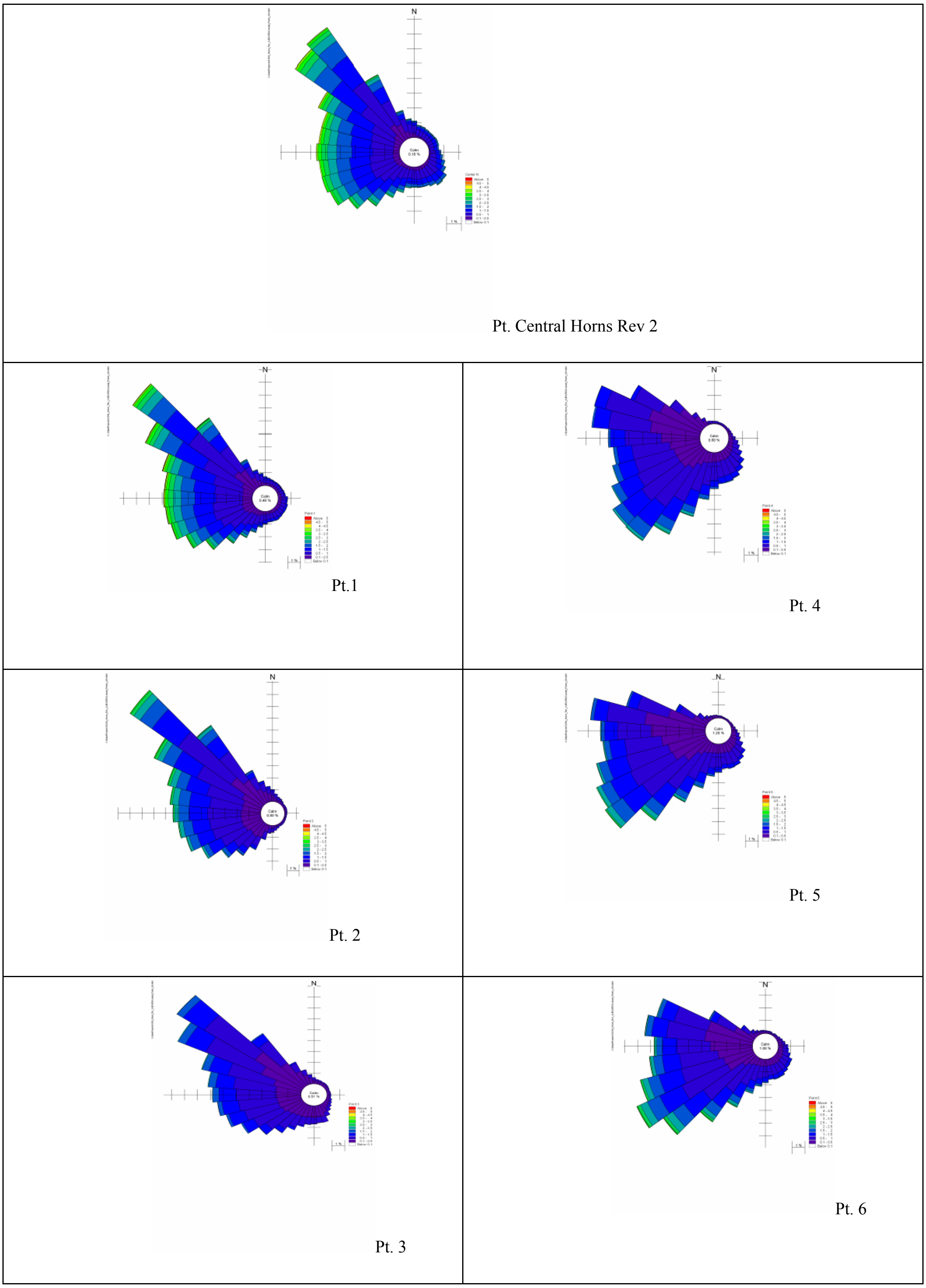

Figure 4.6 Directional wave height distribution (wave roses) at Central point in the Horns Rev 2 area and in 3 locations along the coast North of Blåvands Huk (Points 1 – 3) and in 3 locations SE of Blåvands Huk (Points 4 - 6) at an approximate water depth of 10 m, see Figure 4.5 for locations.

It is generally seen that the waves are significantly influenced by the shallow water at Horns Rev, the waves break on the reef and no waves higher than about H_s = 0.6 m times the local water depth can pass over the reef. This means that Horns Rev significantly limits the nearshore wave condition in the lee area of the reef. This results in the characteristic wave conditions described in the following.

4.1.1 Wave Conditions along the Coast North of Blåvands Huk

The northernmost part of this section, represented by Point 1, is only insignificantly affected by Horns Rev because it is so far northward that most waves, which reach the Horns Rev 2 area, also reach Point 1. The wave roses for the two points are therefore very similar.

The influence by Horns Rev is increasing further towards south. This is seen on the wave roses for Points 2 and 3, in which wave heights from all directions are decreasing gradually from north to south due to the shelter provided by Horns Rev. This is also seen clearly in the wave patterns for the area for all the offshore directions 330° through 210°, refer Figure 4.1 and Figure 4.4.

4.1.2 Wave Conditions along the Coast Southeast of Blåvands Huk

The entire section represented by Points 4 through 6 is sheltered by Horns Rev for waves greater than about 2.0 m from directions more northerly than 230°. Waves from more southerly directions can penetrate south of Horns Rev and reach this coastal section, the more southerly in the stretch the more wave penetration from these directions.

5 BASELINE DESCRIPTION OF CURRENT CONDITIONS IN THE AREA

The design current conditions in the area are described in Ref. /11/ on basis of a comprehensive modelling study. Furthermore, detailed modelling of waves, currents and sediment transport was performed in the study described in Ref. /4/.

The currents in the area are dominated by the tidal currents during meteorologically calm conditions, which give rise to shifting south- and northward currents of magnitude of up to 0.5 m/s in the Central point. However, the strongest currents occur during storm conditions where the wind impact on the water surface gives rise to storm surges and associated currents. These situations cause current speeds, which are considerable higher than the regular tidal currents, but with the same main directions, N- and S-ward, respectively. The current speeds during these extreme situations can be up to more than 1 m/s in the Central point, where data has been extracted, see Figure 5.3 and the analyses in the Metocean report, Ref. /11/.

It is evident from the illustrations of current patterns in the area as presented in Figure 5.1 and Figure 5.2, that there is considerable variation in current directions and speeds over the area due to the influence by the outer and inner Horns Rev and Slugen and the other secondary channels (dyb) in the area.

Horns Rev constitutes a major hydraulic resistance element in the area, which caused much higher current speeds on top of the reef than in adjacent areas and which causes a deviation of the flow around Horns Rev and through Slugen. The geology of the area and the associated morphological processes, which have been discussed in Section 2, have resulted in this complicated system of “fixed” geological elements (outer Horns Rev) and associated hydraulic conditions (waves, currents and water level variations) and quasi stable morphological processes.

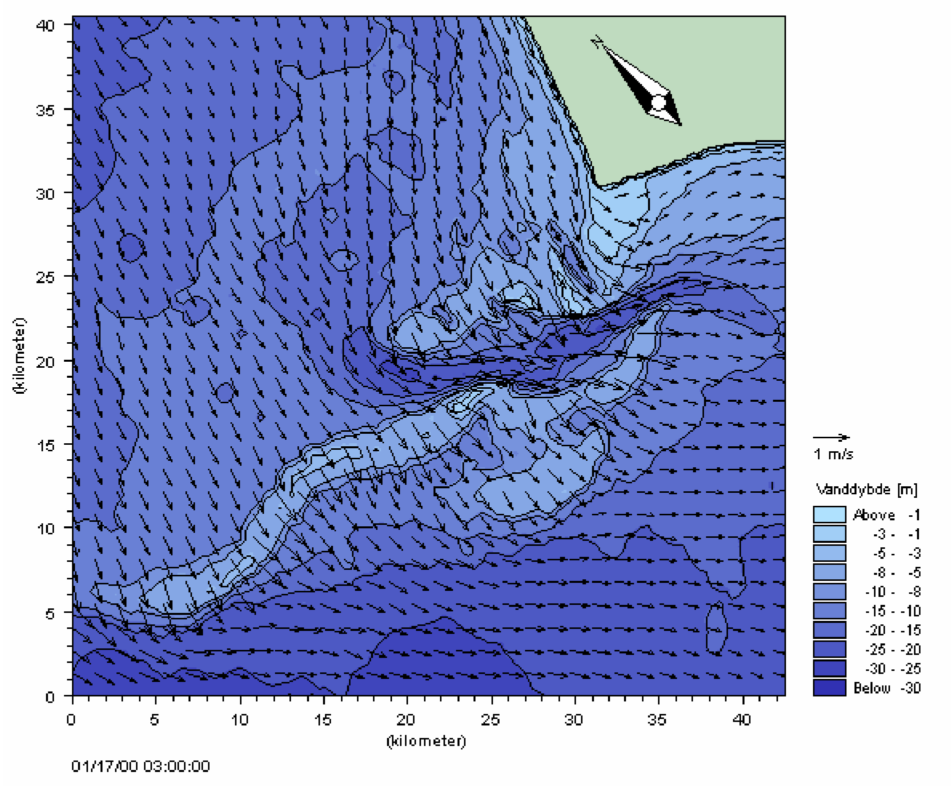

Figure 5.1 *Typical S-ward current, situation 17 January 2000 at 03.00, with underlying depth contours, green is land. From Ref. /4/.*

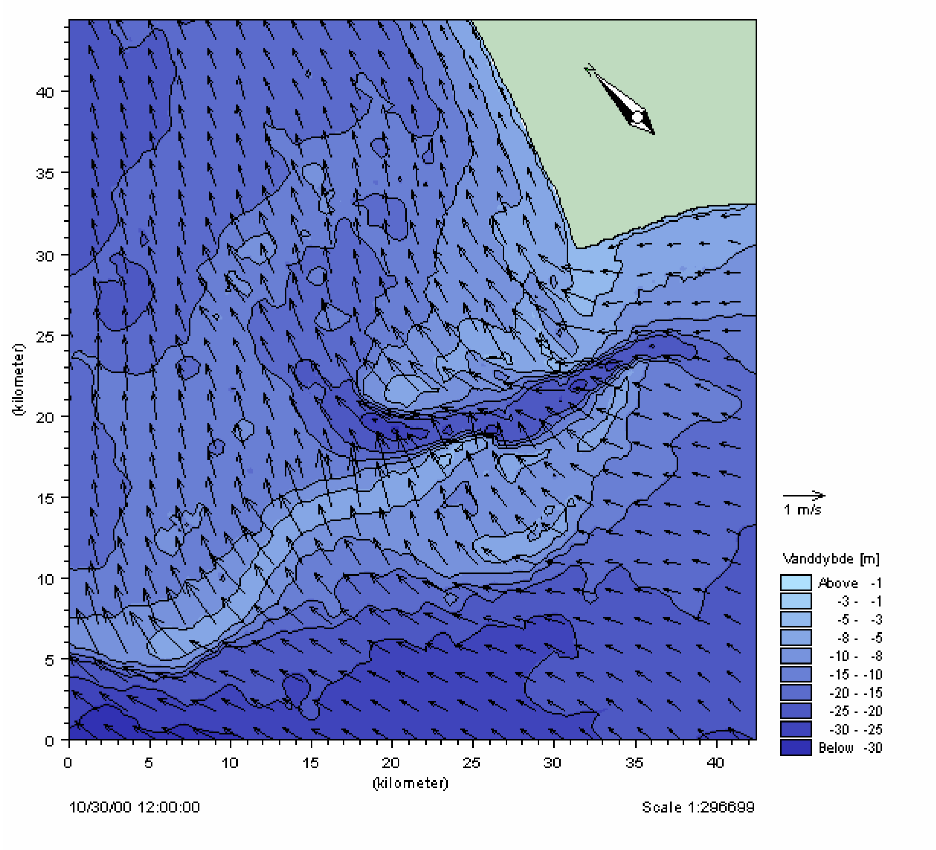

Figure 5.2 Typical N-ward current, situation 30 October 2000 at 12.00, with underlying depth contours, green is land. From Ref. /4/.

A directional distribution of currents in the central point of Horns Rev 2 is presented in Figure 5.3.

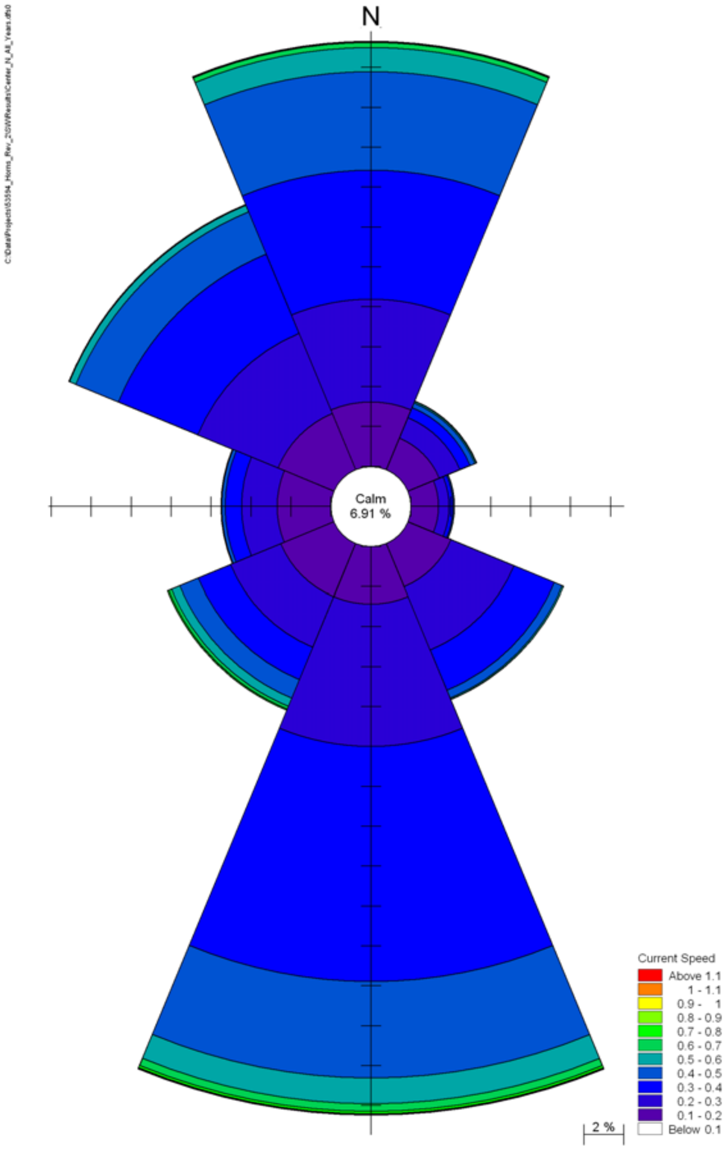

Figure 5.3 Directional distribution of current speeds in the Central Point (55.60 N; 7.58 E). For location, see Figure 4.5.

6 ASSESSMENT OF IMPACT OF HORNS REV 1 AND 2 ON WAVES, CURRENTS AND COASTAL MORPHOLOGY

6.1 Attenuation of the Waves by the Monopile Foundation for the Turbines

Attenuation of waves by the Horns Rev 1 Wind Farm
The attenuation of the waves when passing through the Horns Rev 1 Wind Farm has previously been evaluated in Ref. /3/. The conclusion of the evaluation was that the nine rows of wind turbine monopiles cause a reduction in the wave height of **3.3%,** based on the conservative assumption that all wave energy hitting the pile is reflected**.**

Attenuation of waves by the Horns Rev 2 Wind Farm
The evaluation in the following is performed for Horns Rev 2 North with the results for Horns Rev 2 South shown in parenthesis.

The attenuation of the waves when passing the Horns Rev 2 North (South) wind farm is evaluated in the following by utilising the same method as that used in Ref. /3/.

The flux of energy transported by a progressive linear wave $E_f\left(\frac{J}{sm}\right)$ is proportional to the wave height, H^2, and can be written as (see Ref. /12/)

$$E_f = \frac{1}{16}\rho g H^2 c\left[1+\frac{\frac{4\pi}{L}depth}{\sinh\left(\frac{4\pi}{L}depth\right)}\right]$$

where L is the wave length, c is the phase velocity and g is the gravity.

The integrated flux $E\left(\frac{J}{s}\right)$ over a distance *dy = 850 (540) m* hereby becomes

$$\mathrm{E} = E_f dy = \frac{1}{16}\rho g H^2 c\left(1+\frac{\frac{4\pi}{L}depth}{\sinh\left(\frac{4\pi}{L}depth\right)}\right)dy$$

If one assumes that all wave energy (conservative assumption) hitting the foundation with diameter D is reflected, the integrated reflected flux E^{ref} becomes

$$E^{ref} = E_f D = \frac{1}{16}\rho g H^2 c\left(1+\frac{\frac{4\pi}{L}depth}{\sinh\left(\frac{4\pi}{L}depth\right)}\right)D$$

The ratio between the incoming wave height and the wave height after one wind turbine has been passed hereby becomes

$$\frac{E - E^{ref}}{E} = \left(\frac{dy - D}{dy}\right) = \left(\frac{H^{pass}}{H}\right)^2$$

Inserting D=4.2 m one finds a conservative estimate of the wave height reduction for Horns Rev 2 North (and South) equal to 0.24% and (0.37%), respectively. With 7 foundations (14) after each other in approx. E-W direction a conservative estimate of the wave height reduction for Horns Rev 2 North (South) is **1.7%** and **(5.2%),** respectively**,** over a N-S stretch of approx. 11 km and (4 km) immediately in the lee of the wind farm. It is thus seen that the Horns Rev South Wind Farm causes more reduction of the waves than the Horns Rev 2 North Wind Farm.

Overall evaluation of the influence of Horns Rev 1 and 2 on the nearshore wave conditions

Making a conservative assumption that all wave energy hitting a foundation is absorbed, it can be shown that the wave height will be reduced as presented in Table 6.1 for the two alternative wind farm configurations.

Table 6.1 Reduction in wave height for Horns Rev 1 in combination with Horns Rev 2 North and South, respectively.

Alternatives	**R: Reduction in wave height**	**W.: Width of shadow zone**	**RxW: Resulting reduction for individual farms**	**Σ RxW: Resulting reduction for both farms**	**Average resulting reduction over total impact width**
Horns Rev 1 Horns Rev 2 North	3.5%	5 km	17.5	36.2	2.26% over 16 km
	1.7%	11 km	18.7		
Horns Rev 1 Horns Rev 2 South	3.5%	5 km	17.5	38.3	4.26% over 9 km
	5.2%	4 km	20.8		

It is seen that the resulting reductions for both combinations of Horns Rev 1 and Horns Rev 2 give approximately the same resulting reduction: Σ RxSt (36.2 and 38.3, respectively), however distributed differently as seen in the last column of the table.

This reflects that the total impact from a wind farm depends mainly on the number of wind turbines, which is the same. For Horns Rev 2 North, the reduction is small immediately behind the short rows of wind turbines, but the width of the shadow zone is larger. For Horns Rev 2 South, the reduction is larger because the waves have to pass more wind turbines when going through the farm, but the width of the shadow zone is correspondingly smaller. Further away, in the lee of the wind farm, the effect will be the same for the two configurations.

It is noted that the reductions in the wave height behind the various stages of the wind farms are in all cases relatively small, less than about 5%. The average reduction for Horns Rev 1 plus Horns Rev 2 North is 2.3% over a total width of 16 km whereas the average reduction for Horns Rev 1 plus Horns Rev 2 South is 4.3% over a total width of only 9 km. The total reductions for the two alternative combinations of Horns Rev 1 and 2 are thus nearly the same.

It is evaluated that the relatively small reduction in the wave height immediately leeward of the combined wind farms will be smoothed out before the waves reach the nearshore area due to the following reasons:

- The importance of the reduction of the waves immediately landward of the wind farms will be reduced as many of the waves will be attenuated anyway because of the presence of the Horns Rev, refer to the description of the wave conditions in the area in Section 4.

- Because of the long distance between the wind farms and the nearshore area, which is more than 15 km for Horns Rev 1 and about 30 km for Horns Rev 2.

- Strong currents in the area will also tend to smooth out the impact of the wave reduction.

It is consequently concluded that the nearshore wave climate as well as the wave climate in areas adjacent to the wind farms will be practically unaffected by the presence of the wind farms.

The wind farms will also affect the wind field in the farm area and in the lee of it. This will modify the generation of waves by the wind. However, this is considered of minor influence when considering that the waves entering the wind farm from the west have been generated over a stretch of the order of 100 km and that the stretch to the east of it has an extension of 20-30 km, over much of which the waves are attenuated by breaking rather than increased by wind generation.

6.2 Reduction of the Currents by the Monopile Foundation for the Turbines

Reduction of currents by the Horns Rev 1 Wind Farm
The attenuation of the currents when passing through the Horns Rev 1 wind farm has previously been evaluated in Ref. /3/. The conclusion of the evaluation was that the current velocity in the wind farm area is reduced with 2% at a maximum.

Reduction of currents by the Horns Rev 2 wind farm alternatives
The evaluation in the following is performed for Horns Rev 2 North, however, the reduction for the Horns Rev 2 South is identical.

The reduction of the currents when passing the Horns Rev 2 north (south) wind farm is evaluated in the following by utilizing the same method as used in Ref. /3/.

By making a simple analogy with the channel flow it can be shown that there will be very little reduction in current speed around the foundations. This is based on the assumption that the channel flow in a stationary situation is a balance between the driving force, i.e. the pressure gradient, and the restricting forces, i.e. the bed friction and the drag force, on the wind turbines (Ref. /13/). The analogy to a channel flow will result in conservative results as some of the water in the real situation can be diverted around the wind farm area not being restricted by the channel walls, whereby the resistance of the wind farm will be smaller. Furthermore, in a non stationary flow, part of the pressure gradient is used to accelerate the water, which has not been taken into account when assuming that the flow is stationary. Consequently, the assumption that the flow is stationary leads to conservative results.

The drag on one wind turbine foundation can be written as

$$F_{drag} = \frac{1}{2}\rho D\, Depth\, C_D V|V|$$

where D is the diameter (taken to be D=4.2m), C_D is a drag coefficient typically equal to one, and V is the depth-averaged velocity, ρ is the water density.

The bed friction in an area Dx times Dy is found from

$$F_{fric} = \rho Dx\, Dy\, U_f |U_f|$$

where the friction velocity U_f can be estimated from the equation

$$U_f = \frac{0.4V}{\ln\left(\frac{11 Depth}{k}\right)}$$

k is the bed roughness, for a plane bed taken to be 2.5 times the grain diameter. $k = 2.5 * d_{50}$. Inserting typical values in the wind farm area d_{50} = 1.0 mm and Depth=8m one finds:

$$U_f = 0.04 * V$$

Looking at a situation where the flow is stationary and driven by a constant pressure difference ∇P (water level difference), the flow in an area corresponding to n wind turbines in a row in the direction of the current at distances Dx=850m in the row and with a distance between the rows Dy=540m can be found:

Situation without a wind turbine

$$\rho n Dx\, Dy 0.0016 V^{before} \left| V^{before} \right| = nDx * Depth \nabla P$$

Situation with a wind turbine

$$\frac{1}{2} n \rho D\, Depth\, C_D V^{after} \left| V^{after} \right| + \rho n Dx\, Dy 0.0016 V^{after} \left| V^{after} \right| = nDx * Depth \nabla P$$

Comparison

The velocity with a wind turbine compared with the situation without:

$$\frac{V^{after}}{V^{before}} = \sqrt{\frac{Dx\, Dy 0.0016}{Dx\, Dy 0.0016 + \frac{1}{2} D\, Depth\, C_D}}$$

Inserting the above numbers one find

$$V^{after} = 0.99 V^{before}$$

The above calculations show that the current velocity in the Horns Rev 2 wind farm area is reduced by 1% at a maximum. As mentioned above, for a natural non stationary flow not restricted by a channel this reduction will be even smaller.

Overall evaluation of the influence of Horns Rev 1 and 2 on the current conditions in the nearshore area

It is evaluated that the impact on the current conditions of the two wind farms will be negligible due to the following reasons:

- The evaluated local reductions in current velocities inside and downstream of the two wind farm areas are very small

- The natural current pattern is very variable and complex

- The impact on the nearshore current pattern will be nil because the impacts near the wind farms are very small and because the current direction in principle is parallel to the shoreline

- It is in no way causing any blocking of the water transport along the Jutland coast and is therefore deemed insignificant with respect to the environment

6.3 Evaluation of the Impact on the Existing Coastal Morphology and Sediment Transport in the Area

Assessment of impact of Horns Rev 1 wind farm
The impact of the Horns Rev 1 wind farm has in Ref. /3/ been evaluated as follows:

On the basis of the calculated impact of the monopile foundations on waves and currents it is evaluated that there will be only an insignificant impact on the seabed morphology within the area of the wind farm. This is apart from local scour around each individual foundation, which may be prevented by scour protection. Furthermore, there will be no impact outside the wind farm area, which means that there will be no impact on the nearshore coastal morphology nor on the littoral transport along the coasts N and SE of Blåvands Huk.

Assessment of impact of Horns Rev 2 wind farm
The existing geology and transport conditions in the area, as well as the impact of the Horns Rev 2 wind farm on waves and currents, have been described in detail in the previous sections. The main findings in relation to the assessment of the impact on coastal morphology and sediment transport in the area are the following:

- The geology in the outer Horns Rev area is dominated by coarse and stable sediments on top of the reef, the outer Horns Rev has been stable for as long as records are available.

- The transport conditions are dominated by high transport capacity rates on the reef, which means that all fine and medium sand transported to the reef area will "immediately" be transported over the reef to the relatively more "calm" areas to the North and South of the reef body.

- The main transport directions in the Horns Rev 2 area are Northward and Southward, respectively, which means parallel to the general shoreline direction.

- The impact of the Horns Rev 2 wind farm on waves and current, which are the main driving forces for the sediment transport in the area, has been assessed to be negligible.

Based on the above and similarly to the assessment of the impact of the Horns Rev 1 wind farm, the following assessment is made for the impact of the Horns Rev 2 Wind Farm on coastal morphology and sediment transport in the area:

On basis of the calculated impact of the monopile foundations on waves and currents it is evaluated that there will be only an insignificant impact on the seabed morphology within the area of the wind farm. This is apart from local scour around each individual foundation, which may be prevented by scour protection. Furthermore, there will be no impact outside the wind farm area, which means that there will be no impact on the nearshore coastal morphology nor on the littoral transport along the coasts N and SE of Blåvands Huk.

Overall assessment of the impact of Horns Rev 1 and 2 on the coastal morphology and on the sediment transport in the nearshore area
It has been assessed that there will be no impact on the coastal morphology and sediment transport in the area from the Horns Rev 1 wind farm and from the Horns Rev 2 wind farm when they are evaluated separately. The following items are of importance to the assessment of the combined impact of the two wind farms:

- The two wind farms are located a long distance from each other thus acting as two separate entities in respect of impact on waves, currents and sediment transport.

- The wave, current and transport conditions are very variable over the Horns Rev area.

- The individual impacts on waves, currents and sediment transport of the two wind farms have been assessed to be negligible.

On the basis of the above conditions it is assessed that the combined impact of the two wind farms Horns Rev 1 and Horns Rev 2 on the coastal morphology and sediment transport conditions in the area will be negligible.

7 REFERENCES

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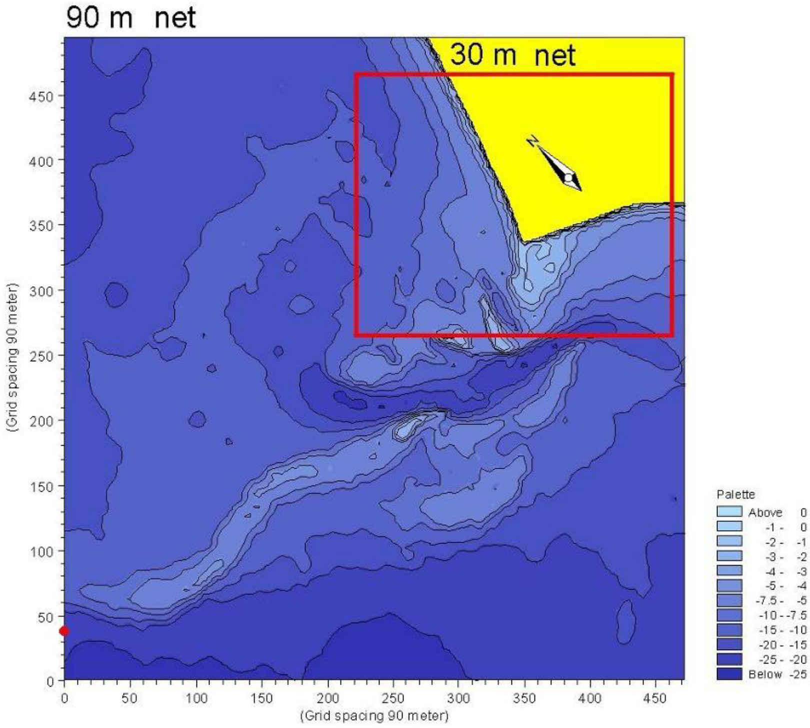
A P P E N D I X A

Summary of the Report:
Sedimenttransport ved Horns Rev og Blåvands Huk
Oktober 2001
DHI for Kystdirektoratet
Ref. /4/

Sammenfatning af Ref. /4/

Nærværende rapport omhandler de sedimenttransportundersøgelser omkring Blåvands Huk og Horns Rev, der er udført for Kystdirektoratet. I forbindelse med Kystdirektoratets opstilling af et sedimentbudget for hele Jyllands vestkyst er det ønsket at få undersøgt og kvantificeret sedimenttransportforholdene omkring Horns Rev og langs kysten ved Blåvands Huk. Området er kendetegnet ved sin komplekse bathymetri – se Figur 2.1 - og en detaljeret beregningsmodel til beskrivelse af bølge-, strøm- og sedimenttransportforholdene er derfor opstillet. Den detaljerede model er opbygget af følgende moduler fra DHI's matematiske modelkompleks (MIKE 21): MIKE 21 NSW, MIKE 21 HD (samt MIKE 21 NHD) og MIKE 21 STQ3. En detaljeret beskrivelse af modellerne kan findes i rapportens afsnit 4.



Figur 2.1 Modelområde hvor detaljerede beregninger foretages. Opløsningen er 90×90 m. Ydermere er kystrelaterede processer opløst i et subnet, markeret med rødt i øverste højre hjørne (kyststrækningen nord og syd for Blåvands Huk). Netvidden for subnet er 30×30 m. Den røde prik tæt ved koordinatsystemets origo angiver omtrentlig placering af sekundær station 4 – se Ref. /5/.

Modelleringen af havstrømmene (tidevands- og vindgenereret strøm) er foretaget i et område, der dækker hele Nordsøen. Dette er gjort med den såkaldte "nestede" udgave af MIKE 21 HD (MIKE 21 NHD), hvor en gradvis forfinelse af opløsningen af bathymetrien gennem 4 net-niveauer foretages ind mod området af interesse. Resultaterne fra MIKE 21 NHD tilvejebringer randbetingelser til selve området af interesse – se Figur 2.1, hvor desuden processer relateret til bølgebrydning medtages. Processerne i dette område er opløst med en netvidde på 90×90 m. I selve kystzonen er bathymetrien yderligere forfinet og beskrevet i et 30×30 m net.

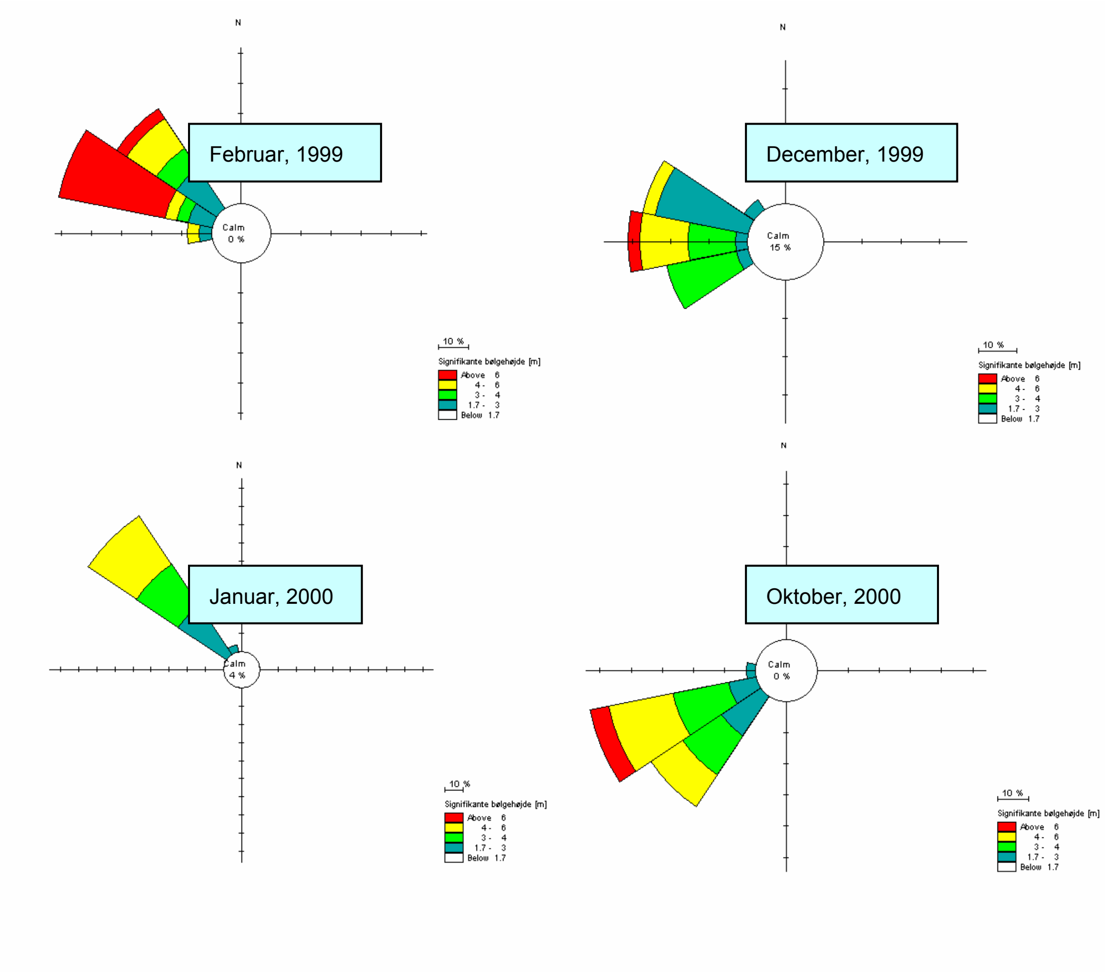
Modelkomplekset er blevet kalibreret og efterfølgende verificeret ved at sammenligne modelresultater og målinger af vandstande, strømhastigheder samt bølgehøjder på Horns Rev, der er fundet god overensstemmelse.

Det opstillede modelkompleks er derefter anvendt til at beregne strømnings-, bølge- samt sedimenttransportfelter under historiske stormsituationer. Datoerne for de modellerede stormperioder er angivet i Tabel 2.1. I Bilag B er tidsserier af bølgehøjder, vandstande samt vindhastigheder vist for hver enkel af disse storme. Tidsserierne er udtaget i sekundær station 4 – se Ref. /5/.

Tabel 2.1 Udvalgte stormperioder.

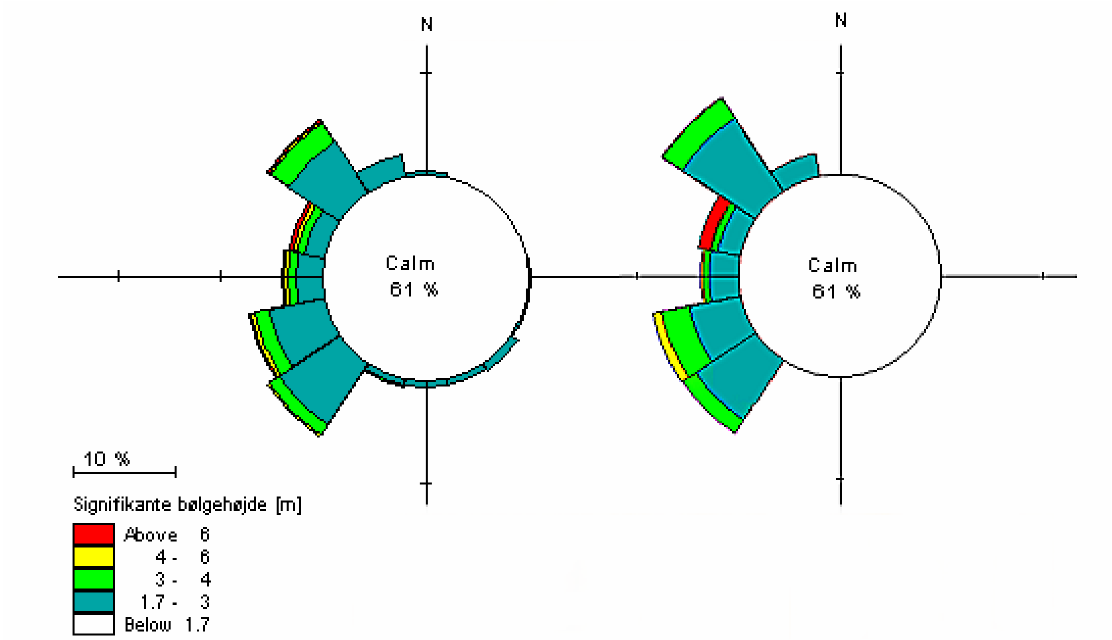
Storm	Dato
Februar	4/2-7/2 – 1999
December	2/12-5/12 – 1999
Januar	16/1-19/1 – 2000
Okt./Nov	29/10-2/11 – 2000

I Figur 2.2a er bølgeforholdene for hver enkel storm præsenteret i form af en bølgerose, der afbilleder fordelingen af signifikante bølgehøjder på udbredelsesretningerne på en lokalitet ved Horns Rev. Øverst i venstre hjørne ses bølgerosen for februarstormen (1999), mens den for decemberstormen (1999) ses øverst til højre. Bølgerosen for januar- hhv. oktoberstormen (begge 2000) ses i nederste venstre og nederste højre hjørne. Bølgeroserne er opstillet på basis af transformerede bølgekonditioner fra Nymindegab til Horns Rev, dvs. sekundær station 4 - se Figur 2.1 – i perioden 1997-2001. For decemberstormen er bølgekonditioner dog transformerede fra Fjaltring-måleren.



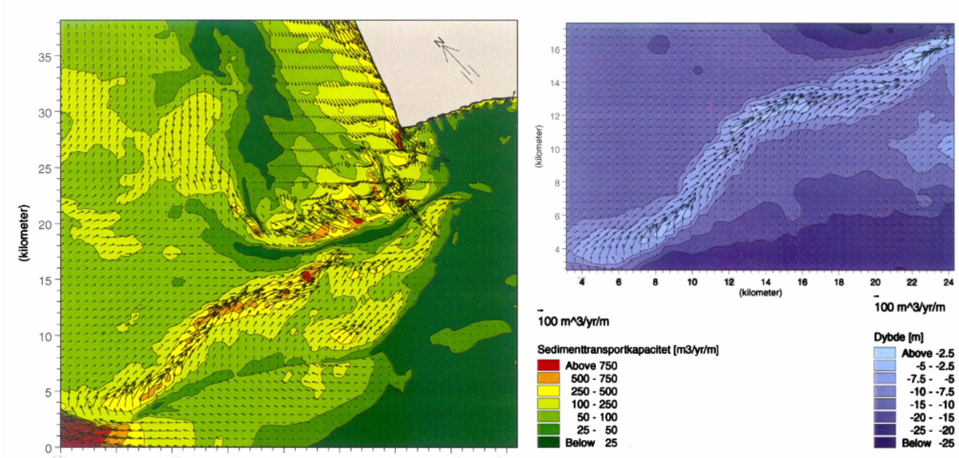
Figur 2.2a *Bølgerose for hver enkel storm. Fordelingen af bølgernes retning og højde (signifikante) ved sekundær station 4 – se Ref. /5/ - beliggende tæt ved koordinatsystemets origo i Fig 2.1. Baseret på transformationsprogram og KDIs bølgekonditioner fra Nymindegab og Fjaltring (december-storm). Februar, 1999: øverste venstre-, december, 1999: øverste højre -; januar, 2000: nederste venstre, oktober, 2000: nederste højre hjørne.*

I Figur 2.2b er bølgeforholdene i perioden 1997-2001 præsenteret i form af en bølgerose, der afbilleder fordelingen af signifikante bølgehøjder på udbredelsesretningerne på en lokalitet ved Horns Rev. Bølgerosen til venstre i figuren er den generelle bølgestatistik, baseret på transformerede bølgekonditioner fra Nymindegab til Horns Rev, dvs. sekundær station 4 - se Figur 2.1.



Figur 2.2b Venstre: Fordelingen af bølgernes retning og højde (signifikante) ved sekundær station 4 – se Ref. /5/ - beliggende tæt ved koordinatsystemets origo i Figur 2.1. Baseret på transformationsprogram og KDIs bølgekonditioner fra Nymindegab. Højre: Bølgerose konstrueret af de enkelthændelser som stormene (se Figur 2.2 a) er sammensat af.

Som man kan se ved en overordnet sammenligning af bølgerosen til venstre i Figur 2.2b og bølgeroserne i Figur 2.2a, repræsenterer de udvalgte storme, herunder bølgens udbredelsesretning, det statistiske billede ganske godt. De mange hændelser og kombinationer af bølger og strøm, som stormene er sammensat af, er – ved at betragte dem individuelt og kombinere dem vha. udvalgte vægtningsfaktorer - brugt til at etablere en bølgestatistik, der afspejler de væsentlige træk i den generelle bølgestatistik. Til dette formål er alle hændelserne tilknyttet en vægt, der er relateret til dens hyppighed i den generelle bølgestatistik. Resultatet, den konstruerede bølgestatistik, er vist til højre i Figur 2.2b. Ved at tildele de enkelte sedimenttransportfelter i stormene vægten af den tilhørende bølgehændelse, er et estimat af det årlige sedimenttransportfelt udarbejdet – se Figur 2.3.

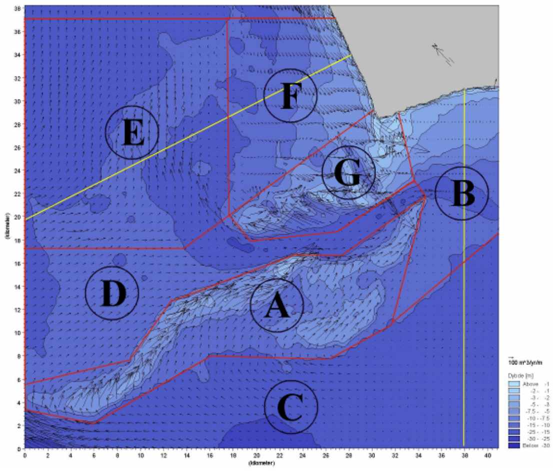


Figur 2.3 Årligt sedimenttransportfelt beregnet med kornkort (Bilag A). Felterne er vist dels i hele interesseområdet og dels i et område omkring Horns Rev. Førstnævnte med underliggende konturer af sedimenttransportkapaciteten og sidstnævnte med dybdekonturer.

Middel-sedimenttransporten for de enkelte storme, beregnet på basis af strøm- og bølgefelterne, er præsenteret i Bilag C1-C4. For hver storm er middel-sedimenttranportfeltet beregnet med i alt 4 korndiameterfordelinger. I 3 af de 4 korndiameterfordelinger er korndiameteren konstant i hele området (0.2, 0.4 og 0.8 mm), og i et tilfælde er et kornkort med variable korndiametre brugt. Det årlige sedimenttransportfelt vist i Figur 2.3 er netop beregnet med kornkortet. Det årlige transportfelt (eller nettotransporten) samt det initielle erosions/aflejringsmønster er vist i Bilag D. Det skal pointeres, at erosions/aflejringsmønstret, beregnet med en variabel fordeling af korndiameteren, kan være vanskeligt at fortolke, da modellen i overgangen mellem to kornfraktioner vil forudsige en for stor morfologisk ændring (da transporten er stærkt afhængig af korndiameteren). Dette skyldes, at sedimenttransportberegningerne er baseret på en model, der antager lokal ligevægt i sedimenttransporten, dvs. den lokale transportkapacitet er fuldt udnyttet.

På basis af det årlige sedimenttransportfelt er variationen af den litorale nettotransport ned langs kysten nord for Blåvandshuk beregnet gennem 7 tværsnit placeret fra kysten og vinkelret ud til 10 m-dybdekonturen. Netto-langstransporten er sydgående og falder fra ca. 900.000 m^3/år til 765.000 m^3/år tættere på Blåvands Huk, hvilket indikerer at kysten er under fremrykning. Dette resultat stemmer fint overens med angivne transportmængder samt variationen af denne beregnet i Ref. /7/ og /11/. Det forhold, at den langsgående nettotransportrate er i overensstemmelse med de i Ref. /7/ og /11/ beregnede, understøtter den metode, der blev anvendt til at vægte resultaterne fra de 4 storme og antyder, at det øvrige sedimenttransportfelt er både kvalitativt og kvantitativt rigtigt.

I Figur 2.4 er interesseområdet opdelt i 7 kontrolkasser (defineret af Kystdirektoratet herefter KDI).



Figur 2.4 Definition af de 7 kontrolkasser (A..G) hvor sedimentbudget opstilles.

Sedimentbudgettet for de 7 kontrolkasser er opstillet i Tabel 2.2, hvor en nettoaflejring angives ved positive tal og erosion ved negative tal. Det skal pointeres, at de givne tal er meget følsomme over for placeringen af kontrolkassegrænserne, specielt ved beregninger med kornkort, hvor transportkapaciteten ændrer sig som følge af abrupte ændringer i korndiameteren.

Tabel 2.2 Sedimentbudget for de i Figur 2.4 definerede kontrolkasser. Resultater med kornkort – se Bilag A.

Kontrol-kasse (se Figur 2.4)	**Sedimentbudget for kontrolkasse [m^3/år]**	**Omtrentligt areal af kontrolkasse [km^2]**	**Initiel opvæksthastighed af havbund [cm/år]**
A	+1.944.000	218	1.49
B	+222.000	105	0.35
C	-1.679.000	359	-0.78
D	-797.000	188	-0.70
E	+534.000	341	0.26
F	-130.000	147	-0.15
G	+1.676.000	94	3.00

Som Tabel 2.2 viser, er kontrolkasse F, dvs. området nord for Blåvands Huk, rimeligt stabilt, da der kun er et tab af sand på ca. 130.000 m^3/år svarende til en gennemsnitlig ændring på –0.15 cm/år (korrigeret for porøsitet). Kontrolkasse F medtager mere end selve den kystnære transport, som forårsager en kystfremrykning.

Et andet interessant resultat er den lille transport, der slipper rundt om Blåvands Huk – se Tabel 2.2, kontrolkasse B. Den mindre transportkapacitet syd for Blåvands Huk bekræftes af tidligere undersøgelser af sedimenttransportforholdene i området og viser, at de store mængder, der aflejres i Grådyb længere mod syd (lige nord for Fanø), således ikke kommer fra området nord for Blåvands Huk. Den sydgående (bølgeinducerede) nettotransport nord for Blåvands Huk aflejres ud for Blåvandshuk på Ulven og vil efterfølgende omlejres af nordgående havstrømme i et større område, der inkluderer de mange knob og render, der ligger ud for vinkelforlandet, Blåvands Huk. Det tyder på, at der ikke er en udveksling af sand på tværs af Slugen, dvs. mellem Horns Rev og den bagvedliggende kyststrækning. Horns Rev er med andre ord en selvstændig enhed, der modtager sand fra de tilstødende områder. Betragtes kontrolkasserne A og C under ét ses, at nettotilførslen af sand er næsten nul, hvilket tyder på, at der inden for dette område sker en isoleret omlejring af sediment, hovedsageligt fra kontrolkasse C til A. Kontrolkasse A modtager således knapt 2.0 mill. m^3/år, svarende til en gennemsnitlig opgrunding i området på ca. 1.5 cm/år. Til sammenligning viser beregningerne, at havbunden i området øst for Slugen (kontrolkasse G) vokser med 3.0 cm/år. Den komplicerede bathymetri i området nordøst for Slugen (kontrolkasse G), hvor havbunden er gennemskåret af nordsydgående render, afspejler sig i et tilsvarende kompliceret sedimenttransportfelt. Retningen af sedimenttransporten, samt størrelsen af den, skifter over meget korte stræk – se Figur 2.3, hvilket – som den gennemsnitlige opvækst på 3.0 cm/år også antyder - indikerer, at morfologien i området er meget dynamisk. I Ref. /8/ er dette område beskrevet som meget mobilt, samt at de morfologiske elementer er forlagt i nordlig retning; begge observationer understøtter beregningerne og vægtningen af de enkelte storme.

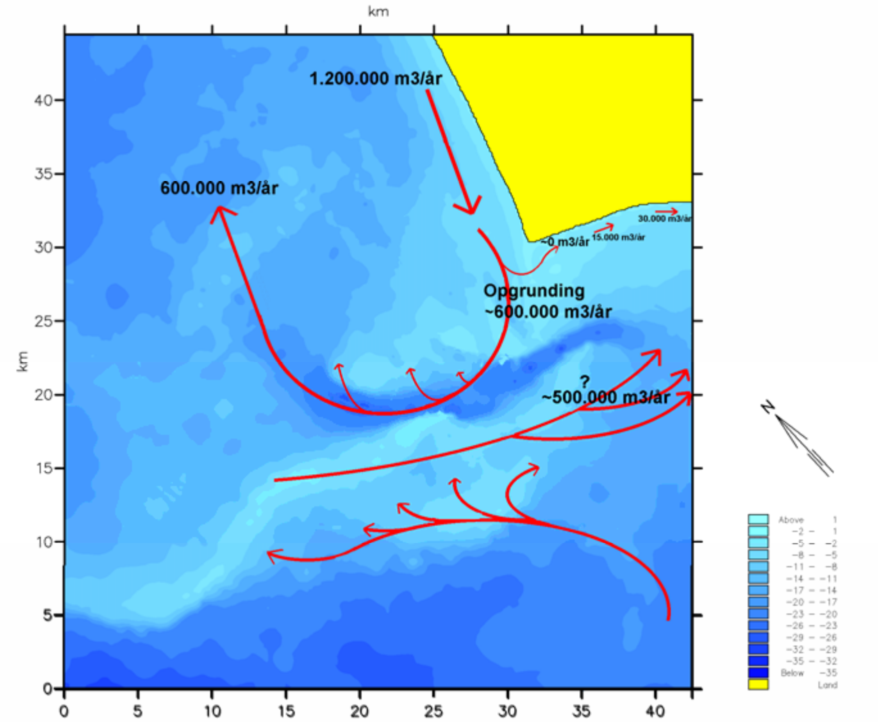
Det skal bemærkes, at en opgrunding i Horns Rev-området vil føre til mere bølgebrydning og større hastigheder ind over revet som følge af lavere vand, hvorfor initielle rater ikke er repræsentative for en morfologisk langtidsfremskrivning. I dette område giver modellen med andre ord en indikation af, hvor morfologien ændrer sig, snarere end hvor hurtigt den ændrer sig. Langtidsændringer i morfologien kan kun beregnes vha. en morfologisk model.

Resultaterne viser en tendens til, at mobilt sand bliver transporteret ind mod revet fra vest-sydvest i den vestlige ende og fra nord i den østlige ende – se Figur 2.3. Det relativt fine sand, der er transporteret ind i kontrolkasse A, vil ikke kunne aflejres på toppen af revet (måske på siderne af revet) og dermed bidrage til dens opvækst, da sedimenttransportkapaciteten er så stor her, at selv sand med korndiametre på 1-2 mm er endog meget mobilt. Da oplysninger om revets beskaffenhed er baseret på få sporadiske observationer gjort af lokale fiskere samt enkelte tilgængelige målinger, er det derfor sandsynligt, at revet flere steder snarere består af grovere materiale og er måske visse steder endog et armeret og stabilt abrationsområde i form af et mere eller mindre stenet rev. Af denne grund vil nærværende resultater sandsynligvis overvurdere transporten og omlejringen på selve revet. Tendensen til nettotilførsel af sand forklarer ikke desto mindre, hvorfor revet - ikke for længst - er bort-eroderet af de ekstreme påvirkninger fra bølger og strøm, samt det faktum, at der rent faktisk er rapporteret om fund af mobilt sand på revet.

Det skal understreges, at ovenstående konklusioner beror på antagelser om, at havbunden er mobil, at anvendte kornkort (se Bilag A) afspejler faktiske bundforhold, og at det samlede antal modellerede hændelser (4 storme) er tilstrækkelig stort til at det vægtede resultat repræsenterer et middelår. Det skal også pointeres, at området er særdeles følsomt for udsving i bølgeklimaet, og stor variabilitet i sedimenttransportmønstret fra år til år er derfor sandsynligt.

I Figur 2.5 er det overordnede årlige nettotransportmønster yderligere kvantificeret. Figuren viser de hovedruter, som sediment transporteres ad. Disse hovedruter er kvantificeret ved at fortolke sedimenttransportresultaterne for de enkelte kornstørrelser, hvorved omsætningen af sand kan estimeres.

Det ses, at mængderne, der transporteres mod syd nord for Blåvands Huk, samt den nordgående retur-transport i offshore-zonen, er beregnet til 1.200.000 m^3/år hhv. 600.000 m^3/år. Heraf ses, at ca. 600.000 m^3 sand vil aflejre ud for vinkelforlandet nord for Slugen hvert år. Transporten rundt om Blåvands Huk ses at være ubetydelig.



Figur 2.5 Hovedruter for nettosedimenttransport i interesseområdet.

Det ses, at revet tilføres sand fra syd, og at dette sand transporteres videre ind langs revet mod den østlige spids af Horns Rev. Mængden af sand, der således transporteres mod øst langs Horns Rev, indgår i langstransporten mod syd, syd for Blåvands Huk. Sammen med den mængde sand i langstransporten, der stammer fra kysttilbagerykningen på strækningen ned mod Skallingen (som følge af den voksende transportkapacitet), kan de mængder, der årligt oprenses i Grådyb, forklares.