

Observation and Modeling of High Individual Ocean Waves and Wave Groups Caused by a Variable Wind Field

W. Rosenthal, A. L. Pleskachevsky, S. Lehner, S. Brusch
German Aerospace Centre (DLR), Remote Sensing Technology Institute,
Oberpfaffenhofen, 82234 Wessling, Germany

The impact of the gustiness on surface waves under storm conditions is investigated with focus on the appearance of rogue waves. The observations from optical and SAR satellites indicate structures of open cells moving across the North Sea during many storms characterized by extremely high individual waves measured near the German coast. According to measurements the footprint of the cell produces a local increase in the wind field at sea the surface, moving as a system with a constant propagation speed. Wave groups with the same speed grow continuously under the influence of this traveling gust. Growth continues until it is balanced by negative source terms as internal friction nonlinear interaction and breaking events. Slow moving gusts support therefore slow wave groups which have short wave length. Breaking occurs already at low wave heights. To create monster waves by this mechanism we need a fast moving gust, so that the wave length is larger than 150m, corresponding to periods larger than 10 s, and group velocities larger than $7.5\text{m}\cdot\text{s}^{-1}$.

The optical and microwave satellite data to connect the atmospheric turbulence and the extreme waves measured are used. The parameters of open cells (size, propagation speed) and their influence on the surface wind are determined and used for numerical spectral wave simulation. The test cases with different conditions are simulated with a spectral numerical wave model to identify the influence of a single and of several open-cells. The North Sea with 1nm horizontal resolution with focus on the German Bight was taken as simulation area. To take into account the rapid moving gustiness structure the input wind field is updated each 5min.

The results show that a single moving open cell can cause the significant wave height increase in order of meters within the cell area, and especially in a small area of 2 -5km. For example, if one individual cell travels with $15\text{m}\cdot\text{s}^{-1}$ over a sea surface with a wind-sea of $H_s=3\text{m}$ (peak at 8sec) and a swell of $H_s=2\text{m}$ (peak at 15sec), it produces a local increase of 3.5m. The results of this study can be important for ship safety and coastal protection. Unfortunately the open-cell caused gustiness can not be incorporated in present operational wave forecasting systems, because it needs an update of the wind field, which is presently not available. However, the scenario simulations for cell structures, observed by optical satellites can be done and applied for warning messages.

1. INTRODUCTION

In the paper, the effect of the gustiness on sea state is analyzed. The implementation of this effect is based on consistent gustiness structures, traveling with a speed comparable to the group velocity of long waves. Such structures were detected by optical and microwave satellite data especially for storms with extreme individual waves.

1.1. Background

The prediction of storm events is an important task for operational oceanographic services. Wave forecasting for the shipping routes, storm prediction, wave and wind related information for coastal protection and sport boats are important. The wave models of the third generation have been developed and used for sea state prediction, e.g. by NOAA

(WAVEWATCH III, <http://polar.ncep.noaa.gov/waves/viewer.shtml>) and forecast services like the German Weather Service (DWD, <http://www.dwd.de>), which are a part of the global marine weather and warning systems. All forecasting systems at global, regional and local scales are based on numerical simulation using spectral determination of the wave field. Once the spectral energy density is estimated, integral wave properties can be obtained, such as significant wave height, mean and peak period and direction.

The input information for the wave modeling are the surface wind at a height of 10m and water depth. The real wind is variable over short distances and short time scales. However, from the random fluctuation of seconds and order of meters the present models resolve the wind over scales of several 10km and over time scales of an hour. As a result, the loss of medium scale wind information leads to an error in the sea state estimate.

The influence of gustiness on waves is studied since a long time. Usually Euler's approach is used, meaning the influence of wind vector fluctuations in time at a fixed location (e.g. Cavaleri et al., 1992, Günther 1981). The new remote sensing data from radar satellites allow estimating wind speed at the sea surface under the clouds, the gustiness can be spatially observed and its parameters can be determined. Thus, a new technique can be used by applying the wind gustiness parameters within numerical modeling by Lagrange's method. This means to follow the cells and their impact across the model domain. The difference between these two approaches is significant: the first method takes into account the wind turbulent fluctuation at a location without connection to other locations. The second one integrates the impact of the cell along its trajectory. The impact of wind energy on individual waves in a group increases significantly for those waves, that propagate with the speed of the wind field. In this case the wind energy input with a strongest value occurs into the same wave group and can cause the strong growth of the local wave height.

For instance, during the heavy and fast developing storms in the North Sea like "Anatol" on Dec. 03, 1999 and "Britta" on Nov. 01, 2006, the forecast atmospheric models (input for the wave simulation), were not capable to predict the rapid increase of the wind with the observed gustiness (Brusch et al, 2008). Correspondingly, the wave height was underestimated with respect to maximal wave height. An example is the damage on the offshore research platform FiNO-1, where the metal construction in 15m over mean sea level was destroyed by waves. The significant wave height was about 12m, however, the individual waves exceed value of 25m wave height: a wave group of three individual waves each with more than 15m amplitude and length of about 600m was measured at FINO platform.

1.2. Methods and Objectives

In the paper the influence of moving gusts with an extension of several kilometers, are investigated for the sea state variability. Satellite data are used to estimate the wind structures applied for numerical wave modeling. The numerical simulations with high temporal resolution (the wind input each 5min) is used to demonstrate the effect of moving open-cells over the North Sea and their impact on sea state in the German Bight for idealized cases. The paper is structured as follows: in the current Section 2, the extreme storms in the North Sea and their connection to gustiness are reviewed. The remote sensing observations are shown in Section 5. The implementation of gustiness into wave modeling is discussed and numerical simulations by implementing open cells into wind field are presented in Section 4. Section 4 is dedicated to the interpretation of results in connection with integrated wave parameters and maximal wave heights. Conclusions are summarized and discussed in Section 5.

2. EXTREME STORMS OBSERVED IN THE NORTH SEA

In this section some storms with extreme wave events were introduced. The extreme events are high individual waves that are not described by the conventional calculated H_s , which is derived from an average energy of 30min time series from a wave staff. We assume the probability of the extreme individual wave is determined by a higher local H_s , defined for a medium sized area of higher windspeed, travelling with the groupspeed of the rogue wave. The common prerequisites and consequences are summarized. A connection of the extreme events to the observed open cells is discussed.

2.1. *Alfried Krupp* 1995, 1 Januar, *Draupner*

The instruments at the oil platform *Draupner* located at N58,11° E2,28° about 160 kilometres offshore Norway in the North Sea measured the first rogue wave, detected on 01.01.1995 at 15:20. This wave had the height with a maximum of 26m while the significant wave height has the value of 12m and a crest height of 18.5m. For the registered period of about 18sec the wavelength should be about 505m with a phase velocity of $28\text{m}\cdot\text{s}^{-1}$ ($101\text{km}\cdot\text{h}^{-1}$).

At 22:14 an accident happened west of Borkum Island, in storm propagation direction at a distance of about 570km from the *Draupner*-platform: the rescue boat *Alfried Krupp* got into an emergency situation, which led to the loss of two crew members. The time delay is about 7h between these two events. Assuming permanent velocity of the rogue wave system, it should need the time of about 6h to cover the distance between the *Draupner* platform and Borkum where the incidence occurred. In Fig.1 the optical images shows the cloud field over the North Sea. The open cell structure is visible.

2.2. Storm “*Britta*” at November 1, 2006 and “*Tilo*” at November 9, 2007

The deep pressure system “*Britta*” was initially developed from a frontal wave of low pressure in the central North Atlantic early on October 28, 2006 and, after moving northeast, turned further east and developed hurricane-force northwest winds on its western side as it passed through the North Sea.

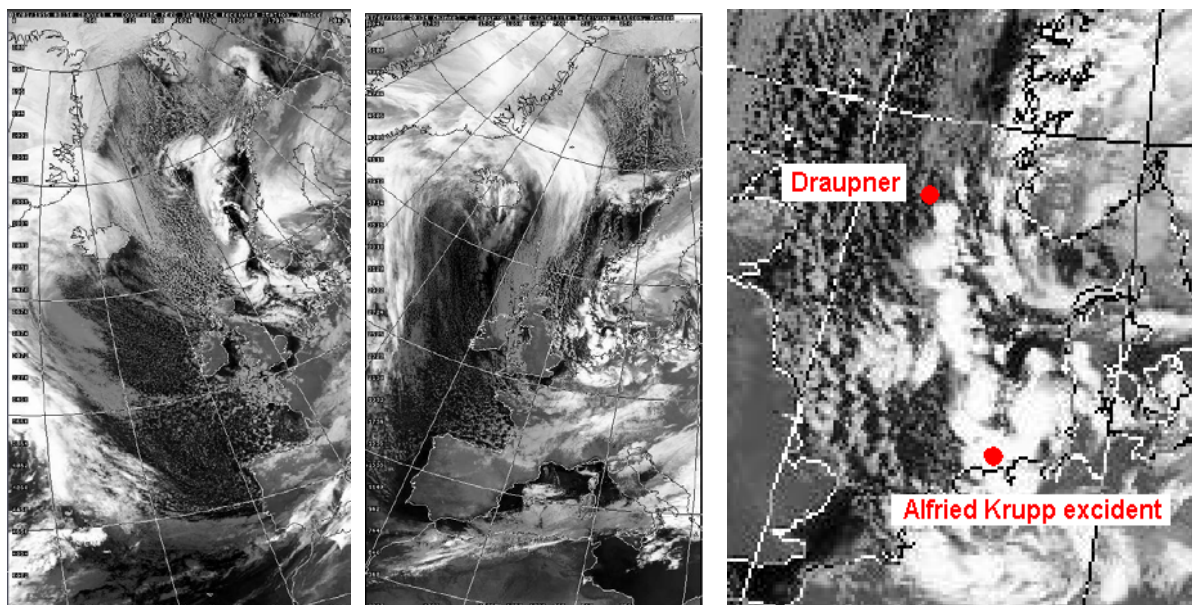


Fig. 1: AVHRR NOAA Thermal Infrared on 1.1.1995 at 8.50 UTC and at 20.34 UTC

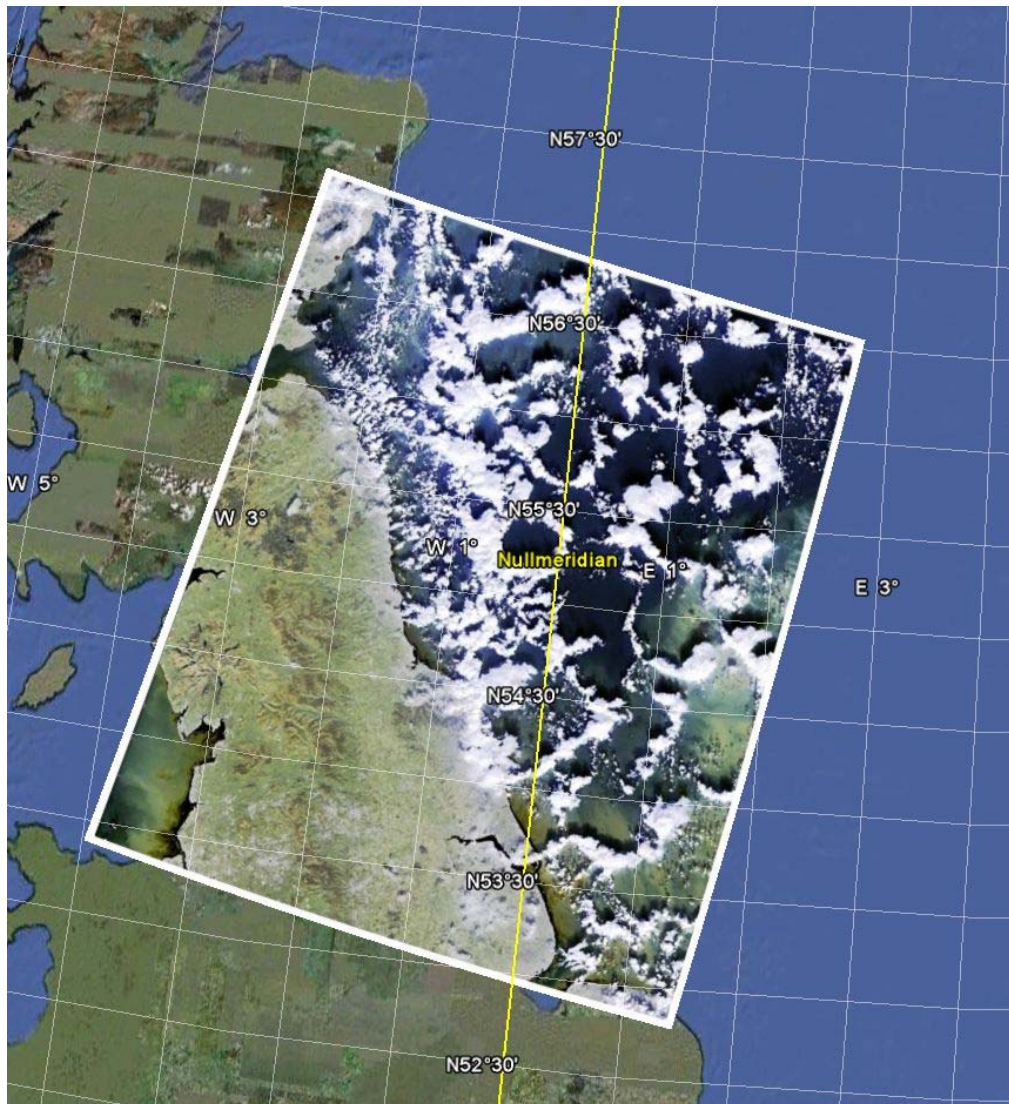


Fig.2: MERIS FR true color composite acquired on November 1, 2006 at 10:42 UTC

Extremely high sea state were observed by the research platform FiNO-1 located at position N 54°0.86'E6°35.26', about 45km north of Borkum. Especially of interest is the appearance of a group of three rogue waves with heights of more than 20m and periods of 25sec on November 1, 2006 at 04:00 UTC. The construction damages take place at a height of 18m and more above normal sea level. Although the significant wave height was about 11m the damages and measurements give estimates of the individual wave up to 30m. Fig.2 shows the optical image acquired on November 1, 2006 at 10:42 over North Sea westward from FiNO-1 from ENVISAT satellite. The open cell structures with width from about 60km up to 100km are clearly visible.

On 8 and 9 November 2007, the low-pressure system "Tilo", with maximum wind speeds of $120 \text{ km} \cdot \text{h}^{-1}$, crossed the German Bight. In the afternoon of 9 November, the low caused waves with significant wave heights in excess of 10m, wave periods of about 15s and wave lengths of more than 220m. On the FINO-1 research platform, the working platform was damaged at a height of 15m again, repeating the occurrence of 1 November 2006 when the low-pressure system "Britta" had caused damage (Outzen et al., 2008). Fig.3 shows the thermal infrared satellite image acquired over North Sea on 9.11.2007, 03.20 UTC. The image shows again the open cell structures with cell width of about 60km -100km.

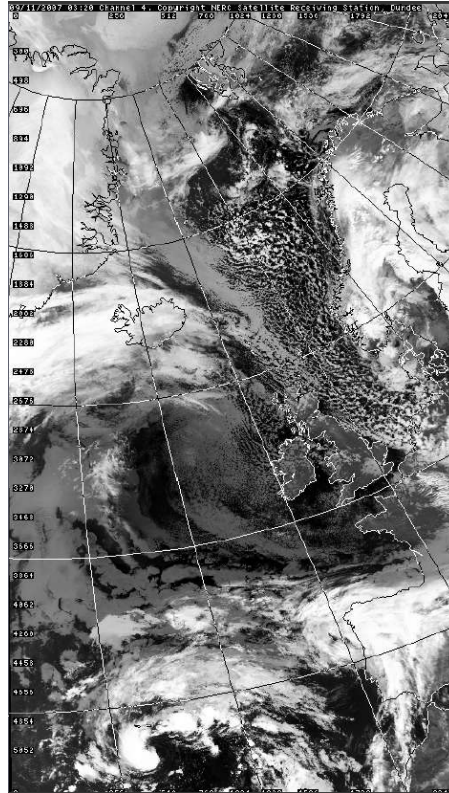


Fig.3: NOAA AVHRR thermal infrared image on 9.11.2007, 03.20 UTC

3. GUSTINESS AND SATELLITE DATA

All storms discussed above indicate a common feature. At the optical satellite images a structure of open cells can be observed. In radar images the open cells manifest themselves by gustiness patterns of similar shape and location.

3.1. Wind and Gustiness

As an atmospheric phenomenon the wind field is turbulent on all scales. For numerical simulation it is important to distinguish the effect on different spatial and temporal scales. Random fluctuations in order of milliseconds and large eddies in order of 10 kilometers and more can occur. The standard mechanism to trigger surface waves uses the wind turbulence at scale of seconds. As the latest is presented, it produce random pressure fluctuations at the surface and due to instability of wind vector the small waves with wavelengths of a few centimetres are produced. As the wind acts on these small waves they becomes larger, wind produces pressure differences along the wave profile and cause the wave to grow exponentially (Miles, 1957). The influence of longer scale gustiness on local wave growth are discussed by Cavaleri and Burgers (1992), Günther (1981). They focus on local turbulence of the wind vector assuming e.g. Gaussian distribution of the fluctuations.

The wind turbulence and gustiness are hidden in the parameterizations of the wind input functions which are usually tuned for wind U_{10} . A typical input for a wave model is a smoothed wind field without strong spatial and temporal variability. For instance, the wind input for the DWD wave model is updated every hour and left constant in between.

For some models, the local turbulence is simulated by introducing a random factor that is multiplied to the wind speed components (Schneggenburger 2002). However, this turbulence

means a random gustiness in wind field at second order and does not mean the structured eddies at a larger scale, which can be initiated by atmospheric effects like open-cell moving. A loss of such information can lead to a loss of wind related waves by modeling.

3.2. Open cells and satellite data.

An alternative approach on gustiness is the assumption of an integrated impact from consistent structures in the wind field, which are moving across the sea, convected by open-cells in the atmosphere.

The convective cells in the atmosphere, forming over the ocean surface, are consequences of an unstable stratification of the atmospheric boundary layer, indicated by a negative air-sea temperature difference (Atkinson and Zhang, 1996). Especially during winter months (the strongest storms occur from November to March in the North Sea) cold air breaks in from the north and is heated from below and the warmer air transfers upward. This results in closed and open convective cellular structures. In general, rain events are associated with wind gusts that roughen the sea surface. Precipitation from convective clouds usually produces a downward airflow, called downdraft, by entrainment and by evaporative cooling under the cloud. The airflow pattern caused by the downdraft of rain is shown schematically on Fig.4. The propagation speed of the cell structures can vary from about $5\text{m}\cdot\text{s}^{-1}$ to $40\text{m}\cdot\text{s}^{-1}$.

The space borne SAR (Synthetic Aperture Radar) as remote sensing instrument is a unique sensor to provide information of the ocean surface. Due to the high resolution, daylight and weather independency and global coverage, space borne SAR's of a new generation are particular suitable for many ocean and coastal applications (Lehner et al., 2008). Satellite images taken by space-borne radar sensors can be used to determine meso-scale high-resolution wind fields in synergy with cloud parameters from optical data and, thus, help in the task of maintenance and planning offshore activities. Fig.5 shows the SAR and optical image simultaneously acquired from ENVISTAT. The cloudiness structure of open cells is quite visible at the optical image. These structures are visible at the sea surface as well and cause variability in the estimated wind field (Brusch et al 2008).

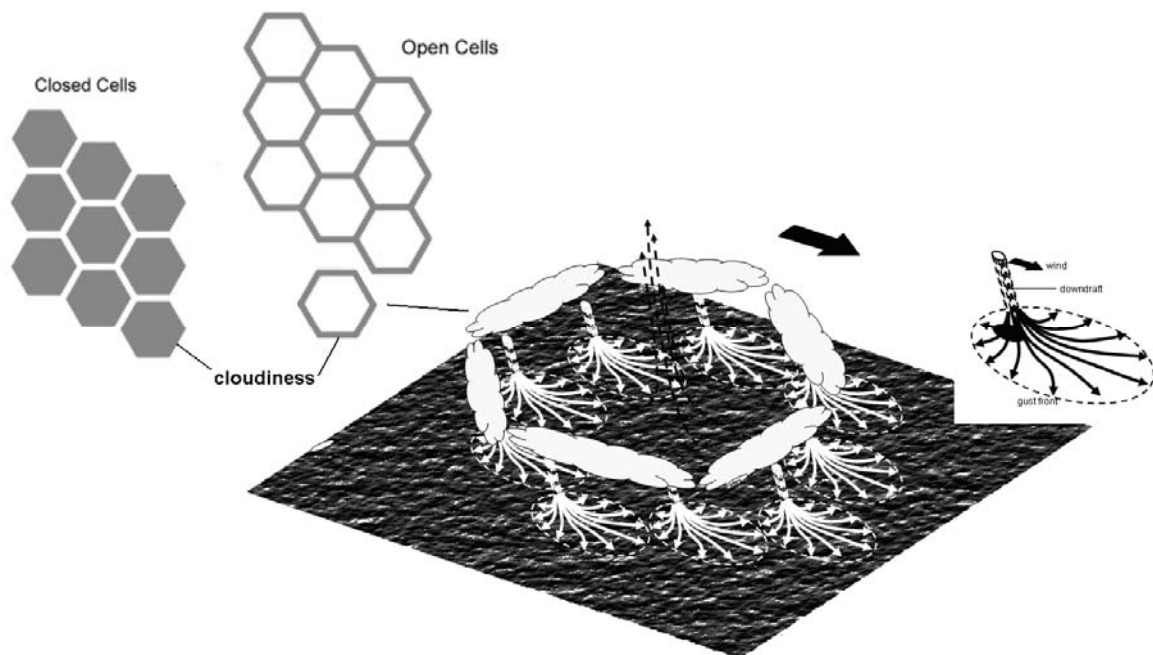


Fig.4: Schema for the downdraft associated with a rain cell according Atlas (1994) and for open and closed cells.

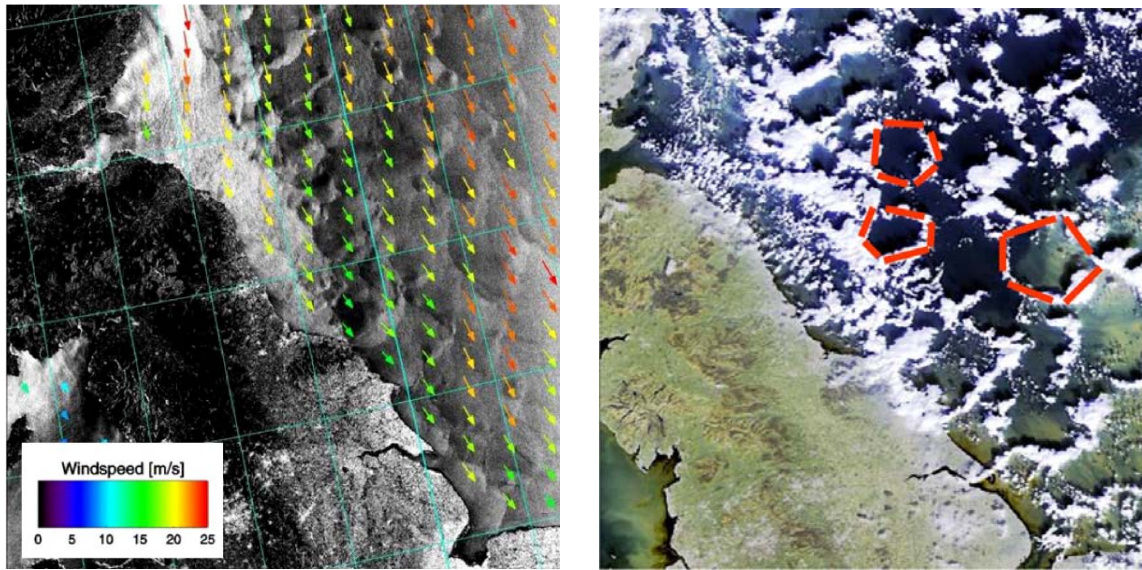


Fig.5: Optical and SAR image from ENVISAT acquired on November 1, 2006 at 10:42 UTC.

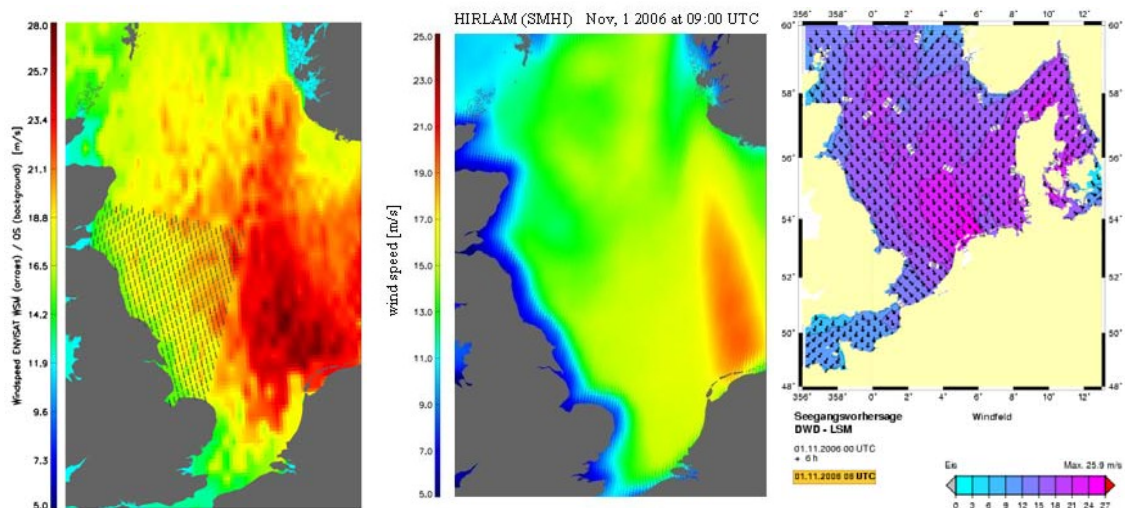


Fig.6: Wind field from A SAR and from QuickSCAT Scatterometer wind field (05:42 UTC, 25x25km) (left), HIRLAM – High Resolution Limited Area Hydrostatic Model, 11x11km Gitter HIRLAM 01.11.2006 09:00 UTC (middle) and wind field from DWD (right). The gustiness are visible in QuickSCAT data. In HILRAM and DWD wind fields the gustiness is not present.

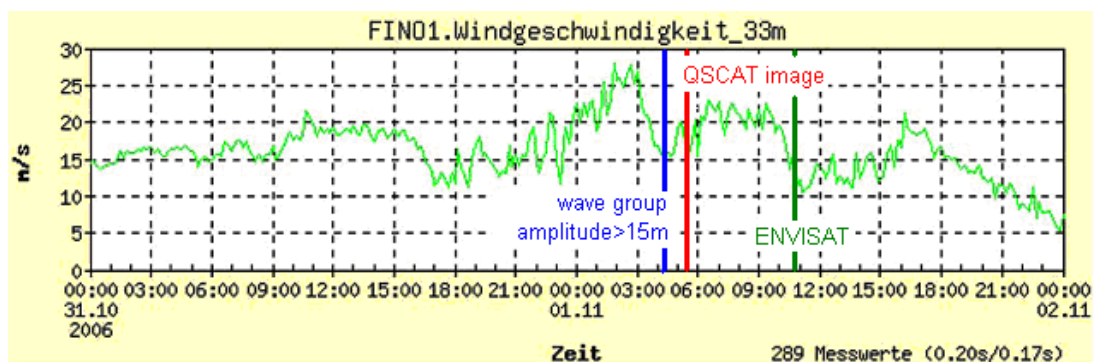


Fig.7: Measurement at FINO-1 Platform. The times of rogue waves entry, Qscat and ENVISAT acquisition are shown.

Summarizing, the main features of the open cells can be implemented into the wind field as an increase in the local wind speed. Idealized, they have ring structure with a diameter of about 30km-70km. They are moving across the model domain with velocities between $5\text{km}\cdot\text{h}^{-1}$ and $40\text{km}\cdot\text{h}^{-1}$.

4. WAVE MODELING IN THE PRESENCE OF OPEN CELLS.

The series of numerical simulations were carried out by using a spectral wave model (Schneggenburger 2002) for the North Sea with 2.5km horizontal resolution. For the simulation an idealized cell pattern was applied, the cell parameters are retrieved from satellite data. On the sub-image in Fig.5 the structure has the width of 40km.

4.1. Modeling for the North Sea

The main point of simulation was the implementation of the moving open-cell structures into the wind field. The open-cell influence on the waves was investigated for different configurations of the cells, which differ by the number of cell's, by propagation speed and by the background sea state (e.g. wind sea and swell available at the open-cell passes).

The first test shows a single moving individual cell in Fig.6. This idealized simulation indicates the waves generated by one cell moving in the direction towards the German Bight. The gust is moving with a speed of $10\text{m}\cdot\text{s}^{-1}$ ($36\text{km}\cdot\text{h}^{-1}$) and crosses the North Sea within 18hours. The wind field is updated each 5 minutes in order to catch exactly the moving structure. Fig.6 presents the results of the simulation in 4 hour steps. For each sea state the corresponding wind field is given. The details are presented in Fig.7 for time $t=20\text{h}$. The scaling is specially tuned to show the details in the wave height within 0-50cm. It can be seen, that the local influence of the cell causes an increase of the significant wave height up to 3m under the cell, in a small area of 4km in diameter. A ship-wake like structures of swell with height of about 20cm-50cm can be seen. This effect becomes important for cell groups moving as a system across the North Sea.

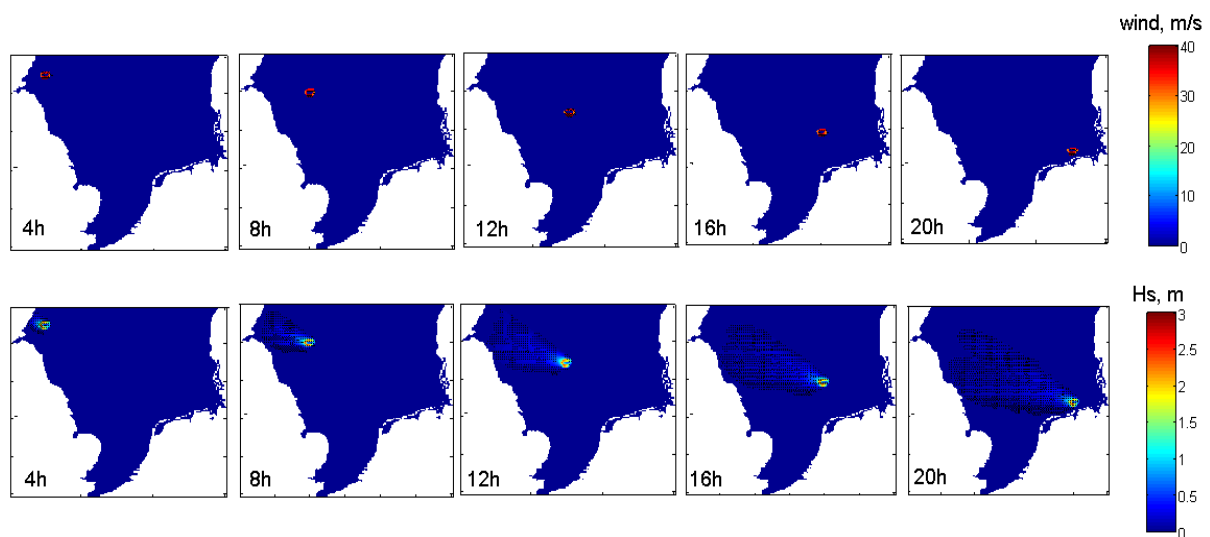


Fig.6: Numerical simulation of a single idealized cell passing across the North Sea. Wind field is updated each 5min, the results are presented in 4h time steps. The cell enters the sea at time $t=2\text{h}$ and need about 15h to make land fall again. Local wave height reaches 3m within the footprint of the cell.

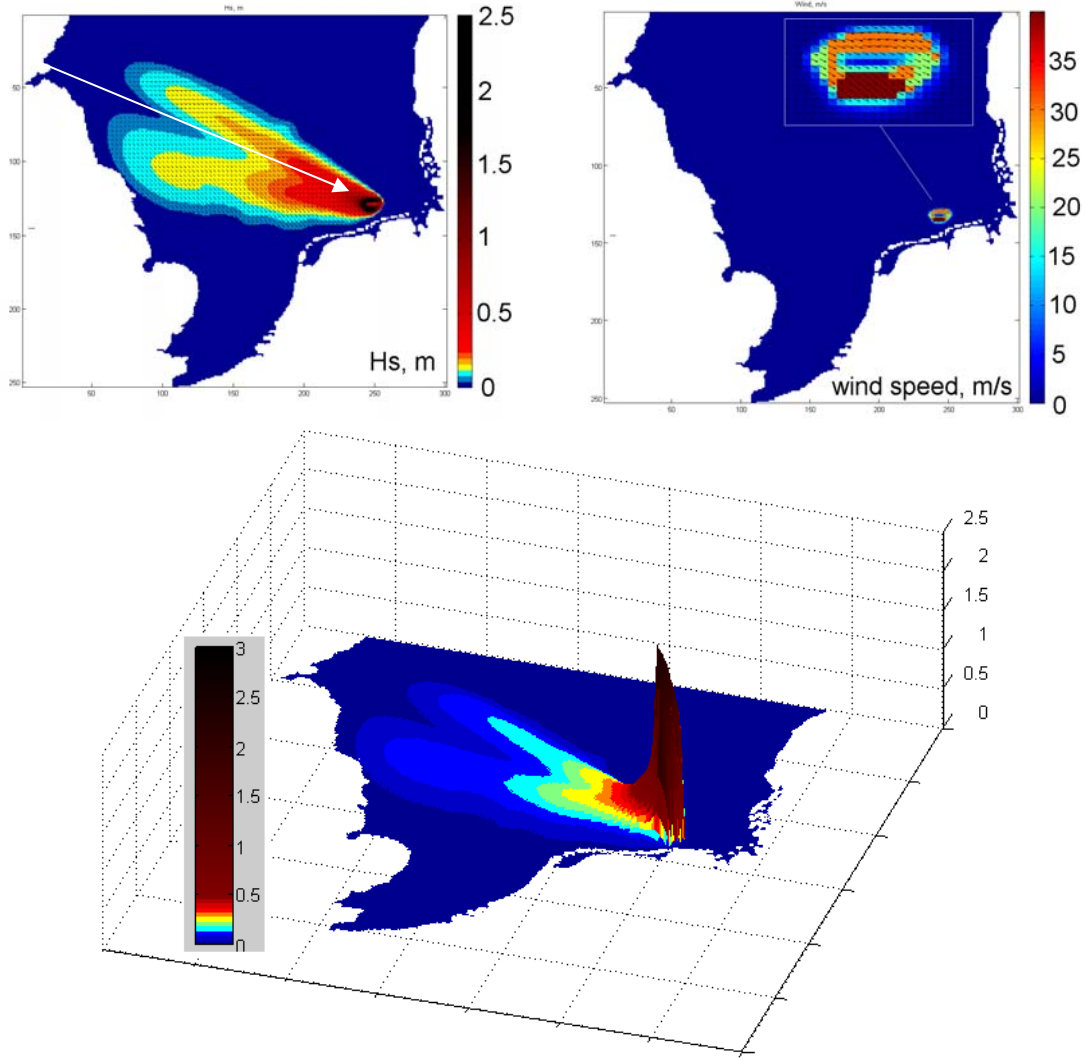


Fig.7: Simulation of one idealized cell moving with a speed of $10\text{m}\cdot\text{s}^{-1}$ across North Sea (no wind except in cell and no background waves). For time $t=20\text{h}$ the cell reaches the German Bight (left). The inset shows the zoom of the cell wind, the wind speed reaches $40\text{m}\cdot\text{s}^{-1}$ inside the cell. Significant wave height reaches the value of 2.9m inside the cell, with a maximum in a small area about 5 by 5 kilometers.

The small spatial size of the wave peak makes it difficult to measure it with a stationary device like a wave buoy since the computed H_s changes too fast for a stationary sensor and time series of 30 minutes at a fixed location. A solution would be a measurement from airborne or space borne platforms that follow individual wave groups. In the present work we accept the fact, that only in results of numerical models we can determine H_s fields of small spatial and temporal extensions.

One open cell rarely appears under real storm conditions. Therefore the second test deals with four identical cells moving as a group with a speed of $15\text{m}\cdot\text{s}^{-1}$ ($54\text{km}\cdot\text{h}^{-1}$). The wave height increases up to 2.1m under the first and up to 3.8m under the second cell. Fig.8 (left) presents this impact of the cell train. The cut along the cells propagation path is shown in the sub-image. As expected the first cell causes a rough sea in order of 2m H_s , which is a trigger for stronger waves under the second cell.

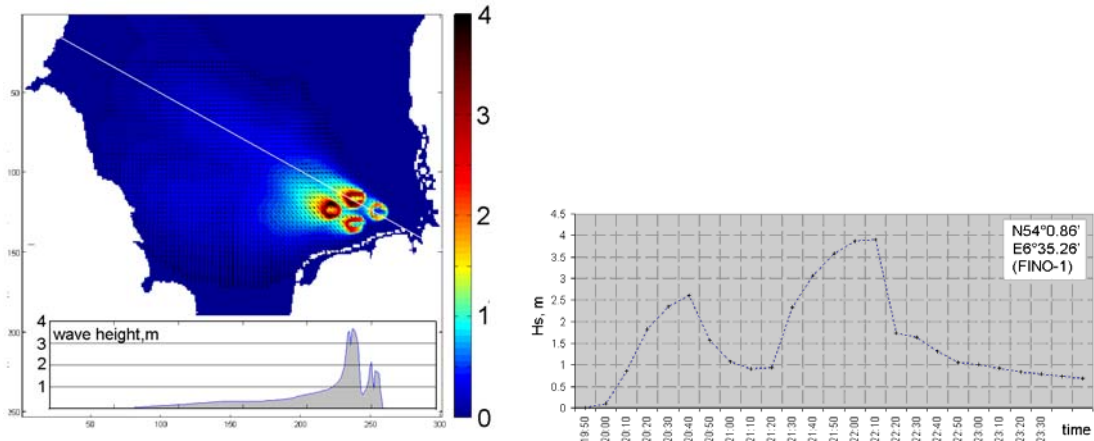


Fig.8: Simulation of a group of idealized cells moving with a speed of $15\text{m}\cdot\text{s}^{-1}$ across the North Sea (no wind and waves in the background). Significant wave height reaches a value of 2.5m under the first cell and 4m under the second cell within an area of about 5x5 kilometers. The wave height time series from location N54°0.86' E6°35.26' (FINO-1) is shown for every 10min. The cell's strongest influence lasts for a time of about 10min.

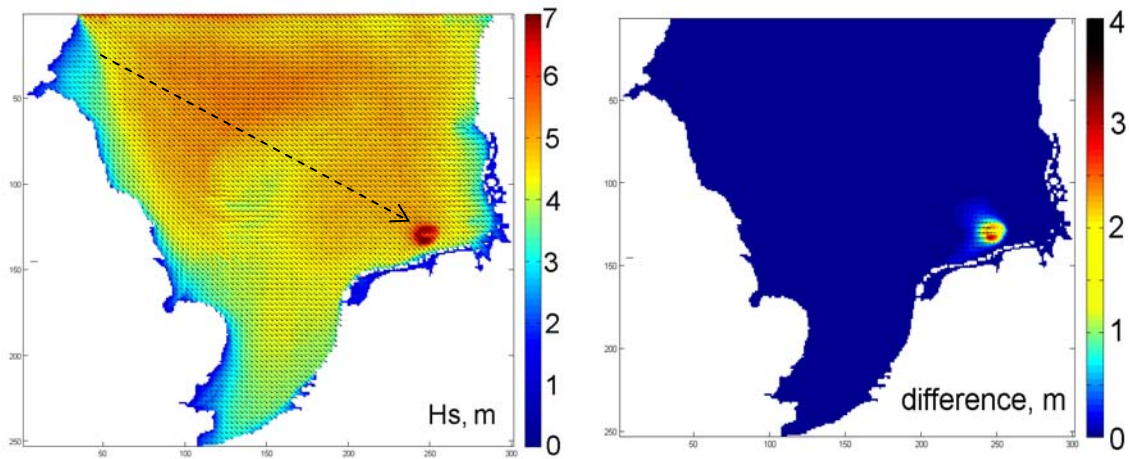


Fig.9: Simulation of one idealized cell moving with a speed of $10\text{m}\cdot\text{s}^{-1}$ across North Sea (constant wind $20\text{m}\cdot\text{s}^{-1}$ with *going to* direction south-east and corresponding sea state pre-simulated with spin-up of 24h). The wind speed again reaches $40\text{m}\cdot\text{s}^{-1}$ inside the cell. Significant wave height reaches value of 7m in cell footprint. Difference between H_s (with cell) and H_s (without cell) reaches the value of 3.9m (right).

In reality, the cell structures will meet a background wind- and wave field, that exists already before the cells are passing. Therefore in the third test case we use a single cell as in the first case and use the following boundary and initial conditions: the wind is $20\text{m}\cdot\text{s}^{-1}$ (constant) with direction South-East (*going to*), the constant wave spectra at the boundary include a swell part ($H_s=2\text{m}$ and 15sec peak period) and a wind sea ($3\text{m } H_s$ with 8sec peak period). The cell enters the area after spin-up of 24 hours (stationary sea state is achieved). The Fig.9 (left) shows the total significant wave height and (right) the difference between sea state simulated with and without the cell impact in German Bight. The impact of the cell is an increase for H_s of 3.9m under the cell. This makes visible, that the effect of cells is stronger, if the waves are already present in the area of cell passage.

These tests show a potential possibility of influence of the local structures in wind field on the sea state. The open cell and the condition are idealized. The real conditions are more complicated. A test case without and with many open cells with variable diameter and moving speed are simulated for the same wind conditions. Fig.10 shows the result for the German Bight. The excesses of H_s with cell reaches 5m against case without cells. The relations

between maximal H_s under the cell group and H_s original are shown in Fig.11 for three locations in the North Sea on the group path. The mean value is a factor of about 1.6 for the simulated conditions.

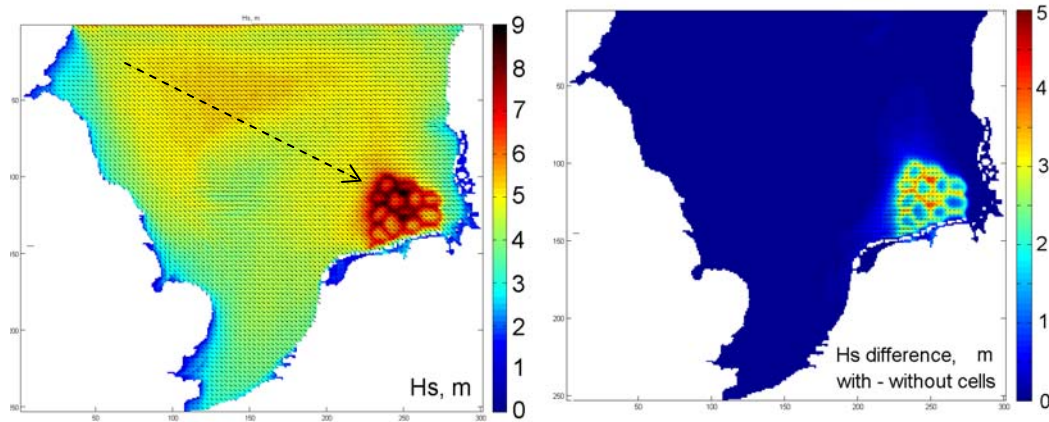


Fig.10: Simulation of a group of cells, moving with a speed of $25\text{m}\cdot\text{s}^{-1}$ across the North Sea (constant wind $20\text{m}\cdot\text{s}^{-1}$ with *going to* direction south-east and corresponding sea state pre-simulated with spin-up time of 24h). The wind speed again reaches $40\text{m}\cdot\text{s}^{-1}$ inside the cells. Significant wave height reaches 10m within the cells. The difference between H_s (with cell) and H_s (without cell) reaches the value of 4.8m (right).

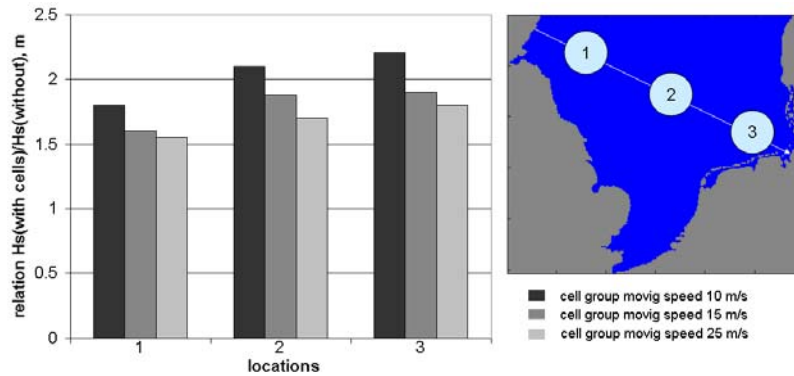


Fig.11: Relation between maximal H_s under cell group footprint and H_s simulated without cells (left) for three locations in the North Sea along cell group trajectory (right).

5. DISCUSSION AND SUMMARY

5.1. Individual waves during storm condition

The numerical simulations of Storm “Britta” in the North Sea show a good agreement with measurements, when comparing the integrated parameters like e.g. significant wave height (Behrens 2008).

The wave model has no information about individual wave heights. They are based on the spectral approach. Created originally by transferring wind energy into the water surface, is the local wind sea dependent on the wind speed, duration and wind affected area (fetch). By nonlinear interactions between waves of different wavelength, the energy is transferred from shorter to the longer waves. With longer wind action duration the longer waves occur. These longer waves (swell) leave the wind influenced area and propagate away with speed faster than the wind speed (Stewart, 2009). The wave spectrum is the mathematical description of the sea state and presents the statistical expectation value of wave energy, which is proportional to the square of wave height, in direction and frequency (or wave number) space.

Once the spectral energy density is estimated, integral wave properties can be obtained, such as significant wave height, mean and peak period and direction. A statistical estimate is given for the maximum of individual wave height $H(n)$, exceeded within an ensemble of n wave groups with a significant wave height H_s :

$$H(n) = H_s \sqrt{0.5 \cdot \ln(n)} \quad (1)$$

It is emphasized once more that n is the number of independent wave groups. This is a smaller number than the number of contributing waves. From measurements and simulations we estimate about 100s as the time period for a wave group. This corresponds to a wave period of $T=14s$ for 7 waves per group and $T=30s$ for three waves per group.

The modeled maximum H_s is valid for a quadratic area of 2.5km by 2.5km. The measured time series to calculate the measured H_s is 30 minutes long. It contains therefore mainly time periods, where the calculated H_s (cell) has dropped to the background value and we may approximate it by the H_s (background) from the case without cells.

If the significant wave height is increased from the measured 11m by a factor of 1.6 up to $H_s=17m$, the wave height value of 24m will be reached at $n=50$ (equivalent to 1.4 hours) according to eq.1. From the wind plot of the FiNO platform in Fig.7 we estimate that number of groups per storm $n_{groups/storm}=6$ passed at the highest wind. If on the average number of storms per year $n_{storm/y} = 2$ occur with the characteristics of Britta, it will need number of years $n_y=4$ to exceed the value of wave height of 24m and to meet the criteria $n_{H>24}=48$.

$$n_{H>24} = n_{storm/y} \cdot n_{groups/storm} \cdot n_y \quad (2)$$

This 4 years of estimated return period may be compared with the 3 events of individual waves exceeding 20m in 12 years at the FiNO platform.

5.2. Reconstruction of sea surface under cell footprint

If linear wave theory is applied, the ocean surface can be estimated from spectra simulated by the model. Fig.12 shows the random surface simulation for two cases: the same location before and during cell passing. The surface is more distorted and the surface excess stronger the significant value during the cell passing.

5.3. Summary

The rogue wave incidences during strong storms in the North Sea can be explained by increased significant wave height, extending over small areas and traveling fast. In the North Sea they are often connected with typical cloud formations, originating from cold air outbreaks from the northern to the southern North Sea.

Acknowledgments

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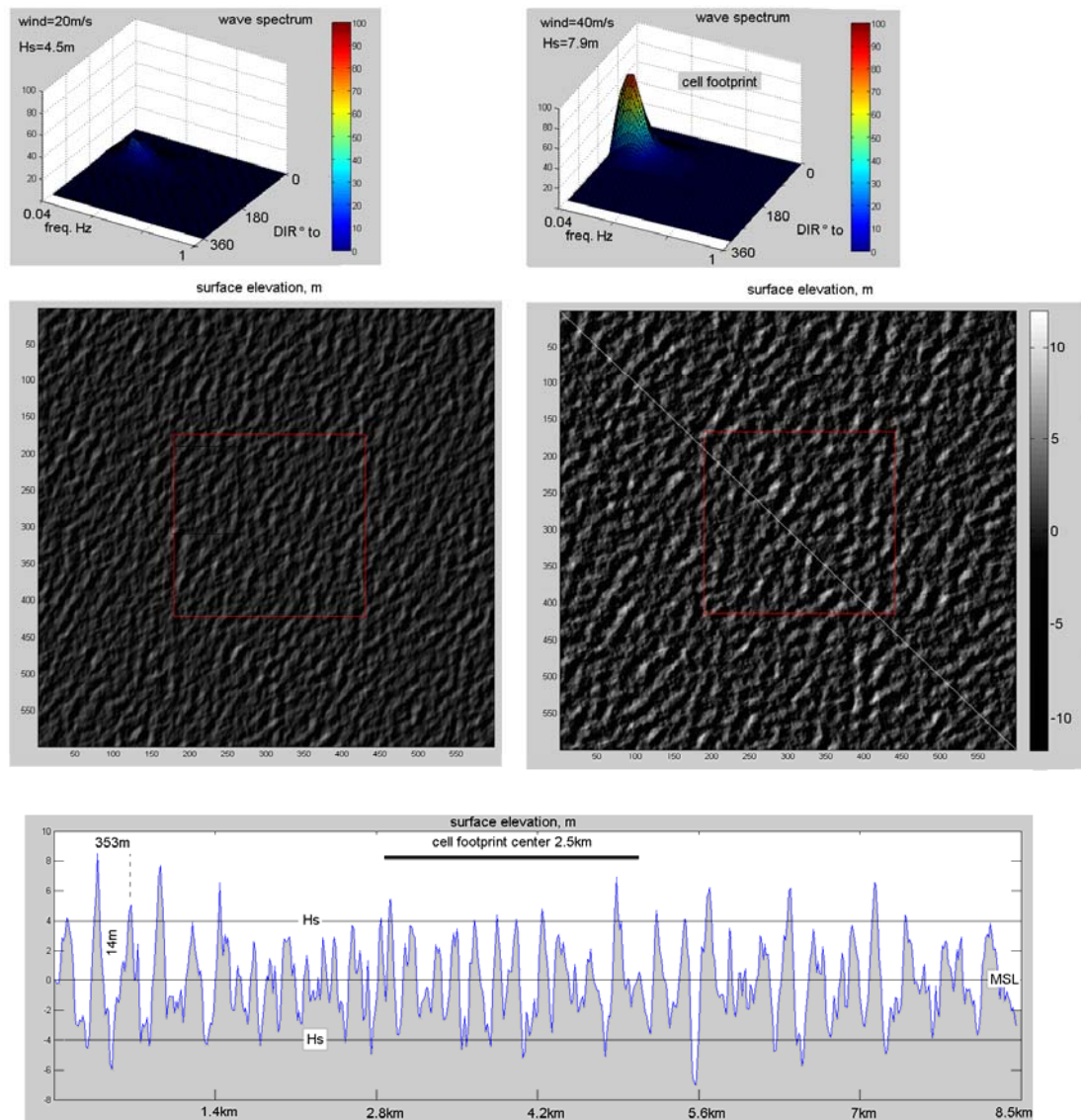


Fig.12: first row - wave spectra simulated for FINO-1 location before cell passing (wind speed $20\text{m}\cdot\text{s}^{-1}$, left) and during cell passing (right). Second row – surface simulation by random initial phases from the spectra for the $6\times 6\text{km}$ area (resolution of 10m). The spectra are responsible for the area of 2.5km by 2.5km (red square). Third row - a cut for the cell-passing case show surface elevation.

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