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Interaction of Waves, Currents and Tides, and Wave-Energy Impact on the Beach Area of Sylt Island

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Abstract

Erosion due to waves is an important and actual problem for most coastal areas of the North Sea. The objective of this study was to estimate the impact of wave action on the coastline of Sylt-island. From a two-years' time series (November 1999 to October 2001) of hydrological and wave parameters generated with a coupled wave-current modelling system a period comprising storm 'Anatol' (3rd to 4th of December 1999) is used to investigate the effects of waves on currents and water levels, and the input of wave energy into the coastline. The wave-generated radiation stress causes an increase of the current velocity of 1 m/s over sand and an additional drift along the coast of about 20 cm/s. This produces a water level increase of more than 20 cm in parts of the tidal basin. The model system also calculates the wave energy input into the coastline. Scenario-runs for December 1999 with a water level increase of 50 cm and wind velocity increased by 10 % show that the input of the wave energy into the west coast of Sylt island increases by 30 % compared to present conditions. With regard to the forecasted near-future (WOTH ET ALL., 2006) increase of strong storm surges, the scenario results indicate an increased risk of coastal erosion in the surf zone of Sylt island.

Keywords: Numerical modelling, waves, currents, coupled models, radiation stress, wave energy, storm Anatol, climate scenario, Sylt island, Wadden Sea.

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1 Introduction

The Southern North Sea coast has been shaped and endangered by the sea over millennia, and people living there have developed high skills in constructing sea-defence structures. The lasting thread is felt to increase by the climate change to come manifesting itself through sea-level rise, intensifying storms with ensuing higher storm surges. Sylt island among many other islands is the most prominent not sheltered by Wadden areas which absorb wave and current energy during storm surges.

In this contribution, the impact of wave energy on currents, tides and on the coast line is investigated. The complicated topography around Sylt island (see Figure 1) allows to investigate the wave influence in open-coastal regions (West of Sylt) and in half-closed embayments with large dry-falling areas (South-East of Sylt). The tool for investigating the intricate interplay between waves and currents, is MOPS (Morphodynamic Prediction System) which comprises a current model coupled to a wave model. From the two-years' time series of hydrological and wave parameters (November 1999 to October 2001) generated with MOPS within the BELAWATT Project (see EPPEL ET ALL., 2006) the episode of the storm "Anatol" (3rd to 4th of December 1999) is investigated where the interplay between waves and currents in shallow waters is most prominent.

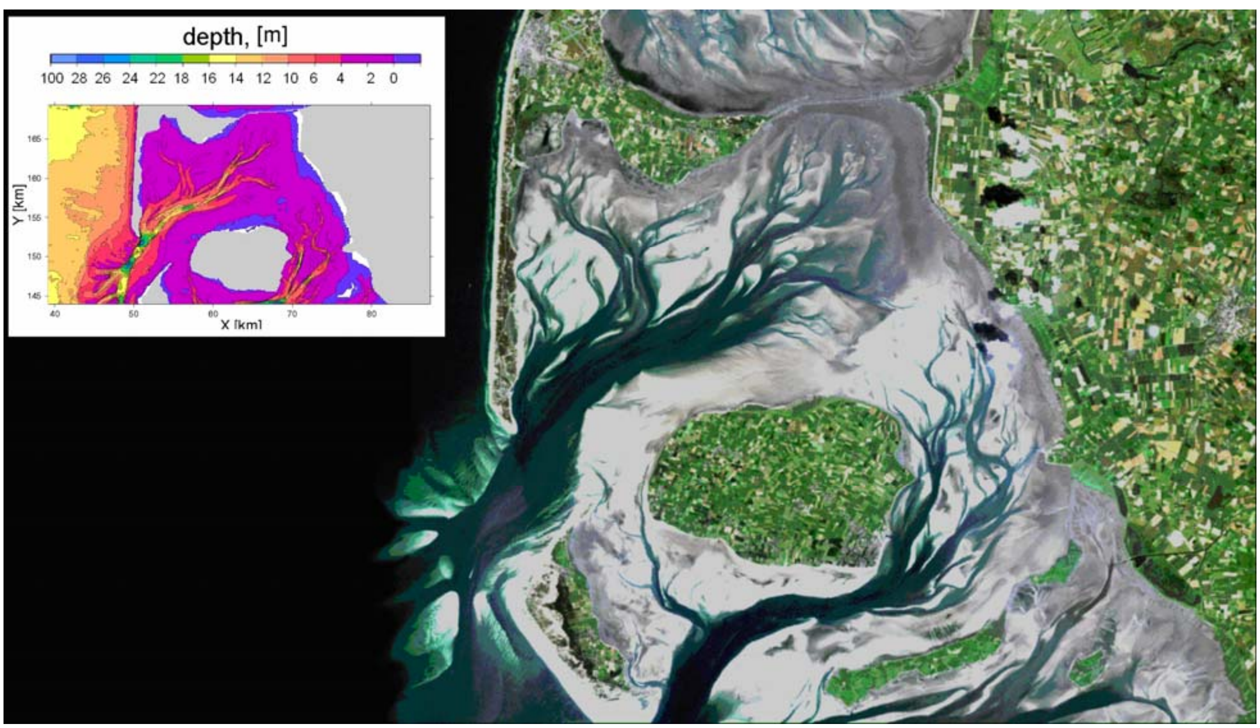

Figure 1: Area photo and model topography of the area of investigation at low tide. The intertidal sand bars and mud flats are coloured from light to dark grey. The topography is based data from BSH (Bundesamt für Schifffahrt und Hydrographie, Hamburg) and from ALR Husum (Amt für ländliche Räume, Husum).

2 The Model System

2.1 The Concept

In shallow waters, the necessarily separate mapping of wave activity and current into different models becomes questionable. Therefore these two models were used as sub-modules within a coupled system exchanging data periodically after short time intervals. To reduce the high CPU-time requirements, the whole system was set up to run on multiprocessor systems.

The MOPS-system (see Figure 2) consists of two sub-modules and the main driver routine: the current model TRIM, the wave model K-model and the main program MOPS which monitors the execution of both models and their data transfer. The TRIM model uses a grid cascade with four grids of 800, 400, 200, 100 m horizontal resolution. They are calculated one after another, the results from the coarse grid are used as boundary values for the next finer grid. The K-model uses the grid of 400 m horizontal resolution. Details describing both models will be given below.

Both models are designed for shallow-water applications with strong depth gradients and temporarily dry-falling areas. Validation work with data from in-situ ship measurements and long-term observations (bottom ADCP, wave rider buoy, and measure post) has been performed within the BELAWATT project (EPPEL ET ALL., 2006).

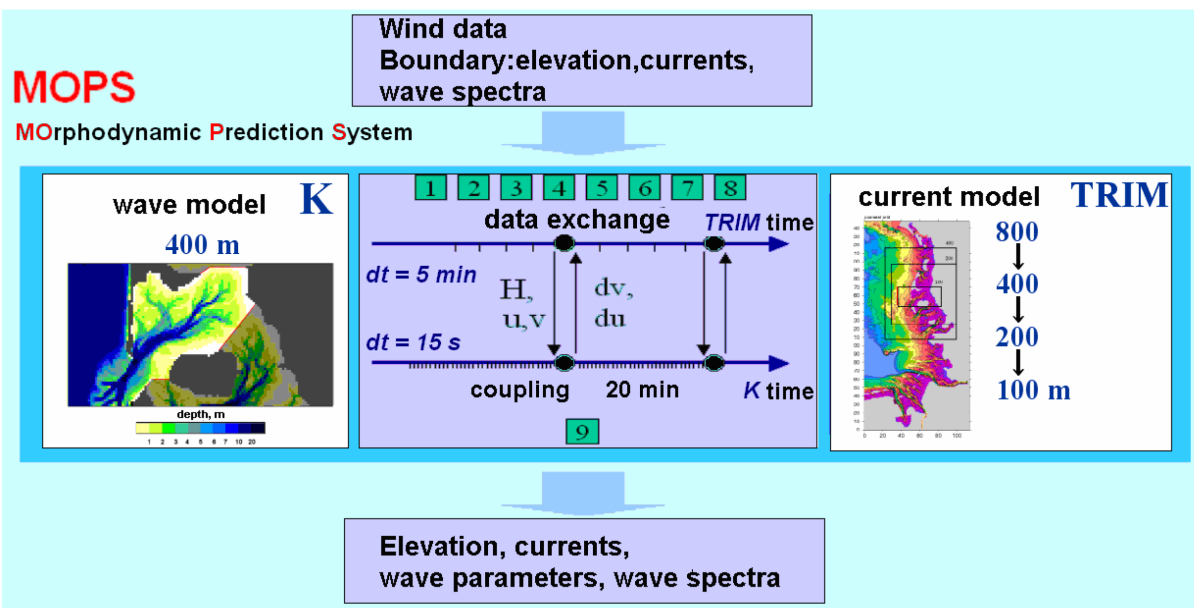

Figure 2: The model system MOPS. Right: the current model TRIM with 4 model grid cascade: 800, 400, 200 and 100 m horizontal resolution. Left: the K-model (horizontal resolution of 400m, the results are interpolated onto 100 m grid). Middle: The coupling and data exchange (upper axis points the TRIM model time (uses 8 processors), the lower axis shows the time of the K-model (1 processor). The coupling occurs every 20 minutes: The water elevation and currents calculated by TRIM are sent to the K-model. At the same time the current accelerations caused by radiation stress are provided by the K-model for TRIM. When the processes are finished the models run parallel and independent to the next coupling time. The system is adapted such that both models need more or less the same CPU time to calculate the coupling time interval of 20 min resulting in negligible waiting time.

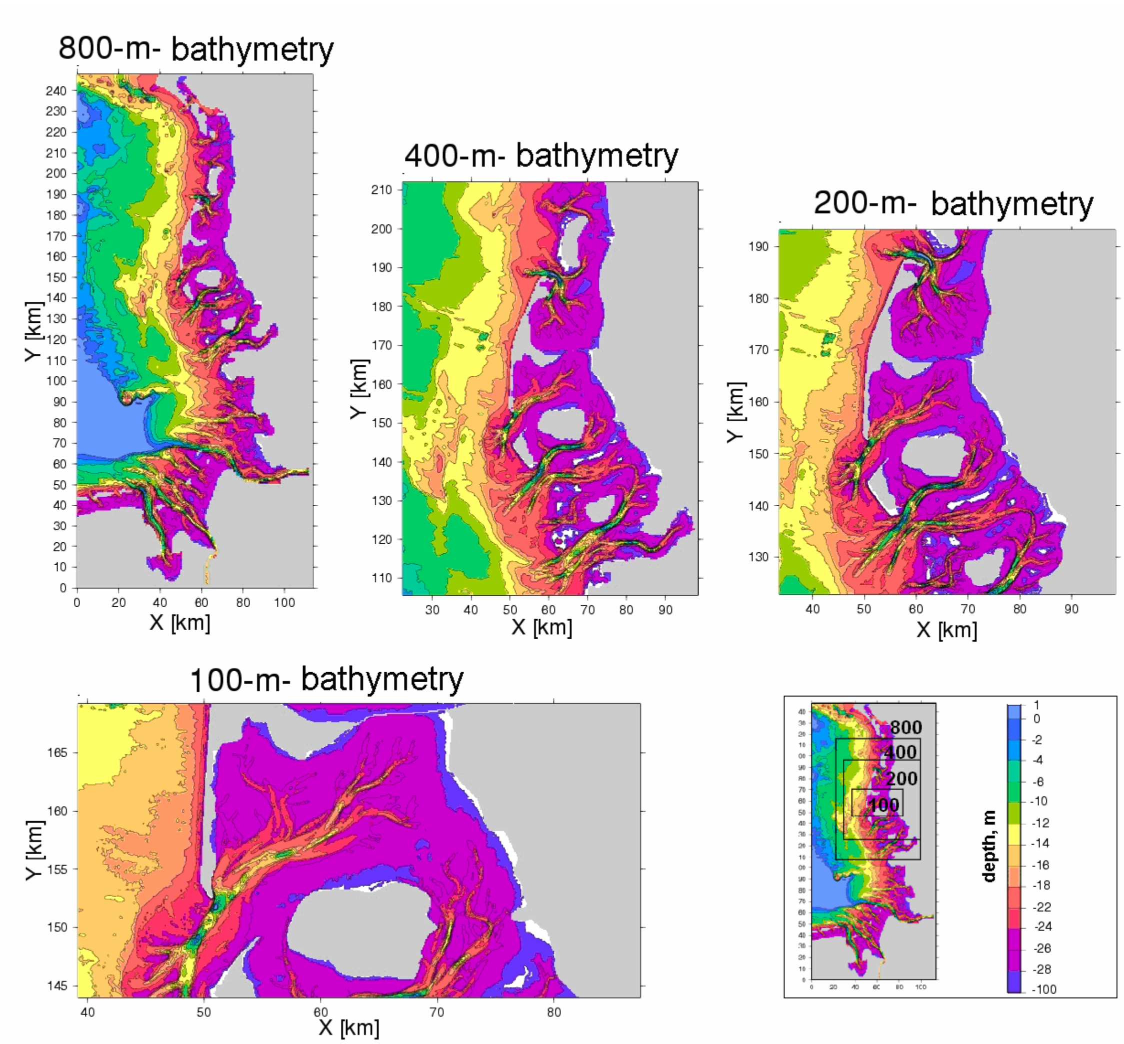

Figure 3: The TRIM model topography: four grids are tied to cascade: 800, 400, 200 and 100 m horizontal resolution. The topography is based on the data from BSH and measurements from ALR-Husum. The grid cascade coupling is shown at the bottom right corner.

The necessary large-scale boundary- and forcing data are obtained from BSH data sets. The boundary water elevation, salinity and currents for forcing of both currents and wave models are provided by results of the BSH North Sea Circulation Model. The wind data were also provided by BSH (originally DWD forecast wind data). One exception poses the storm "Anatol" from 3rd to 4th of December 1999: wind data measured every hour by DWD (Deutscher Wetterdienst) were used instead of the forecast wind data which turned out to be too low (max 25 m/s predicted instead of 32 m/s measured). As boundary values for the wave model the wave spectra, provided by project HIPOCAS (WEISSE ET ALL., 2003) were used.

2.2 The System Component TRIM

The TRIM model solves the 3-dimensional Navier-Stokes equation, discretized with the finite difference method, can take into account non-hydrostatic effects. The aspect ratio of average depth (10 m) to smallest horizontal resolution (100 m) is small enough to omit these effects and to use the model in the hydrostatic mode resulting in a saving of about 50 % CPU time. More details as well as model validation are contained in CASULLI AND STELLING, (1998). For initialising TRIM and for driving the open boundaries values of water elevation, salinity and currents as resulting from the BSH 3-dimensional Circulation Model for Germany Bight are used. These data have a horizontal resolution of 1 nautical mile (1.8 km). The second forcing is the wind, provided by BSH wind fields. These are initially DWD forecast wind data used by BSH model runs as the input and stored as output with other data. The wind stress component is calculated according to

$$\tau^w = c_D \frac{\rho_a}{\rho} \left(U_{10}^w - u\right)\left|U_{10}^w\right| \quad (1)$$

Here $U^w{}_{10}$ means the wind speed 10 m above sea surface, u is the surface current of the sea, the ratio atmosphere density/water density, ρ_a/ρ is assumed to be $1.25 \cdot 10^{-3}$ and the friction coefficient $C_D = 1.4 \cdot 10^{-3}$.

To minimise the scale discrepancy between the coarsest grid resolution of the input-data (1800 m) and the model resolution of 100 m downscaling with a grid cascade was applied. It uses four downscaling grids, which are calculated one after another. The results from coarser grids are used as boundary values for the next finer grid. The first coarse 800 m grid uses originally BSH input data.

The bathymetry of the 4-grid cascade is shown in Figure 3. The vertical grid resolution is 0.5 m, the temporal resolution is 300 s for 800 m grid, 150 s for 400 m grid, 60 s for 200 m grid and 30 s for 100 m grid. The calculations were carried out with 8 processors (Pentium 4, 2,6 GHz). The turnaround-time is 3 CPU-hours for 24 h real time. The communication overhead time (standard 100 MBit/s ethernet) was about 40 %.

2.3 The System Component K-Model

The K-model is a discrete spectral model adapted to shallow waters and strong bottom gradients. Being an offspring of the WAM-Model, it contains some different source terms (SCHNEGGENBURGER ET ALL., 2000). The K-model calculates the distribution of energy density E in the wave number domain (k,θ), θ is the wave direction. The wind input is used in form of Snyder wind input and Philips wind input. The wave breaking effect is implicitly considered in the model via adequate energy loss due to non-linear dissipation (Kitaigorodski-scaling). For details see SCHNEGGENBURGER ET ALL., (2000). The K-model was run with a directional resolution $\Delta\theta$=30◦ (12 sectors) for calculation of energy density spectra $E(location, k, \theta)$, the temporal resolution is Δt= 15 sec and the wave number k is resolved with 25 nodes (frequency space 0-1 Hz) .

First, the K-model was implemented on the TRIM fine grid with 100 m horizontal resolution. But by using a LINUX-Workstation the K-model needed (about 70000 active points) 3 days to calculate the real time of 24 h. For the BELAWATT goal (calculating of 2 years time series) this was an impossible value. To reduce the number of points, the south tidal-area, unimportant for waves in the Hörnum-bight, was taken out of the model: the south boundary was moved to Amrum-Odde and Föhr (W-E line) and between Föhr and the mainland (SW-NE line). By using the grid with 400 m horizontal resolution instead of 100 m the CPU time was reduced by a factor dx·dy·dt=4·4·3=48 (the CPU time was reduced to 1.5 h for 24 h physical time). By this approach the hydrodynamic data from 100 m TRIM model grid are interpolated for the same area onto 400 m K-model grid: currents and water elevation data at 16 points are averaged to 1 point for wave simulation.

The K-model output is saved every 20 min. The energy spectra $E(location, k, \theta)$ are integrated to provide the wave parameters: wave height H_s, periods (Tm-1, Tm-2, mean and peak periods) and wave direction. These parameters are stored separately and gathered for wind and swell parts of the waves. The energy spectra are converted to Frequency (0-1 Hz)/directional spectra and saved every hour. The corresponding wind and sea surface currents are also stored in these data sets. The wave model results are extrapolated later on 100 m grid for calculation of the bottom stress (see EPPEL ET ALL., 2006).

3 Interaction between Waves, Currents and Tides

An impact of currents on waves modifies the wave period: for a fixed observer the waves run faster when they run into the same direction as currents. The water depth (incoming parameter is water elevation) also influences the wave: low tide effects the waves more, due to bottom influence, than high water. These influences are implemented as the coupling part ’current model to wave model’.

On the other hand a part of wave energy can be transferred to currents (radiation stress). This effect occurs when strong energy gradients appear, especially in shallow water. The waves lose their energy here due to stronger bottom friction and slow down. This results in a momentum to generate a wave-induced current and additional drift (long shore current) typical along the coast. This drift can change the water depth in some places like the bights. The consequence of this is a modifying of waves in those areas due to depth change. These dependences are implemented as the coupling part ’wave model to current model’. The radiation stress was implemented in the model according to YAMAGUCHI, 1988.

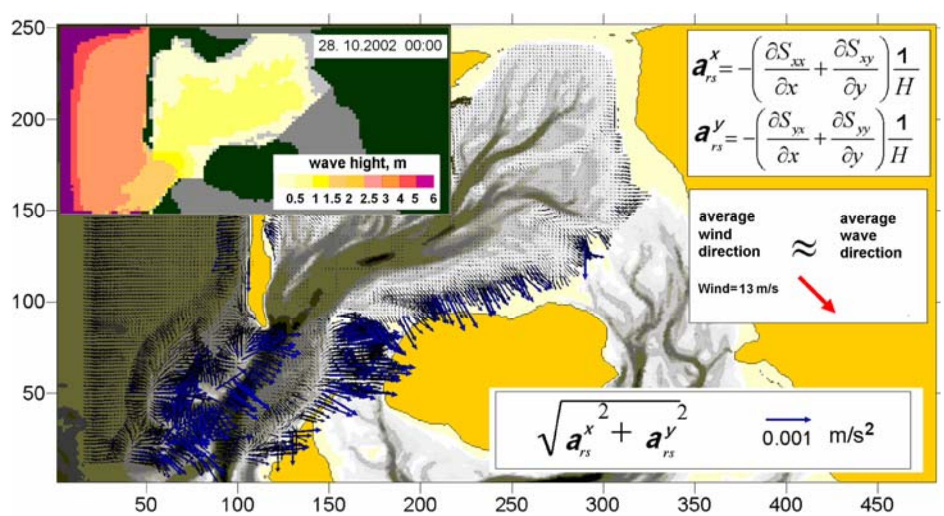

Figure 4: Acceleration due to radiation stress prepared with MOPS system on 28.10.2002 00:00 UTC. The wind came from north-west with about 15 m/s speed. on 27.10.2002. The x- and y- components of this acceleration are calculated from radiation stress tensor S. The topography is underlined with gray colour. On the top left: Actual significant wave height. The acceleration is strongest in the places where a lot of wave energy is dissipated: over sand banks and near the coast.

The wave module supplies the current module with the current acceleration due to radiation stress a_{rs}. Figure 4 shows the snapshot of this acceleration field for the strong wind situation on 27- 28 October 2002. On Figure 4 the formulas for calculation of a_{rs} are shown. For the 2-dimensional version of the current model H is the actual water depth. For the 3-dimensional TRIM version, a_{rs} was added to the upper water layer current component (the same way as wind acceleration). In this case H means the thickness of the upper water layer.

Figure 5 shows the difference in the current field due to radiation stress. You can see clearly the 'long-shore current', directed to south. This drift is about 20-30 cm/s for the Sylt's west coast. The additional current over the sand banks in the Ebb-delta is about 1 m/s toward the bight. The water-depth changes due to radiation stress are shown at the bottom picture on Figure 5. The difference between depths calculated with and without radiation stress are about 20 cm. These results show that the radiation stress impacts the current dynamic in the coastal areas.

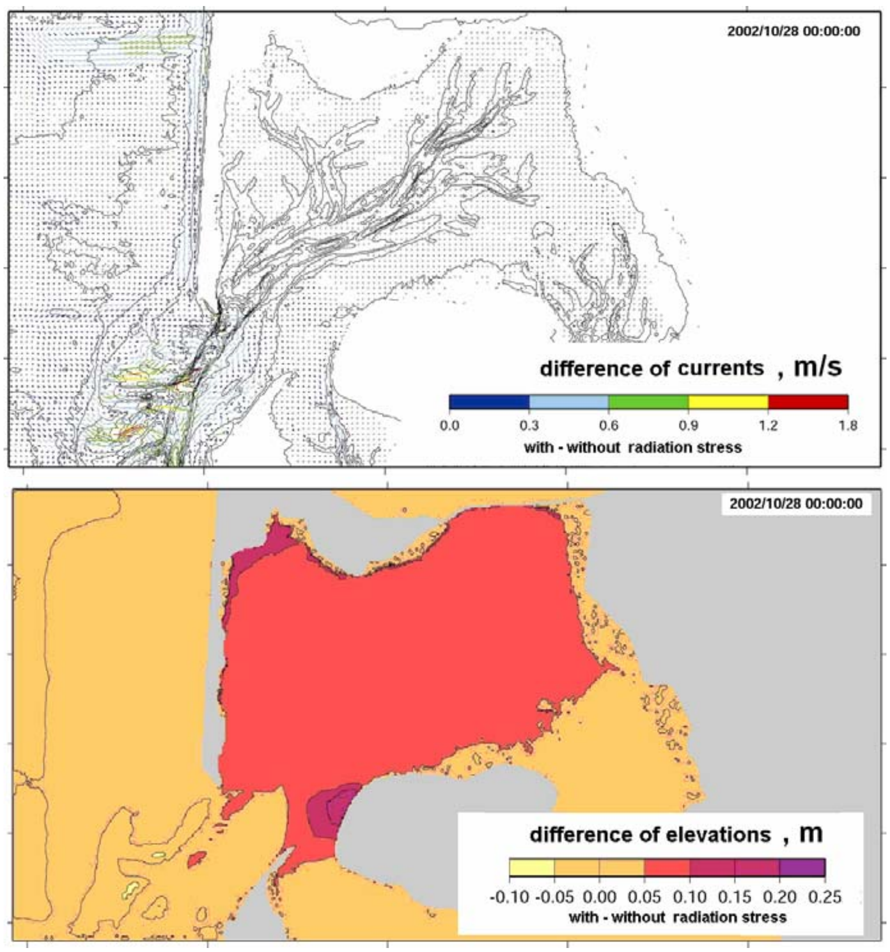

Figure 5: Change in the current field (top) and in the depth field (bottom) on 28.10.2002 00:00 UTC. Top: Difference=current field calculated with radiation stress - the same without radiation stress. Bottom: Difference=depth field calculated with radiation stress - the same without radiation stress. The strong additional current (around 1 m/s) can be shown over the sand banks in the bight mouth where the depth strongly changes within a small space (from 12 m to 1 m within 100 m distance). The additional drift along the coast directed to south is about 20 cm/s ('long-shore current'). The depth difference at the bottom picture is average about 15 cm and in some places it reaches values about 30 cm.

4 Impact of Waves on the Coastline

4.1 Wave Energy Flux

Data of wave impact on the coast and beaches are important for aftermath risk estimations used for the planning of engineer measures and coastal management. To obtain this information is a really complicated task. One method is getting the information from the wave rider buoys. The measured wave parameters are used to estimate the wave energy dissipation on the buoy location. With the mathematical formulas the energy flux and energy dissipation on the coast are extrapolated (see WITTE ET ALL., 2000). The suitable wave model can calculate this process without extrapolations and solve this task.

The starting point is calculated by model wave energy density E_w (wave energy per unit area, [kg/s2] =[J/m2] = [Ws/m2]). The energy flux (power transported by waves) is given by:

$$\boldsymbol{F}=E_w\boldsymbol{C_g} \quad [\mathrm{Ws\ s^{-1}\ m^{-1}}], \qquad (2)$$

in which C_g is the wave group velocity. Figure 6 shows the spatial distribution of the maximal wave energy flux during the storm “Anatol” in December 1999 (on the left panel). For comparison, the average energy flux for the calm weather condition (after the storm) is shown on the right panel. The values differ by two orders of magnitude.

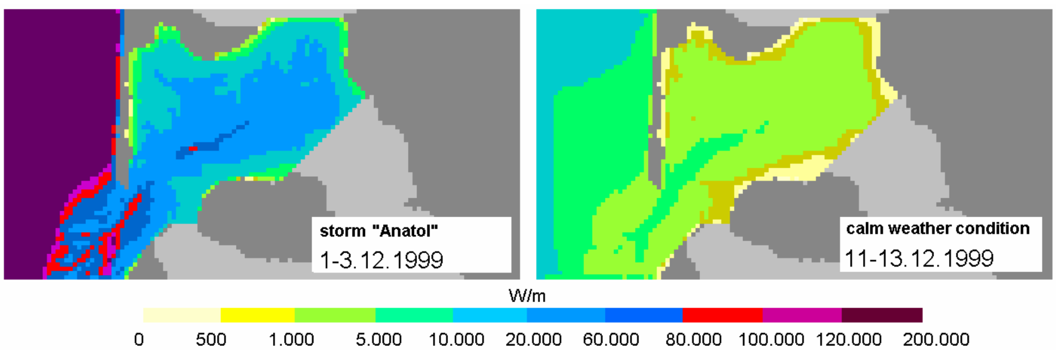

Figure 6: Left: The spatial distribution of the maximal wave energy flux during the storm “Anatol” from 1st to 3rd of December 1999. Right: The average energy flux for the calm weather conditions from 11th to 13th of December 1999 (after the storm “Anatol”).

We are interested on wave energy input on the coastal line. As coastal line we understand here the border between first dry point and next to last wet point (Figure 7). The coastal line is spatially and temporary variable due to tide. We assume that the wave energy (going in the coast direction) is completely dissipated in last wet point within the dx = dy = 400m beach line.

To calculate the wave energy input into the coast, two components of this energy are considered: parallel and perpendicular to the modelled coastline (shown on the Figure 7). The perpendicular component causes the erosion of the coast, the parallel component serves as transport drift along the coast for a eroded matter.

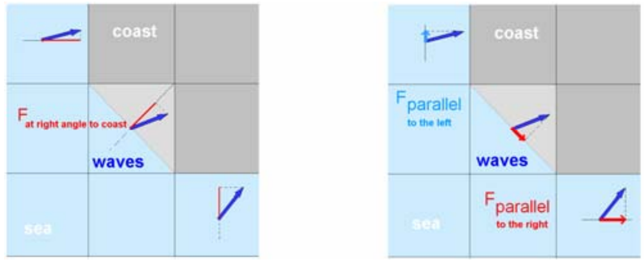

Figure 7: Scheme for calculation of the perpendicular component (F_s) and parallel component (F_p) of the waves energy, coming to the coast line. By F_p the blue colour points at left direction (observer is standing in the sea and looking at the coast), the red colour points at the right direction of F_p.

The two upper diagrams of Figure 8 show temporal averaged components F_s and F_p of energy flux for December 1999. For the averaging of the F_p the energy flux to north (left at the coast) and south (right at the coast) is considered separate. The dots on the lines are the model grid points with 400 m horizontal resolution. F_s is more than twice greater than F_p. The third diagram shows the maximum and mean of the absolute value of wave energy flux. All diagrams have a similar feature: in the area with water depth < 10 m the waves and thus wave energy flux are decreasing.

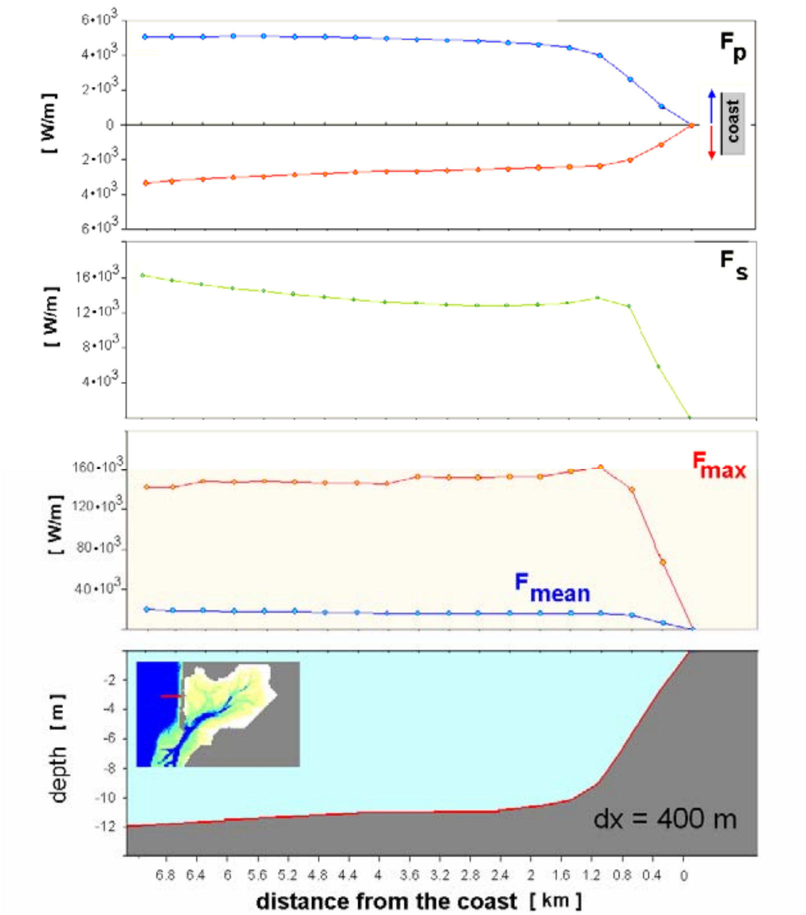

Figure 8: The wave energy flux in a 7 km long profile perpendicular to the Sylt coast (the profile location is shown in the picture at bottom left). The lower picture shows the water depth (at NN): the depth is mostly constant (around 12 m), only on the last 1,500 m from the coast the depth is nearly zero.

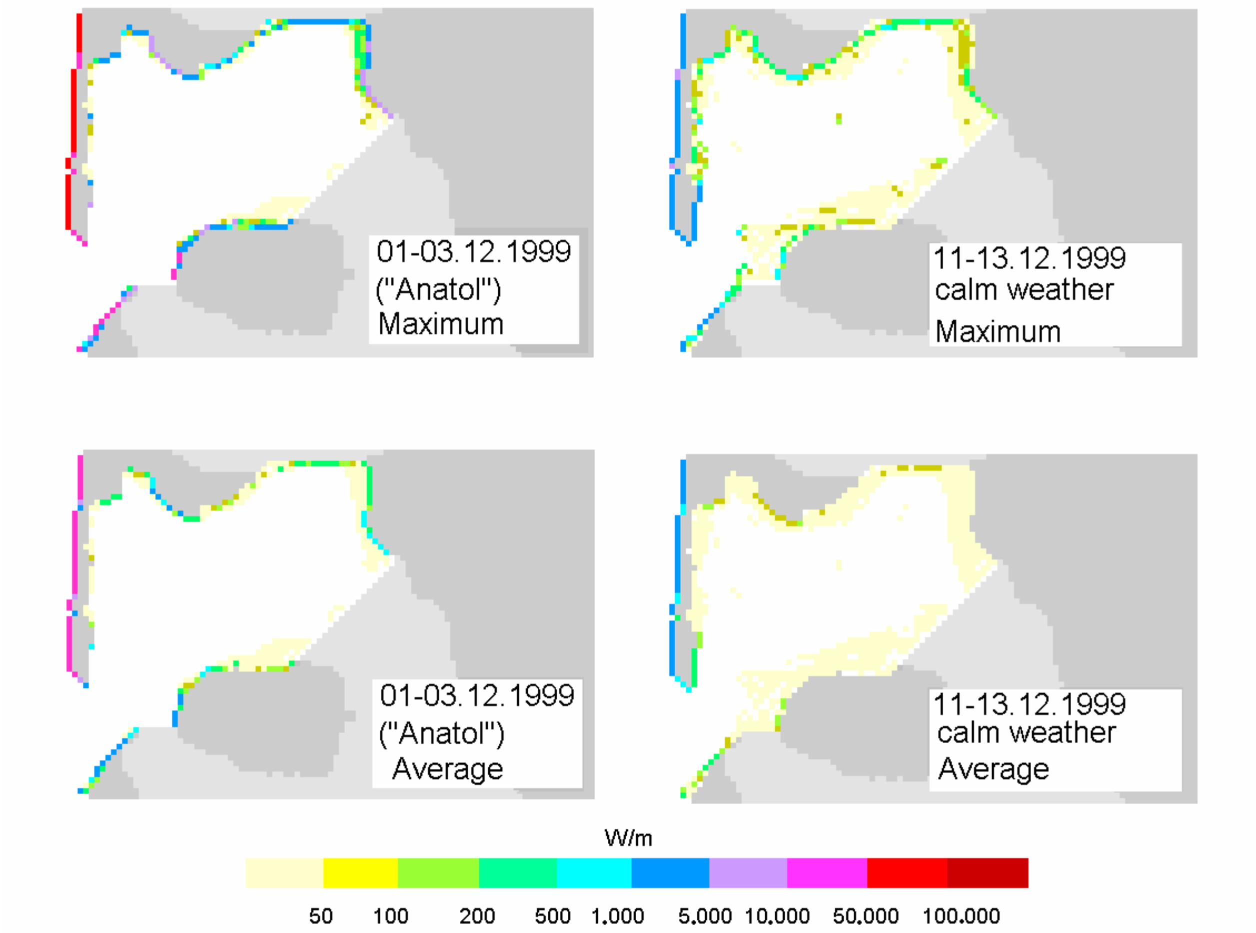

Figure 9: The perpendicular component F_s of the wave energy input into the coast line for two three-days' time series: Storm "Anatol" (left) and calm weather condition after storm (right), maximum values (top), average values (bottom). This component causes coastal erosion. The coastal line is spatially variable due to tide.

Figure 8 shows temporal averaged components F_s and F_p of energy flux as well as maximum and mean of the absolute value of energy flux in a 7 km profile, perpendicular to the coast of Sylt for December 1999.

Figure 9 shows the perpendicular component F_s for the storm situation (on the left panels) and for the calm weather condition (on the right panels). The maximum values are shown on the top: so we can see the points with maximal wave impact and thus maximal risk of the coastal erosion. On the bottom the average values of the wave impact are shown: so we can see the places threatened by not strong but long-term influence of the waves.

Figure 10 shows the parallel component F_p of the wave energy input into the coast in the same way as Figure 9. This component is important for the coastal parallel drift and slow transport of the eroded matter along the coastal line. The values of this component are not as big as F_s, but they still reach 10 KW/m.

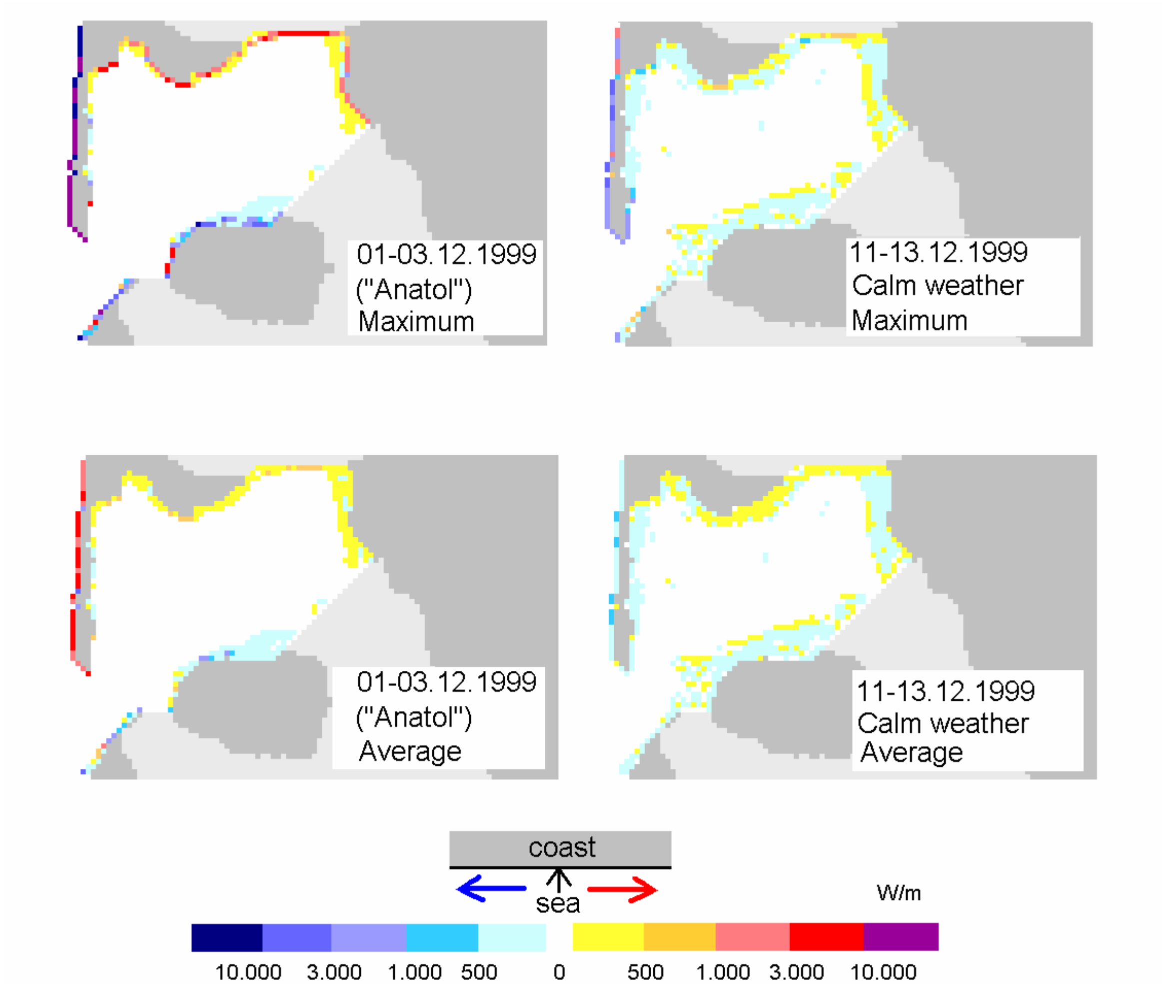

Figure 10: The parallel component F_p of the wave energy input into the coast for two three-day time series: Storm "Anatol" (left) and calm weather condition after storm (right), the maximal values (on the top), the average values of the wave impact (on the bottom). This component causes slow transport of the eroded matter along the coastal line. According the legend the blue colour points at left direction (observer is standing in the sea and looking at the coast), the red colour points at the right direction of F_p.

4.2 Scenarios

In analogy to the two-years' time series from the BELAWATT project three scenarios of climate change were simulated. The first had the increased water depth for the entire North sea of 25 cm (N1), the second one had the same at 50 cm rate (N2) and the third was the scenario two (50 cm) with additional wind speed increase of 10 % (N3).

These scenarios were calculated for December 1999 (including storm "Anatol") as well as for September 2000 (calm weather conditions). The results of the most interesting scenario N3 are presented in Figure 11 and in Figure12 (two different locations: inside and outside the bight). These figures show the time series in two points for December 1999 and contain (top down): significant wave height, current (absolute value), perpendicular component F_s and parallel component F_p of the wave energy input into the coast line, wind speed and depth. The line gaps mean that the areas fall temporarily dry. The blue colour means the present-state, the violet colour presents the scenario, and the difference between both is red coloured.

In December, the storm “Anatol” plays the most important role, especially during the evening hours of the December, 3rd. Fast turning of the wind direction from SW to NW causes the F_p direction to change (Figure 11). The increase of the depth (+50 cm) and wind speed (+10%) causes the wave increase (significant wave height increases about 10 %) in the point location Sylt-coast (at sea side). Since the wave energy is quadratically proportional to wave height (see formula 2, $E_w=H_s^2/16$ because of significant wave height $H_s=4\sqrt{E_w}$), the energy growth at about 25% (80 KW/m) is compared to the present-state (60 KW/m, see Figure 11, day=4).

On the station Föhr (inside the bight) the depth is small and its change at 50 cm plays a stronger role than in the station Sylt-coast. The energy growths at about 50%.

The newest storm surge scenarios show the possible increase of its value up to 50 cm at the time horizon of 70 years (WOTH ET ALL., 2006). This means not only an increase of the surge, but also an increase of wave impact of the coast. In case of surge increase on 50 cm (about 5 % of the depth for the Sylt coast) the coastal engineers must have in view the increase of the coastal stress due to storm following waves at 25-50 %.

5 Concluding Remarks

With the consequences of climate change becoming more and more obvious, there is a demand for useful information when planning measures to counteract harmful consequences. The investigation presented here showed that - assuming the models and the methods being essentially correct - a slight increase of the forcing parameters (10 % stronger wind, 50 cm higher sea level) results in 30 % higher (of the already high) wave energy input on the sea side of Sylt island. A considerable increase of the risk of loss of land can therefore be expected.

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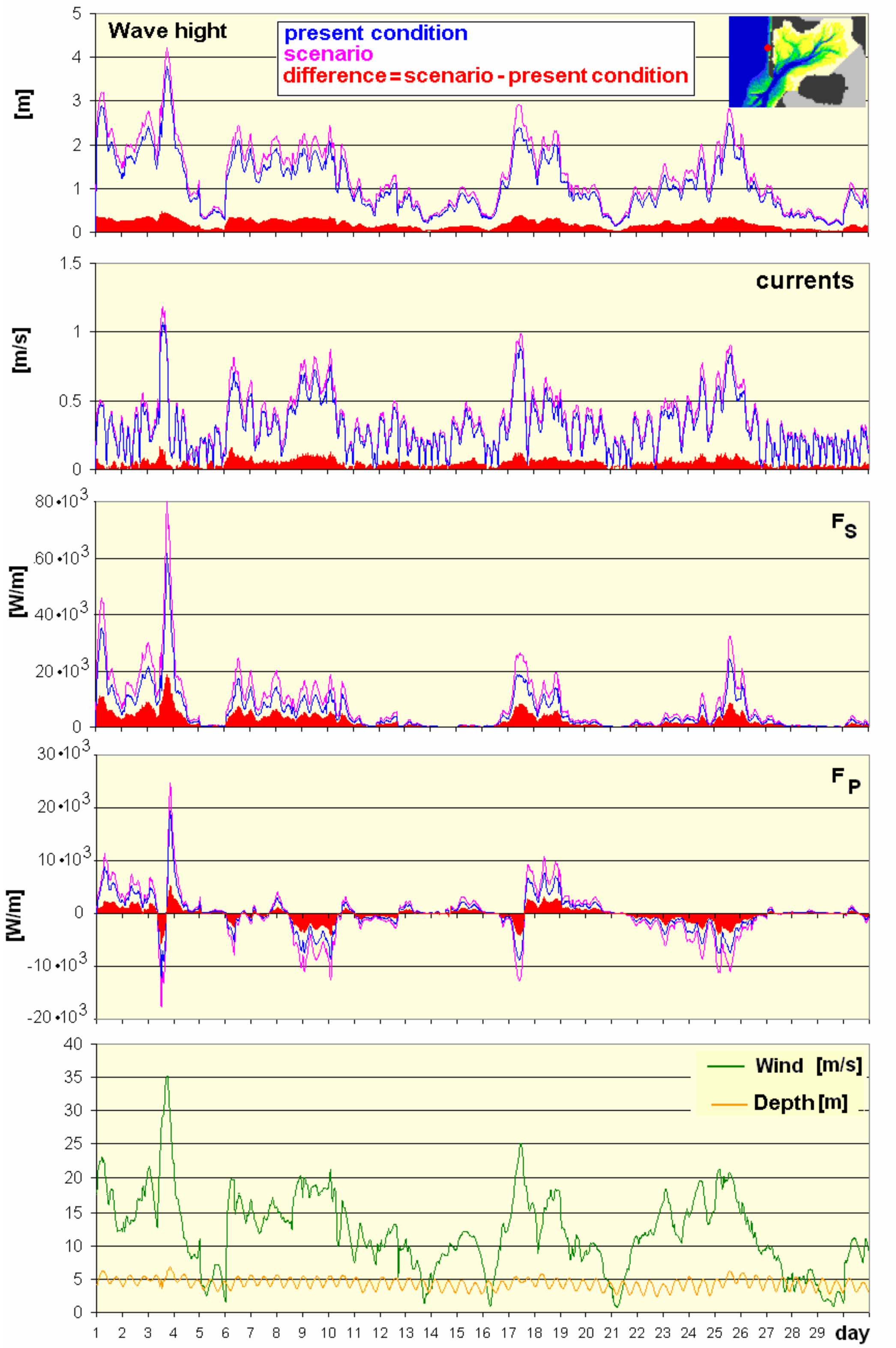

Figure 11: The time series for December 1999 on the station of Sylts west coast (the location is shown on the top right). Top to bottom: significant wave height H_s, currents (absolute value), the perpendicular component of the energy flux coming to the coast line F_s, parallel component of this flux F_p, wind speed and actual depth. The blue colour means the present-state, the violet colour presents the scenario (increase of the water depth on 50 cm and wind speed at 10 %) and the difference is red coloured.

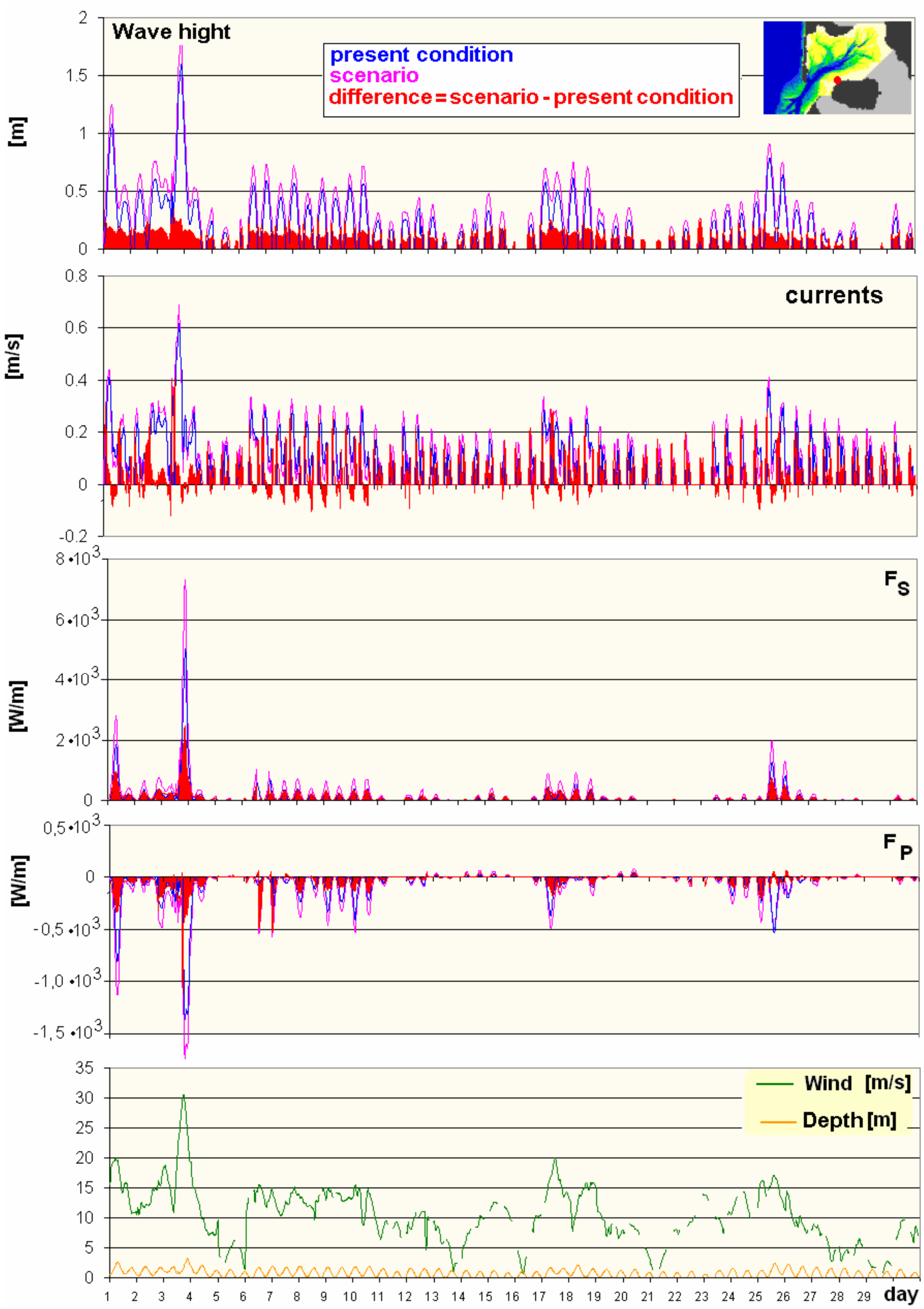

Figure 12: The time series for December 1999 on the station Föhr inside of the bight (the location is shown on the top right). Top to bottom: significant wave height Hs, currents (absolute value), the perpendicular component of the energy flux coming on the coast line Fs, parallel component of this flux F_p, wind speed and actual depth. The blue colour means the present-state, the violet colour presents the scenario (increase of the water dept by 50 cm and wind speed by 10 %), and the difference is red coloured. The line gaps mean temporarily dry.