Projection of wind wave and bed shear stress in the inner Danish waters

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Background

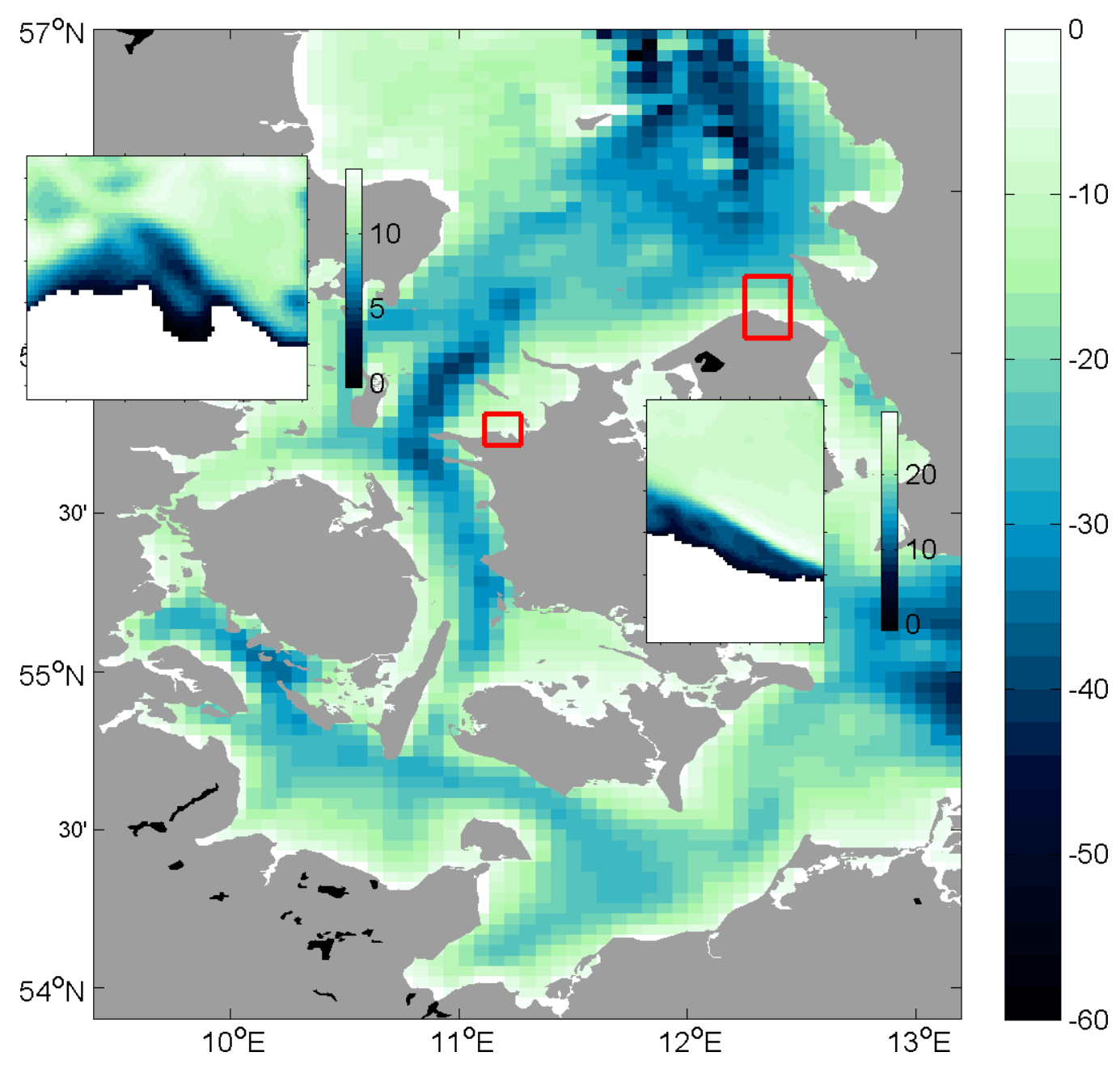
Coastal areas in the inner Danish waters, i.e. the transition zone between the North Sea and the Baltic Sea, are facing the prospect of rising sea level and changes in wind forcing due to climate change. Each of these changes exacerbates increased risks for floods and coastal erosion (Arms et al., 2017).

However, increased sea level also reduce bottom friction on near-coastal surface waves and this **amplifying effect from sea level rise on near-coastal waves and coastal erosion** is analysed here.

Changes in the wave climate influence the transport of suspended particulate matter and, thereby, causes changes in erosion and deposition areas. These effects have to be considered in future coastal management and in the design of coastal protection.

We investigate the potential effects from a 1 m sea level rise compared to a present day simulation. The scenario below apply the wind forcing from the storm "Bodil" in December 2013.

Wave model for the inner Danish waters



Model domain of the inner Danish waters and the two high-resolution nested model domains.

Wave model

The wave model is based on the third-generation wave model SWAN (Simulating WAves Nearshore, version 41.10). SWAN is designed for obtaining realistic estimates of wave parameters in coastal areas, lakes and estuaries from given wind, bottom and current conditions (Booij et al., 2001). The model is based on the wave action balance equation with sources and sinks.

Model domain and high resolution nested models

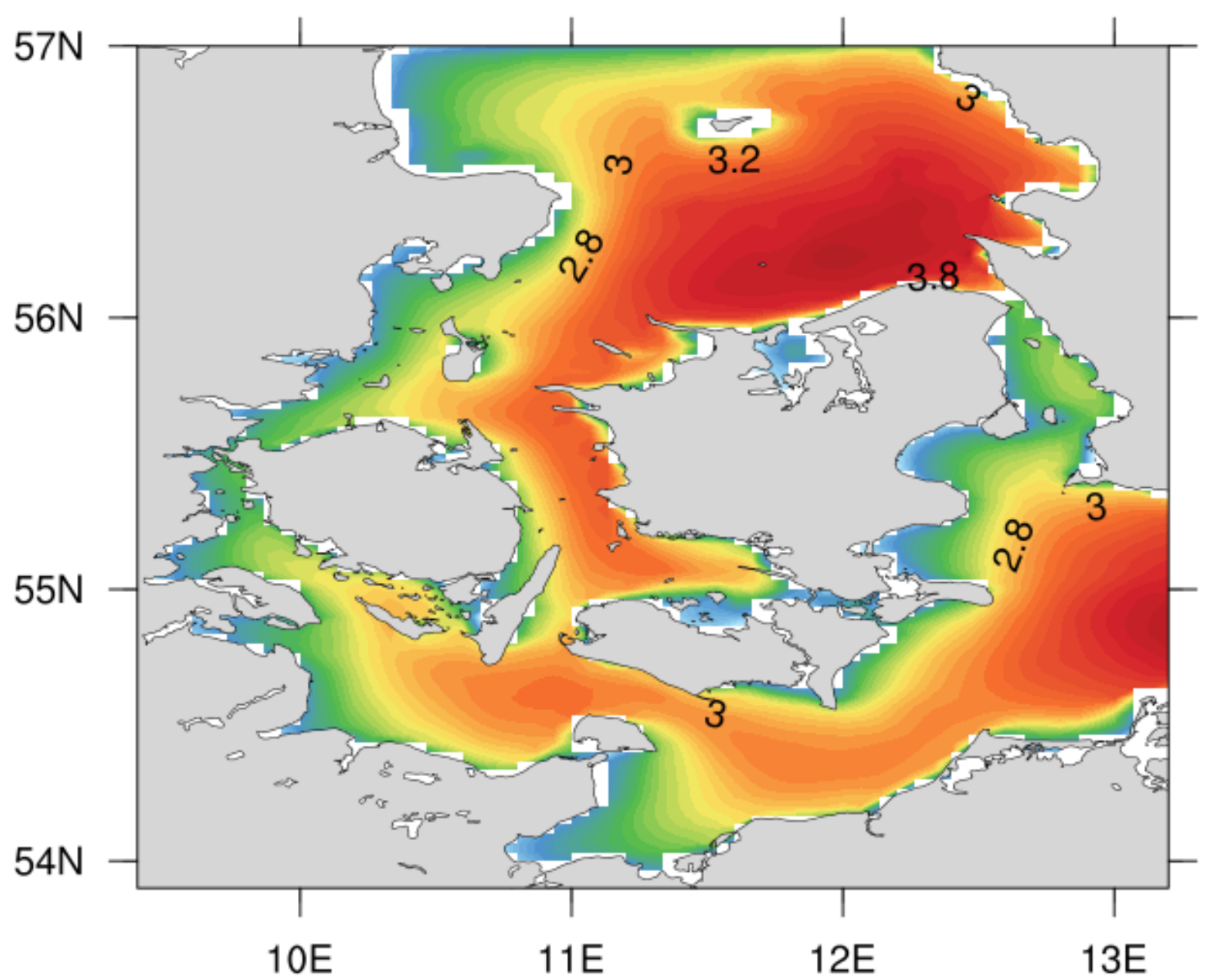
The model domain has a resolution of 2 x 2 km and covers the inner Danish waters. Two high-resolution nested model domains are defined along the coast of northern and north-western Zealand (covering ~20x20 km in 200 m resolution). The high resolution models resolve the wave dynamics when waves propagate from deep to shallow areas. The two areas are characterized by a relatively steep and modest sea bottom slope, respectively.

Simulated waves during Bodil

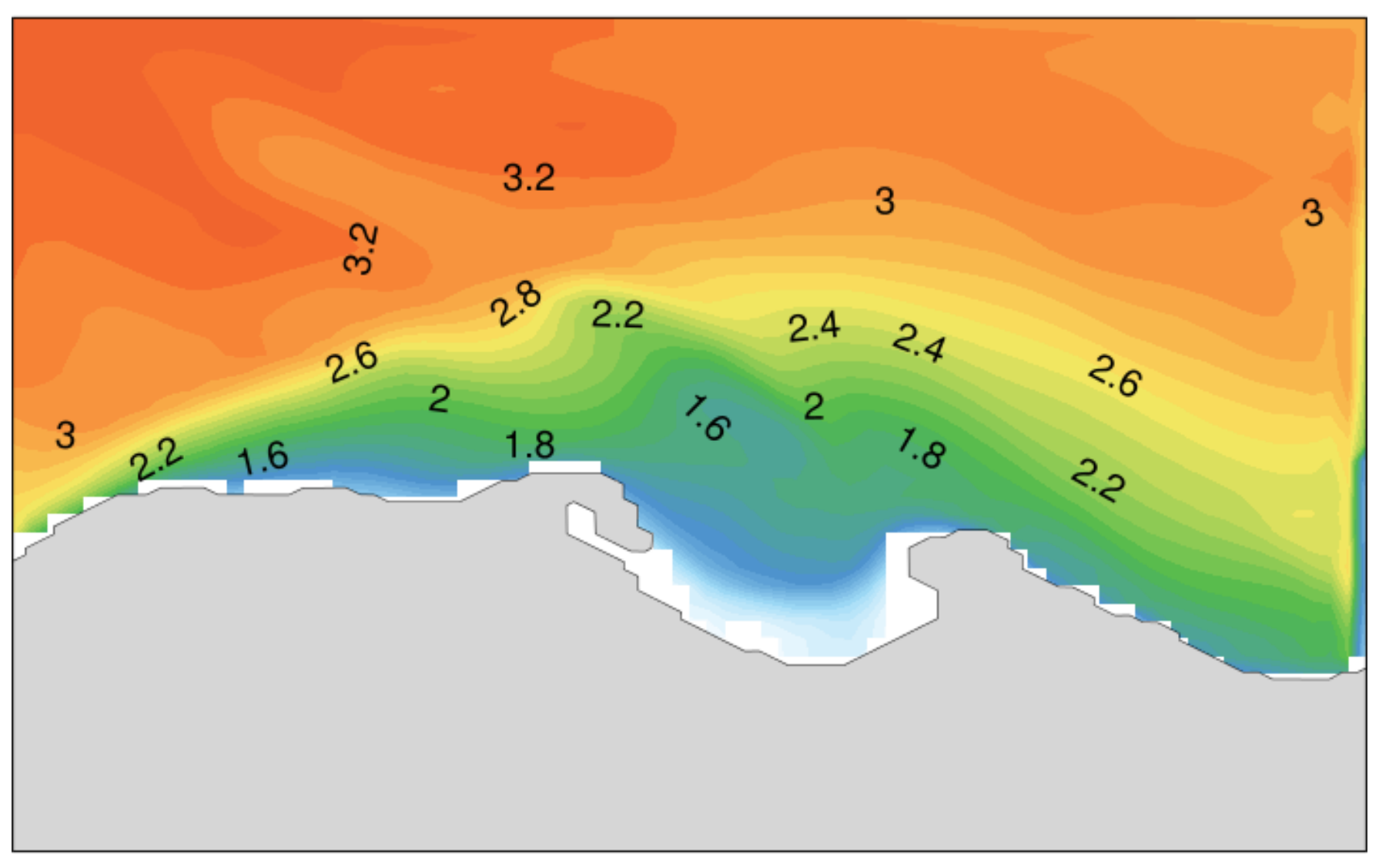
Significant wave height under the Bodil storm event, Dec 2013

A deep low-pressure system crossed the North Sea in December 2013 and the following storm in Denmark was named Bodil (ref. DMI). The storm affected northern Europe and became also known as the the North Sea flood of 2013. Force 12 winds and heavy snowfall were observed along the storm's path. Meteorological forcing in the model is determined from ERA-interim reanalysis data.

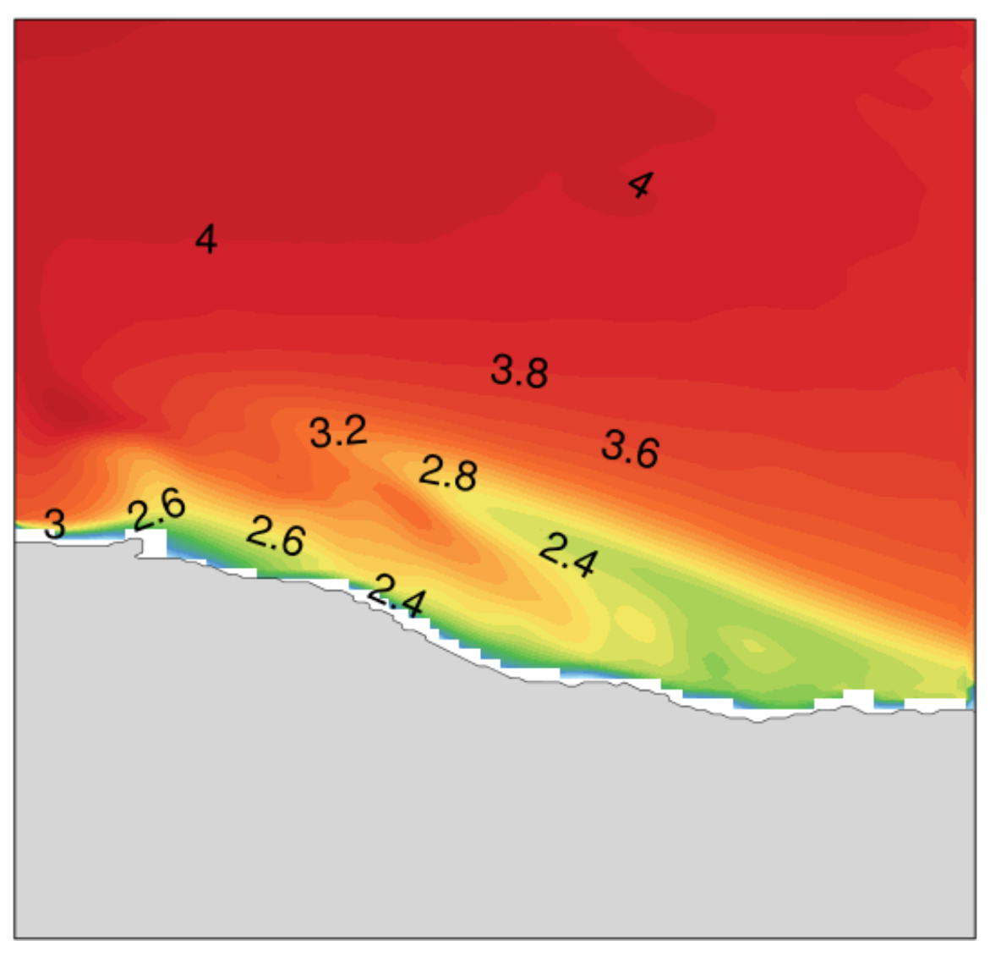
The simulated significant wave height (Hs) were over 4m during the storm off shore northern Zealand. In the finer resolution nested domain, Hs decreased near the shore, especially in the north-western nested area characterized by a modest sea bottom slope (below left figure)



Simulated significant wave height (m) dring Bodil (6/12 0h)



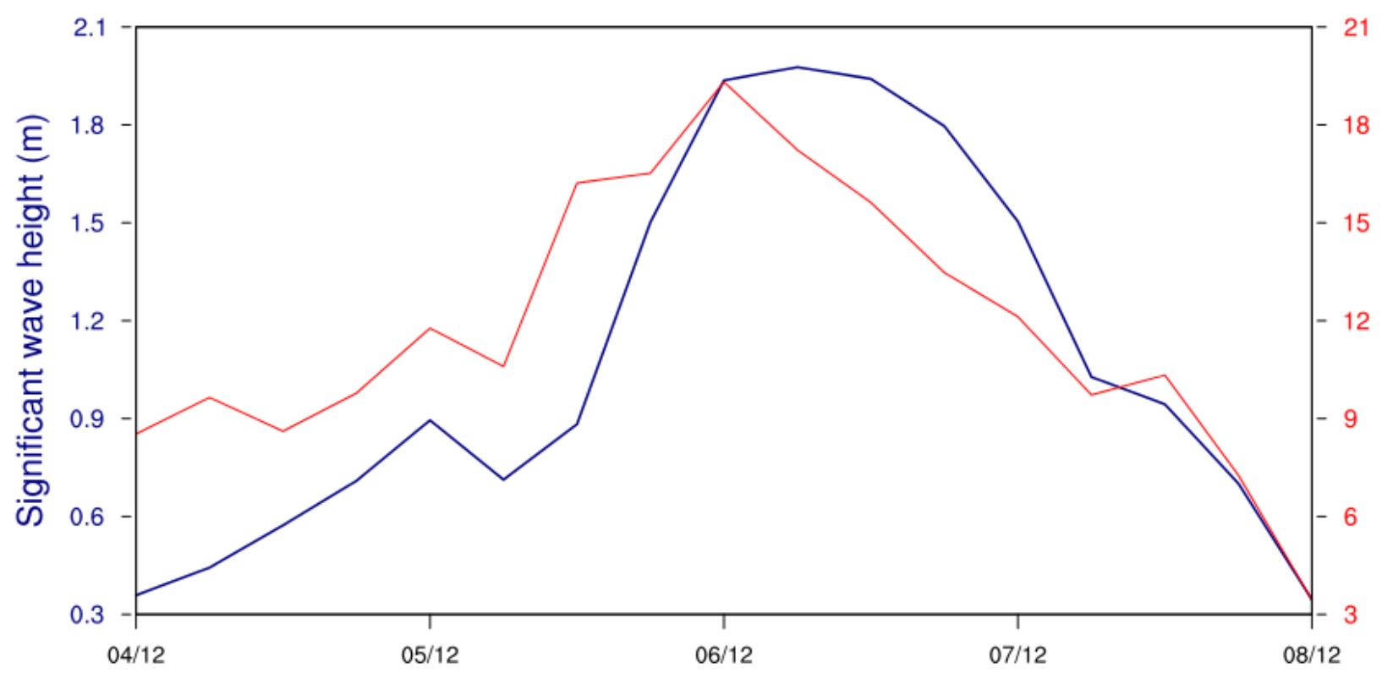
High-resolution simulation of significant wave height (m) off north-western Zealand during Bodil (6/12 0h)



High-resolution simulation of significant wave height (m) off northern Zealand during Bodil (6/12 0h)

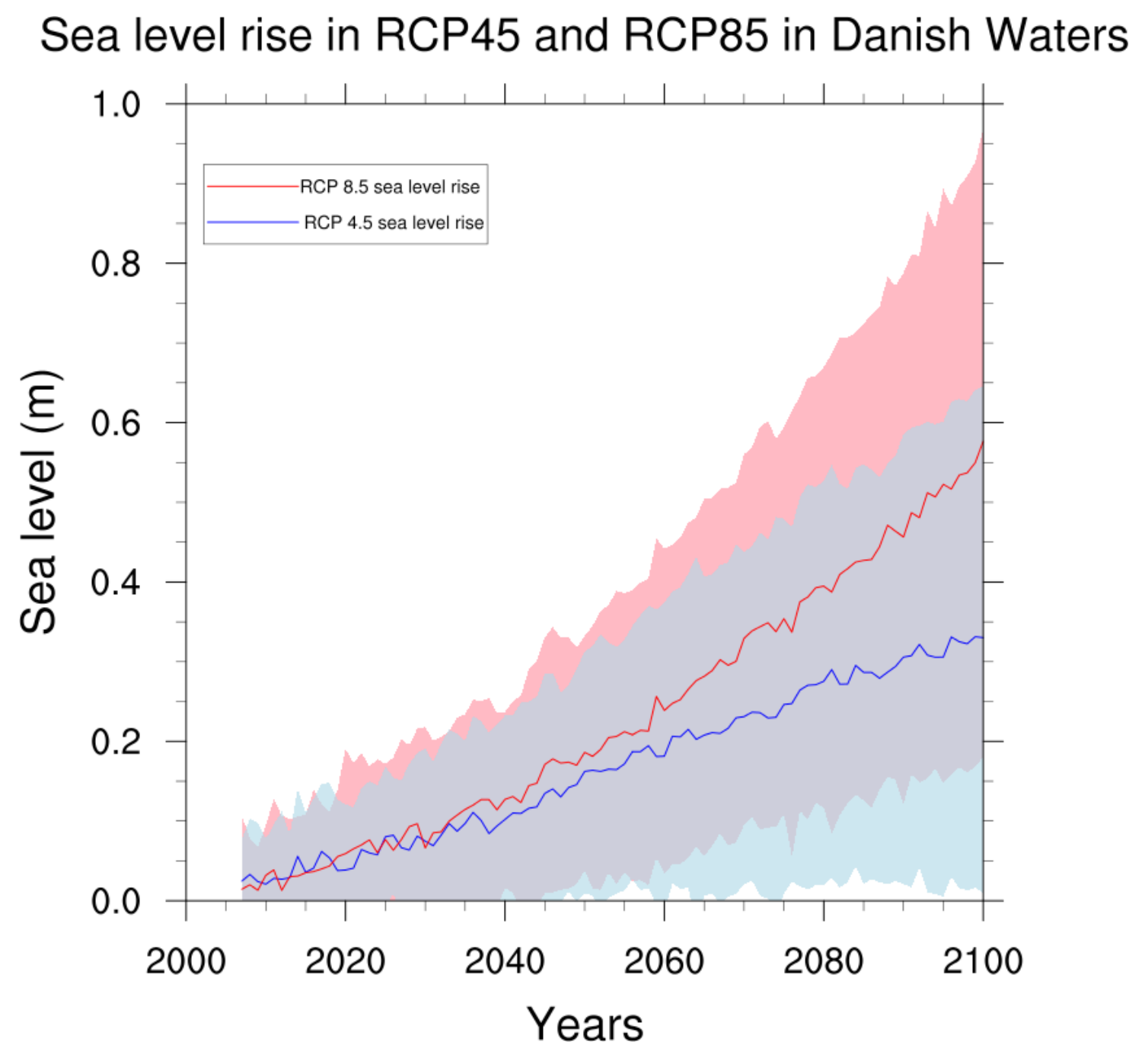
The passage of Bodil

The passage of Bodil (5-6 December 2013) caused maximum wind speeds in Denmark above 35 m/s. However, the wind forcing applied in this study is based on a coarse resolution model product (ERA-Interim) and, therefore, model winds are significantly less than the observed winds. The applied wind forcing off northern Zealand is shown in the figure along with the simulated signficant wave heights. The passage of Bodil also caused increased sea levels along the Danish coast of up to almost 3 meter above normal sea level. The effect from this transient increase in sea level is not included in the sensitivity experiments discussed here.



Model simulation of significant wave height (blue) near the coast in the northern nested model domain (off northern Zealand). The applied wind forcing, corresponding to the passage of Bodil, is also shown for the same location. Wind speeds increase from 9 m/s (4/12) to maximum values of 20 m/s (6/12) and the significant wave height changes correspondingly from 0.4 to 1.9 m.

Projection of sea level rise



Sea level rise in Danish waters

Based on data from ensemble sea level projections from the IPCC AR5 report (Church et al. 2013), we calculated the sea level rise in the inner Danish waters. The IPCC data product is relatively coarse (1x1 degree), however several grid points were included in our model domain.

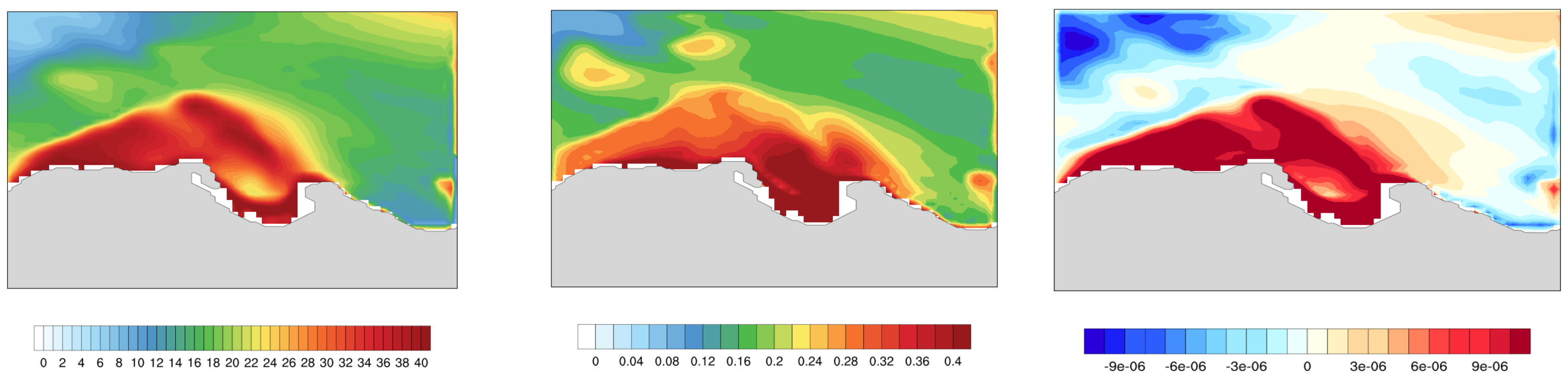
The solid lines show the ensemble mean results in the two representative concentration pathways scenarios RCP 4.5 (blue) and RCP 8.5 (red). The shaded areas show the 5% and 95% percentile uncertainty (overlapping colors are shown in gray). The RCP4.5 (RCP 8.5) ranged from ~0 (~0.15) to 0.65 m (0.95 m) at the 5 and 95 percentile levels, respectively.

In the sensitivity study below we consider a sea level rise of 1 m, i.e. corresponding to the extreme of the RCP 8.5 scenario at the end of the 21st century.

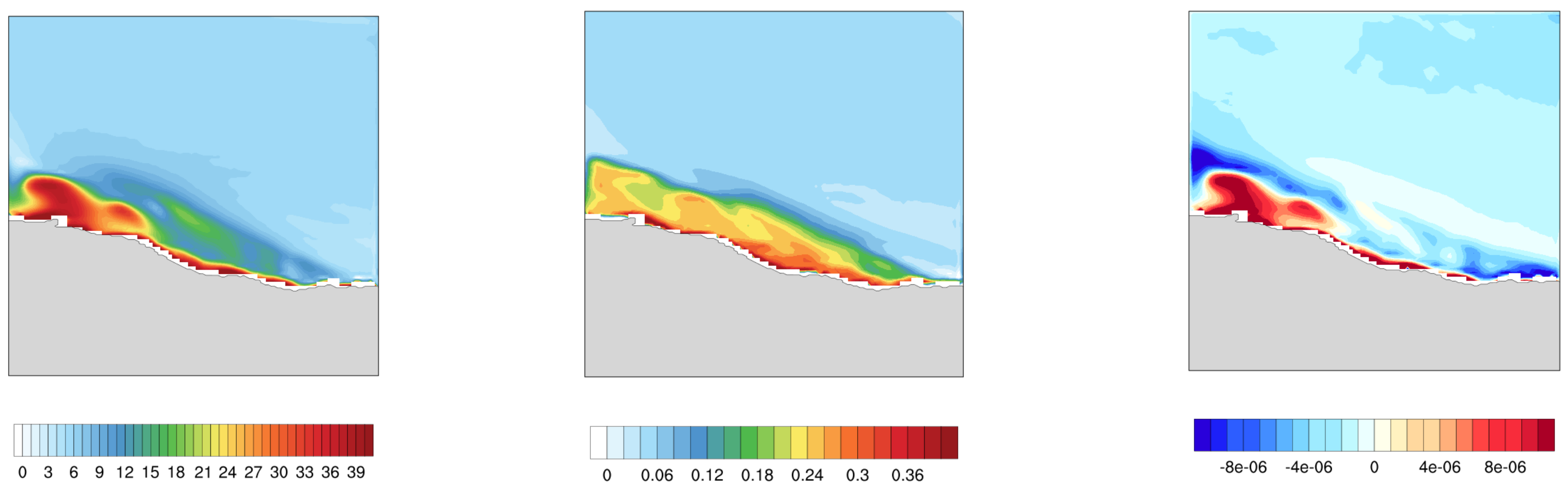
Results

Increased sea level affects the bottom stress induced by the waves because a deeper water column cause a smaller orbital motion at the sea bed. We compared model simulations of significant wave height, period and bottom stress induced by the waves between two model simulations.

In the reference scenario we simulate the wave field given from the meteorological forcing from the passage of Bodil. In the climate change scenario we increase the depth in the whole model domain by 1 meter and apply the same wind field as in the reference case. The difference between the two simulations for the two nested model domains at the northern and north-western part of Zealand, respectively, are shown below.



High-resolution simulation of the difference between the climate change scenario (i.e. 1 m increase of sea level) and the reference scenario. Change of (left) significant wave height (cm), (middle) wave period and (right) energy dissipation due to bottom stress at the nested model domain off north-western Zealand during Bodil (6/12 0h).

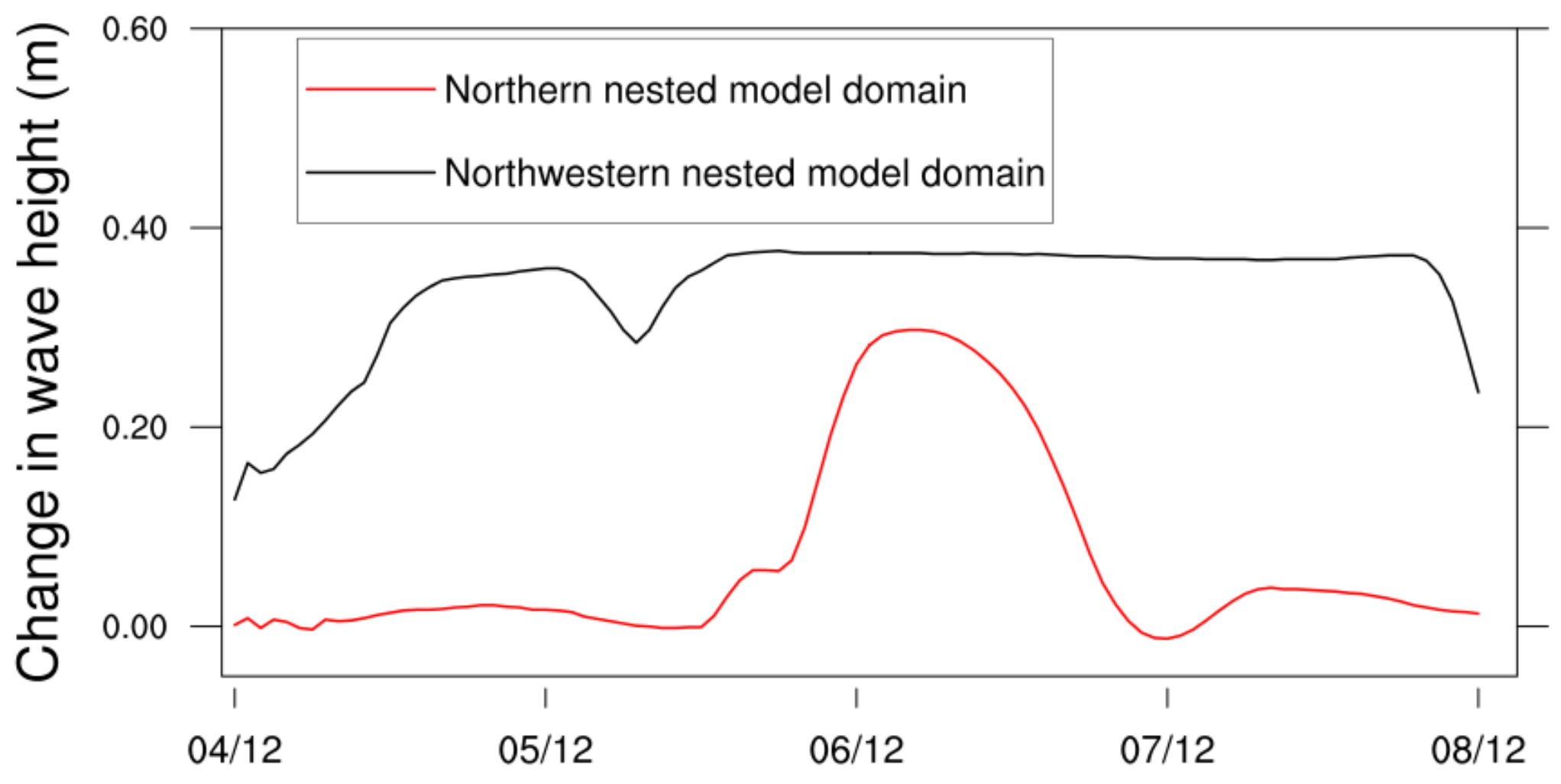


High-resolution simulation of the difference between the climate change scenario (i.e. 1 m increase of sea level) and the reference scenario. Change of (left) significant wave height (cm), (middle) wave period and (right) energy dissipation due to bottom stress at the nested model domain off northern Zealand during Bodil (6/12 0h).

Changes in significant wave height between the climate change and the reference case at the northern nested model domain (Figure, red) and at the northwestern domain (black).

Wave heights increased by ~0.4 m at the northwestern location for more than two days, whereas wave heights only increased by about 0.3 m for half a day at the northern location.

Changes in wave heights at the northern location were also minor before the passage of Bodil.



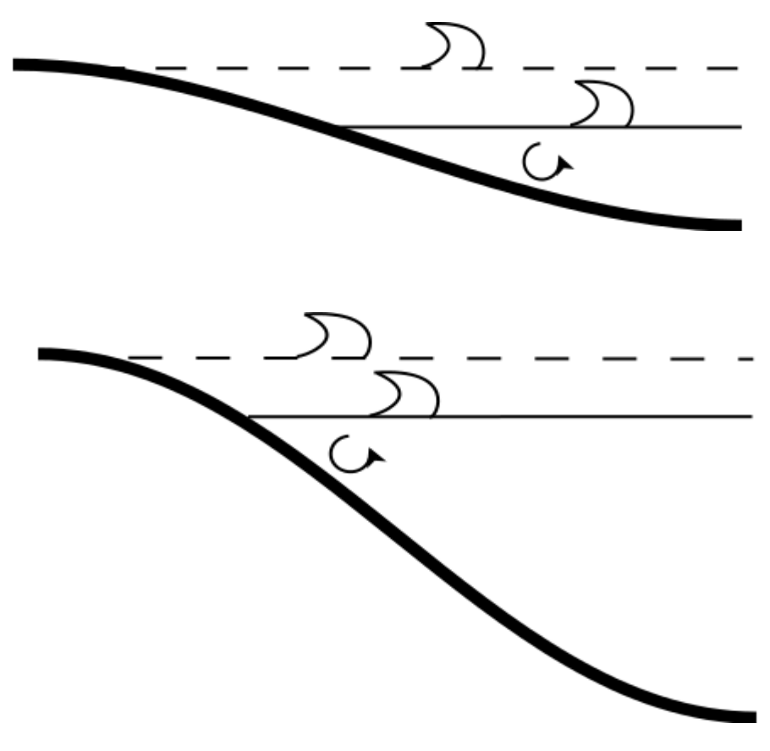
Conclusion

Sea level rise has the following consequences for the near-shore wave field:

- *Wave heights increased significantly in areas with modest sea bottom slope*
- *Wave breaking due to bottom friction occurs closer to the shore, in particular in areas with modest sea bottom slope*

Summary from the simulated storm passage

- *Wave heights increased by 0.4 m in the northwestern nested model domain, corresponding to a 44 % increase in the wave energy flux.*
- *The near-shore wave period increased by 0.4 s during the storm.*
- *Areas with modest sea bottom slope showed a significant impact on wave height from changes in sea level change, even during periods with relatively low wind speeds (< 10 m/s).*



The bottom stress from surface waves is more sensitive to sea level rise in areas with a modest bottom slope (top) than in areas with a relatively steep bottom slope (bottom). A modest bottom slope also tends to increase wave breaking closer to the shore.

References
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