The Baltic Sea Wave Field

Impacts on the Sediment and Biogeochemistry

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Abstract

The wave field in the Baltic Sea has been modelled for a two-year period with the spectral wave model HYPAS. There is a large seasonal variation in the field and a minor annual one, both reflect the wind variation in the area. Since the Baltic Sea is fetch limited, the dominant wind direction is important for the maximum wave heights.

By studying the modelled wave energy density in combination with bottom type maps, the effect of the wave field on the sediment surface is examined. Up to half the bottoms in the Baltic Sea are affected ~25% of the time. A statistical relation between wave energy density and bottom types is found for the Gulf of Riga, but in the rest of the area the sediment maps were too coarse. It is, due to this, not possible to say if the result is valid for the whole area or if it is site specific.

During resuspension events the remineralisation is increased since deposited organic material is reintroduced into the watermass and there exposed to higher levels of oxygen. This process could act as an increased regional source of nitrogen in nutrient budgets and thus influence the conditions for nitrogen fixation and perhaps explain some of the geographical differences in the nitrogen fixation rates.

Keywords: HYPAS; Wave modelling; Significant wave height; Wave energy density; Bottom types; Resuspension; Nitrogen fixation; Baltic Sea
This thesis is based on the following papers referred to by their Roman numerals (I–III).


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Introduction

Along the coastlines we encounter the most visible impacts of ocean waves. Walking along a beach before and after a storm reveals the sometimes drastic re-sculpturing of the beach while the subtle lapping more gently reshape the same. Remedy actions to protect the beaches from this erosion are numerous but often in vain since the problem in many cases is moved to another part of the beach (e.g., Viles and Spencer, 1995). It is a natural process, which slowly erode the coastlines, bringing out huge quantities of solid and dissolved matter to the oceans. Man-made constructions, both along the coasts and offshore, stationary as well as mobile, are other things where the impact of waves easily is seen and which can cause great material, economical and in really bad cases human losses.

Though not as spectacular there are other important effects of the waves. Wind generated surface waves set the water below into orbital motion and act as an energy source to the water column. In shallow regions the wave motion may reach the bottom and give rise to a frictional force on the sediment surface. If large enough, the bottom stress can mobilise the sediment particles and bring them into suspension. Resuspension processes are responsible for the long-term transport of particulate matter from the shallow erosion bottoms to the deep accumulation ones. When the fine particles once are resuspended much less energy is needed to keep them in suspension than what is needed for the actual resuspension process (Friedrich et al., 2000). It is not only the physical state of the sediments that are changed by the waves. During resuspension organic material is reintroduced into the water mass and nutrients which earlier might have been a limiting factor for the pelagic production may become present as a fresh source. In shallow coastal zones like the Baltic Sea, the sediments play a crucial role in the annual nutrient recycling. The concern of this thesis is about these less visible, but yet important different effects and about the wave field that is one cause of them.

Small area studies of waves in the Baltic Sea have been made before (e.g., Blomgren et al., 2001; Gayer et al., 1995), however in Paper I a model study over the entire region is performed. It is done with a spectral wave model for the year 1999. In this thesis that study is extended with another year. To estimate the impact of waves a study of the wave energy density is made in Paper II. Further studies of wave effects will be made in my continuing work with focus on the resuspension and sediment-water exchange processes. In Paper III the distribution of nitrogen fixation rates is
modelled with the assumption that nitrogen fixation is the only internal nitrogen source in the model. However, one reason for the spatial differences seen in the blooms between the eastern and western side of the Baltic Proper may be a difference in the nutrient recycling triggered by waves.

The following two sections of this thesis may be regarded as background information, mainly for readers that are not too familiar with water waves and their nomenclature. There are no results presented in these sections so if you know the background you can start to read from Section “The Baltic Sea Waves”. In that section and onwards a discussion around the three included papers is found as well as some new results from the extended wave modelling.
Some wave theory

When looking at a wavy sea surface it seems almost impossible to describe the waves in any useful way. However, this is not the case, a wave field may be described as composed of a number of sinusoidal waves with different heights (amplitudes) and wavelengths (or periods) travelling in different directions. This enables us to describe the basic properties of a wave field e.g., by using the concept of a wave energy spectrum.

Wave data is found either in the form of wave records from pointwise observations, visual or instrumental, areal estimates by remote sensing or as wave model data. From wave records the wave spectrum can be computed by using discrete Fourier transform. Wave models on the other hand uses often different predefined forms of spectra in their numerics.

Wave spectrum

A WAVE ENERGY SPECTRUM shows the distribution of wave energy over e.g., the frequency space. The wave energy is proportional to the square of the amplitude \( \frac{1}{2} \rho_w g a^2 \) where \( \rho_w \) is the density of water and \( g \) the acceleration of gravity. The frequency is the inverse of the period.

A wave energy spectrum says more about a wave field than other statistical properties since it reveals within which frequency range the energy is concentrated, if it is in one single peak or two, if the peaks are sharp or more gentle and so on. A time series of wave energy spectra show how the wave field evolve within different frequencies. The shape of the spectra is thought to arise due to a balance between atmospheric input, non-linear transfer between waves and dissipation.

Spectral wave models use spectra in an explicit form that is possible to parameterise. For this, there are many proposed shapes of the wave energy spectrum that empirically have been derived from different field experiments. One such example is the PM-SPECTRUM used for a fully developed sea (Pierson and Moskowitz, 1964), it reads

\[
E_{pm}(f) = \frac{\alpha g^2}{(2 \pi)^2 f^5} \exp\left(-0.74 \left(\frac{g}{2 \pi u f}\right)^4\right).
\]

Here \( f \) denotes the wave frequency and \( u \) the wind speed at 19.5 m above the

"The basic law of the seaway is the apparent lack of any law."
—Lord Rayleigh
Figure 1. A general form of a PM and Jonswap spectrum. The picture is from Hasselmann et al. (1973) and show the parameters used in the Jonswap spectrum.

Another example of a wave spectrum is the JONSWAP SPECTRUM that applies to a growing sea in fetch-limited conditions (Hasselmann et al., 1973). This spectrum is obtained by multiplying a PM-spectrum by a “peak enhancement” factor as

$$E_j(f) = E_{PM}(f)\gamma \exp\left(\frac{(f-f_m)^2}{2\sigma^2 f_m}\right),$$

where $f_m$ denotes the peak frequency, $\gamma = \frac{E_{max}}{E_{PMmax}}$ and $\sigma = \sigma_a$ for $f \leq f_m$ or $\sigma_b$ for $f > f_m$. The main difference is that the energy at the peak frequency is higher during the wave growth phase than in the fully developed sea (Fig. 1).

When a wave field approaches shallow water it is influenced by the bottom and additional processes such as bottom friction, percolation and bottom motion might become present. Here a third spectrum can be used, the TMA (TEXEL-MARSEN-ARLOE) SPECTRUM (Bouws et al., 1985), which is a modification of the Jonswap spectrum. A function $\phi$ that ranges between 0 and 1 and depends on water depth $H$ and frequency is multiplied with the Jonswap spectrum as

$$E_{TMA}(f) = E_j(f)\phi(f, H).$$

In practice the Jonswap spectrum could be replaced with the TMA spectrum since the latter by definition transforms into the Jonswap spectrum.
in deep water. However, these three spectra are the ones used in the wave model in Paper I.

**Significant wave height**

Since a wave field is composed of waves with different periods and wave heights, its properties are usually described by statistical means. The **significant wave height** is one such parameter frequently used. It is the average height of the highest one-third of the waves. The origin of this somewhat odd measure is that it has been found more or less equivalent to the visually observed wave height. From a wave record this parameter \( H_{1/3} \) is calculated as

\[
H_{1/3} = \frac{H_{10}}{\sqrt{\frac{1}{2} \ln \left( \frac{n}{10} \right)}},
\]

where \( H_{10} \) is the lowest of the ten highest waves in the record and \( n > 10 \) is the total number of waves during one recording period (WMO, 1998). A recording period is typically 15–35 minutes per hour. If instead the significant wave height \( H_{m0} \) would be derived from a wave energy spectrum, we would use

\[
H_{m0} = 4 \sqrt{m_0}
\]

where \( m_0 = \int E(f) df \) is the zeroth moment of the one-dimensional energy spectrum \( E(f) \).

**Wave period**

Another parameter is the wave period. If the height and period of a wave are known, almost anything can be calculated regarding the wave. A problem however, is what period to choose. Due to the large number of waves that a wave field is composed of it is hard to say where one single wave begin and end. Of course, people have found out operational ways for this as well. By taking the number of zero-downcrossings (or upcrossings) from a wave record and divide this number by the record length, the zero-
downcrossing period is calculated. From a wave spectrum the same period is calculated using the zeroth and second moments as

\[
T_{m02} = \frac{m_0}{m_2}
\]

where the second moment is defined as \( m_2 = \int f^2 E(f) df \).
Figure 2. Wave type classification according to its time scale. On the y-axis the relative kinetic energy is shown (from Boudreau and Jørgensen, 2001).

Another period is the peak period that is the period at the peak of the spectrum. Both these periods are used in Paper I and the latter in Paper II.

Wind waves and swell

Waves are distinguished by its origin into different types. The waves I have been studying are wind waves and swell. Wind waves get their energy directly “at the spot” from the wind blowing over the sea surface. Swell on the other hand are “old” waves without any energy source. These are e.g., generated as normal wind waves but as the wind ceases or turns into another direction the waves simply continue as swell until all their energy have dissipated. Swell waves are often very long waves with low amplitude. Wind waves on the other hand have different shapes according to its generation phase; i.e., if the wave is still growing or has reached a more stable state. Wave types can be classified by the period, Fig. 2.
Wave models

The interest in wave prediction and modelling increased sometimes around the Second World War when the armies needed to land their troops more efficiently. However, the actual theories for wave predictions are much older ranging all the way back to the old Greeks. More about the wave prediction history can be found e.g. in Khandekar (1989) or Komen et al. (1994).

There exist numerous wave models world wide of different sorts. Many of them are classified and described within the Sea Wave Modelling Project (SWAMP Group, 1985). In the following I will recall some facts about one of the types, namely the spectral wave models, since this is the type of model that has been used in our studies.

Spectral wave models

SPECTRAL WAVE MODELS is a group of wave models that all are based on the spectral energy balance equation (e.g., WMO, 1998)

$$\frac{\partial E}{\partial t} + \mathbf{c}_g \cdot \nabla E = S$$

where $E(f, \theta, x, t)$ denotes the two-dimensional wave energy spectrum that depends on frequency $f$, direction of propagation $\theta$, position $x$ and time $t$. The vector $\mathbf{c}_g(f, \theta)$ represents the deep-water group velocity. $S$ denotes the source function that includes all processes that add/remove energy to/from the spectrum. These are the mean energy input from the atmosphere, the non-linear energy transfer by wave-wave interactions and the dissipation of energy.

A historical problem has been the non-linearity of the waves and how to handle these. The exact form of the non-linear wave-wave interactions has been described e.g., by Hasselmann (1962) but this form is difficult to solve numerically. The so-called FIRST GENERATION WAVE MODELS did not include the non-linear interactions at all. Instead these models let each spectral component evolve independent of the other components. Since the non-linear interactions mainly are important during the growth phase, these models usually underestimates the wave growth (Khandekar, 1989). The SECOND GENERATION WAVE MODELS solve the non-linear problem in a simplified way by parameterizing the wave-wave interactions. Even though this works rather well, its drawbacks are found in rapidly shifting winds.
(e.g., hurricanes, intense, small-scale cyclones or fronts) as well as in the transition between sea and swell (e.g., *WAMDI Group, 1988*). The youngest models, the *Third generation wave models*, solve the exact form of the equation but are quite computer intense.

**HYPAS**

For our wave studies we have chosen to use the second generation spectral wave model HYPAS (*Hybrid parametrical shallow water*, Günther and Rosenthal, 1995). We did this for a number of reasons:

- The model was accessible from SMHI (Swedish Meteorological and Hydrological Institute).
- It was already set up for the region of interest with a reasonable grid size (11x11 km).
- It was possible to run the model on an ordinary PC.

HYPAS is an improvement of an earlier model (NORSWAM model, Günther et al., 1979) and was used in at least two large model intercomparison studies (*SWAMP Group, 1985; SWIM Group, 1985*). The fact that HYPAS is used daily at SMHI in their ship routing services indicate in some context that the model gives reasonable output. Validations of the model are otherwise quite scarce since there are few measuring sites in the area. However, we validated the model at five stations in *Paper I* and it was shown to perform quite well (see Table 2 and 3 in *Paper I*).

**Wind forcing**

HYPAS is forced every third hour with wind data. Since the wind field is the only forcing it is important that it is reliable. We have used analysed wind fields as they improve wind prognoses with about 12–17% (*Häggmark et al., 1997*). The analysed fields are formed by MESoscale wind field ANalysis (MESAN, Hägmark et al., 2000) that is based on an optimal interpolation technique. The start field of the analyse (the first guess) is adopted from the atmospheric circulation model HIRLAM (HIgh Resolution Limited Area Model, Källén, 1996) and then modified by wind observations and measurements from different weather stations. Since the HIRLAM field underestimates the winds slightly (*SMHI, 1999*) the MESAN fields might do the same. If this is the case our modelled wave fields might be somewhat lower than in reality.
The Baltic Sea waves

Our studies are based on the waves in the Baltic Sea, Kattegat and Skagerrak, Fig. 3. This area is chosen because it is an interesting area from many points of view. With the exception of Skagerrak, these seas are rather shallow, which means that particle motions set up by the surface wave reach down to the bottom over large areas. Mean and maximum depths in the different basins can be found in Table 1. The Baltic Sea is also a semi-enclosed sea and the only connection to the North Sea is through Skagerrak. The actual sills are in the Sound and the Belt Sea but the whole of Kattegat can be regarded as a transition region due to its shallowness. The sills control the water exchange and the density stratification in the Baltic Sea (Stigebrandt, 1987), which in its turn affects the biogeochemistry of the area. Yet another result of the narrow and shallow entrance is that the tides are more or less non-existent in the Baltic Sea (Stigebrandt, 2001) and an otherwise important energy source to the benthic boundary layer is by this excluded.

Table 1. Mean and maximum depths from the region (Sjöberg, 1992)

<table>
<thead>
<tr>
<th></th>
<th>Mean depth [m]</th>
<th>Max depth [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bothnian Bay</td>
<td>43</td>
<td>148</td>
</tr>
<tr>
<td>Bothnian Sea</td>
<td>68</td>
<td>293*</td>
</tr>
<tr>
<td>Baltic Proper</td>
<td>62</td>
<td>459</td>
</tr>
<tr>
<td>Gulf of Finland</td>
<td>37</td>
<td>115</td>
</tr>
<tr>
<td>Gulf of Riga</td>
<td>22</td>
<td>56</td>
</tr>
<tr>
<td>Kattegat</td>
<td>23</td>
<td>124</td>
</tr>
<tr>
<td>Skagerrak</td>
<td>174</td>
<td>711</td>
</tr>
</tbody>
</table>

*301 m in the Åland Sea.

Studies of the entire Baltic Sea wave field have not been published before. Blomgren et al. (2001) modelled the wave field in the Southern Baltic Proper and even if Paplińska (1999) modelled the whole Baltic Sea area for 6 months it is only validations from two points outside the Polish coast that is presented. In Paper I the Baltic Sea wave field is modelled for one year with the wave model HYPAS. Both the temporal and spatial
Figure 3. The study area with its bathymetry.

Variations in the area are found to be large. Here that study is prolonged with one year to see possible differences between years. Two years is far too short time to say anything about the wave climate, changes can exist over timescales of decades (e.g., Bacon and Carter, 1991) but it gives an example of how different or similar two years can be.
Figure 4. Percent of the total wind that is above 10 m/s from January 1999 to March 2001.

Temporal variations

The temporal variation of the waves follows that of the wind and consequently the highest waves appear during storm events. Storm frequency thereby becomes a way of indirectly studying high wave events (e.g., Eckhêll et al., 2000).

The percentage of the total wind above 10 m/s differ quite a lot between the two studied years, Fig. 4. It is particularly the winter 1999/2000 that exerts higher winds than the other two winter periods available. The winter at the turn of the century encountered five storms with wind speeds over 20 m/s. These occurred from late November to January and in early March. The storm that passed 3 December 1999 is the worst in Swedish waters since the beginning of 90’s (Karlström and Häggsström, 2000). These five storms should be compared with three (in February) during the last winter 2000/01. Data from 1998 is not available but the winter 1998/99 encountered at least one storm in February.

It is not only the winter periods that differ in Fig. 4, the two summer periods do as well. The seasonal pattern with higher winds in winter and lower in summer is clearly visible both years, but the summer 2000 was windier. This might be coupled to a number of thunderstorms that summer.
As a curiosity, the year 2000 was one of the warmest years ever (in the southern Sweden since the 16th century) but the summer was still slightly colder than average and extremely rainy (Karlström and Vedin, 2001).

Spatial variations of the wave field
One of our conclusions from Paper I is that the spatial variation of significant wave height mainly depends on water depth and fetch. If this is right, we should see no large differences in the spatial wave distribution in-between years. During 1999 we got the highest waves in the eastern
Baltic Proper and in the outer part of Skagerrak where the fetches are the longest and the water the deepest. During the following year the highest waves are found more or less in the same areas, Fig. 5. On average, the waves during 2000 were lower than the year before but the maximum waves showed higher values in Skagerrak and Gulf of Bothnia, Fig. 6.

Wave energy density

The energy of one wave is proportional to the square of its amplitude. To get a measure of the wave energy available in the whole water column the energy is calculated in every grid point and divided by the corresponding water depth. We call this the wave energy density and calculations of this measure are presented in Paper II. The wave energy density varies over time as the wave heights, while the spatial variation is a combination of wave height and water depth. A striking feature in the result is the energy difference between the western and eastern side of the Baltic Sea, especially in the Baltic Proper. This is a result of the dominant wind direction from south to west that gives longer fetches on the eastern side while Sweden shelters the western side.
Effects of the surface waves...

Even though the waves are interesting enough they are not the main objects of my work, it is the effects of the waves that is the really interesting thing. A lot of work has been done on wave impacts in near shore waters, mainly on sediment transport and beach erosion (e.g., Blomgren, 1999), but in “off shore” discussions surface waves are often omitted. However, in Paper II we show that there is a coherence between the wave energy density and the bottom dynamics and that the waves have an influence over large bottom areas. The dynamic, energy rich conditions that surface waves put on some areas may also explain the high production and nutrient recycling in the same. For example, some of the differences between nitrogen fixation rates in the western and eastern Baltic Proper (Paper III) may depend on wave dynamics.

…on sea bottoms

A common classification of bottom types is suggested by Håkanson and Jansson (1983). They divide the bottoms into accumulation, transport and erosion bottoms according to the water content in sediment samples Table 2. A sample taken from an accumulation bottom have high water content and consists of smaller particles while a sample from an erosion bottom consists of coarser material with lower water content. Transport bottoms represents an intermediate state, which allows for deposition during calm periods and resuspension during others. The frequency of these resuspension events differs from place to place but depend on the physical activity at the spot (i.e., waves and currents.) A simple model have earlier been used e.g., in Gulf of Bothnia in order to classify transport bottoms from wave induced resuspension (Brydsten, 1993).

Table 2. The water content for different bottom types as defined by Håkanson and Jansson (1983) with corresponding particle sizes.

<table>
<thead>
<tr>
<th>Bottom type</th>
<th>Water content [%]</th>
<th>Particle size [µm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accumulation</td>
<td>75 – 99</td>
<td>&lt;20</td>
</tr>
<tr>
<td>Transport</td>
<td>50 – 80</td>
<td>20 – 60</td>
</tr>
<tr>
<td>Erosion</td>
<td>0 – 50</td>
<td>&gt;60</td>
</tr>
</tbody>
</table>
Bottom type maps based on sediment samples exist but we have tried to make a similar one based on wave energy density (Paper II). It was only in the Gulf of Riga, where the resolution of the sediment data was high enough, that a comparison could be made between the two classification types (from sediments and from wave energy density). But here the statistical correlation is good. For example, about 75% of the transport bottoms were “rightly” classified.

...on the biogeochemistry

The main source of material to the sediments is of mineralogenic origin (clay, fine sand etc). To this is added organic matter mainly from the pelagic production. Of the primary production, only a few percent is buried “permanently” in the sediment, the rest is degraded in some way and/or recycled (e.g., Danielsson et al., 1998). More than 80% of the accumulated sediments come from resuspended erosion bottoms (e.g., Jonsson et al., 1990).

During resuspension deposited organic material is lifted up into the water column where it exerts an increased demand of oxygen. If the water column is stratified and resuspended sediments are trapped below the pycnocline, the oxygen could become severely depleted there. Nevertheless, resuspended material can also be an important source of nutrients and organic matter to the water column (e.g., Christiansen et al., 1997). It has been shown to stimulate microbial production in the pelagic (Wainright and Hopkinson Jr., 1997). Moreover, by exposing organic matter to oxic conditions, it could decrease the denitrification and thereby the loss of DIN (dissolved inorganic nitrogen) from the system.

In Paper III we make a budget of the nitrogen fixation rates in the Baltic Proper where we assume that nitrogen fixation is the only internal source of nitrogen. One reason for nitrogen fixation to occur during summer time in the photic zone is the almost complete lack of bioavailable nitrogen while phosphorus still exists in useful concentrations. During these conditions various cyanobacteria have a competitive advantage in that they can utilise gaseous nitrogen solved in the water as a nitrogen source in their assimilation (Larsson et al., 2001). In a continuing study by Rahm et al. (2001) this relation is investigated further with probability mapping. They investigated how often the ratio between DIN and DIP (dissolved inorganic phosphorous) were below a threshold value of 8 (cf. Redfield ratio N:P 16:1) at different locations in the Baltic Proper, i.e., how often the nitrogen were “lacking”. This study show more clearly the difference between the available nitrogen on the western and eastern side of the Baltic Proper (Fig. 7). Since the highest wave energy density and the highest nitrogen amounts both are found on the eastern side of the Baltic Proper it might be that
Figure 7. Striped squares show areas with a significant higher number of hits when DIN/DIP<8, i.e., areas where nitrogen fixation is more likely to occur. The number in the squares refer to different seasonal periods (from Rahm et al., 2001).

frequent sediment resuspension keep the nitrogen in the aerobic system instead of letting it be denitrified in the partly anoxic sediments.
Discussion and conclusions

The Baltic Sea wave field discussed in Paper I and in this thesis is found to be quite variable not only seasonally, but annually as well. Despite the variation in time the highest waves are found in more or less the same areas. This is due to the fact that the waves in the Baltic Sea are fetch limited and as long as the dominant wind directions not change, the highest waves will occur in the same areas as before with about the same maximum heights. However, if the wind would change its dominant directions or if we get a higher storm frequency, the impact on e.g., the bottoms could increase even without larger maximum waves (Wainright and Hopkinson Jr., 1997). Wave records from the North Atlantic and North Sea show that the waves in these areas have increased during the last 30 years (Bacon and Carter, 1991; Carter and Draper, 1988; Gulev and Hasse, 1999). The same holds for the waves in the eastern North Pacific (Allan and Komar, 2000). In the Baltic

![Figure 8. Average of standardised 95\textsuperscript{th} (Θ) and 99\textsuperscript{th} (+) percentiles of the geostrophic winds and corresponding smoothed curves (solid and dotted lines respectively) from 1881–1998 over Scandinavia (from Alexandersson et al., 2000).]
Sea region the storm climate has increased since the 1960th to reach a peak around 1990. However, this peak was not as large as the one in the beginning of 1880th (Alexandersson et al., 1998; Alexandersson et al., 2000). So on a longer time scale it looks like there has been no change in the storm climate at all, Fig. 8. If the years 1999 and 2000 fit the general picture is unfortunately not known.

Waves are often omitted in “offshore” discussions about sediment distribution, but Paper II show that surface waves might affect large bottom areas in shallow regions. However, it will probably not be possible to make a correct bottom type map with regard only to surface waves since they are not the only factor that influence the sediment distribution. Currents are another important mechanism that in our studies so far has been omitted. For one reason because we do not have data with similar resolution of the bottom currents, but also because there is a point in studying the two factors separately to see the effect of each. Waves and currents work in different ways. The waves may loosen up and lift the sediment particles into the bottom current, while the currents carry them away. There is a co-operation between the two but mainly in the way that the sediment transport increases if waves are present (e.g., Soulsby et al., 1993).

The high-energy areas found on the eastern side of the Baltic might have a large influence on the biogeochemistry. This is achieved by feeding the surface layer with fresh material from the sediments to increase the total system mineralization and productivity, which leads to increased oxygen demand in the water column. By reintroducing DIN to the watermass we might have an additional internal nitrogen source besides the nitrogen fixation suggested in Paper III.

**Future outlook**

In this thesis much of the background for my future work has been set up and modelled. In my continuing work I will concentrate more on the effects of wave resuspension. One example is the phosphorus distribution in the sediment and the resuspension frequency in Kattegat.

I will hopefully also be able to study the bottom currents in the area to get a more complete picture of the large-scale physics of the benthic boundary layer.
Acknowledgement

First of all I would like to thank my supervisor Lars Rahm and his two earlier PhD-students Åsa Danielsson and Lotta Pers. Lars has always had the time when I have needed it and an exuberant enthusiasm whenever he finds something interesting. Statistics would have been a lot more difficult without Åsa, not to mention modelling without Lotta. Thanks for all your time, help and inspiration.

I have done much of my wave modelling at SMHI in Norrköping and I am grateful for the help and support that I have got from different people there. Some of them need to be mentioned specially. Lennart Funkquist introduced me to the world of HYPAS and provided me with (several versions of) the code to the model. I would not have managed to model any HYPAS waves without his help. Barry Broman patiently answered all my wave questions and made a lot of filing of model result. Thank you also, Lasse Johansson, for taking your time reading my papers through carefully and for giving an excellent summary of my work at my “slutseminarium”. It was really nice to hear.

Among my colleagues at the University there are some people I want to mention separately. For getting most of my literature Christina Brage has been an invaluable help and time saver. Without Ian Dickson, “the happy Scot”, I guess not many result would have appeared on paper, but trapped inside my computer without any connection with the surrounding world. Finally, my former “ever smiling” room mate Annika, “the two who moved to Stockholm”, Tessan and Anna, and Mimmi, thank you for all nice talks and laughs over meals and teas. I miss you at tema!

And Claes, thank you for valuable discussions about the mathematics involved but mainly for making my latest year in Linköping a lot, lot nicer.

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