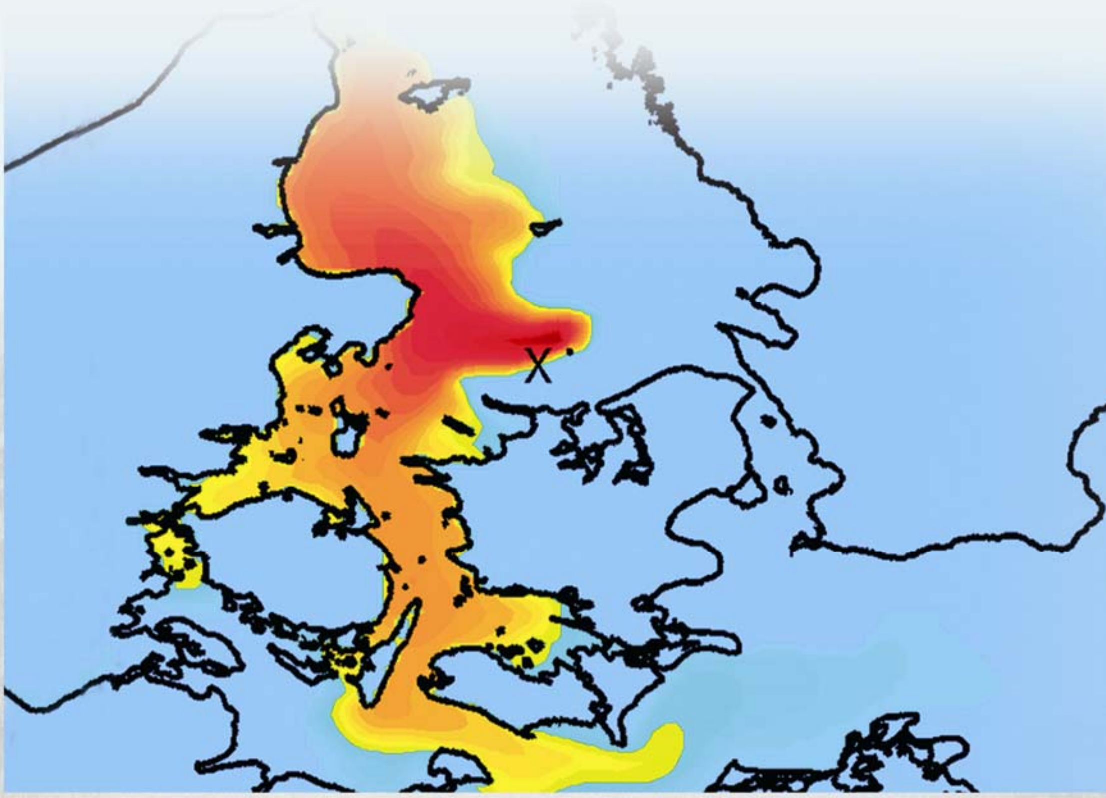
BALANCE Interim Report No. 9

Model simulations of blue corridors in the Baltic Sea



Baltic Sea Region
INTERREG III B

BALANCE

Title **Model simulations of blue corridors in the Baltic Sea**	BALANCE Interim Report No. 9
Authors Jørgen Bendtsen 1) Johan Söderkvist 1) Karsten Dahl 1) Jørgen L.S. Hansen 1) Johnny Reker 2) 1) National Environmental Research Institute, University of Aarhus, Denmark 2) National Forest and Nature Agency, Denmark	Date 18 April 2007 Approved by Åsa Andersson

Revision	Description	By	Checked	Approved	Date

Key words Blue corridors; coherence; dispersal of larvae and propaguels	Classification ☒ Open ☐ Internal ☐ Proprietary

Distribution	No of copies
BALANCE Secretariat	3 + pdf
BALANCE partnership	20 + pdf
BSR INTERREG IIB Joint Secretariat	1
Archive	1

CONTENTS

APPENDIX 1
Institutes that agreed to let the BALANCE project use their data, stored at the BED database

0 PREFACE

The aim of this report is to demonstrate the importance of transport pathways of pelagic life stages of marine flora and fauna. This kind of knowledge is very important when connectivity between existing Marine Protected Areas (MPA’s) is evaluated, when arguing for an ecological coherent network of MPA with an improved connectivity and for evaluating existing MPA networks.

Transport pathways for marine pelagic larvae and propagules are simulated in a local model of the Danish straits and a regional model covering the whole North Sea – Baltic Sea area. The simulated distributions of passive tracers from different source regions represent transport pathways in the Baltic Sea during a six-month period.

Results from a high-resolution model of the Danish straits of dispersal of tracers show large variations in the spatial scales on which a source region influences the surrounding waters. Based on the overall dispersal pattern, 9 different source areas located in Natura 2000 areas in the open inner Danish waters can be categorised according to the concept of “up- and downstream hierarchy”.

Karsten Dahl

National Environmental Research Institute, University of Århus

1 INTRODUCTION

Development of the “blue corridor” concept is an important part of the project. A comprehensive literature study describing applicability of the corridor concept for the Baltic Sea was initiated in the first phase of the Balance project and is now available (Martin et al. 2006).

The aim of this report is to demonstrate the importance of passive transport pathways of pelagic life stages of marine flora and fauna. This kind of knowledge is very important when connectivity between existing Marine Protected Areas (MPA’s) is evaluated or when arguing for new protected areas to improve connectivity in the existing MPA network.

The report describes two different tracer studies that show the dispersal by currents (advection) and turbulent mixing (diffusion) of water masses within a three dimensional hydrodynamic models set up for different parts of the Baltic Sea area. The first study includes a so-called “conservative tracer”. A conservative tracer has no decay and therefore its distribution is controlled solely by currents and mixing. The second study includes a so-called “non conservative tracer”. The non conservative tracer has a decay rate and represents the behaviour of a larva, a propagule or other kinds of biomass which are also controlled by biological processes, e.g. mortality. These studies simulate potential “blue corridors” between several locations in the Baltic Sea.

The report describes the methods applied including a short description of the model and the data used. The results of the tracer study are described and shortly discussed at the end of the report. Other results from the model simulation, giving average temperature, salinity and velocity in different parts of the Baltic Sea, are described in another BALANCE report dealing with marine landscapes (Al-Hamdani et al. 2007).

2 ESTABLISHING A BALTIC SEA CLIMATOLOGY FOR TEMPERATURE, SALINITY AND BOTTOM VELOCITY

For establishing a long-term mean value of the conditions at the bottom in the Baltic Sea area, a comprehensive data set of temperature and salinity was compiled. Subsequently this data set was assimilated into a model and from this simulation a spatial gridded data set of the annual average conditions was created, as described below.

2.1 Model description

A three-dimensional ocean circulation model was used for quantifying transports and distributions of temperature, salinity and additional tracers in open waters. The model is based on the COHERENS model (Luyten et al. 1999) and it solves the equations for transports, mixing, water level, temperature and salinity on a numerical grid of the model domain.

Vertical mixing intensity in the surface boundary layer is explicitly described as a function of turbulent diffusive momentum- and energy transports across the air-sea interface, using a k-epsilon turbulence closure scheme. The model has a free surface, allowing an explicit description of the tides. The model is driven by hourly meteorological fields of wind, temperature, cloudiness, air pressure and relative humidity generated by an operational weather forecast model (Brandt et al. 2001).

Two different model setups were used in this study. A regional model setup for the North Sea – Baltic Sea region with a horizontal grid resolution of 7.5 x 7.5 km and 20 vertical grid layers were used for analysing the bottom conditions in the Baltic Sea. This model setup was forced with the 4 most important tidal constituents at the open boundaries in the North Sea and in the English Channel, and river runoff was included by using the climatologically monthly mean values from the 19 largest rivers in the area. The bathymetry was generated by a 5' bathymetric atlas in the North Sea (ETOPO5 1988), a 0.5' x 1.0' bathymetric atlas in the inner Danish straits and a 1' x 2' bathymetric atlas in the Baltic Sea (Seifert et al. 2001). The high resolution 30" x 30" GLOBE atlas has been used for generating the coastline (Hastings & Dunbar 1999). The bottom topography was determined as the mean depth obtained from these bathymetric data sets in each model grid cell. A lowpass filter was applied to smooth the bottom bathymetry in the North Sea and in the Skagerrak region. The model was initiated with temperature and salinity fields obtained from WOA01 (Conkright et al. 2002) and calculations were carried out with the meteorological fields for the year 2002. The model was then subsequently initiated with the temperature, salinity, velocity and water level fields from 1 January 2003 and integrated for one more year. A high resolution model was applied for describing the dispersion of tracers illustrating the spreading of larvae, propagules or other pelagic life stages of macro algal vegetation and bottom fauna in the Danish straits. The high resolution model had a horizontal resolution of 3.7 x 3.7 km, 10 vertical grid levels and had open boundaries in the northern Kattegat and in the Arkona Sea. The open boundary conditions of sea level, temperature and salinity were obtained from the regional North Sea – Baltic Sea model described above.

2.2 Data sources

A comprehensive analysis of the salinity and temperature was made from a collected data set for the Baltic Sea region. This analysis provided a data based description of the bottom conditions of temperature and salinity in the region. These data were also used during the data assimilation process.

The salinity and temperature data cover stations from the Bothnian Bay to the Baltic Proper, including the Gulf of Finland and the Gulf of Riga. Also stations in the Danish straits, the Kattegat, the Skagerrak and the German Bight were included in the analysis. A summary of contributing institutes is presented in Appendix 1. The depths at the stations used are shown in *figure 2.1*.

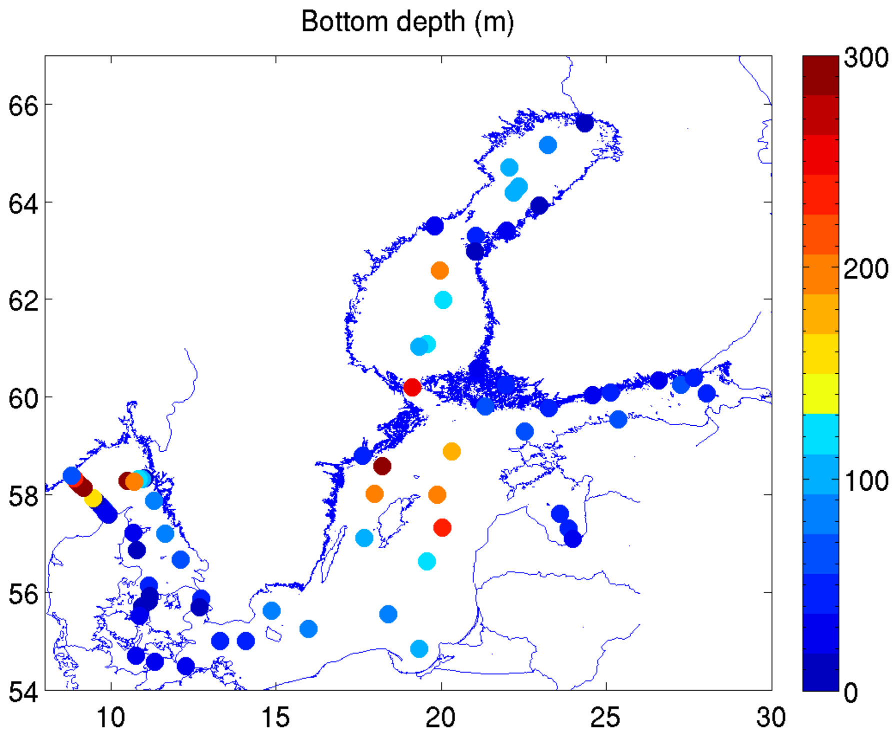


Figure 2.1 Map showing the location and depth at the stations from Skagerrak to the Bothnian Bay used in the model.

2.3 Observed distributions of temperature and salinity

The annual average salinity showed a decrease from the Arkona to the Bothnian Bay (*figure 2.2*). The variance of the bottom and surface salinity around the annual average showed the largest values in the Danish straits. The bottom salinity had a relatively low variance in the Bothnian Bay and in the Baltic Proper. The annual average temperature decreased from Arkona to the Bothnian Bay. The sea surface temperature (SST) had a relatively constant level of variation in the area whereas bottom temperature had the lowest values in the Baltic Proper (*figure 2.3*).

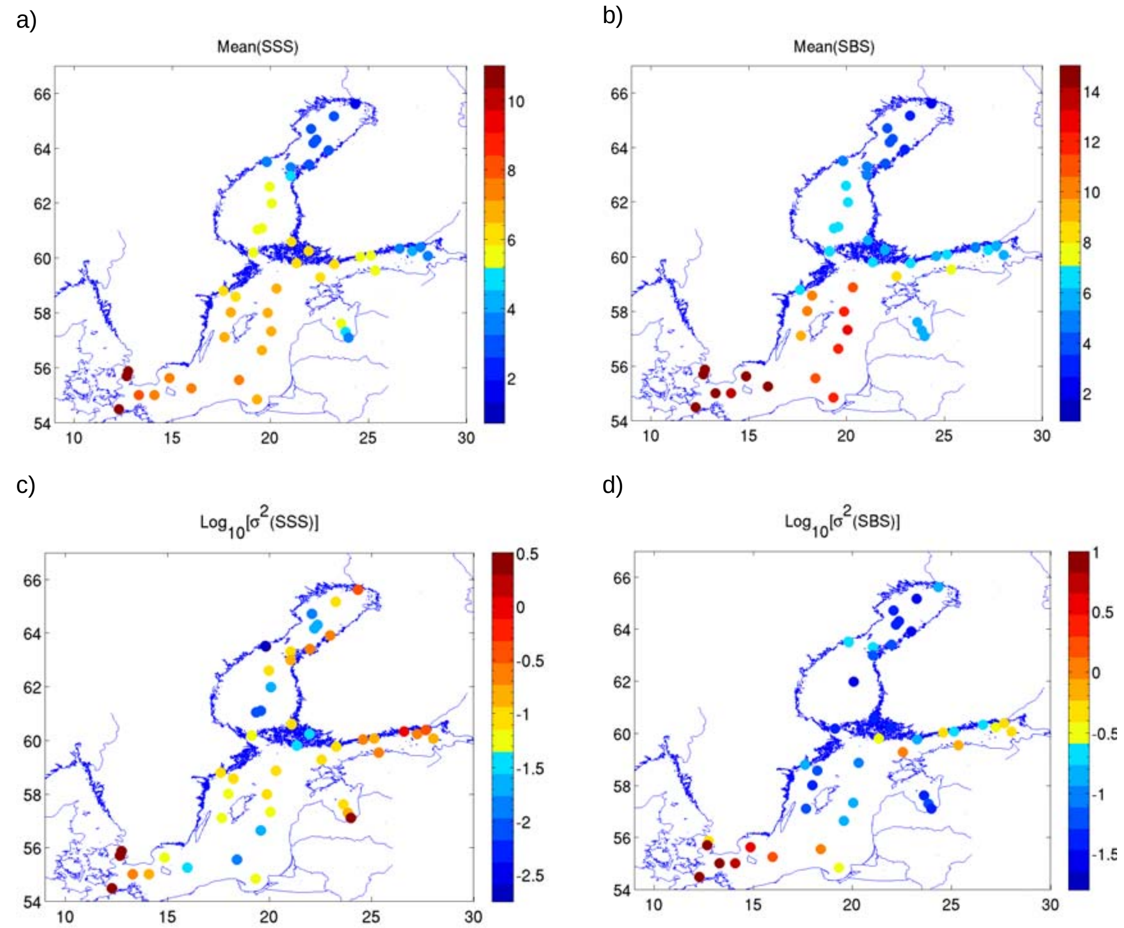


Figure 2.2 *Observed average salinity (psu) for the period 1999 to 2004 at stations in the Baltic Sea. a) Average sea surface salinity (SSS), b) Mean sea bottom salinity (SBS), c) Base-10 logarithm (log$_{10}$) of the variance of the SSS, and d) Log$_{10}$ of the variance of the SBS.*

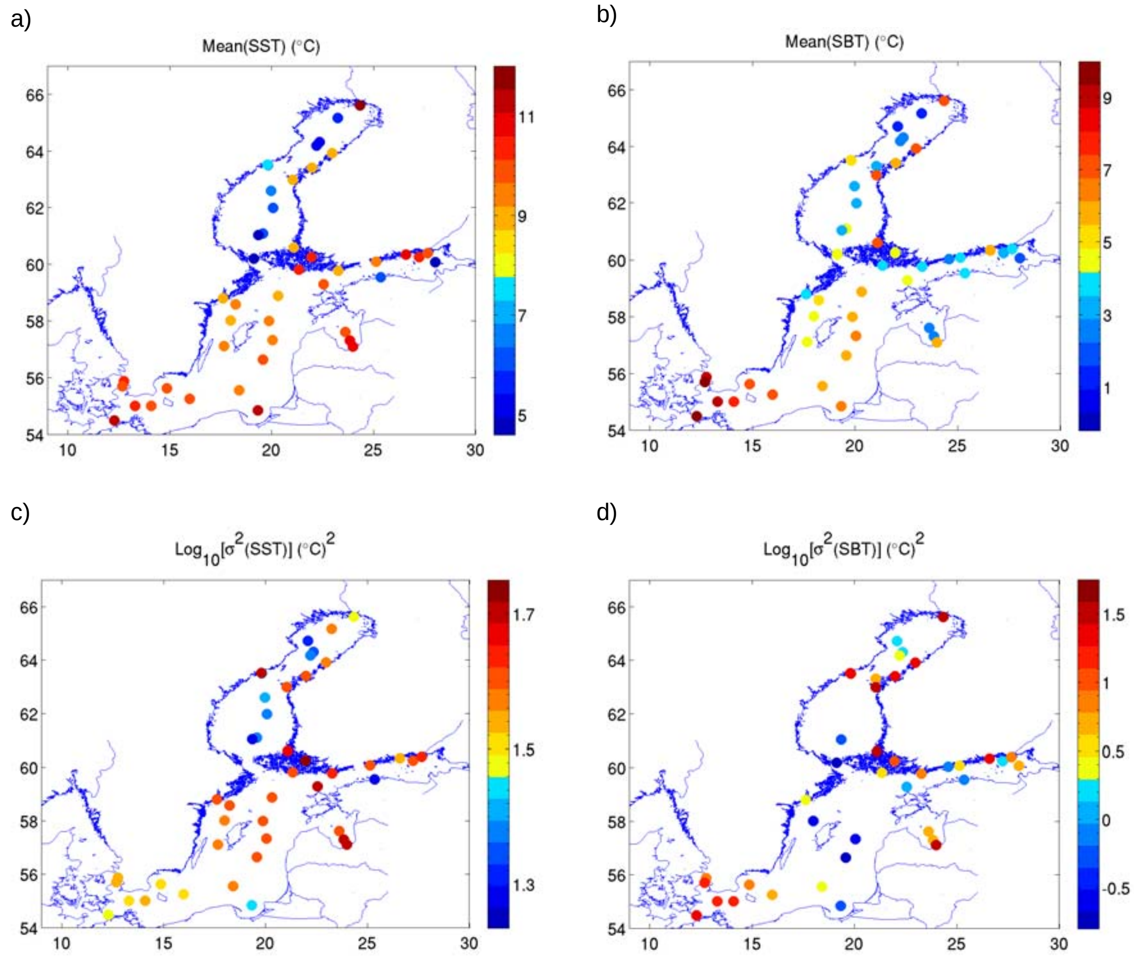
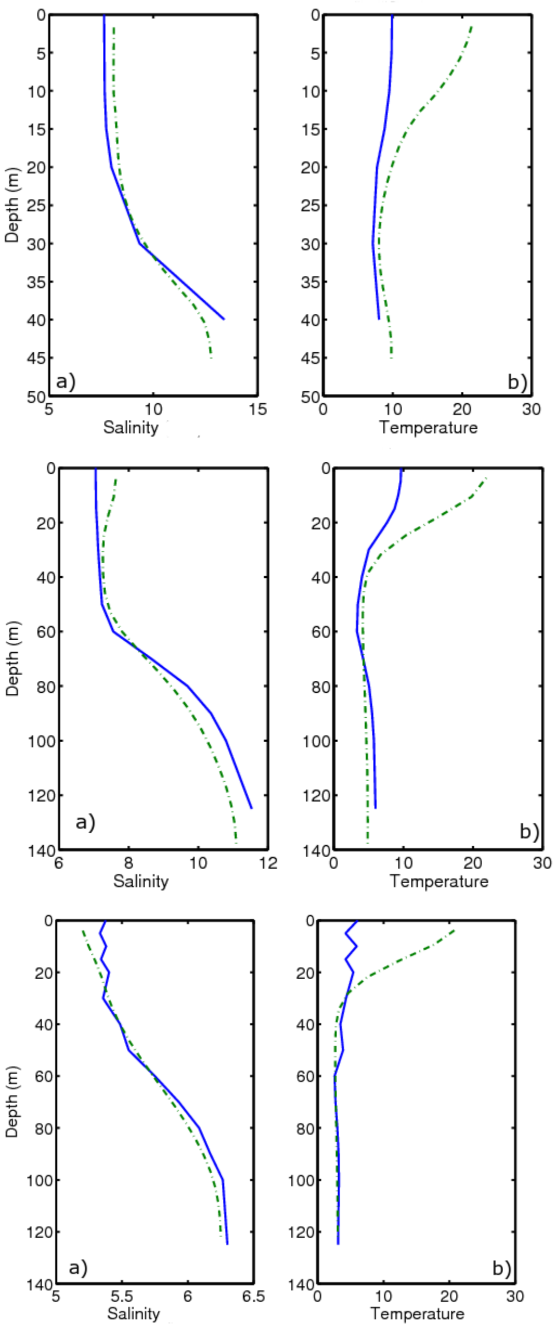


Figure 2.3 *Observed average temperature (°C) for the period 1999 to 2004 at stations in the Baltic Sea. a) Mean sea surface temperature (SST), b) Mean sea bottom temperature (SBT), c) Base 10 logarithm (log$_{10}$) of the variance of the SSS, and d) Log$_{10}$ of the variance of the SBT.*

2.4 Modelled distributions of temperature, salinity and velocity

Throughout the calculations the modelled temperature and salinity were adjusted towards observed average temperature (April-August) and salinity (January-December) values from 1999-2004. There was a good correspondence between modelled and observed temperature and salinity in the annual average profiles (*figure 2.4*). The modelled temperatures in *figure 2.4* are summer profiles while the observed temperatures are yearly mean values, which explain the difference in the surface layer.

The modelled results of the mean bottom temperature and salinity and their variance (*figure 2.5*) are in general in accordance with the observations seen in *figure 2.2* and 2.3. Bottom velocities showed the largest values in the Danish straits and in the southern entrance to the Bothnian Sea (*figure 2.6*). A cyclonic circulation is seen in the Baltic Proper.



Arkona, 14° 7.08' E, 54° 58.88' N.

Baltic Proper, 19 32° 11' E, 56° 36.00' N.

Bothnian Sea, 20° 01.0' E, 61° 59.80' N.

Figure 2.4 *Vertical profiles of salinity and temperature at 3 locations in the Baltic Sea in 2003. Solid lines show the observations (annual average) and dashed lines show the model result (average for August).*

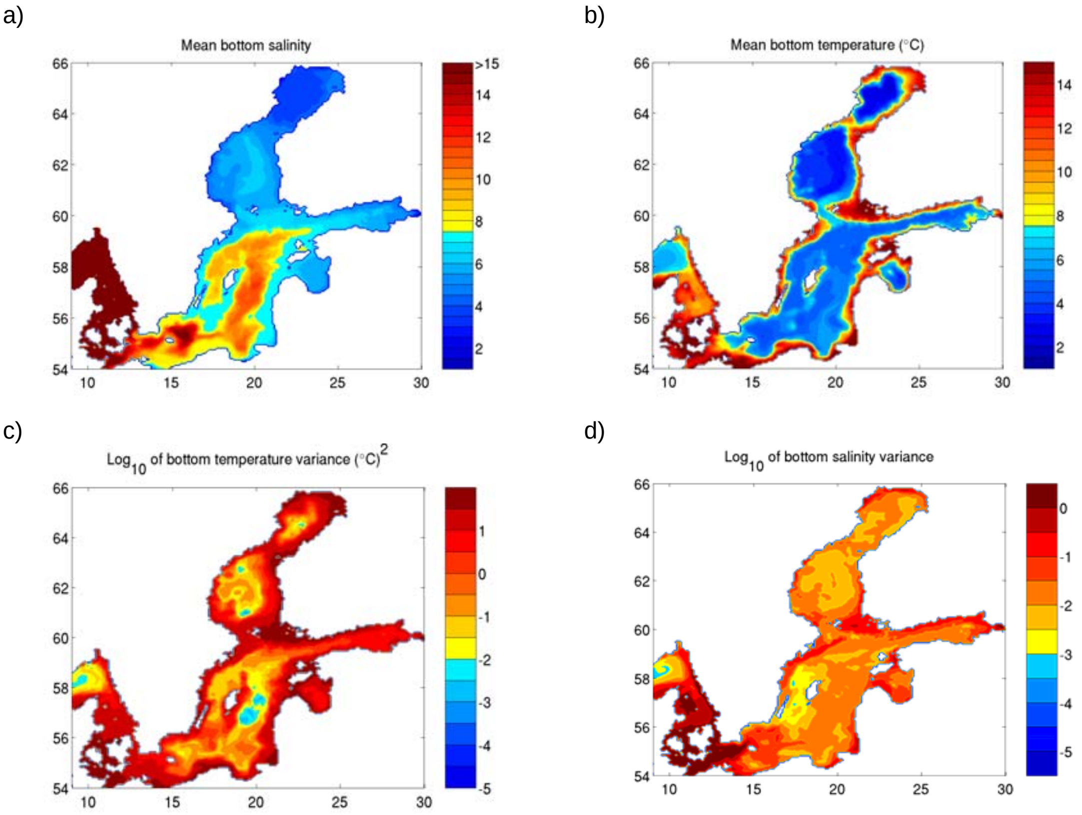


Figure 2.5 *Model results showing the salinity (psu) and temperature (ºC) in the Baltic region. a) Annual mean bottom salinity, b) Mean bottom temperature for the period April to September(ºC), c) Log$_{10}$ of the variance of the bottom salinity (psu)^2, and d) Log$_{10}$ of the variance of the bottom temperature (ºC)^2.*

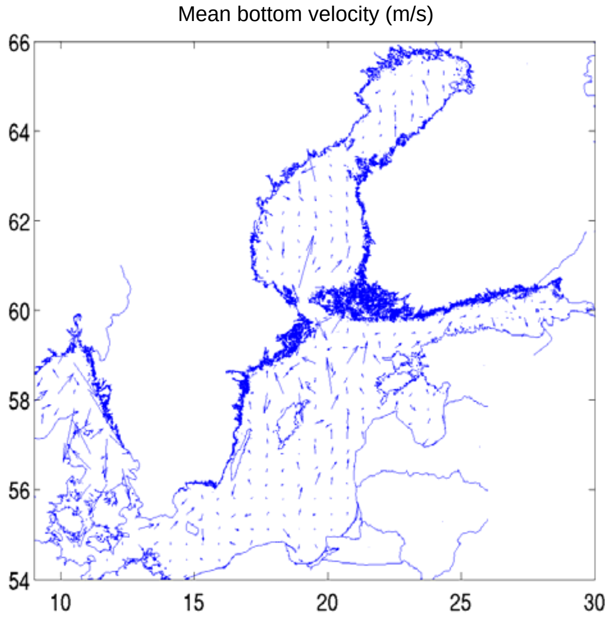


Figure 2.6 *Model results showing the annual mean bottom velocity (m/s).*

3 MODELLING BLUE CORRIDORS

A. Conservative tracers

The transport of larvae, propagules or other dispersal units was modelled by implementing a number of conservative tracers in 5 grid cells in the regional Baltic Sea model. The selected grid cells, representing 5 source areas, were distributed in different parts of the Baltic Sea and all of them are located within existing Natura 2000 sites (*figure 3.1*). The tracers were evenly distributed vertically in the water column of a grid cell and the tracer was then transported freely by current and turbulent mixing in the model.

The initial tracer concentration in the water column above the source regions was arbitrary given the value 1. During the whole period of tracer release its concentration was set to one above the source area. The concentration of the tracer therefore showed the spreading and the dilution in this non dimensional unit. The tracer distribution in the bottom and surface grid layer was then calculated after a simulation period of 6 months.

B. Non-conservative tracers

Transport patterns of larvae, propagules or other types in the Danish straits were analysed with the high resolution model using 9 grid cells in the model as source regions (*figure 3.2*). These 9 grid cells are all located within areas designated as Natura 2000 sites due to the presence of the Natura 2000 habitat “reef”. The names of the boulder reefs in the Natura 2000 areas have also been used as names of the grid cells used in the model.

The dispersal rate was set to 20000 dispersal units (larvae, propagules or other types) m^{-2} day^{-1}. It was assumed that only 10% of the bottom area within a grid cell (3.7*3.7 km^2) contributed with dispersal units. This assumption was made to cope with presents of different substrates, depths and spatial patterns of the biological source. This source provided a continuous supply of dispersal units during the integration period.

The dispersal unit was supposed to have a survival rate (e-folding time) of 5 days in the water column, corresponding to a decay of 0.2 day^{-1}. The spreading of the dispersal units was initiated from an initial condition of zero on 1 January 2003, and the average tracer concentration in the bottom grid layer was then determined for July 2003 after 6 months, assuming that only larvae, propagules or other pelagic dispersal stages in the bottom layer settle at the seabed.

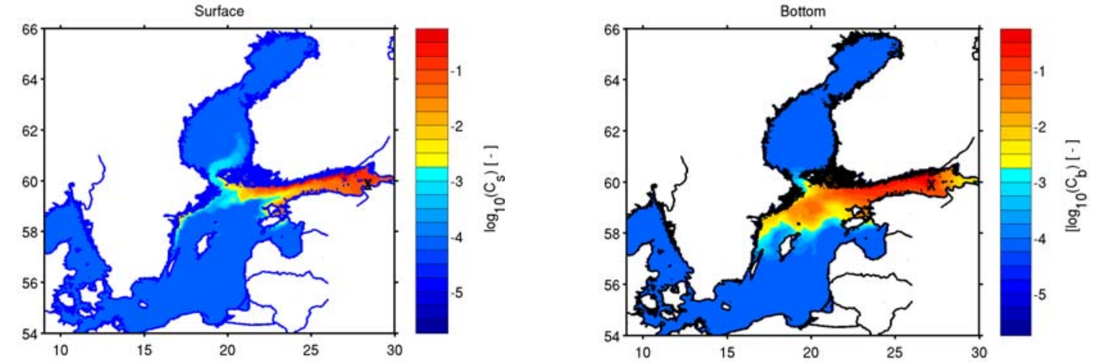
3.1 Model solutions of tracer distributions

A. Conservative tracer

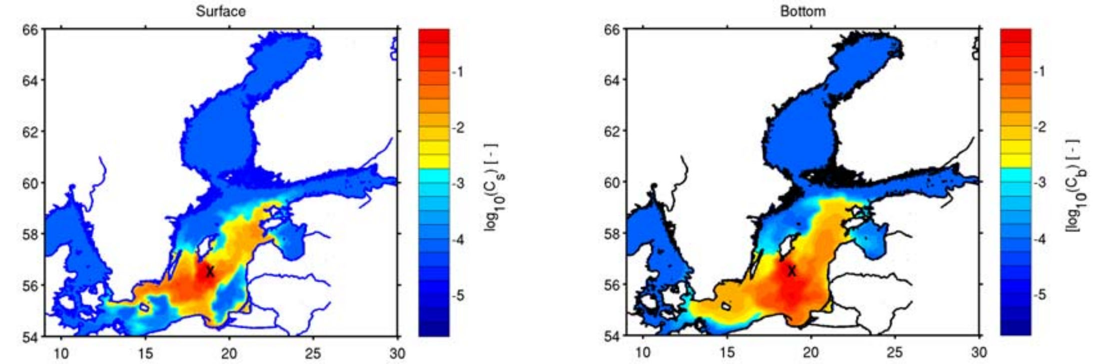
Conservative tracers were released at 5 locations in the Baltic Sea.

Deviations between surface and bottom distributions are due to the layered structure of the current fields. The spreading of bottom water from the Gulf of Finland into the Baltic Proper is more intense than the spreading of surface water (*figure 3.1 a,b*). Similarly, the bottom water in the Baltic Proper was dispersed over a larger area than the surface water during the 6-month period (*figure 3.1 c,d*). The spreading of surface water from the Baltic Proper into the Gulf of Finland was less intense than the intrusion of bottom water (*figure 3.1 e,f*). This could be due to outflowing low-saline surface water from the Gulf of Finland. Spreading of a tracer from the Arkona Sea and the Kattegat (*figure 3.1 g-j*) was relatively large for a 6-month period, due to the intense mixing and dynamics in the transition zone between the North Sea and the Baltic Sea.

a) Itäisen Soumenladen saaristo ja vedet b)



c) Hoburgs Bank d)



e) Upava f)

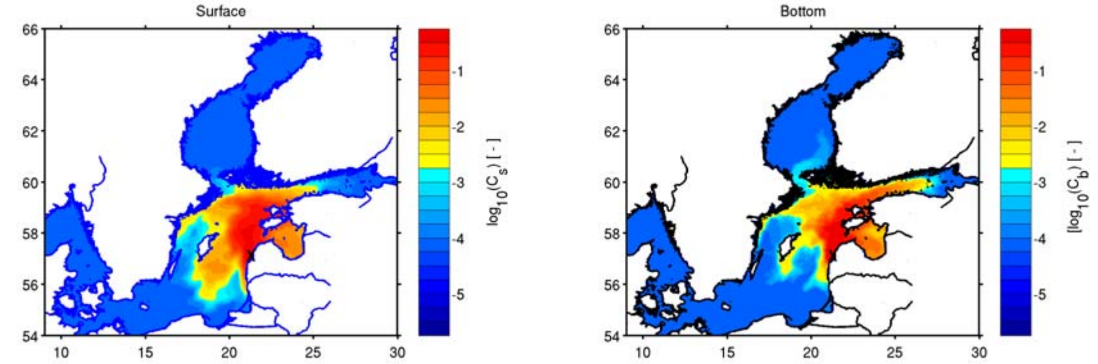
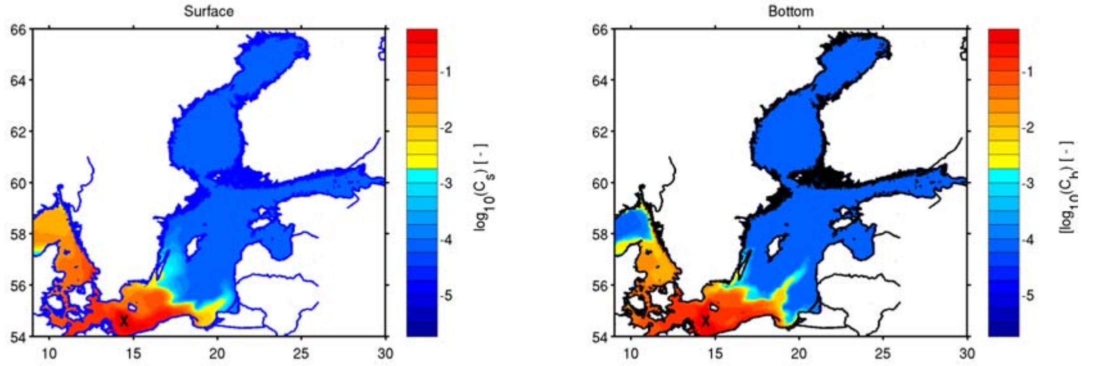
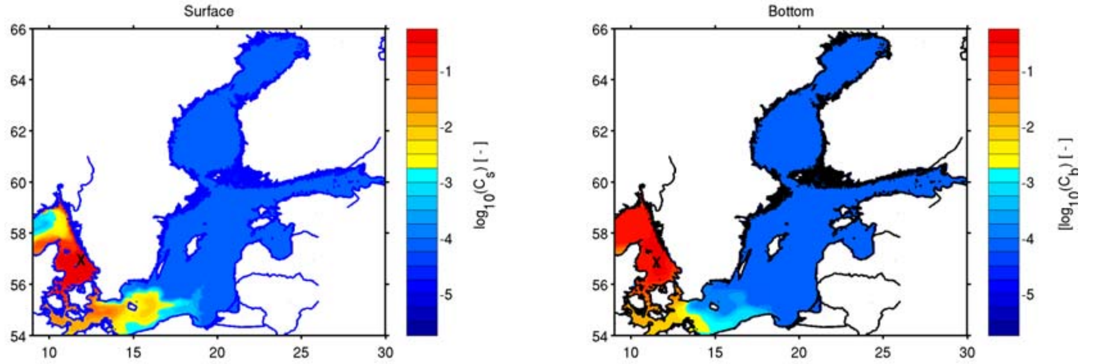


Figure 3.1 Model results that show the mean concentration in July of conservative tracers that continuously have been released throughout the water column during a 6-month period at 5 locations. The source is marked with X, where the concentration is always one.
a and b) The concentration at the surface and bottom for a tracer released at position 27° 0'E 60° 20'. c and d) The concentration at the surface and bottom for a tracer released at position 18° 35'E 56° 35'N. e and f) The concentration at the surface and bottom for a tracer released at position 21° 0'E 57° 10'N (figure continues on next page).



g) Adler Grund

h)



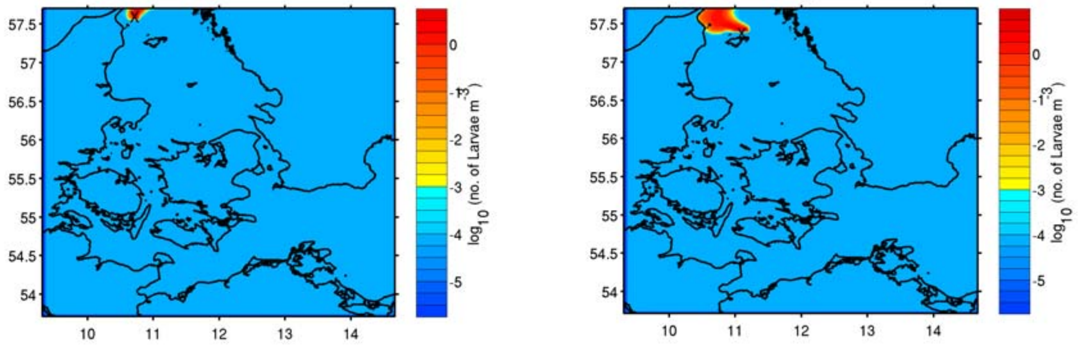
i) Kim’s Top?

j)

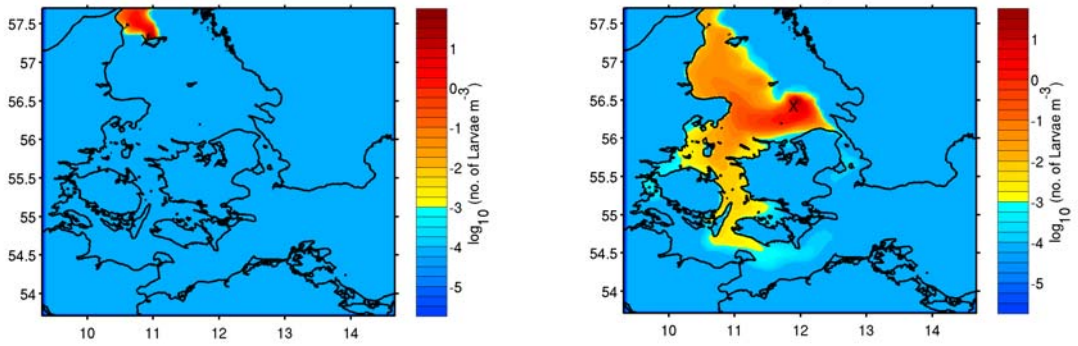
Figure 3.1 *(continued) Model results that show the mean concentration in July of conservative tracers that continuously had been released throughout the water column during a 6-month period at 5 locations. The source is marked with X, where the concentration is always one. g and h) The concentration at the surface and bottom for a tracer released at position 14° 10'E 54° 40'N. i and j) The concentration at the surface and bottom for a tracer released at position 11° 35.42'E 57° 01'N.*

B. Non-conservative tracers

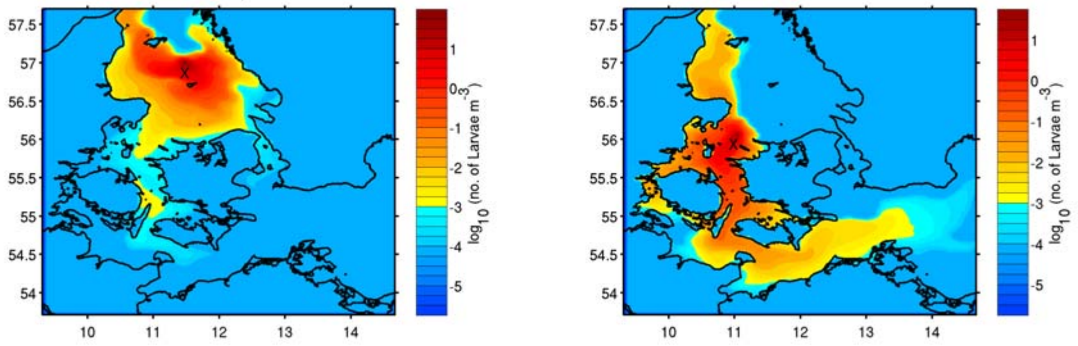
The tracer concentration in the bottom water of Kattegat and the Danish straits showed that the concentration decreased several orders of magnitude in a relatively short distance from the source regions (*figure 3.2*). This is due to the decay rate of 0.2 day^{-1} representing the mortality of the larvae, propagules or other dispersal units. However, the tracer concentrations showed a significant spatial variation around the different source regions due to the prevailing bottom currents. In the interpretations of the figures, it is important to keep in mind the intense dynamics which characterise this area, and therefore the bottom distributions would to some extent depend on the simulated period. For example, periods with strong in- or outflow to the Baltic Sea would influence the bottom distributions differently.


a) Herthas Flak

b) Tønneberg Banke

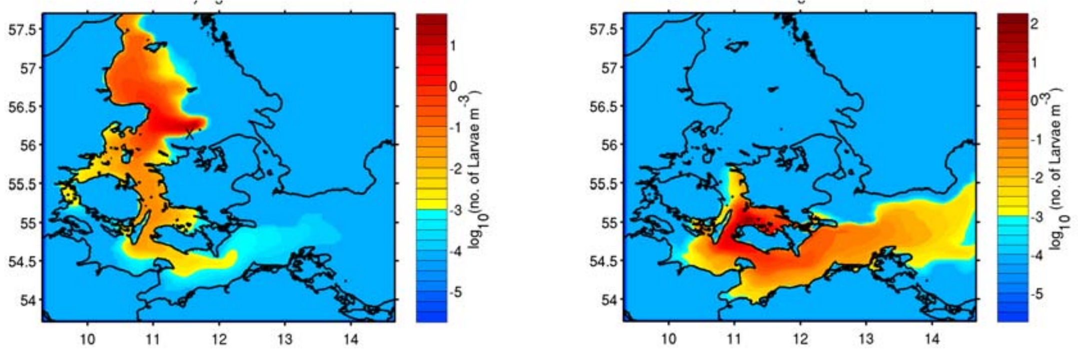

c) Per Nilen

d) Store Middelgrund


e) Kim's Top

f) Schultz's Grund

Figure 3.2 *Model results that show the mean concentration in July of non-conservative tracers in the model bottom layer. The tracer had continuously been released from 9 location marked with X throughout the water column during a 6-month period.*
a) Herthas Flak: 10° 52,11'E 57° 38,59'N, b) Tønneberg Banke: 11° 16,26'E 57° 28,328'N, c) Per Nilen: 11° 02,50'E 57° 22,697'N, d) Store Middelgrund: 12° 04,18'E 56° 33,302'N (figure continues on next page).


g) Lysegrund

h) Kirkegrund

i) Broen

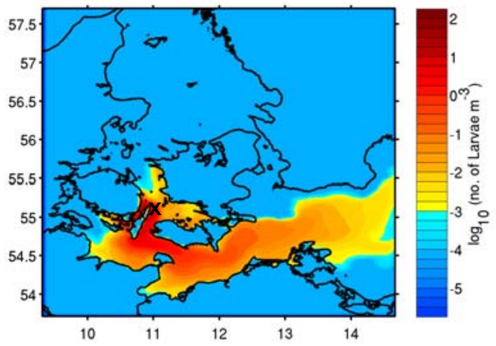


Figure 3.2 (continued) Model results that show the mean concentration in July of non-conservative tracers in the model bottom layer. The tracer had continuously been released from 9 locations marked with X throughout the water column during a 6-month period.
g) Lysegrund: 11° 46,62'E 56° 17,39'N, h) Kirkegrund: 11° 22,26'E 55° 06,847'N, i) Broen: 11° 01,49'E 55° 11,917'N.

3.2 Interpretation of the tracer distributions in terms of dispersal patterns within and between source areas in the Kattegat and the Belt Sea

The mean water depths in the nine modelled source regions in the Kattegat and the Belt Sea differ from area to area. The mean depths of some areas are below the pycnocline (>16 m) and in others above the pycnocline (<13 m).

The tracers in the model are released in grid cells hosting known boulder reef locations in inner Danish waters; all of them are also located within Natura 2000 sites. However, the depth distributions of reefs are not in total accordance with the average depth distribution in the grid cells used in the model. Since the tracers are not released in the grid cell layers with water depth equal to known presence of boulders, it restricts the use of biological data to validate the model. For this reason the results better reflect coherence between the landscape type “hard bottom complex”, according to Alhamdani et al. 2007, than the habitat “reef”.

As the dispersal units were allowed to distribute evenly throughout the entire water column in this model setup, the dispersal patterns are constrained by the specific mean depths of the source area relative to the position of the halocline. After the release the halocline acts as a barrier for exchange between the two water masses. This means that "units" in this model setup disperse from the source predominantly in the same water mass or water masses in which they are released (surface or bottom layer). Dispersal units from an area only situated above the halocline will therefore face a barrier in order to colonise an area below the halocline whereas this is not the case in the opposite situation (*figure 3.3*).

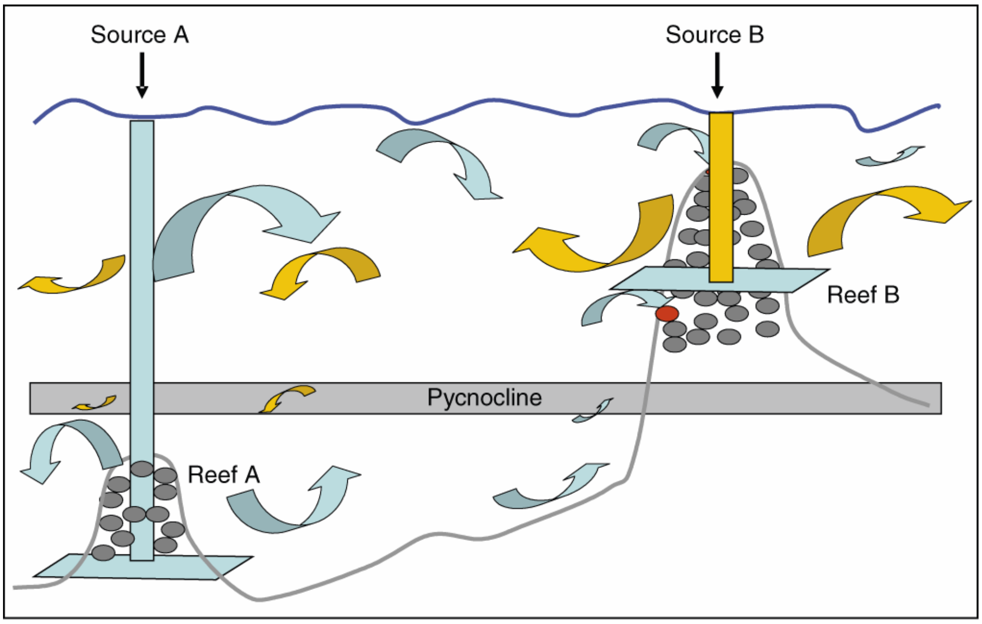


Figure 3.3 *Schematic drawing showing tracer "feeding" to the water column above the source area in the present model set-up using average depth in model grid squares and the subsequent spreading from area A to B, but not the other way around due to the barrier formed by the pycnocline.*

In this example where we have modelled the dispersal of tracers released simultaneously from all nine grid cells, each area has been subdivided into 3 classes which allows to determine the hierarchy among locations according to the concept up- and downstream. The three classes are: 1) areas above the pycnocline, 2) areas within the pycnocline and 3) areas below the pycnocline (*figure 3.4*).

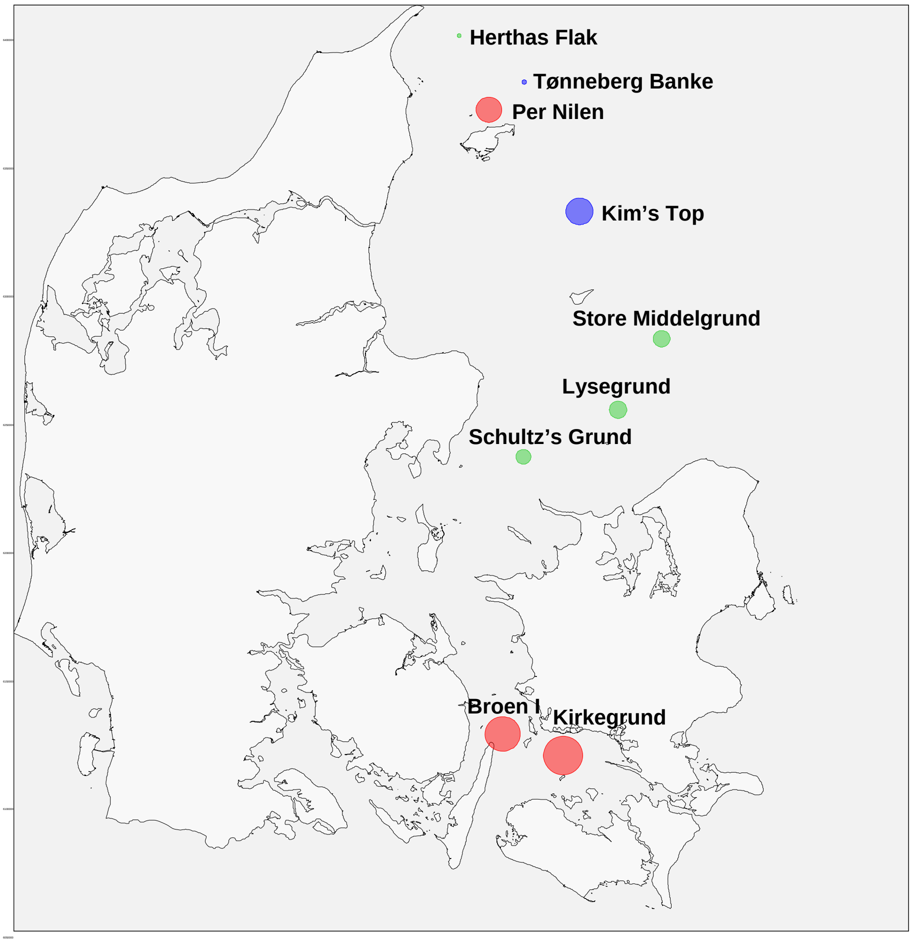


Figure 3.4 *Dispersal unit source areas used in the tracer study named by the boulder reef present in each area. A specific tracer is released from each location. Red circles indicate areas with a mean water depth above the halocline, blue circles indicate areas with a mean water depth around the halocline (13-16 m) and green circles indicate areas with a mean water depth below the halocline. Diameters of circles are scaled proportionally to average tracer concentration in the bottom layer.*

3.2.1 Loses of recruits within a population

From *table 3.1* it is seen that the standing average concentration of dispersal units ready in July in the grid layer just above the bottom is reduced by 2-3 orders of magnitude compared to the 20,000 units released from the same location. These numbers are arbitrary as they do not represent any specific life cycle or settling behaviour. However, they illustrate the difference among areas with respect to dispersal intensity. Populations in the northern part of Kattegat disperse most. Here the standing concentrations at Herthas Flak (5.07) and Tønneberg Banke (7.49) were about one order of magnitude lower than in areas located in the central Kattegat and in the southern Belt Sea.

Table 3.1 *Bottom concentration of dispersal units as determined from different locations in the Kattegat. The first column indicates the location of the source, and the columns 2-10 show the concentration of dispersal units per m^2 transported from the source area and found at the bottom at the other selected locations given by the index number. The coloured cells show comparisons between source stations that are shallower or in the same depth interval (0-14 m, around 15, and 16-50 m) as the stations that receive the dispersal units. The green colour indicates source locations that are deeper than the typical pycnocline depth in the Kattegat (15 m), blue colour indicates locations with depths around the pycnocline depth, and red colour indicates locations that are shallower than 15 m. The change of keeping recruits within the population at a given source area is given in cells: pos-x*pos-x.*

	Pos 1 Herthas Flak	Pos 2 Kim's Top	Pos 3 Lyse-grund	Pos 4 Per Nilen	Pos 5 Schultz's Grund	Pos 6 Store Middel-grund	Pos 7 Tønne-berg Banke	Pos8 Broen	Pos 9 Kirke-grund
Pos 1 (Herthas Flak)	5.07	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Pos 2 (Kim's Top)	0.0045	82.4	0.0181	0.276	0.0035	0.186	0.0001	0.0013	0.0006
Pos 3 (Lysegrund)	0.0017	0.0003	50.1	0.0503	0.305	0.0	0.0	0.0425	0.0177
Pos 4 (Per Nilen)	1.77	0.0	0.0	77.1	0.0	0.0	0.0	0.0	0.0
Pos 5 (Schultz's Grund)	0.0001	0.0	0.0	0.0069	41.7	0.0	0.0	0.241	0.0765
Pos 6 (Store Middelgrund)	0.0005	0.0001	1.35	0.0158	0.0834	47.8	0.0	0.0061	0.0029
Pos 7 (Tønneberg Banke)	1.43	0.0	0.0	0.0	0.0	0.0	7.49	0.0	0.0
Pos 8 (Broen)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	109	0.0141
Pos 9 (Kirkegrund)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0246	122

Figure 3.5 *Exchange of dispersal units within and between source areas above the halocline (Per Nilen, Broen and Kirkegrund). Numbers inside symbols denote dispersal unit exchange within the same grid cell and the thickness of the arrows reflects the exchange rate which is also shown with numbers in red.*

3.2.2 *Exchange of larvae, propagules or other dispersal life stages among source areas*

Source areas with mean water depth above the halocline (marked red) were distributed with one location in the northern Kattegat (Per Nilen) and two location in the southern Belt Sea (Broen and Kirkegrund), shown in *figure 3.5*.

There was no exchange over the long distance between the northern position and the two southern positions. Dispersal units released from the northern location only spread to the north (*figure 3.5*). There was an exchange between the two locations in the southern, however, to a different extent. “Kirkegrund” to the east feeded “Broen” to the west with twice as many tracers as was the case the other way around. This may be explained by the fact that the currents at “Broen” are generally much stronger and are directed north-south due to the main water exchange trough the Great Belt, while the current pattern at “Kirkegrund” also has an east-west component due to water exchange through the narrow strait “Grønsund” – a shortcut between the Great Belt and the Arkona Sea.

There are only two source areas with an average water depth equal to the halocline: “Kim’s Top” and “Tønneberg Banke”. The environment is about 10 times more dispersive at “Kim’s Top” than at “Tønneberg Banke”. The exchange of dispersal units between the two locations separated with about 60 km is almost insignificant and only directed from “Kim’s Top” in the south toward “Tønneberg Banke” in the north. This is also seen in *figure 3.6* where dispersal units from “Tønneberg Banke” spread towards northwest.

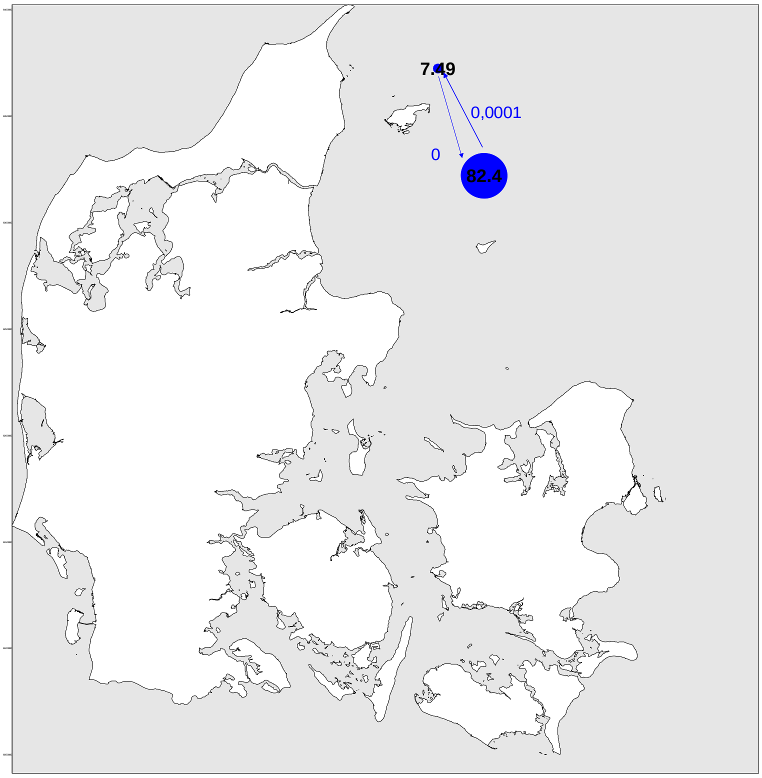


Figure 3.6 *Exchange of dispersal units within and between source areas with an average depth equal to the halocline (Tønneberg Banke and Kim’s Top). Numbers inside symbols denote dispersal unit exchange within the same grid cell and the thickness of the arrows reflect the exchange rate which is also shown with numbers in blue.*

The group of source areas with average mean water depth below the halocline consists of 4 locations (marked green): “Herthas Flak”, “Store Middelgrund”, “Lysegrund” and “Schultz’s Grund” with Herthas Flak located on the boarder between the Skagerrak and the Kattegat while the other three are located in the central Kattegat. The dispersal rate is much higher at “Herthas Flak” than in the central Kattegat. There was no exchange of dispersal units from Herthas Flak to the central Kattegat and the supply in the opposite direction was almost insignificant (*figure 3.7*).

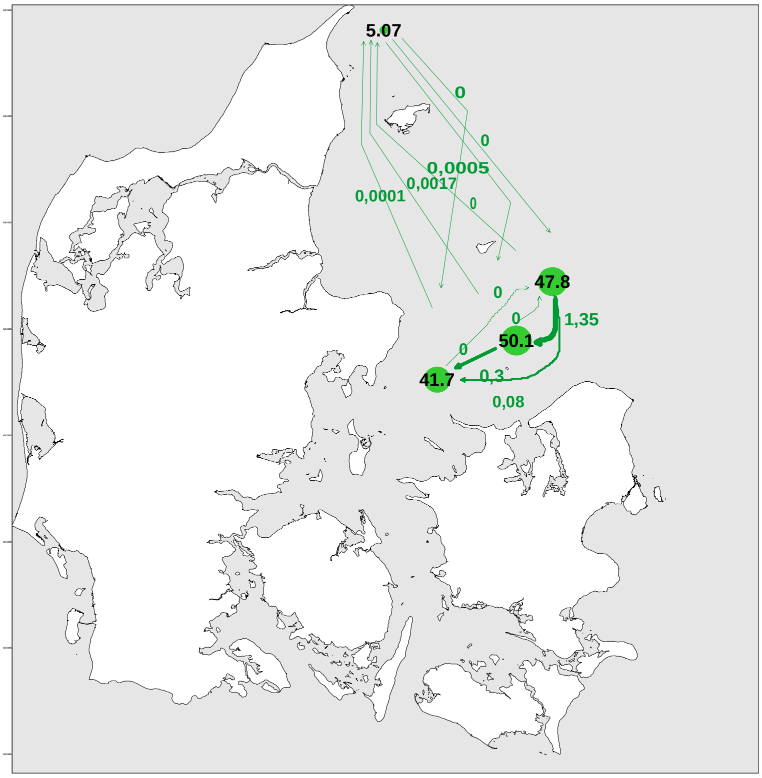


Figure 3.7 *Exchange of dispersal units within and between source areas with an average depth below the halocline (Herthas Flak, Store Middelgrund, Lysegrund and Schultz’s Grund). Numbers inside symbols denote dispersal unit exchange within the same grid cell and the thickness of the arrows reflect the exchange rate which is also shown with green numbers.*

Dispersal among the three areas in the central Kattegat goes from the north to the south. “Store Middelgrund” function as a source of dispersal units for both the closest area “Lysegrund” and “Schultz’s Grund” more to the west. Dispersal units from “Lysegrund” spread towards “Schultz’s Grund” but not to “Store Middelgrund” and there is no input from Schultz’s Grund to the other two areas.

3.2.3 *Overall dispersal patterns*

It is possible to construct the overall dispersal pattern within the entire area, accepting the model setup and by acknowledging that the dispersal is more efficient from source areas with deep average water depth compared to areas with shallow average water depth than the other way around. This is illustrated in *figure 3.8.*

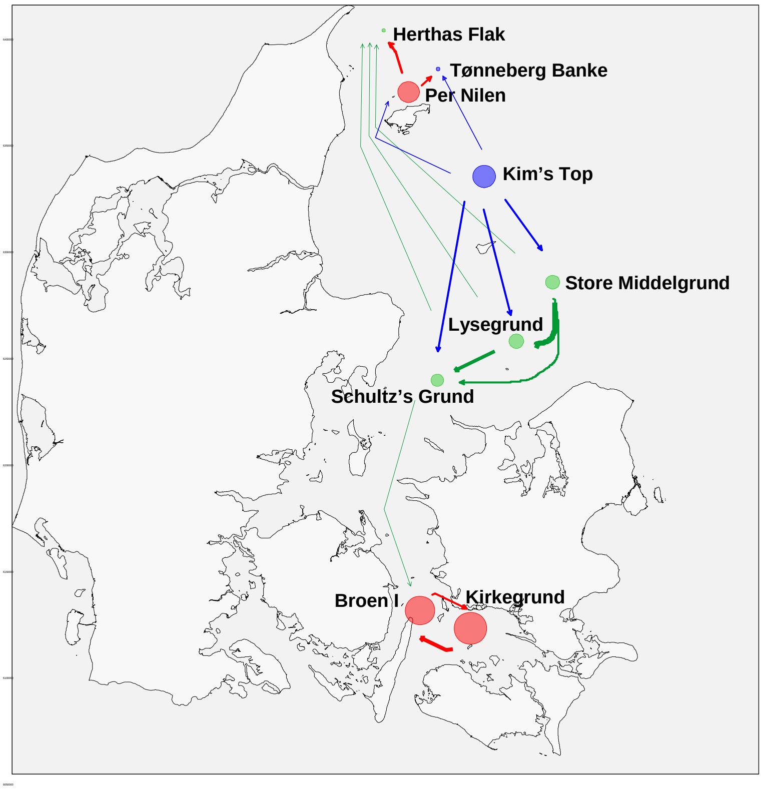


Figure 3.8 *Overall dispersal routes of tracers in the Kattegat and Belt Sea. Diameters of circles are scaled proportionally to average tracer concentration in the bottom layer.*

Here it is seen that "Kim's Top" in the central Kattegat supplies the other locations with dispersal units while "Kim's Top" hardly receives any from other area and at the same time it has a rather low dispersal rate itself compared to most other areas. As the grid cell area hosting "Kim's Top" has an average water depth that is shallower than the neighbouring areas in the Kattegat, the export from "Kim's Top" to those areas is underestimated, while an import, if any occurred, would have been overestimated. A larvae or another dispersal unit from Herthas Flak or Tønneberg Banke north of Læsø only spread to the north and those areas do not act as a source for locations in the central Kattegat within this model setup. Within the central Kattegat there is a clockwise circulation pattern and some tracers are exported to the northern region following a route west to the island "Læsø".

The two southern stations receive some tracers from the central Kattegat. The circulation pattern suggests that no dispersal units are exported in the other direction, but as the southern locations in the Belt Sea area are shallower this is uncertain.

3.2.4 Upstream and downstream hierarchy

Based on the overall dispersal pattern in the selected scenario, the 9 different source areas located in Nature 2000 areas in the open inner Danish waters can be categorised according to the concept of "up- and downstream hierarchy". This is illustrated in *figure 3.9*.

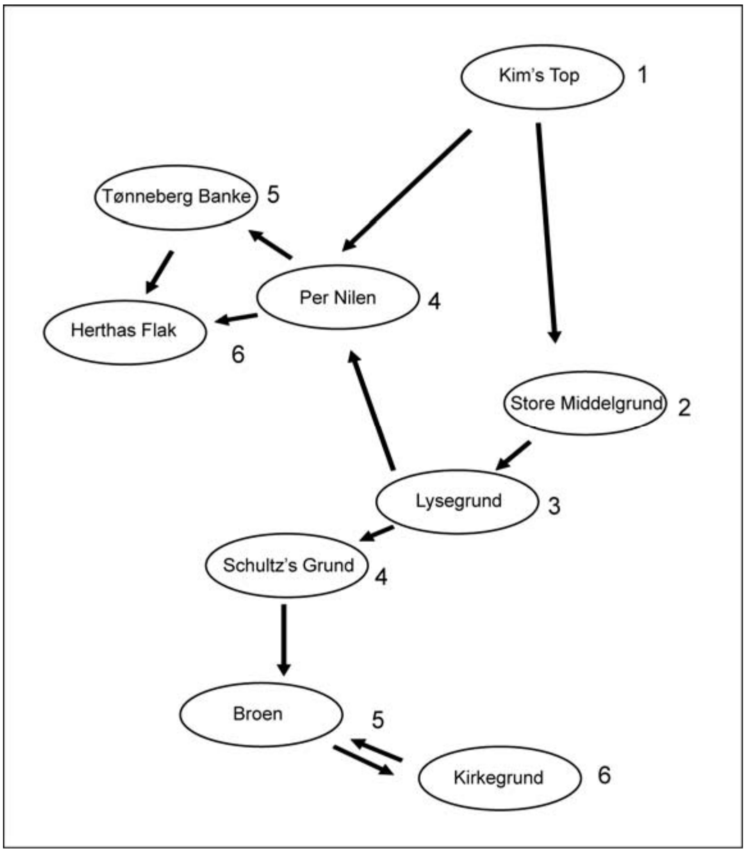


Figure 3.9 *Hierarchy of source areas for inner Danish waters according to the concept of upstream and downstream position as sources and sinks with respect to exchange of larvae, propagules or other dispersal units. Arrows indicate main dispersal routes and numbers indicate position in the hierarchy.*

4 DISCUSSION AND CONCLUSION

The attempt to quantify the role of blue corridors concerning passive dispersal using the tracer approach confirms that dispersal in fact can be a limiting factor concerning both the maintenance of populations at one given location and the exchange of individuals between locations. The modelling of tracers showed that internal recruitment at one given area varies considerably between source areas as tracers released from the two northern stations were diluted ten times more than in the central Kattegat. This means that a greater proportion of the dispersal units potentially are lost as they may spread over unsuitable areas.

Furthermore these tracer studies also show that the relative role of a certain area as a source of pelagic larvae or propagules indeed varies and that the concept of downstream and upstream locations makes sense. In this example the tracer study showed that the central part of Kattegat was the highest ranking area in the “upstream and downstream hierarchy” of the inner Danish waters and thus an upstream area, whereas the northern Kattegat clearly was “downstream” area. This pattern actually conforms to the hypothesis that the species pool of soft-bottom invertebrates located in the central part of Kattegat exports larvae, propagules or other dispersal life stages to other areas, thereby help to maintain population and biodiversity in adjacent areas (Josefson & Hansen 2004).

In case of hard substrate communities associated with a more limited distribution of suitable substrate than the soft bottom communities, dispersal may be even more critical and the role as stepping stones of certain stone reef could be evaluated using the same tracer approach.

The present examples have assumed one type of life cycle, including vertical distribution of dispersal units, a decay rate of 0.2 per day and settling behaviour limited to the bottom grid layer. The modelled period and settling time are also limited. Other approaches may result in different dispersal patterns.

A more general ranking of areas would need testing of many different dispersal strategies and that the modelled period was extended for a whole year. Running the model for several years characterized by different weather conditions would also be a major step forward.

This work demonstrates the variability and importance of passive transport pathways of pelagic life stages of marine flora and fauna. This kind of knowledge is very important when connectivity between existing Marine Protected Areas (MPA’s) is evaluated. Knowledge of blue corridors is also important if or rather when zoning of marine areas become an important management tool.

Protection of important steppingstone areas and habitats acting as donor areas or nursing areas during a life cycle is an obvious way to protect or restore biodiversity in a highly effected and exploited area like the Baltic Sea.

5 RECOMMENDATIONS REGARDING FURTHER DEVELOPMENT AND TESTING OF PELAGIC BLUE CORRIDORS

The following recommendations are directed at policymakers, scientists and environmental managers for the future refinement of the blue corridors work with the long-term goal of supporting a sustainable development in the Baltic Sea region through an informed transnational approach to the management of the marine ecosystem.

It is recommended that further modelling on pelagic blue corridors should be done with model setups and outputs pinpointed to be tested on identified available and highly relevant biological datasets at large transnational scales. Such examples will effectively demonstrate the need to manage marine resources through spatial planning both in regard to maintaining and restoring the marine ecosystem but also to secure a sustainable commercial exploitation of marine resources in the Baltic Sea.

It is also recommended that further development of the blue corridors focuses both on different ecological levels such as species, habitats and ecosystems.

Fish species exploited for commercial purposes are an obvious choice at the species level. Most fish stocks are highly overexploited and some also affected by eutrophication and other human impact. Stock restoration is needed and identification of breeding areas and pelagic corridors for fish larvae would be important tools in future management.

Recruitment of the fish species plaice in the Kattegat area seems to be an excellent case story. Time series of plaice recruitment are available from several years and model outputs of pelagic blue corridors for the flatfish larvae can be generated for relevant periods. Modelling the plaice larval “corridors” will link the nursery areas along the Kattegat coasts to important spawning areas in the Kattegat and the Skagerrak.

At ecosystem levels work focus on off-shore hard bottom habitats seems very promising. The offshore reef areas are all isolated from one another and a large amount of fauna and vegetation depends on pelagic recruitment either by “self-recruitment” or by recruitment from other reef areas. Biological data on species communities are available for most Danish, Swedish, German and Finish areas designated as Nature 2000 area according to the EU Habitats Directive. Comprehensive modelling of blue corridors between the reef sites and tests of the model results using the biological data will give an excellent picture of the upstream-downstream ranking between the reef sites. Results like this will not only be an excellent quantitative measurement of the coherence between the appointed nature protection sites. The model will also indicate the dependence of self-recruitment at specific sites, an important knowledge when site specific vulnerability to human pressure should be judged in a management perspective.

Other species or habitats supported by large international comparable biological datasets should be identified and included in this kind of analysis.

Acknowledgement
Ole Manscher at NERI (National Environmental Research Institute, University of Aarhus), Denmark, Jan Szaron at SMHI (Swedish Meteorological and Hydrological Institute), Sweden, Ritta Olsonen from FIMR (Finnish Institute of Marine Research), Finland, and Maria Gästgifvars from SYKE (Finnish Environmental Institute), Finland, sent us the data directly from their institutes. Jesper H. Andersen for facilitating some Finish data. Buoy data from the German Oceanographic Data Centre, Hamburg was obtained from the ftp site ftp.bsh.de. Mr. Detlev Machoczek at the German Data Centre authorized the access to the ftp site. Miguel Rodriguez provided salinity and temperature data from the BED database at Stockholm University. Finally thanks to Åsa Anderson from WWF Sweden for valuable comments.

6 REFERENCES

Alhamdani, Z., (Ed.) Reker, J. (Ed.), Andersen, J.H., Bendtsen, J., Bergström, U., Dahl, K., Dinesen, G., Elhammer, A., Hermansen, B., Kotilainen, A., Leth, J., Lindeberg, G., Reijonen, A., Riabtchouk, D., Sparrevohn, C., Söderkvist, J., Thougaard, L. 2007: Towards benthic marine landscapes in Kattegat and the Baltic Sea. Balance Interim report no. 12 (*in press*).

Brandt, J., Christensen, J.H., Frohn, L.M., Palmgren, F., Berkowicz, R. & Zlatev, Z. 2001: Operational air pollution forecasts from European to local scale. - Atmospheric Environment 35 (1): 91 - 98.

Conkright, M.E., Locarnini, R.A., Garcia, H.E., O'Brien, T.D., Boyer, T.P., Stephens, C. & Antonov, J.I. 2002: World Ocean Atlas 2001: Objective Analyses, Data Statistics, and Figures, CD-ROM Documentation, National Oceanographic Data Center, Silver Spring, MD, 17 pp.

ETOPO5 1988: Data announcement 88-MGG-02. Digital relief of the surface of the Earth. NOAA, National Geophysical Data Center, Boulder, Colorado.

Hastings, D.A. & Dunbar, P.K. 1999: Global land one-kilometer base elevation (GLOBE) digital elevation model, Documentation, Volume 1.0, Key to Geophysical records documentation (KGRD) 34. National Oceanic and Atmospheric Administration, National Geophysical Data Center, 325 Broadway, Boulder, Colorado 80303, U.S.A. 1999.

Josefson, A.B. & Hansen, J.L.S. 2004: Species richness of benthic macrofauna in Danish estuaries and coastal areas. - Global Ecology and Biogeography 13: 273-288.

Luyten, P.J., Jones, J.E., Proctor, R., Tabor, A., Tett, P. & Wild-Allen, K. 1999: COHERENS - A coupled hydrodynamical-ecological model for regional and shelf seas: user documentation. - MUMM report, Management Unit of the Mathematical Models of the North Sea, Belgium, 911 pp.

Martin, G., Makinen, A., Anderson, A., Dinesen, G.E., Kotta, J., Hansen, J., Herkül, K., Ockelmann, K., Nielson, P. & Korpinen, S. 2006: Literature Review of the "Blue Corridors" concept and it's applicability to the Baltic Sea. - Balance report no. 4. 67 pp.

Seifert, T., Tauber, F. & Kayser, B. 2001: A high resolution spherical grid topography of the Baltic Sea, revised edition. - Proceedings of the Baltic Sea Science Congress, Stockholm, 25-29 November 2001.

APPENDIX 1

Institutes that agreed to let the BALANCE project use their data, stored at the BED database

GROUP CODE	COMPLETE NAME	COUNTRY
IOW	Baltic Sea Research Institute, Warnemünde	Germany
LNUG/LANU	German Oceanographic Data Centre, Hamburg	Germany
CORPI	Coastal Research and Planning Institute, Klaipeda University	Lithuania
EMI	Estonian Marine Institute in Tallinn	Estonia
IOW	Baltic Sea Research Institute, Warnemünde	Germany
MIRYB	Morski Instytut Rybacki / Sea Fisheries Institute	Poland
MMCIAE_LA	Marine Monitoring Centre of Institute of Aquatic Ecology, University of Latvia	Latvia
RSHU	Russian State Hydrometeorological University, St. Petersburg	Russia
RSHU	Russian State Hydrometeorological University, St. Petersburg	Russia

About the BALANCE project:

This report is a product of the BSR INTERREG IIIB project "BALANCE".

The BALANCE project aims to provide a transnational marine management template based on zoning, which can assist stakeholders in planning and implementing effective management solutions for sustainable use and protection of our valuable marine landscapes and unique natural heritage. The template will be based on data sharing, mapping of marine landscapes and habitats, development of the blue corridor concept, information on key stakeholder interests and development of a cross-sectoral and transnational Baltic zoning approach. BALANCE thus provides a transnational solution to a transnational problem.

The BALANCE partnership is composed of the following institutions based in 10 countries: The Danish Forest and Nature Agency (Lead), The Geological Survey of Denmark and Greenland, The National Environmental Research Institute, The Danish Institute for Fisheries Research, WWF Denmark, WWF Germany, Institute of Aquatic Ecology at University of Latvia, Estonian Marine Institute at University of Tartu, Coastal Research and Planning Institute at Klaipeda University, Metsähallitus Natural Heritage Service, The Finnish Environment Institute, The Geological Survey of Finland, WWF Finland, The Swedish Environmental Protection Agency, The National Board of Fisheries – Department of Research and Development, The Geological Survey of Sweden, County Administrative Board of Stockholm, Department of Marine Ecology at Gothenburg University and WWF Sweden.

The following institutes contribute as consultants to the partnership: The Geological Survey of Norway, Norwegian Institute for Water Research, DHI Water and Environment, The Leibniz Institute of Marine Sciences, The Sea Fisheries Institute, The Finnish Game and Fisheries Research Institute, Metria Miljöanalys and The Nature Conservancy.

The **BALANCE Report Series** included at the 30th of March 2007:

BALANCE Interim Report No. 1 "Delineation of the BALANCE Pilot Areas".
BALANCE Interim Report No. 2 "Development of a methodology for selection and assessment of a representative MPA network in the Baltic Sea – An interim strategy".
BALANCE Interim Report No. 3 "Feasibility of hyperspectral remote sensing for mapping benthic macroalgal cover in turbid coastal waters of the Baltic Sea".
BALANCE Interim Report No. 4 "Literature review of the "Blue Corridors" concept and its applicability to the Baltic Sea".
BALANCE Interim Report No. 5 "Evaluation of remote sensing methods as a tool to characterise shallow marine habitats".
BALANCE Interim Report No. 6 "BALANCE Cruise Report – The Archipelago Sea".
BALANCE Interim Report No. 7 "BALANCE Cruise Report – The Kattegat".
BALANCE Interim Report No. 8 "BALANCE Stakeholder Communication Guide".
BALANCE Interim Report No. 9 "Model simulations of blue corridors in the Baltic Sea".

For more information please see www.balance-eu.org and http://maps.sgu.se/Portal