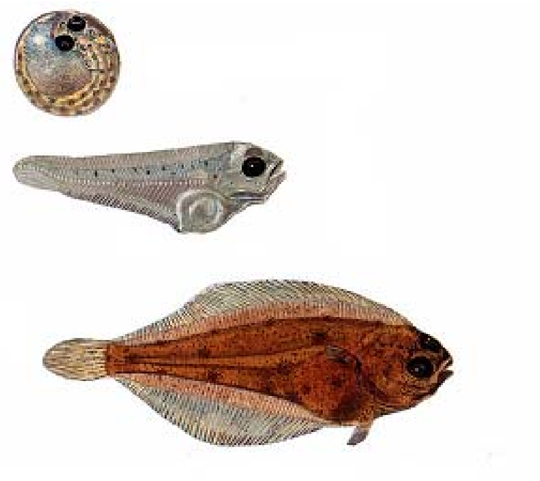

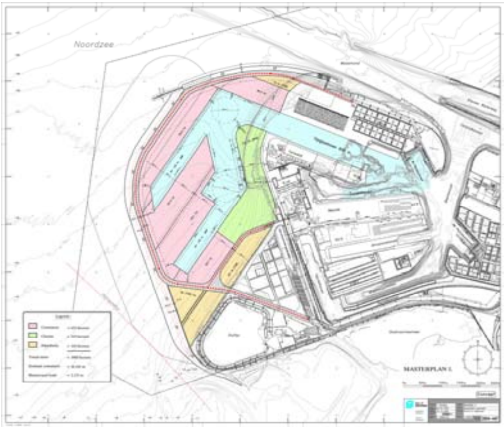

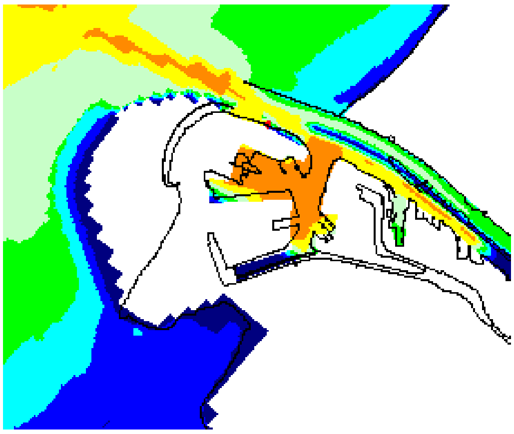

Impacts of Maasvlakte 2 on the Wadden Sea and North Sea coastal zone

Track 1: Detailed modelling research

Part IV: Fish Larvae

Baseline study MEP Maasvlakte 2

Lot 3b: Fish Larvae

Clients: Port of Rotterdam & National Institute
for Coastal and Marine Management /RIKZ

28 October 2005

Final Report

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Report

Number: C072/05

Transport of Fish Larvae in the Southern North Sea.

Impacts of Maasvlakte 2 on the Wadden Sea and North Sea coastal zone. Track 1: Detailed modelling research. Part IV: Fish Larvae.

Baseline study MEP Maasvlakte 2. Lot 3b: Fish Larvae.

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Summary

An investigation was carried out into the possible effects of the Maasvlakte 2 land reclamation project on the transport of herring, plaice and sole larvae in the southern North Sea. Specifically, the impact of the land reclamation on the delivery of larvae into the Wadden Sea (a Natura 2000 site protected by the European Birds' and Habitats Directives) was investigated.

Of the Delft3D package, which consists of modules for hydrodynamics, water quality, ecology, transport of suspended matter and bottom morphology, the hydrodynamic model (Delft3D-Flow) that simulates both 2D (in either the horizontal or the vertical plane) and 3D was used. The flow equations were solved on a staggered, curvilinear finite-difference grid and in the vertical by sigma coordinates. Hydrodynamic transport was computed using detailed bathymetry and open boundary forcing based on tidal constituents and air pressure, with variable wind forcing and variable river discharges.

The transport of fish eggs and larvae was modelled using Delft3D-WAQ. This module contains the physical schematisation, calculated transport of substances as a function of the advective and dispersive transport, accumulated fluxes and computed resulting concentrations for each time-step. Internally, Delft3D-WAQ multiplied fluxes with concentrations to obtain masses across internal and external boundaries. This was coupled with biological models of behaviour and development of eggs and larvae. Behaviour rules were developed to mimic the behaviour of larvae in the field. These rules included pelagic passive drift, diel vertical migration and selective tidal stream transport. The sensitivity of the modelled transport of eggs and larvae to the assumptions of the model was tested to provide an estimate of precision. The model was also run for nine years of hydrodynamic data from December of a year until June of the following year (1988/1989 and 1995/1996 to 2002/2003). This provided information on the inter-annual variability. The modelled transport was compared to empirical estimates of abundance, growth and timing of delivery from surveys of larvae, post-larvae and juveniles. December 1988 to June 1989 was chosen as the core year for the final modelling, as most hydrodynamic validation had occurred in this data set. The core year was used to test three model scenarios;

i) the current situation
ii) the current scenario with new constructions added (new wind farms and changes to the Haringvliet sluices)
iii) scenario ii) but with the Maasvlakte 2 reclamation ('Doorsteekvariant') also added

The results suggest that the transport of herring larvae (with a predominately pelagic lifestyle) is not very sensitive to the choice of behaviour rules, whereas the choice of behaviour rule for flatfish (with demersal and pelagic phases) has a greater impact on transport. In all cases the inter-annual variability in transport was large. The differences between the scenarios with respect to the transport of larvae (both in terms of timing and abundance) to the Wadden Sea and the protected area were very small. The modelled transport was broadly in agreement with estimates from the field.

The simulated differences in transport caused by the reclamation of Maasvlakte 2 were much smaller than the model's precision, and insignificant in comparison to the inter-annual variability. Based on the current model and its inherent assumptions and uncertainties, it is concluded that the effect of the Maasvlakte 2 is close to zero, in other words negligible.

1 Introduction

1.1 Background to the study

The Rotterdam Mainport Development Project

A substantial expansion of the Port of Rotterdam, called the Maasvlakte 2 (MV2), is planned in the near future. It will be located at the seaside of the present Maasvlakte along the southern part of the Dutch coast (Figure 1.1). This new port and industrial area will comprise 1000 hectares of industrial sites for deep-sea-related customers in chemicals, new industry and container handling, plus the associated distribution activities. To plan this significant land reclamation the Rotterdam Mainport Development Project (PMR) was established. The Dutch Government, represented by the Ministry of Transport, Public Works and Water Management, and the municipality of Rotterdam, represented by the Port Authorities are the two partners within the PMR.

To establish the conditions under which the PMR constituent projects can be developed, the national government followed the Core Planning Decision Plus (PKB+) procedure. This PKB+ contains several material policy decisions, which are components of spatial planning decisions that have to be complied within the spatial planning procedures by other authorities, such as local municipalities. This procedure started in 1998 and resulted at the end of 2001 in a PKB+ part 3, i.e. the Cabinet's position on the project. An environmental impact assessment (MER) forms part of the PKB+. The PKB+/MER procedure involves various participatory and decision events. The Dutch parliament will take the ultimate government decision (i.e. PKB+ part 4).

Verdict Council of State

In January 2005, the Council of State rejected the material policy decisions made by the Dutch government in the PKB+ part 3 regarding PMR. Although the Key Planning Decision (PKB) itself is not affected by this rejection and continues to represent the applicable government policy, the realization of the various project components has become less certain because of the verdict of the Council of State.

The verdict by the Council of State stated that "…*it has not been made sufficiently plausible that the proposed Maasvlakte-2 reclamation would have no impact on the ecological values of the Wadden Sea, a Natura 2000 site protected by the European Birds' and Habitats Directives".*

The verdict further stated that *"it has not been made sufficiently clear that further research could not contribute to obtaining a greater understanding with regards to the potential scale and consequences of a reduced supply of silt and fish larvae for the conservation values and functions of the Wadden Sea within the framework of the goals and objectives of this protected area*".

Because of this verdict the PMR partners have decided to rectify the material policy decisions in the PKB^+ Part 3. This rectification has to be carried out with great care but as rapidly as possible. One of the objectives of the rectification is to carry out an Appropriate Assessment ("Passende Beoordeling") of possible impacts of the MV2 land reclamation on the ecological values in the Wadden Sea, an important nature area protected under both the Habitats and the Bird Directive. An appropriate assessment is defined as an investigation into the impacts of certain plans and projects on the ecological values in an area that is protected by the European Directives, in this case the Wadden Sea. The hypothesis in this assessment is that the MV2 land reclamation may have a significant effect on the transport of fish larvae, nutrients and suspended sediments along the Dutch coast and that this could have significant consequences for the 'favourable conservation status' of the Wadden Sea.

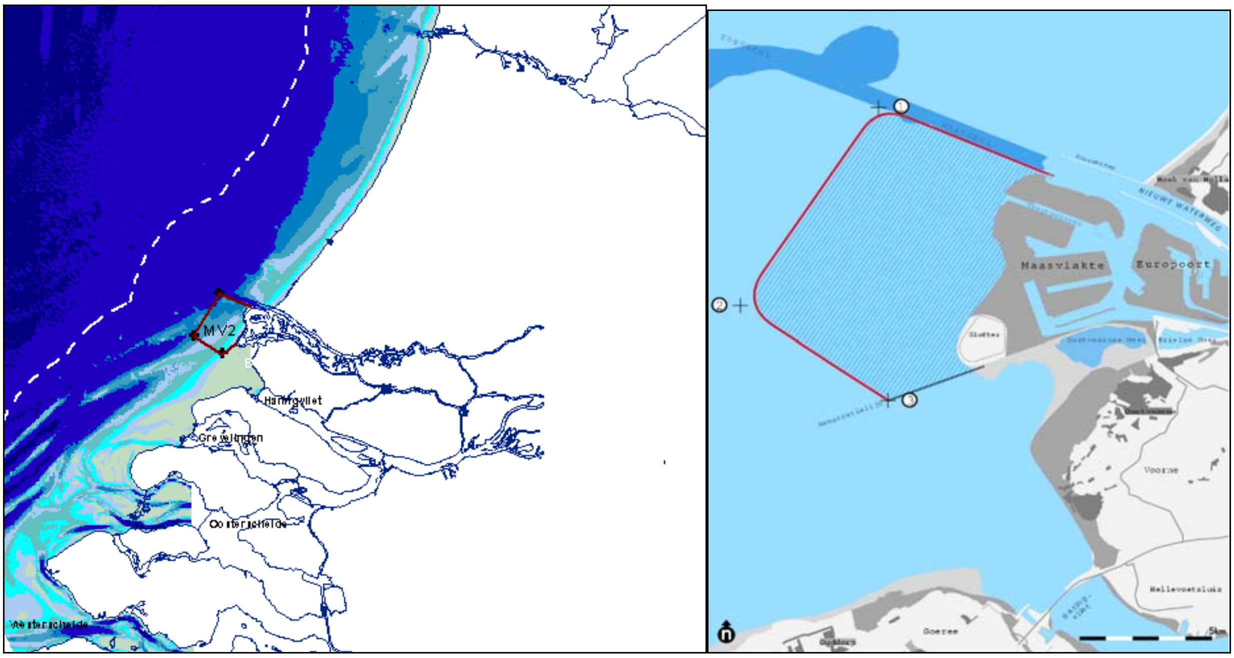


Figure 1.1. Map showing the Dutch coast with the location for the intended Maasvlakte 2 and an enlargement of the intended area for reclamation. For location of Wadden Sea see Figure 3.4.1.

1.2 Baseline MEP-MV2 and PB-MV2 studies

The Port Authorities of Rotterdam (HbR) and the National Institute for Coastal and Marine Management /RIKZ commissioned a consortium consisting of Royal Haskoning (Haskoning), WL I Delft Hydraulics (WL) and the Netherlands institute for Fisheries Research (RIVO) to carry out a series of additional studies to provide information for the 'Appropriate Assessment' (Passende Beoordeling, PB MV2). This included studies on the impact of Maasvlakte 2 on hydrodynamics, sediment transport, nutrient dynamics & primary production and the transport of fish larvae. The present report describes the results of the study on the transport of fish larvae.

This report not only presents the results of PB MV2 Fish Larvae mentioned in the previous paragraph but also gives the results of the Baseline Study MEP MV2. The Baseline Study MEP MV2 was commissioned in 2004 by RIKZ to a consortium of RIVO, WL and the Netherlands Institute of Ecology (NIOO-CEME) and constitutes a study of the baseline situation for the Monitoring and Evaluation Programme MV2 (MEP MV2). The objectives of MEP MV2 are to monitor whether the effects of the land reclamation on species and habitats are sufficiently compensated by the proposed compensatory measures (e.g. the establishment of a Marine Protected Area). Furthermore MEP MV2 intends to monitor whether the effects predicted by the Environmental Impact Assessment for MV2 will take place and to what extent. Within MEP MV2 the consortium of RIVO, WL and NIOO-CEME focuses on benthic fauna, fish and fish larvae. Results on the baseline situation of benthic fauna and fishes will be reported elsewhere, whilst this report solely presents the results with respect to the baseline situation for the transport of fish larvae along the Dutch coast.

Despite the conclusion of the Environmental Impact Assessment (PKB+ part 1/MER, Goderie et al., 1999) stating that the influence of the MV2 land reclamation on fish larvae was expected to be negligible, it was already acknowledged within the MEP MV2 program that no confident statements could be made without additional analyses. Therefore larval transport studies focussing on plaice and sole were included in the baseline study MEP MV2. Due to the verdict by the Council of State the larval transport studies as originally proposed in Baseline MEP MV2 needed to be elaborated (i.e. PB MV2 study). Firstly, by decreasing the uncertainties incorporated in the larval transport model. Secondly, by including herring in the analyses. Finally, by modelling the effect of the land reclamation itself. The Baseline MV2 project only aimed at modelling the baseline situation (without MV2) with respect to larval transport, and giving an expert judgement on the effects of MV2.

The progress and results of the modelling study were regularly and intensively discussed in a supervision group (the so-called 'Larvenbegeleidingsgroep'), which consisted of Loes Bolle and Mark Dickey-Collas (RIVO), Paul Erftemeijer and Jan van Beek (WL), Mathijs van Ledden (Royal Haskoning), Johan de Kok and Zwanette Jager (RIKZ). The quality control of the report was done by Zwanette Jager and Johan de Kok (on behalf of RIKZ/Havenbedrijf Rotterdam), Mathijs van Ledden (Haskoning), Adriaan Rijnsdorp and Eric Jagtman (RIVO).

1.3 Problem definition

The problem definition and gaps in knowledge with respect to the transport of fish larvae in relation to MV2 are described in detail in the strategies of approach for the Baseline MEP MV-2 study (Asjes et al., 2004) and the PB MV2 study (Winterterp et al., 2005). They are summarized in this section.

For many fish species, such as plaice and sole the shallow coastal zone of the North Sea and the Wadden Sea are essential as nursery areas (Zijlstra, 1972; Van Beek et al., 1989). These areas are rich in food and, because of their shallowness, protect juveniles from predators. Plaice spawn in offshore areas (Figure 2.2.1) and their eggs and larvae are transported from the spawning grounds to the nursery areas by a combination of passive transport and selective tidal transport. Although sole spawn closer to the shore than plaice (Figure 2.3.2), their eggs and larvae are transported further inshore, mainly by passive transport. For other species, such as herring, the Wadden Sea and the shallow coastal waters are relatively less important as nursery areas, but the presence of these species in shallow waters is of ecological significance (e.g. prey for coastal birds). Herring larvae are transported from the offshore spawning and hatching grounds (Figure 2.1.1) to the coastal areas, mainly by passive transport. Consequently, residual currents and tidal movements are crucial for the larval transport of many species.

The land reclamation for MV2 may alter the currents along the Dutch coast, which could influence transport routes and thus the final destination of fish larvae. As larval transport is an essential element for the recruitment of some commercially important species, altered larval transport could affect the size of exploited stocks. The basic concern of the MV2 land reclamation is that the hydrodynamics of the southern North Sea in general and the ‘Coastal River’ in particular will be changed in such a way that the transport of fish larvae will be affected, with two potential negative scenarios:

1) The number of larvae reaching the coastal areas will be reduced
2) The transport of larvae to the coastal areas will be delayed

In both cases, the ‘transport success’ of fish larvae to the coastal (nursery) areas within a specific time period may decrease, leading to a decreased recruitment and stock sizes and/or decreased prey availability for predators.

Within the framework of the PKB/MER it was concluded that the influence of MV2 on larval transport would be limited (Goderie et al, 1999). However, these effects have until now never been quantified. In this study the transport of fish larvae in the southern North Sea has been described and the ‘transport success’ has been quantified through a combination of hydrodynamic modelling and behavioural modelling of fish larvae.

1.4 Choice of fish species

In the project ‘Baseline MEP MV2’, plaice and sole were chosen as the relevant species to study with respect to larval transport. Firstly, because both species depend on water movements to transport the eggs and larvae from the spawning grounds further offshore to the shallow inshore nursery areas. Secondly, both species are abundant in the southern North Sea and of great importance to the fisheries. Thirdly, a large amount of scientific knowledge is available for both species, which allows the modelling egg and larval transport. Finally, an important part of the transport phase is within the area in which the hydrodynamics are expected to be affected most by the MV2 land reclamation, i.e. the ‘Coastal River’.

The verdict of the Council of State explicitly states that further research should focus on the scale and consequences of a reduced supply of fish larvae for the conservation and functioning of the Wadden Sea. This immediately leads to the question: “On which species should the PB MV2 study focus?” Although the Wadden Sea is an important nursery area for sole and especially for plaice, other fish species are more important in terms of ‘conservation and functioning of the Wadden Sea’, i.e. more important prey item for birds and mammals included in the Birds and Habitat directives. In this respect herring and sandeel are important species.

Herring has been included in the PB study because of its importance as prey item within the Wadden Sea and the fact that its larval transport phase is within the area that may be affected by the MV2 land reclamation. Furthermore, sufficient information on the spawning grounds and on the larval distribution and behaviour of herring is available to be able to model larval transport.

Little is known about sandeel in the southern North Sea. Although some information is available on larval behaviour, the lack of knowledge on the locations of the spawning grounds and the spatial distribution of the larvae in the southern North Sea makes it impossible to include sandeel in the present modelling study. Based on studies in the northern North Sea, a concentration of larvae may be expected in the frontal zone of the Coastal River. However, a change in the path of the Coastal River is expected only to have local influences (personal comment Dr. P. Munk, Danish Fisheries Institute).

1.5 Objectives

The objectives for Baseline MEP MV2 Fish Larvae are:

- Define the current hydrodynamic transport routes between spawning grounds and nursery areas for plaice and sole;
- Quantify the current occurrence of different developmental stages at certain locations to describe the spatial and temporal patterns of larval transport in the baseline situation;
- Quantify the current transport success for fish larvae arriving in the nursery areas;
- Judge how possible effects of MV2 on larval transport influence population sizes;

The PB MV2 Fish Larvae study strongly relies on the successful achievement of the first 3 objectives of the baseline study, not only for plaice and sole, but also for herring. Furthermore the new study aims at:

- Decreasing the uncertainties incorporated in the larval transport model.
- Quantifying the effects of the Maasvlakte 2 land reclamation on larval transport success to the Wadden Sea for plaice, sole and herring.

1.6 Reading guide

The present report presents the background, methods, results and implications of both the Baseline MEP MV2 study and the PB MV2 study on fish larvae. The report is divided into 7 chapters, which subsequently describe the background of the study (chapter 1), published information on the biology of herring, sole and plaice relevant for modelling larval transport (chapter 2), the model design and set-up (chapter 3), the results of the baseline study describing the natural variability in larval transport patterns and the sensitivity of the model to assumptions on biological processes and parameters (chapter 4), an overview of available field data and the validation of the fish larvae model (chapter 5), results of the impact assessment of MV2 (chapter 6), and a general discussion of the results and conclusions (chapter 7).

2 Biology of the species

2.1 Herring

The ecology and biology of herring in relation to larval transport and the southern North Sea is reviewed in Annex 1. There has been a large amount of research on herring over the last 200 years. This section summarises the findings. The North Sea herring stock is made up of a number of components (sub-populations) of fish that show different physical characteristics, spawning strategies and migration behaviour, Downs herring which spawn and hatch in the southern North Sea are one such component (Jennings & Beverton1991; McQuinn, 1997).

2.1.1 The population dynamics

The population of herring collapsed in the 1960s and 1970s. This was caused by over fishing. The population did not recover until the late 1980s, and now the population is thought to be “healthy” and may be so large that growth of some year classes has been reduced (Figure 2.1.1). The year class strengths of newly recruiting herring are dependent on the spawning stock size of the population (SSB) but additionally they vary in strength due to other factors. The main additional variability (other than due to SSB) occurs between hatching and the following February, i.e. during the larval phase (see Cushing & Bridger, 1966; Nichols, 2001; Nash & Dickey-Collas, 2005, ICES 2005).

2.1.2 Spawning and hatching

Herring lay eggs on the sea bed, which incubate for 10 to 15 days depending on temperature. The yolk sac larvae hatch and slowly take in water which increases their buoyancy and they rise into the upper water column. The time of spawning and hatching varies greatly in herring, and in the North Sea spawning begins in the north in August to September, and finishes in the south in December and January (Figure 2.1.2). The spawning grounds are gravel beds and thus associated with areas of faster flowing bottom water. In the Downs area, spawning starts in the western area in December and spreads to the whole area by early January (Figure 2.1.3). After spawning, the adult herring migrate away from the spawning grounds, either to overwinter or in the case of Downs herring, to begin feeding (see Cushing, 1955; Cushing & Burd, 1957; Blaxter & Hunter, 1982; Heath et al., 1997; Stratoudakis et al., 1998; Corten, 2001).

2.1.3 Larval transport and behaviour

After hatch the larvae drift in a passive manner. Their distribution is only affected by the hydrodynamics of the water column and their buoyancy. As they grow, they begin to search for food and this search becomes more extensive the larger they are. If there is plenty of food and light available and the water column is well mixed, the main driver of their transport will still be the hydrodynamics. However if food is limited, firstly they will take on water as they starve, and hence become more buoyant and they will also search larger areas looking for food. For the smaller larvae this change in behaviour is insignificant to the effect of hydrodynamics but to the larger larvae the individual movement can be significant in relation to the hydrodynamics alone. This looking for food results in diel vertical migrations with larvae accumulating nearer the surface at day (see Heath et al., 1988; 1991; Munk et al., 1989; Gallego 1994; Fox et al., 1999).

Older larvae begin to exhibit shoaling behaviour at 35mm, but only fully shoal after metamorphosis at 50-55mm. This requires active swimming, and being influenced by other fish (both of their own species and of others e.g. predators). There is no evidence for salinity triggers of behaviour in herring larvae, other than one speculative record (see Gallego & Heath, 1994; Gallego et al., 1995).

2.1.4 Larval growth

The larvae of herring change their growth rate with size, temperature and feeding (influenced through prey density, turbulence and light). Many studies have tried to measure growth rates empirically but it is often difficult to resolve the variability in the field due to the interaction of sampling effects and the influencing variables themselves. This is confounded by the inability to read with accuracy the otoliths of slow growing larvae. Energetic models can provide information on maximum possible growth rates and if you assume that the survivors of a population of larvae tend to be the fastest growers, these maximum growth rates can be used within transport models as long as the assumptions are acknowledged. Larval growth does effect behaviour, see section above (see Gallego et al., 1996; Folkvord et al., 1997; Gallego & Heath 1997; Fiksen & Folkvord, 1999; Fox et al., 2003; Folkvord et al., 2004).

2.1.5 Nursery areas

The German Bight and Skagerrak are the main nursery areas for North Sea herring. These lie in the east of the region, which suggests an eastward transport of larvae. Early modelling studies support the idea that the larvae are transported eastwards. However these earlier studies concentrated on the northern spawning components of North Sea herring; not until 1997 was Downs herring properly considered. Year class strength is generally determined prior to arrival on the nursery grounds (see Burd, 1978; Bartsch et al., 1989; Nichols & Brander, 1989; Bartsch, 1993; Heath et al., 1997).

The Wadden Sea is a nursery ground for herring, but it is not the most important ground. Larvae from both the northern and southern spawning components of North Sea herring enter the Wadden Sea in spring. No study has tried to assess the relative importance of the Wadden Sea as a nursery ground compared to the German Bight and Skagerrak (see Bückman, 1950; Corten & Kamp, 1979).

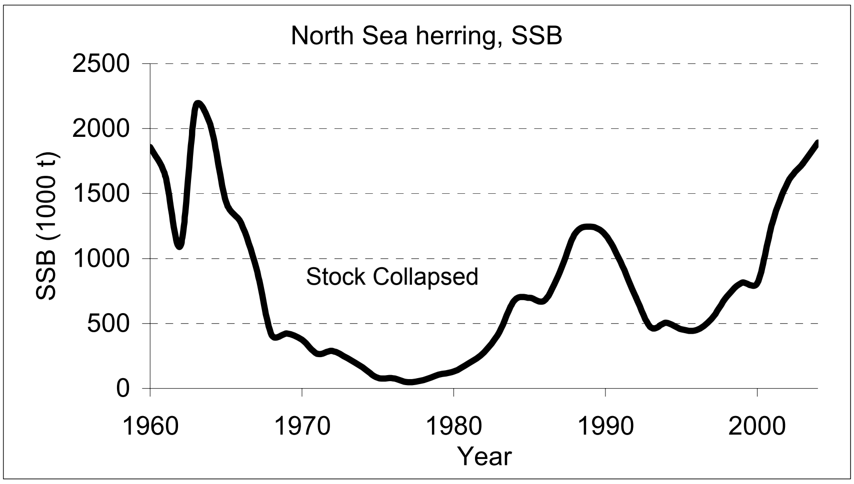


Figure 2.1.1. Herring. Time series of spawning stock biomass (SSB) of North Sea herring from 1960 to 2004. (ICES 2005)

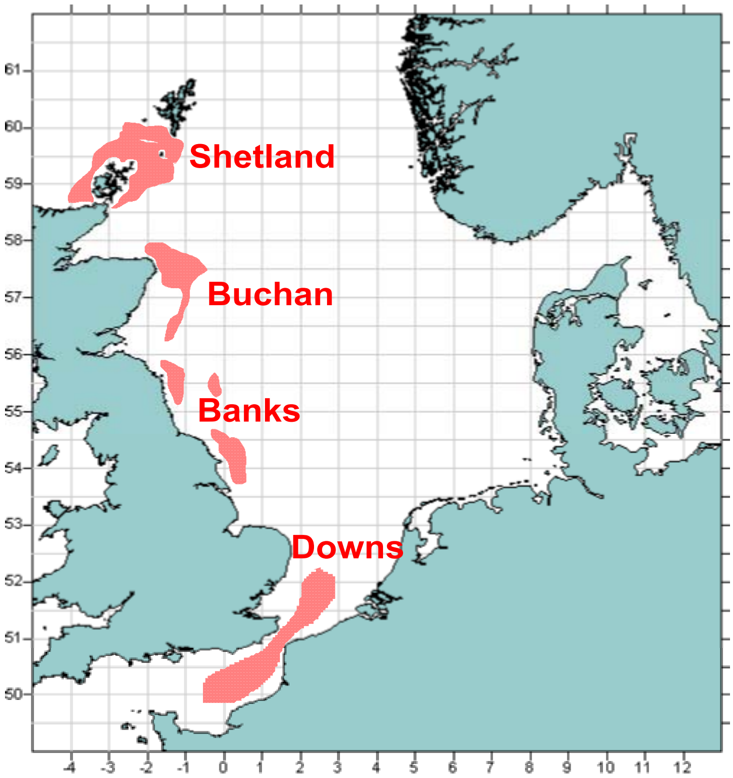


Figure 2.1.2. Herring. Spawning and hatching sites of North Sea herring, based on literature and the International Larval Herring survey (see annexes 1 and 3a).

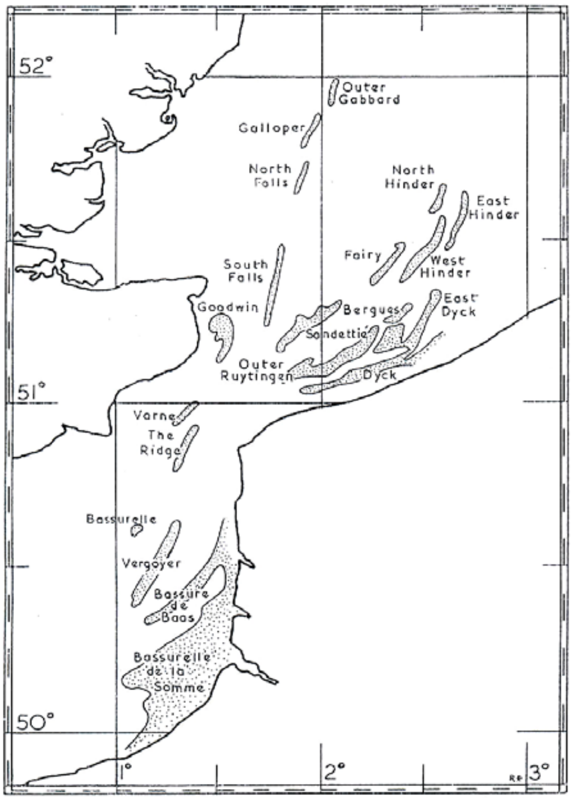


Figure 2.1.3. Herring. Historic spawning beds of herring in the southern North Sea (Downs herring). From Cushing & Burd, 1957.

2.2 Plaice

2.2.1 Spawning

There have been numerous studies of plaice egg distributions since the beginning of the 20th century (Buchanan-Wollaston, 1923; Simpson, 1959; Harding et al., 1978; Harding & Nichols, 1987; Heessen & Rijnsdorp, 1989; Van der Land et al., 1990). These show that plaice eggs are distributed widely throughout the English Channel and the southern and central North Sea (Figure 2.2.1). High egg concentrations have been observed in a number of locations, which presumably mark the centres of spawning activity. The regions of spawning are generally confined within the 50-meter depth contour (Harding et al., 1978). Major spawning centres were found in the eastern English Channel, the Southern Bight, the central North Sea and the German Bight. Other less important local spawning centres were found in the western English Channel and off the UK coast from Flamborough Head northwards to Moray Firth (Houghton & Harding, 1976; Harding & Nichols, 1987). Recent ichthyoplankton surveys also show spawning activity off the coasts of Denmark, an area that had not been surveyed before (Fox et al., 2005). Overall these studies suggest that the position of the spawning areas have changed little over the last century.

Spawning commences in December in the eastern English Channel and is progressively later moving northwards through the North Sea. Peak spawning occurs in mid-January in the Southern Bight, and in February-March in the more northern regions (Simpson, 1959; Cushing, 1969; Bromley, 2000). The increased proportion of younger females in the spawning population, due to increased exploitation rates, may cause a delay and contraction of the spawning season (Rijnsdorp, 1989). However, although the timing and duration of spawning can vary annually by ± 20 days, no clear trend through time was observed (Rijnsdorp & Vethaak 1997; Bromley, 2000).

Although the general pattern of spatial and temporal distribution of plaice spawning appears to change little between years (Cushing, 1990), egg production studies have provided evidence that the relative importance of particular grounds as spawning locations may have changed through time. (Bannister et al., 1974) reported increased spawning activity in the German Bight and central North Sea compared to former years. Furthermore inter-annual fluctuations in total egg production have been observed on a regional (Harding et al., 1978) and North Sea scale (Van der Land et al., 1990). The latter study estimated the total egg production in the Southern Bight in 1987-1989 at 1.8-2.6*1012, which is approximately half of the egg production (5*1012) estimated by Buchanan-Wollaston (1923) for the years 1913-14. These fluctuations presumably reflect variations in spawning stock biomass, however changes in fecundity have also been observed (Horwood et al., 1986; Rijnsdorp, 1991).

2.2.2 Egg and larval development

Several stages and sub-stages can be distinguished in the development of eggs and larvae (Ryland, 1966; Ryland & Nichols, 1975; Russell, 1976). In flatfish larvae, metamorphosis is characterised by very clear morphological transformations (eye migration and a 90° rotation in posture). Early plaice larvae (stage 1-3) have a symmetrical body shape. The typical flatfish shape starts to develop in stage 4a, when 1 eye starts to migrate. The metamorphosis is completed at the end of stage 5, when the eye reaches its final position (stages according to Ryland, 1996). The transition from symmetrical to flatfish shape is associated with the transition from pelagic to demersal life style.

Development rates of plaice eggs and larvae are largely determined by water temperature, with higher temperatures giving shorter stage durations. Published and unpublished data on stage durations in relation to temperature are described in section 4.2.7 and summarised in table 4.2.2.

2.2.3 *Egg and larval transport behaviour*

Plaice eggs are passive and their dispersal is dependent on hydrodynamic forces and the physical properties of the eggs and ambient water (Talbot, 1977; Coombs et al., 1990; Sundby, 1991). Water movements, by which plaice eggs are transported as passive particles, determine the horizontal distribution of plaice eggs. Developing eggs and larvae from the Southern Bight spawning grounds drift on residual currents parallel to the coastline (Talbot, 1977). The vertical distribution of eggs presumably will affect the horizontal distribution through exposure to variations in current speed and direction at different levels in the water column. The vertical distribution is firstly determined by the specific gravity of the eggs, which is slightly positively buoyant. But plankton sampling in the southern North Sea showed eggs at all stages of development to be distributed throughout the water column, despite their positive buoyancy. This implies that tidally and wind induced mixing can strongly affect the vertical distribution of eggs (Coombs et al., 1990). Under calm weather conditions Pommeranz (1973, cited in Coombs et al., 1990) reported plaice egg aggregations towards the surface.

The swimming speeds of plaice at all larval stages do not enable them to resist horizontal displacement by currents. Therefore plaice larvae are often assumed to be passively transported by water movements (Talbot 1977, Van der Veer et al. 1998). However, vertical migration behaviour may affect the results of transport by residual currents and this behaviour has been described in several species of flatfish larvae (Koutsikopoulos et al. 1991, Campos 1996). Plaice larvae move to the seabed during metamorphosis, while they are still offshore outside of the nursery areas (Harding & Talbot 1973). Cushing (1975) suggested that the bottom dwelling larvae are passively transported towards the inshore nursery areas by residual bottom currents. Creutzberg (1978) and Rijnsdorp et al. (1985) reported that the late larval stages of plaice entering the estuarine nurseries of the Dutch coast show vertical migrations synchronised to the tidal cycle, resulting in a net onshore movement (Figure 2.2.2). This selective tidal stream transport has also been reported as mechanism for larval transport in other species and for adult migrations in plaice (Harden Jones et al., 1979; Boehlert & Mundy, 1988; Hill, 1991; Jager, 1999a).

2.2.4 *Nursery areas*

For plaice the nursery grounds are spatially segregated from the feeding and spawning areas of the adults. Juveniles inhabit sandy and muddy habitats in shallow coastal and estuarine waters along all of the coastlines of the English Channel and the southern and central North Sea (Edwards & Steele, 1968; Zijlstra, 1972; Riley et al., 1981; Riley et al., 1986; Van Beek et al., 1989; Rogers et al., 1998). The 0-group mainly occupies the intertidal regions and plaice exhibit a progressive offshore movement with increased fish length (Figure 2.2.3).

The most important nursery areas for North Sea plaice are the German Bight and the Wadden Sea. These nurseries contribute the majority (50-90%) of the recruits to the North Sea plaice stock (Zijlstra, 1972; Van Beek et al., 1989). Growth and survival conditions are favourable in the Wadden Sea, due to large food resources and the relative scarcity of predators. Optimal growth rates and relatively low mortality rates have been observed for 0-group plaice in the Wadden Sea (Zijlstra et al., 1982; Bergman et al., 1988; Van der Veer et al., 1990; Beverton & Iles, 1992; Van der Veer & Witte, 1993). In the last decade, an offshore shift in distribution of juvenile plaice has been observed in the autumn surveys (Grift et al., 2004; Van Keeken et al., 2004). This shift is not caused by declined settlement in shallow areas, but is caused by the fact that juvenile plaice move into deeper water earlier in life, possibly as a result of increased temperatures (Bolle et al., in prep).

2.2.5 *The population dynamics*

The spawning stock biomass (SSB) of North Sea plaice has strongly decreased since the late 1980s to the lowest SSB ever observed in 1995. Since then SSB appears to more or less stable (ICES, 2005). Nevertheless, it is assumed that SBB has not decreased below the level at which recruitment is impaired, i.e. recruitment is not related to SSB (Kraak et al., 2005). In the recent past, relatively strong year classes have been observed 1985, 1996 and 2001 (Figure 2.2.4).

The year-class strength in North Sea plaice appears to be determined during the pelagic egg and larval phase, but the mechanisms involved are unclear (Bannister et al., 1974, Van der Veer, 1986). Cold winters often produce strong year-classes (Bannister et al., 1974; Van der Veer & Witte, 1999; Fox et al., 2000; Dickey-Collas et al., 2003). Low temperatures are associated with low egg mortality rates (Harding et al., 1978; Van der Land et al., 1990). It has been suggested that cold temperatures may reduce egg and larval mortality by influencing predator activity or by synchronisation with the production of food organisms. Water temperature is also a reflection of the general weather system and associated atmospheric circulation patterns. Atmospheric conditions could in turn affect water circulation patterns and thus impact transport success to the inshore nurseries (Van der Veer et al., 1998).

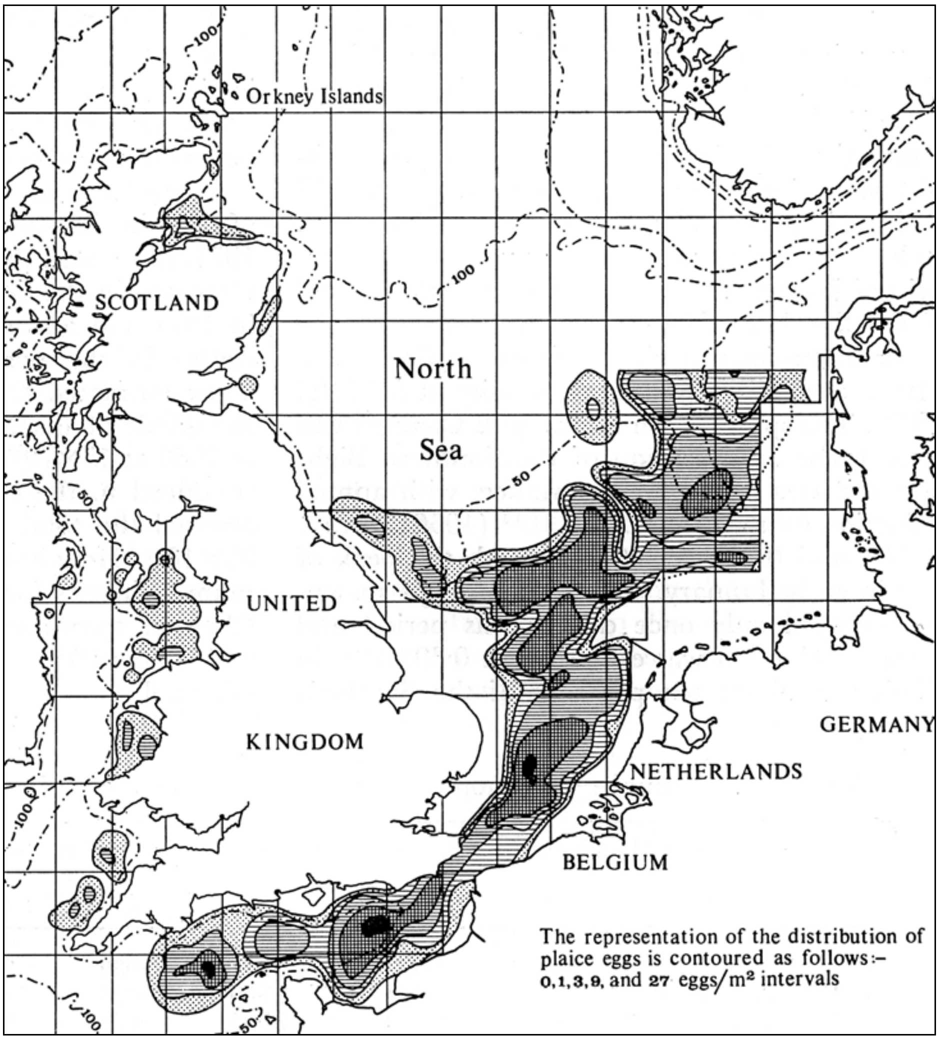


Figure 2.2.1. Plaice. Spawning grounds of plaice as inferred from the distribution of stage 1 eggs (Harding et al., 1978).

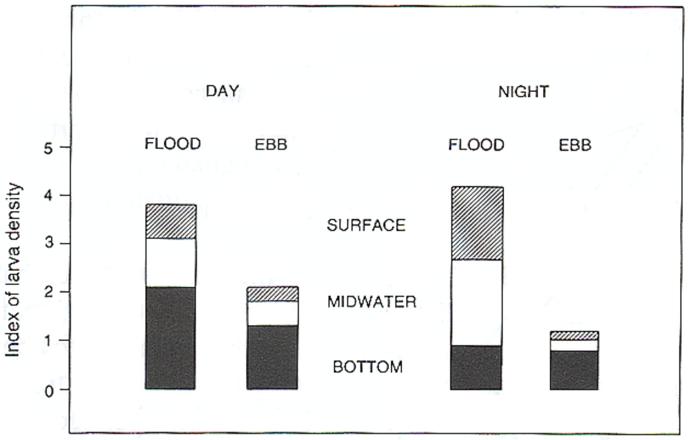


Figure 2.2.2. Plaice. Catches of plaice larvae in the Eastern Scheldt at different levels in the water column, during the day and night, and during flood and ebb tide (Rijnsdorp et al., 1985).

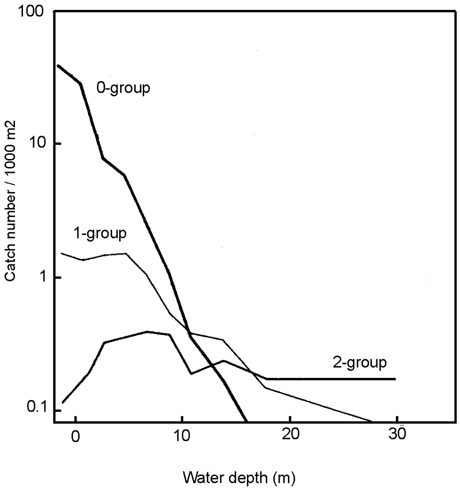


Figure 2.2.3. Plaice. Catch rates (N/1000m^2) of 0-, 1- and 2-group plaice in relation to water depth (modified from Riley, 1981).

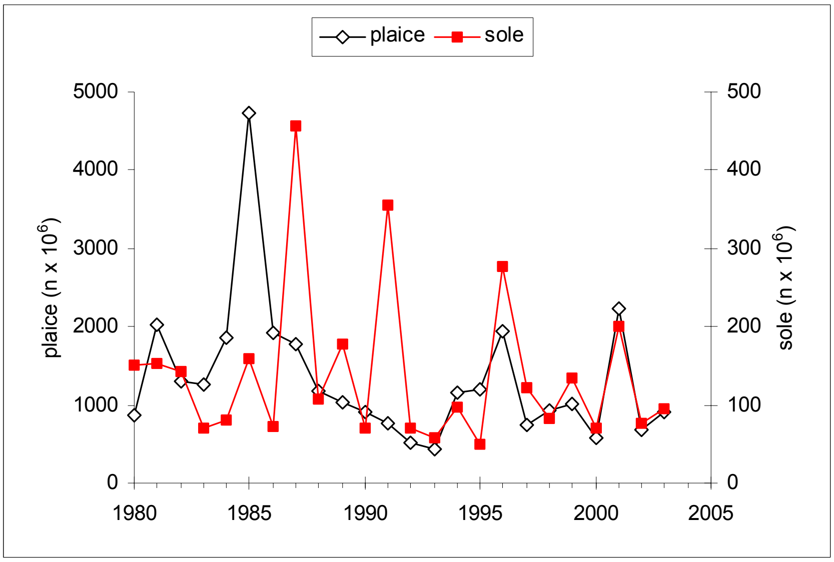


Figure 2.2.4. Plaice and Sole. Year class strength estimated at age 1 (ICES, 2005)

2.3 Sole

2.3.1 Spawning

Spawning activity is observed along the English Channel and southern North Sea coasts up to Flamborough on the UK coast and Esbjerg on the Danish coast (Lee and Ramster, 1981, see Figure 2.3.1). Sole predominantly spawn at a depth of <30 m, and concentrations in spawning activity have been observed off the coasts of Northern France, Belgium and in the German Bight (Van Beek, 1989; Van der Land, 1991; unpublished RIVO data, see Figure 2.3.2). Eastwood et al. (2001) modelled the spawning habitat suitability in the eastern English Channel and concluded that the spatial distribution of sole eggs was determined by depth, temperature, salinity and sediment type.

Spawning starts in the south and progressively shifts to the north (Lee and Ramster, 1981; Rijnsdorp et al., 1992). In 1989, peak spawning in the south-eastern North Sea was observed in April (Van der Land, 1991). However, inter-annual differences in spawning period are observed which appear to be related to temperature. Spawning occurred relatively early in 1988 and 1989 probably due to high temperatures in winter and spring (Van Beek, 1989; Van der Land, 1991; unpublished RIVO data). In the Bay of Biscay seawater temperature does not seem to affect the timing of spawning (Koutsikopoulos and Lacroix, 1992).

2.3.2 Egg and larval development

Usually the same criteria for the staging eggs are used for sole as have been defined for plaice (Ryland & Nichols, 1975). However, sole eggs hatch before reaching stage 5.

Different stage definitions have been used for the staging of sole larvae. Some authors (e.g. Koutsikopoulos et al., 1991) use the definitions by Ryland (1966), whereas others (e.g. Amara et al., 1993; Lagardère et al., 1999; Amara et al., 2000) have adopted the revised stage definitions by Al-Magazachi and Gibson (1984). Both definitions use the same ontogenetic changes for the distinction between stages but the numbering has been shifted in the revision proposed by by Al-Magazachi and Gibson (e.g. initiation of eye migration is called stage 4b instead of stage 4a, metamorphosis is completed in stage 5b instead of stage 5).

Development rates of sole eggs and larvae are related to water temperature, with higher temperatures giving shorter stage durations. Published data on stage durations in relation to temperature are described in section 4.3.5 and summarised in table 4.3.2.

2.3.3 Egg and larval transport behaviour

Larval development and behaviour in sole has been studied extensively under laboratory conditions and in the field, in the Bay of Biscay. In this region sole spawn further offshore than in the North Sea (Koutsikopoulos and Lacroix, 1992), but the mechanisms by which the larvae cross the distance between the spawning grounds and the nurseries areas further inshore are not fully understood. Sole larvae exhibit diurnal vertical migrations, the range of which increases until the beginning of metamorphosis. As no evidence was found for a behavioural selection of onshore currents, diffusion was assumed to play a prominent role in the inshore transfer of the early larval stages (Koutsikopoulos et al., 1991). Laboratory studies suggest that the vertical migration patterns of early larval stages are mainly related to endogenous rhythms and light, whereas behavioural changes occur during metamorphoses related to sensitivity to pressure (differences in water level between high and low tides) and currents. It has been suggested that the pelagic larvae exhibit diurnal vertical migrations, but that recently settled juveniles may develop semi-diurnal vertical migrations resulting in onshore movement (Champalbert & Koustikopoulos, 1995; Macquart-Moulin et al., 1989). It has furthermore been suggested that spring-neap tide periodicity in swimming activity related to feeding behaviour will also contribute to the onshore movement of late larval and early juvenile sole (Lagardère et al., 1999).

Beyst et al. (2002) examined the tidal and diurnal periodicity of macrocrustaceans and demersal fish on an exposed sandy beach off the coast of Belgium. Despite the turbulent conditions of the site, a clear diurnal periodicity was observed for sole, whereas a clear tidal periodicity was observed for plaice.

2.3.4 Nursery areas

The nursery grounds of plaice and sole show considerable overlap. Both species inhabit shallow coastal and estuarine waters along North Sea and English Channel coasts, and both species prefer sandy or muddy sediments and avoid hard substrata. Differences are observed in the depth distribution; 0-group plaice mainly occupy the intertidal regions, whereas the highest density of 0-group sole is observed in the sublitoral (Zijlstra, 1972; Riley, 1986). Furthermore the regional distribution differs between these 2 species, the Wadden Sea is of far less importance for sole than for plaice, whereas the nursery areas along the Belgian and southern Dutch coasts are relatively more important for sole than for plaice (Van Beek et al., 1989).

2.3.5 The population dynamics

The spawning stock biomass (SSB) of North Sea sole decreased in the early 1990s to the lowest SSB ever observed in 1998. Since then SSB appears to have slightly increased (ICES, 2005). In the recent past, relatively strong year classes have been observed 1987, 1991, 1996 and 2001 (Figure 2.2.4).

The factors causing recruitment variability in sole have received little attention compared to plaice. Recruitment variability and the factors causing this variability appear to differ between adjacent populations. Winter temperatures may be a variability-generating factor in the North Sea but this does not seem to be the case for the Irish Sea. The year-class strength in North Sea sole appears to be determined before the end of the first year of life, but cold winters may affect the relative year-class strength at older ages (Rijnsdorp et al., 1992).

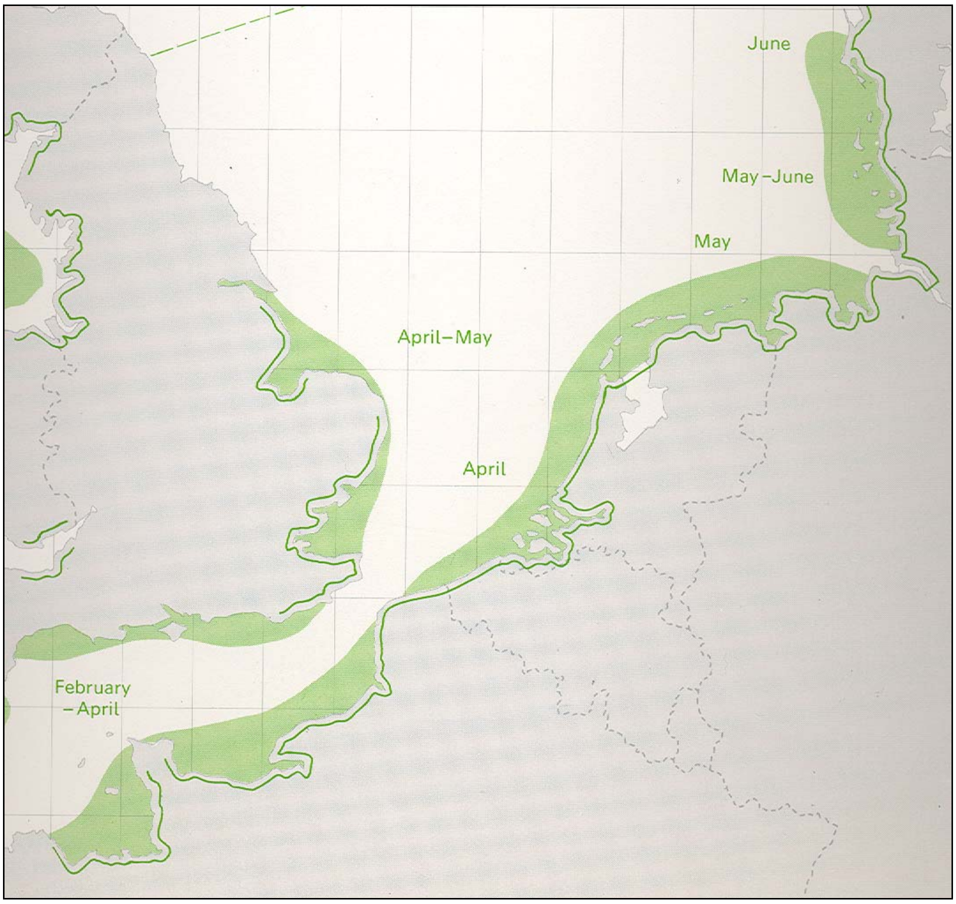


Figure 2.3.1. Sole. Spawning grounds of sole according to Lee and Ramster (1981)

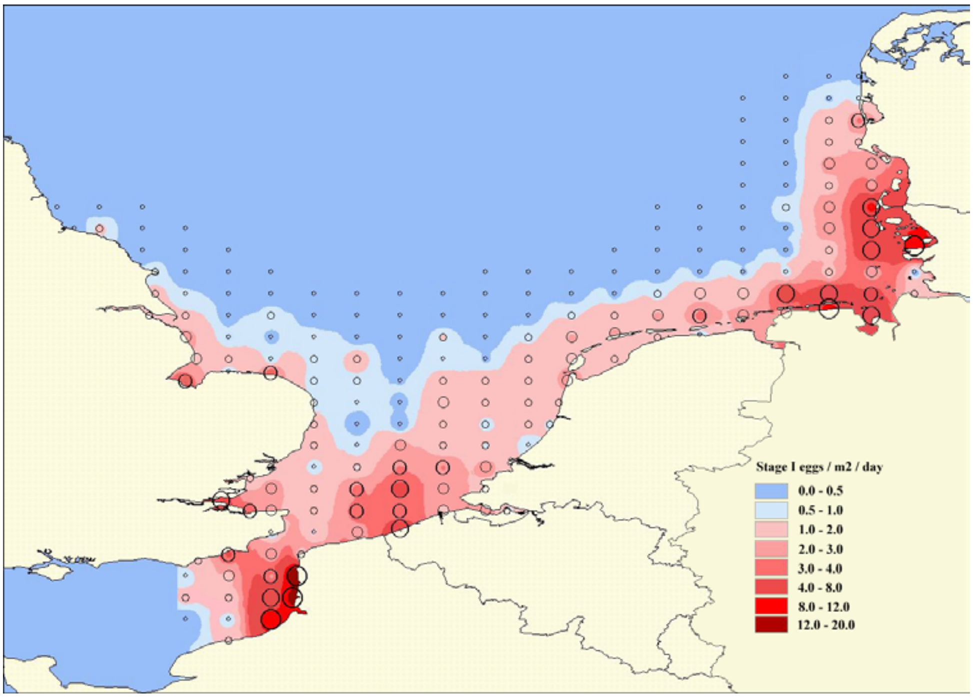


Figure 2.3.2. Sole. Spawning grounds of sole as inferred from the distribution of stage 1 eggs (unpublished RIVO data).

3 Model design

In the present study, a model has been developed in which concentrations of fish eggs and -larvae with certain characteristics (buoyancy, behaviour) are transported by hydrodynamic flows. In the model set-up, the output from the hydrodynamic modelling is used as input for the biological modelling. This chapter provides a description of the design and set-up of the hydrodynamic (section 3.1) as well as the biological model (section 3.2).

3.1 Hydrodynamic model

3.1.1 Advection-diffusion model

The hydrodynamic modelling for the present project was carried out using Delft3D-FLOW. Delft3D-FLOW is the hydrodynamics module of the WL I Delft Hydraulics modelling suite, Delft3D. The Delft3D modelling environment is a modular system that simulates both 2D (in either the horizontal or the vertical plane) and 3D hydrodynamics, waves, water quality, ecology, transport of suspended matter and bottom morphology. The simulations of hydrodynamic flows in the present study were done with the Delft3D-FLOW module, with built-in transport solver, which can smoothly communicate with the other modules. Delft3D-FLOW solves the unsteady shallow-water equations in two or three dimensions. The large number of processes included in this module means that Delft3D-FLOW can be applied to a wide range of river, estuarine, coastal and marine situations. The flow equations are solved on a staggered, curvilinear finite-difference grid. This makes it possible to align the grids with curving boundaries and channels and to concentrate the resolution in areas of interest, while maintaining an accuracy and computational speed comparable to using rectangular grids. For the vertical dimension, two options are available: sigma coordinates or fixed layers. Hydrodynamic transport is computed using detailed bathymetry and open boundary forcing based on tidal constituents, with variable wind forcing (Section 3.1.3) and variable river discharges (Section 3.1.4).

3.1.2 Model grid resolution

Two grid lay-outs covering the southern North Sea (including the Wadden Sea) were used in this study: a moderately fine grid (ZUNOGROF) and a domain decomposition model grid (ZUNO-DD) with a much higher grid resolution in areas of particular interest (Maasvlakte 2 area, Dutch coastal zone and Wadden Sea).

ZUNOGROF

The ZUNOGROF grid (Figure 3.1.1), which consists of 8710 computational elements, was developed in an earlier study of the effects of the proposed reclamation of an airport island (“Flyland” project). This model grid was considered suitable for the study of the baseline situation of fish larval transport and sensitivity analyses of various parameter settings of the model. A more detailed description of the ZUNOGROF model (including its calibration and validation) is beyond the scope of the present report, but can be found in Roelvink et al. (2001). Specific parameters of this model, as applied in the present study, are summarized in Table 3.1.1. The run time of the hydrodynamic model for a year long simulation on a 3.2 GHz Intel processor required approximately 15 hours. This relatively short run time made ZUNOGROF particularly suitable to perform a series of year-runs (simulating a total of 9 different years) that differ in their forcing of wind, air pressure and river discharges.

ZUNO-DD

The ZUNO-DD grid (Figure 3.1.2), which consists of 76340 computational elements, was newly developed for the Maasvlakte 2 project to study the effects of Maasvlakte extension variants in a sufficiently detailed way. By applying a domain decomposition approach (local grid refinement) it was possible to apply a much higher grid resolution in areas of particular interest, such as the region around the proposed Maasvlakte 2 reclamation site, the Dutch coastal zone and the Wadden Sea. In this way, the overall model grid consisted of 5 different subdomains, each with a different grid resolution. A more detailed description of the ZUNO-DD model (including its parameter settings, calibration and validation) is beyond the scope of the present report, but can be found in De Goede and Van Maren (2005a). The run time of the hydrodynamic model for a year long simulation on the fastest available calculation computer cluster (HYDRAX) required approximately 16 days.

Water layers

For the vertical dimension, the water column was subdivided into 10 layers, using a sigma-coordinated approach to ensure sufficient vertical resolution in the near-coastal zone (Stelling & Van Kester, 1994). From top to bottom, these layers respectively represent 4.0%, 5.9%, 8.7%, 12.7%, 18.7%, 18.7%, 12.7%, 8.7%, 5.9% and 4.0% of the water depth. This vertical resolution was identical in ZUNOGROF and ZUNO-DD.

Aggregation

The original output from the hydrodynamic modelling (10-layered coupled communication files, generated every hour in ZUNOGROF and every half hour in ZUNO-DD) was used as input for the modelling of the transport of herring larvae. For the modelling of the transport of flatfish larvae (plaice and sole), these hydrodynamic communication files were vertically aggregated to 2-layers (representing the lower 4% and upper 96% of the water depth). Horizontal aggregation of the grid resolution was not applied in any of the model runs.

3.1.3 Hydrodynamic forcing

Windforcing

The hydrodynamic model was forced with spatially and temporally varying meteorological data. With the exception of 1988/89, for which data were derived from an earlier NOMADS project (NOMADS2, 2001), all these data were obtained from the Royal Dutch Meteorological Service (KNMI) and are the output from the so-called HIRLAM numerical meteorological model. The HIRLAM data are comprised of two horizontal wind velocity components (at 10 m above mean sealevel) and air pressure, archived every 6 hours. All data ordered for the purpose of this project (i.e. from the years 1996, 1997, 1998, 1999, 2000, 2001, 2002 and 2003) were enclosed between 14° west and 15° east & 46° and 65° north (ensuring complete coverage of the ZUNOGROF and ZUNO-DD grids). The orientation and projection of the HIRLAM data were adjusted so as to obtain the same orientation and projection as the ZUNOGROF/-DD grids. Missing values (few, mainly in 1997) were interpolated linearly in time between the previous and next available data fields. The meteo data were interpolated bilinearly in space from the meteo grid and linearly in time within Delft3D-flow to obtain the same timestep and grid resolution as the hydrodynamic model. HIRLAM data quality was checked against measured hourly wind data as available on the website http://www.knmi.nl/samenw/hydra/index.html for the locations of the stations Vlissingen, Hoek van Holland, IJmuiden and Den Hoorn (Terschelling). Modelled (HIRLAM) and measured wind data showed very good agreement.

River Dischages

Eighteen discharge points are defined in the model (see Figure 3.1.1). Each of the discharge point is associated with a river that discharges freshwater into the open sea. For 7 of these points, i.e. the Westerschelde, Oosterschelde, Haringvliet, Nieuwe Waterweg, IJmuiden, Den

Oever and Kornwerderzand, time-varying discharges have been applied, using discharge rates for every 10-minutes (Haringvliet, Nieuwe Waterweg) or daily averages (other points) downloaded from the Waterbase web-site of the Dutch Ministry of Transport (http://www.waterbase.nl/). For the remaining 11 discharge points a constant discharge rate is prescribed, based on long-term averages for these river discharges (see Table 3.1.2). For all discharges, the temperature and the salinity concentration are assumed to be constant, respectively 10 °C and 0 ppt.

The ZUNO-DD model has a different approach towards the modelling of the Haringvliet and Nieuwe Waterweg discharge. The reason is that the future scenarios need an outflow here as well as a inflow due to the changes management of the Haringvliet sluices. For the these scenarios time dependent discharges with a frequency of ten minutes are derives from SOBEK model calculations (see De Goede & Van Maren (2005a) for details).

3.1.4 Calibration and validation hydrodynamics

Calibration of the ZUNOGROF and ZUNO-DD model was carried out for the 1988/89 year-run, with a focus on reproduction of the tidal water levels (southern North Sea, Dutch coast, Wadden Sea, flows through Wadden Sea tidal inlets). Calibration was done by making adjustments to certain model parameters (boundary conditions, bathymetry and bottom roughness) to find an optimal similarity between model predictions of water levels and observed tidal amplitudes, phases and other specific tidal constituents. These calibrations resulted in a good model performance for 1988/89. Accuracy of computed hydrodynamics was validated by verification for currents and salinity patterns. This validation revealed reasonable (residual flows) to good agreement between modelled and measured hydrodynamic parameters. A detailed description of the calibration of the ZUNOGROF model can be found in Roelvink et al. (2001). A detailed description of the calibration and validation of the ZUNO-DD model can be found in De Goede and Van Maren (2005a).

For the purpose of modelling the year-to-year variability in transport of fish larvae, several "year"-runs (i.e. from 1 Dec. – 1 July) of hydrodynamics were conducted using ZUNOGROF. Using actual river discharges, meteorological data (HIRLAM) and open boundary forcing based on tidal constituents, hydrodynamic flows were modelled for the following 9 periods:

- 1 December 1988 – 1 July 1989
- 1 December 1995 – 1 July 1996
- 1 December 1996 – 1 July 1997
- 1 December 1997 – 1 July 1998
- 1 December 1998 – 1 July 1999
- 1 December 1999 – 1 July 2000
- 1 December 2000 – 1 July 2001
- 1 December 2001 – 1 July 2002
- 1 December 2002 – 1 July 2003

These were the only years with meteorological data readily available at the start of the project.

Validation of these runs was done by comparison of model predictions of salinity (contours and time series) with field measurements available for monitoring stations at Noordwijk (at 4, 10, 20 and 30 km from the coast) and Terschelling-4. Two examples of such comparisons are presented in Figure 3.1.3. Overall, these comparisons showed reasonably good agreement between modelled and measured salinities, but there is a tendency of too low computed salinities near the Dutch Coast. Residual (net) flows through Dover Strait calculated from the 9 year-runs ranged from 50,000 to 170,000 m^3s^{-1} (see Table 3.1.3) which is in line with data from literature (Prandle et al., 1996). Residual (net) flows through the Marsdiep predicted by these 9 year-runs ranged from -1360 to -3260 m^3s^{-1}, which compares well with a net flow of -2500 m^3s^{-1} computed by Ridderinkhof (2001) on the basis of a three-year measurement campaign.

The overall results of the validation indicate that both the spatial and temporal variability of salinity in surface waters show a reasonable to good agreement between the modelled predictions and actual field measurements from monitoring campaigns. Similarly, the net (residual) flows through Dover Straits and Marsdiep computed by the model is in reasonable agreement with values reported in literature. In conclusion, the validation process demonstrated that the 9 years of ZUNOGROF model runs yield acceptable and reliable results on hydrodynamic flows which can be used to study the year-to-year variability in the transport of fish larvae in the study area.

3.1.5 Comparison ZUNOGROF and ZUNO-DD

Whereas the ZUNOGROF model has been used in the various sensitivity analyses and assessment of baseline and year-to-year variability, the actual impact assessment of the proposed Maasvlakte 2 reclamation on transport of fish larvae was done using the ZUNO-DD model (in line with the other components – sediment transport, nutrients and primary production - of the overall impact assessment). To enable the use of results of the assessment of year-to-year variability and other sensitivity analyses of the fish larval transport model (conducted using ZUNOGROF) in the interpretation of the results obtained for the impact assessment study (using ZUNO-DD), hydrodynamic flows for 1988/89 from both the ZUNOGROF and the ZUNO-DD model were compared. Water levels, current velocities and mean transport time between Calais, Hoek van Holland and Den Helder are very comparable between the two models. Net flows through Dover Strait vary from 120,000 m^3s^{-1} in ZUNOGROF to 90,000 m^3s^{-1} in ZUNO-DD, while net flows through Marsdiep range from -1360 m^3s^{-1} (ZUNOGROF) to -310 m^3s^{-1} (ZUNO-DD). Model predictions of salinity (contours and time series) also showed reasonably good agreement between ZUNOGROF and ZUNO-DD for monitoring stations at Noordwijk (at 4, 10, 20 and 30 km from the coast) and Terschelling-4. Examples of such comparisons are presented in Figure 3.1.4 (contours) and Figure 3.1.5 (time series). For further details see De Goede and Van Maren (2005a).

The overall results of the comparison of the hydrodynamic flows for 1988/89 between ZUNOGROF and ZUNO-DD indicate that both the spatial and temporal variability of salinity in surface waters and the net (residual) flow through Dover Straits show a reasonable to good match between the two models and that both are in adequate agreement with field measurements and literature. The too low salinities near the Dutch Coast are present in both models and are not understood yet so they add to the overall uncertainty of the larvae model. The mismatch in salinity could influence the transport of larvae in two ways. Indirectly as an indication that the transport of water is not accurate, it is believed that this inaccuracy is independent of the introduction of the proposed Maasvlakte 2 reclamation in the model. Directly because the direction of the salinity gradient influences the selective tidal stream transport behaviour (see section 3.2.3), the direction of the salinity gradients are however well represented by the model and the absolute value of the gradient is not of importance. The net (residual) flow through Marsdiep is much lower in ZUNO-DD than in ZUNOGROF, it can however be substantiated that the transport of larvae towards the Wadden Sea is more dependent on the gross transport of water into the Wadden Sea than on the net transport. Once the larvae are within the Wadden Sea they will be dispersed and retained within the Wadden Sea, especially if selective tidal stream transport behaviour is assumed. On the basis of these results it is concluded therefore that the hydrodynamic flow results from the baseline study (obtained using ZUNOGROF) can be used in the interpretation of the results obtained using ZUNO-DD in the impact assessment.

Table 3.1.1. Summary of important model parameters (ZUNOGROF).

Parameters	***Values***
Number of points (M,N,K)	64, 134, 10
Layer distribution (% of the depth)	4.0, 5.9, 8.7, 12.7, 18.7, 18.7, 12.7, 8.7, 5.9, 4.0
Integration time step	5.0 minutes
Resolution along the Dutch coast	Approximately 2.5 km perpendicular to the coast and 5.5 km along the coast
Hydrodynamic boundary condition	Astronomical Tide (49 tidal components)
Heat exchange with atmosphere	Ocean Model as described by Gill (1982) & Lane (1989)
Turbulence model	K-epsilon model
Bed-stress coefficient	0.026 (Manning)
Horizontal eddy viscosity and diffusion coefficients	10.0 m^2/s and 10.0 m^2/s
Background vertical eddy viscosity and diffusion coefficients	$1 * 10^{-6}$ m^2/s and $1 * 10^{-6}$ m^2/s
Wind	see detailed description further in this report
River discharges	see detailed description further in this report
Sigma-correction	No

Table 3.1.2. Constant river discharges (m^3/s).

Location	**Discharge (m^3/s)**
Thames	82
Solent	15
Seine	461
Humber	246
Tyne	41
Tees	21
Firth of Forth	63
Wash	48
Ems	125
Weser	326
Elbe	726

Table 3.1.3. Average computed discharge trough Marsdiep and Dover Strait (m^3/s).

Year	**Marsdiep**		**Dover Strait**	
	ZUNOGROF	ZUNO-DD	ZUNOGROF	ZUNO-DD
1988/1989	-1361	-306	122314	90468
1995/1996	-3260		49178	
1997/1998	-2144		145881	
1998/1999	-1831		177173	
1999/2000	-2103		135378	
2000/2001	-1938		144458	
2001/2002	-1843		154525	
2002/2003	-2221		119441	

Figure 3.1.1. Overview of the ZUNOGROF model grid

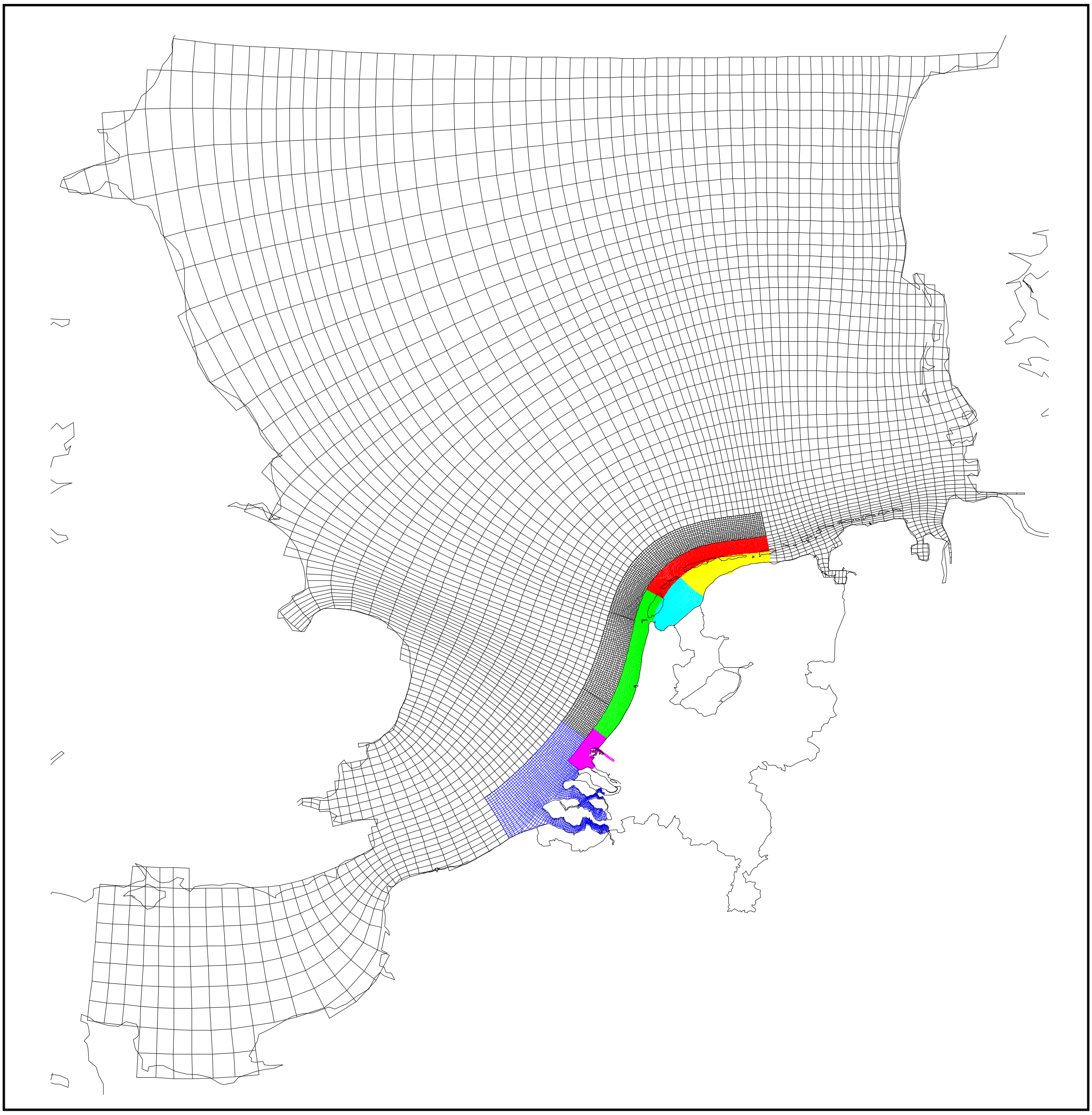


Figure 3.1.2. Overview of the ZUNO-DD model grid (very high grid resolution in the coloured

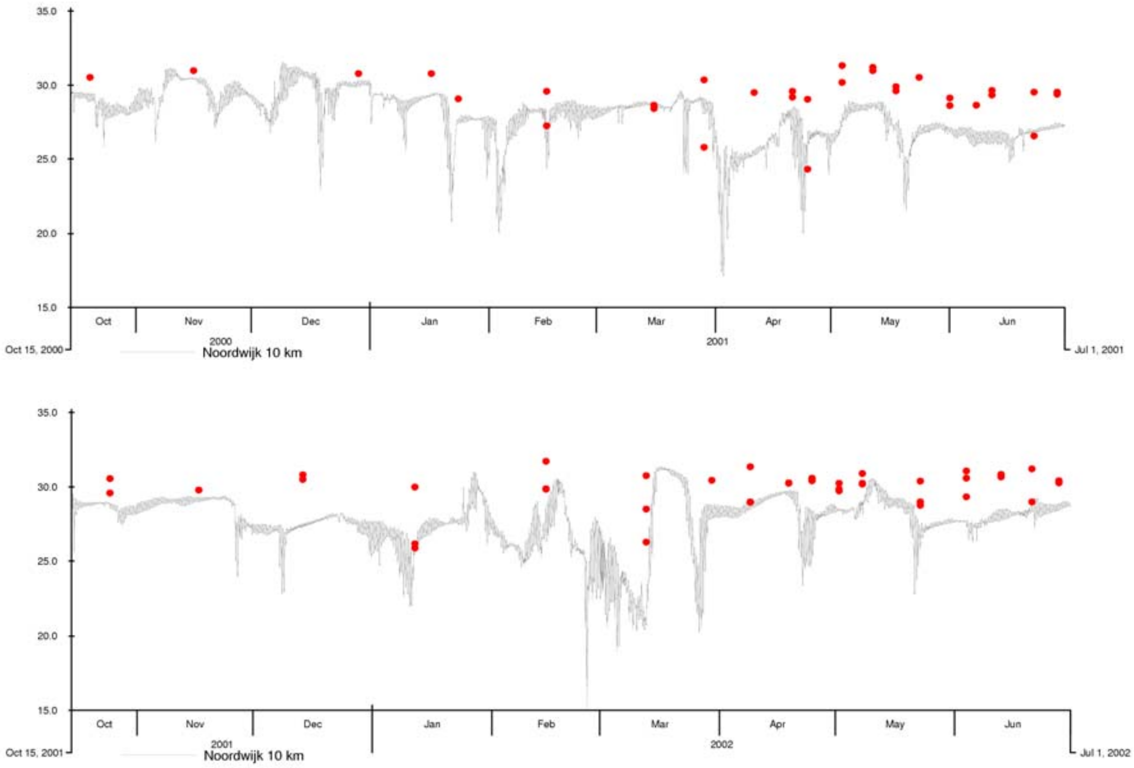


Figure 3.1.3. Validation of the ZUNOGROF hydrodynamic modelling results, showing time series of modelled (in grey) and measured (in red) surface salinity at Noordwijk-10 during 2000-01 (upper) and 2001-02 (lower).

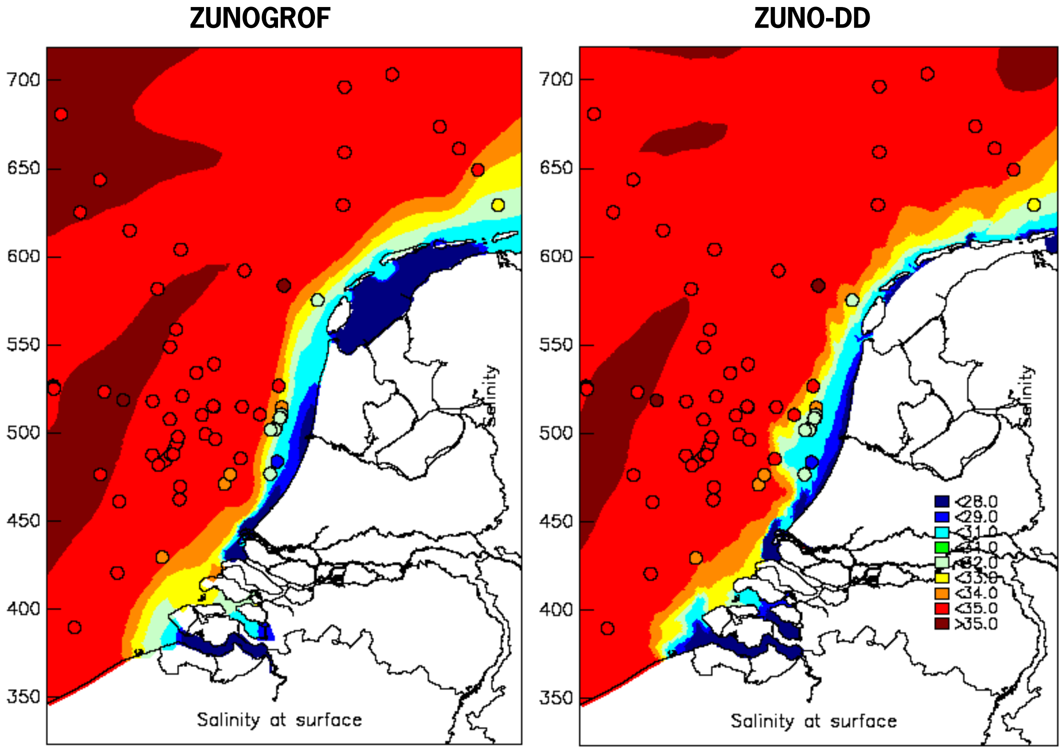


Figure 3.1.4. Mean salinity distribution (surface water) along the Dutch coast in March 1989, as computed with ZUNOGROF (left) and ZUNO-DD (right) in comparison with measured salinities (small circles).

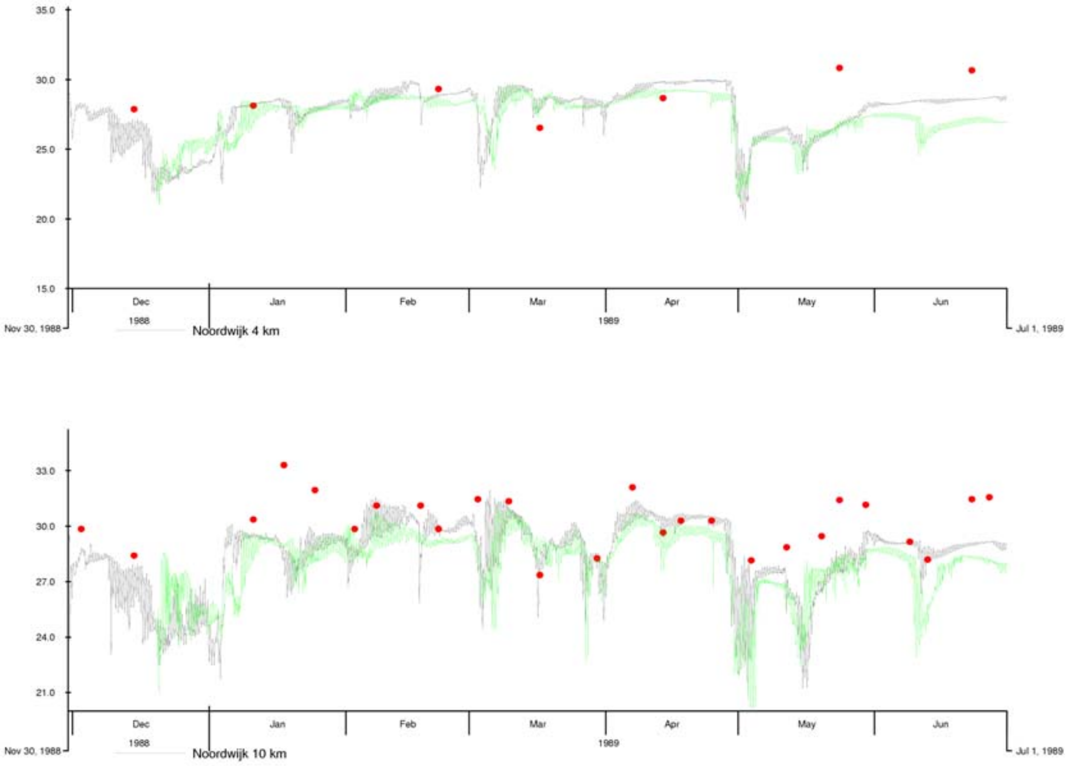


Figure 3.1.5. Time series of modelled surface salinity (ZUNOGROF in grey; ZUNO-DD in green) and measured surface salinity (in red) at Noordwijk-10 during Dec.1988 – June 1989.

3.2 Modelling fish eggs and larvae

The transport of concentrations eggs and larvae were modelled from specific release points. No attention was given to the quantity released as this study was relative in nature, i.e. it only considered the relative change caused by behaviour, inter-annual variability or coastal developments.

3.2.1 Finite-volume method versus particle-tracking

The transport of fish eggs and larvae was modelled using Delft3D-WAQ. Delft3D-WAQ is the water quality module of the Delft3D modelling suite (Postma, 1988). This module contains the physical schematization, calculates transport of substances as a function of the advective and dispersive transport, processes and loads, accumulates fluxes and computes resulting concentrations for each time-step, includes a large selection of numerical solution schemes, and produces outputs in a standardized way which can easily be processed further, creating graphs and statistics. The actual water system is represented within Delft3D-WAQ by means of computational elements (segments). Transport between segments are derived from dedicated models (e.g. simulated in Delft3D-FLOW). Internally, Delft3D-WAQ multiplies fluxes with concentrations to obtain masses across internal and external boundaries. Delft3D-WAQ has been used successfully in the simulation of dredging plumes, thermal discharges and various water pollution studies (Van Gils et al., 1993; Van der Molen et al., 1994; Ouboter et al., 1998). Delft3D-WAQ was also used within a preliminary modelling study on the impact of a proposed airport island (“Flyland” project) to simulate the transport of fish larvae in the North Sea.

For the present study, we developed a generic model, which - by choosing different parameter settings - can be applied to simulate transport of fish eggs and larvae of different fish species. We have chosen for the finite-volume method offered by Delft3D-WAQ (applying a scheme that was explicit in time and with a central discretisation in space) rather than a particle tracking model approach. When properly used, both finite-volume methods and particle tracking model approaches can (in principle) provide the same type of results. We opted for the finite-volume model approach for the following practical reasons:

- Particle tracking models are generally used (primarily) for the study of near-field (or mid-field) effects, where the main focus of interest is at the level of sub-grid resolution. The transport of fish larvae takes place over large distances (far-field). For this reason, results that can be obtained with Deft3D-WAQ are more than sufficiently detailed at the scale of interest. Besides, the run-time of both models is roughly the same (because it depends on the transport rates). Provided that the cells of the model grid are small enough in size, the relative differences within a grid cell are negligible;

- Particle tracking models (such as Delft3D-PART) generally cannot operate with domain decomposition model grids (such as ZUNO-DD) as their hydrodynamic calculations demand the full matrix. Delft3D-WAQ, on the other hand, is fully capable of working with domain decomposition grids;

- Delft3D-WAQ offers greater flexibility for building in all types of processes in relation to other parameters, such as temperature- or salinity-dependent changes in the behaviour of fish larvae (this is very complicated in Delft3D-PART);

- In the Baseline project (MEP-MV2), we had to fulfill the contractual agreement to carry simulations of transport of fish larvae using the “Flyland-model” (in Delft3D-WAQ) already available from an earlier study. By the time the impact study (“Passende Beoordeling”) was commissioned, the baseline study was already well underway making it more than logical to use and improve this existing model for the impact study (incl. scenarios) rather than setting up an entirely new (particle tracking) model;

- Particle tracking models have the advantage that they allow tracking of the history of individual particles (both in time and space), which – in principle – is not possible in Delft3D-WAQ. However, by introducing different cohorts in Delft3D-WAQ as different 'substances' (e.g. from different spawning grounds or at different times) and by subsequently monitoring these seperately from each other, a sensitivity analysis of such matters can be made feasible even within Delft3D-WAQ.

3.2.2 *Herring*

As herring lay benthic eggs, no modelling of the egg stage was carried out. The growth parameters used were parameterised using the energetic model of Fiksen & Folkvord (1999), and assuming full feeding throughout the larval phase. The values from the Fiksen and Folvord model were estimated and refitted to this current model. The Fiksen and Folkvord model works in weight so the hatched larvae (at 9mm length) were converted to dry weight using the relationship

$$W = 6.1807 \bullet e^{(0.263\ L)}$$

W is weight in µg and L is length in mm. This comes from unpublished data on the dry weight to length relationship of Downs herring larvae (Clemmensen, University of Kiel, unpublished data).

Hatching sites are described in section 4 based on empirical studies (section 2.1).

In the model, the yolk-sac larvae developed and respired dependent on the temperature, until they reached 80% of their initial hatch weight (weight reduced due to respiration of the yolk, see Fiksen & Folkvord, 1999). Then they began to feed. This change from yolk sac to feeding occurred as a switch and denotes the difference between herring behaviour stage 1 and herring behaviour stage 2. The larvae continued to develop (assuming full feeding thus only dependent on temperature) until they reached the weight associated with 30mm (16.5mg). This represents the beginning of metamorphosis, which can last until 50-55mm in length Gallego & Heath, 1994). Once greater than 30mm in length the larvae switched to behaviour stage 3.

The behaviour rules were:

Stage 1 - yolk sac. Larvae hatched and then slowly increased buoyancy, so that at the end of stage 1 they were in the upper 10m of the water column. This was based on the work of Blaxter & Ehrlich (1974) and Ying & Craik (1993) but re-parameterised to fit this model.

Stage 2. The behaviour of larvae would be influenced by the hydrography and feeding. The impact of zooplankton on the feeding behaviour could not be modelled in this model construction, so the larvae were made to aggregate nearer to the surface during the day and allowed to be influenced by dispersion due to turbulence alone during the night (Heath et al., 1988; 1991; Munk et al., 1989). This enforced behaviour would act as a proxy for the vertical movement of the larvae caused by feeding. Stage 2 allowed the larvae to begin with small vertical movements directly after the yolk sac phase but as the stage progressed the amplitude of the aggregations would increase.

Stage 3 had these amplitudes of aggregation fixed, i.e. the development of this proxy for feeding behaviour was thought to be complete.

Initial runs of the model suggested that the larvae never reached full metamorphosis during the simulated time period. Hence the aggregation behaviour was not modelled or investigated in this study. Salinity effects which have been mentioned by one author were also not modelled in this study as the evidence is weak and parameterisation difficult.

3.2.3 *Flatfish*

The larval transport module for plaice and sole has been designed in a generic way; different flatfish species can be modelled by changing the parameter settings or the input. Inputs to the model are the species-specific spawning grounds and spawning periods. The spatial distribution can be modelled either as an initial condition (spawning area) or as one or more discharges (by grid cell). A temporal distribution in spawning can be simulated by a time series (in the case of discharges) or by including several substances in the model (in the case of initial conditions). The growth parameters determine the stage durations and different behaviour and physical traits can be associated with different stages. At present the flatfish module includes 5 stages they have been defined as follows:

Stage 0 – no transport

This is not a real behavioural stage and in principle the duration is set to an infinitely small number. This stage is included in the model to be able to differ the spawning date of different spawning groups (modelled as different substances).

Stage 1 – passive pelagic transport (eggs)

The eggs are transported passively in the top water layer, which in the case of the flatfish module is an aggregation of the top 9 water layers of the hydrodynamic model.

Stage 2 – passive pelagic transport (larvae)

At present the behaviour in stage 2 is the same as in stage 1. The distinction between eggs and pelagic larvae has been built in to facilitate parameter settings and testing, and to be able to differentiate between eggs and larvae in the future (e.g. diel vertical migration patterns in larvae, egg/larval specific buoyancies) .

Stage 3 – passive demersal transport (larvae)

In stage 3 the larvae move from the top water layer to the bottom water layer and are transported passively. Strictly speaking the term demersal is correct, but for flatfish it may cause confusion as demersal often used to refer to the period after settlement. Within this study demersal is defined as near the seabed (bottom water layer), but not on the seabed (which would result in no transport).

Stage 4 – selective tidal stream transport (larvae)

In stage 4 the larvae exhibit selective tidal stream transport, i.e. the stay on the seabed with ebb and move into the water column (bottom water layer) with flood. In the present study this behaviour has been related to salinity differences, but it can also be related to the direction of the currents. Furthermore thresholds can be used to limit the area in which selective tidal stream transport occurs (see sections 3.2.4 and 4.2.4). In the present study stage 3 and 4 are presumed to be alternatives for the behaviour of larvae after the onset of metamorphosis. The stages can also be used consecutively.

Stage 5 – juveniles

This stage reflects the period after metamorphosis is completed. The juveniles either continue to exhibit the behaviour of the previous stage, or stay on the seabed at the location they have reached (thus simulating settlement). In the present study this stage has been used to end the transport after the temperature dependent egg and larval phases and an assumed period of additional transport in the juvenile phase (as an alternative to cutting of the simulation on a specific date). This stage can also be used to define the nursery areas, i.e. no further transport if a certain area is reached.

The transition from one stage to the next is determined by temperature. The relation between temperature and stage duration has been defined as: $\ln(D) = \alpha + \beta T$, in which D= stage duration, T=temperature, and α and β are species and stage dependent growth parameters. The choice of the parameter settings is discussed in section 4.2.7 and 4.3.5.

3.2.4 Technical description of processes and parameters

In the computer model developed for this study, fish eggs and -larvae with certain characteristics (buoyancy, behaviour) are being transported by hydrodynamic flows. Information on the temporal and spatial distribution of egg production and descriptions of the characteristics of eggs and larvae are used in the biological modelling to simulate larval transport. These characteristics change during larval growth and development and are described in terms of specific weight (buoyancy) and behaviour (passive phases vs. active migration phases). The larval growth and development - and thus the duration of the various phases - is related to temperature (which is being calculated continuously during the hydrodynamic modelling).

Depending on their stage of growth and development, fish larvae can display different types of behaviour which influences their transport. These behavioural types (different between species) may include: pre-hatching with total mass on bottom (no transport); passive pelagic (all in water column); vertical migrations (spread out during night-time, concentrated during daytime); passive demersal (all in bottom layer of water column); active 'STST' (Selective Tidal Stream Transport) with larvae in water column during rising tide and on seafloor during falling tide; inactive upon arrival in nursery ground (otherwise STST). In order to implement these different types of behaviour in Delft3D-WAQ, a number of model routines have been developed:

'LARVEN(i)' Vertical migration of flatfish larvae

This model routine determines for flatfish in which layer the fish larvae are situated. The flatfish model has two water layers, the top layer consists of 96% of the water column, and a lower water layer which consists of 4% of the water column, and a bottom layer. The top water layer is the result of the aggregation of the top nine hydrodynamic layers and will give the average flow of these layers. The lower water layer is equal to the remaining one hydrodynamic layer. If the larvae are within the water column they will be transported with the current. If the larvae are located on the seabed (the bottom layer) than the larvae are not transported. The vertical distribution depends on the development stage of the larvae and can be dependent on the tidal phase during the STST stage. There is no vertical dispersion or settling/buoyancy acting on the flatfish larvae. The process is implemented for all the larvae populations (i)

```
if stage = 0 (pre-spawning stage)
        $F_t = 0.0$
        $F_l = 0.0$
        $F_b = 1.0$
if stage = 1 (egg stage passive pelagic)
        $F_t = 0.96$
        $F_l = 0.04$
        $F_b = 0.0$
if stage = 2 (larvae stage passive pelagic)
        $F_t = 0.96$
        $F_l = 0.04$
        $F_b = 0.0$
if stage = 3 (larvae stage passive demersal)
        $F_t = 0.0$
        $F_l = 1.0$
        $F_b = 0.0$
if stage = 4 (Selective Tidal Stream Transport)
        if trigger = 1 or totaldepth > threshold
                $F_t = 0.0$
                $F_l = 1.0$
                $F_b = 0.0$
        else
                $F_t = 0.0$
                $F_l = 1.0-efficiency$
                $F_b = efficiency$
if stage = 5 (Arrival in nursery ground)
        if nursery = 1
                $F_t = 0.0$
                $F_l = 0.0$
                $F_b = 1.0$
        else
                (The same behaviour as stage 4 STST)
```

with:
F_t = Fraction larvae in top water layer (-)
F_l = Fraction larvae in lower water layer (-)
F_b = Fraction larvae on bottom (-)
stage = indication of the stage (0,1,2,3,4 or 5)
trigger = trigger for STST behaviour (-)
totaldepth = total depth of the water column (m)
threshold = depth threshold for STST behaviour (m)
efficiency = efficiency of the STST behaviour (-)
nursery = indication of nursery ground (-)

The *stage* is set by the routine L(i)STAGE for each of the specific larvae populations.
The *trigger* for STST behaviour is set by the routine VKUST
The *totaldepth* is set by the model.
The *threshold*, *efficiency* and *nursery* are input process parameters of the model.

The table below provides the definitions of the parameters occurring in the formulations.

Name in formulas[1)]	Name in input	Definition	Units
stage	*eig_larv(i)*	Development stage larvae (i)	-
trigger	*kusttransp*	indicates if the flow has a coastal component	-
totaldepth	*totaldepth*	total depth water column	m
threshold	*DepthThres*	depth threshold for STST behaviour	m
efficiency	*eff_larv(i)*	efficiency of the STST behaviour	-
nursery	*end_larv(i)*	indication of nursery ground	-

1) species *(i)* are 01, 02, 03 ,04 and 05

'VZLARV(i)' Vertical migration of Herring larvae

The herring model is a 3D model with 10 layers. The vertical migration of herring larvae is achieved by giving the larvae a settling/buoyancy velocity. The actual vertical distribution of the larvae is the resultant of the settling/buoyancy and the vertical dispersion as calculated by the hydrodynamic model.

Only larvae in stage 0 (pre-spawning) reside on the bottom.

$$F_w = 0.0$$

$$F_b = 1.0$$

with:
F_w = Fraction larvae in the water column (-)
F_b = Fraction larvae on bottom (-)

During stage 1 (yolk sac stage) the larvae have an increasing buoyancy

$$v_z = v_{start}+(v_{stop}-v_{start})*fstage$$

$$fstage = age/duration$$

with:
v_z = settling velocity (m/d)
v_{start} = settling velocity at begin of stage 1 (m/d)
v_{stop} = settling velocity at end of stage 1 (m/d)
fstage = fraction of stage 1 which has passed by (-)
age = age of larvae within stage 1 (d)
duration = duration of stage 1 (d)

During stage 2 and 3 the larvae are concentrated in a specific part (the larvae layer) of the water column. In the model this is achieved by giving the larvae which reside above this part a settling velocty (*vztop*), larvae within that part a neutral settling velocity (*vzmid*) and larvae which reside below this part a negative (buoyant) settling velocity (*vzbot*). The part of the water column in which the larvae reside is dependent on the development of the larvae and on the time within the day. During the day the larvae layer increases and decreases, implemented as a sine curve on the placement of the bottom of the layer. The amplitude of the sine function can increase during the stage.

```
if localdepth < ztop
        vz = vztop
else if localdepth < zbotact
        vz = vzmid
else if localdepth >zbotact
        vz = vzbot

zbotact = ztop + zbot + (sin((time-phase)*2.*pi)+1.0)*zampl
zampl = astart + (astop-astart)*fstage
fstage =age/duration
```

with:

v_z = settling velocity (m/d)
vztop = settling velocity above the larvae layer (m/d)
vzmid = settling velocity within the larvae layer (m/d)
vzbot = settling velocity below the larvae layer (m/d)
localdepth = depth within the water column (m)
ztop = location top of larvae layer (m)
zbot = minimum thickness of larvae layer (m)
zbotact = actual location of bottom of larvae layer (m)
zampl = amplitude of varying thickness of larvae layer (m)
astart = amplitude at start of stage (m)
astop = amplitude at end of stage (m)
phase = phase of the sine function relative to midnight (d)
time = model time (d)
fstage = fraction of stage 1 which has passed by (-)
age = age of larvae within stage 1 (d)
duration = duration of stage 1 (d)

The *stage* is set by the routine L(i)STAGE for each of the specific larvae populations.

Definitions of the parameters in the above equations for VZLARV(i).

Name in formulas1)	Name in input	Definition	Units
stage	*eig_larv(i)*	Development stage larvae (i)	-
vstart	*VstrtL(i)S1*	Vertical velocity start stage 1	m/d
vstop	*VstopL(i)S1*	Vertical velocity stop stage 1	m/d
astart	*AstrtL(i)S2*	amplitude vert.migration start stage2	m
astop	*AstopL(i)S2*	amplitude vert.migration stop stage2	m
astart	*AstrtL(i)S3*	amplitude vert.migration start stage3	m
astop	*AstopL(i)S3*	amplitude vert.migration stop stage3	m
vztop	*VzTopL(i)*	vertical velocity above larvae layer	m/d
vzmid	*VzMidL(i)*	vertical velocity in larvae layer	m/d
vzmid	*VzBotL(i)*	vertical velocity beneath larvae layer	m/d
localdepth	*localdepth*	depth within the water column	m
ztop	*ztopL(i*	location top of larvae layer	m
zbot	*zbotL(i))*	minimum thickness of larvae layer	m
phase	*phaseL(i)*	phase of the sine function relative to midnight	d
time	*ITIME*	model time	d

1) species *(i)* are 01, 02, 03 ,04 and 05

‘VKUST’ STST trigger, direction of the coast

This model routine generates a trigger for fish larvae with active STST (“selective tidal stream transport”). Larvae will reside in the water phase when the tidal flow has a component towards the coast. When the flow has a component from the coast the larvae will reside on the water bed. The trigger indicating the STST behaviour is available for output. The trigger can be calculated in two ways depending on a switch set by the user. The first method looks at the flow over a specific exchange direction and a process parameter set by the user indicating the direction towards the coast. The second method looks at the temporal gradient in salinity. When the salinity rises the flow direction is supposed to have a component towards the coast. When the salinity falls the flow direction is supposed to be from the coast. These two methods have been formulated as follows:

SWkusttr = 1: look at the direction of the flow

```
    if $Q_i > 0$
        $trigger = 1$
    else
        $trigger = 0$
```

if kustdir = 1 : Q_i= second direction positive flow
if kustdir = 2 : Q_i= first direction negative flow
if kustdir = 3 : Q_i= second direction negative flow
if kustdir = 4 : Q_i= first direction positive flow

SWkusttr = 2: look at the temporal salinity gradient

```
    dsal = $(sal_{t+dt}sal_t)/dt$
    if $dsal > dsal_{threshold}$
        $trigger = 1$
    else if $dsal < dsal_{threshold}$
        $trigger = 0$
    else
        $trigger = old\ trigger$
```

with:
Q_i = flow component in the coastal direction
kustdir = parameter indicating the direction of the coast in the grid
sal = salinity (g/kg)
dsal = salinity gradient (g/kg/d)
$dsal_{threshold}$ = threshold in salinity gradient (g/kg/d)
trigger = trigger for STST behaviour

Definitions of the parameters in the above equations for ‘VKUST’

Name in formulas1)	Name in input	Definition	Units
Q_i kustdir	Flow kustdir	flow parameter indicating the direction of the coast	m^3/s -
sal $dsal_{threshold}$	salinity salthresh	salinity threshold in salinity gradient	g/kg g/kg/d
trigger	kusttransp	indicates if the flow has a coastal component	-

'L(i)STAGE' Development stages of fish larvae

Fish larvae develop through several stages. These stages influence the behaviour and therefore the transport of the larvae. In the model the development stage is represented by a process parameter which can have the integer values 0, 1, 2, 3 or 4. The behaviour associated with the stage depends on the specific species and is described elsewhere. The duration of each stage can be defined by the user by entering the process parameter in the input but the duration of the stages can also be calculated by the model with the process described here. Process L(i)STAGE has been implemented for five larvae populations (i), namely: Vislarve01, Vislarve02, Vislarve03, Vislarve04 and Vislarve05.

The duration of a stage is calculated for the complete population of a certain species and depends on the average temperature the population encountered during that stage. The average temperature is calculated as the average temperature weighted with the larval density for every segment above a certain threshold concentration of larvae. This temperature is then averaged over time.

$$t_s = \mathrm{e}^{(\alpha_s + \beta_s * \overline{T}_s)}$$

$$\overline{T}_s = \overline{\frac{\sum_{iseg=1}^{noseg} (T \times c \times A)}{\sum_{iseg=1}^{noseg} (c \times A)}} ; (c > c'_{threshold})$$

$$c = \frac{c_{susp} \times V + c_{bottom}}{A}$$

with:

s = indication of the stage (0,1,2,3, or 4)
t_s = duration of stage s (d)
α_s = temperature independent coefficient stage s (log(d))
β_s = temperature dependent coefficient stage s (log(d/°C))
$\overline{T}_s$ = average temperature during stage s (°C)
T = temperature segment (°C)
c = larvae density (#/m2)
V = Volume (m3)
c_{susp} = Larvae concentration water phase (#/m^3)
c_{bottom} = number of larvae on the water bed (#)
$c_{threshold}$ = threshold concentration larvae (#/m^2)
A = Surface area (m^2)

Definitions of the parameters in the above equations for L(i)STAGE.

Name in formulas$^{1)}$	Name in input	Definition	Units
C_{susp}	Vislarve(i)	concentration of larvae (i) in water phase	#.m^{-3}
C_{bottom}	Bodlarve(i)	number of larvae (i) on the water bed	#
$C_{threshold}$	ThrLarve(i)	Threshold Vislarve(i) for development calc.	#.m^{-2}
α_0	aL(i)Stage0	a coefficient in larvae (i) stage 0 development	log(d)
β_0	bL(i)Stage0	b coefficient in larvae (i) stage 0 development	log(d/°C)
α_1	aL(i)Stage1	a coefficient in larvae (i) stage 1 development	log(d)
β_1	bL(i)Stage1	b coefficient in larvae (i) stage 1 development	log(d/°C)
α_2	aL(i)Stage2	a coefficient in larvae (i) stage 2 development	log(d)
β_2	bL(i)Stage2	b coefficient in larvae (i) stage 2 development	log(d/°C)
α_3	aL(i)Stage3	a coefficient in larvae (i) stage 3 development	log(d)
β_3	bL(i)Stage3	b coefficient in larvae (i) stage 3 development	log(d/°C)
α_4	aL(i)Stage4	a coefficient in larvae (i) stage 4 development	log(d)
β_4	bL(i)Stage4	b coefficient in larvae (i) stage 4 development	log(d/°C)
V	Volume	Volume	m^3
A	Surf	Horizontal Surface area	m^2
T	Temp	temperature	°C
s	eig_larv(i)	Development stage larvae (i)	-

1) species (i) are 01, 02, 03 ,04 and 05

When the time expired since the last stage change exceeds the duration of the stage then the stage will be increased with one. The computation will start by default with stage 0 (prespawning) with a infinite small duration. In practice this means that the computation starts with stage 1. The α_0 can be changed by the user to simulate spawning after the start of computation. The stage will not be increased anymore if stage 4 is reached. The process parameter for the stage indication (s) is available for output. It can be used to monitor the development of the larvae.

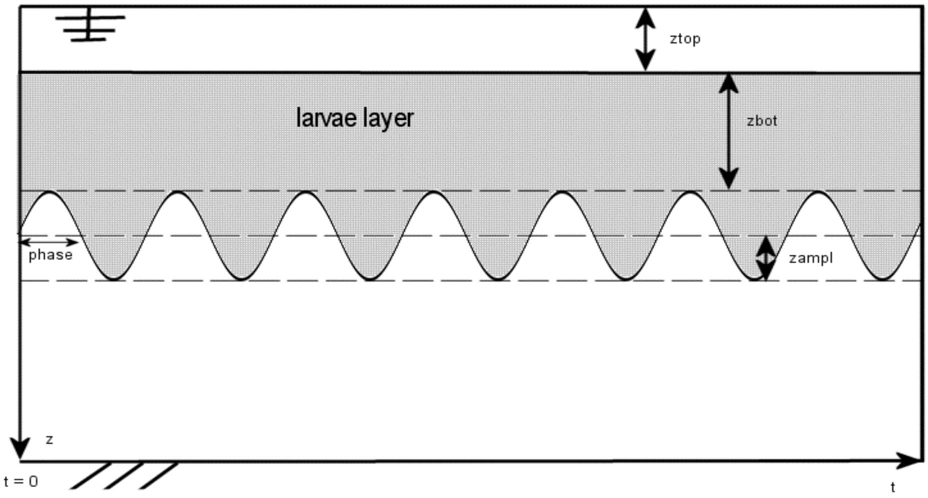


Figure 3.2.1 Schematisation of the vertical migration of Herring larvae.

3.3 Scenario's

For the study of the impact of the Maasvlakte 2 reclamation on the transport of fish larvae from their spawning grounds in the southern part of the North Sea to their nursery areas (esp. the Wadden Sea), the following three scenarios were considered in the modelling (all using the ZUNO-DD model):

1. **Current Situation (T_0):** This scenario represents the present situation (i.e. the "baseline situation"), modelled using the hydrodynamics from the ZUNO-DD year-run for 1988-1989;

2. **T_0 + Autonomous Developments**: This scenario is similar to scenario 1, but includes two autonomous developments that are likely to take place before the construction of Maasvlakte 2 and are likely to affect baseline conditions: [a] the so-called "Kierbesluit" which refers to proposed changes to the discharge regime (management) of the Haringvliet sluices, and [b] a proposed offshore wind mill park, consisting of two areas each of which will cater for 60 wind mills;

3. **MV2 (Doorsteekvariant)**: This scenario includes not only the autonomous developments but also one of the designs for the Maasvlakte 2 extension ("Doorsteekvariant"). The overall impact of MV2 is assessed by looking at the differences in model results between scenarios 2 and 3.

Changes in the morphology of the coastline caused by MV2 have not been included in the hydrodynamic modelling of the MV2 scenario, because these changes are expected to be small and local (WLIDelft Hydraulics, in press)

3.4 Analyses of model output

To meet the objectives of the Baseline and PB study, i.e. describe and quantify the current larval transport patterns and quantify the effects of MV2, post-model processing was carried out and the following 'output parameters' were calculated.

1. **Distribution patterns:** This output parameter, in the form of a graphic contour plot of the densities (N/m^2) on a certain date, gives an impression of the temporal and spatial distribution of eggs and larvae.

2. **Transport success:** This output parameter is defined as the total number of fish larvae that has arrived in a certain nursery area by the end of the model run, expressed as a percentage of the total number spawned. Within in the DELWAQ fish larvae model, the concentrations (N/m^3) of larvae per water layer and the number of larvae on the seabed (N/m^2) were aggregated and converted to total numbers per m^2. In the post-model processing these densities were converted to total numbers per area (multiplication of densities and surface area). For this, the model grid area has been sub-divided into a number of compartments: 4 offshore areas and a number of compartments within the coastal zone (Figure 3.4.1). The juvenile herring are associated with the off shore areas in the International Bottom Trawl Survey (IBTS), and the coastal zone (denoted by the 20m depth) corresponds to the nursery areas of plaice and sole. Within the Dutch coastal zone relatively small compartments were distinguished, based on the area definition in the Demersal Fish Survey (Figures 3.4.1 right panel). The number of larvae per area was calculated for each compartment and then summed to calculate the transport success for larger geographic areas (e.g. western Dutch Wadden Sea). This aggregation was different for herring compared to plaice and sole. All plaice and sole larvae that hadn't reached the coastal nursery areas by the end of the model run, including the larvae lost from the model grid area, were considered "unsuccessful". This is different for herring, as the herring nursery areas cover a much larger area. The Dutch Wadden Sea and the adjacent coastal

waters (from Petten to the German border, to a depth of 20m) are protected by the European Birds' and Habitats Directives. This area is further referred to as "protected area". The transport success to the protected area was calculated for all species.

3. **Timing of arrival:** This output parameter, in the form of a time series plot, describes the timing of arrival of fish larvae in a certain coastal area. The time series can plot either the density (N/m^2) at an observation point (one grid cell) showing the larvae that enter a coastal area, or they plot the total number in a coastal area showing the accumulation of larvae in this area. The first approach was chosen for the present study.

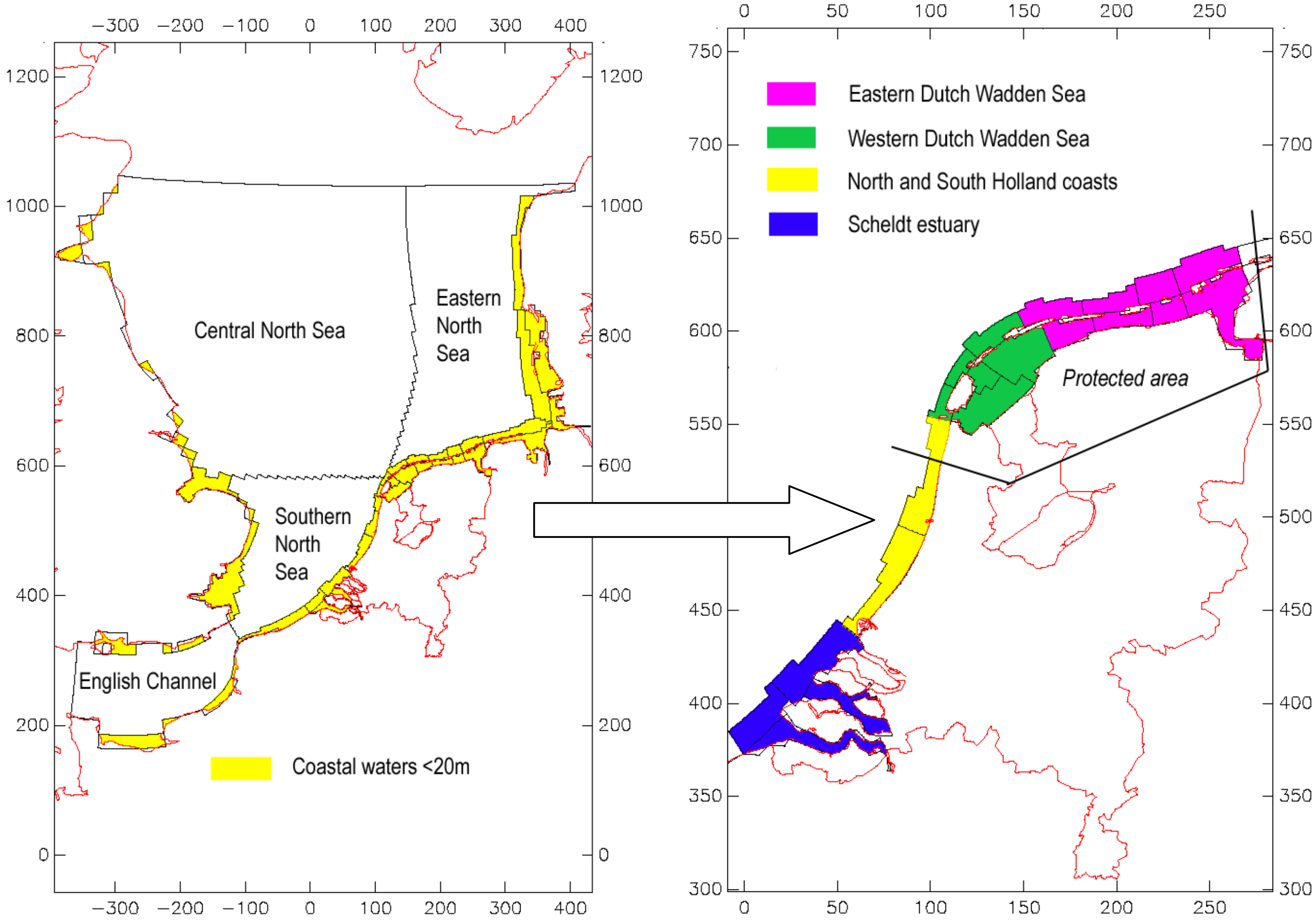


Figure 3.4.1. Areas used to estimate transport success.

4 Baseline study

In this chapter the egg and larval transport is described and quantified for the baseline situation. Inter-annual variability is examined and the sensitivity of the model to assumptions about the biological processes and parameters is tested. At no point was mortality of the larvae considered, and thus this study was completely targeted at transport variability. All analyses were carried out using the ZUNOGROF grid.

4.1 Herring

The sensitivity of the transport of larvae by the model due to the assumptions and parameters settings for herring larvae behaviour and development were investigated using the ZUNOGROF grid and the hydrographic data from 1988/1989 (Table 4.1.1). To allow ease of comparison between model runs, all runs modelled larvae that were released on the sea bed from a simple patch in the centre of the observed spawning aggregation (herring hatching grid 1, Figure 4.1.1) on 20 December 1988. The result of this standard run of the 1988/1989 data and settings, was that by 31st May only 4.5% of the larvae were in the Wadden Sea and Dutch coastline, with 1% in the protected area (Table 4.1.2). The majority were in the deeper (>20m) eastern and central North Sea (86%, Table 4.1.2). Four main sensitivity tests were carried out; phase, amplitude of vertical diffusion, stage effect and the effect of temperature on the transport of the larvae.

4.1.1 Effect of phase

The parameter “phase” determines whether any expressed diel behaviour in stage 2 and 3 larvae is either day/night or night/day. The model allows a diel pattern of dispersion and aggregation on the vertical plane to replicate visual searching for prey. Phase= 0.25 means that larvae are more likely to be concentrated higher in the water column at night and more dispersed throughout the water column in the day. Whereas phase= 0.75 means that the larvae are more concentrated, higher in the water column in the day and more dispersed at night. 0.75 was chosen as the standard setting as it was assumed that the vertical distribution of feeding larvae in daylight would be more aggregated than at night (see section 3.6).

The sensitivity of the transport of larvae to either choice of phase (0.25 and 0.75) was found to be negligible (Figure 4.1.2). There was no detectable difference in transport of larvae to locations (4.3% of larvae were in the Wadden Sea and Dutch coast by late May with phase=0.25, compared to 4.5% when phase= 0.75) and there was no effect on the timing of the transport (Figure 4.1.2).

4.1.2 Effect of amplitudes

The sensitivity of the transport to the size of the diel dispersions was investigated by reducing the amplitude of the dispersion allowed in stage 2 and stage 3 and also by increasing the amplitudes (see text table below). To account for the possibility of year effects in the hydrodynamics affecting the result, the sensitivity test was carried out with both 1988/1989 and 1997/1998 hydrographic conditions. The same amount was released on 20th December using herring hatching grid 1 (Figure 4.1.1).

	Parameter	Standard	Reduced Amplitude	Increased Amplitude
Stage 2	AstrtL01S2	0.5	0.5	0.5
	AstopL01S2	5	0.5	10
Stage 3	AstrtL01S3	1	0.5	0.5
	AstopL01S3	5	0.5	10

These changes to the amplitude of the vertical dispersion and aggregation (modelled to mimic diel feeding behaviour) had no significant effect on the timing of the transport of herring larvae in both 1988/89 and 1997/98 (Figure 4.1.3). At single point observations, slight changes in the scaling occurred but they were not consistent between the two years (Figure 4.1.3). However in terms of the overall delivery of larvae to specific locations, the reduction in amplitude of diel vertical migration reduced the delivery to coastal areas (Table 4.1.3), and the reverse occurred when amplitude was increased. This probably reflects the shoreward movement of water closer to the sea bed. These changes due to assumptions about behaviour were however very small when considering transport to the main nursery area (central and eastern North Sea, change of 2%) but were more substantial when considering transport to the coastal areas (5 to 20% change, Table 4.1.3).

Considering the mixed nature of the water column in the southern North Sea, it is not surprising that there was no difference in the average temperature experienced by the larvae what ever the amplitude of diel dispersal (Figure 4.1.4). If the larvae where in a thermally stratified water column, one would expect to see greater temperature difference between the larvae with increased or reduced amplitudes of diel vertical migration.

4.1.3 Effect of behavioural stage

Individual behaviour stages were removed from different model runs. This was done to test again the influence of the choices of behaviour rules on the transport of the concentrations of larvae. It was carried out by replacing the standard parameter settings for stage duration with -10 for each run for stages 1, 2 and 3 respectively. This meant that with the removal of the yolk sac stage, the larvae were immediately pelagic after hatch, and with the removal of stage 2 that the larval went from yolk sac to large diel amplitudinal changes (up to 5m).

The lack of a yolk sac stage resulted in the larvae passing through the Dover Straits earlier than if the yolk sac stage was maintained (Figure 4.1.5) but this earlier entrance into the North Sea did not have an effect on the timing of their delivery into the Wadden Sea or the German Bight (Figure 4.1.5). The previous results on the sensitivity of transport to behavioural assumptions (immediately above) suggest that the behaviour as modelled here has a small impact on the transport or delivery of larvae. Hence the effect of removing the stage 1 (yolk sac) behaviour is more an issue of the timing of the release of larvae into the water column. This will be further addressed below in section 4.1.7.

4.1.4 Effect of temperature

The estimates of temperature used to determine the development rate, hence stage duration, were varied. The standard model settings used estimates of the average temperature of the larvae determined by modelled field estimates of temperature per grid cell and the concentrations of larvae in that cell. In 1988/1989, the mean temperatures of the larvae by behavioural stage were:

Stage 1	Yolk sac	8.9°C
Stage 2	Early Feeding larvae	8.0°C
Stage 3	Post larvae/premetamorphosis	8.7°C

For each of three extra model runs, the estimates of temperature were changed to be fixed at 8°C, 9°C and 10°C respectively (for all cells on all days). This clearly would effect the estimated development times (Figure 4.1.6) and resulted in differences in total time to 30mm in length (assumed jump from behavioural stage 2 to stage 3) of 24 days between 8°C and 10°C. As seen in section 4.1.1.3, choice of behaviour stage (other than yolk sac) had very little effect on the transport of larvae, and hence it is not surprising that slight changes to the temperature regimes only had small scaling effects on the transport of larvae (Figure 4.1.7). The observation point at the entry to the Wadden Sea (Marsdiep) showed that the standard settings were closer to the 8°C run during stage 2, and then the standard, 8°C and 9°C runs converged by the end of the run. There was also no discernable difference spatially (Figure 4.1.8) between the 4 runs by mid-May.

4.1.5 *Effect of 10 layer model*

The logistics of running the models and the time required to create the model substance files and hydrographic files prevented any testing the sensitivities of using a 10 layer model compared to 2 or 5 later models. It is assumed that the use of a ten layer model has no major effect compared to a model at lower vertical resolution.

4.1.6 *Effect of zooplankton on horizontal movement*

In the current model the influence of zooplankton on the vertical distribution of herring larvae was simulated by applying diel vertical migration rules, however no effect of horizontal gradients of zooplankton were included in the model. Zooplankton concentrations do vary at a range of scales. Small larvae will respond to small scale patterns and patches, whilst juveniles and adults are known to be associated with zooplankton at scales greater than 5km. Older herring (>50mm) with a stronger ability to swim and aggregate will thus be more affected by large scale gradients in zooplankton. It can be argued that if the herring are large enough to show wide scale changes due to zooplankton distribution, i.e. able to actively swim, they should be older and have already passed the Maasvlakte development. Thus although absent from this study, the sensitive due to large scale zooplankton gradients are thought to be negligible when considering the influence of the Maasvlakte 2 on the transport of herring.

4.1.7 *Inter-annual variability*

The inter-annual variability of larval transport was modelled using 9 different years hydrographic data (forced by 9 years of meteorological data). In the herring study, variability was further increased by releasing hatched larvae on different dates of the respective years. This was possible because data on the peak timing of spawning for each year of herring was available from annual surveys of herring larvae (see annex 3a). These data (from an internal RIVO report on Downs herring larval production by Sascha Fässler and Mark Dickey-Collas) show that the peak hatching can vary by up to two weeks between years (Figure 4.1.9). These peak hatching dates were used as the start dates for the model in each year and the spatial distribution of hatching followed in the herring hatching grid 2 (Figure 4.1.10). The variability introduced by changing hatching date is briefly reviewed in the section below. The hatching grid was changed from that used in the earlier analysis to reflect the full spatial distribution of hatching on the seabed of Downs herring. Other than these two changes (hatch date and hatch site), the standard model settings were used for the investigation of inter-annual variability (Table 4.1.1).

The effect of variable hatching dates

Two years with very different hydrographic regimes (1995/1996 and 2001/2002) were chosen to investigate the influence of varying the hatch date on the transport of larvae. Hatched larvae were released on:

	Early hatching	Peak of hatching	Late hatching
1995/1996	27/12/1995	03/01/1996	10/01/1996
2001/2002	29/12/2001	05/01/2002	12/01/2002

The time of hatch did have an effect on the final location of the larvae, this was more marked in 1995/1996 compared to 2001/2002 (Figure 4.1.11). This can be seen even more clearly in the concentrations of larvae from point observations (Figure 4.1.11). In 1996 an event (around 10th January) pushed the larvae through the Channel Mouth, but then the northern easterly movement ceased. The later spawned larvae were just hatching at this point and hence had a slower passage through the Channel. This is reflected in their transport to the Wadden Sea (Marsdiep point observations, Figure 4.1.11), as the larvae had not arrived by late May to the same extent as the earlier hatching (Table 4.1.4).

However, in the more hydrographically dynamic 2001/2002, the timing of hatch seems to have little influence on the distribution of the larvae by late May (Figure 4.1.12). The larvae leave the English Channel within a three week window (15 January to 3 February, Figure 4.1.11), and the mixing in the southern North Sea means that they all arrive with similar timing at the Wadden Sea (see Marsdiep Figure 4.1.11).

The coefficient of variation (CV) for transport to locations in 1995/1996 from early to late hatching ranges from 10 to 100% dependent on location (CV for Wadden Sea as a whole 61%), but the CVs are much reduced in 2001, when all locations have CVs less than 10% between early, peak and late spawning.

So it is clear that timing of hatching, can have a large effect on the modelled transport of herring larvae, but this is highly dependent on yearly variations in hydrodynamic conditions.

Year effects.

As stated above, the transport of herring larvae hatched in the English Channel and southern North Sea was modelled for 9 years (Table 4.1.5) using varying hydrographic and temperature data. Different hatch dates were used to reflect and account for the measured variability in the Down herring population, and Herring Hatching grid 2 was used to reflect the possible spatial spread of hatching (Figure 4.1.10). Other model settings follow Table 4.1.1.
There were large differences between years in the predicted distribution of concentrations of herring post larvae by late May (Figure 4.1.13). There were 3 outliers;

1995/1996	larvae remained in the south and appeared to hardly have moved
1998/1999	larvae appeared to reach the extreme north east of the grid
2001/2002	larvae appeared to reach the extreme north east of the grid

All of the other years had larvae in the centre of the southern North Sea or in the German Bight, although 2000/2001 was near the south of the area.

In terms of timing, the simulations suggest that in 1988/1989 and 1998/1999 the larvae moved through the mouth of the channel in one large pulse in early January (Figure 4.1.14), a pulse also occurred in 1996/1997 but this was much later in early February. 1995/1996 and 2002/2003 were noticeable as the simulations suggest that the concentrations remained high in the eastern mouth of the Channel from January to March. These were the years when very few larvae entered the Wadden Sea (see Marsdiep Figure 4.1.14). Based on transport alone (i.e. no active swimming in the horizontal plane, or salinity induced behaviour) the simulations suggest that the herring enter the Wadden Sea from late march onwards, probably peaking in late April/early May. The between year variability in the delivery of larvae to the Wadden Sea is very large (3 or 4 more successful years out of the 9, Figure 4.1.15).

The between year variability has a very small influence on the duration of the yolk sac phase (mean = 6 days Standard deviation = 0.3 days, CV= 5%, Figure 4.1.16). The variability in the duration to 30mm in length (the end of stage 2 in this simulation) increases slightly to CV=8% (Figure 4.1.16, mean= 71 days, standard deviation= 5.6 days). Unsurprisingly, considering the construction of the model, the variability in duration is caused by the between year average temperatures of the larvae (7.9 to 9.2 °C, Figure 4.1.16). The mean temperature of the larvae up to 30mm in length from the simulations was 8.5 °C, CV=5%). There is a significant negative correlation between the annually simulated durations to 30mm long and the empirically estimated abundances of post larvae in the MIK net (see annex 3c) in the southern North Sea ($p=0.05$, df=7), suggesting the larger year classes come from years with warmer temperatures and shorter larval durations.

In almost all years, the larvae reach 30mm length approximately 1 month before they reach the Wadden Sea. The model suggests that they should be between 37 to 40 mm in length by the time they enter the Wadden Sea. The only exception is simulated year 2001/2002 (the coldest year) when the larvae start to enter the Wadden Sea at just 30mm in length.
The simulated delivery of larvae, as a percent of the total hatch concentration, into the protected area has a CV= 86% between years (Table 4.1.6). Analysis of the between year variability suggests that the maximum possible transport of herring larvae hatching in the Downs area to the Wadden Sea and Dutch coastal areas is 7.5% (This is based on the upper 95% confidence interval from the 9 year time series). The minimum is 0.5%, and accounting for variability in larval mortality (daily rate of decline (z) between 0.05 and 0.1), this still represents between 10^7 and 10^9 postlarvae in the Wadden Sea and Dutch coastal zone by mid April from the Downs herring.

By late May the open sea has much higher concentrations of post larvae/juveniles, with over 90% being found in areas deeper than 20m. Of the coastal areas, both the English Coast and the Scheldt estuary are likely to have higher numbers than the Dutch Wadden Sea (Figure 4.1.17). The inter year variability in transport is generally between 70 to 170% depending on destination.

4.1.8 Summary

In all runs, the larvae moved in a north easterly direction from the English Channel and Southern Bight towards the German Bight. The sensitivity of the transport to adjustments in the modelled behaviour rules appears small for herring. Greater amplitude of diel migration does result in slightly more coastal movement, which is probably caused by the coastward movement of the bottom currents. This lack of sensitivity to behaviour rules, also results in the development rates having virtually no impact on the transport as well. The timing of hatching does cause greater variability, but this varies with year. The largest variability comes from the between year differences in the hydrodynamics. This influenced both the final location of the concentrations of larvae and the timing of delivery of the larvae.

Table 4.1.1. Herring. Standard Input parameters for Sensitivity tests of Behaviour Assumptions and Parameter settings for herring.

Integration		Dispersion methods		Parameter settings		Observation points
Integration method	14	First-direction	1	VstrtL01S1	0.1	*Channel mouth*
Option-zero-flow	Yes	Second-direction	1	VstopL01S1	0.001	Grid cell 24 37
Option-open-boundary	Yes	Interface- depth	1	ZtopL01	5	*Marsdiep*
Option-first-order	Yes	Vertical diffusion-values	1x10^{-6}	ZbotL01	10	Grid cell 73 45
Output-balances	No	Vertical diffusion-from	Hydro	AstrtL01S2	0.5	*Spawning Point*
Aggregation	No	Vertical diffusion-scale	1	AstopL01S2	5	Grid cell 13 40
Use-forester	No	Use dispersion array	No	AstrtL01S3	1	*German Bight*
Use-anticreep	No			AstopL01S3	5	Grid cell 115 26
Lump-processes	No			PhaseL01	0.75	
Lump-boundary-watse	Yes			VzTopL01	5	
Lump –int-transport	Yes			VzMidL01	0	
Suppress-space	No			VzBotL01	-5	
Suppress-time	No			ThrLarve01	0	
Output-unit	total			Temp (file)	Hydro 88/89	
				aL01Stage0	-10	
				bL01Stage0	0	
				aL01Stage1	2.725	
				bL01Stage1	-0.0958	
				aL01Stage2	5.775	
				bL01Stage2	-0.1896	
				aL01Stage3	20	
				bL01Stage3	0	

Table 4.1.2. Herring. Location of transported larvae by 31st May 1989, as percent of the all those released 20th December 1988 for the standard run for sensitivity analysis. Input parameters shown in Table 4.1.1.1. Areas described in Figures 3.4.1 and 3.4.2

Location	% of those released
Lost from grid	0.3
English Channel Coast	0.0
English Coast North	0.3
Belgium Coast	0.2
French Coast	0.0
Scheldt estuary	**1.9**
Dutch coast	**1.2**
Western Dutch Wadden Sea	**0.4**
Eastern Dutch Wadden Sea	**0.5**
Danish & German Wadden Sea	**0.5**
Danish coast	0.0
North Sea (Central)	27.7
North Sea (East)	58.2
North Sea (South)	8.1
English Channel	0.8
Protected Area	*1.0*
Total Wadden Sea and Dutch Coast	**4.5**

Table 4.1.3. Herring. Proportion of original hatched larvae transported to various locations by 31st May with reduced and increased amplitude in vertical migration in 1988/1989 and 1997/1998. Standard input parameters shown in Table 4.1.1.1 and parameter changes in text table in section 4.1.2. Grey shading denotes an increase in the % of larvae at that location from the standard setting model runs. Areas described in Figure 3.4.1.

Area	**1988/1989**			**1997/1998**		
	standard amplitude	reduce amplitude	increase amplitude	standard amplitude	reduce amplitude	increase amplitude
North Sea	85.9	87.8	84.9	84.8	86.2	84.0
English Channel	0.8	0.6	0.9	0.9	0.7	1.1
Scheldt estuary	1.9	1.6	2.1	1.5	1.4	1.7
Wadden Sea	4.5	3.6	4.7	4.7	4.1	4.8

Table 4.1.4. Herring. Proportion of original hatched larvae (as percent) transported to various locations by 31st May whether spawned at the empirically measured peak of hatching, one week earlier or one week later in 1995/1996 and 2001/2002. Standard input parameters shown in Table 4.1.1 and hatch grid 2. Areas described in Figure 3.4.1.

Area	**1995/1996**			**2001/2002**		
	Early hatch	Peak hatch	Late hatch	Early hatch	Peak hatch	Late hatch
North Sea Central and East	3.0	4.9	0.5	70.0	72.9	70.0
North Sea South + Channel	75.4	74.7	68.7	11.1	11.1	11.1
Wadden Sea	0.8	1.2	0.3	6.9	8.2	6.9
Scheldt estuary	0.5	0.8	0.2	2.1	2.3	2.1

Table 4.1.5. Herring. Hatch dates of herring used for each year in the inter-annual variability simulations.

Simulation period	hatch date
1988/1989	16/12/1988
1995/1996	03/01/1996
1996/1997	02/01/1997
1997/1998	29/12/1997
1998/1999	18/12/1998
1999/2000	05/01/2000
2000/2001	20/12/2000
2001/2002	05/01/2002
2002/2003	26/12/2002

Table 4.1.6. Herring. The relative amount of larvae (as percent of those hatched) at each location on the 31st May for 9 different years. Note no mortality assumed in the model. Areas described in Figure 3.4.1.

	1988/ 1989	1995/ 1996	1996/ 1997	1997/ 1998	1998/ 1999	1999/ 2000	2000/ 2001	2001/ 2002	2002/ 2003	mean	stdev
English Channel Coast	0.1	1.8	0.3	0.1	0.0	0.4	3.8	0.1	0.2	0.7	1.3
English Coast North	0.3	2.6	0.8	0.8	0.3	1.5	2.2	0.3	2.4	1.3	0.9
Belgium Coast	0.1	1.1	0.4	0.1	0.1	0.4	1.5	0.1	0.6	0.5	0.5
French Coast	0.0	2.0	0.2	0.1	0.0	0.3	1.5	0.0	0.5	0.5	0.7
Scheldt estuary	1.0	0.5	2.5	1.0	1.4	2.8	0.1	2.3	1.3	1.5	0.9
Dutch coast	0.7	0.2	1.0	0.6	1.1	1.0	0.0	1.9	0.6	0.8	0.6
Western Dutch Wadden Sea	0.3	0.0	0.7	0.5	0.7	0.7	0.0	1.1	0.2	0.5	0.4
Eastern Dutch Wadden Sea	0.3	0.0	0.4	0.5	0.8	0.3	0.0	1.4	0.1	0.4	0.5
Danish & German Wadden Sea	0.4	0.0	0.0	0.0	0.5	0.0	0.0	0.4	0.0	0.2	0.2
Danish coast	0.1	0.0	0.0	0.0	0.4	0.0	0.0	0.5	0.0	0.1	0.2
North Sea (Central)	23.6	2.4	29.9	16.0	11.1	19.7	0.0	5.9	16.8	13.9	10.0
North Sea (East)	60.8	0.6	26.8	60.1	66.5	29.7	0.0	67.0	13.0	36.1	28.0
North Sea (South)	5.8	45.6	24.1	15.5	8.2	33.4	51.6	10.6	53.1	27.6	19.0
English Channel	0.8	29.8	4.9	1.6	0.5	5.1	34.7	0.5	4.4	9.2	13.3
protected area	0.7	0.0	1.2	1.1	1.7	1.2	0.0	2.7	0.3	1.0	0.9
Dutch coast and Wadden Sea	2.8	0.7	4.6	2.7	4.5	4.9	0.1	7.2	2.2	3.3	2.2
Lost from grid at boundaries	5.5	13.3	8.0	3.1	8.3	4.6	4.5	7.8	6.8		

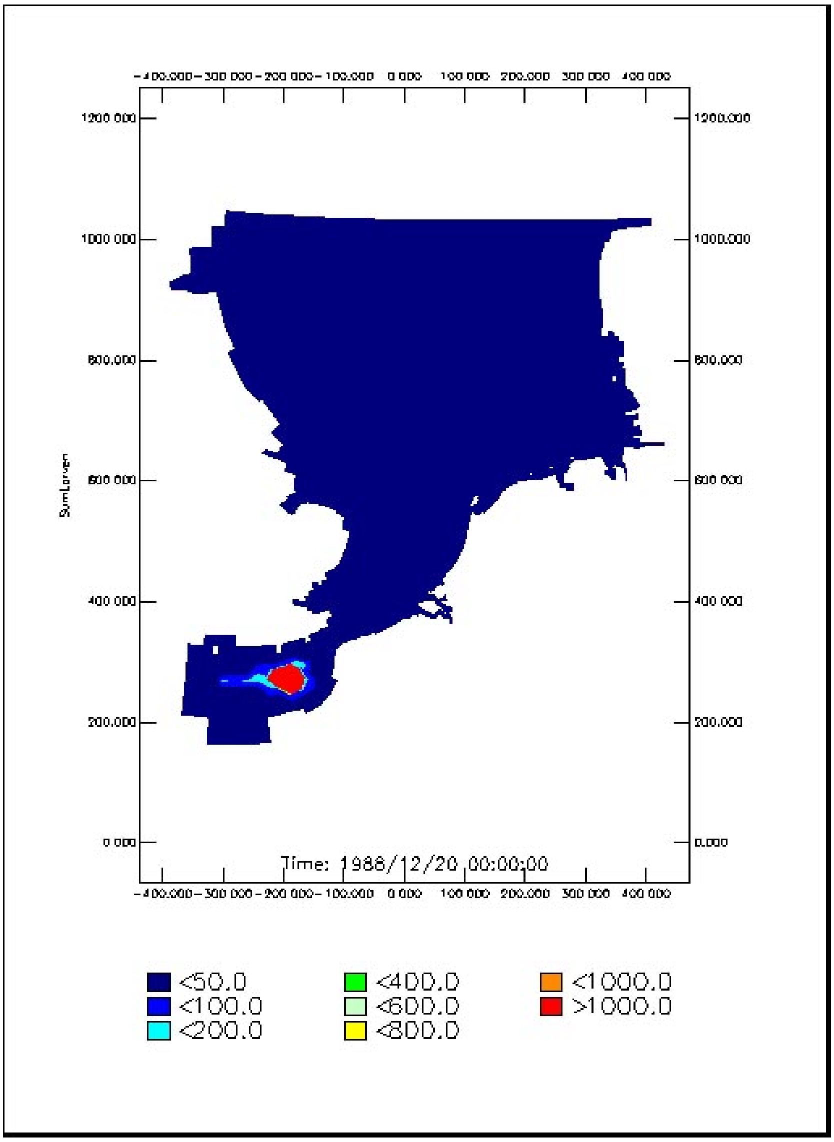


Figure 4.1.1. Herring Hatching Grid 1. Distribution of hatching larvae on the seabed used for parameter and behaviour sensitivity testing.

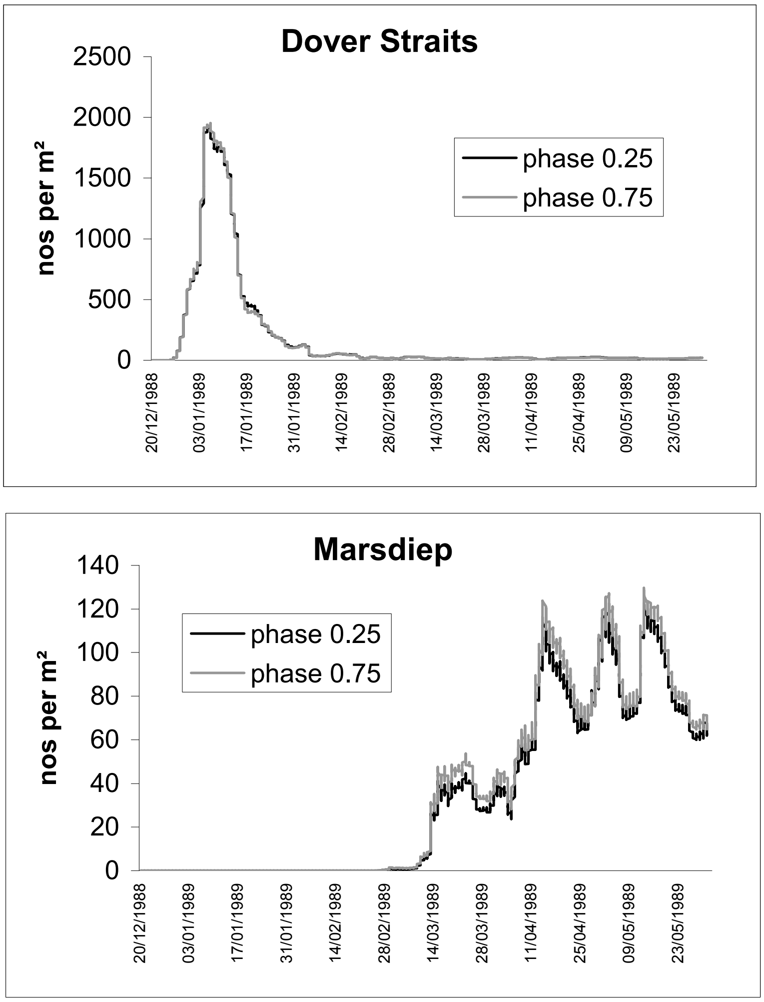


Figure 4.1.2. Herring sensitivity to "Phase". Concentrations of larvae at two grid cells (Dover Straits, and entry into the Wadden Sea- Marsdiep) from two model runs. See Table 4.1.1 for standard settings, phase varied from 0.75 to 0.25 (0.75 is the standard setting). Data shown are daily moving averages of 24 hours.

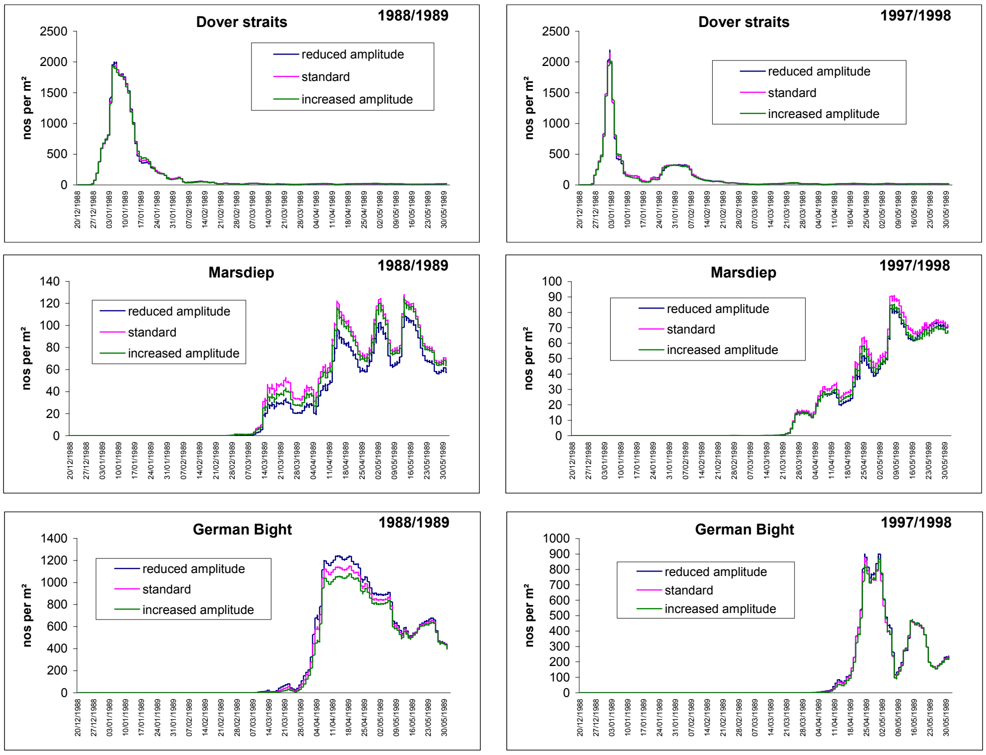


Figure 4.1.3. Herring sensitivity to "amplitude" of diel vertical distribution. Concentrations in two years of larvae at three grid cells (Dover Straits, and entry into the Wadden Sea- Marsdiep, and one cell in the German Bight) from three model runs (reduced, standard and increased amplitude). See text table in section 4.1.2 for changes to parameters and Table 4.1.1 for standard settings. Data shown are daily moving averages of 24 hours.

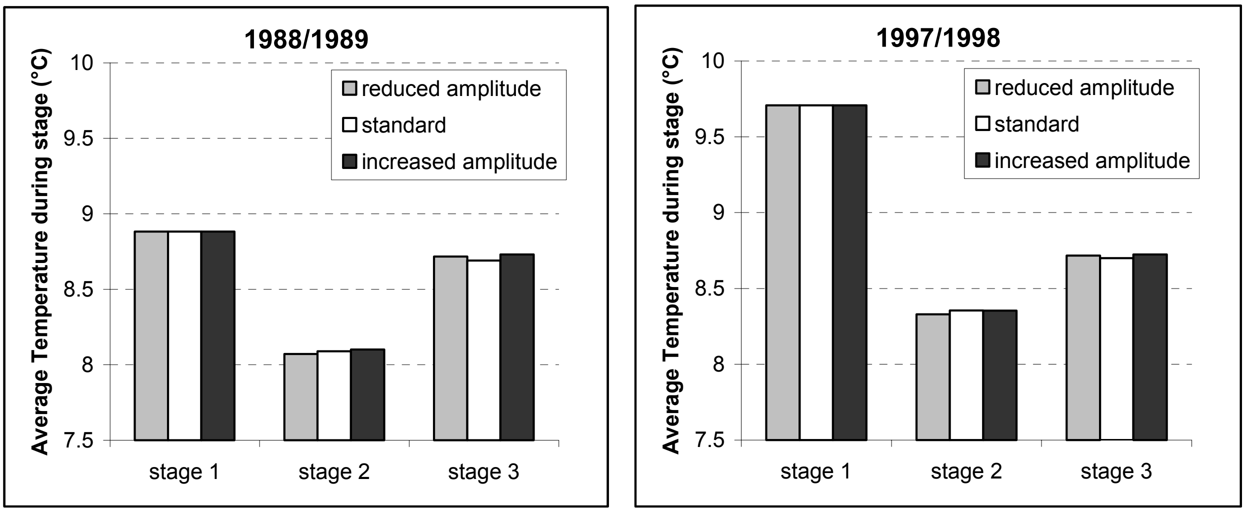


Figure 4.1.4. Herring – Average temperature(°C) of larvae experiencing different levels of "amplitude" of diel vertical distribution in two years. See text table in section 4.1.2 for changes to parameters and Table 4.1.1 for standard settings.

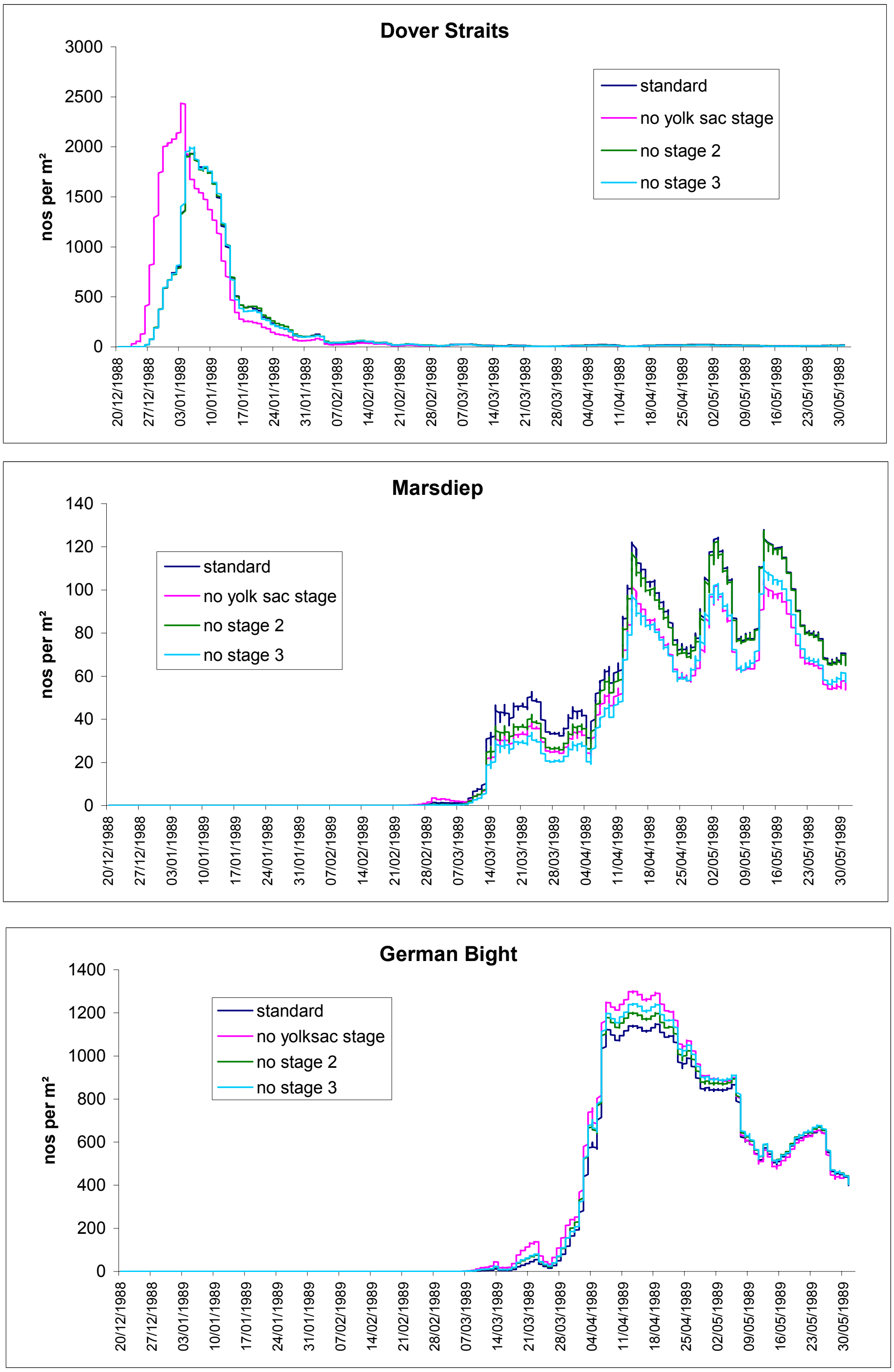


Figure 4.1.5. Herring sensitivity to "behavioural stages". Concentrations of larvae at three cells (Dover Straits, and entry into the Wadden Sea- Marsdiep, and one cell in the German Bight) from four model runs (standard, no yolk sac stage, no stage 2 and no stage 3). See Table 4.1.1 for standard settings. Data shown are daily moving averages of 24 hours.

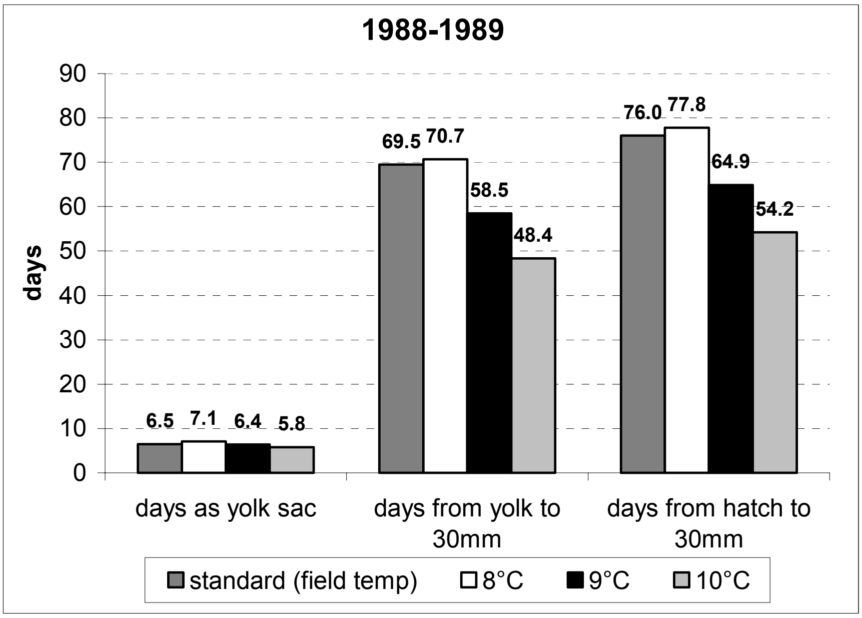
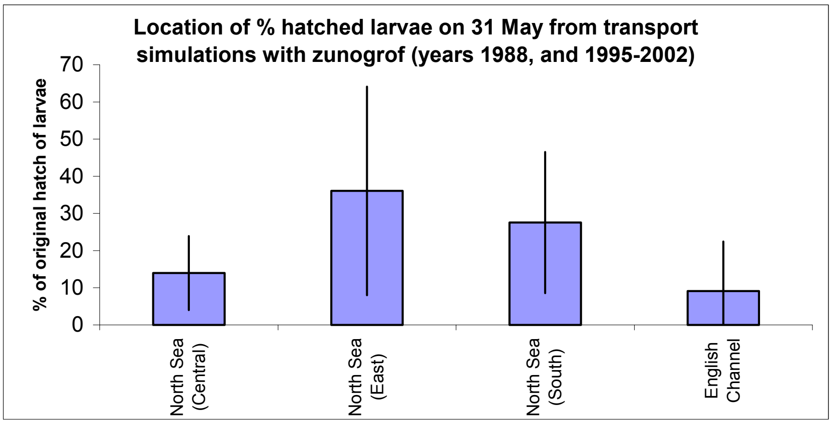


Figure 4.1.6. Herring sensitivity of stage duration to temperature. Stage duration of larvae in 1988/1989 from development rate parameter settings (Table 4.1.1) and four different temperature regimes (standard- field temperature, 8°C, 9°C and 10°C). Value labels show the number of days conforming to each respective column.



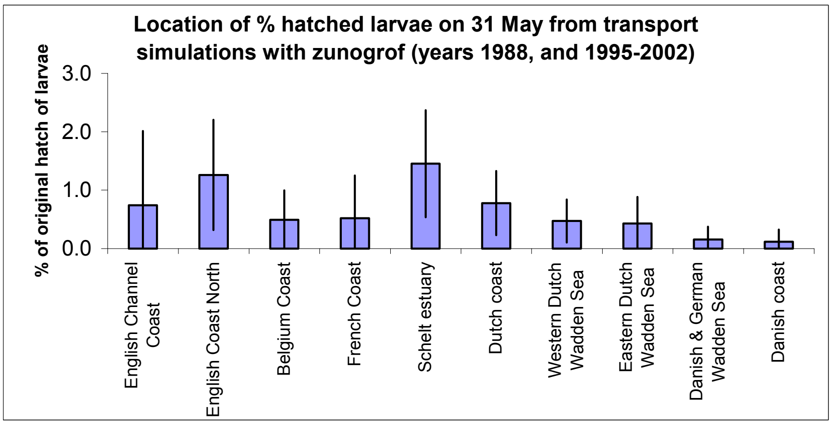


Figure 4.1.17. Herring. Mean estimates of the percentage of hatched larvae at a location after simulated transport from herring hatch grid 2 on the 31 May. Mean of nine years (1988/1998 and 1995/1996 to 2002/2003) and error bars denote standard deviation. Note different scales on the y axis. Areas described in Figure 3.4.1.

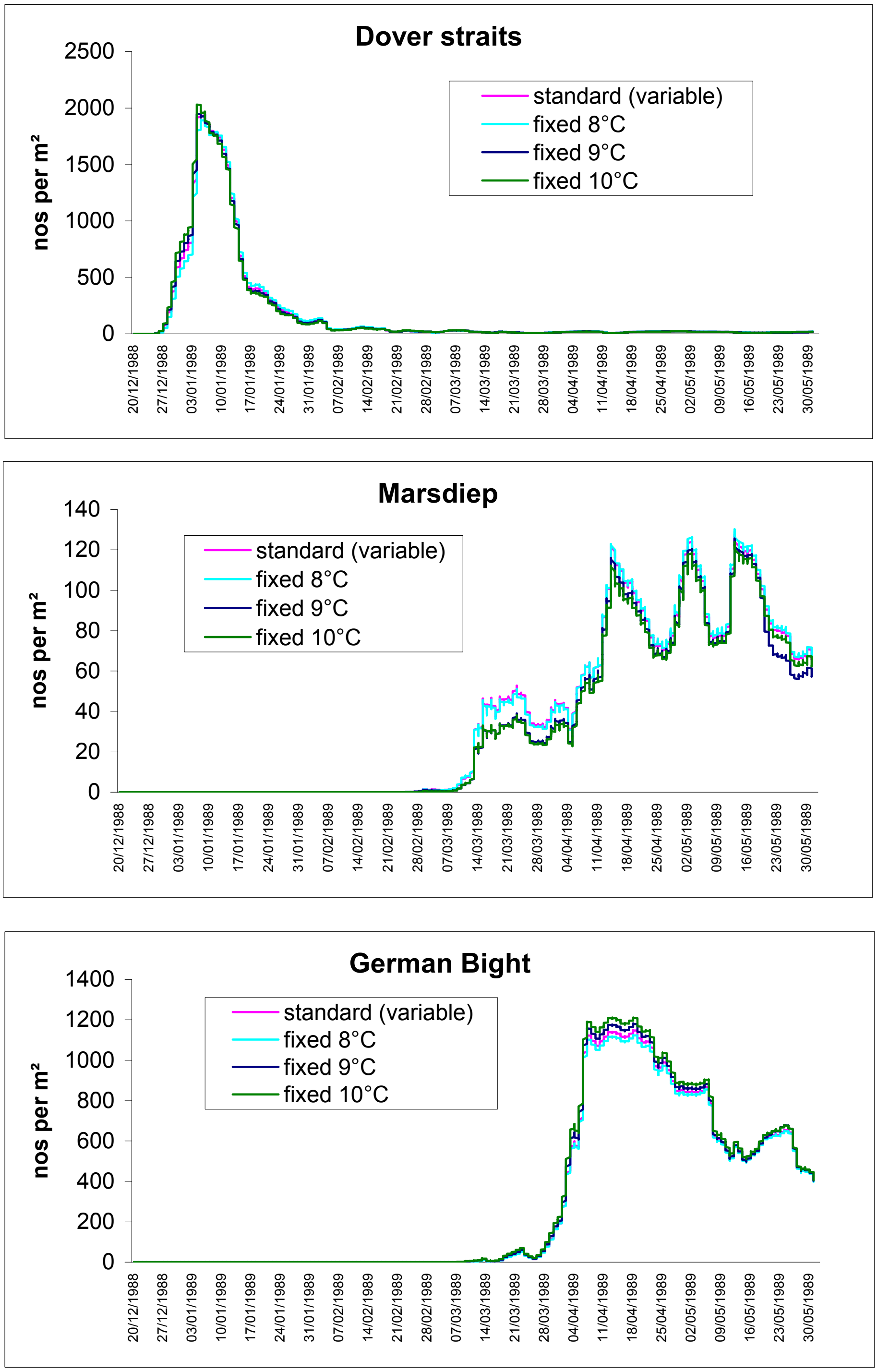
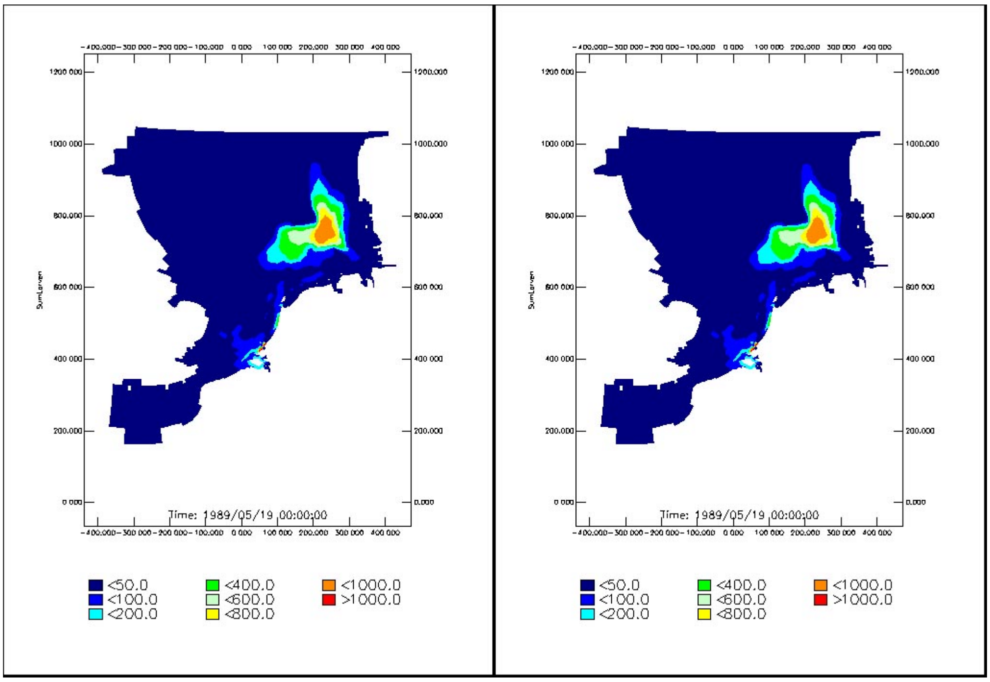
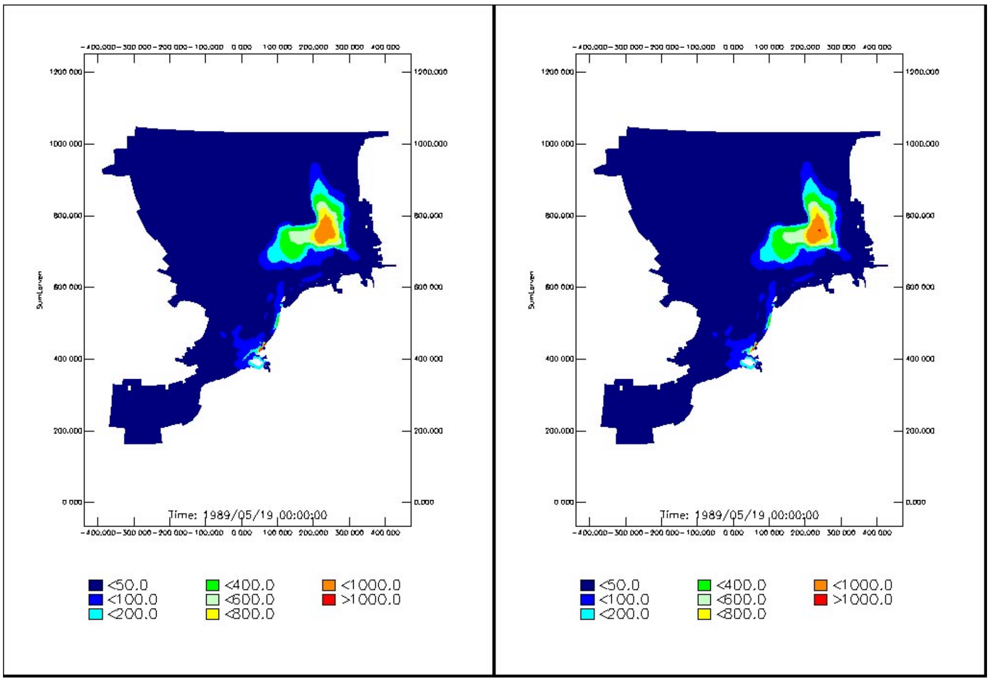


Figure 4.1.7. Herring sensitivity to temperature. Concentrations of larvae at three grid cells (Dover Straits, and entry into the Wadden Sea- Marsdiep, and one cell in the German Bight) from four model runs (standard-field temperature, 8°C, 9°C and 10°C) in 1988/1989. See Table 4.1.1 for standard settings. Data shown are daily moving averages of 24 hours.



Standard (variable field temperature) Fixed temperature at 8°C



Fixed temperature at 9°C Fixed temperature at 10°C

Figure 4.1.8. Herring sensitivity to temperature. Predicted concentrations of larvae in the middle of May 1989, assuming 4 different temperature regimes effecting development (field temperature, 8°C, 9°C and 10°C). See Table 4.1.1 for standard settings.

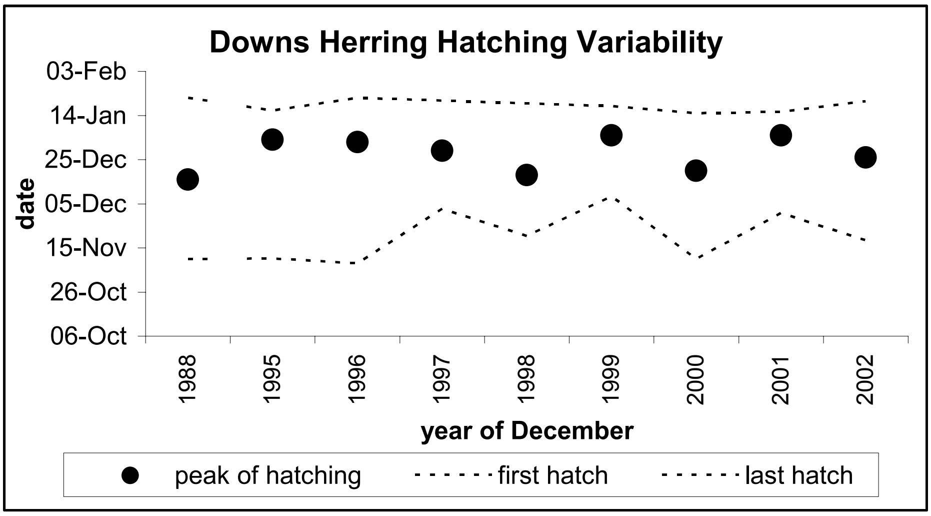


Figure 4.1.9. Herring – temporal distribution of Downs herring hatching of larvae. Taken from Fässler and Dickey-Collas internal RIVO report. From survey estimates of larval abundance (3 per hatching season) which are hind caste using growth models and fitted annual rates of daily mortality.

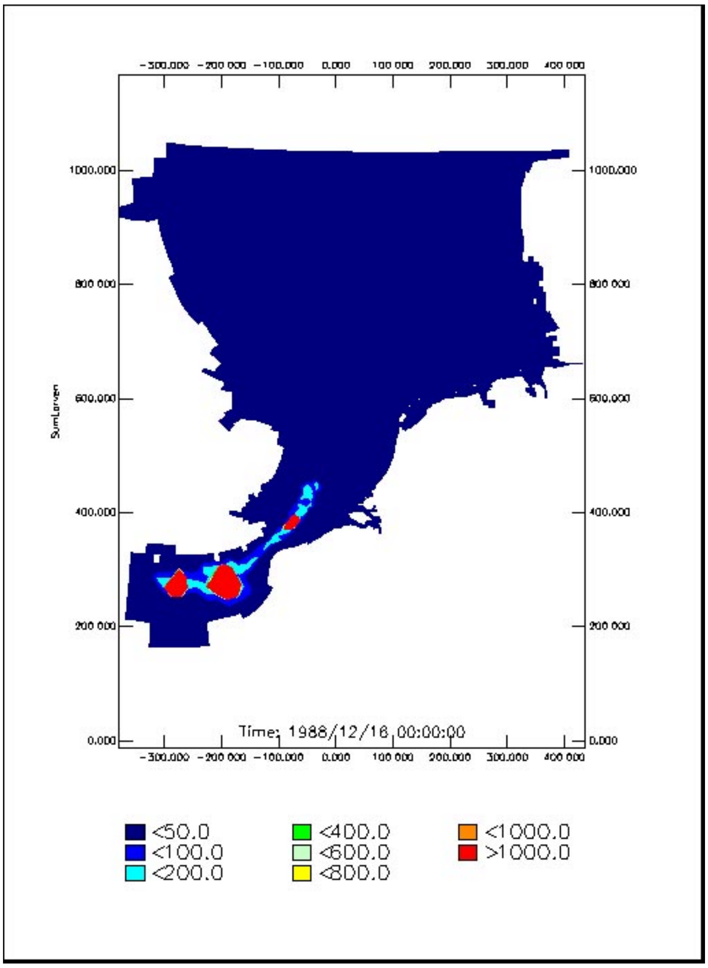


Figure 4.1.10. Herring Hatching Grid 2. Distribution of hatching larvae on the seabed used for testing the sensitivity of larval transport to inter-annual variability in hydrodynamics.

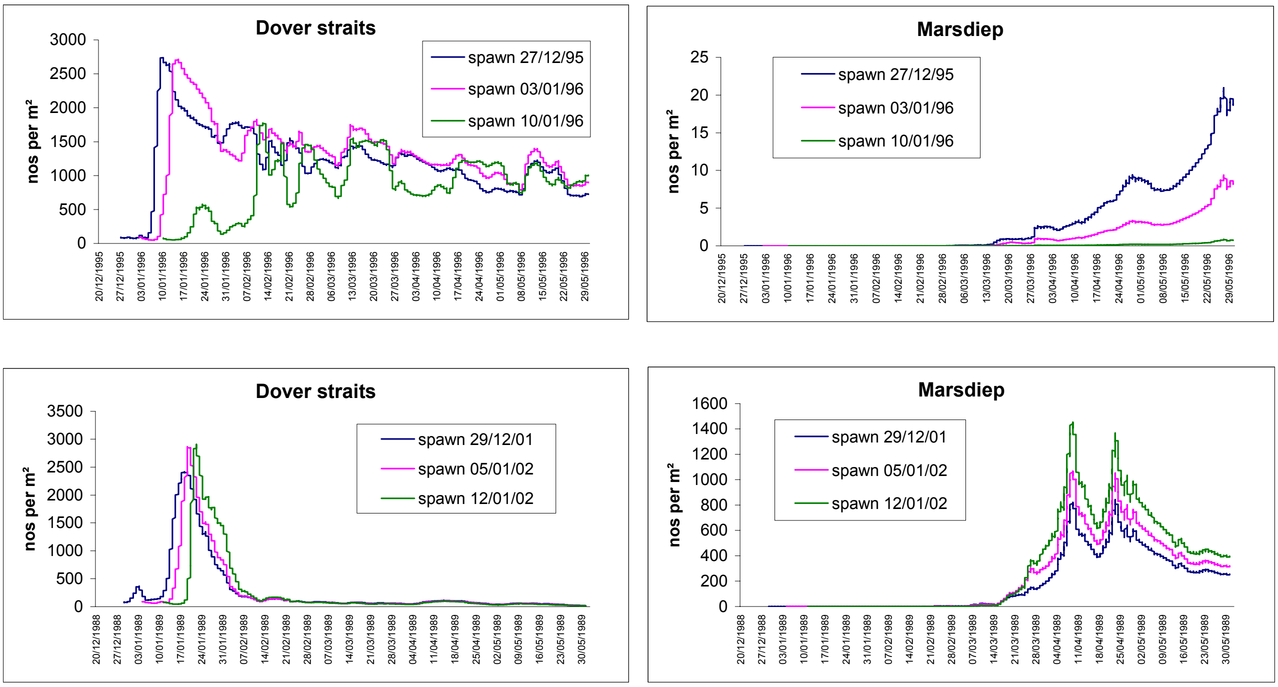
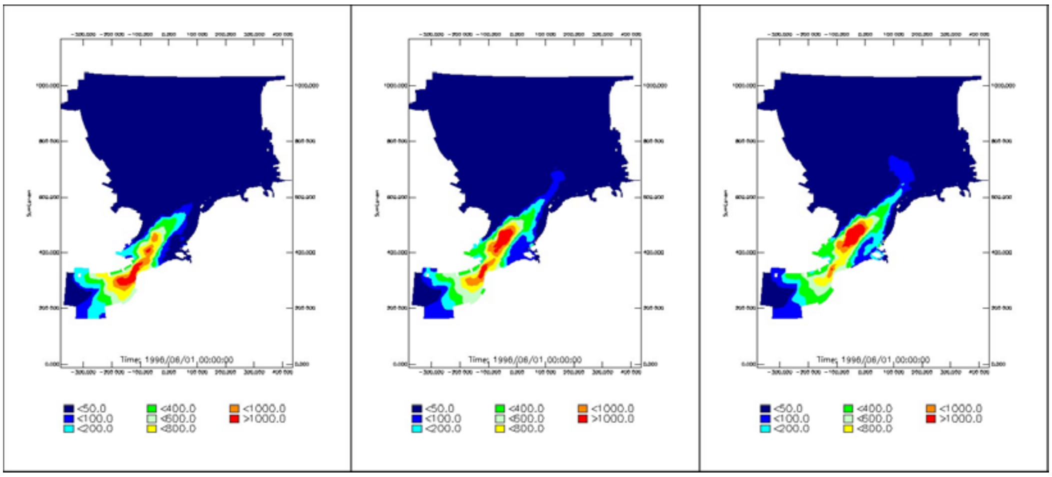
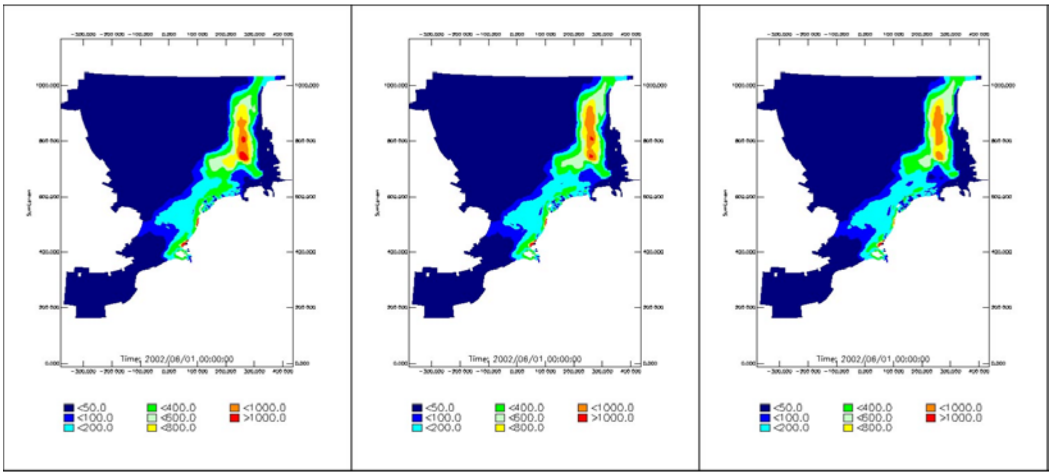


Figure 4.1.11. Herring sensitivity to hatch week. Concentrations of larvae at two grid cells (Dover Straits, and entry into the Wadden Sea- Marsdiep) from six model runs (hatching time varying across 2 weeks) in two years of widely differing hydrodynamics, 1995/1996 and 2001/2002. See Table 4.1.1 for standard settings. Data shown are daily moving averages of 24 hours.

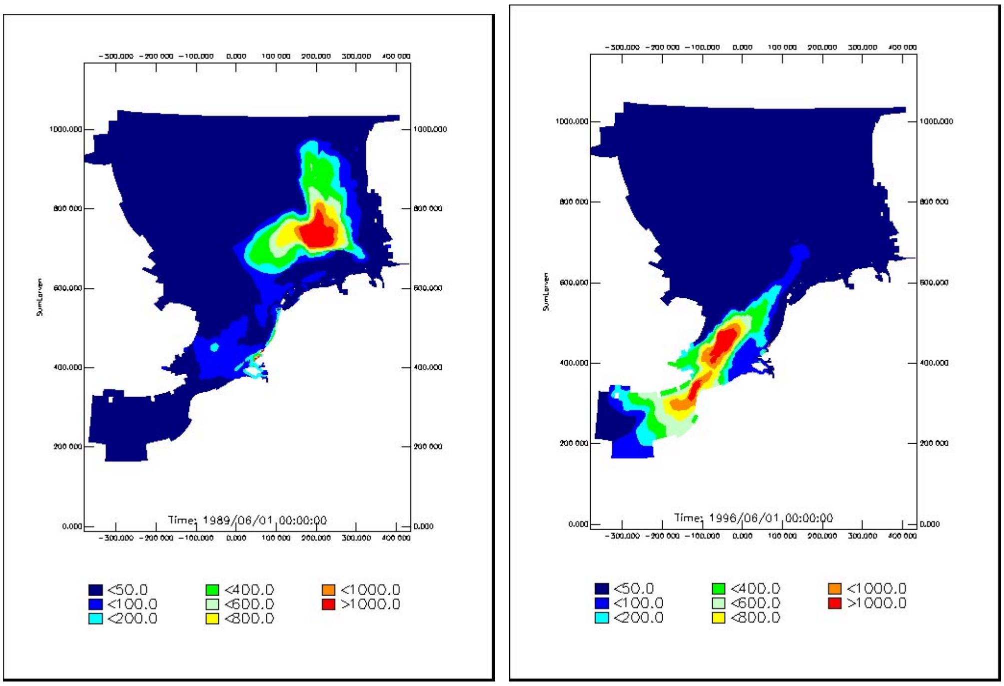


	Early	Peak	Late
Hatch:	27/12/1995	03/01/1996	10/01/1996



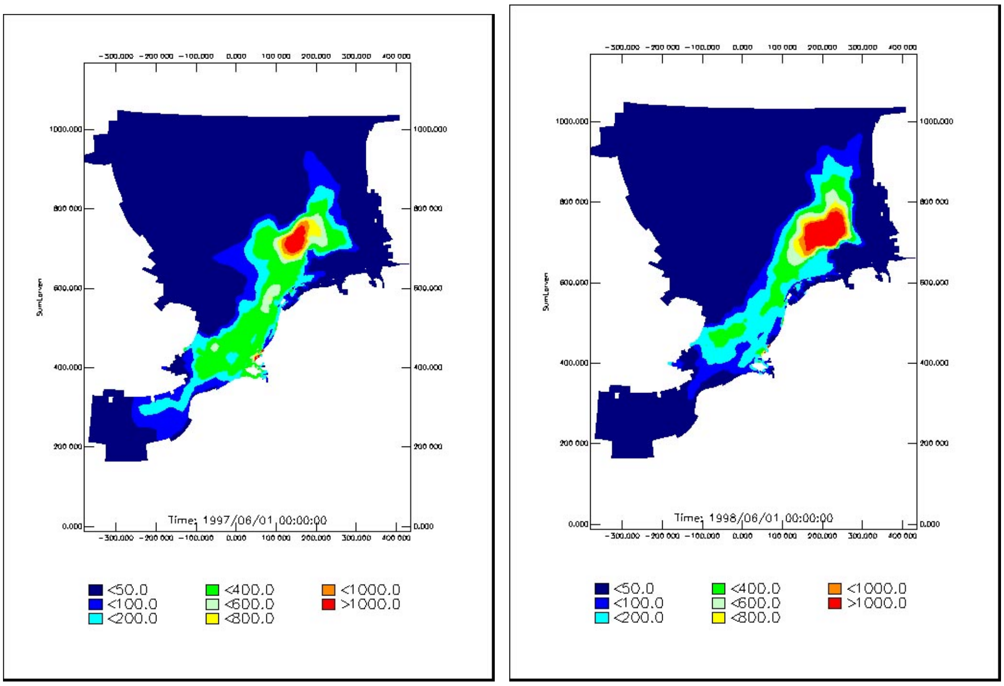
	Early	Peak	Late
Hatch:	29/12/2001	05/01/2002	12/01/2002

Figure 4.1.12. Herring – Predicted concentrations of larvae on the 31st May hatched either early, at the peak or late in the hatching season in 1995/1996 and 2001/2002. See Table 4.1.1 for standard settings, hatching from herring hatching grid 2.



Season Dec 1988 to May 1989

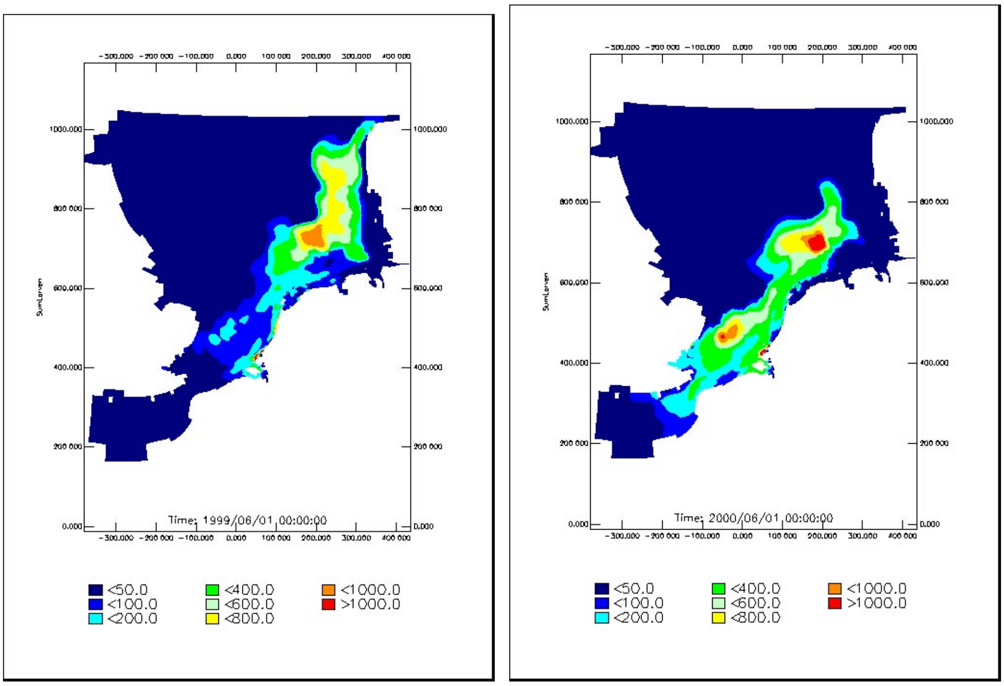
Season Dec 1995 to May 1996



Season Dec 1996 to May 1997

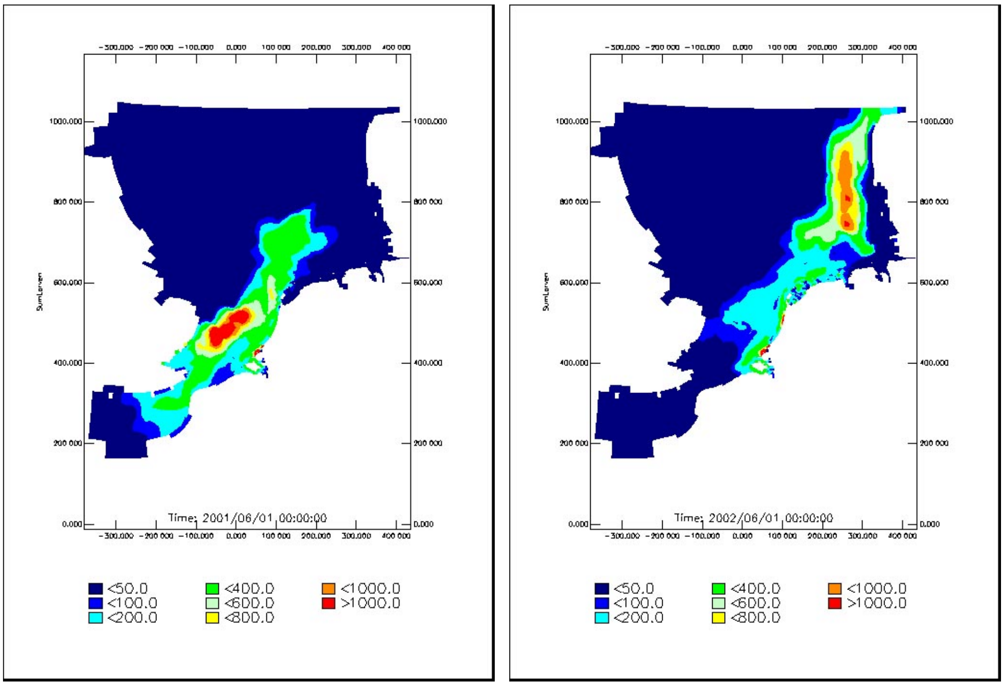
Season Dec 1997 to May 1998

Figure 4.1.13. Herring – Predicted concentrations of late stage postlarvae in late May by year: Results of transport simulations of herring larvae using the ZUNOGROF grid from hatch to the end of May for 9 selected years. See Table 4.1.1 for standard settings, hatching from herring hatching grid 2.



Season Dec 1998 to May 1999

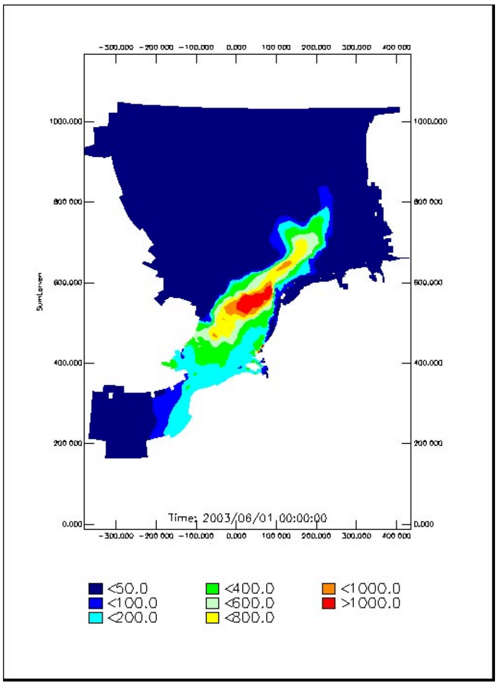
Season Dec 1999 to May 2000



Season Dec 2000 to May 2001

Season Dec 2001 to May 2002

Figure 4.1.13. Herring – continued.



Season Dec 2002 to May 2003

Figure 4.1.13. Herring – continued.

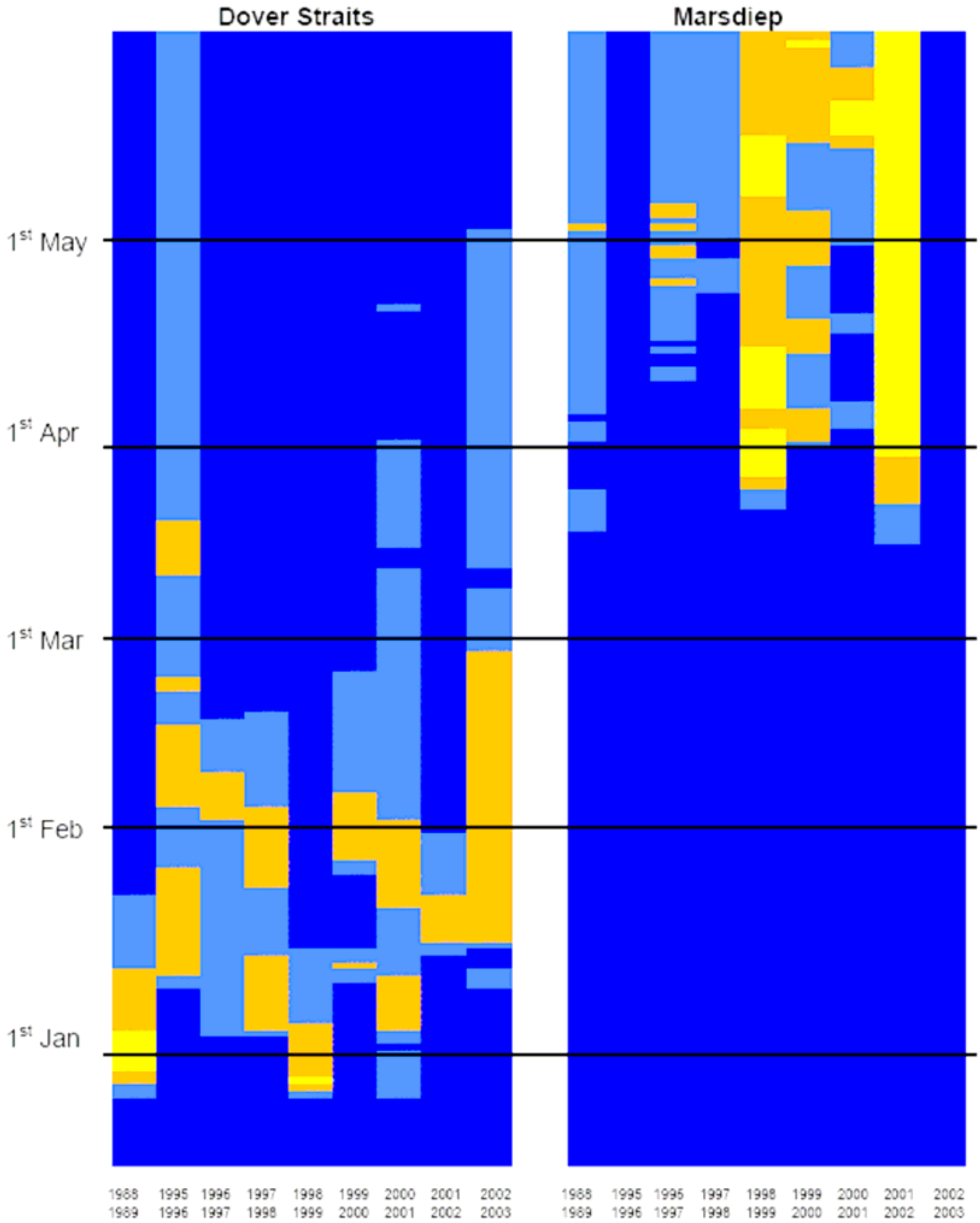


Figure 4.1.14. **Herring** – Timing of transport of larvae by year. Concentrations of larvae at two fixed points (The Straits of Dover and Marsdiep) from 9 simulated years. Each column represents 9 year's simulated concentrations at one point. Dark blue being the lowest concentrations and yellow being the highest (Dover Straits: yellow= >3000 per m², orange= >1500 per m², dark blue= <500 m², Marsdiep: yellow= >300 per m², orange= >150 per m², dark blue= <50 m²). See Table 4.1.1 for standard settings, hatching from herring hatching grid 2 on dates shown in Table 4.1.5.

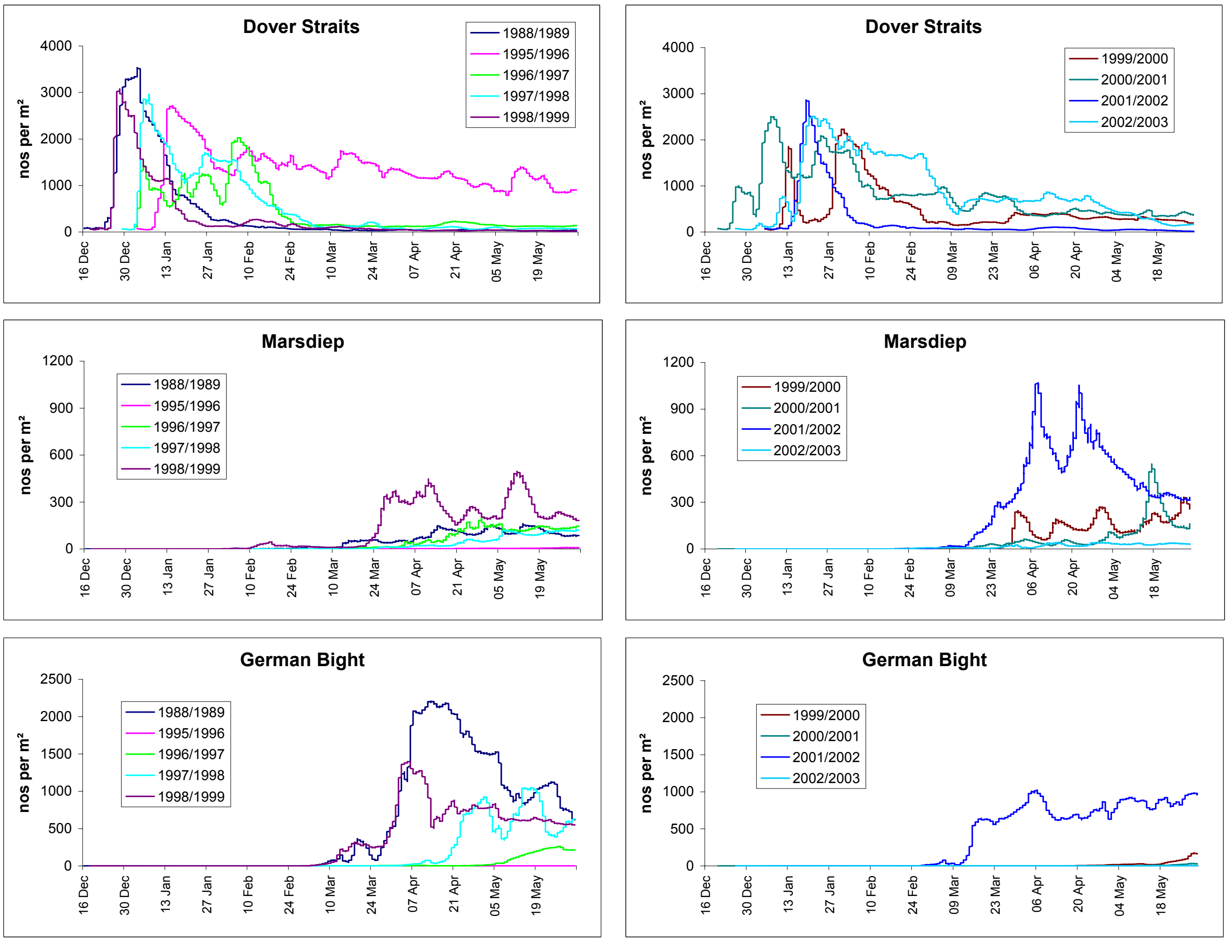
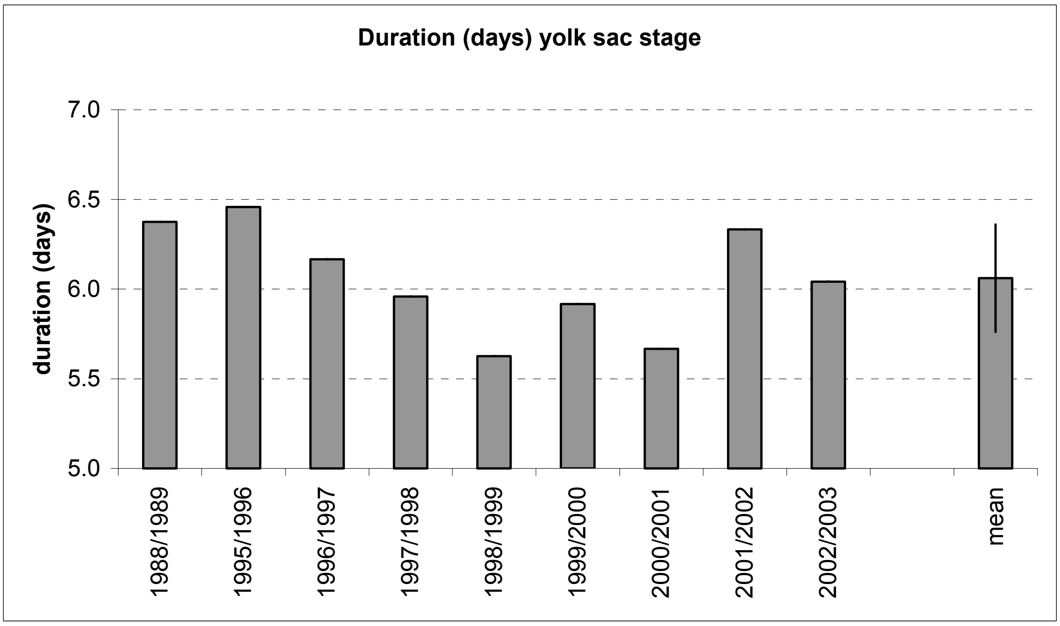


Figure 4.1.15. Herring between year variability. Concentrations of larvae at three grid cells (Dover Straits, and entry into the Wadden Sea- Marsdiep, and German Bight) from nine model runs with different hydrodynamics (based on years 1988/89 and 1995/1996 to 2002/2003) and hatch dates (Table 4.1.5). See Table 4.1.1 for standard settings. Data shown are daily moving averages of 24 hours.



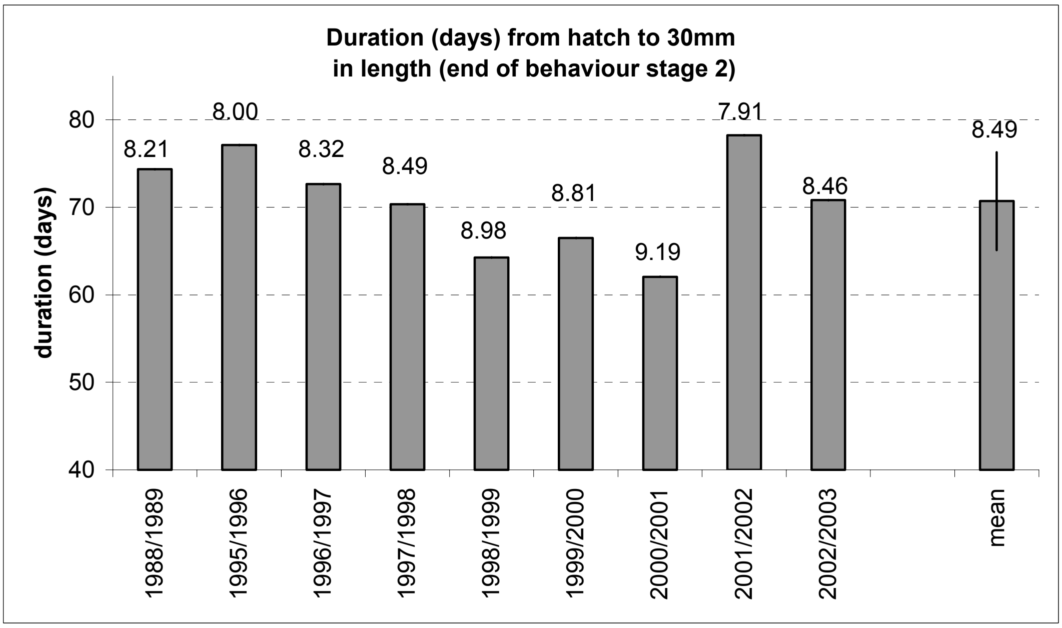


Figure 4.1.16. Herring between year variability in stage duration. Upper panel simulated duration of yolk sac stage in days, lower panel simulated duration from hatch to 30mm in length in days and labels show mean temperature of the larvae for that year (°C). Error bars denote one standard deviation of the mean duration.

4.2 Plaice

The egg and larval transport patterns are modelled based on species-specific biological input. However this input is subject to a certain degree of uncertainty and variability. Furthermore year-to-year variability in hydrodynamics and temperature may affect the model results. The sensitivity of the model for these potential sources of variability and uncertainty has been tested. The variables included in the analyses are listed in table 4.2.1 and discussed separately in the sections below. In all analyses the variables have been set to default values (last column in table 4.2.1) unless specified otherwise.

4.2.1 Spawning grounds

For plaice, the location of the spawning grounds is well documented (see section 2.2) and not considered to be an uncertain factor. A simplification of the distribution maps of stage I eggs as published by Harding et al. (1978) has been used as input for the model. The Southern Bight spawning ground (Figure 4.2.1.A) is considered to be the most important contributor to the nursery grounds in the Dutch Wadden Sea and is therefore used as input for most of the sensitivity analyses. A small proportion of the larvae from the eastern English Channel spawning grounds (Figure 4.2.1.B) and the spawning grounds south of the Dogger Bank (Figure 4.2.1.C) reach the Dutch Wadden Sea. All three spawning grounds combined have been used as input for the model runs carried out for validation purposes. The Southern Bight and eastern English Channel spawning grounds combined have been used as input for the impact assessment of MV2.

Published data indicate that there is little variation in the spatial distribution of spawning between years (see section 2.2). Therefore the location of the spawning grounds has been fixed for all model runs. The egg production per m^2 has also been fixed for all model runs. This however does not correspond with reality. Inter-annual variation in egg production does occur but egg productions are not estimated annually and can therefore not be used as model input. It is assumed that variations in egg production do not affect the geographic distribution of spawning and consequently will not affect the relative distribution of the eggs and larvae.

Figures 4.2.2 and 4.2.3 show the modelled distribution of the larvae and the end of the transport phase for the 3 spawning grounds included in the present study. In general, the eggs and larvae drift with the residual currents in northeasterly direction. Differences are observed between in years; in 1996 the northeasterly flow of eggs and larvae is much lower than in 1989 and 2000. The 9-year average (assuming stst) of the proportion spawned that reach the protected area is 19% for the Southern Bight spawning ground and 0.4% for the eastern English Channel spawning ground, and the overall transport success (i.e. to all nursery areas) is on average 40% and 31% respectively. The larval transport of plaice originating from the Dogger Bank spawning grounds has only been quantified for the 3 years included in Figure 4.2.3

4.2.2 Horizontal dispersion rate

The flatfish model with its two layers is essentially a 2D model. In this way, the flatfish model does not include dispersion due to vertical velocity shear and vertical mixing. In order to compensate for this, extra horizontal diffusion had to be added. This issue received detailed attention in the study on the impact of MV2 on nutrient dynamics, where it was found that a horizontal dispersion rate of 100 m^2/sec provided the best approximation.

The distribution pattern of larvae at the end of the transport phase is compared for 2 horizontal dispersion rates in Figure 4.2.4. Evidently the larvae are dispersed over a larger area if a higher dispersion rate is used.

4.2.3 Transport mechanisms

The transport of plaice eggs and larvae has been defined as passive pelagic, i.e. transported in the top water layer of the model without a behavioural component. This implies a homogeneous distribution of the eggs and larvae in the top water layer, which is plausible for the mixed waters of the southern North Sea (see section 2.2).

At the onset of metamorphosis the larvae move into the bottom water layer and either continue being transported passively or start selective tidal stream behaviour. Although selective tidal stream transport is known to occur in the late larval and early juvenile stages of plaice, the extent to which this behaviour is exhibited is debated (see section 2.2 and annex 2d). Introducing selective tidal stream transport (‘stst’) will by definition increase the proportion of larvae that reach the inshore areas. The alternative hypotheses, passive demersal transport (‘dem’) in the late larval and early juvenile stages, will give a lower proportion of the larvae reaching the inshore areas. These 2 hypotheses describe the potential range associated with stst behaviour. If the efficiency or occurrence of tidally related behaviour is high than the distribution pattern of the larvae will resemble the model results using selective tidal stream transport hypotheses, alternatively if the efficiency or occurrence of tidally related behaviour is low than this is best modelled using the passive demersal transport hypotheses. The increase in the proportion of larvae reaching a certain inshore area due to selective tidal stream transport is not necessarily linear. Therefore, most of the sensitivity analyses have been carried out for both transport hypotheses.

4.2.4 Definition of stst behaviour

Defining the process of selective tidal stream transport (stst) is not straightforward, because little is known about the conditions that trigger this behaviour, and the exact period in which this behaviour occurs is also uncertain. The latter is discussed in the following section. It is unlikely that a fish actually knows where the coast is; it presumably reacts to environmental cues. Flatfish can sense salinity changes (Jager, 1999b) and it is assumed that this is the environmental cue which both triggers stst behaviour as well as determines the direction of the coast. If the larvae stay on the seabed when salinity decreases and move into the water column when salinity increases, than the result will be that the larvae are transported towards the coast by the tidal currents. Although flatfish can sense salinity and stst behaviour has been reported for plaice, no experimental evidence exists which actually relates stst behaviour to salinity.

Stst has been observed in coastal waters and presumably does not occur further offshore. A logical way to incorporate this in the model would be to assume that the larvae only react to differences in salinity above a certain threshold. This approach has been tested but results in a very patchy distribution pattern, which is probably a reflection of the temporal resolution of the salinity data in the model and not a reflection of the real distribution of the larvae. In reality the larvae probably react to instantaneous salinity changes, whereas in the model the time step for salinity changes is 1 hour. An alternative approach to define the boundaries of the area in which stst occurs by depth.

Figure 4.2.5 shows the distribution of plaice larvae under different assumptions for stst. A salinity threshold of 0.5 ppt per 15 min (in effect an instantaneous salinity sensitivity of 2ppt) gives almost the same distribution pattern as in the situation without stst (compare Figure 4.2.5A and B). A salinity threshold of 0.5 ppt per 60 min does affect the distribution of the larvae, but in this case the distribution is very patchy (Figure 4.2.5C). A patchy distribution is also observed if no stst-thresholds are included in the model (Figure 4.2.5D). The results of the model runs using a depth threshold are more realistic (Figure 4.2.5E and F), and a depth threshold of 30m has (arbitrarily) been chosen as default setting for the model runs.

4.2.5 Duration transport

The duration of the egg and pelagic larval stages is determined by the growth parameters and the ambient temperature (see following section). It appears to be safe to assume that the larvae end their pelagic life-style at the onset of metamorphosis, because stage 4a larvae disappear from the pelagic offshore catches and appear in the inshore demersal and stow net catches (see appendix 2d). Uncertainty exists however on how long the transport phase can be continued after metamorphosis is completed. The recently metamorphosed juveniles probably continue to use selective tidal (or passive demersal) transport until they have reached a suitable nursery area. Gibson (1973) showed that on the more exposed coasts plaice appear to settle deeper and then move onshore into shallower water. The decision to stay or move can be determined by food availability (Creutzberg et al., 1978), or by predation pressure (Gibson et al., 2002), but this cannot be included in the model. It is uncertain how long the larvae/juveniles can survive in their search for a suitable nursery ground, no dedicated research addressing this issue has been published. Anecdotal information suggests that recently metamorphosed juveniles can survive at least 30 days without food. The delayed appearance of juveniles the German Bight (Rauck, 1974) suggests that the period of transport after metamorphosis may be longer.

The sensitivity of the model results has been tested for a situation with 0 days, 30 days and 60 days of selective tidal stream transport after metamorphosis is completed. Not surprisingly, the proportion of larvae that reaches the coastal nursery areas increases if the duration of the transport phase is prolonged (Figures 4.2.6-4.2.7). The geographical distribution of the larvae shifts towards the northeast with prolonged duration of transport. Despite this shift in distribution, the proportion of larvae that reaches the protected area is linearly related to the duration of the last transport phase (Figure 4.2.7). So, at least partly, the effect of the assumption on the duration of transport after metamorphosis is a scaling-effect.

4.2.6 Growth parameters

The development of the eggs and larvae is related to temperature, with higher temperatures giving higher development rates and shorter stage durations. This relationship is curvilinear and has been defined by an exponential regression: $\ln(D) = \alpha + \beta T$, in which D= stage duration and T=temperature. Several authors present estimates of the duration of egg and/or larval stages. These studies are based on laboratory experiments, day ring analyses (larval stages only) or peak densities by stage (egg stages only). In some cases the parameters of a fitted relationship have been published in other cases the observations have been presented. These published data have been used to obtain parameter estimates for an exponential regression for each behavioural stage (Table 4.2.2).

The different studies on egg stage duration produce very similar results. Note that the parameter estimates (logarithmic regression) presented by Talbot (1977) are probably based on the observations presented by Harding et al. (1978), and are therefore probably not an independent series. Relatively few stage duration estimates have been published for the larval stages of plaice. Therefore unpublished estimates based on day ring analyses have been included. Van der Veer et al. have estimated the larval stage durations for plaice settling in the western Wadden Sea in the years 1995-2002. The estimates for the years 1995-1996 have been published (Van der Veer et al., 2000), and for the remaining years were made available for the present study. Part of these data (1996, 1999, 2001, 2002), combined with the modelled temperature, has been used for the calibration of the growth parameters. The remaining data have been used for model validation (see section 5.2). Unpublished data were also provided by Audrey Geffen.

In general laboratory studies tend to underestimate development rates and the higher development rates estimated in field studies are considered to be more reliable (Russell, 1976). The highest development rates for each stage have been chosen as default setting for the model, with an exception for stage 2. The stage duration estimates published by Hovenkamp (1991) are very low, which, according to the author may be a bias due to an underestimation of the duration of the yolk-sac phase. The default growth parameters of stage 2 have been set to fit the stage durations of the unpublished data provided by Van der Veer and Geffen.

The sensitivity of the model for growth parameters has been tested by comparing the model results using default settings with those using the lowest development rates, and those using the higher development rates for stage 2 according to Hovenkamp (1991). The differences in stage 1 are negligible (Figure 4.2.8). The largest differences are observed in stage 2; compared to default settings, the stage duration is 14 to 20 days shorter if growth parameters according to Hovenkamp (1991) are used, and 11 to 13 days longer if growth parameters according to Talbot (1977) are used. In stage 3-5 the difference between the slower development rates (Talbot, 1977) and default settings (based on the unpublished day ring data by Van der Veer and Geffen) is 11-12 days.

The choice of growth parameters affects the modelled distribution of fish larvae. The proportion of larvae reaching the coastal nurseries as well as the regional distribution is affected. A decrease in growth rate appears to shift the distribution of the larvae towards the German Bight. A decreased growth rate does not cause a consistent increase or decrease of the proportion of larvae reaching the coastal nurseries or the protected area.

4.2.7 Spawning period

The spawning period of plaice in the Southern Bight is approximately a 3 month period with peak spawning in mid-January (see section 2.2). Inter-annual variability in the timing of spawning is considered to be small. Larval transport has been modelled assuming a single event of spawning on Jan 15th for the Southern Bight spawning population. This is a simplification of reality as plaice spawn for a period of approximately 3 months. The sensitivity of the model has been tested for different spawning times; the default setting of spawning on Jan 15th has been compared to spawning on Jan 1st and Feb 1st. These analyses clearly show that the variability in the distribution of larvae due to temporal differences in the hydrodynamics is large. In 1989, the northeasterly flow of larvae decreases if the spawning period is later. In 1996 the distribution of larvae is very different compared to 1989, but again the early spawned eggs and larvae appear to be transported further towards the German Bight than the eggs and larvae spawned later in the spawning season. The same effect is observed in 2000 (Figure 4.29 and 4.2.10). This may partly be caused by the fact that later spawners experience higher ambient temperatures and hence shorter stage durations. Although this effect is consistent over the 3 years examined, it is not unthinkable that the reverse effect can occur in other years, because the displacement in northeasterly direction is predominantly determined by the strength of the residual currents and thus related to (variable) weather conditions.

The sensitivity of the model for timing of spawning has not been tested for the spawning grounds in the eastern English Channel and south of the Dogger Bank. Peak spawning in the eastern English Channel is approximately 1 month earlier (model setting = Dec 15th), and in the Dogger Bank regions approximately 1 month later (model setting = Feb 15th) than in the Southern Bight.

4.2.8 Inter-annual variability

The inter-annual variability in the distribution of larvae is large. The 2 most extreme years of the 9 years examined are 1996 and 2002. In 1996 the eggs and larvae hardly leave the Southern Bight, whereas in 2002 the majority of eggs and larvae are transported to the eastern part of the southern North Sea (Figure 4.2.11 and 4.2.12). In 1989 and 1997 the northeasterly flow of larvae is relatively high compared to the years 1998 to 2001, and 2003. These differences are mainly generated in the pelagic egg and larval phases (Figures 4.2.11A and B). During the pelagic phase the larvae are transported along the coast and this displacement is related to the residual currents. The direction of transport during the late larval and early juvenile phase is mainly cross-shore, i.e. the larvae move towards the coast from the position they have reached during the pelagic phase. This cross-shore transport is achieved by passive demersal transport, but is more effective if the larvae/juveniles exhibit selective tidal stream transport (Figures 4.2.11C and D).

The large year-to-year variability is also evident if expressed as transport success to the protected area or to all nursery areas combined (Table 4.2.3). The proportion of larvae (from the Southern Bight spawning ground) that reaches the protected area ranges from 6% to 30% if selective tidal stream transport is assumed, and from 3% to 22% if passive demersal transport is assumed.

The time series of the densities (N/m^2) of larvae at several observation points in the southern North Sea (Figure 4.3.13) illustrate what can already be inferred from the distribution maps by stage (Figure 4.2.11). The inter-annual variability in the drift of larvae does not only result differences of the number of larvae reaching a certain nursery area, but also causes differences in the timing of arrival.

The year-to-year variability in the distribution of the larvae can be caused by 2 physical factors: water movements and temperature. Stage duration is related to temperature (Figure 4.2.14), as this is the way stage duration has been defined in the model (see section 4.2.7). Differences in stage duration affect the period in which the larvae drift along the shore and hence the distribution of the larvae/juveniles at the end of the transport phase. The effects of water movement and temperature can be disentangled by carrying out model runs with fixed temperature in stead of modelled temperatures, as is done for herring. However, based on the fact that 1996 and 2002 are the most extreme years in terms of larval dispersal (Figures 4.2.11 and 4.2.12) and that on the other hand, the temperature and stage duration in these 2 years are almost identical (Figure 4.2.14), it is concluded that water movement is by far the most important factor underlying the observed inter-annual variability.

4.2.9 Summary

The sensitivity analyses are summarized in Tables 4.2.4 and 4.2.5. Inter-annual variability and the variability and uncertainty in the duration of transport after metamorphosis has the greatest effect on the transport of larvae to the protected area (Table 4.2.4) and to all nurseries combined (Table 4.2.5). Note that the sensitivity of the model to variability/uncertainty in biological processes varies between years (Tables 4.2.4 and 4.2.5).

One of the purposes of the sensitivity analyses was to create a deterministic probability range to be able to assess the biological significance of any effects of MV2. It is assumed that the comparison of scenarios for the impact assessment of MV2 is not affected by the choice of year, i.e. the relative effect of MV2 will be the same in different years. This assumption, however, cannot be tested and the previous paragraph may give reason to doubt it.

The sensitivity analyses have focussed on the variability and uncertainty in the biological parameterisation of the model. Any potential uncertainty in the hydrodynamic forcing has not been included in the sensitivity analyses.

Table 4.2.1. Plaice. Overview sensitivity analyses

Variables	Classes		
	#	levels	default
horizontal dispersion	3	5, 50, 100 m^2/s	100
transport mechanism of last larval stage	2	dem, stst	stst
salinity threshold for stst	3	none, 0.5 ppt/15 min, 0.5ppt/60 min	none
depth threshold for stst	3	none, 20, 30m	30m
duration transport after metamorphosis	3	0, 1, 2 months	1 month
growth parameters	3	default, quicker, slower	default
spawning grounds	3	sb, ec, db	sb
spawning period	3	peak, -2, +2 weeks	peak
annual variability	9	1989, 1996-2003	1989

Table 4.2.2. Plaice – Growth parameters. Stage duration by temperature based on published estimates or regression parameters. An exponential regression, $\ln(D)=\alpha + \beta T$ in which D= stage duration and T=temperature, was (re-)fitted except if the temperature range was too small. The parameter estimates α and β are input parameters for the model, the default settings for each model stage area are printed bold.

model	**references**	α	β	**Stage duration if temperature =**							
				5	**6**	**7**	**8**	**10**	**11**	**12**	**x**
stage 1	**egg stages 1-5 ***										
passive pelagic	Apstein, 1909	3.70	-0.11	24	21	19	17	14	13	11	-
	Ryland and Nichols, 1975	3.95	-0.15	25	21	18	16	12	10	9	-
	Talbot, 1977	3.94	-0.15	25	21	18	16	12	10	9	-
	Harding et al., 1978	3.64	-0.10	23	21	19	17	14	13	12	-
model settings		**3.95**	**-0.15**	**25**	**21**	**18**	**16**	**12**	**10**	**9**	-
stage 2	**larval stages 1-3 ****										
passive pelagic	Dannevig, 1897	-	-	-	-	-	-	-	-	-	35
	Ryland, 1966	-	-	-	-	49	49	-	-	-	-
	Talbot, 1977	5.43	-0.18	91	76	63	52	36	30	25	-
	Harding et al., 1978	-	-	-	70	70	-	-	-	-	-
	Hovenkamp, 1991	-	-	49	-	36	30	-	-	-	-
	unpubl Geffen	-	-	-	-	-	-	33	-	-	-
	unpubl Van der Veer	-	-	-	-	50	47	-	-	-	-
model settings		**5.00**	**-0.15**	**70**	**60**	**52**	**45**	**33**	**29**	**25**	-
stage 3 or 4	**larval stages 4-5 ****										
demersal or stst	Dannevig, 1897	-	-	-	-	-	-	-	-	-	10
	Ryland, 1966	-	-	-	-	-	-	17	17	-	-
	Talbot, 1977	4.53	-0.16	41	35	30	25	18	16	13	-
	Harding et al., 1978	-	-	-	34	34	-	-	-	-	-
	unpubl Geffen	-	-	-	-	-	-	5	-	-	-
	unpubl Van der Veer	-	-	-	-	9	9	-	-	-	-
model settings		**3.40**	**-0.15**	**14**	**12**	**10**	**9**	**7**	**6**	**5**	-
total				**109**	**94**	**81**	**69**	**51**	**44**	**38**	

* according to definitions Ryland and Nichols (1975)

** according to definitions by Ryland (1966)

Table 4.2.3. Plaice – Inter-annual variability. For each year and both transport mechanisms (stst = selective tidal stream transport; dem = passive demersal transport), the proportion of the total number spawned in the Southern Bight that reaches the protected area or all coastal nursery areas.

year	Transport succes to protected area		Transport succes to all nursery area's	
	stst	dem	stst	dem
1989	17%	9.2%	34%	13%
1996	9%	5%	41%	24%
1997	9%	6%	21%	8%
1998	23%	18%	42%	24%
1999	22%	19%	39%	24%
2000	30%	22%	45%	27%
2001	24%	17%	53%	33%
2002	6%	3%	37%	11%
2003	28%	18%	47%	25%
mean	19%	13%	40%	21%
sd	9%	7%	9%	8%

Table 4.2.4. Plaice – Summary sensitivity analyses. Variability in the transport success to the protected area due to natural variability and uncertainty of the assumptions.

Variable	Spawning ground	Transport type	Year	min	max	mean	sd	CV	Variability (range/mean)
Annual variability	SB	stst	9	6%	30%	19%	9%	47%	129%
		dem	9	3%	22%	13%	7%	53%	140%
	SB+EC	stst	9	3%	15%	10%	4%	46%	126%
		dem	9	2%	11%	7%	3%	53%	138%
	SB+EC+DB	stst	9	2%	9%	6%	3%	45%	125%
		dem	9	1%	2%	1%	0.4%	33%	105%
Duration transport	SB	stst	1989	5%	23%	15%	9%	60%	118%
			1996	3%	16%	10%	6%	68%	137%
			2000	11%	42%	28%	15%	56%	111%
Growth parmeters	SB	stst	1989	14%	20%	17%	3%	17%	34%
			1996	9%	12%	10%	1%	14%	25%
			2000	24%	35%	30%	6%	19%	37%
Spawning period	SB	stst	1989	10%	17%	15%	4%	26%	46%
			1996	9%	17%	12%	4%	32%	60%
			2000	24%	36%	30%	6%	20%	41%

Table 4.2.5 Plaice – Summary sensitivity analyses. Variability in the transport success to all nursery areas due to natural variability and uncertainty of the assumptions.

Variable	Spawning ground	Transport type	Year	min	max	mean	sd	CV	Variability (range/mean)
Annual variability	SB	stst	9	21%	53%	40%	9%	23%	79%
		dem	9	8%	33%	21%	8%	39%	118%
	SB+EC	stst	9	23%	42%	35%	6%	16%	54%
		dem	9	9%	22%	16%	4%	27%	82%
	SB+EC+DB	stst	9	15%	26%	22%	4%	16%	51%
		dem	9	5%	6%	5%	1%	11%	28%
Duration transport	SB	stst	1989	9%	54%	32%	23%	71%	141%
			1996	19%	63%	41%	22%	53%	106%
			2000	16%	63%	42%	23%	57%	112%
Growth parmeters	SB	stst	1989	34%	51%	41%	9%	22%	43%
			1996	41%	55%	48%	7%	15%	30%
			2000	36%	50%	44%	7%	15%	31%
Spawning period	SB	stst	1989	31%	35%	33%	2%	7%	14%
			1996	35%	41%	39%	3%	8%	15%
			2000	36%	47%	43%	6%	14%	27%

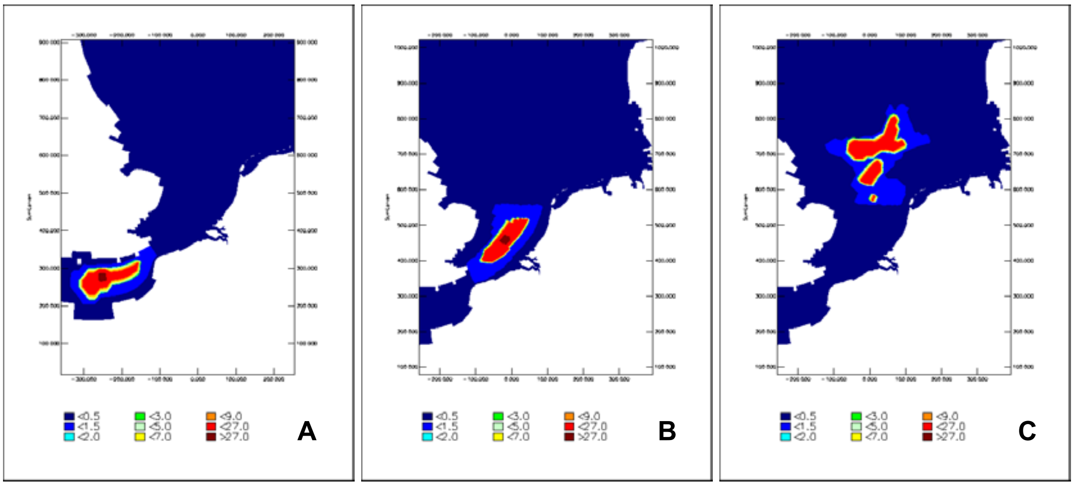


Figure 4.2.1. Plaice – Spawning grounds in the eastern English Channel (A), Southern Bight (B), and south of the Dogger Bank (C).

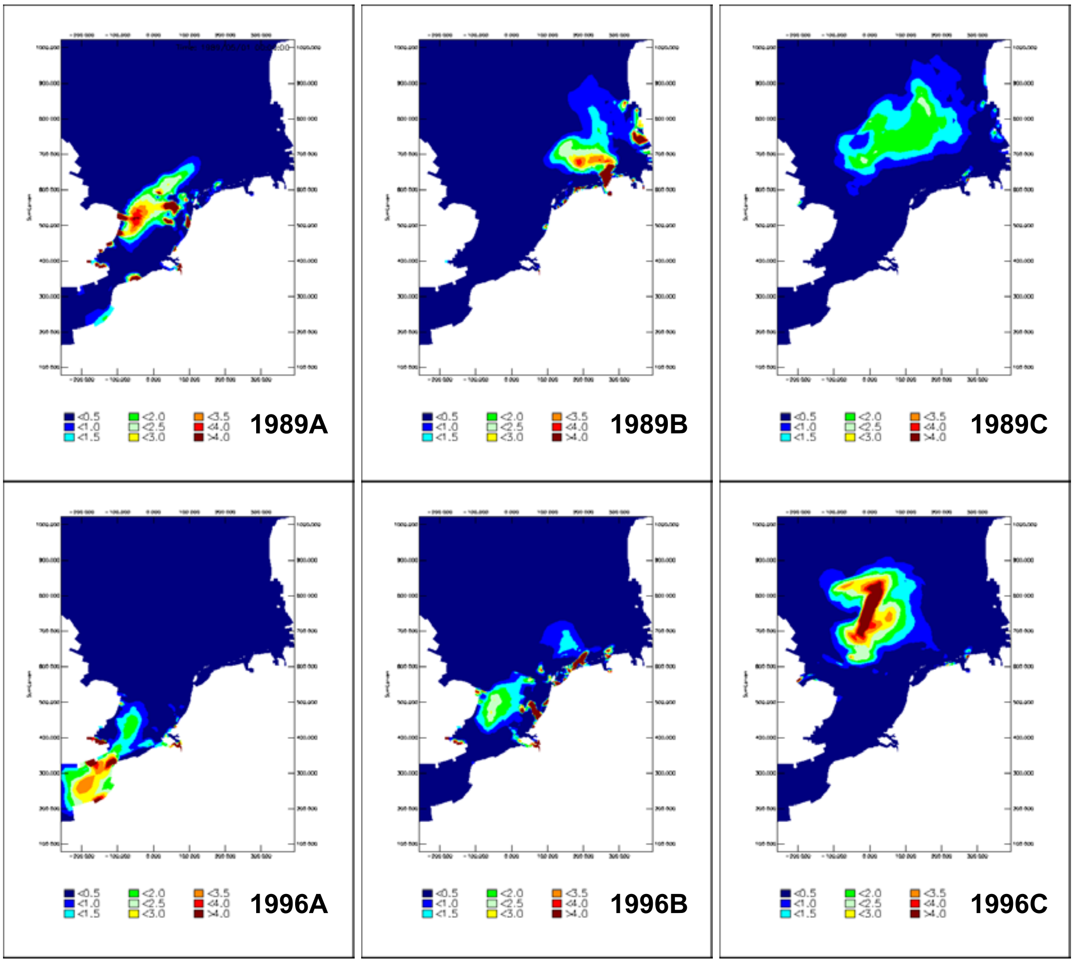


Figure 4.2.2. Plaice – Spawning grounds. Distribution pattern at the end of the transport phase for larvae originating from spawning grounds in the eastern English Channel (A), the Southern Bight (B), and south of the Dogger Bank (C), for the years 1989 and 1996.

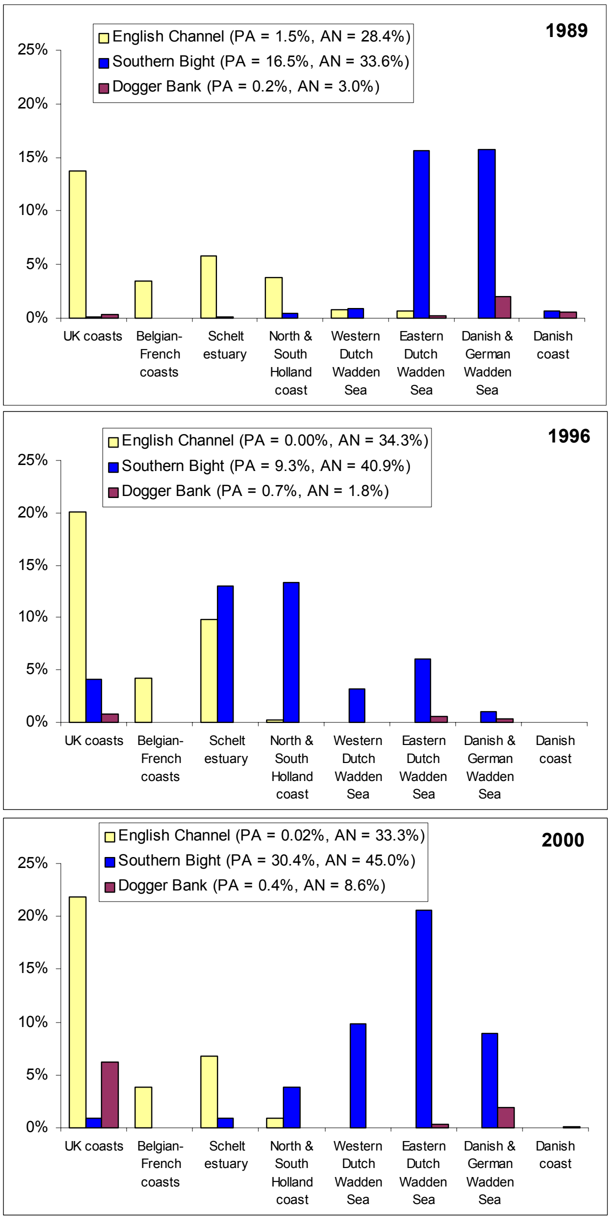


Figure 4.2.3. Plaice – Spawning grounds. Transport success by region for larvae originating from the spawning grounds in the eastern English Channel, the Southern Bight, and south of the Dogger Bank for the years 1989, 1996 and 2000. The proportion of larvae that reach the protected area (PA) or all nursery areas combined (AN) is listed in the legends.

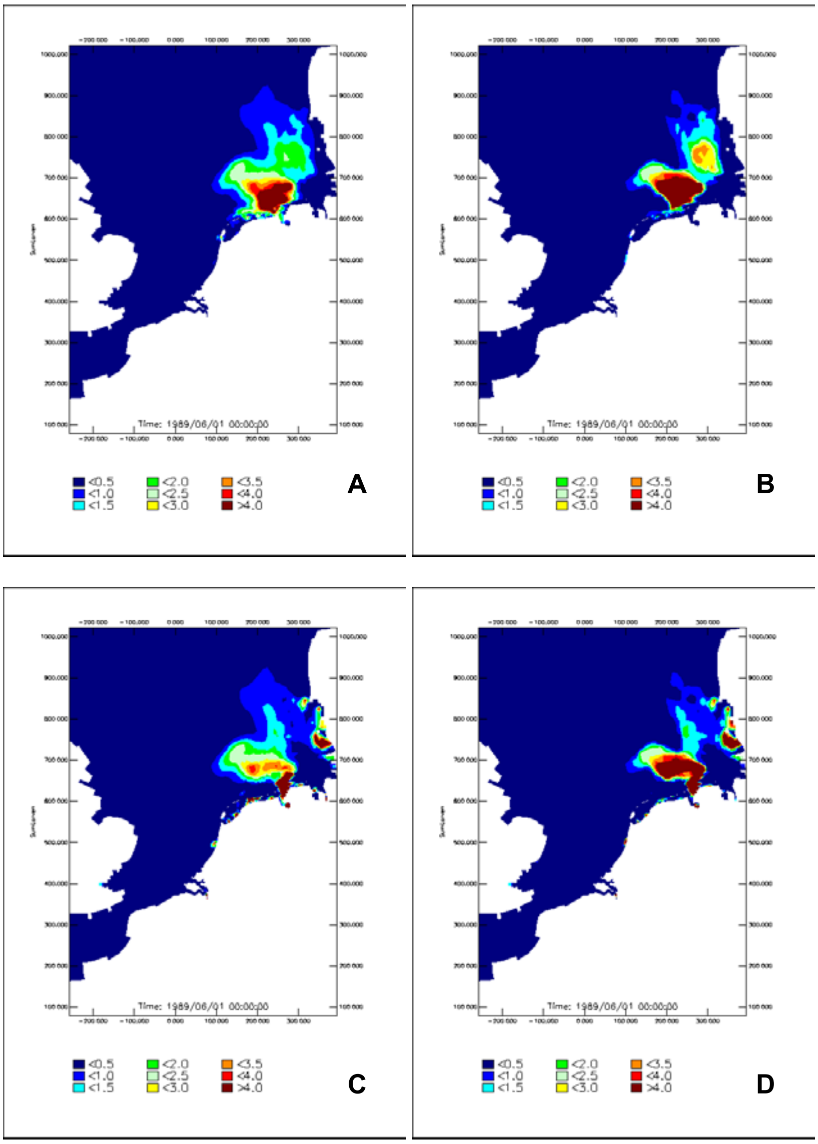


Figure 4.2.4. Plaice – Horizontal dispersion. Distribution pattern at the end of the transport phase assuming a horizontal dispersion rate of 100 m^2/s (A & C) or 5 m^2/s (B & D), and passive demersal transport (A & B) or selective tidal stream transport (C & D) in the late larval and early juvenile stages.

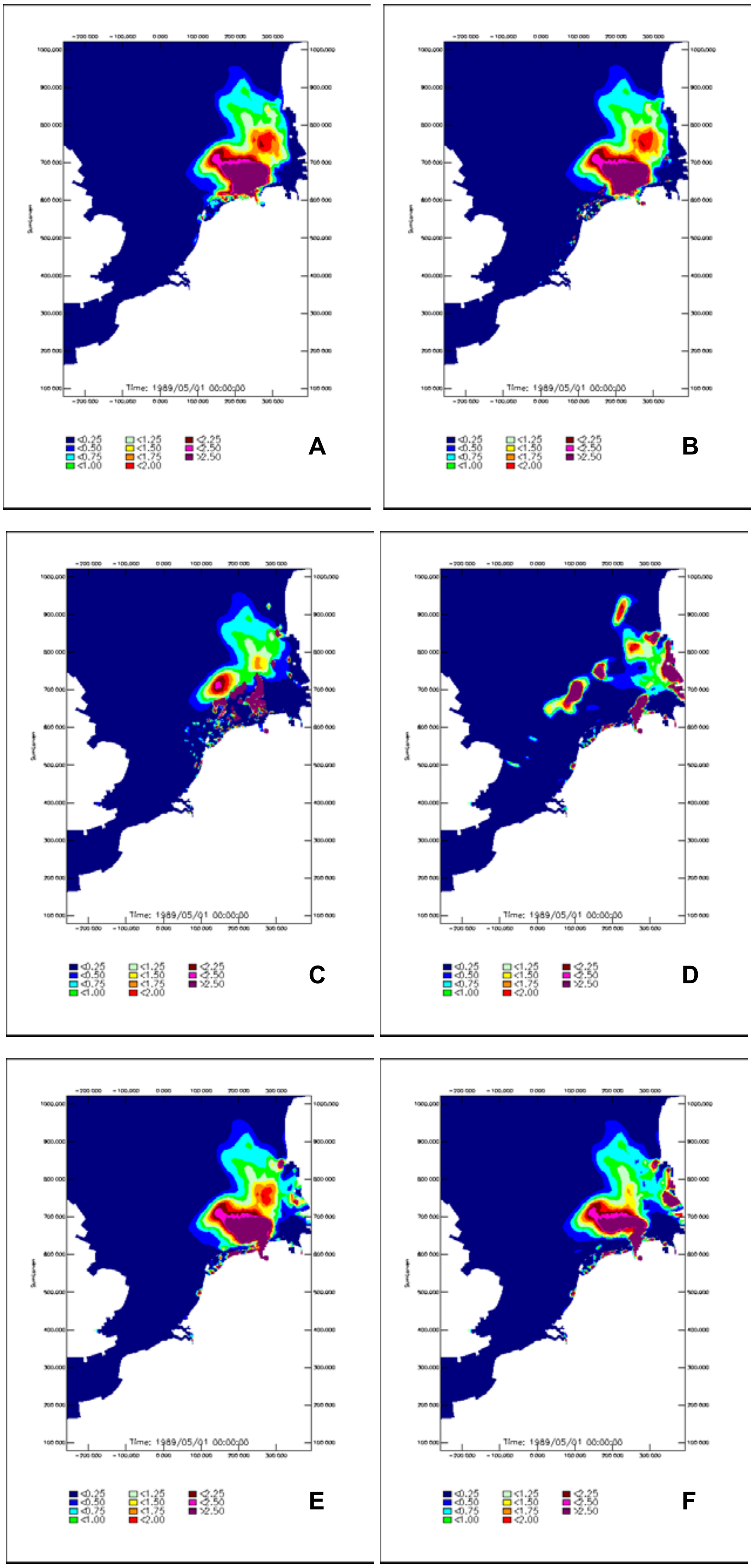


Figure 4.2.5. Plaice – Thresholds for stst behaviour. Distribution pattern at the end of the transport phase without stst behaviour (A), with stst behaviour and a salinity threshold of 0.5 ppt per 15 min (B), a salinity threshold of 0.5 ppt per 60 min (C), no threshold (D), a depth threshold of 20 m (E) and a depth threshold of 30 m (F).

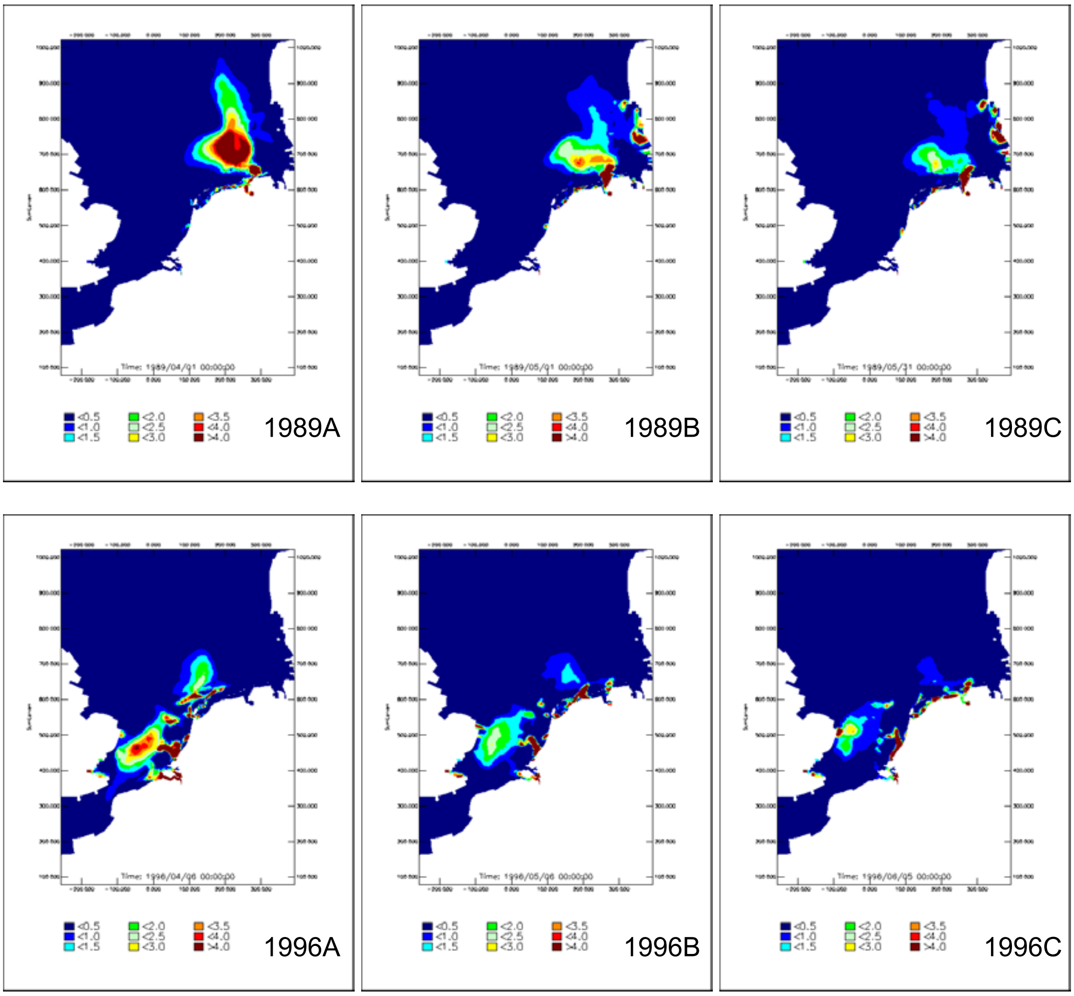


Figure 4.2.6. Plaice – Duration transport after metamorphosis. Distribution pattern at the end of the transport phase if the duration of transport after metamorphosis is 0 (A), 30 (B) or 60 (C) days for the years 1989 and 1996. The plaice originate form the Southern Bight spawning ground and selective tidal stream transport is assumed for the late larval and early juvenile stages

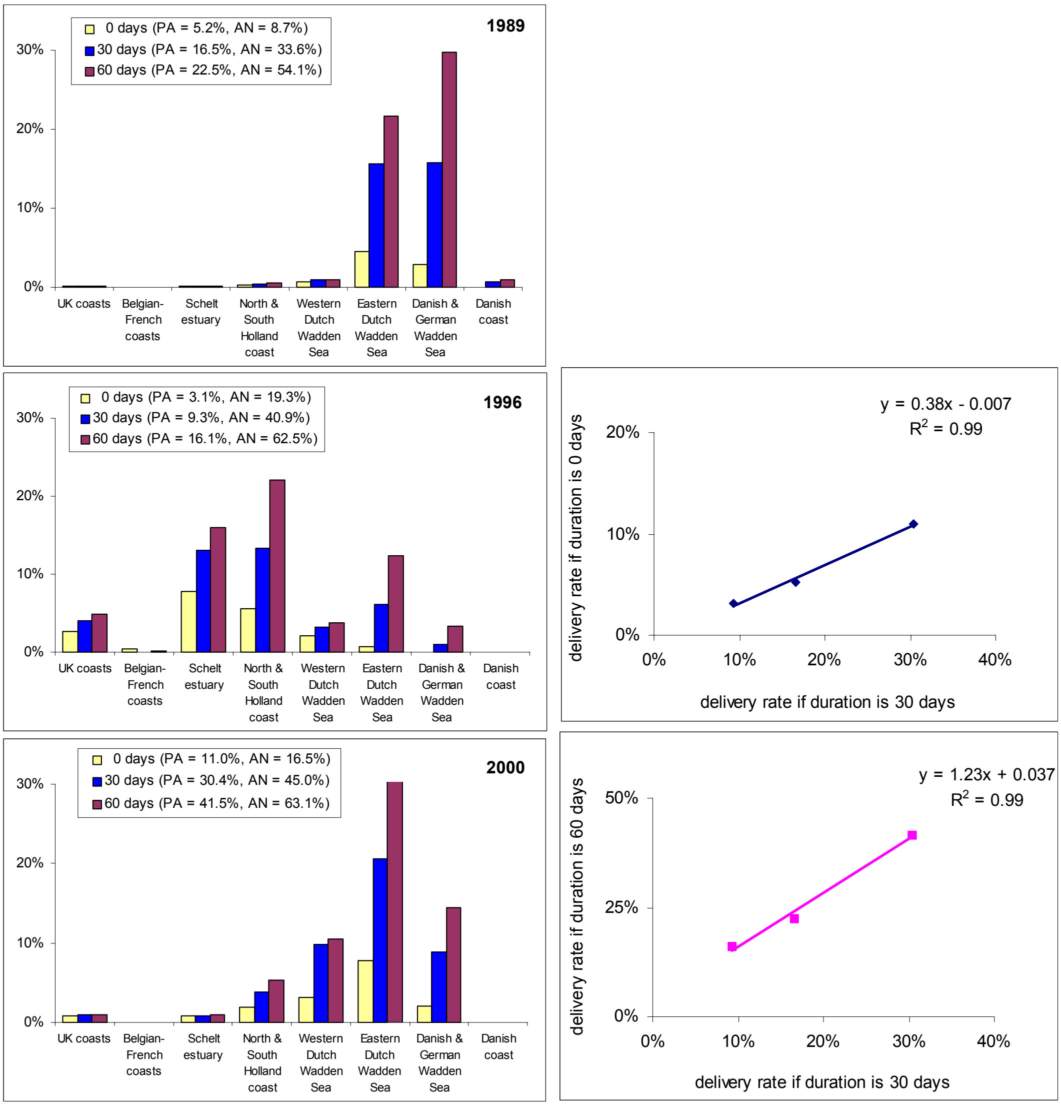


Figure 4.2.7. Plaice – Duration transport after metamorphosis. Left panels: Transport success by region for 3 years (1989, 1996 and 2000) and for 3 assumptions on the duration of transport after metamorphosis (0, 30 or 60 days), the proportion of larvae that reach the protected area (PA) or all nursery areas combined (AN) is listed in the legends. Right panels: the correlation between the proportion of larvae that reach the protected area assuming a prolongation of the transport phase by 30 days and 0 days (top panel), or 30 days and 60 days (bottom panel).

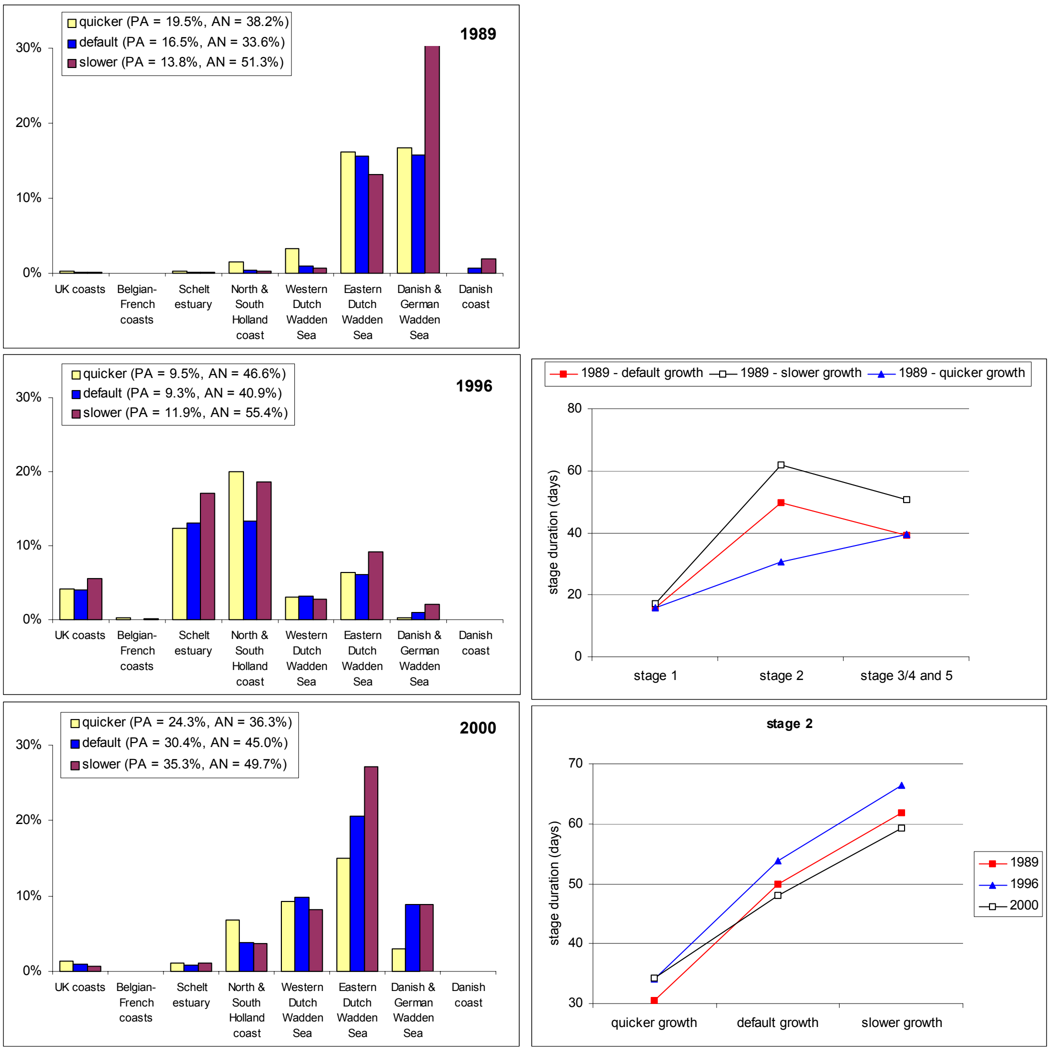


Figure 4.2.8. Plaice – Growth parameters. Left panels: Transport success by region for 3 years (1989, 1996 and 2000) and for 3 hypotheses on development rates (default; slower based on Apstein, 1909 and Talbot, 1977; quicker based on Hovenkamp, 1991, see table 4.2.2). The proportion of larvae that reach the protected area (PA) or all nursery areas combined (AN) is listed in the legends. Top right panel: stage durations in 1989 for the 3 hypotheses on development rates. Bottom right panel: Duration of stage 2 for 3 years and the 3 hypotheses on development rates.

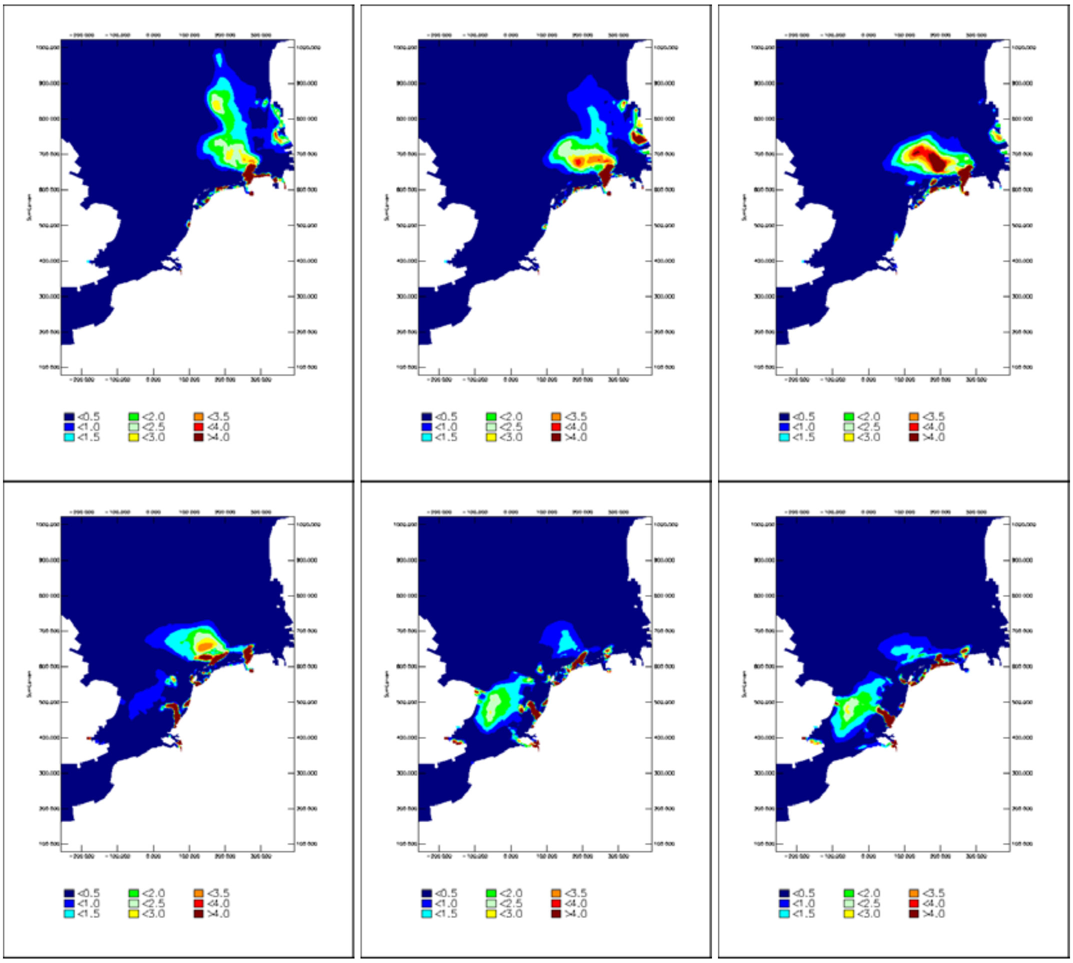


Figure 4.2.9. Plaice – Spawning period. Distribution pattern at the end of the transport phase if spawned at peak spawning (B), 2 weeks earlier (A) or 2 weeks later (C) for the years 1989 and 1996. The plaice originate form the Southern Bight spawning ground and selective tidal stream transport is assumed for the late larval and early juvenile stages.

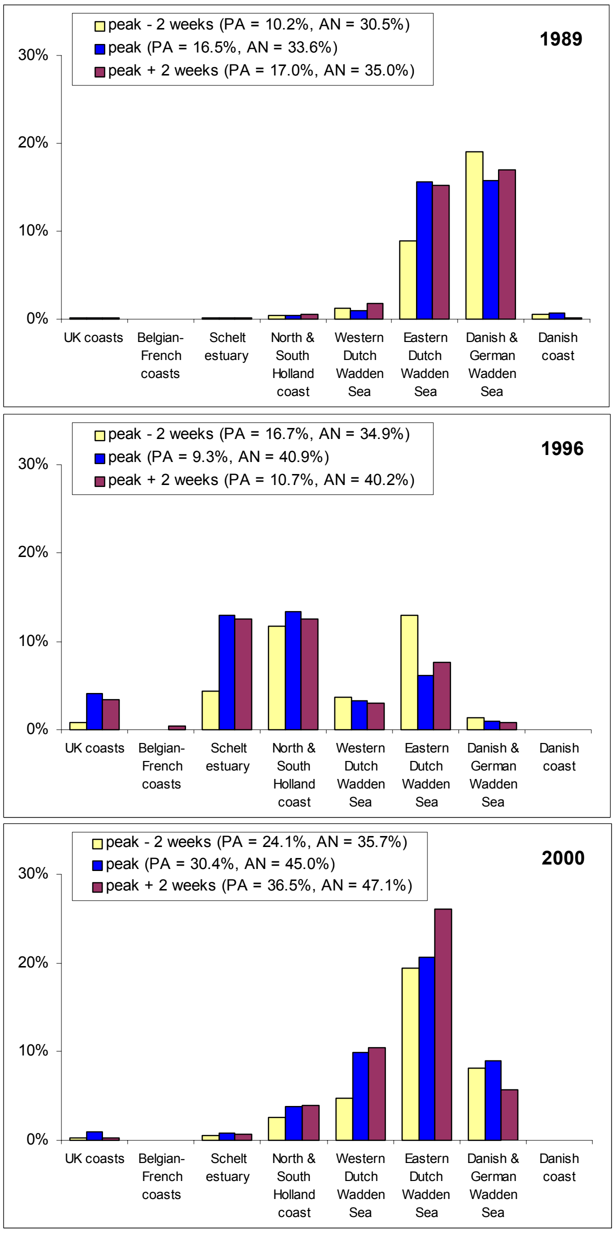
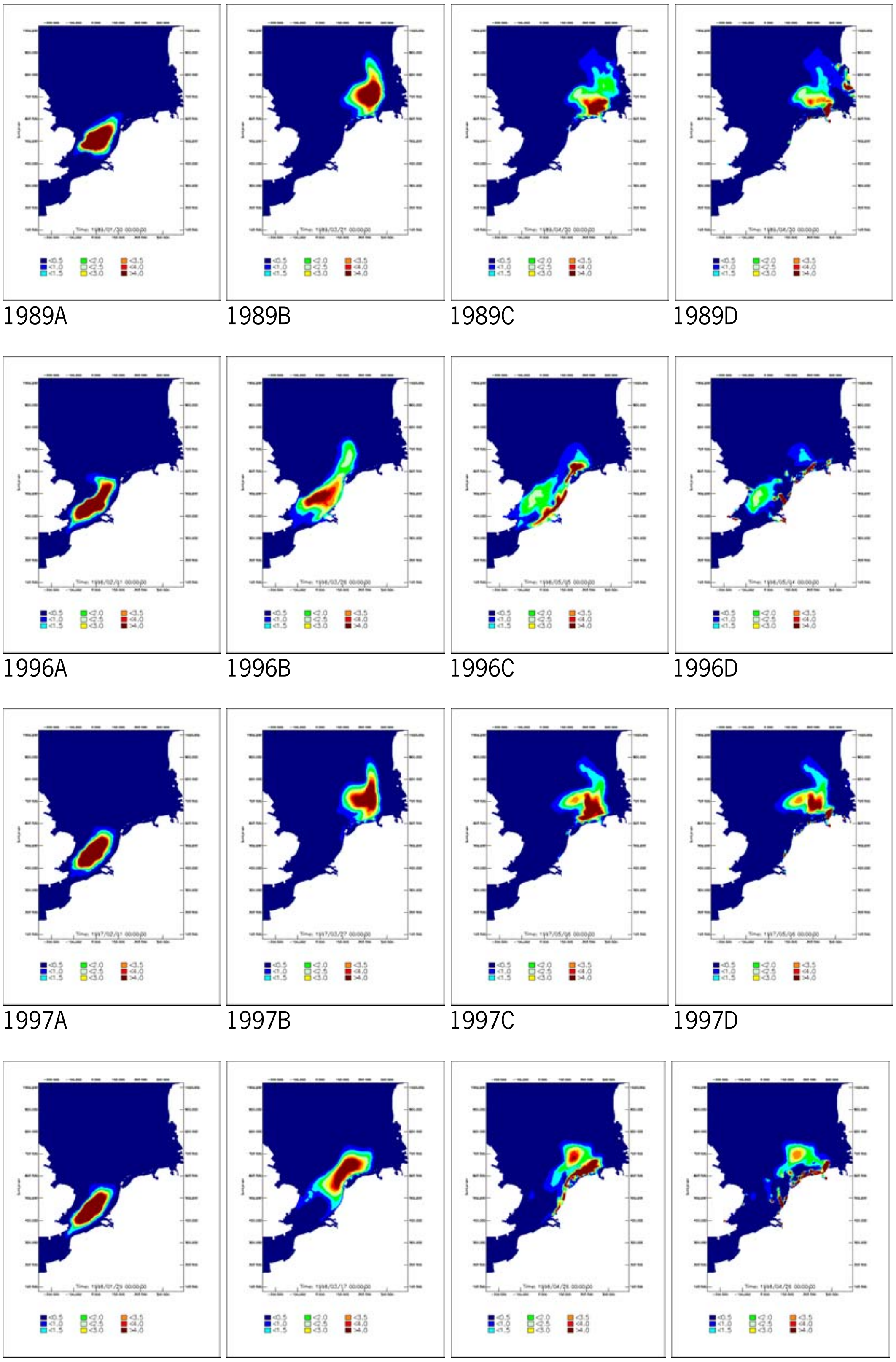


Figure 4.2.10. Plaice – Spawning period. Transport success by region for 3 years (1989, 1996 and 2000) and for 3 hypotheses on spawning date (peak spawning, 2 weeks earlier, 2 weeks later). The proportion of larvae that reach the protected area (PA) or all nursery areas combined (AN) is listed in the legends.



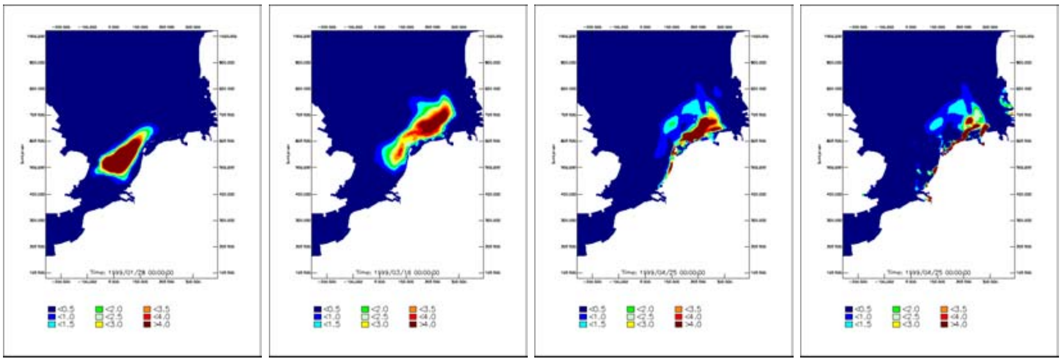
1989A 1989B 1989C 1989D

1996A 1996B 1996C 1996D

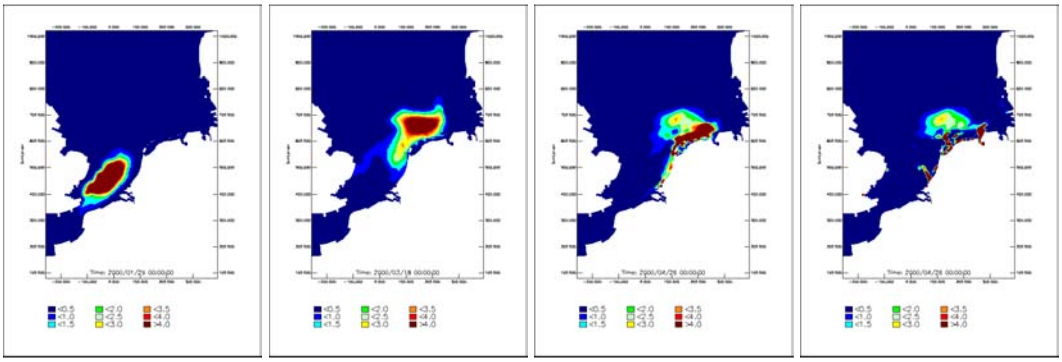
1997A 1997B 1997C 1997D

1998A 1998B 1998C 1998D

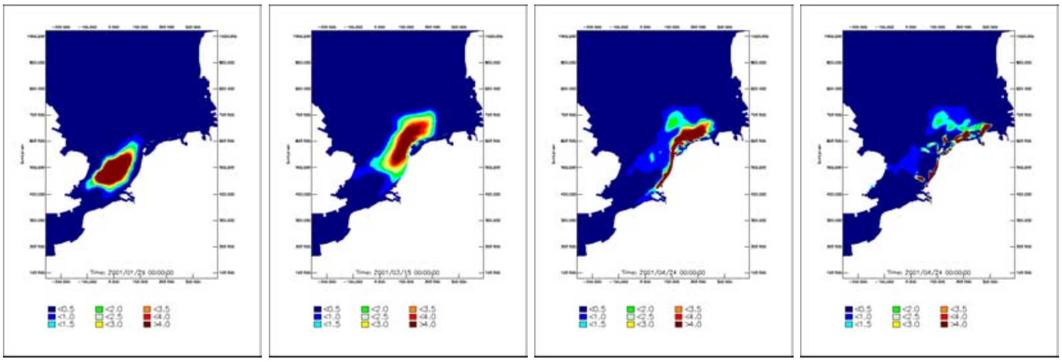
Figure 4.2.11. Plaice – Inter-annual variability. Distribution pattern at the end of the egg stage (A); the pelagic larval stage (B); the transport phase assuming passive demersal transport (C) or selective tidal stream transport (D) in the late larval and early juvenile stages.



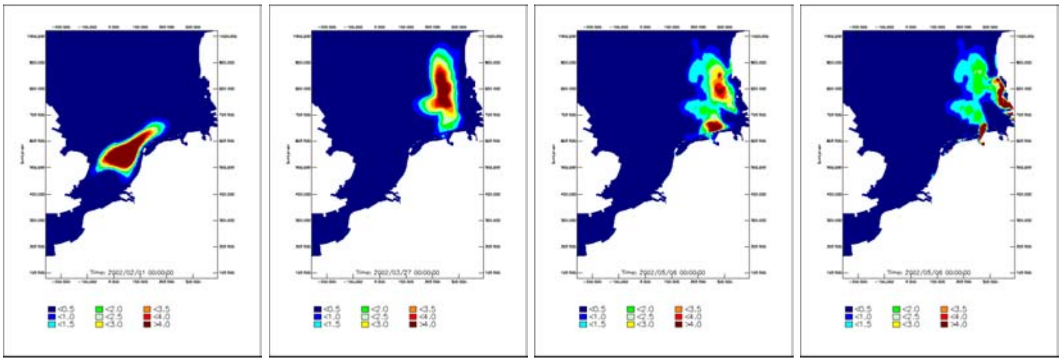
1999A 1999B 1999C 1999D



2000A 2000B 2000C 2000D

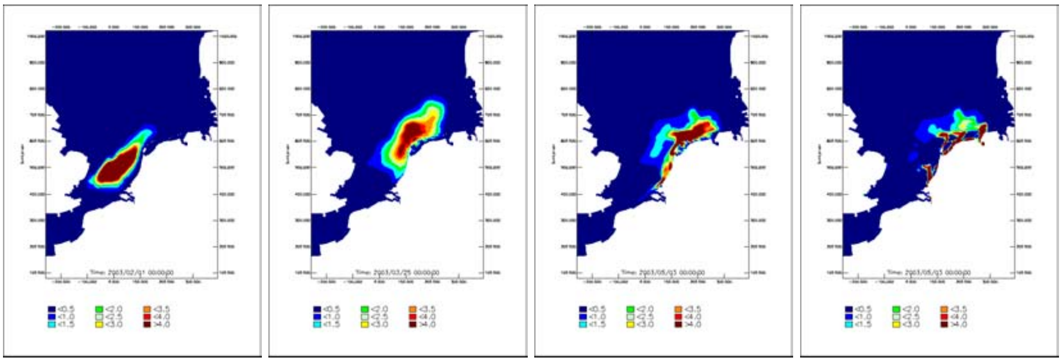


2001A 2001B 2001C 2001D



2002A 2002B 2002C 2002D

Figure 4.2.11. Plaice – Inter-annual variability. Continued.



2003A 2003B 2003C 2003D

Figure 4.2.11. Plaice – Inter-annual variability. Continued.

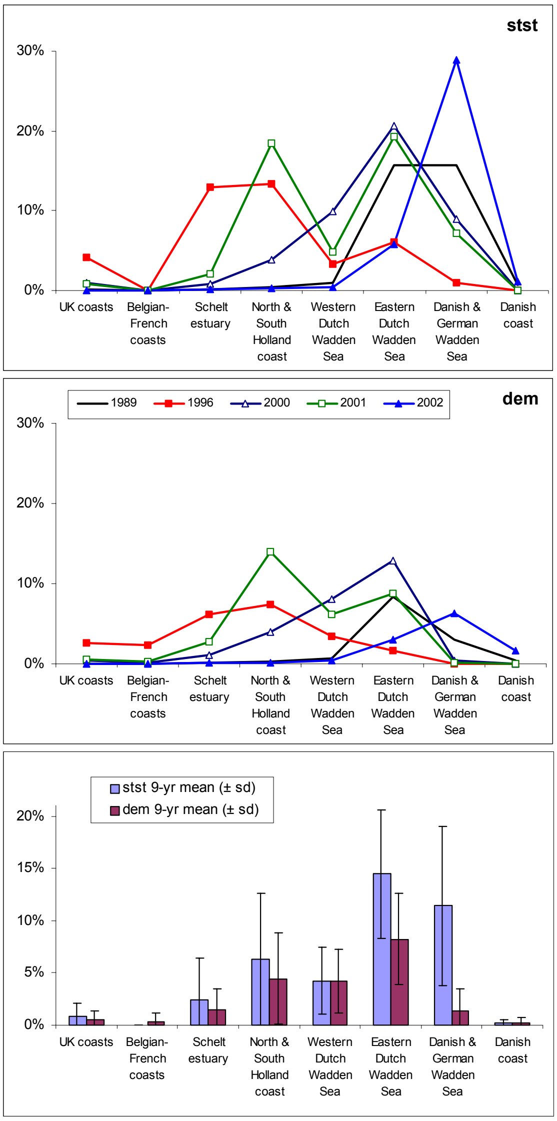


Figure 4.2.12. Plaice – Inter-annual variability. Transport success by region in 1989, 1996, 2000, 2001 and 2002 and averaged (± sd) over 9 years (1989, 1996-2003) for both assumptions on transport mechanisms (stst=selective tidal stream transport, dem = passive demersal transport). The proportion of larvae that reach the protected area (PA) or all nursery areas combined (AN) is listed in Table 4.2.3.

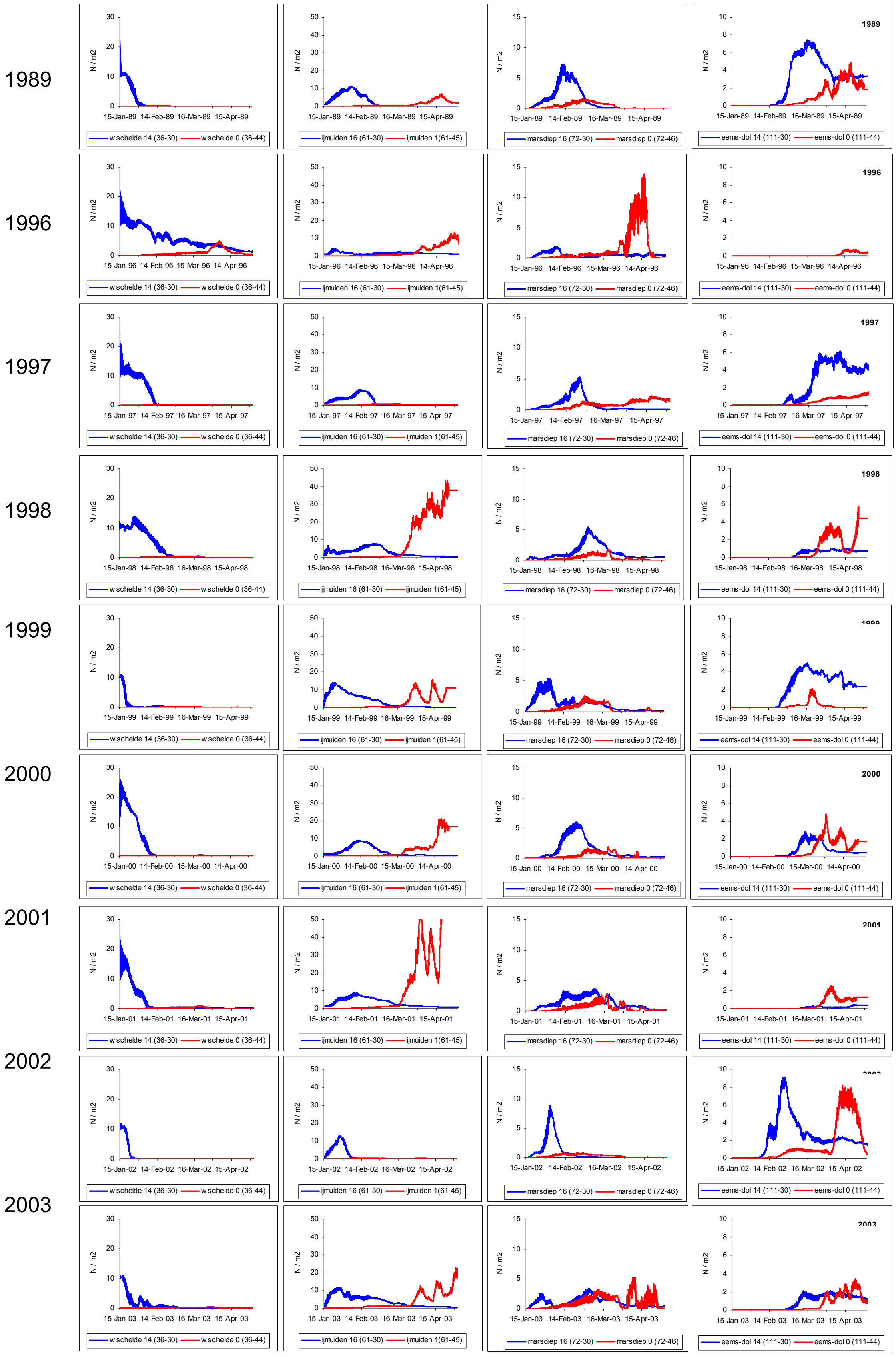


Figure 4.2.13. Plaice – Inter-annual variability. Time series of the densities (N/m^2) of larvae at 8 observation points in the southern North Sea. The red lines are observation points close to the coast or in the inlet of an estuarine area; these show the timing of larvae entering a coastal or estuarine nursery area. The blue lines are offshore observation points, which show the larvae that pass this nursery area

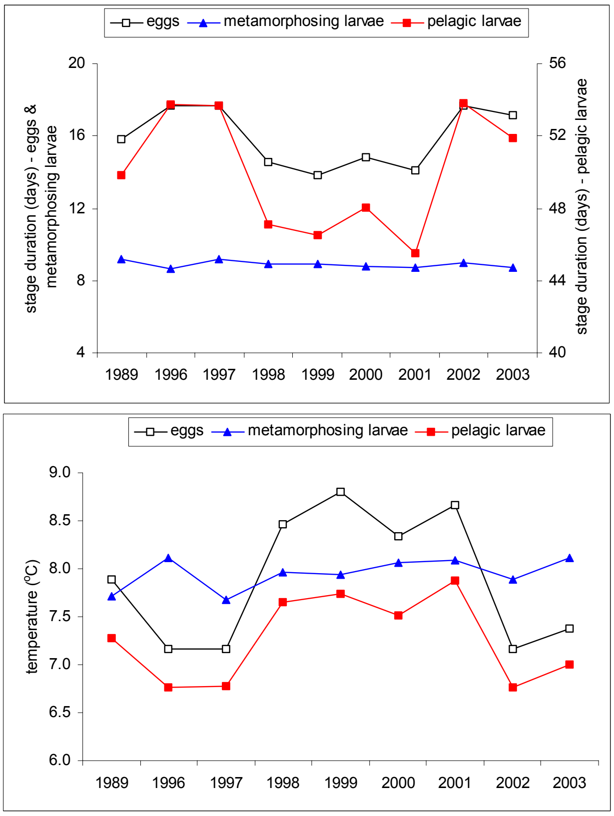


Figure 4.2.14. Plaice – Inter-annual variability in stage duration (top panels) and ambient temperature (bottom panels)

4.3 Sole

The same approach has been chosen for sole as for plaice (see section 4.2.1), and the same variables have been included in the sensitivity analyses (Table 4.3.1), with exception of horizontal dispersion and stst-thresholds. As in plaice all variables have been set to default values (last column in table 4.3.1) unless specified otherwise. Note that the default values of some variables differs between both flatfish species.

4.3.1 Spawning grounds

Sole spawn further inshore than plaice and the spawning grounds are less segregated. Spawning activity is observed along all the English Channel and southern North Sea coasts, although hot spots appear to occur off the coast of northern France, Belgium and in the German Bight (see section 2.3). A simplification of Figure 2.3.2, with all spawning grounds combined, has been used as input for most of the model runs for sole (Figure 4.3.1C), because a spatial segregation of the spawning grounds is less obvious for sole than for plaice. For the impact assessment of MV2, only the Eastern English Channel and the Southern Bight spawning grounds have been used as input, because no effect of MV2 is expected on the transport of larvae originating from the spawning grounds further to the north.

In 1989 a large proportion of the eggs and larvae that were spawned in the English Channel, enter the North Sea and reach the nursery areas in the Scheldt estuary and along the North- and South Holland coasts (Figure 4.3.1A and Figure 4.3.2 top left panel). However, in 1996 and 2000 none of the English Channel larvae reach Dutch waters (Figure 4.3.2). The majority of the larvae spawned in the Southern Bight are transported to the Belgian coast and the Scheldt estuary, but in all three years examined a substantial proportion of the larvae reaches the western and eastern Dutch Wadden Sea. When all spawning grounds are combined (based on the unpublished spawning ground maps, Figure 4.3.1C), the majority of larvae end up in the German and Danish Wadden Sea region.

The location of the spawning grounds is less certain for sole than for plaice. It is clear that sole spawn in coastal waters but the degree of concentration is uncertain. Therefore the sensitivity of the model has been tested for the hypotheses of no spatial concentration in spawning activity within the coastal zone (Figure 4.3.1D). Comparison of this analysis with the default assumption on spawning concentrations shows that the variability in transport success by region is largely determined by the spatial distribution of spawning hot spots (Figure 4.3.2, right panels). Especially in the German and Danish Wadden Sea region, the high concentration of larvae appears to be largely due to concentration of spawning activity in the region. Noteworthy is the fact that the overall transport success to all nursery areas is higher if concentrations in spawning activity are assumed.

4.3.2 Transport mechanisms

Like in plaice, the transport of sole eggs and larvae has been defined as passive pelagic, i.e. transported in the top water layer of the model without a behavioural component. The implied homogeneous distribution of the larvae is considered to be plausible for the mixed waters of the southern North Sea, despite the diurnal vertical migration patterns that have been observed in sole larvae.

The mechanism by which sole larvae cross the distance from the spawning grounds to the nursery grounds further inshore is not fully understood. Selective tidal stream transport does not appear to occur in the larval stages, although an adaptation of the diurnal vertical migration patterns toward a semi-diurnal pattern may occur in the early juvenile stages (see section 2.3). The default setting for sole behaviour from the onset of metamorphosis onwards is passive demersal transport. In a number of model runs (inter-annual variability and impact studies) the alternative hypothesis of stst-behaviour has been tested as well.

4.3.3 *Duration transport*

Like in plaice, uncertainty exists on how long the transport phase can be prolonged after metamorphosis is completed (see section 4.2.6). Therefore, the sensitivity of the sole model has also been tested for a situation with 0 days, 30 days and 60 days of transport after metamorphosis is completed, but in the case of sole passive demersal transport instead of selective tidal stream transport is assumed for this last transport phase.

The concentration of the larvae in coastal waters increases with an increase in the duration of transport after metamorphosis (Figure 4.3.4), but the difference between 30 and 60 days is very small. Furthermore, a slight shift in the distribution of the larvae towards the north-east is observed with an increase in the duration of transport after metamorphosis, but once again the differences between 30 and 60 days is very small (Figure 4.3.5).

4.3.4 *Growth parameters*

As in plaice, relationship between temperature and stage duration has been defined by an exponential regression: $\ln(D) = \alpha + \beta T$, in which D= stage duration and T=temperature. Table 4.3.2 presents the published data on stage durations in relation to temperature. These studies differ in the way the data have been obtained (e.g. field or laboratory studies) and in the way the data are published (e.g. parameters of a fitted relationship or the observations).

The results of laboratory experiments carried out by Fonds (1979) compared to the results of the other studies suggest lower development rates and longer stage durations in all stages. The other studies only show small differences with each other in duration by stage, with exception of the stage duration estimates by Flüchter (1970) for the pelagic larval stage. The default model settings have been chosen so that they fit the higher development rates obtained in field studies (Table 4.3.2).

The sensitivity of the model for growth parameters has been tested by comparing the model results using default settings with those using the lower development rates published by Fonds (1979). The choice of growth parameters has a small effect on the modelled distribution of fish larvae. A decrease in growth rate causes a slight decrease in the proportion of larvae reaching the coastal nurseries and the protected area, but has almost no effect on the regional distribution of the larvae (Figure 4.3.6).

4.3.5 *Spawning period*

Sole spawn approximately 2.5-3 months later than plaice (Van der Land, 1991). Spawning starts in the south and progressively shifts to the north. The standard model for sole includes all spawning grounds, but as 3 different 'substances' so differentiation in the spawning period can be incorporated. Peak spawning is set to Mar. 1st for the English Channel, Apr 1st for the Southern Bight, and May 1st for the spawning grounds north of the Frisian Islands and in the German Bight. Although 3 spawning dates are included in the model, this is still a simplification of reality as the spawning period within for example the eastern English Channel is longer than 1 day.

The sensitivity of the model has been tested for different spawning times; the results using default settings for spawning time (i.e. Mar. 1st, Apr 1st and May 1st) have been compared with the results of model runs in which the spawning time is set 2 weeks earlier or 2 weeks later.

The variability in the distribution of larvae due to temporal differences in the hydrodynamics is much smaller for sole than for plaice. The distribution maps (Figure 4.3.7) suggest that the spawning period mainly affects the flux of larvae through the Dover Straits; early spawning appears to increase the flux in 1989, but reduce the flux in 1996. The transport success by region (Figure 4.3.8) quantify the previously described effect but also suggests a slight increase in the transport success to the Danish and German Wadden Sea in the case of early spawners.

4.3.6 Inter-annual variability

In the previous section it was concluded that the variability in distribution of larvae, due to temporal differences in the hydrodynamics, is much smaller for sole than for plaice. This is also evident when comparing year-to-year differences. The distribution maps show relatively small differences between years (Figure 4.3.9-4.3.10), and the distribution by region is very similar in all years (Figure 4.3.11). The largest difference between years is observed in the flux of larvae going through the Dover Straits (Figure 4.3.9-4.3.10), which is reflected by the proportion of larvae reaching the Scheldt estuary and the Belgian-French coasts (Figure 4.3.11).

The large year-to-year variability in plaice and herring is mainly driven by inter-annual variability in the residual currents. Apparently sole is much less affected by this variability in the residual currents, except when going through the Dover Straits. This is probably caused by the location of the spawning grounds in relation to the nursery grounds and by the fact that the pelagic life-phase is relatively short due to higher temperatures during this phase.

The year-to-year variability expressed as transport success to the protected area or to all nursery areas combined is presented in Table 4.3.3. The proportion of larvae (from all spawning grounds combined) that reaches the protected area ranges from 2.3 to 3.8% if selective tidal stream transport is assumed, and from 1.9% to 3.1% if passive demersal transport is assumed.

4.3.7 Summary

The sensitivity analyses for sole are summarized in Tables 4.3.4 and 4.3.5. Inter-annual variability and the variability and uncertainty in the duration of transport after metamorphosis has the greatest effect on the transport of sole larvae to the protected area (Table 4.2.4) and to all nurseries combined (Table 4.2.5). Note that the sensitivity of the model to variability/uncertainty in biological processes varies between years (Tables 4.2.4 and 4.2.5). Overall, the variability in the transport of eggs and larvae is smaller for sole than for plaice.

The remarks in section 4.2.10, concerning the interpretation of the sensitivity analyses, also apply for sole.

Table 4.3.1. Sole. Overview sensitivity analysis

Variables	Classes		
	#	levels	default
horizontal dispersion	1	100 m^2/s	100
transport mechanism of last larval stage	2	dem, stst	dem
salinity threshold	1	none	none
depth threshold	1	30m	30m
duration transport after metamorphosis	3	0, 1, 2 months	1 month
growth parameters	2	default, slower	default
spawning grounds	3	sb, ec, sb+ec+gb	sb+ec+gb
spawning period	3	peak, -2, +2 weeks	peak
annual variability	9	1989, 1996-2003	1989

Table 4.3.2. Sole – Growth parameters. Stage duration by temperature based on published estimates or regression parameters. An exponential regression, $\ln(D)=\alpha + \beta T$ in which D= stage duration and T=temperature, was (re-)fitted except if the temperature range was too small. The parameter estimates α and β are input parameters for the model, the default settings for each model stage area are printed bold.

model	**references**	α	β	**Stage duration if temperature =**							
				9	**10**	**12**	**13**	**15**	**16**	**19**	**x**
stage 1	**egg stages 1-4 ***										
passive pelagic	Cunnigham, 1890	-	-	10	8	-	-	-	-	-	-
	Butler, 1895	-	-	-	-	-	5	-	-	-	-
	Flüchter, 1970	3.44	-0.15	8	7	5	5	4	3	2	-
	Fonds, 1979	3.38	-0.10	12	11	9	8	7	6	4	-
	ICES, 1986	3.29	-0.12	9	8	6	6	4	4	3	-
	Baynes & Howell, 1996	3.19	-0.12	8	7	5	5	4	3	2	-
model settings		**3.50**	**-0.15**	**9**	**7**	**5**	**5**	**3**	**3**	**2**	-
stage 2	**larval stages 1-3 ****										
passive pelagic	Flüchter, 1970	-	-	-	-	-	-	22	22	-	-
	Fonds, 1979	5.14	-0.13	53	47	36	32	24	21	14	-
	Lagardère, 1989	-	-	-	-	28	-	-	-	12	-
	Boulhic et al., 1992	4.86	-0.14	37	32	24	21	16	14	9	-
	" + Amara et al., 1993	-	-	42	36	26	22	16	14	9	-
model settings		**5.00**	**-0.15**	**38**	**33**	**25**	**21**	**16**	**13**	**9**	-
stage 3 or 4	**larval stages 4-5 ****										
demersal or stst	Fonds, 1979	4.21	-0.16	16	14	10	9	6	5	3	-
	Boulhic et al., 1992	-	-	10	8	-	-	-	-	-	-
	Amara et al., 2000	-	-	-	-	-	-	-	-	-	10
model settings		**3.70**	**-0.15**	**10**	**9**	**7**	**6**	**4**	**4**	**2**	-
total				**58**	**50**	**37**	**32**	**23**	**20**	**13**	-

* according to definitions Ryland and Nichols (1975)

** according to, or converted to definitions by Ryland (1966)

Table 4.3.3. Sole – Inter-annual variability. For each year and both transport mechanisms (stst = selective tidal stream transport; dem = passive demersal transport), the proportion of the total number spawned (combined spawning grounds) that reaches the protected area or all coastal nursery areas.

year	Transport succes to protected area		Transport succes to all nursery area's	
	stst	dem	stst	dem
1989	3.7%	3.0%	63%	35%
1996	2.9%	1.9%	59%	28%
1997	3.8%	3.1%	67%	34%
1998	3.2%	2.8%	64%	37%
1999	3.5%	3.1%	61%	36%
2000	2.8%	2.1%	61%	29%
2001	3.8%	3.0%	64%	36%
2002	2.6%	2.6%	61%	36%
2003	2.3%	2.0%	56%	32%
mean	3.2%	2.6%	62%	34%
sd	0.6%	0.5%	3.0%	3.3%

Table 4.3.4. Sole – Summary sensitivity analyses. Variability in the transport success to the protected area due to natural variability and uncertainty of the assumptions.

Variable	Spawning ground	Transport type	Years	min	max	mean	sd	CV	Variability (range/mean)
Annual variability	SB	stst	9	4.0%	7.2%	5.5%	1.0%	19%	58%
		dem	9	2.3%	6.4%	4.4%	1.2%	27%	93%
	SB+EC	stst	9	1.2%	2.3%	1.7%	0.3%	19%	58%
		dem	9	0.7%	2.0%	1.4%	0.4%	27%	93%
	SB+EC+DB	stst	9	2.3%	3.8%	3.2%	0.6%	18%	47%
		dem	9	1.9%	3.1%	2.6%	0.5%	19%	45%
Duration transport	SB+EC+DB	dem	1989	1.8%	3.2%	2.7%	0.8%	28%	52%
			1996	1.6%	2.0%	1.8%	0.2%	9%	17%
			2000	1.7%	2.1%	1.9%	0.2%	10%	18%
Growth parmeters	SB+EC+DB	dem	1989	2.8%	3.0%	2.9%	0.1%	5%	7%
			1996	1.7%	1.9%	1.8%	0.1%	5%	7%
			2000	1.7%	2.1%	1.9%	0.2%	12%	17%
Spawning period	SB+EC+DB	dem	1989	3.0%	3.5%	3.2%	0.2%	6%	13%
			1996	1.88%	1.94%	1.90%	0.03%	2%	3%
			2000	2.0%	2.4%	2.2%	0.2%	10%	18%

Table 4.3.5. Sole – Summary sensitivity analyses. Variability in the transport success to all nursery areas due to natural variability and uncertainty of the assumptions.

Variable	Spawning ground	Transport type	Year	min	max	mean	sd	CV	Variability (range/mean)
Annual variability	SB	stst	9	57%	78%	72%	7%	10%	29%
		dem	9	36%	48%	40%	3%	8%	28%
	SB+EC	stst	9	40%	53%	46%	4%	9%	29%
		dem	9	19%	25%	22%	2%	8%	24%
	SB+EC+GB	stst	9	56%	67%	62%	3%	5%	17%
		dem	9	28%	37%	34%	3%	10%	27%
Duration transport	SB	stst	1989	27%	36%	33%	5%	15%	27%
			1996	26%	29%	27%	1%	5%	10%
			2000	27%	31%	29%	2%	8%	15%
Growth parmeters	SB	stst	1989	32%	35%	34%	2%	5%	7%
			1996	26%	28%	27%	1%	5%	7%
			2000	27%	29%	28%	2%	6%	8%
Spawning period	SB	stst	1989	33%	37%	35%	2%	5%	11%
			1996	28%	30%	29%	1%	3%	6%
			2000	29%	31%	30%	1%	4%	8%

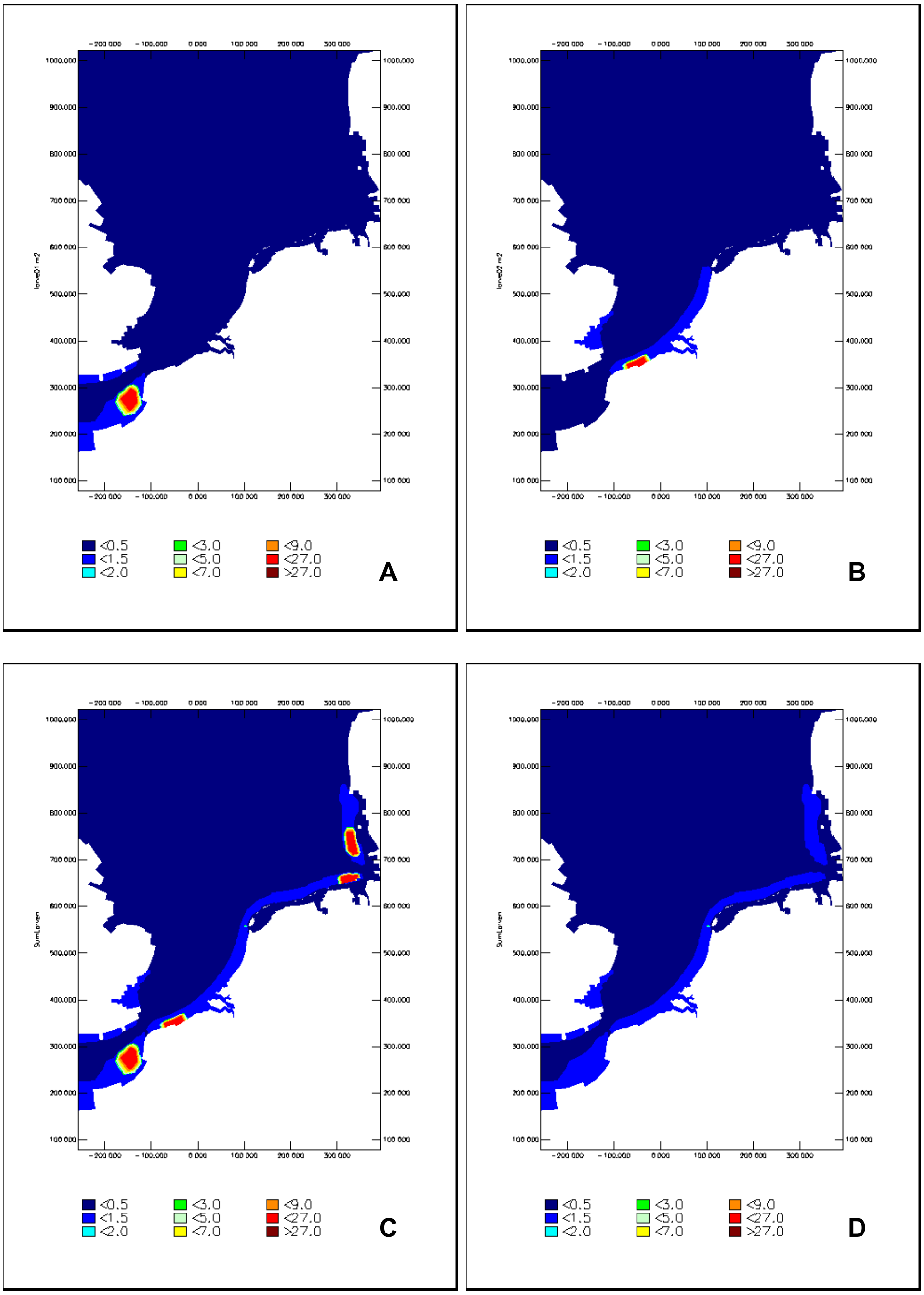


Figure 4.3.1. Sole – Spawning grounds in eastern English Channel (A), Southern Bight (B), and all spawning grounds based on unpublished data (C) and on Lee and Ramster, 1981 (D).

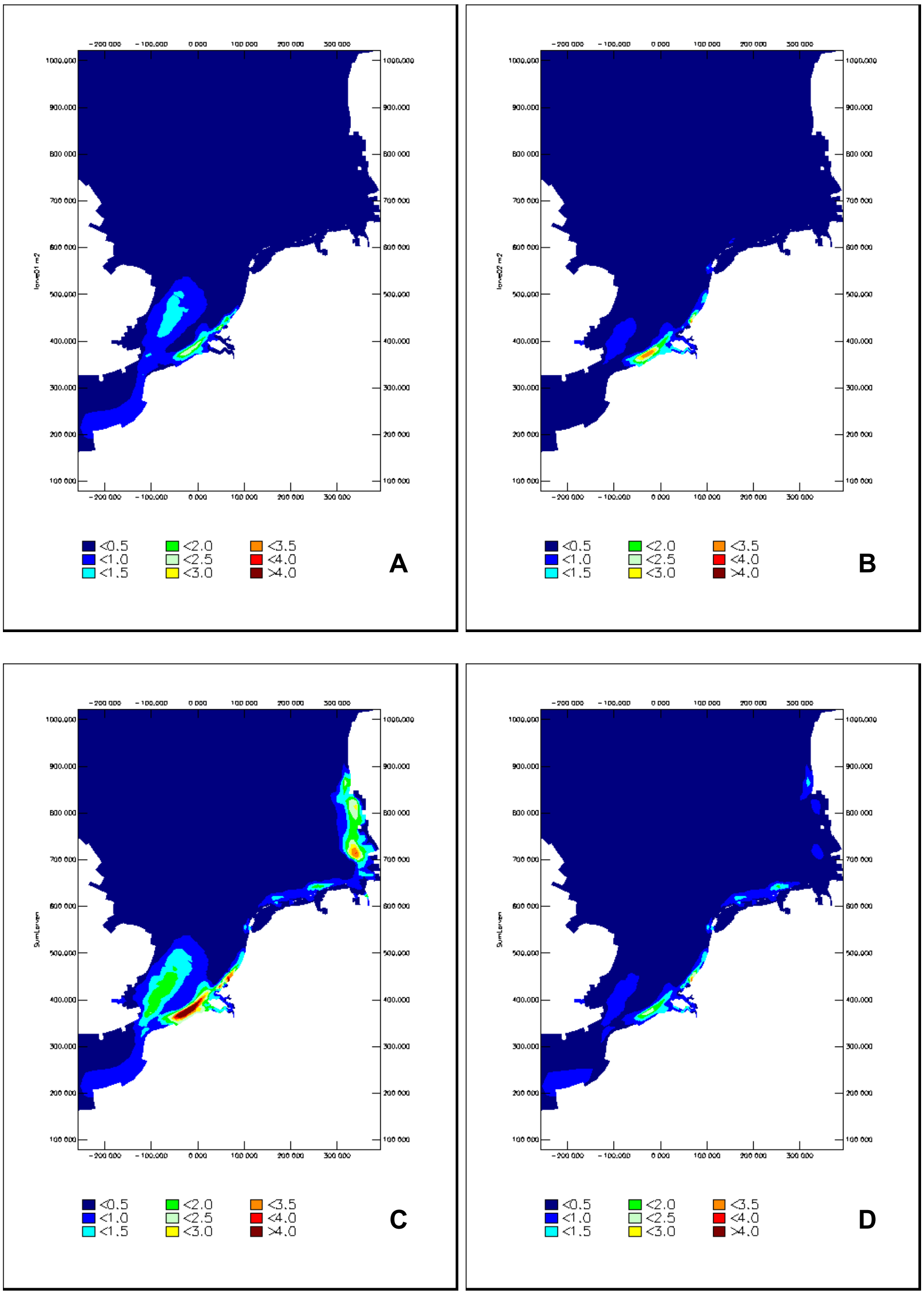


Figure 4.3.2. Sole – Spawning grounds. Distribution pattern at the end of the transport phase for larvae originating from the English Channel (A), Southern Bight (B), and from all spawning grounds combined in which the spawning grounds are based on unpublished data (C) and on Lee and Ramster, 1981 (D), for the year 1989.

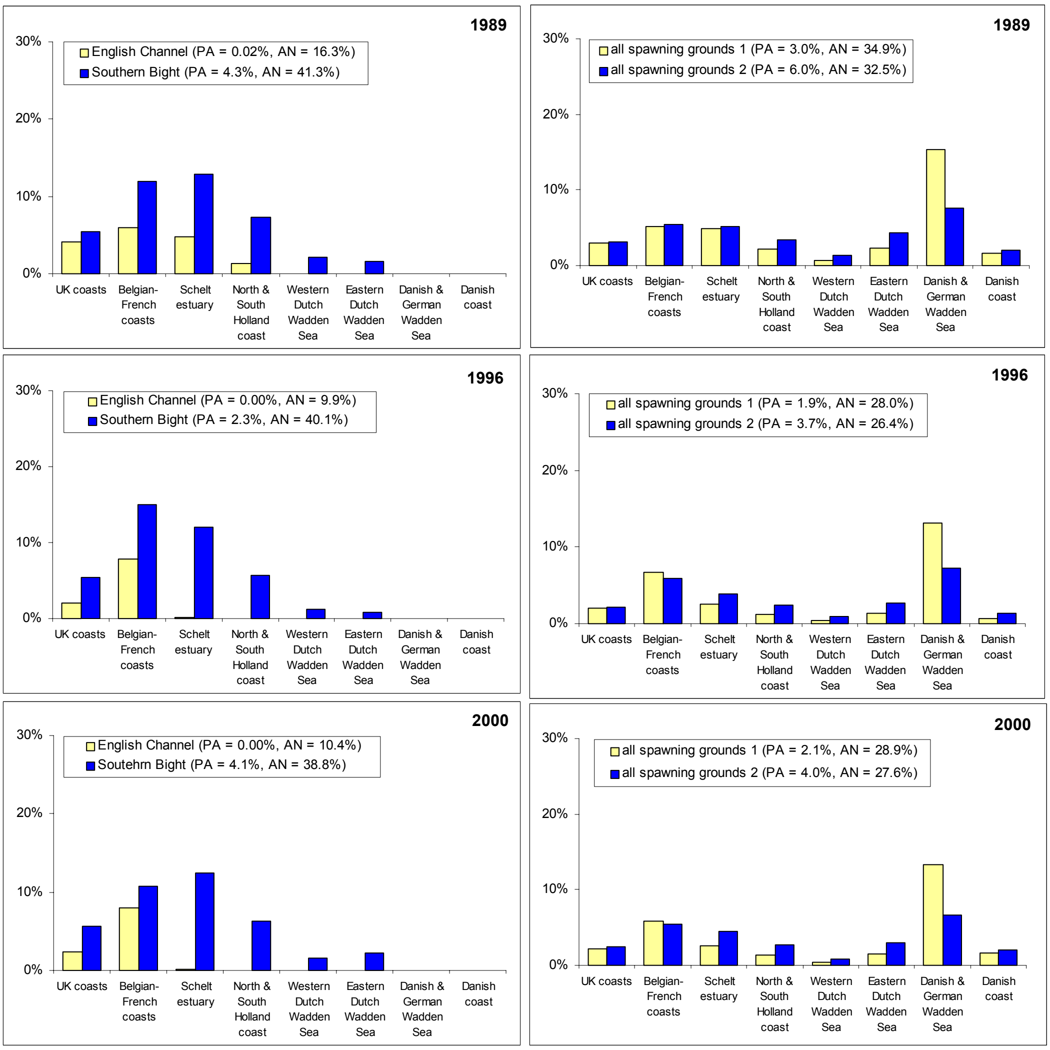


Figure 4.3.3. Sole – Spawning grounds. Transport success by region for larvae originating from the spawning grounds in the eastern English Channel, the Southern Bight, and for all spawning grounds combined in which the spawning grounds are based on unpublished data (all spawning grounds 1) and on Lee and Ramster, 1981 (all spawning grounds 2), for the years 1989, 1996 and 2000. The proportion of larvae that reach the protected area (PA) or all nursery areas combined (AN) is listed in the legends.

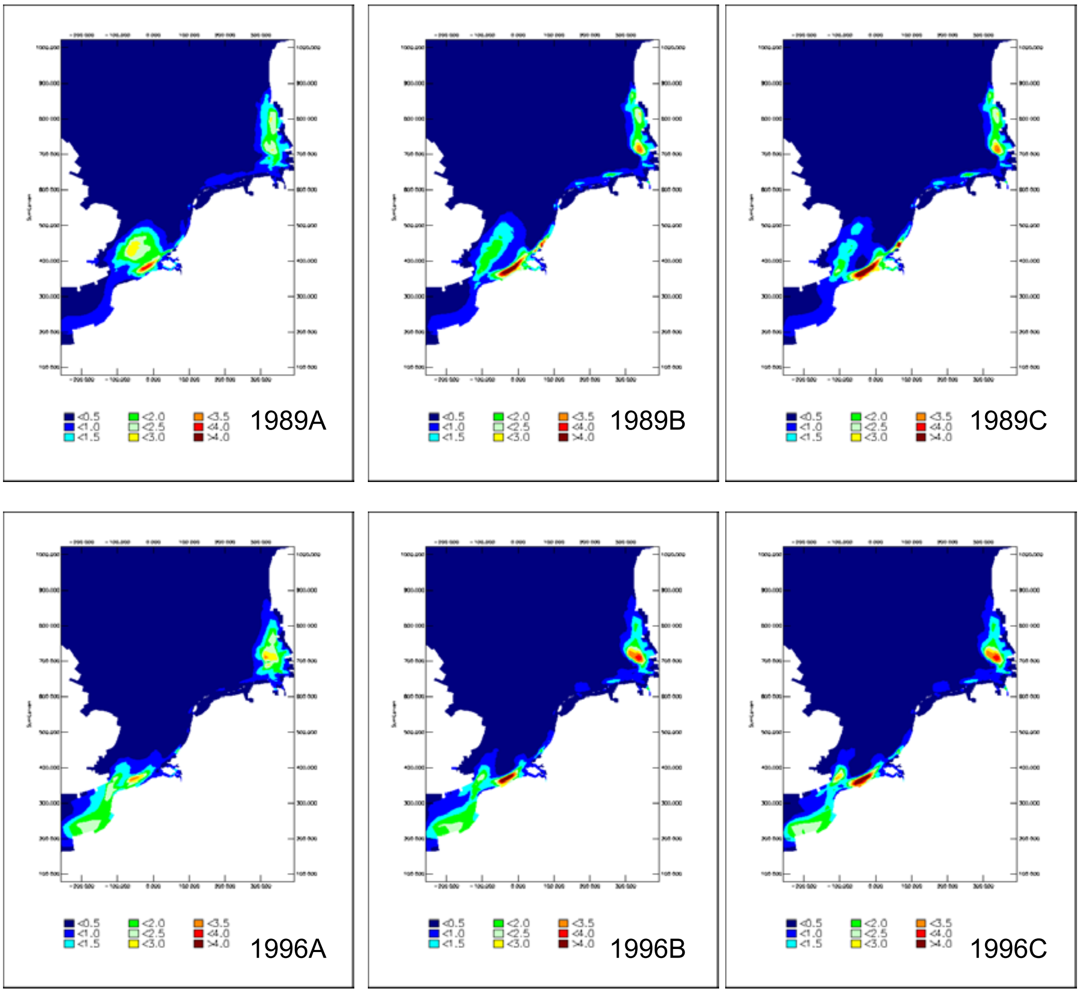


Figure 4.3.4. Sole – Duration transport after metamorphosis. Distribution pattern at the end of the transport phase if the duration of transport after metamorphosis is 0 (A), 30 (B) or 60 (C) days for the years 1989 and 1996. The sole originate from all spawning grounds combined and passive demersal transport is assumed for the late larval and early juvenile stages.

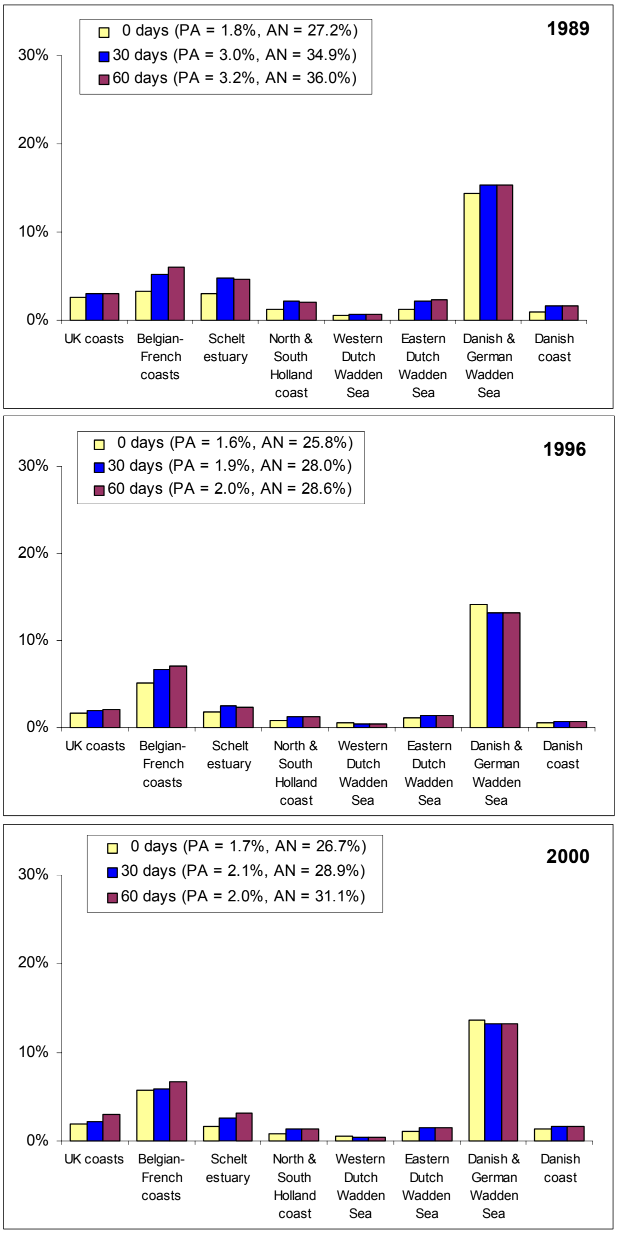


Figure 4.3.5. Sole – Duration transport after metamorphosis. Transport success by region for 3 years (1989, 1996 and 2000) and for 3 assumptions on the duration of transport after metamorphosis (0, 30 or 60 days), the proportion of larvae that reach the protected area (PA) or all nursery areas combined (AN) is listed in the legends.

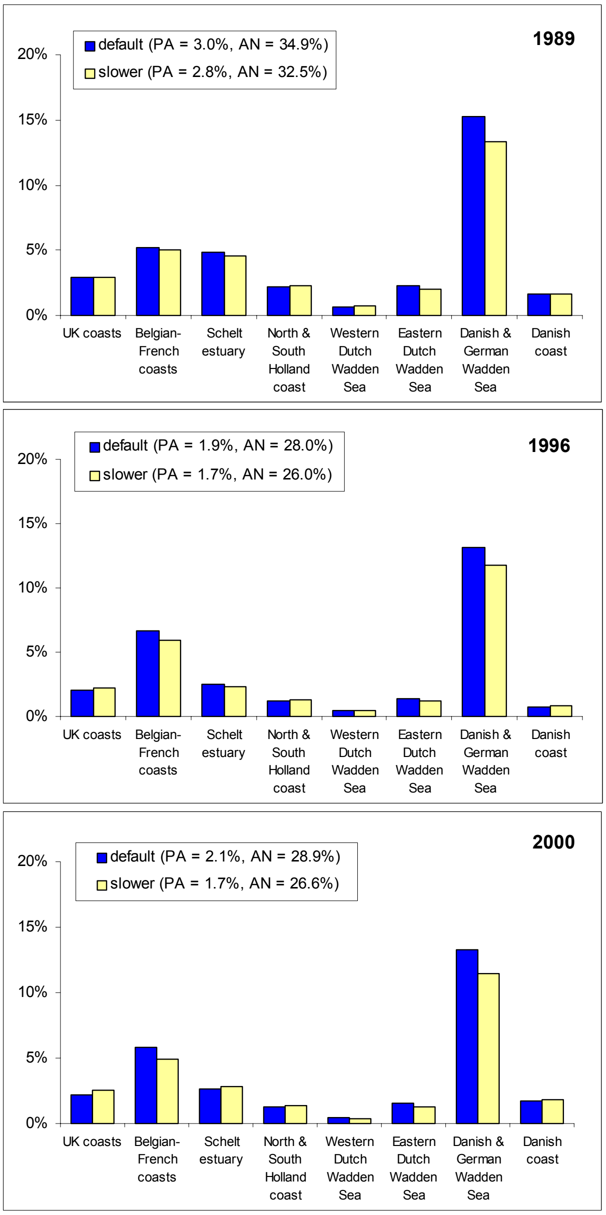


Figure 4.3.6. Sole – Growth parameters. Transport success by region for 3 years (1989, 1996 and 2000) and for 2 hypotheses on development rates (default and slower based on Fonds, 1979, see table 4.3.2). The proportion of larvae that reach the protected area (PA) or all nursery areas combined (AN) is listed in the legends.

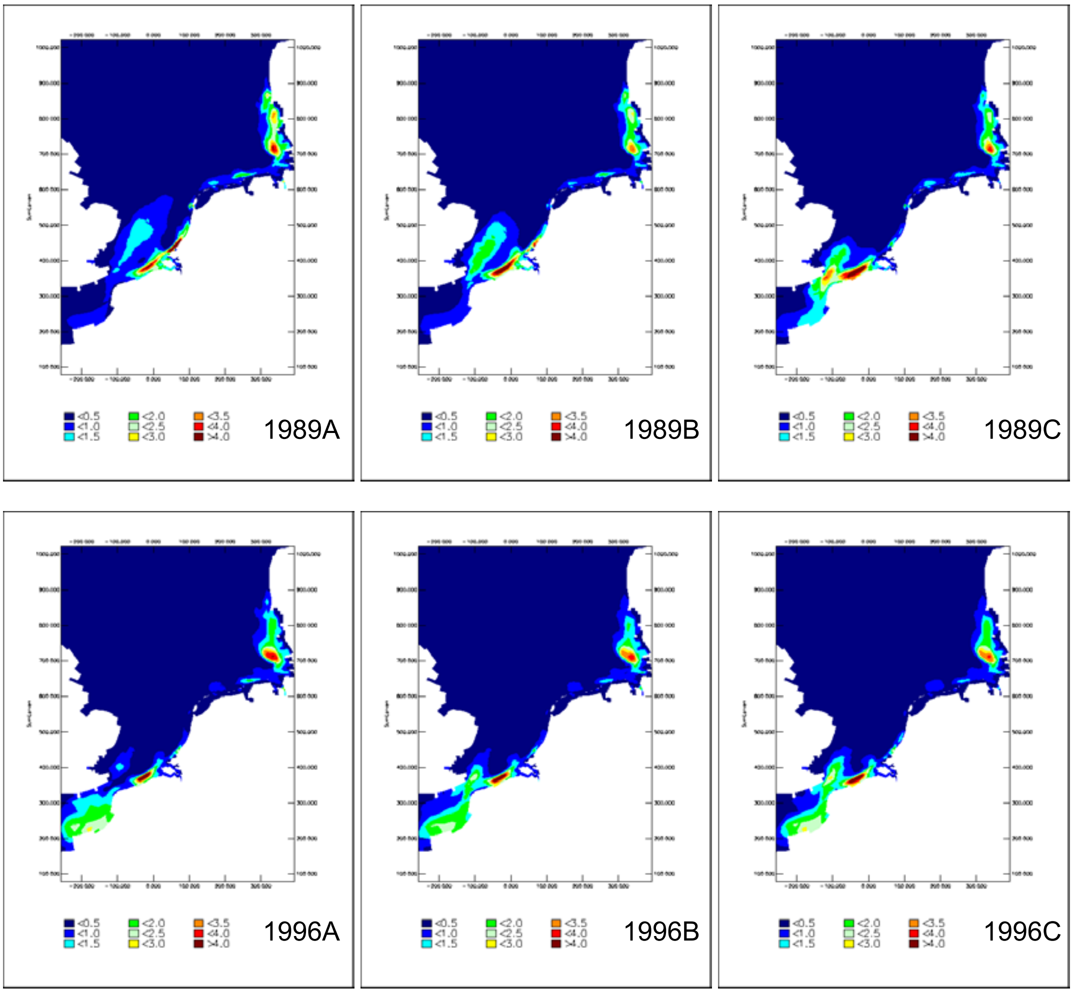


Figure 4.3.7. Sole – Spawning period. Distribution pattern at the end of the transport phase if spawned at peak spawning (B), 2 weeks earlier (A) or 2 weeks later (C) for the years 1989 and 1996. The plaice originate from all spawning grounds combined and passive demersal transport is assumed for the late larval and early juvenile stages.

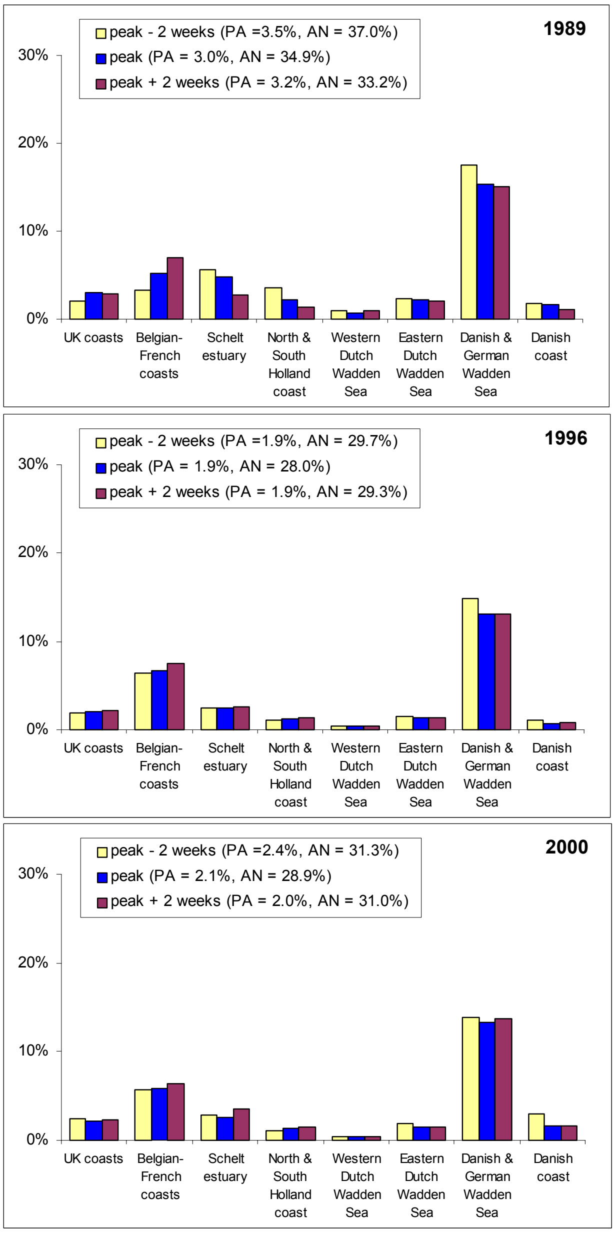
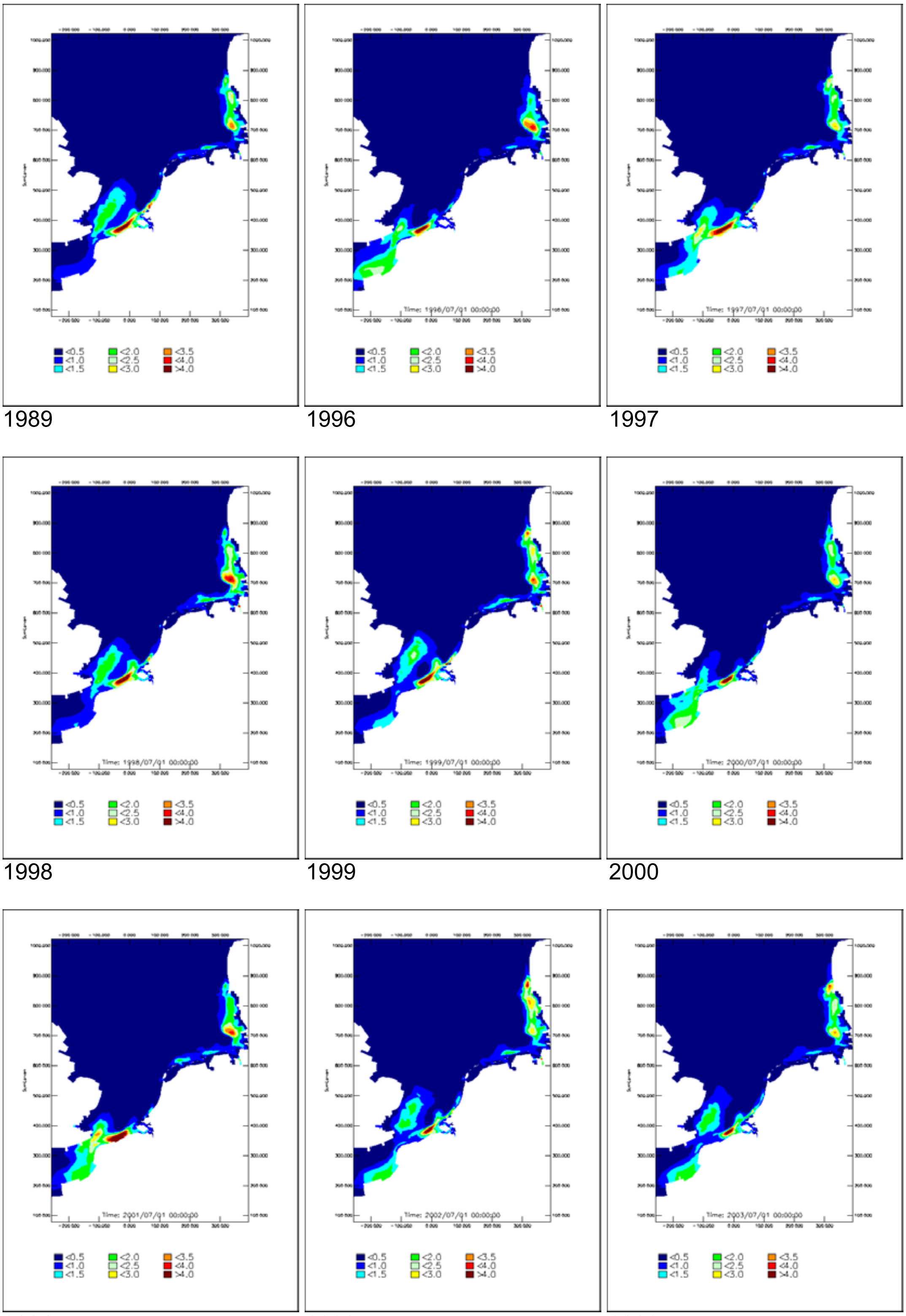


Figure 4.3.8. Sole – Spawning period. Transport success by region for 3 years (1989, 1996 and 2000) and for 3 hypotheses on spawning date (peak spawning, 2 weeks earlier and 2 weeks later). The proportion of larvae that reach the protected area (PA) or all nursery areas combined (AN) is listed in the legends

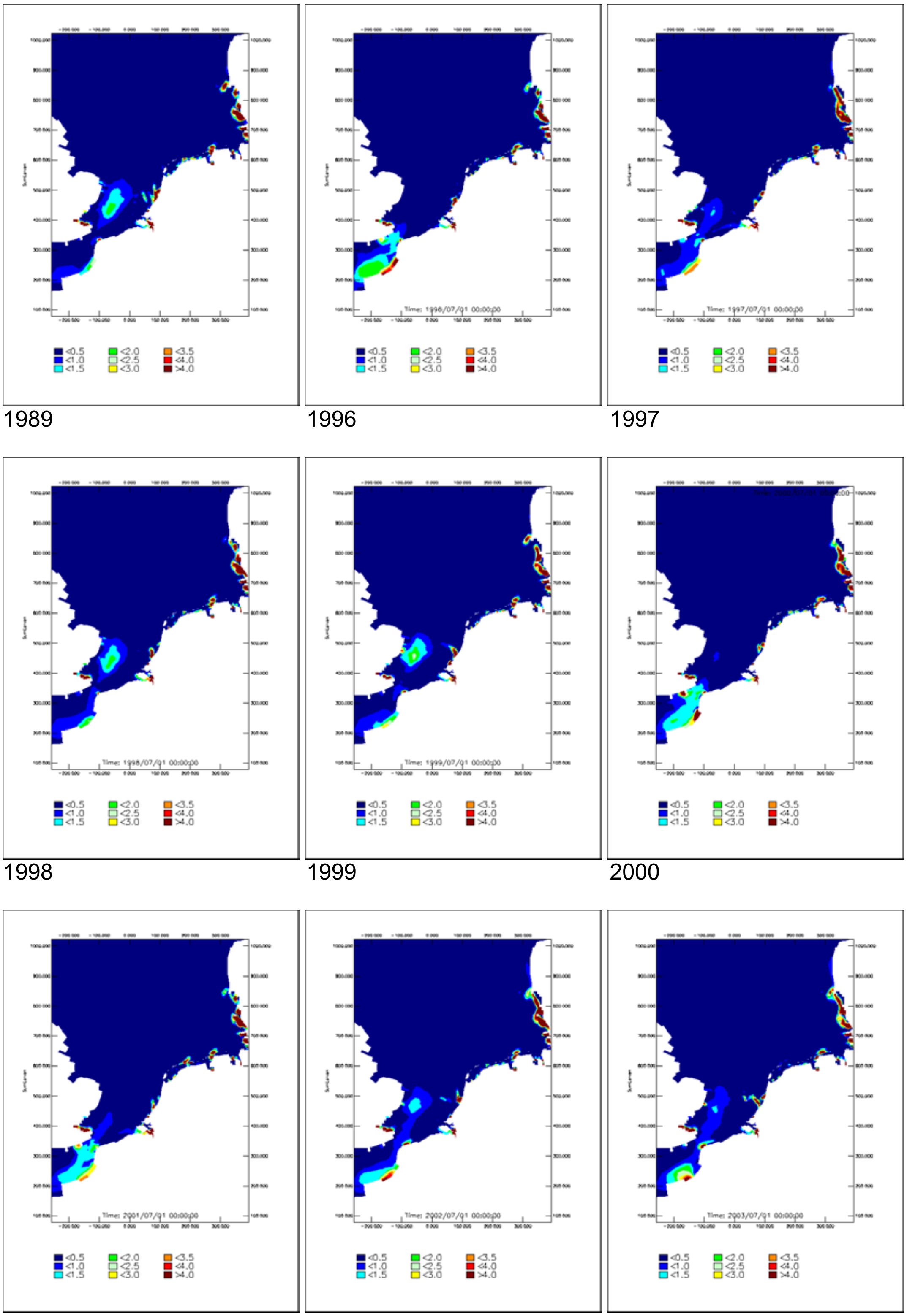


1989 1996 1997

1998 1999 2000

2001 2002 2003

Figure 4.3.9. Sole – Inter-annual variability. Distribution pattern at the end of the transport phase assuming passive demersal transport in the late larval and early juvenile stages.



1989 1996 1997

1998 1999 2000

2001 2002 2003

Figure 4.3.10. Sole – Inter-annual variability. Distribution pattern at the end of the transport phase assuming selective tidal stream transport in the late larval and early juvenile stages.

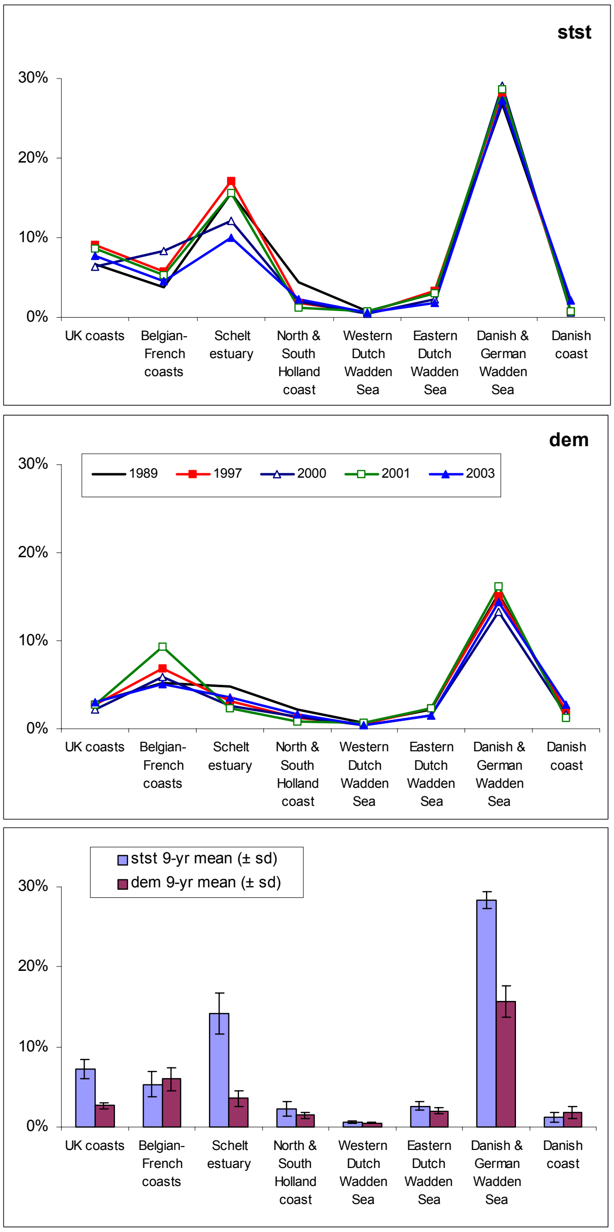


Figure 4.3.11. Sole – Inter-annual variability. Transport success by region in 1989, 1996, 2000, 2001 and 2002 and averaged (± sd) over 9 years (1989, 1996-2003) for both assumptions on transport mechanisms (stst=selective tidal stream transport, dem = passive demersal transport). The proportion of larvae that reach the protected area (PA) or all nursery areas combined (AN) is listed in Table 4.3.3

5 Field data and validation

5.1 Herring

There are four survey time series that can provide valuable information to compare to the model simulations and validate the results:

i) The ICES coordinated International larval herring surveys (IHLS, annex 3a)
ii) The ICES coordinated International bottom trawl surveys (IBTS, annex 3b)
iii) The ICES coordinated Methot Isaacs Kidd net surveys (MIK, annex 3c)
iv) The RIVO Wadden Sea stow net larvae surveys (Stow, annex 3d)

Importantly very little information from these surveys was used to initially calibrate the herring model parameters. The initial hatching grids were taken from published information, and the distribution of newly hatched larvae in the 1990s in the IHLS. The behaviour rules and growth parameters were taken from published information and models (see section 3 above). So apart from the hatching grids and variable hatching dates, no other empirical information was used to parameterise the model.

5.1.1 IHLS

The IHLS takes place in late December and early January, and it shows that over the whole times series the larvae do not move swiftly from the spawning area. This is in broad agreement with the model simulations (see Figure 4.1.14). The fact that the survey does not detect any north-easterly drift or change in the weighted centre of distribution (see annex 3a) is probably caused by the combination of sampling error and an interaction of the spatial and temporal trend in hatching. This was not modelled in this study. Larvae from the more westerly sites hatch earlier and continue to do so for longer than those in the north eastern area, which has lower abundances.

What is important to this study is the strong year signal in area detected in all larvae size classes. This reflects the high inter-annual variability seen in the simulations of transport of the larvae. It has proved difficult to find the meters from the empirical data and simulations to compare the effects of specific years.

5.1.2 IBTS

These surveys describe well the juvenile nursery grounds of herring in the southern North Sea. They are not suited to provide information on the larvae, post larvae of the relative importance of herring in the Wadden Sea. Using the quarter 3 surveys and the distribution of 0 group and 1 group juveniles, it is possible to infer where the larvae should be heading to, as a result of their transport. The IBTS covers all North Sea herring and they cannot be easly spilt into component spawning sites. So this information does not reflect Downs herring alone. The IBTS shows that the German Bight is the most important nursery area for herring, and that they move further offshore as they grow (at ages 1 and above). The IBTS does not sample in waters less than 20m, and hence is of no use if considering the Protected area.

The German Bight and the Dutch coastal zone (as described in annex 3b) are the main nursery areas for herring in the southern North Sea. This agrees with the simulated transport of herring larvae which show a transport in a north east direction and a major delivery of larvae to the German Bight. The IBTS also shows strong interactions between year and area (annex 3b) and this is also in broad agreement with variable delivery of larvae to locations in the southern North Sea.

5.1.3 MIK net

The MIK net survey targets late/post larvae of herring. Unfortunately sampling intensity in the southern North Sea has only been increased in recent years. However the low resolution samples collected throughout the last ten years (annex 3c) show broad agreement with the simulated results of this study. Larvae by mid February are generally in the Southern Bight and off the Belgian and the southern Dutch coasts (Figure 5.1.1). Due to the poor sampling resolution direct year to year comparisons of spatial variability are not possible. However the mean length of larvae caught in the MIK net is 18mm which is in broad agreement with the simulated results of the transport model (Figure 5.1.2).

5.1.4 Stow

This survey is of most relevance to this study, as it surveyed the abundance of herring larvae at the mouth of the Wadden Sea (annex 3d). The estimated delivery date by the modelled simulations of herring larvae from the Downs component is April of each year (Figure 4.1.14). This is in broad agreement with the empirical data (Figure 5.1.3). Specifically in the spring of 1989, which is the main year for this investigation, the larvae appeared in the Marsdiep in early April and peaked in mid April. This agrees with the survey data from 1989. However in all years and particularly in 1989, the model predicts that larvae keep arriving in the Wadden Sea when the surveys show clear peaks with no more larvae entering in May. This can be explained as the current simulations do not account for mortality in general or the selective mortality of slow growers.

Due to the increasing biomass of Downs herring over the survey period (1970s to 1980s) it was not possible to disentangle the variable delivery of larvae due to hydrodynamics and the increasing number of larvae due to greater larval production in the Downs area. In fact, these data suggest that despite the high inter-annual variability in transport of larvae, the variable production of larvae, caused by fishing pressure on the adults decreasing reproductive potential, has a greater impact on the delivery of larvae to the Wadden Sea than the hydrographic variability and transport events.

The current model does appear to overestimate the growth rate. The Stow survey suggests that the Downs larvae were between 30-34mm in length by mid April as they entered the Wadden Sea, whereas for most years the simulated larvae were 37 and 40mm in length by this time. However, the growth model in the simulation did not account for poor growth due to lack of prey, and we assumed that the surviving larvae had fed well, but this may not be the case. Larvae as large as those from the simulation were caught in the surveys (Figure 5.1.4) but the majority of larvae were smaller. Hence the temperature dependent growth model (based on the energetics of well fed larvae) did produce realistic estimates but at the higher edge of the range. Note that the differentiation between Banks and Downs larvae in the Stow results is based on arbitrary criteria, and more in-depth analysis is required.

If the larvae do grow slower in the sea, compared to the model, then the move to active swimming will be later, and hence the transport model used here is still relevant to answering questions about the MV2. In addition, the lack of influence of stage (see sections 4.3.2 and 4.3.3) means that this growth difference will not have that much effect on the outcome of the transportation into the Wadden Sea and protected area and the conclusion derived from the present study.

5.1.5 Summary

Apart from the slightly higher growth rate of the larvae, the survey data suggest that the model parameterisation is coherent with field estimates. There is broad agreement between the field data and the model in terms of the spatial distribution and timing of transport. The influence of the larger sized larvae in the model compared to the field is difficult to determine, as mortality impacts the larvae in the field, but not in the model. However this slightly larger size at age will not influence the conclusions of the study because the behavioural stages have little impact on the transport compared to other factors.

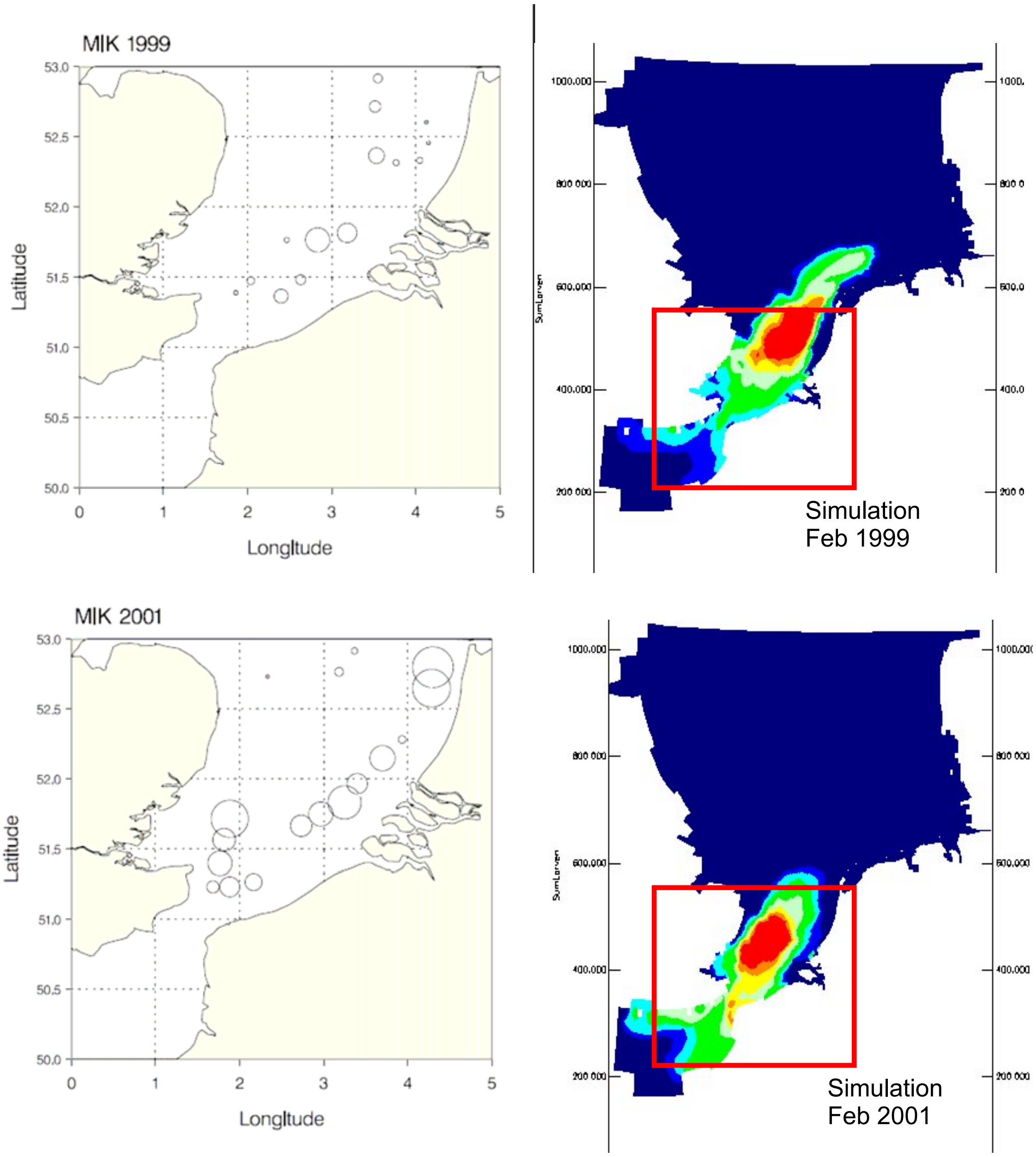


Figure 5.1.1. Herring. Comparison of spatial distribution of herring larvae estimated from MIK net surveys in 1999 and 2001, and modelled in the transport simulations. Circles denote nos per m^2 on a linear scale. Scale of contour plots same as Figure 4.1.1. Direct comparisons of the abundances cannot be made. Red rectangle denotes area in map of MIK survey.

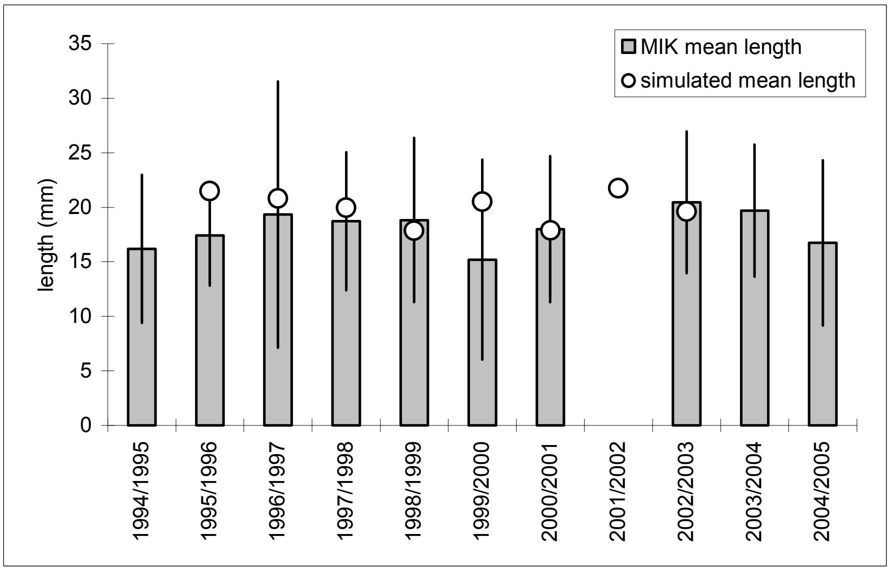


Figure 5.1.2. Herring. Mean lengths of herring larvae in Mid February by year as estimated from empirical catches in the MIK net and by the temperature dependent growth model used in the simulation of larval transport. Error bars not 95% confidence intervals of empirical estimates. Empirical data from 1988/1989 not available.

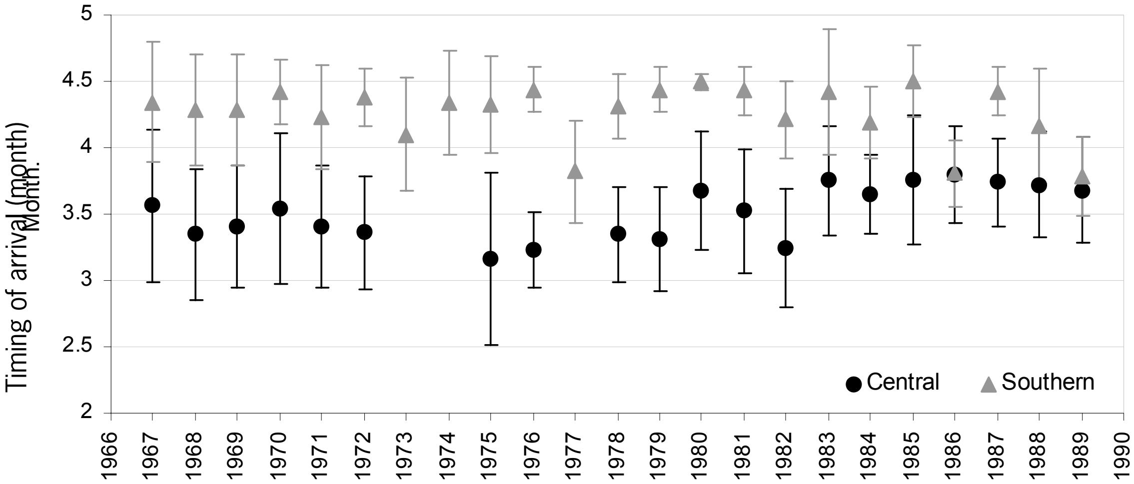


Figure 5.1.3. Herring. Timing of arrival (mean ± sd) of (southern/Downs-▲ and central/Banks-●) herring larvae in the western Wadden Sea as observed in the Stow net survey.

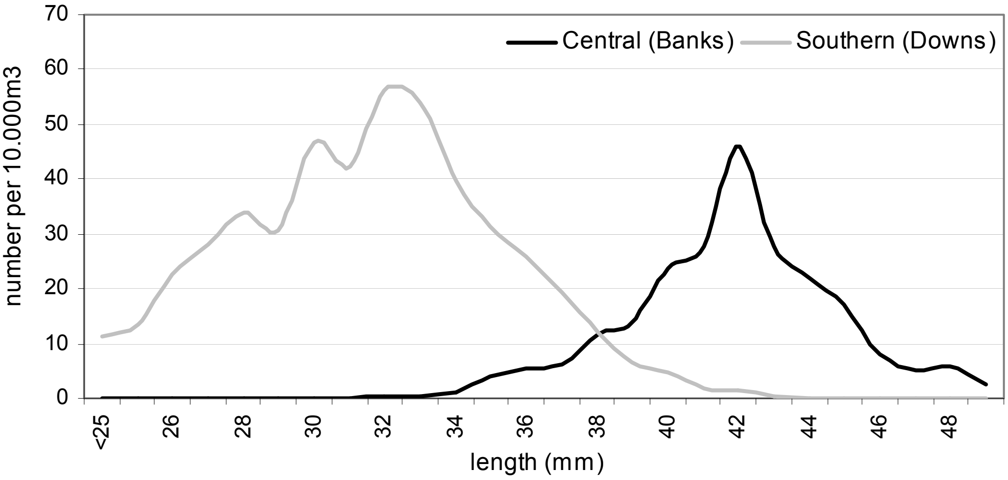


Figure 5.1.4. Herring. Length distribution of herring larvae in the Stow surveys. Mean values for all surveys in the year 1967-1978.

5.2 Plaice and Sole

There are several surveys that can provide information for comparison and validation of the model results. Three surveys provide information on the spatial distribution of plaice and sole:

- The ongoing Demersal Fish Survey (DFS, annex 2a)
- The survey carried out in 2002 for the Flyland project and the continuation of this survey in 2003 financed by R&D funds of RIVO (Flyland, annex 2b)
- The survey carried out in 2005 for the MV2 baseline study on fish (MV2, annex 2c)

And two surveys provide information on the temporal distribution of plaice:

- The NIOZ survey carried out in the western Wadden Sea and the day ring data collected during this survey (NIOZ, annex 2d)
- The stow net survey in the western Wadden Sea (Stow, annex 2e)

5.2.1 DFS

The DFS is an ongoing monitoring programme in which the Wadden Sea, the Scheldt estuary and the coastal waters from Zeeland to Esbjerg are sampled each autumn (September-October). This survey was designed to obtain abundance estimates for juvenile plaice and sole. The spatial distribution of 0-group plaice and sole as observed in the DFS has been used to compare to the model results. Note that the model simulates the distribution of recently settled juveniles, whereas the DFS is carried out in autumn. It is assumed that the geographical distribution of 0-group fish doesn't change much in the period between settlement and autumn. The DFS survey and the spatial distribution patterns are described in more detail in annex 2a.

For most years the modelled numbers of larvae per region fall within the probability ranges of the DFS numbers per region (Figure 5.2.1 and 5.2.2). But in some years, the modelled numbers of plaice larvae in the Scheldt estuary or along the North- and South Holland coasts, and the modelled numbers of sole larvae in the Danish and German Wadden Sea, fall outside of probability range of the DFS data.

For plaice, the model tends to overestimate the number of larvae in the Scheldt estuary, along the North- and South Holland coasts, and in the eastern Wadden Sea, and it tends to underestimate the number of larvae that reach the western Wadden Sea and the Danish and German Wadden Sea (Figure 5.2.1). Overall the model results based on the selective tidal stream transport hypotheses fit the field data better than the results based on the passive demersal transport hypothesis.

For sole, the model tends to overestimate the number of larvae that reach the Danish and German Wadden Sea and the Scheldt estuary, and underestimate the number of larvae reaching the other regions (Figure 5.2.2). This difference in the model results and field data is probably caused by an overestimation of the density of sole larvae in the spawning hot spots off the coast of Belgium and in the German Bight (see Figure 5.3.3). Overall the model results based on the hypotheses of passive demersal transport fit the field data better.

5.2.2 Flyland

This survey was carried out in 2002 for the Flyland project and was continued in 2003 after the Flyland contract was broken open. The objective was to describe the spatial and temporal distribution of metamorphosing and recently settled flatfish. Sampling was carried out with a beam trawl with a very fine-meshed cod-liner, and the survey area consisted of 3-4 transects in Dutch coastal waters. The methods and results are described in more detail in Annex 2b.

The sampling frequency, both spatially and temporally, was low in comparison to high haul-to-haul variability. Therefore the comparison of these field data with the model results should be treated with care. Nevertheless, the field observations fit the model results quite well.

According to the Flyland survey, very few plaice larvae reached the North and South Holland coasts (Egmond & Noordwijk transects in Annex 2b, Figure 1) in 2002. This corresponds closely to the model results as is shown in the distribution maps (Figure 4.2.11) and the time series for the observation points along the North and South Holland coasts (IJmuiden in Figure 4.2.13 and Scheveningen, not presented). In 2003, both the model simulations as well as the Flyland survey suggest that a much larger proportion of the larvae end up on the North and South Holland coasts (Figures 4.2.11, 4.2.13 and Annex 2b-Figure 1).

For sole, survey data on spatial distribution are only available for 2002 and these show a decline in abundance from Noordwijk to Schulpengat (Annex 2b-Figure 1). These results correspond to the modelled distribution if passive demersal transport is assumed for the late larval and early juvenile stages (Figure 4.3.9).

With respect to timing, the only information provided by the Flyland surveys is the presence of plaice larvae and the virtual absence of sole larvae in late March, and the presence of sole larvae and absence of plaice larvae in early June. This fits in the range of the model results (Figure 4.2.13 for plaice, not presented for sole).

The results of the Flyland survey show (if anything) that it will take a tremendous effort to obtain field data with sufficient spatial and temporal resolution to describe and examine (changes in) larval transport patterns. On the other hand, a modelling approach cannot be taken if there aren’t sufficient field data, such as the Flyland survey, available. Field data (and laboratory experiments) in general are essential to be able to define the processes and parameters in a model, and to validate the model results.

5.2.3 MV2

In the MV2 baseline study for fish, a survey was carried out in which the area designated for land reclamation, the area designated for a marine protected area, and an adjacent reference area were sampled (Figure 1 in Annex 2c). This survey was used as a platform to collect additional data on the distribution of recently settled and metamorphosing flatfish. The same gear and procedures were used for sampling larvae as during the Flyland cruises (see Annex 2b). The results are presented in Annex 2c.

The survey was carried out in late May 2005, which was expected to be after the influx of plaice larvae, but within the period that sole larvae arrive in the coastal nurseries. However, only 1 sole larva was caught in all 52 hauls. It is not clear whether this low catch rate is related to the place or the time of sampling.

Although dab is not included in the present study, the catch rates of this species are presented in Annex 2c because they show an interesting phenomenon: Dab is much more abundant in the area designated for MV2 than in the other areas. The same spatial distribution pattern seems to occur for plaice, although less convincing due to low catch rates (Table 2 in Annex 2C). This small-scale distribution pattern was also examined in the model simulations. As hydrodynamic data was not available for 2005, the year 1988/89 (ZUNO-DD grid) was used. The model results show a distinct concentration of larvae/juveniles in the MV2 area if passive demersal transport is assumed in the last transport phase. The concentration does not occur under the assumption of selective tidal stream transport (Figure 5.2.3). This local concentration of larvae is observed in several years for herring as well (Figure 4.1.13).

5.2.4 NIOZ

From 1993 to 2002, the Royal Netherlands Institute for Sea Research (NIOZ) has surveyed the abundance of 0-group plaice on the tidal flats in the western Wadden Sea (Balgzand), and from 1995 onwards otoliths were collected from the catches for day ring analyses. These data are of great value within the present study. Firstly, they are the only reliable source of information on the seasonal pattern of plaice larvae entering the Wadden Sea (note that the temporal coverage of the Flyland survey (section 5.2.2) and the stow net survey (section 5.2.5) are in inadequate). Secondly, because the day ring data provide information on larval stage durations of plaice settling in the Wadden Sea for the years included in the model simulations. The methods and results of the survey and the day ring analyses are described in more detail in Annex 2d, and part of the time series has been published (Van der Veer & Witte, 1999; Van der Veer et al., 2000).

Stage durations
Otolith day ring analyses provide an estimation of the duration between hatching and the onset of metamorphosis (model stage 2) and between the onset of metamorphosis and the catch date (model stages 3 -5). The catch date is presumed to be equal to the settlement date as only recently settled plaice were included in the otolith analyses. These observations on stage duration have been used to calibrate and validate the model. The day ring data for 1996, 1999, 2001, 2002, in combination with other published and unpublished data on larval development, were used to estimate the parameters of the relationship between temperature and stage duration. Therefore, only the data for the 1997, 1998 and 2000 can be used for validation.

The modelled and observed stage durations are very similar for both the pelagic larval as well as the demersal/stst stages (Figure 5.2.4). The modelled stage durations for all years fall well within the 95% probability range of the field observations. Slight differences between the modelled and observed stage durations occur for the years used in the calibration, because the parameter settings were not only based on the NIOZ day ring data (Table 4.2.2).

With exception of 1995, the mean stage durations do not vary much between years (Figure 5.2.4). Apparently the between year variability is smaller than the within year variability. The duration of the larval phase, from hatching to settlement, ranges from 50 to 64 days for the means by year (Annex 2d, Table 1), and from 26 to 81 days for the basic observations.

Seasonal distribution
The Balgzand survey data provide estimates of the timing of arrival and of the relative abundance at the time of settlement. Recently settled juveniles are distinguished from the rest of the 0-group by length (<15mm). The seasonal pattern in the catch rates (N/1000m^2) of recently settled plaice is compared to the modelled densities (N/m^2) for an observation point in the Marsdiep Channel (Figure 5.2.5). This is a relative comparison because mortality is not included in the modelled densities. In principle, a slight delay in peak abundance between the Marsdiep observation point and the Balgzand tidal flats is expected, but no information is available on how long it takes the larvae to cover this distance.

The field data and the model simulations match very well in all years except 1997 and 2000. In these 2 years, the modelled time series show 2 peaks, whereas the field data show 1 peak approximately in between the 2 model peaks. This difference may be caused by the fact that the model results are based on 1 spawning event (see section 4.2.8). If a spawning period had been modelled instead, than the seasonal distribution pattern would have been smoothed and presumably would have corresponded better with the field data. Note the remarkable results for 2002, both the model simulation as well as the Balgzand survey suggest an extremely early arrival of plaice larvae in the western Wadden Sea

The correspondence between the field data and model results in terms of inter-annual variability in the level of peak density is high. Both approaches estimate the abundance in 1996 to be approximately 3-4 times higher than in the other years (Figure 5.2.5, bottom right panel).

Stage duration compared to seasonal abundance

The day ring analyses suggest that, on average, plaice settle at more or less the same age every year. The seasonal distribution data, however, indicate inter-annual variability in the timing of settlement. This discrepancy can be explained by inter-annual variability in the time of peak spawning, or inter-annual variability in which part of the cohort reaches the western Wadden Sea. For all years except 2002, this discrepancy is small: –8 days to +10 days (compared to assumed peak spawning, i.e. January 15th). But in 2002, the date of peak density, in combination with the observed larval duration and modelled egg duration, puts (the successful part of) spawning back to December 12th, which is outside the spawning period of the Southern Bight spawning population.

The model simulations appear to produce the same discrepancy between stage duration and timing of arrival in the Western Wadden Sea. However it should be borne in mind that the modelled stage durations apply for the whole cohort, i.e. all plaice from the same spawning ground have the same age. The duration between spawning and arrival in the western Wadden Sea is simply the difference between the date of spawning and the date of arrival. This means that in some years and nursery areas (e.g. the western Wadden Sea in 2002) the larvae arrive while they are still in the pelagic larval phase. According to the day ring data these larvae will not speed up their development and settle at a younger age, so either they hang around until they are ready to metamorphose or they die. In both cases the apparent match between the modelled and observed densities in 2002 is no longer valid. An obvious explanation for the early arrival of larvae in 2002 is that these plaice originate from the English Channel spawning grounds. However, the results of a model run including only the English Channel spawning ground do not support this explanation, both the timing and the relative abundance at peak density are different from the field data.

In summary, in all years except 2002 the difference in larval duration according to the seasonal distribution data and the day ring data is small and can be explained by variability in spawning period and/or differential survival. But, no explanation can be given for the 2002 results. Either the day ring data are incorrect and the larvae originate from the Southern Bight spawning grounds, or the model results are incorrect and the larvae originate from the English Channel spawning grounds (in which case the close match between the model results and the seasonal distribution data is spurious).

5.2.5 Stow

The stow net survey, carried out in the western Wadden Sea in 1967- 1989, was designed to sample herring larvae (Corten and Van de Kamp, 1979), but in some years the flatfish larvae were also sorted out from the catches. Only the raw data were available and within the current project all data collected in 1988 and 1989 has been inputted and analysed (see annex 2e). 1989 is the only year that overlaps with the year range of the model simulations, but unfortunately, in this year flatfish were only sampled during part of the survey. The density estimates of plaice larvae in time for the Marsdiep has been compared to modelled densities (Figure 5.2.6). Peak density according to the model simulation is approximately on March 1st, whereas the survey density estimates are highest on April 6th. It should however be noted that the density estimates for 1989 are based on relatively few hauls, and that the estimate for April 6th is determined by 1 outlier. If this 1 outlier is removed than the mean decreases to approximately the same level as is observed on March 20th. Furthermore, no sampling was carried out prior to march 8th, so an earlier episode of larval influx may have been missed.

The 1988 data cannot be used for model validation, as the year-to-year differences in larval transport are large (see section 4.2.9). However this survey provides valuable information to corroborate assumptions used for the model settings. Firstly, the data clearly show a higher proportion of the larvae in the water-column during flood than ebb (see Figure 6 in Annex 2e), which supports the hypotheses of selective tidal stream transport. Secondly, only larvae from stage 4a onwards are caught in the stow net, which supports the hypotheses that the change in behaviour starts at the onset of metamorphosis.

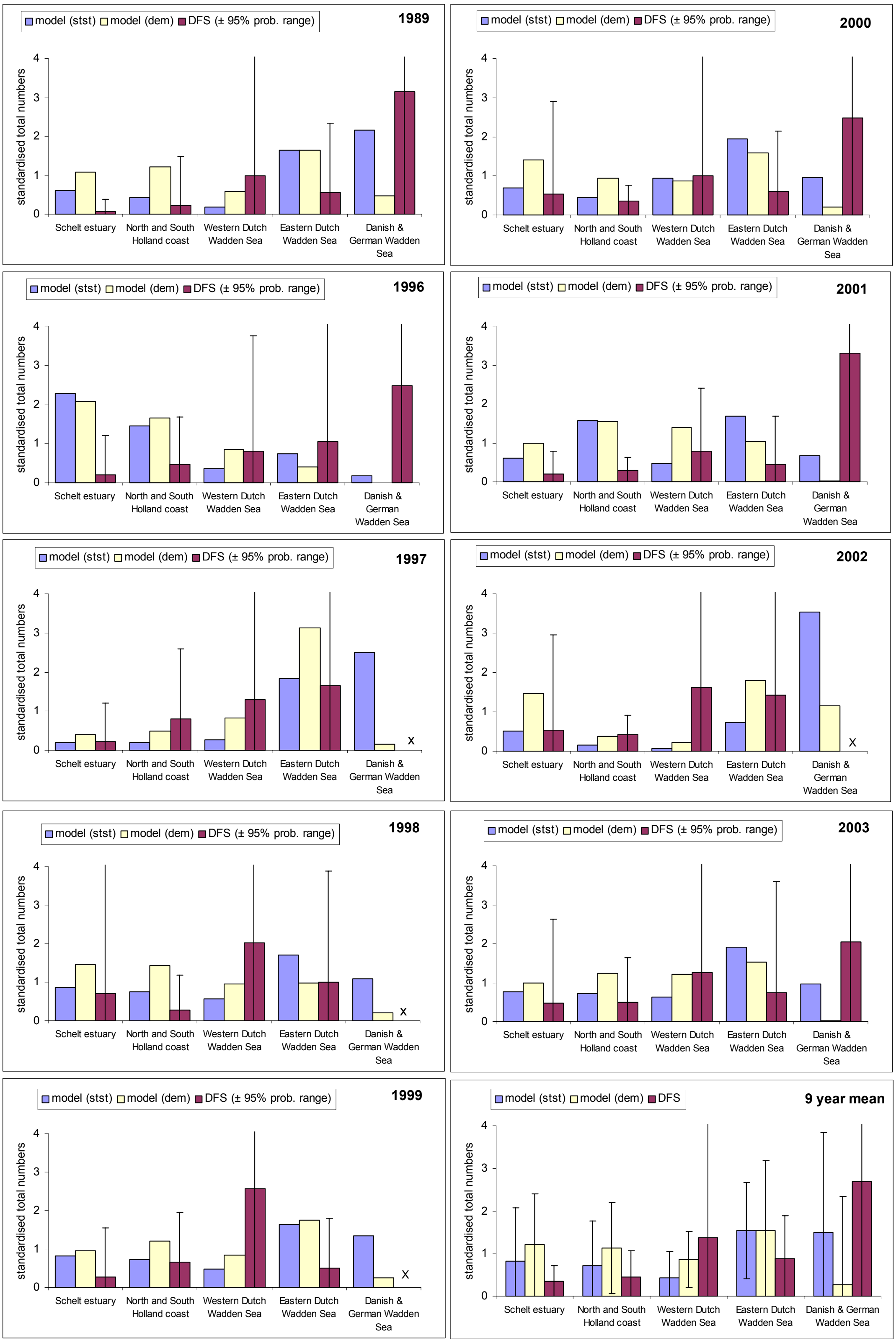


Figure 5.2.1. Plaice. The modelled distribution of recently settled juveniles for both assumptions on transport mechanisms (stst=selective tidal stream transport, dem=passive demersal transport) and the distribution of juveniles in autumn according to the Demersal Fish Survey. Plotted are the total number (density * surface area) of juveniles by region standardised to the mean, for each year separately and averaged over 9 years.

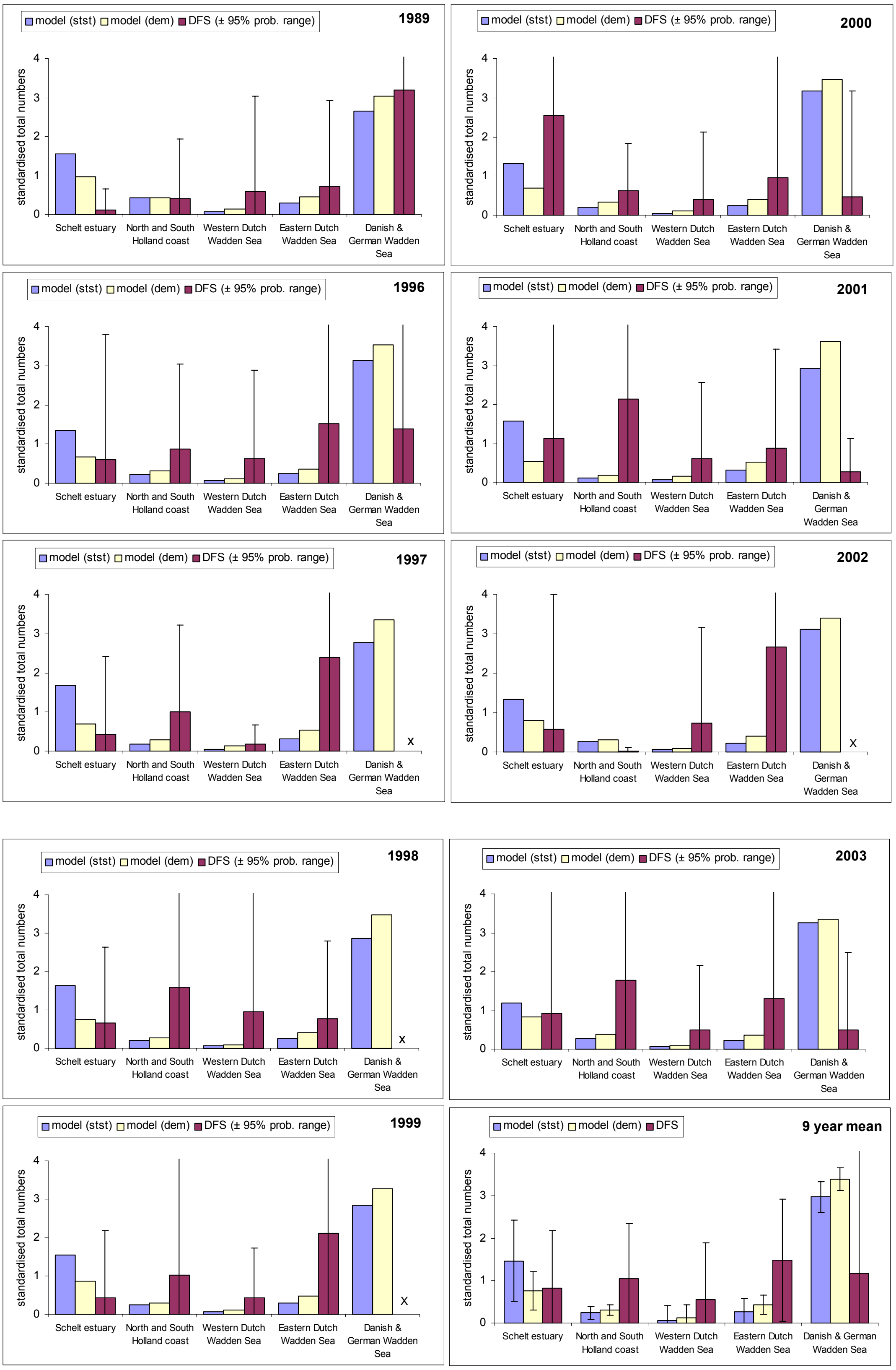


Figure 5.2.2. Sole. The modelled distribution of recently settled juveniles for both assumptions on transport mechanisms (stst=selective tidal stream transport, dem=passive demersal transport) and the distribution of juveniles in autumn according to the Demersal Fish Survey. Plotted are the total number (density * surface area) of juveniles by region standardised to the mean, for each year separately and averaged over 9 years.

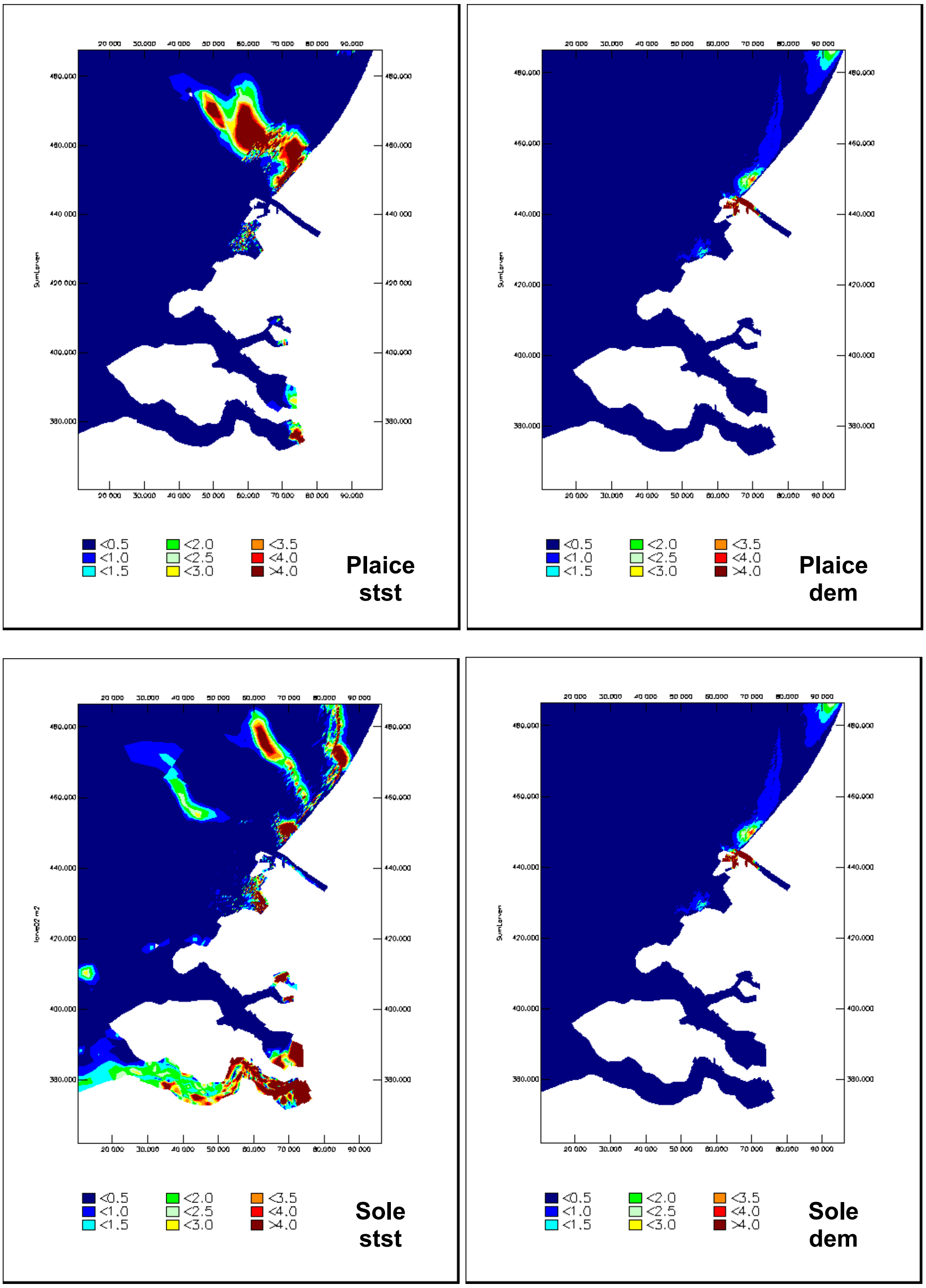


Figure 5.2.3. Plaice and Sole. The distribution of plaice (top) and sole (bottom) larvae/juveniles assuming selective tidal stream transport (stst) or passive demersal tranport (dem).

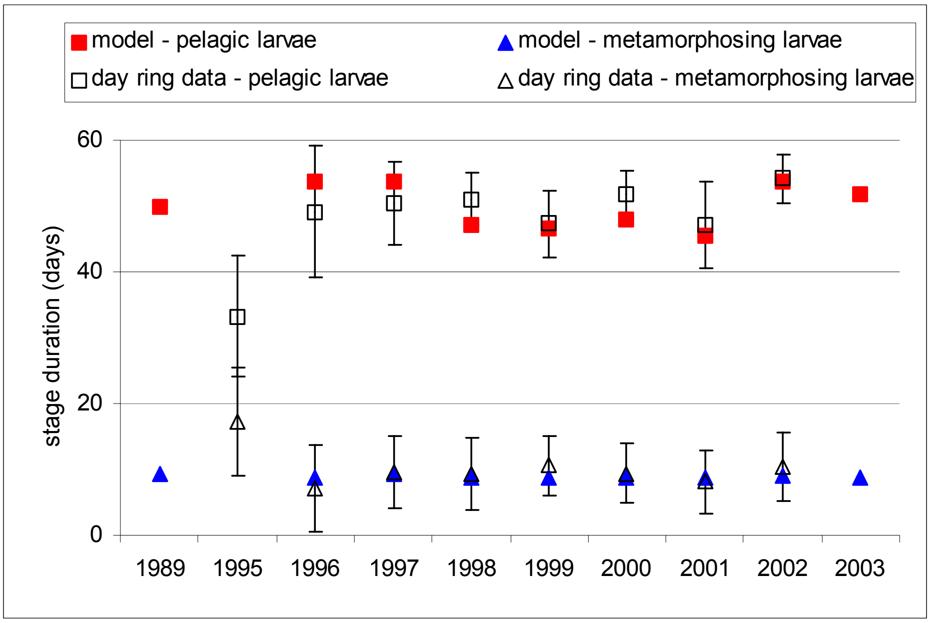


Figure 5.2.4. Plaice. Stage duration of the pelagic larval phase (squares) and the phase of metamorphosis (triangles) according to the model results (closed symbols) and day ring data (open symbols, NIOZ data).

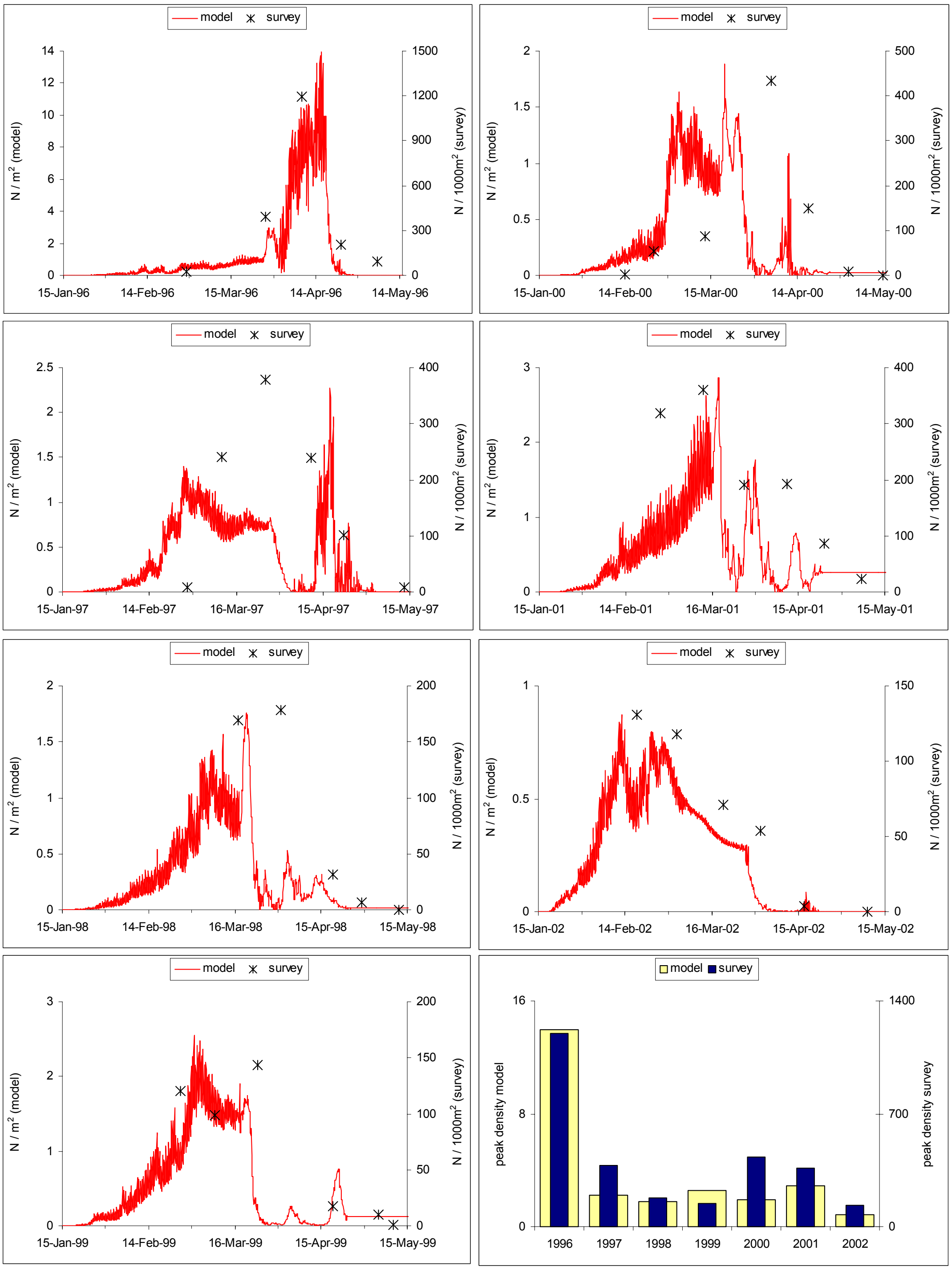


Figure 5.2.5. Plaice. Timing of appearance of plaice larvae in the western Wadden Sea, according to the model simulations and to the NIOZ survey data.

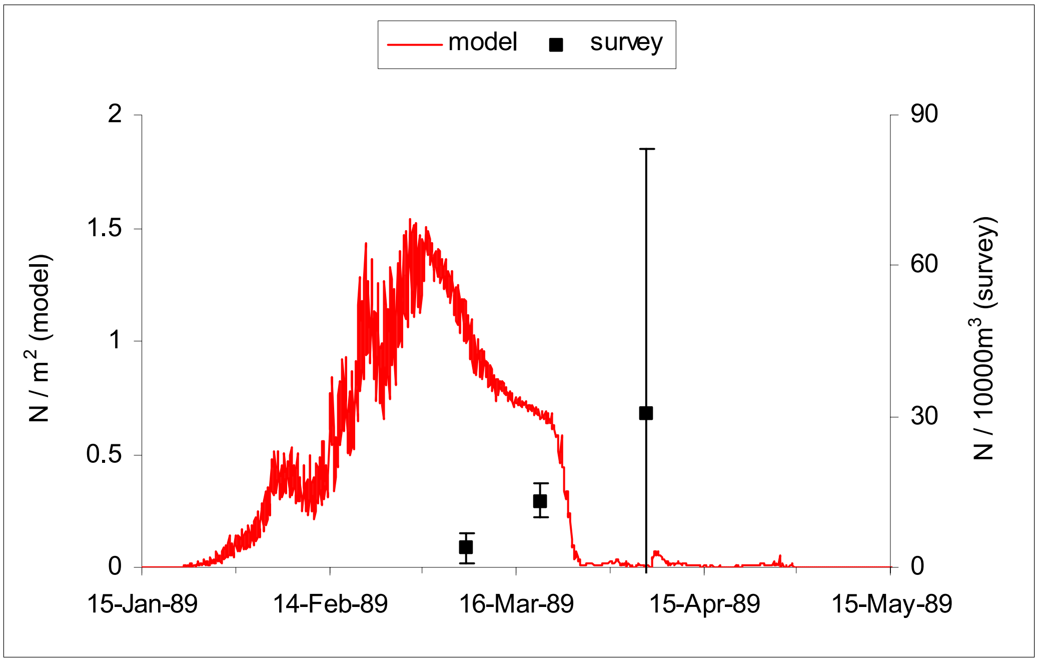


Figure 5.2.6. Plaice. Timing of appearance of plaice larvae in the western Wadden Sea according to the model simulations and to the stow net survey data.

6 Impact assessment MV2

The main thrust of the project was the influence of the Maasvlakte 2 reclamation on the transport of larvae. The effect of the reclamation on spawning was not investigated because there is no proposed spatial overlap between the areas of aggregate extraction and the spawning grounds. At no point was mortality of the larvae considered, and thus this study was completely targeted at transport variability.

6.1 Comparison ZUNOGROF and ZUNO-DD

A finer grid (ZUNO-DD) was required than used in the sensitivity analyses (ZUNOGROF) to be able to incorporate Maasvlakte 2 in the model (see section 3.1.5). It is apparent that switching from a course model grid (in the horizontal plane) to a finer one had an effect on the estimates of larval transport for herring (Figure 6.1.1) and for plaice (Figure 6.1.2). The concentrations of larvae appeared to move further north if the simulation used the course grid (ZUNOGROF) compared to the finer grid.

For herring, the estimates of the percent of larvae that reach certain locations by late May also varies depending on the model used (Figure 6.1.3). The biggest difference is between the eastern and central North Sea. The estimates of the percent reaching the protected area differ by over 50%, depending on the choice of model grid (0.69% using ZUNOGROF, 1.15% using ZUNO-DD).

Likewise for plaice, the percent of larvae that reach certain locations by the end of the transport phase varies depending on the grid used (Figure 6.1.4). 16.5% of the larvae reach the protected area in the ZUNOGROF model compared to 23.8% in the ZUNO-DD model (under the assumption of selective tidal stream transport).

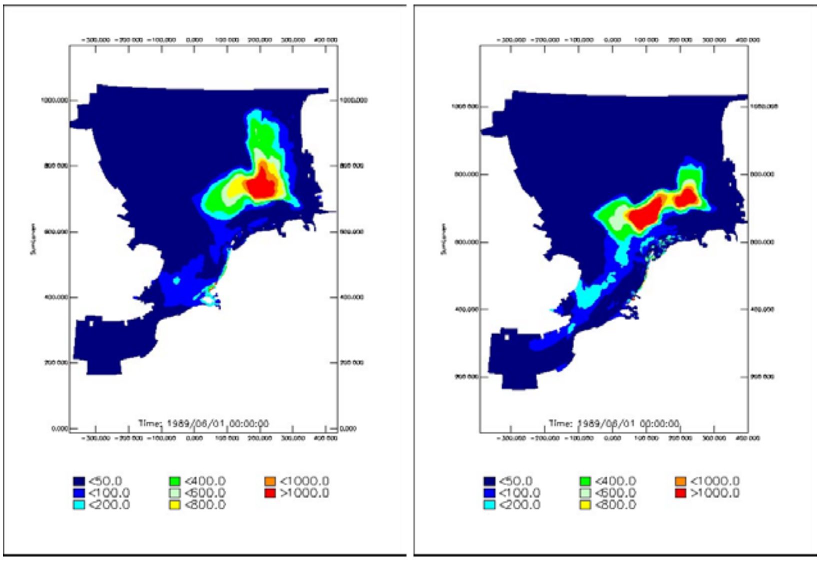


Figure 6.1.1. Herring. Spatial distribution of concentration of herring larvae in Late May 1989 from two model simulations, a) using ZUNOGROF b) using ZUNO-DD.

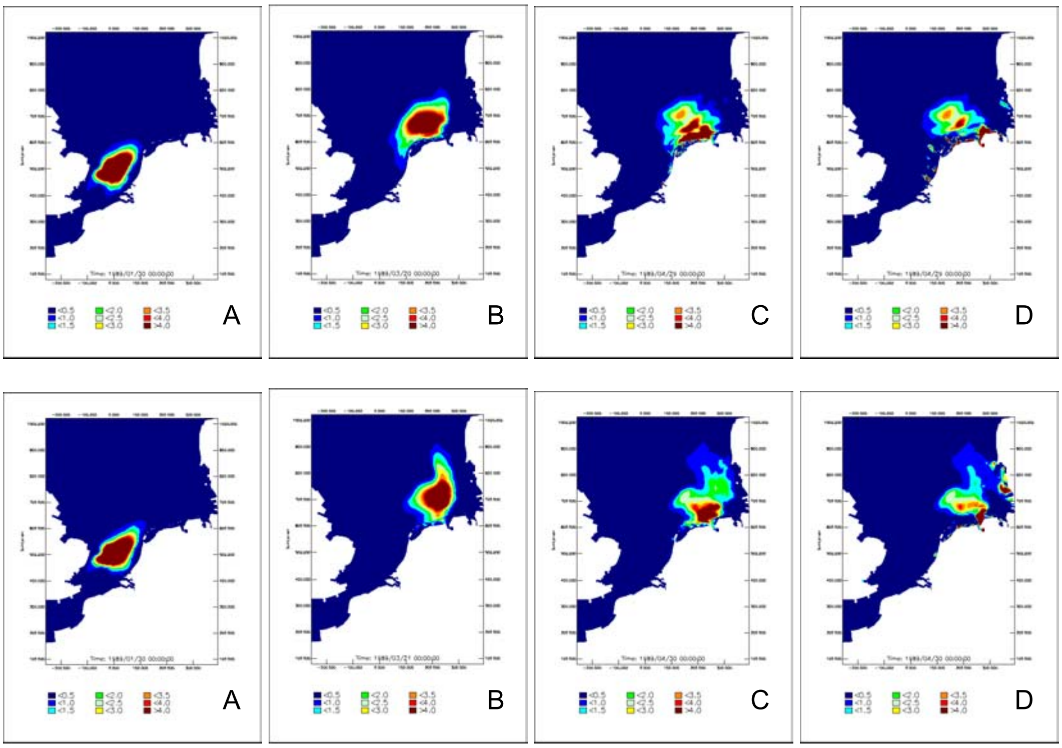
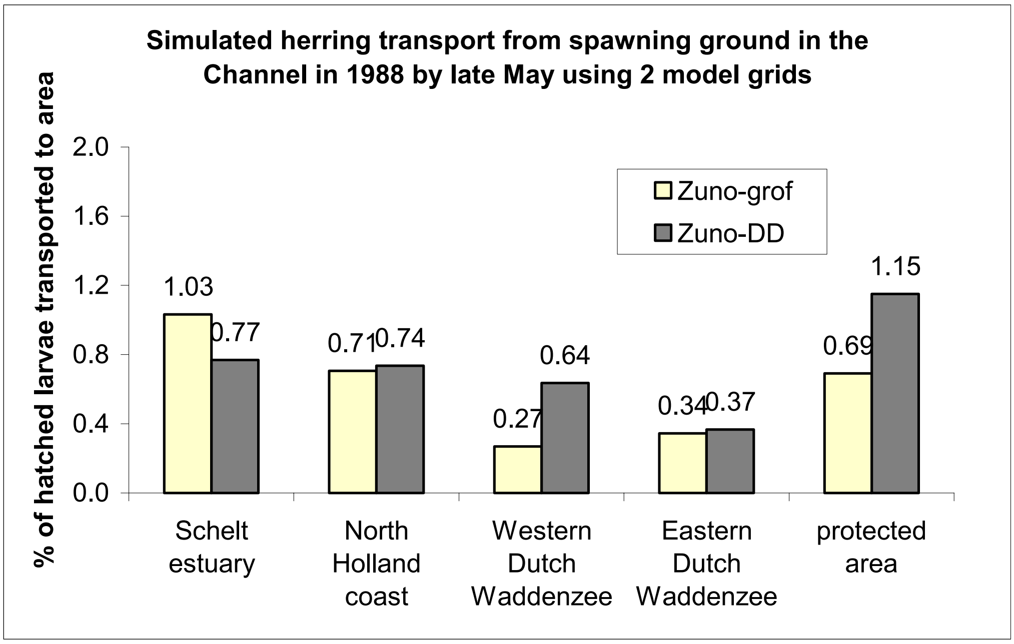


Figure 6.1.2. Plaice. Comparison ZUNO-DD (top panels) and ZUNOGROF (bottom panels): Spatial distribution at the end of the egg stage (A); the pelagic larval stage (B); the transport phase assuming passive demersal transport (C) or selective tidal stream transport (D) in the late larval and early juvenile stages.



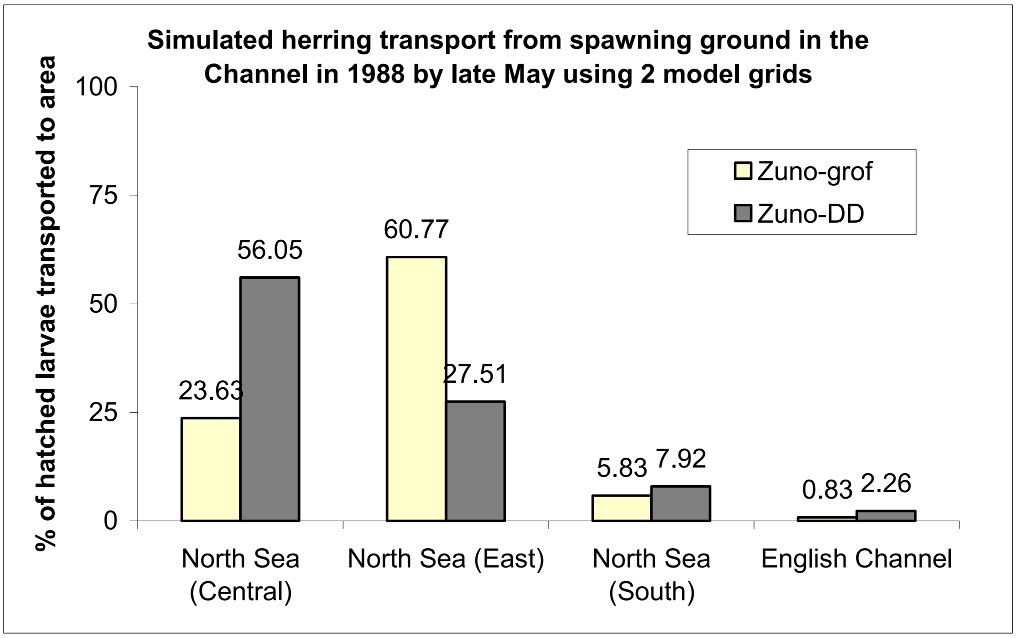


Figure 6.1.3. Herring. Comparison of final locations of herring larvae from 1988/1989 simulations of transport from 2 model grids, ZUNOGROF (used for the sensitivity analysis and inter-annual variability) and ZUNO-DD (used for the scenario runs). Values also show as numbers. Areas described in Figure 3.4.1.

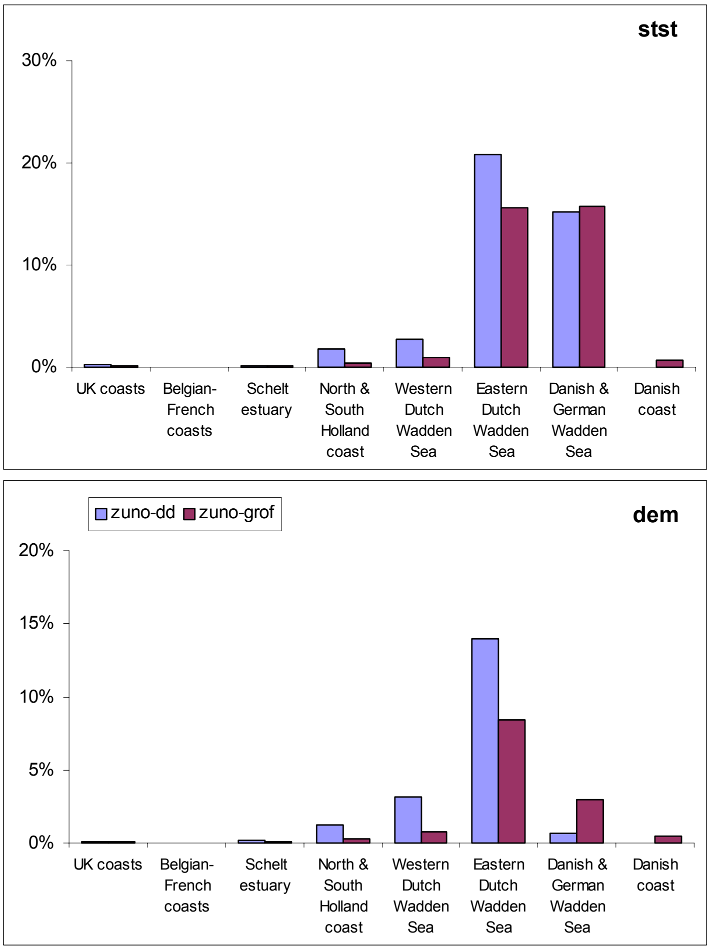


Figure 6.1.4. Plaice. Comparison of final locations of plaice larvae from 1988/1989 simulations of transport from 2 model grids, ZUNOGROF (used for the sensitivity analysis and inter-annual variability) and ZUNO-DD (used for the scenario runs). The comparison has been carried out for 2 assumptions on the transport mechanism in the late larval stages, selective tidal stream transport (stst) and passive demersal transport (dem).

6.2 The effect of MV2 on larval transport

6.2.1 Herring

The final settings, other than the temperature and hydrodynamic files are all described in Table 4.1.1. The sensitivity due to the amplitude of diel vertical aggregation was small (5-20% in the coastal areas, 2% in the open sea) compared to the variability between choice of spawning date (10-100% for all areas, 11-98% for the protected area) and between year variability (CV= 70-170% for all areas, and 86% for the protected area). So these parameter settings were maintained in the final run. The herring hatching grid 2, was chosen as the most representative distribution of hatching of Downs herring based on historic and current information. Hatching was set to occur on 16th December 1988, which was the peak time of hatching in the season 1988/1989, as determined from filed data and simple hind caste modelling.

There is no discernable difference in the distribution of the concentrations of larvae between the three scenarios (Figure 6.2.1). By area, there is also no major difference between the three scenarios (Figure 6.2.5). For transport to the protected area, the simulations suggest a reduction of 1% between the autonomous development scenario and the MV2 scenario. For the Dutch coast as a whole the simulations suggest a reduction of 3% due to the MV2 construction. None of this change occurred in the Wadden Sea itself, but along the Dutch coast and Scheldt estuary. There was no difference in terms of the timing in any area.

6.2.2 Plaice and sole

The spatial distribution has been compared for the 3 scenarios (current situation, autonomous developments and MV2) for plaice larvae from the Southern Bight spawning ground (Figure 6.2.2), plaice larvae from the English Channel spawning ground (Figure 6.2.3) and sole larvae from all spawning grounds combined (Figure 6.2.4). All comparisons have been carried for both assumptions on transport mechanism in the late larval and early juvenile stages (dem and stst). None of these distribution maps show any discernable differences between the scenarios.

For both plaice and sole, the percent of the larvae that reach certain regions differs slightly between the 3 scenarios. This has been examined for larvae from the English Channel and Southern Bight spawning grounds separately, and for both assumptions on transport mechanism in the late larval and early juvenile stages. The differences between the scenarios are very small compared to the year-to-year differences (Figure 6.2.6).

For plaice, the percent of the larvae from the Southern Bight and English Channel spawning grounds that reaches the protected area increases by 0.2% (stst) to 1% (dem) in the MV2 scenario compared to the autonomous development scenario (Table 6.2.1B). This is considered to be negligible compared to the inter-annual variability (126-138%). The transport success to all nursery areas decreases by -0.5% (stst), or increases by 0.6% (dem) due to the MV2 land reclamation.

For sole, the percent of the larvae from the Southern Bight and English Channel spawning grounds that reaches the protected area decreases by 5.8% (stst) to 6.3% (dem) in the MV2 scenario compared to the autonomous development scenario (Table 6.2.1C). Despite the fact that this difference is larger than observed in plaice, and fact that the inter-annual variability in sole is smaller than in plaice (58-93%), this difference is still considered to be of no biological significance. The transport success to all nursery areas increases by 0.2% (stst and dem hypotheses) due to the MV2 land reclamation.

The timing of arrival has been examined at 6 observation points close to the coast or in the inlets of estuarine areas (Figures 6.2.7 and 6.2.8). The comparison of these time series for the 3 scenarios shows slight differences in the densities of the larvae, but does not indicate any differences in the timing of arrival.

Table 6.2.1. Proportion of larvae reaching the protected area or, in the case of plaice and sole, all nursery areas for 3 scenarios: the current situation (T0), autonomous developments (AD) and Maasvlakte 2 (MV2), and the inter-annual variability (9-year range) in transport success. The scenarios are modelled based on the hydrodynamic situation of 1989 and the ZUNO-DD grid, the inter-annual variability is based on the sensitivity analyses using the ZUNOGROF grid. The relative effect compares AD to T0, MV2 to AD, and the inter-annual range to the mean.

A. Herring. The herring originate from the hatching distribution in Figure 4.1.10.

Transport mechanism	Scenario	Transport success protected area	Relative effect * protected area
diel vertical migration	T0	1.15%	
	AD	1.17%	1.2%
	MV2	1.16%	-0.8%
	annual variability	0 - 2.7%	273%

B. Plaice. The plaice originate from the spawning grounds in the Southern Bight and English Channel combined, and selective tidal stream transport (stst) or passive demersal transport (dem) is assumed for the late larval and early juvenile stages.

Transport	Scenario	Transport succes to		Relative effect *	
mechanism		protected area	all nurseries	protected area	all nurseries
stst	T0	11.72%	36.8%		
	AD	11.84%	36.8%	1.0%	0.0%
	MV2	11.86%	36.7%	0.2%	-0.5%
	annual variability	3 - 15%	23 - 42%	126%	54%
dem	T0	8.83%	15.3%		
	AD	8.84%	15.3%	0.2%	-0.2%
	MV2	8.94%	15.4%	1.0%	0.6%
	annual variability	2 - 11%	9 - 22%	138%	82%

C. Sole. The sole originate from the spawning grounds in the Southern Bight and English Channel combined, and selective tidal stream transport (stst) or passive demersal transport (dem) is assumed for the late larval and early juvenile stages.

Transport	Scenario	Transport succes to		Relative effect *	
mechanism		protected area	all nurseries	protected area	all nurseries
stst	T0	1.39%	48.80%		
	AD	1.43%	48.32%	2.5%	-1.0%
	MV2	1.34%	48.43%	-5.8%	0.2%
	annual variability	1.2 - 2.3%	40 - 53%	58%	29%
dem	T0	1.37%	21.38%		
	AD	1.43%	21.20%	5.0%	-0.8%
	MV2	1.34%	21.25%	-6.3%	0.2%
	annual variability	0.7 - 2.0%	19 - 25%	93%	24%

* Relative effect MV2 vs AD= (MV2 – AD)/AD
Relative effect AD vs T0 = (AD – T0)/T0
Relative effect annual variability = (max – min)/mean

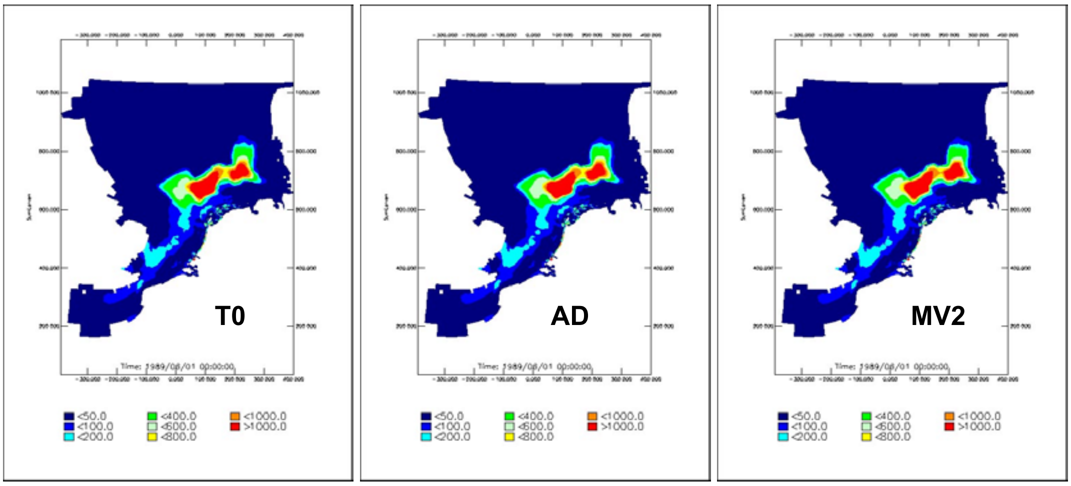


Figure 6.2.1. Herring. Distribution of concentrations of late post larvae in late May 1989 for 3 scenarios: Current situation (T0), autonomous developments (AD) and autonomous developments + MV2 (MV2). Model run with settings in Table 4.1.1, 1988/1989 hydrographic data on the ZUNO-DD grid, using herring hatch grid 2 hatched on 16th December 1988.

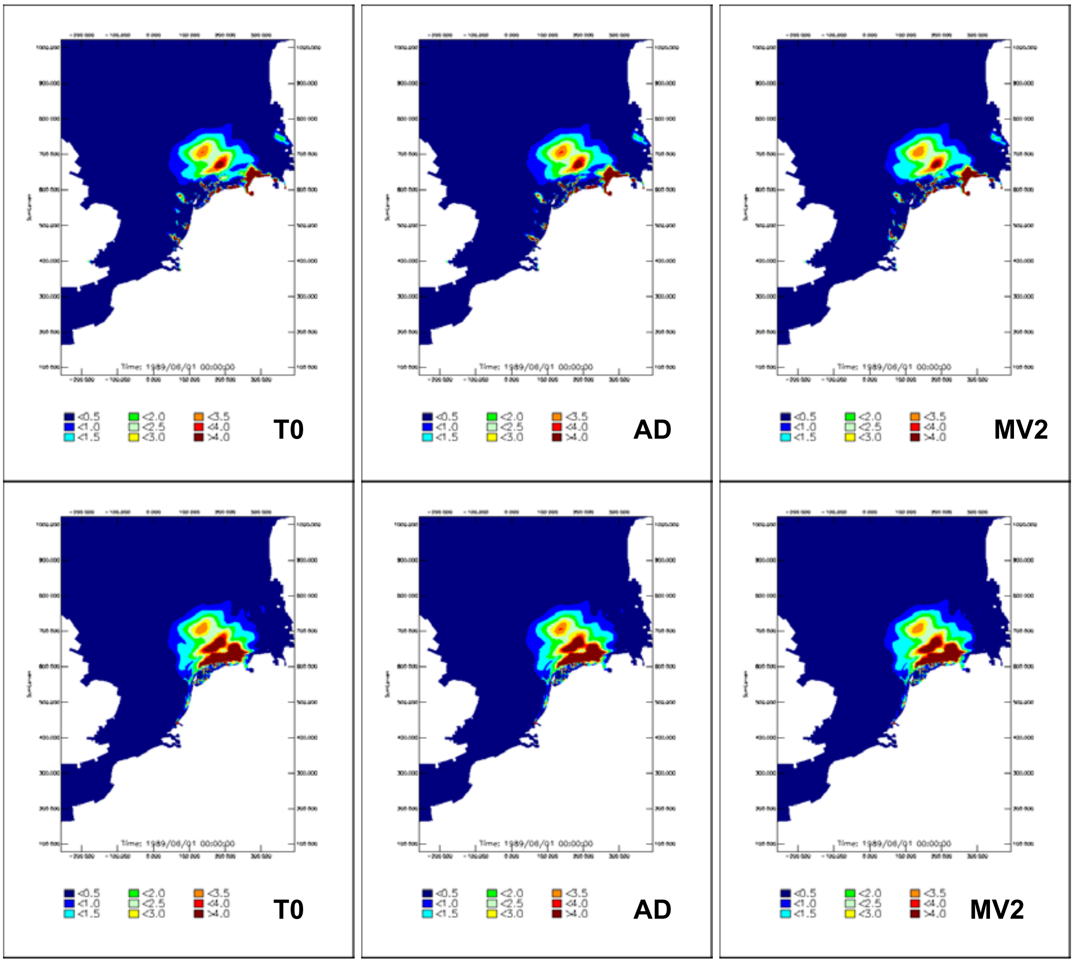


Figure 6.2.2. Plaice - Southern Bight spawning ground. Distribution pattern at the end of the transport phase for 3 scenario's: Current situation (T0), autonomous developments (AD) and autonomous developments + MV2 (MV2), assuming selective tidal stream transport (top panels) or passive demersal transport (bottom panels).

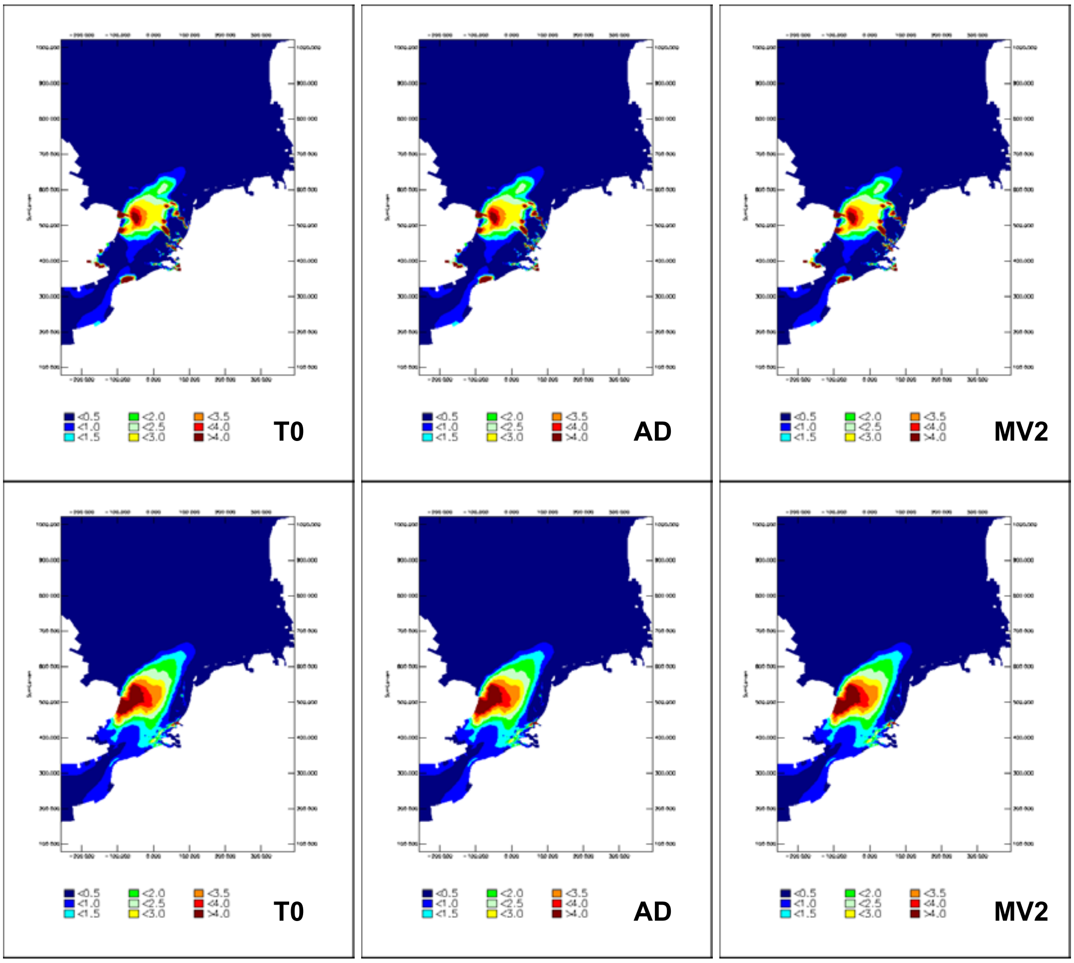


Figure 6.2.3. Plaice - English Channel spawning ground. Distribution pattern at the end of the transport phase for 3 scenario's: Current situation (T0), autonomous developments (AD) and autonomous developments + MV2 (MV2), assuming selective tidal stream transport (top panels) or passive demersal transport (bottom panels).

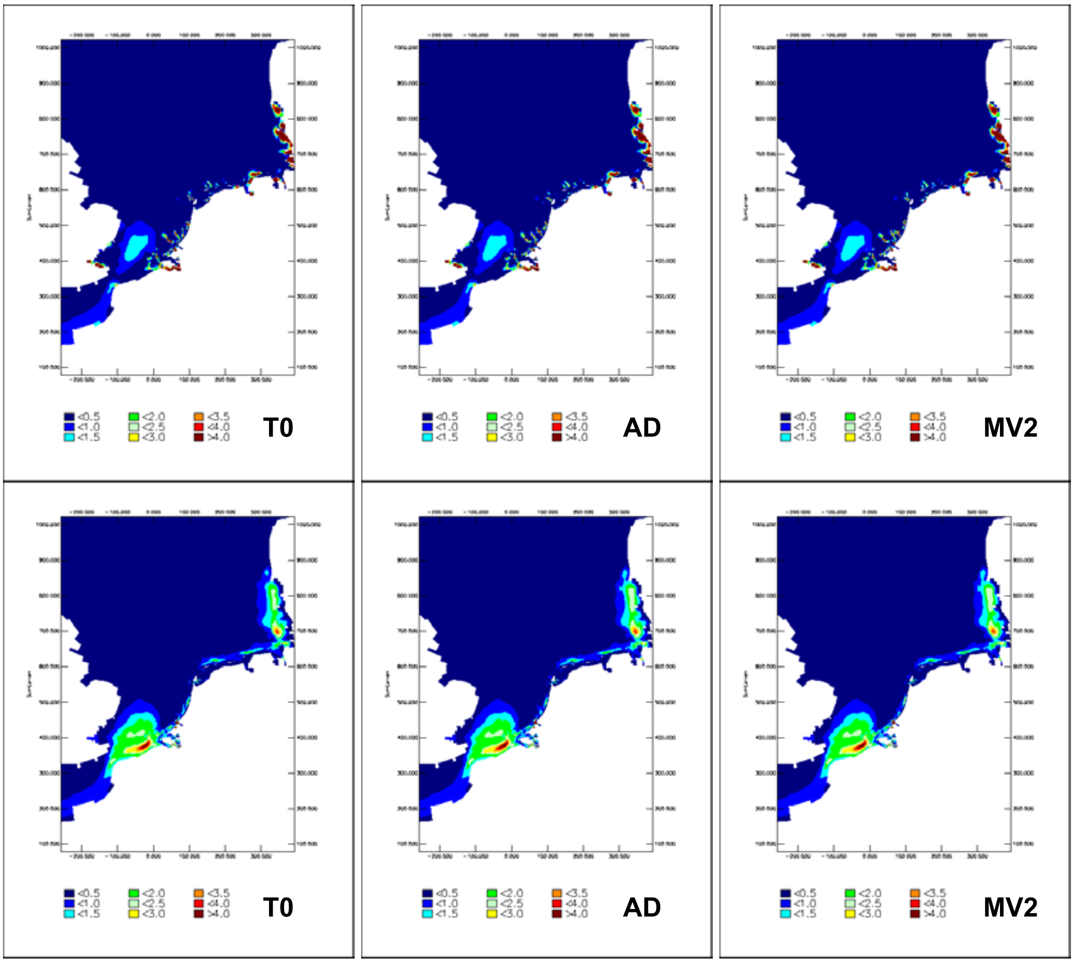
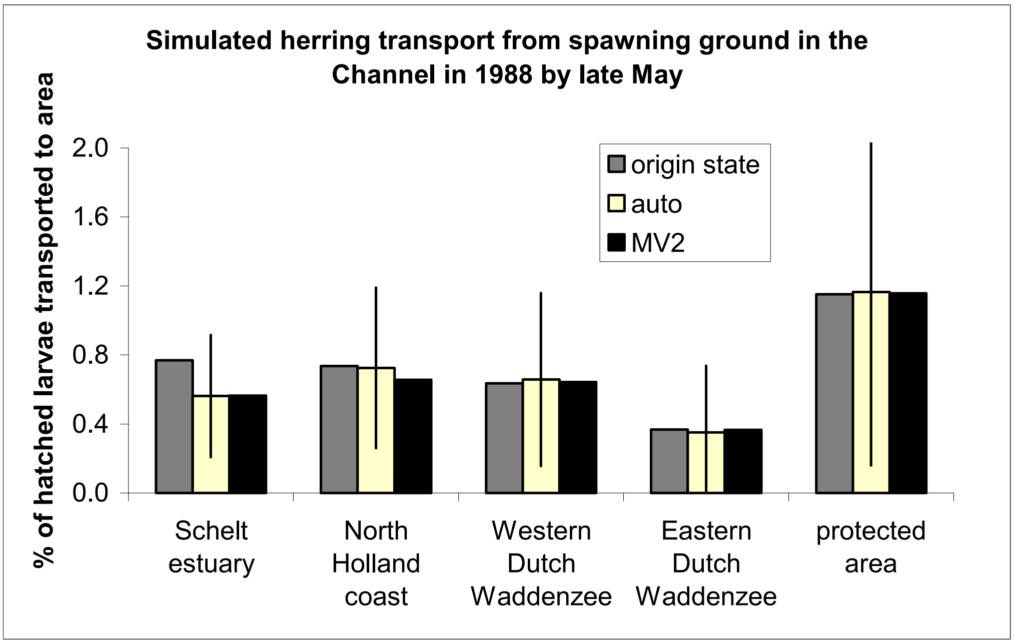


Figure 6.2.4. Sole - All spawning grounds combined - Distribution pattern at the end of the transport phase for 3 scenario's: Current situation (T0), autonomous developments (AD) and autonomous developments + MV2 (MV2), assuming selective tidal stream transport (top panels) or passive demersal transport (bottom panels).



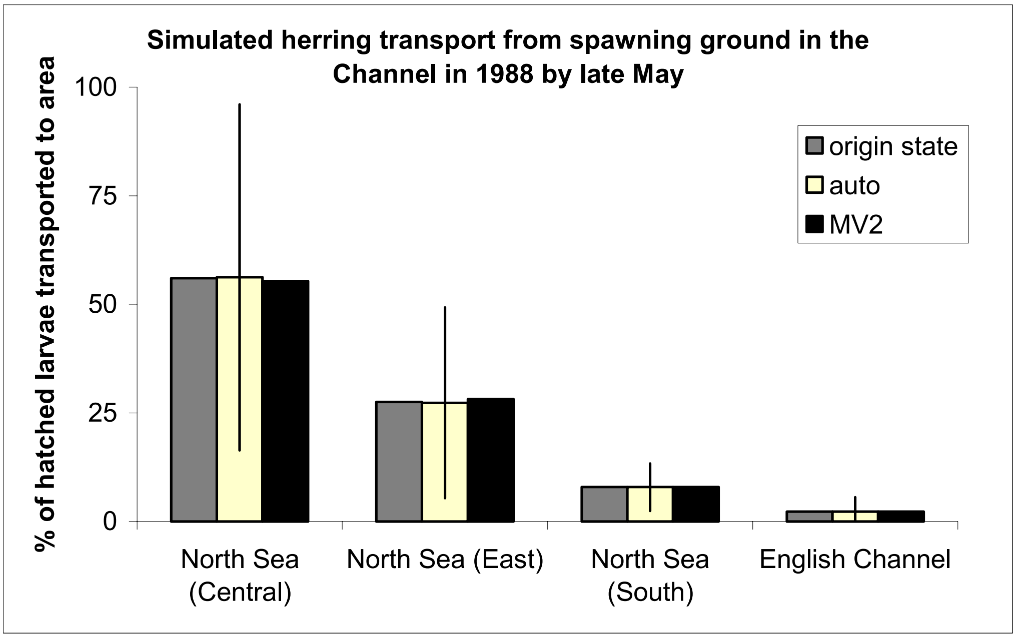


Figure 6.2.5. Herring. Percent of hatched larvae transported to each location by the end of May 1989 under three different scenarios (original state- T0, the autonomous developments (auto) and Maasvlakte 2- MV2). Model run with settings in Table 4.1.1, 1988/1989 hydrographic data on the ZUNO-DD grid, using herring hatch grid 2 hatched on 16th December 1988. Note different y axes. Areas described in Figure 3.4.1. Error bars denote simulated standard deviation of inter-year variability of transport to each location (from ZUNO- grof grid).

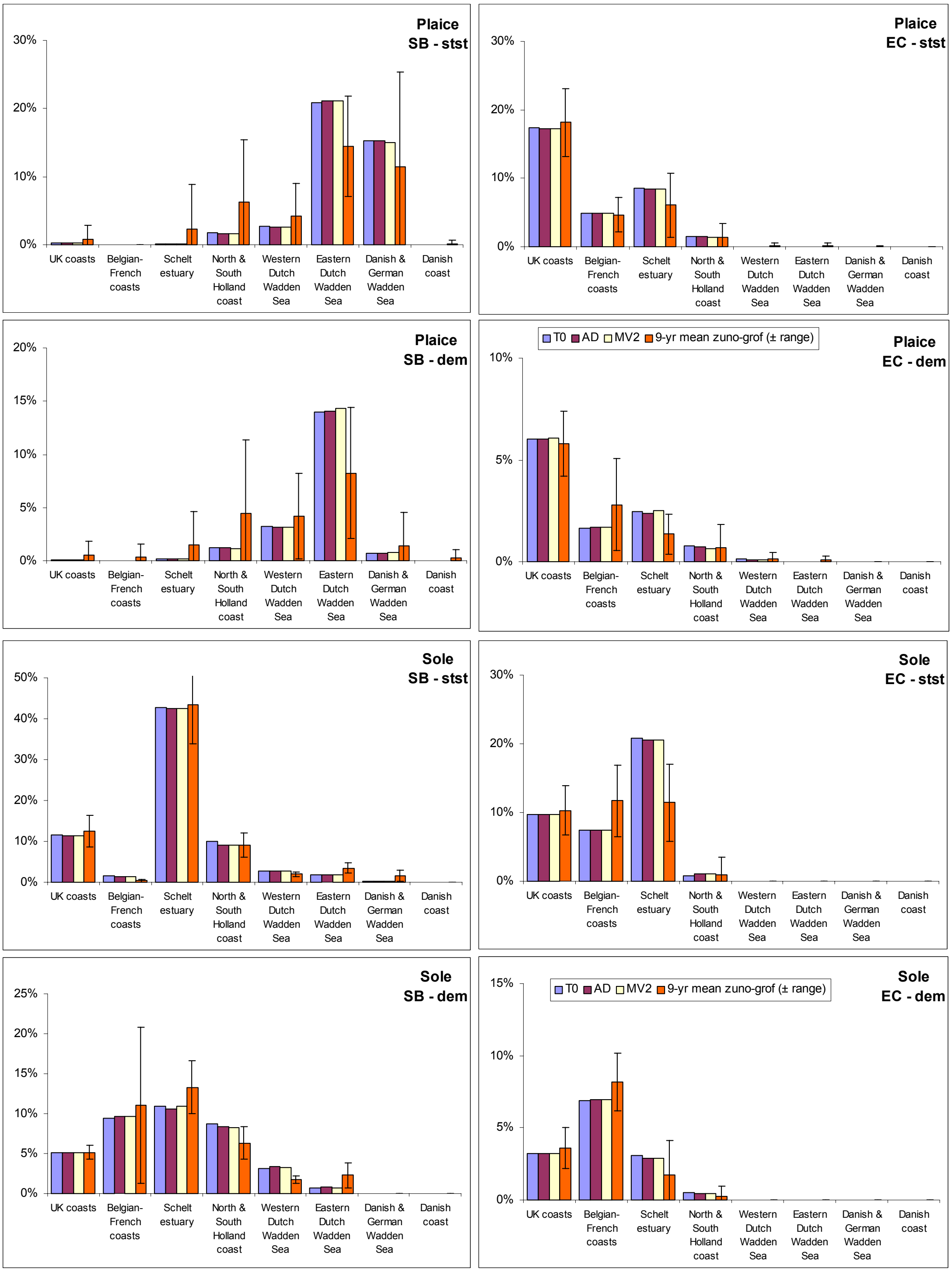


Figure 6.2.6. Plaice and Sole. The transport success by region for 3 scenario's (based on the hydrodynamic situation of 1989 and the ZUNO-DD grid): the current situation (T0), autonomous developments (AD) and Maasvlakte 2 (MV2); and the inter-annual variability (9-year mean ± range) in transport success by region (based on the sensitivity analyses using the ZUNOGROF grid). The plaice originate from the spawning grounds in the Southern Bight (SB) or English Channel (EC) and selective tidal stream transport (stst) or passive demersal transport (dem) is assumed for the late larval and early juvenile stages. The proportion of larvae that reach the protected area or all nursery areas combined is listed in Table 6.2.2 (plaice) and 6.2.3 (Sole).

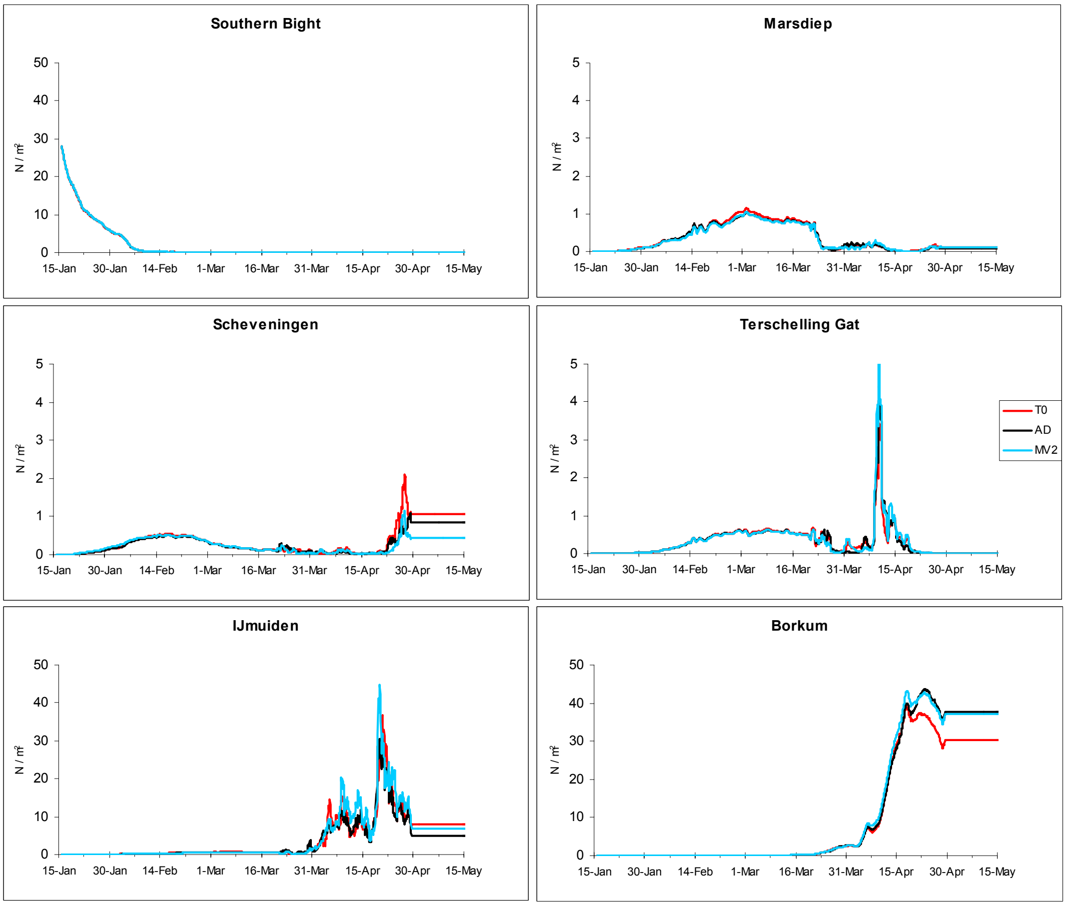


Figure 6.2.7. Plaice. Time series of densities (N/m^2) at 6 observation points close to the coast or in the inlets of estuarine areas, for 3 scenario's: the current situation (T0), autonomous developments (AD) and Maasvlakte 2 (MV2). The plaice originate from the Southern Bight spawning grounds and selective tidal stream transport is assumed for the late larval and early juvenile stages.

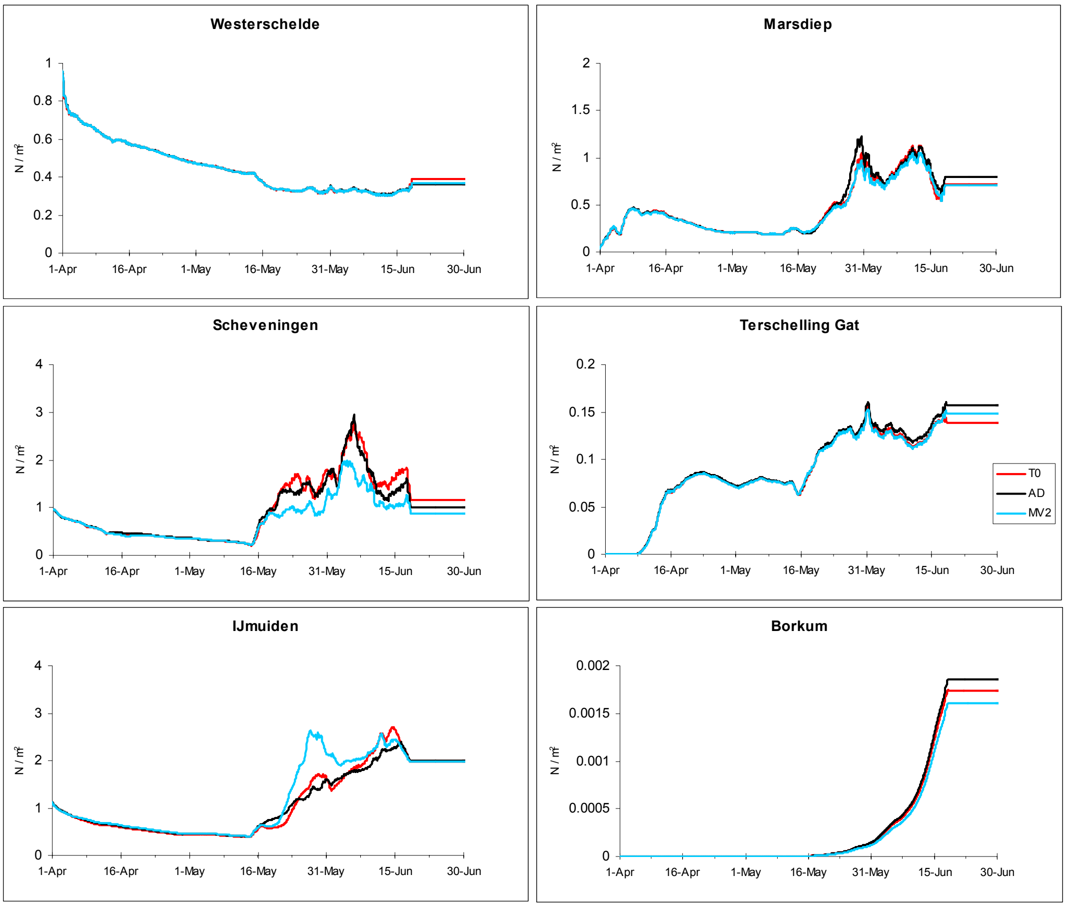


Figure 6.2.8. Sole. Time series of densities (N/m^2) at 6 observation points close to the coast or in the inlets of estuarine areas, for 3 scenario's: the current situation (T0), autonomous developments (AD) and Maasvlakte 2 (MV2). The sole originate from the Southern Bight spawning grounds and passive demersal transport is assumed for the late larval and early juvenile stages.

6.3 The effect of MV2 on population sizes

Considering that:

i) the majority of the **herring** larvae recruit to nursery areas in the open sea and the transport to this area is affected by 0.01% by the MV2 development (Figure 6.2.5),

ii) the transport of **plaice** larvae to all coastal and estuarine nursery areas is affected by -0.5% to +0.6% by the MV2 development, which is considered to be of negligible biological significance taking into account the inter-annual variability of 54-82% (Table 6.2.1),

iii) the transport of **sole** larvae to all coastal and estuarine nursery areas is affected by +0.2% by the MV2 development, which is considered to be of negligible biological significance taking into account the inter-annual variability of 24-29% (Table 6.2.2),

iv) the aggregates for constructing the site will be extracted from areas well away from the spawning sites of herring and plaice, and the area of extraction and potential disturbance is very small compared to the total spawning area of sole,

v) turbidity will not rise above levels to prevent feeding of the larvae (see Fox et al 1999),

we conclude that there are no likely direct effects of the building or the presence of the MV2 on the populations of herring, plaice and sole in the southern North Sea. Any changes in productivity to the region due to the MV2 land reclamation may influence herring, plaice or sole, but this is outside the remit of this project.

7 Discussion and conclusions

This study is the first to look at the transport of larvae in the southern North Sea using real time hydrodynamic forcing (with wind, air pressure and river discharge), inter-annual variability and behaviour rules that incorporate salinity triggers. It was carried out in 5 months according to specific requirements of the Dutch Government (the PMR partners).

The study started out within the framework of the Baseline study for the Monitoring and Evaluation Programme Maasvlakte 2 ('Baseline study'). The objectives were to describe and quantify the current larval transport patterns, and judge how the possible effects of MV2 on larval transport, influences the population sizes. Due to the verdict of the Council of State the objectives of the study on larval transport were elaborated: to improve the model to decrease the uncertainties and quantify the effects of MV2 ('PB study'). This report addresses the objectives of both the Baseline and the PB study.

7.1 General discussion

The transport of the larvae of three species was modelled: herring, plaice and sole. The two flatfish species use shallow coastal waters, such as the Wadden Sea as their juvenile nursery grounds. Herring was selected in the PB study because of its importance as prey item in the Wadden Sea. All three species depend on larval transport to reach these inshore areas and for all 3 species a sufficient amount of knowledge is available to model the transport of larvae. The model results were different for the 3 species examined because different, species-specific behaviour, parameters and spawning grounds were incorporated in the model. These inter-specific differences show that it is tricky to extrapolate the model results for herring, plaice or sole to other species with larval drift. Despite the fact that sandeel is one of the most important prey items for birds in the Wadden Sea, it was not included in present modelling study due to the lack of knowledge on spawning and larval distribution in the southern North Sea and Wadden Sea. Assumptions on, for example the location of the spawning grounds or vertical migration, would have a large effect on the modelled larval transport patterns and the estimation of the impact of MV2.

The study shows that there is large inter-annual variability in the transport of herring, plaice and sole larvae. The variability due to the parameterisation of the model appears to be greater for plaice and sole compared to herring. This is probably due to the more sensitive and contrasting behaviour rules (e.g. in flatfish, the pelagic and demersal forms of transport are very different and hence the importance of the development rates is greater compared to herring). It is encouraging though, that despite the variability caused by the model assumptions, the model results still show broad agreement with the available field data. The large variability between years as simulated by the model, probably does occur in the field, and the variability caused by the sensitivity of the model to the assumptions can be viewed as a (deterministic) precision estimate of the model. This precision estimate partly reflects uncertainties in the assumptions due to knowledge gaps and partly reflects natural variability. The very small differences apparently caused by the land reclamation for Maasvlakte 2 are much smaller than the model's precision, and insignificant in comparison to the inter-annual variability. It is unlikely, at this stage of model development that the precision of the model can be greatly increased; therefore the conclusion of the current project must be that the effect of the Maasvlakte 2, as measured through the current model and its inherent assumptions, is close to zero, in other words negligible.

The findings of this project should be carefully interpreted; accounting for all of the assumptions of the model. Transport and delivery rates should not be interpreted as recruitment success or rates. The model was designed to investigate variability in hydrodynamic driven transport, and not the variability in year class strength.

At no point was mortality applied to the concentrations of eggs or larvae. Mortality cannot be considered as just a scaling factor, as it is selective, in terms of space, time and physical rates (Gallego & Heath, 1997; Pepin et al., 2002; Pepin, 2004). Within each species the same amount of eggs or larvae were released each year or for each scenario, which is not representative of the actual annual production. Approximations of realistic variability in the timing of spawning or hatching were examined in the sensitivity analysis, but only single spawning or hatching date per spawning ground were used in the final model runs. Hence this model, not counting the structural and theoretical differences, is in no way comparable with the types of Individual Based Models (IBMs) used to investigate recruitment variability (Heath et al., 1997; Hinrichsen et al., 2003; Peck et al., 2003 etc). This investigation has looked purely at the transport patterns of concentrations with behaviour, the delivery to specific locations from specific sources, and whether future constructions will impact on that delivery.

There are many ways in which the investigation could be improved. The approach taken has been deterministic, and precision has been inferred. The creation of a stochastic model or a Bayesian approach might have provided a more robust assessment of the precision of the model.

Clearly the parameterisation of the model could be improved, as there are uncertain processes in the behaviour and development of the larvae. For flatfish, one of the most important knowledge gaps is the potential survival outside the nursery areas after metamorphosis is completed; do the fish die if they haven't reached a suitable nursery area by the time metamorphosis is completed, and if not how long can they survive? The model is very sensitive to the assumptions on this aspect. Another important knowledge gap for flatfish is the importance of selective tidal stream transport, and the environmental factors that trigger this behaviour.

The realism of the model could be improved if larval behaviour could be linked to biological factors. In the current version of the model, the behaviour of larvae can only be related to physical factors. For herring it has been shown that the diel vertical migration patterns are related to the distribution of zooplankton. For flatfish the determination of 'suitable' nursery grounds could be linked to benthic production. The realism of the flatfish model could also be improved if the vertical resolution of 10 water layers is maintained instead of aggregating into 2 water layers (top 96% of the water column and the bottom 4% of the water column). This elaboration would require a quantitative description of the physical and behavioural traits of eggs and larvae that influence the vertical distribution. But, although some studies have focussed on the vertical distribution of flatfish eggs or larvae (Coombs et al., 1990; Sundby, 1991; Lagardère et al., 1999; Jager, 1999a), much less is known about this topic in flatfish compared to herring. Moreover, in the southern North Sea mixing has a greater effect on the vertical distribution of eggs than buoyancy (Coombs et al., 1990), and the transition from a pelagic to a demersal life style is considered to be of greater importance for larval dispersal than vertical distribution patterns during the pelagic phase. In general, there is no gain in elaborating the fish larvae model if the parameterisation hereof is based on guestimates.

The present study clearly shows large year-to-year differences in the transport patterns of larvae related to inter-annual variability of the hydrodynamics. But more work is required to understand the mechanisms that drive the hydrodynamics and the species specific responses, e.g. examine larval transport with varying fluxes through the Channel, river discharges, wind fields, etc. Furthermore the sensitivity of the larval model has not been examined for uncertainties in the forcing of the hydrodynamic model, such as some of the river discharges being variable while others are constant, or the assumption that all discharges are at 10°C, or differences in the spatial and temporal bins of the wind data. Despite the apparent agreement in the hydrodynamics between ZUNOGROF and ZUNO-DD, there appear to be differences in the transport of larvae. It has been argued that the differences caused by the choice of grid are small compared to the inter-annual variability, thus making them negligible within the context of the MV2 impact assessment, however these differences are indicative that the modelled hydrodynamics are affected by factors other than the climate, discharge and tidal forcing.

In a similar manner the current hydrodynamic model does not account for extreme far field effects (i.e. beyond the grid). The hydrodynamics are driven by tides, wind, air pressure and river discharges. Far field oceanographic influences are not accounted for, e.g. would the model cope with the great salinity anomaly of the 1970s (Cushing, 1995) or the increase salinity of the North Sea in early 2005 (ICES pers com)? However it can be argued that the inclusion of air pressure does account for many of the likely far field influences on the southern North Sea.

Considering the large inter-annual variability, the choice made on operational grounds to investigate the effect of the Maasvlakte reclamation on one year (1988/1989) only, may lead to criticism. As shown in section 4, the choice of year gives large differences when testing the sensitivity of variables such as hatch date or spawning date or uncertainties such as duration of transport. Hence the Maasvlakte 2 may have different effects in different years.

The MV2 land reclamation is expected to affect the water movements of the 'coastal river' (De Goede & Van Maren, 2005a; 2005b; Van Ledden et al., 2005). An important aspect of the coastal river is the difference in residual currents over the water column. Near the water surface, the residual currents are directed more or less parallel to the shoreline with a small component offshore, and near the bed the residual current is directed towards the coast. This difference has important consequences for the inshore transport of fish larvae. The expected effect of MV2 is an increased mixing of fresh water from the River Rhine and salt water from the North Sea, which implies a widening of the coastal river and a decrease of the residual coastward current near the bed.

The large inter-annual variability in larval transport patterns appears to be mainly caused by differences in the along-shore transport outside of the coastal river, which is presumably not affected by MV2. However, it is difficult to disentangle the effects of changes in the offshore (along-shore) water movements and inshore (cross-shore) water movements. Comparison between the offshore spawning species (herring and plaice) and the inshore spawning species (sole) suggest that the inter-annual variability of water movements in coastal waters is relatively small. Nevertheless, it may still be argued that the impact of MV2 differs between years.

The width and shape of the 'coastal river' and its associated salinity gradients and residual currents depend partly on the quantity of discharges into the coastal waters along the Dutch coast, which is dominated by the discharge of the River Rhine (related to the amount of rainfall and melting snow in its watershed). The long-term average discharge of the Rhine is approximately 2200 m^3/s. In this respect, the year 1989, which was chosen for the baseline situation, is a rather unusual (dry) year, as the Rhine discharge only reached approximately 1650 m^3/s. However, the coastal river and its salinity gradients are influenced to a major degree by the dominant hydrodynamic flows, the tide and weather conditions (especially wind). Therefore it cannot simply be stated that the coastal river and its salinity gradients are proportional to the amount of discharge. In the impact studies on hydrodynamics, nutrients & primary production and silt transport, the effects of MV2 have not only been quantified using the 1988/89 year-run simulation, but also using an average spring-neap cycle (based on long-term average discharges and wind conditions). The results of these spring-neap cycle simulations, did not differ much from the year-run simulation, indicating that the fact that 1988/89 was a rather unusual year with low discharges and unusual wind patterns is unlikely to have affected the impact predictions very much. It would therefore appear unlikely to assume that simulations based on a different year with greater discharges would have resulted in a proportionally greater effect of MV2 on the transport of fish larvae.

Various alternatives of the land reclamation layout have been proposed in recent years. In the PKB+ part 1/MER phase (see section 1.1), the Reference Designs I (GAN) and II (GAB) were considered. The major difference between these two designs is that Reference Design II (GAB) has its own harbour entrance, including an extension of the harbour breakwaters, whereas the entrance in Reference Design I (GAN) is realised by extending and widening the harbour in the existing Maasvlakte. The current design is called the 'Doorsteekvariant'. The geometry of this design is quite similar to Reference Design I (GAN), but it is slightly smaller on the southwest side. The impact assessment of MV2 on fish larvae has only been modelled for the Doorsteekvariant, which is considered to be comparable to the Reference Design I (GAN). No model results are available for Reference design II (GAB). The model results from the baseline study and the impact assessment of the Doorsteekvariant suggest that the larval transport towards the Wadden Sea is mainly influenced by the large-scale water movements determined by the flow through the English Channel, and to a much lesser extent influenced by local hydrodynamics and changes in the Coastal River. As all MV2 designs only affect the local hydrodynamics around the outflow of the Rhine-Meuse, and the Coastal River at a larger distance (De Goede & Van Maren, 2005a; 2005b; Van Ledden et al., 2005), we assume that the effect of Reference design II (GAB) on the transport of fish larvae will also be negligible.

For the construction of MV2, sand will be extracted from areas in the North Sea. These sand mining activities will cause a temporary increase of the mud concentration in the water column (Van Kessel, 2005; Van Ledden et al., 2005). As this increase in turbidity will not rise above levels that prevent feeding of the larvae (see Fox et al 1999), no effect on larval mortality is expected. The direct disturbances of sand mining activities on spawning or larval transport is also expected to negligible because the area of extraction is well away from the spawning sites of herring and plaice, and very small compared to the total spawning area of sole.

7.2 Future research needs

This investigation has highlighted the need for research in four main areas:

i) Studies to improve and refine the current model with respect to stochastic processes.
ii) Process studies to improve and refine the parameterisation of the current model.
iii) Studies to monitor the impact of the Maasvlakte 2 development prior, during and after construction.
iv) Studies to address new, applied and highly relevant questions relating to larval transport and recruitment processes.

Stochastic processes

The model, at present, is deterministic, with the levels of precision applied by multiple runs of parameter settings. This in a sense, is a simplistic form of bootstrapping the model settings. The model needs to be further developed to be able to cope with uncertainty and distributions of parameters. This will allow a more coherent assessment of uncertainty and variability to take place and will ensure that the conclusions are based on more robust estimates of precision.

Parameterisation of the current model.

For plaice, sole and herring, process studies are required to investigate further the development of the larvae. Particularly in relation to growth and stage duration, diel vertical migration and environmental triggers of behaviour. For plaice and sole, the behaviour immediately prior to settlement and the effect of postponed settlement also needs to be investigated. To apply the larval transport model to other species sufficient knowledge must be available to parameterise the model. In this respect the knowledge gap on the ecology of sandeel in the southern North Sea is very prominent. This species is of ecological significance, not only in the Wadden Sea, but at present insufficient information is available to include this species in the modelling studies for the southern North Sea.

Monitoring

The model should be run from 2003 to at least 2010 with real hydrodynamic data, to determine the variability over the construction period and post construction. These model findings should be linked to a resumption of the Stow net survey, to monitor the delivery of larvae into the Wadden Sea and thus provide greater confidence in the between year variability seen in the model. A study should also be launched to investigate, by means of the otolith microchemistry, the source of juvenile herring, sandeel and flatfish in the Wadden Sea, and also in the adult North Sea populations to determine the likely contribution of the Wadden Sea as a nursery ground to these populations.

New applied studies

The model needs to be further developed to allow variables other than hydrographical conditions to affect the behaviour of concentrations of eggs or larvae. Factors such as zooplankton abundances, aggregation ability and perhaps predator abundances and benthic food availability should be included in the model. In other words concentrations of a range of substances should be allowed to interact. This elaboration of the model will require a better understanding of processes during in early life history and therefore additional studies on larval behaviour, transport and survival in relation to abiotic and biotic factors are necessary.

7.3 Conclusions

The conclusions of the Baseline MEP-MV2 study are essential for the interpretation of the PB-MV2 study. Therefore the conclusions of both studies are summarized below:

- The modelled larval transport patterns were different for the 3 species examined because species-specific behaviour, parameters and spawning grounds were incorporated in the model.

- The simulations suggest that the modelled transport of larvae is highly sensitive to the inherent assumptions and parameterisation.

- The simulations show large between year variability in the transport of larvae, related to inter-annual variability in hydrodynamics. These differences appear to be mainly caused by large-scale water movements driven by the residual flows through the Dover Straits.

- The simulated results show broad agreement with the available field data

- The simulated differences in transport caused by the reclamation of Maasvlakte 2 were much smaller than the model's 'precision', and insignificant in comparison to the inter-annual variability. Based on the current model and its inherent assumptions and uncertainties, it is concluded that the effect of the Maasvlakte 2 is close to zero, in other words negligible.

- Consequently, it is concluded that changes in water movements due to the presence of Maasvlakte 2 will not have a direct effect on the abundance of herring, plaice and sole in the Wadden Sea (PB-MV2 study) or on the recruitment of plaice, herring or sole (Baseline MEP-MV2).

- The effect of the actual process of the construction of Maasvlakte 2 (i.e. sand mining) has not been examined in the present study. However, based on the locations proposed, the limited area of disturbance and the expected degree of turbidity increase, no significant effects are expected on the populations of plaice, sole or herring larvae.

- No conclusions on the indirect effects of Maasvlakte 2 on fish populations, such as changes in the productivity of the ecosystem, can be drawn from the present study.

- No model simulations have been carried out with regards to the Reference Design II (GAB). However, it seems reasonable to assume that the effects on the transport of fish larvae, due to Reference Design II, will also be negligible as a result of its limited effect upon the large-scale hydrodynamics.

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Annexes

1 Literature study herring (20pp): Dickey-Collas, M. 2005. Desk Study on the transport of larval herring in the southern North Sea (Downs herring), .RIVO Report nr C031/05.

2 Field data plaice and sole (25pp)
    2a Demersal Fish Survey
    2b Flyland survey
    2c MV2 survey
    2d NIOZ data
    2e Stow net survey western Wadden Sea

3 Herring surveys (19pp)
    3a International Herring Larvae Survey
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Report

Number: C031/05

Desk Study on the transport of larval herring in the southern North Sea (Downs herring).

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Summary

Current understanding about the drift and behaviour of larval herring is reviewed with particular emphasis on the Downs herring and the development of a model for larval transport. Downs herring are the component of North Sea herring that spawn in the southern North Sea and English Channel. Generally the larvae of the Downs herring drift east towards the German Bight and Skagerrak, but this is dependent on the meteorological forcing of local hydrography. Whilst it has been possible to model the broad trajectory of the larvae, modelling the yearly variability in drift patterns has proved difficult. The drift of the larvae and post-larvae does take them close to the Dutch coast in some years (as shown by survey results). It is during this phase of their life cycle (from larvae to metamorphosis) that the strength of the recruiting year class is determined. The larvae show vertical migration as they grow and also begin to aggregate after metamorphosis. There is no evidence in the primary literature for triggers for directional movement (such as salinity or depth of water column). There is no work published to date, on the impact of anthropogenic disruption of larval drift on the productivity of Downs herring or on the fishery.

Samenvatting

De huidige kennis over de driftpatronen en het gedrag van larvale haring is onderzocht, waarbij gekeken is naar kanaalharing (Downs herring) en het ontwikkelen van een model om larvale driftpatronen te beschrijven. Kanaalharing is het deel van Noordzee haringpopulatie dat in het zuidelijk deel van de Noordzee en het Kanaal paait. Over het algemeen driften larvale kanaalharingen oostelijk richting de Duitse Bocht en het Skagerrak, maar dit is afhankelijk van de zeestromen. Het is mogelijk om het algemene traject te modelleren dat larvale kanaalharing afleggen, maar jaarlijkse variaties hierin zijn moeilijk te modelleren. In sommige jaren komen de larven en post-larven dicht bij de Nederlandse kust (gegevens afkomstig van surveys). Gedurende deze levensfase (metamorfose van larve naar jonge haring) wordt de jaarklassterkte bepaald. De larven vertonen verticale migratie gedurende de groei en beginnen na de metamorfose met samenscholen. In de wetenschappelijke literatuur is geen bewijs gevonden dat gerichte bewegingen van larven worden veroorzaakt door bepaald gedrag ten gevolge van omgevingsfactoren als zoutgehalte of diepte. Op dit moment is in de literatuur geen werk beschikbaar over veranderingen in de larvale driftpatronen door menselijk ingrijpen en de gevolgen hiervan op de productiviteit van kanaalharing en op de visserij.

Introduction

Unusual for a commercial fish species in the North Sea, herring (*Clupea harengus* L.) spawn benthic eggs in large mats and clumps that tend to hatch together (Harden Jones, 1968; Burd, 1978; Blaxter & Hunter 1982). This results in high densities of larvae being dispersed from specific points over a short period of time (Boeke, 1906; Wallace, 1924). There has been much debate as to whether herring prefer retention or dispersion as a life history strategy (Iles & Sinclair, 1982; Sinclair & Tremblay, 1984; Cushing, 1986; Heath & Richardson, 1989; Fortier & Gagné, 1990), but in the North Sea herring larvae are dispersed from their spawning sites and drift hundreds of kilometres towards their nursery areas (Munk & Christensen, 1990; Bartsch, 1993; Heath et al., 1997). It is during this drifting period that the year class strength of herring is determined (Cushing, 1967; Anthony & Fogarty, 1985; Nash & Dickey-Collas 2005) and variability in climatic forcing of the larval drift may actually help explain some of the variability in the year class strength in North Sea herring (Bartsch et al., 1989; Bartsch 1993).

Herring in the North Sea

The North Sea herring stock is made up of a number of components (sub-populations) fish that show different physical characteristics, spawning strategies and migration behaviour (Zijlstra, 1958). They were originally called races of herring (Heincke, 1898; Redeke & van Breemen, 1907; Bjerkan, 1917) but are now considered to be parts of the same stock as they are genetically indistinguishable (EU HERGEN project, in prep) and all mix at certain points of their life cycle (ICES, 1965; Cushing & Bridger, 1966; Cushing, 1992). Variability in their environment (particularly temperature) at spawning, hatching and during the first year of life is thought to create the differences between component parts of the stock by influencing growth and physical development (Jennings & Beverton, 1991; Hulme, 1995; McQuinn 1997) and these physical differences are called meristic characteristics (Zijlstra, 1958; Hulme, 1995; Heath et al., 1997).

North sea herring live up to 17-20 years (38-39 cm length; RIVO database) and they spawn once a year (Bowers & Holliday, 1961; Blaxter & Hunter, 1982, referred to as group-synchronous determinate total spawners; Murua & Saborido-Rey 2003) meaning that the ovules in their ovary develop at approximately the same time with no additional ovules appearing during the spawning season, and that the population tends to spawn in unison).

In North Sea herring, the term year class refers to the year of spawning and preparation to spawn. In the southern North Sea, where the herring spawn late in the year from December to January, the term year class then refers to the year leading to this spawning event e.g. the 2000 year class would be spawned from December 2000 to January 2001.

Spawning sites

The spawning sites of herring in the southern North Sea are part of the Downs component of the larger North Sea herring stock. Spawning of the North Sea herring stock begins in the north of the North Sea in September and then progresses southwards with time, ceasing in January in the eastern English Channel with the Downs component (Boeke, 1906; Cushing & Burd, 1957, Zijlstra, 1969; Burd & Howlett, 1974; Figure 1). The number of spawning sites in the North Sea varies with stock size (Burd, 1985; Corten 1999; 2001) with a decline in the number of spawning sites at lower biomasses of North Sea herring. A time series of surveys of herring larvae show that the main centres of spawning have not changed since the 1950s (Figure 1, ICES 2005).

The Downs herring spawn on gravel beds that are generally between 20-40m depth (see Cushing & Burd, 1957; Parrish et al., 1959). The thicker egg mats can suffer high mortalities due to oxygen deficiency (Parrish et al., 1959; Aneer, 1985) and the mats attract predators (spurdog, haddock, mackerel, lemon sole and other herring; Hempel & Schubert, 1969; de Groot, 1980; Skaret et al., 2002; and personal observations). These gravel beds are spread throughout the southern North Sea and eastern English Channel (Cushing & Burd 1957; Figure 2). Due to the variability in drift, temperature and growth, the recruits from one spawning will not necessarily mature in synchrony (McQuinn, 1997; Brophy & Danilowicz, 2003).

Recruitment from each spawning site in the North Sea varies between years and the relative importance of sites to the productivity of the whole stock also varies over time (Cushing, 1968; Corten, 1986; Johannessen & Moksness, 1991). This is due to the complicated multi-component nature of the North Sea herring stock and the different dynamics shown by each component. The larvae produced in the southern North Sea supported the largest herring fishery throughout the 1930s to the early 1950s (Hodgson, 1936; Cushing & Burd, 1957; Cushing & Bridger, 1966), suggesting that recruitment from these areas was strong. Then, once overfishing reduced the biomass in the southern areas, the northern spawning sites, namely off Scotland and Shetland, produced the majority of recruits (Burd, 1985). Larval production and recruitment from the central North Sea increased in the mid 1980s and then declined again (Nichols & Brander, 1989) and increased again in the late 1990s (ICES, 2005). As larval production increased in the southern North Sea (ICES, 2005) the recruitment also improved in the late 1990s (Figure 3). Recent evidence suggests that the very strong 2000 year class comes almost entirely from larvae spawned in the southern North Sea (ICES, 2005). Hence, the strongest recorded year classes from the southern component in the last 100 years were 1921, 1924 and 1929 and now again in 1996, 2000 and 2002 (Cushing & Burd, 1957; ICES, 2005). The 2000 year class is so large that it is the dominant age group in the catch and made up over 60% of the Dutch catch of herring in 2004.

Larval Behaviour

The Downs herring produce bigger eggs and are less fecund than fish of the more northern components (Baxter 1959; 1963; Cushing, 1958; Almatar & Bailey, 1989), hence the hatched larvae are bigger than their northern counterparts (Heath et al., 1997). Upon hatching, herring larvae rise to the plankton (from the seabed) by increasing their buoyancy by taking on water (85% water content at hatch to 92% water content after hatch, Craik & Harvey, 1984; 1987; Ying & Craik, 1993). The larvae hatch between 7.5 and 9.5 mm in length and have faster escape responses than the smaller northern larvae (Batty et al., 1993). The escape response in herring larvae is not full operational until they are over 20mm in length (Fuiman, 1993). Feeding on microplankton and copepod nauplii begins just before yolk sac absorption, usually within the first week (Checkley, 1982; Munk, 1992) and the larvae feed on a wider range of sizes of prey items as they grow. Herring larvae are predominantly visual feeders (Batty et al., 1990).

As the larvae grow they also begin to express other behaviour such as vertical migration and more active swimming. Small larvae are found in layers near the surface but as they grow they begin to show diel variation with layering during the day but dispersal throughout the top 60m during the night (Heath et al., 1988; Johannessen & Mokness, 1991). Temperature effects the swimming speed of the larvae (Batty et al.,1993) and by 20mm the average swimming speed of the larvae is 2.9 mm per second (Gallego & Heath, 1994). Swimming and shoaling becomes more active after metamorphosis (Heath & Richardson, 1989). This happens in late spring and early summer at about 50mm length (Galllego & Heath, 1994) for herring spawned in the southern North Sea. The presence of already metamorphosed juveniles increases the likelihood of early shoaling in pre-metamorphic herring larvae (Gallego et al., 1995).

It is well documented and understood that any modelling of the transport of herring larvae must account for larval diel behaviour (Bartsch et al., 1989; Lazzari et al., 1993) and also the development and change in larval behaviour with size (Bartsch, 1993; Bryant et al., 1995; Heath et al., 1997).

Although alluded to by Miller (1998), an intensive literature search for further information on the triggers of the behaviour of larvae and post metamorphic juveniles, resulted in no further evidence being found for triggers of directional movement. Personal communication with Dr Mike Heath (Fisheries Research Services Aberdeen), Dr Richard Nash (Marine Institute, Bergen), Dr Peter Munk (Danish Fisheries Institute) and Dr Øyvind Fiksen (University of Bergen) supported this finding of the paucity of information particularly in relation to directional movement and salinity triggers.

It has been suggested that apparent tidal transport may be caused by the negative buoyancy of the larvae. With the larvae sinking at slack tide and being resuspended by turbulence from tidal flows (Henri et al., 1985) but again the evidence for this is weak. However it is clear that stavation has an effect on buoyancy and hence vertical distribution of the larvae (Blaxter & Ehrlich, 1974; Øyvind Fiksen pers com.). Starvation increases the water content of the larvae and they become more neutrally buoyant and hence stop sinking. The sinking rate of a fed and healthy larvae at 10°C and salinity of 33, are 0.4 cm per second (Blaxter & Ehrlich, 1974; Yin & Blaxter, 1987). The sinking rates decrease at higher salinities. During the early life stages, plaice are more neutrally buoyant than herring larvae (Blaxter & Ehrlich, 1974; Ying & Craik, 1993). As herring larvae grow their sinking rate increases to 1.0 cm per sec at 20mm length. Starving herring larvae also show reduced diel vertical migration (Blaxter & Ehrlich, 1974).

Juvenile nursery areas in the North Sea

The transport and drift of larvae in the southern North Sea is towards the juvenile nursery grounds from the Wadden Sea to the Skagerrak and Kattegat (Wallace, 1924; Burd, 1978; Figure 4). In these nursery areas herring from the North Sea herring stock mix with Western Baltic Spring Spawning herring and local fjord populations from the Norway, Sweden and Denmark (Mosegaard, 1997; ICES, 2005). It is clear that the drifting larvae from the Downs component (Figure 5) are dispersed in high numbers along the Dutch coastline as they are transported towards the German Bight and Skagerrak.

The role of the Waddenzee as a nursery ground for herring is not that clear (Rauck & Zijlstra, 1978), as current surveys of juveniles do not enter Waddenzee thus making comparisons of relative numbers by area difficult and sampling gear used in the Waddenzee are not the best for sampling juvenile herring. The number of post-larvae that enter the Waddenzee differ each year (Corten & Kamp, 1979). There appear to be two waves of larvae: firstly in February and March at approximatekly 40mm in length (that are assumed to come from the Northern Autumn spawners) and then in April and May at approximately 30mm in length (from the winter spanners in the southern North Sea; Bückman 1950; Bückman & Hempel, 1957). Although Corten & Kamp (1979) suggested that the smaller larvae may arrive at the Waddenzee slightly earlier in late March to April (using data from 1967 to 1978). Corten and Kamp (1979) also commented that catches of post-larvae were extremely variable, both between and within sampling stations suggesting very patching distributions of larvae, and/or the entry of post-larvae into the Waddenzee in waves. They do not mention any tidal component in the abundance time series. Juvenile herring in the Waddenzee stay a few months until early autumn when they head to the main nursery grounds (ICES, 1969). With the use of otolith microchemistry it would be possible to investigate the importance of the Waddenzee to the whole North Sea herring stock.

The dynamic variability in the nursery grounds can be easily seen in the catches of the International Bottom Trawl survey (IBTS, Figure 6). This survey was started in the 1960s and was targeted specifically at herring (Heessen et al., 1997). The distribution of juveniles has not changed and covers the area from the north of the Netherlands, across the German Bight and into the Skagerrak (Figure 6 compared to Figure 4). Importantly, apart from a very few unusual year classes, the abundance of 1 year olds reflects the year class strength of the fish in the adult fishery (Nash & Dickey-Collas, 2005), i.e. recruitment strength is determined prior to arrival at the nursery grounds. It has also been reported that a small but proportionate numbers of juveniles of Downs origin also use the eastern English coast as a nursery area (Wood, 1983) but this is not apparent in recent years (Figure 6).

Fish leave the nursery grounds between ages 1 and 3, depending on their growth and condition and join the adults in their migrations from feeding grounds to spawning grounds (McQuinn, 1997; Brophy & Danilowicz, 2003).

Drift and dispersion

Many studies on larval drift and transport of herring have occurred in European waters:

North Sea

Most of the studies on the drift of herring larvae in the North Sea have been associated with the ACE (Autumn Circulation Experiment) project in the 1980s. The project's findings are summarised in Bartsch et al. (1989), Bartsch (1993), Nichols & Brander (1989) and Heath et al. (1991). They coupled larval drift inferred from field observations with drift determined by a three dimensional circulation and transport model. The broad characteristics in the transport of larvae could be reproduced but the between year variability was difficult to model. The studies did highlight the influence of variability in hydrographic and meteorological conditions in the variability in drift of herring larvae and the successful delivery of fresh juveniles to the nursery grounds. However one problem with these studies was that the production of Downs larvae was very low in the 1980s and the project concentrated on production from the northern and central North Sea. It also did not consider the possibility of anthropogenic disruption of the transport mechanisms.

Norwegian spring spawning herring

The best and most current description of the transport of Norwegian spring spawning herring is given by Holst et al (2004). This stock can be huge in terms of biomass and is characterised by large variability in spawning behaviour and recruitment strengths. At high population biomass the spawning sites are fairly consistent, but like in the North Sea, spawning sites become restricted at low biomasses. The spawning sites are along the Norwegian coast and generally the larvae drift in a north easterly direction towards the Barents Sea following major hydrographic features (Sætre et al., 2002a). Large between year variability exists in the success of larvae reaching the nursery grounds, depending on spawning site and local hydrography (Sætre et al., 2002b). Some herring juveniles do not reach the Barents Sea and nursery in the Norwegian fjords. Large year classes are associated with years when most of the juveniles come from the Barents Sea.

West coast of Scotland

The dispersal of larvae on the Scottish west coast appears to be determined by the Scottish Coastal Current (Saville & Morrison, 1973; Heath et al., 1987; Heath & Rankine, 1988; Heath, 1989). Hatched larvae from the west coast of Scotland drift north towards the Orkneys and northern North Sea. The juveniles are thought to either remain near Scotland on the east coast or drift towards the eastern North Sea and German Bight (Heath & Walker, 1987). Further evidence from genetic studies (EU projects HERGEN and WESTHER, in prep) suggest that there is widescale mixing between the west coast of Scotland stock and the northern North Sea, as larvae and juveniles.

Clyde

The herring larvae spawned in the Clyde show a highly variable dispersal pattern which seems largely determined by the prevailing winds (Parrish et al., 1959; Saville et al., 1966). Often the larvae are held within the Clyde and nursery in the upper regions, but in some years they are carried out from Ballantrae Bank into the North Channel and Irish Sea. Parrish et al. (1959) describe this as an oscillation between the Clyde and Irish Sea caused by certain meteorological conditions.

Irish Sea

Historically there have been two main spawning areas in the Irish Sea (Dickey-Collas et al., 2001); those in the east, the Manx component and those in the west, the Mourne component. Few dedicated studies of drift have occurred in the Irish Sea and most conclusions have been inferred from meristic and growth data of the larvae and juveniles. Bowers (1980) concluded that the larvae from the Manx spawning ground drift towards the English and Scottish coasts, under the effects of meteorologically determined hydrography. The importance of the prevailing south westerlies in determining the drift of Manx larvae was also highlighted by Özcan (1974). Wood & Howlett (1976) suggested that the Mourne larvae either drift east or north dependent on hydrography. The only study on hatching and growth of Mourne larvae, highlighted the variability in drift along the Irish coast (Anon 1979) and linked it to the prevailing wind direction. Drift of Irish Sea spawned larvae into the Clyde has been mentioned by some authors (Marshall et al., 1939; Özcan, 1974) but no conclusive evidence has been found (Wood & Howlett, 1976).

Celtic Sea

The dispersal of larval herring from the Celtic Sea is even less clear. Some oceanographers describe the residual flows moving in a south westerly direction, away from the Irish Sea, (Monahan, 1977; Grainger, 1980) and others suggest that a flow into the Irish Sea exists (Edwards, 1968; Ramster & Hill, 1969). Most of these studies are based on very small data sets from a few fixed point current meters. Some studies on the drift of larvae have indicated a drift into the southern Irish Sea (Özcan, 1974). Özcan (1974) showed a correlation between wind velocity and the occurrence of Dunmore East larvae and juveniles in the Irish Sea. Recent work by Brophy & Danilowicz (2002) shows large numbers of Celtic Sea juveniles using the Irish Sea as a nursery ground, suggesting large numbers of Celtic Sea herring larvae drift into the Irish Sea.

West coast of Ireland

Data on drift of larvae from the west coast of Ireland are limited. It has been suggested that Donegal herring larvae drift north towards the Scottish west coast (Özcan, 1974; Molloy & Barnwall, 1988) and larvae from Galway disperse south along the Irish coast (Rankine, 1988). However other evidence does not support this (Grainger, 1976), and whilst hatching larvae distributions for north west Ireland are well known (Wood, 1972; Molloy & Barnswell, 1988; Hopkins, 1990), there is little indication of the mechanism controlling larval drift.

Drifting larvae in general

It is clear that the interaction of choice of spawning site and local hydrographic conditions plays an important role in the determination of larval drift or transport. Virtually all stocks in western Europe drift in an easterly direction. In most areas, particularly on the shelf, the local hydrography is highly influence by meteorological forcing through wind, with additional far field effects. Nearer the shelf edge, e.g. west of Ireland and perhaps west of Scotland, the hydrography may well be influenced by more large scale basin effects and oceanographic currents. As most of the studies of herring larval drift occurred prior to the use of geostrophic (density-driven), real-time models with far field forcing it is not surprising that investigators found it difficult to replicate between year variability. Few oceanographic circulation models of the type used in these studies account for, or describe well, the influence of fresh water runoff on the transport of larvae. This may well have important implications particularly in the southern North Sea and Irish Sea.

Anthropogenic impact

There is little work published on anthropogenic effects on larval production, drift and transport. Groot (1980) suggests that gravel extraction in the English Channel would have a detrimental effect on the production of Downs herring, but produced little analysis. In 2003 the ICES herring working group considered the impact of gravel extraction and recommended:
All decisions about the granting of licenses for gravel extraction in the deeper waters of the eastern English Channel should be carried out within the precautionary principle (UNCED, 1992). This principle (no.15) states that "where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason … to prevent environmental degradation". The working group recommends that no gravel extraction occurs

in rectangle 29F0 for the four month period of November to February, as this coincides with herring spawning in the area. Licenses should not be granted for the remainder of the year unless it can be proven unequivocally that gravel extraction does not have a deleterious impact on herring spawning and larval production in 29F0 and VIId. (ICES 2003).

The impact of the closing of the Afsluitdijk in 1932 was catastrophic on the spring spawning Zuiderzee herring which became extinct and the fishery closed by 1939 (Groot, 1980).

However no studies to date have investigated the role of large-scale changes to coast lines on the productivity of herring, or the potential impact of changes to drift on the production of Downs herring.

Glossary and acronyms

ACE	Autumn Circulation Experiment, a large project on North Sea circulation and herring larvae.
Component	Part of a stock, that may express different behavioural or physical characteristics
Downs herring	The component of North Sea herring that spawns in the southern North Sea and English Channel.
EU	European Union (europa.eu.int)
Geostrophic	density driven flow (used in hydrography and oceanography)
HERGEN	An EU funded project into herring genetics in the North Sea (www.hull.ac.uk/hergen)
IBTS	International Bottom Trawl Survey (www.ices.dk/datacentre/ibts.asp)
ICES	International Council for the Exploration of the Sea (www.ices.dk)
Recruitment	The new year classes of young fish that join the adult population each year
Stock	A population of fish that are thought to act independently of others around them, hence are managed separately.
UN	United Nations (www.un.org)
UNCED	Declaration of the UN conference on Environment and Development
WESTHER	An EU funded project into the determination of herring stock identities in western waters (www.clupea.net/westher)

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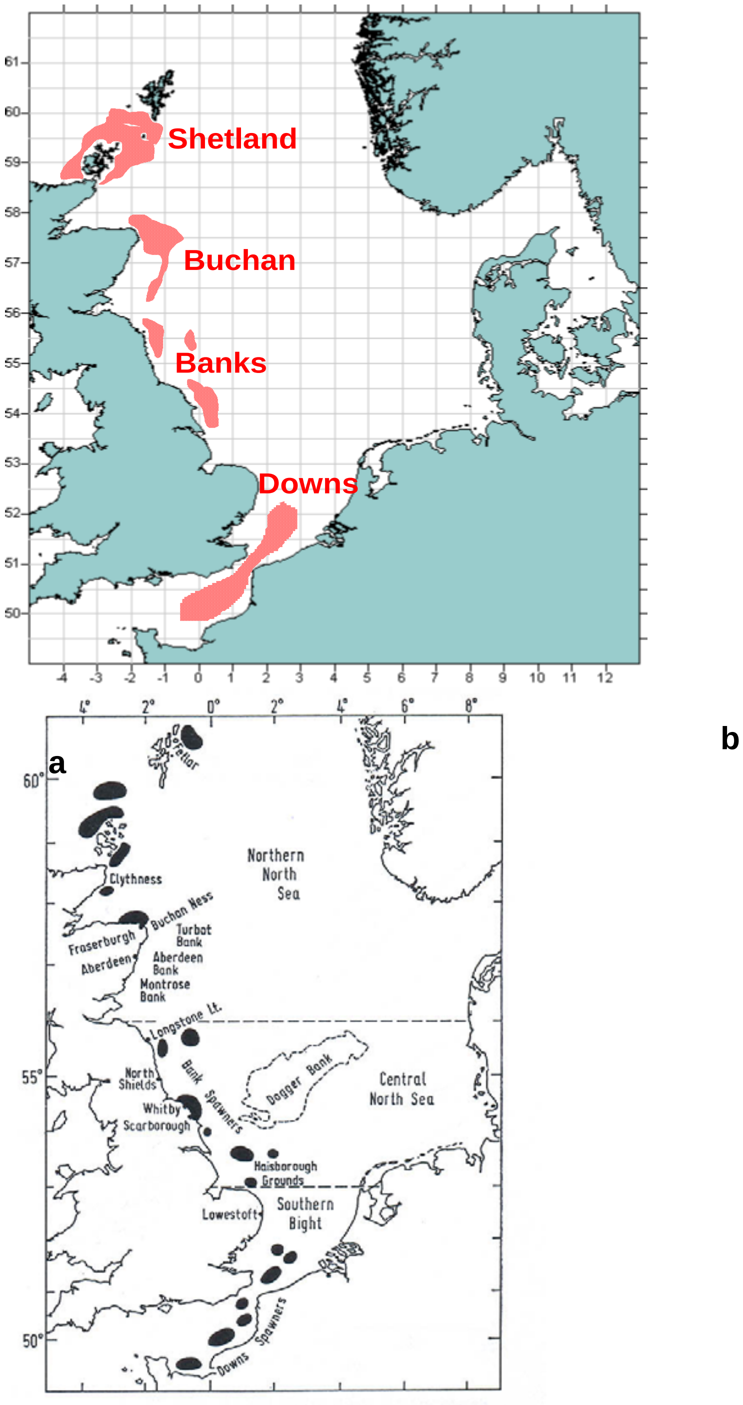


Figure 1. Generalised major spawning grounds of North Sea herring.

a) inferred from the presence of newly hatched larvae in the ICES herring larval survey (1996 to 2003) and labelled by stock components

b) from Burd & Howlett (1974).

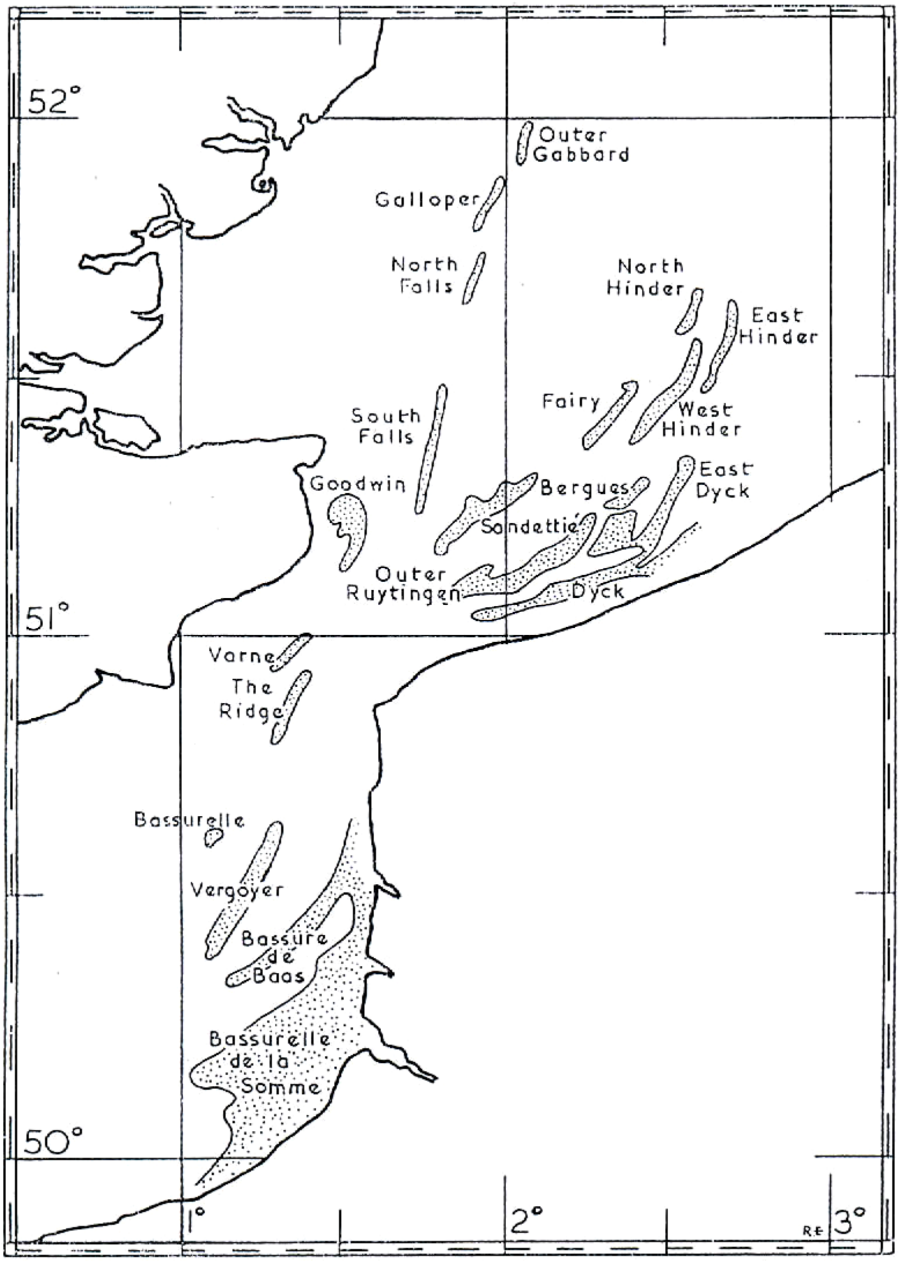


Figure 2. North Sea herring. Specific spawning grounds of Downs component of the North Sea herring stock (from Cushing & Burd, 1957).

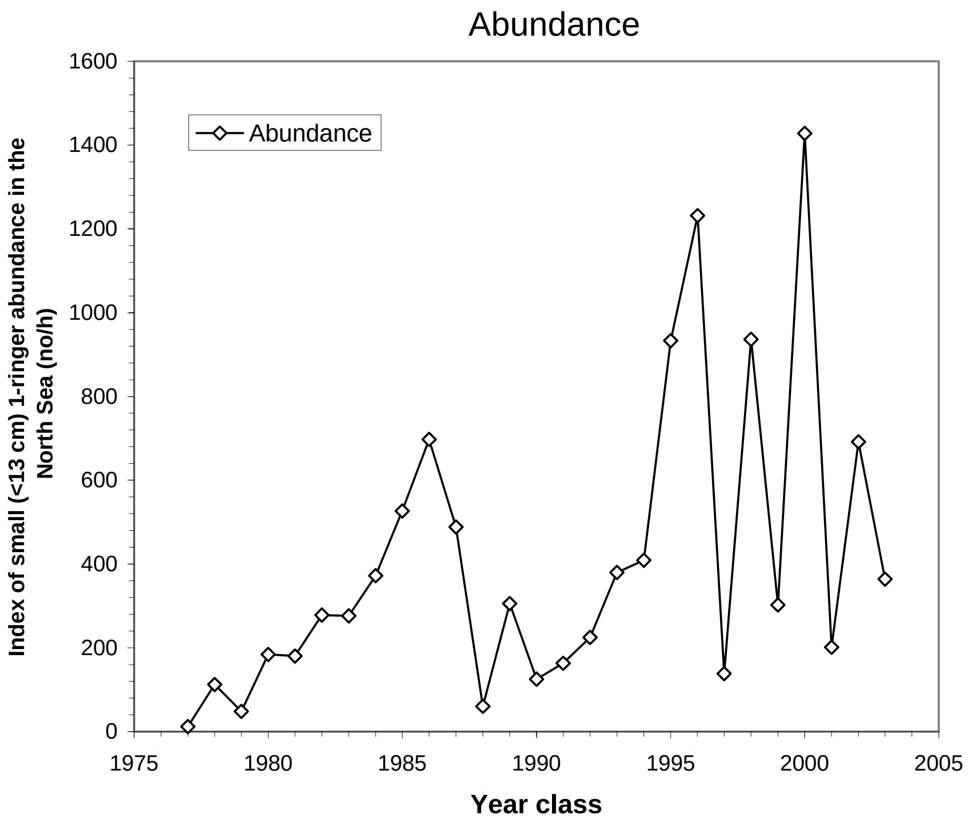


Figure 3. Time series of the abundance of juvenile (age 1) herring assumed to be from the Downs component in the IBTS survey, by year class (from ICES 2005). This series acts as a proxy for recruitment. Downs fish are smaller (<13cm) than the other components at age 1 (see Burd & Hulme, 1984).

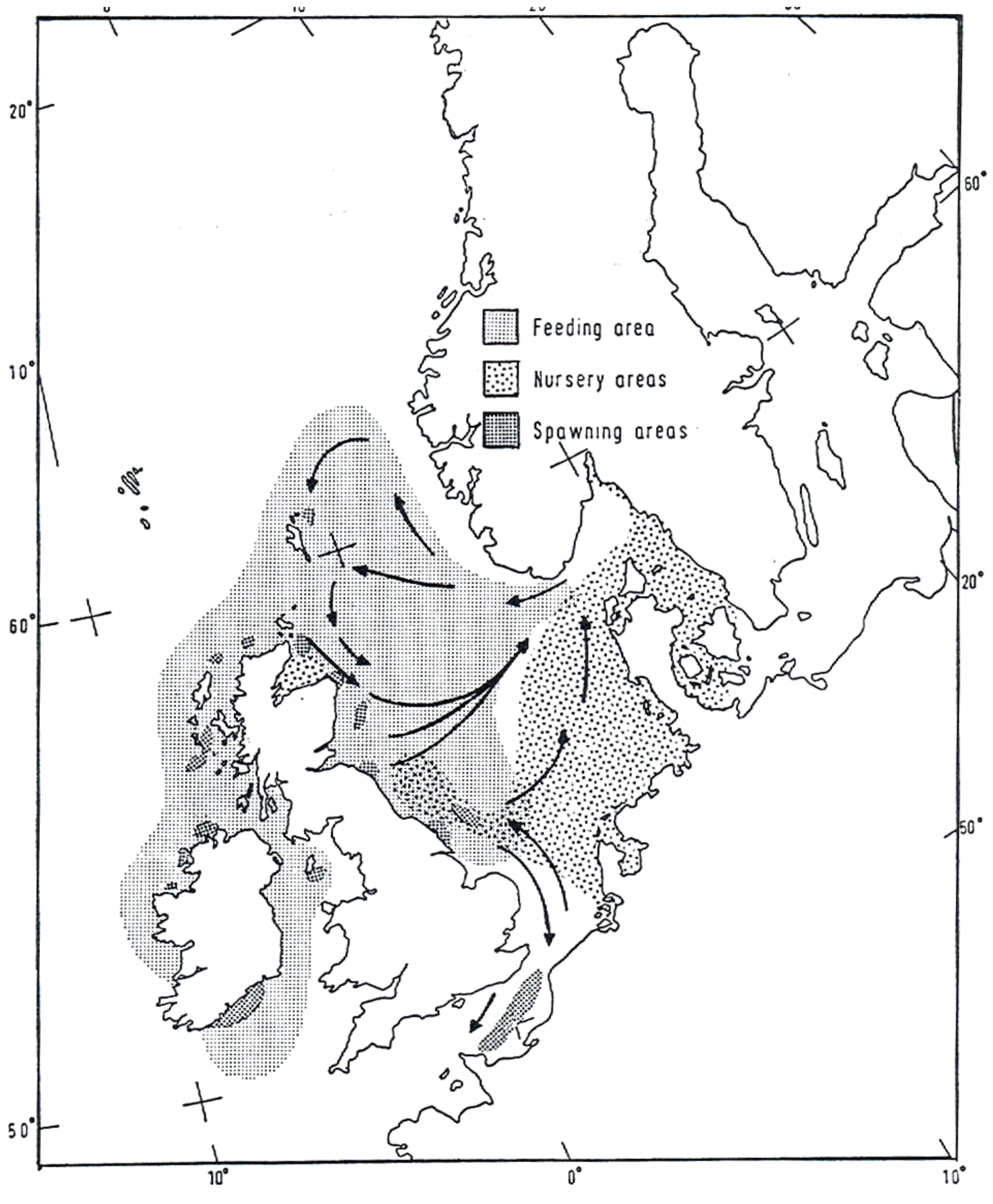
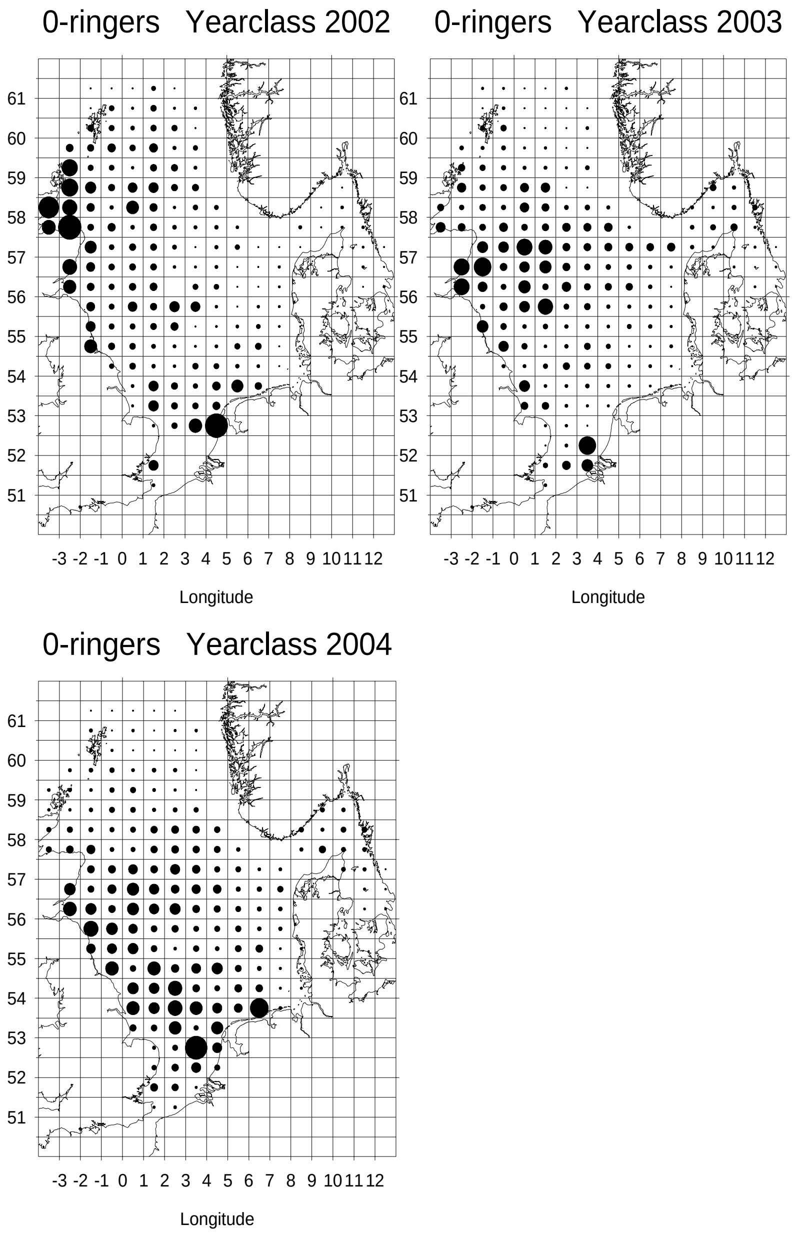


Figure 4. Schematic summary of locations of herring in NW Europe, showing nursery areas for juveniles, from Burd (1978)



0-ringers Yearclass 2002

0-ringers Yearclass 2003

0-ringers Yearclass 2004

Figure 5. DRIFTING LARVAE AND POST LARVAE. North Sea herring. Distribution of age 0 herring, year classes 2002-2004. Abundance estimates of 0-ringers within each statistical rectangle are based on MIK catches during IBTS in February 2003-2005. Areas of filled circles illustrate densities in no m^2, the area of a circle extending to the border of a rectangle represents 1 m^2. (ICES, 2005). Empty rectangles= no sample taken.

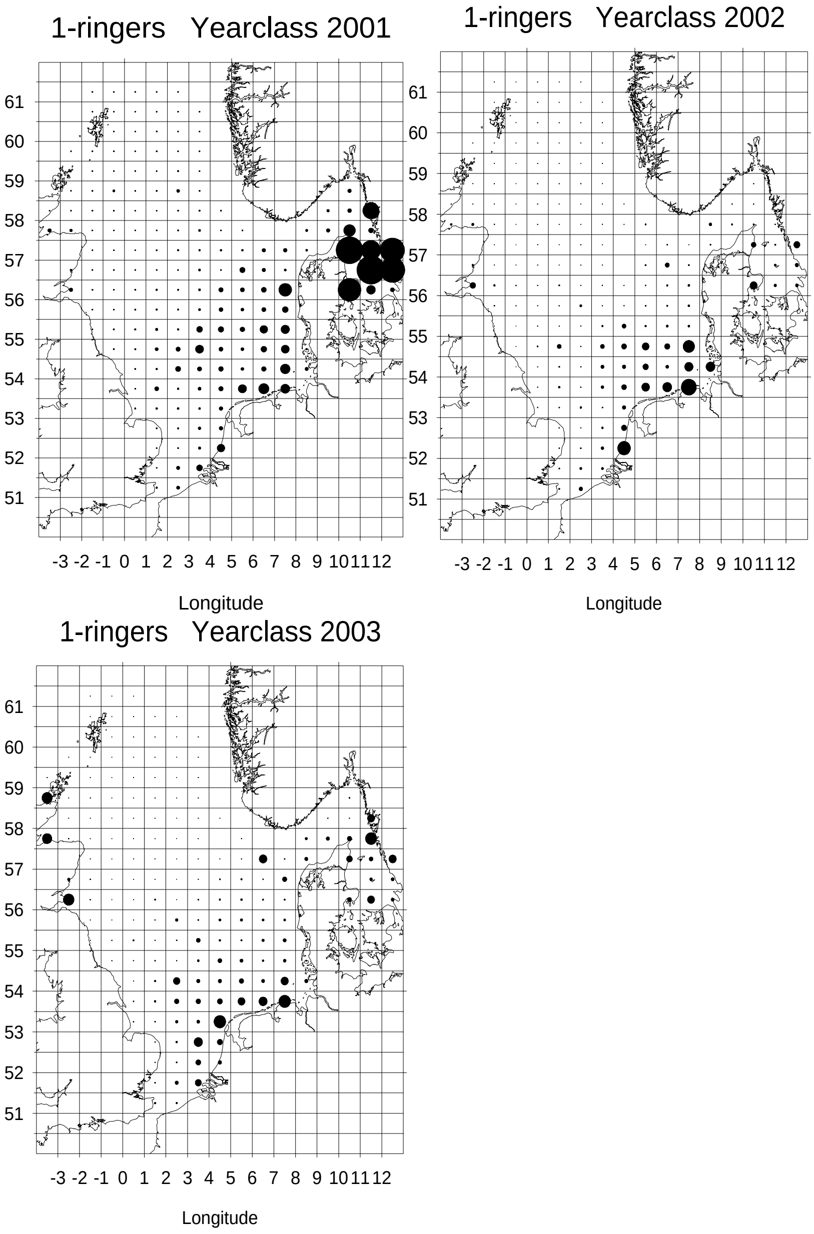


Figure 6. The distribution of juveniles of north Sea herring as determined by survey at age 1 in February 2003-2005. Areas of filled circles illustrate numbers per hour, the area of a circle extending to the border of a rectangle represents 45000 h-1. Empty rectangles= no sample taken.

Annex 2 – Field data plaice and sole

2a Demersal Fish Survey

Introduction

For many flatfishes, such as the commercially important plaice and sole, the shallow coastal zone and the Wadden Sea are essential as nursery areas. They are rich in food and protect juveniles from predators. Plaice and sole eggs and larvae are transported to their nursery grounds by a combination of passive and active transport. Altered currents, induced by MV2, could influence transport routes and thus also the final destination of the larvae.

Basic information on the (inter-annual variation in the) spatial distribution pattern of juvenile sole and plaice during 1989-2003 is shown by field data of the Demersal Fish Survey (DFS). Since flatfish hardly move after settlement, we assume that the spatial distribution pattern of the 0-group fish in autumn represents spatial distribution pattern at the time of settlement.

Materials and methods

Sampling

The Dutch Demersal Fish Survey (DFS) is part of an international inshore survey carried out by The Netherlands, England, Belgium and Germany. Internationally all coastal and estuarine areas of the southern North Sea are covered. The Dutch survey covers the coastal waters from Belgium to Esbjerg, the Wadden Sea and Eems-Dollard estuary and the Wester- and Oosterschelde. The DFS is carried out once a year in September – October. Sampling is stratified by geographical area (Figure 1) and depth (5m depth classes). Plaice and sole move progressively into deeper water as they grow. Therefore the inshore survey (DFS) is only suitable to monitor the abundance 0 and 1-group. Trawling details such as the position, date, time and depth are recorded for each haul.

The catches are sorted out on board. For each haul, the catch numbers and length frequency distributions of all fish species are recorded. In the case of large catch numbers a random sub-sample consisting of at least 50 individuals is measured. Furthermore a length-stratified sample is taken by area (Figure 1) to establish age-length-keys (ALK's).

Data treatment

The catch, trawl and age data are transferred to the national database ("FRISBE") after age determinations and quality controls have been completed. The data are then available for analysis and calculation of abundance indices.

The age data are aggregated by area to establish area-specific age-length-keys (ALK's). These area-specific ALK's are used to convert the length distribution of each haul into an age distribution, i.e. for each haul the catch numbers per length class (cm-classes) are converted into catch numbers per age group.

The abundance for age group 0 is calculated according to the following procedure. A new stratification in geographical areas is made; the coastal areas 401, 404 and 405 (Figure 1) are split and combined with the adjacent estuarine areas. The reason for this is the fact that an offshore shift in distribution of juveniles has been observed in recent years. The catch numbers per haul are first standardized into the catch numbers per 1000 m^2, by multiplying the catch numbers by 1000/(haul-distance x beam-trawl-width). The mean density was calculated per area. These means were not weighted by the surface area of each depth class.

Survey results

Differences in 0-group abundance between areas along the Dutch coastline are pronounced (Figure 2). In all areas, except for area 403, abundance of plaice was much higher than sole. The spatial distribution patterns by year are shown in Figures 3 (plaice) and 4 (sole), and the abundance by area and year are shown in Figures 4 (plaice) and 5 (sole).

The western Wadden Sea is an important nursery area for plaice. Sole show a more dispersed pattern and in general settle along the Dutch coastline and in the eastern Wadden Sea. However, large year-to-year differences are observed. Especially in the years 1990, 1992, 1995, 2000 and 2003, the Oosterschelde (area 638) was an important nursery ground for sole, while plaice hardly make use of this estuary. In some years most important nursery grounds for plaice were situated in the German Bight (1990, 1991, 1994, 2001). Except for 1989, 0-group sole are seldom caught in the German Bight.

Figure 1. DFS geographical areas as indicated in survey

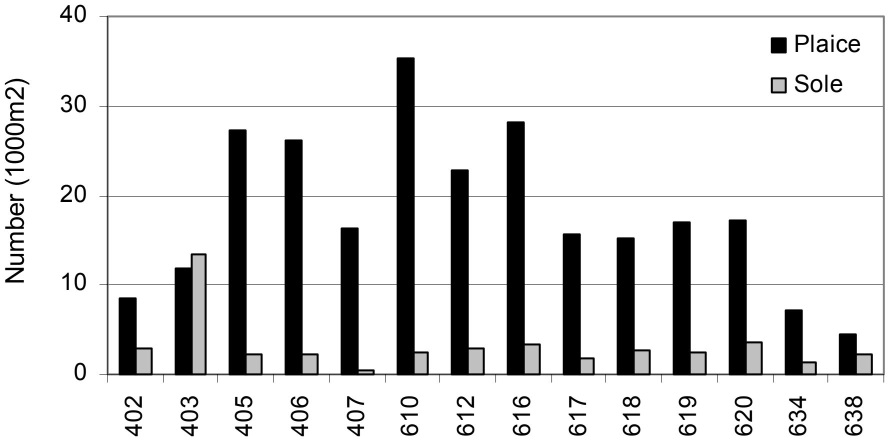


Figure 2. Overall abundance of 0-group plaice and sole by area (1989-2003). Average numbers per $1000m^2$

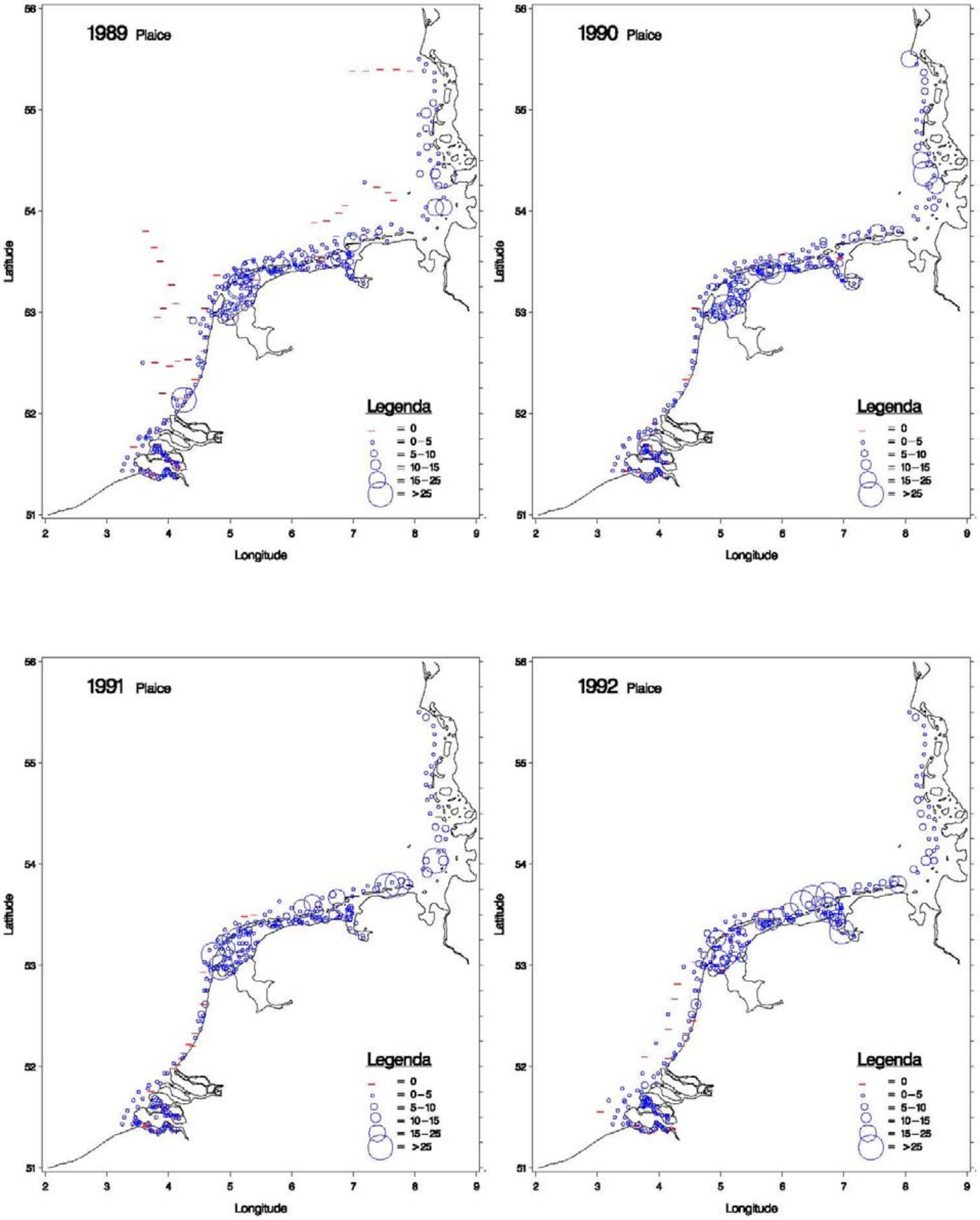
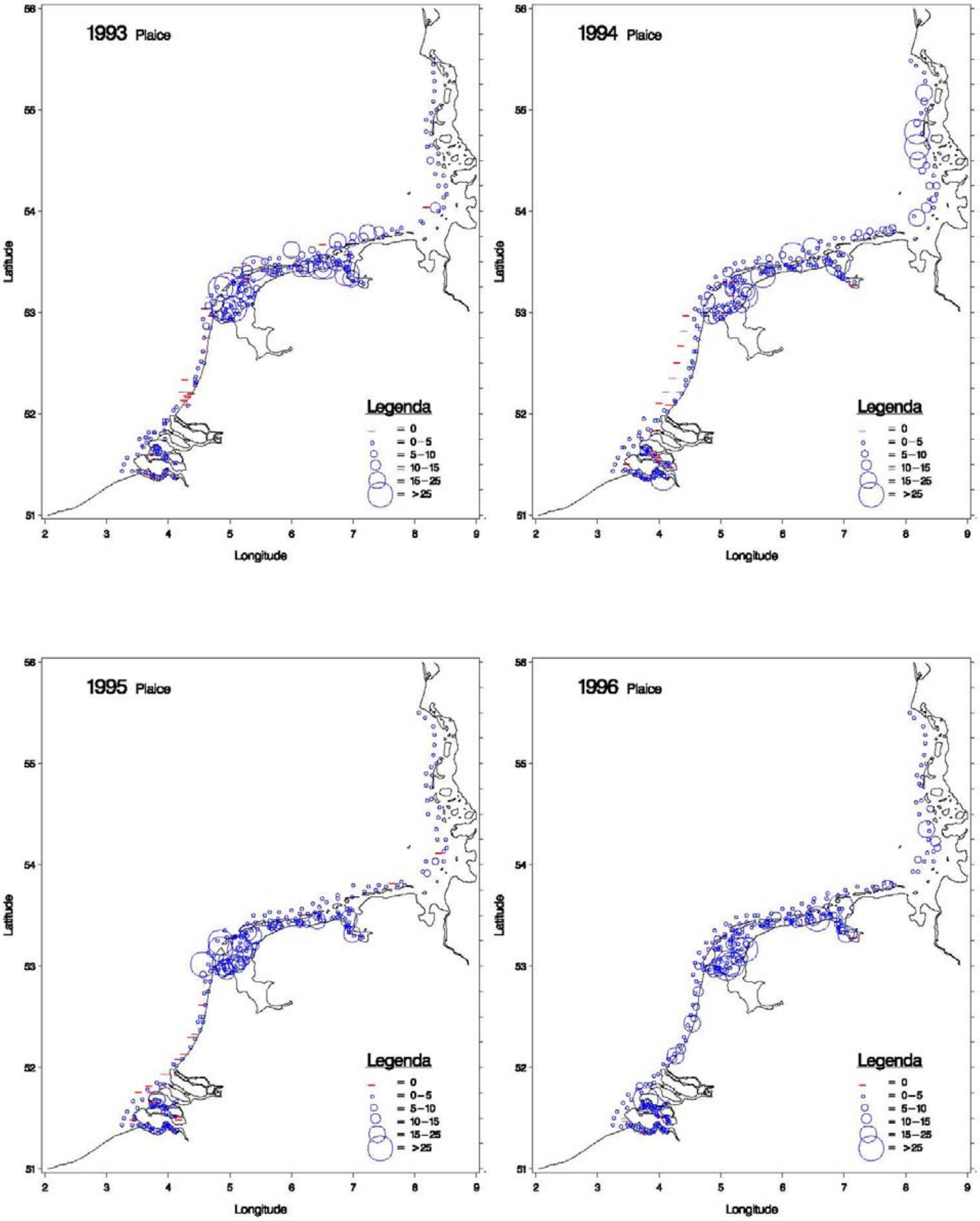


Figure 3. Spatial distribution of 0-group plaice in 1989 to 2003, number per 1000m2 per haul



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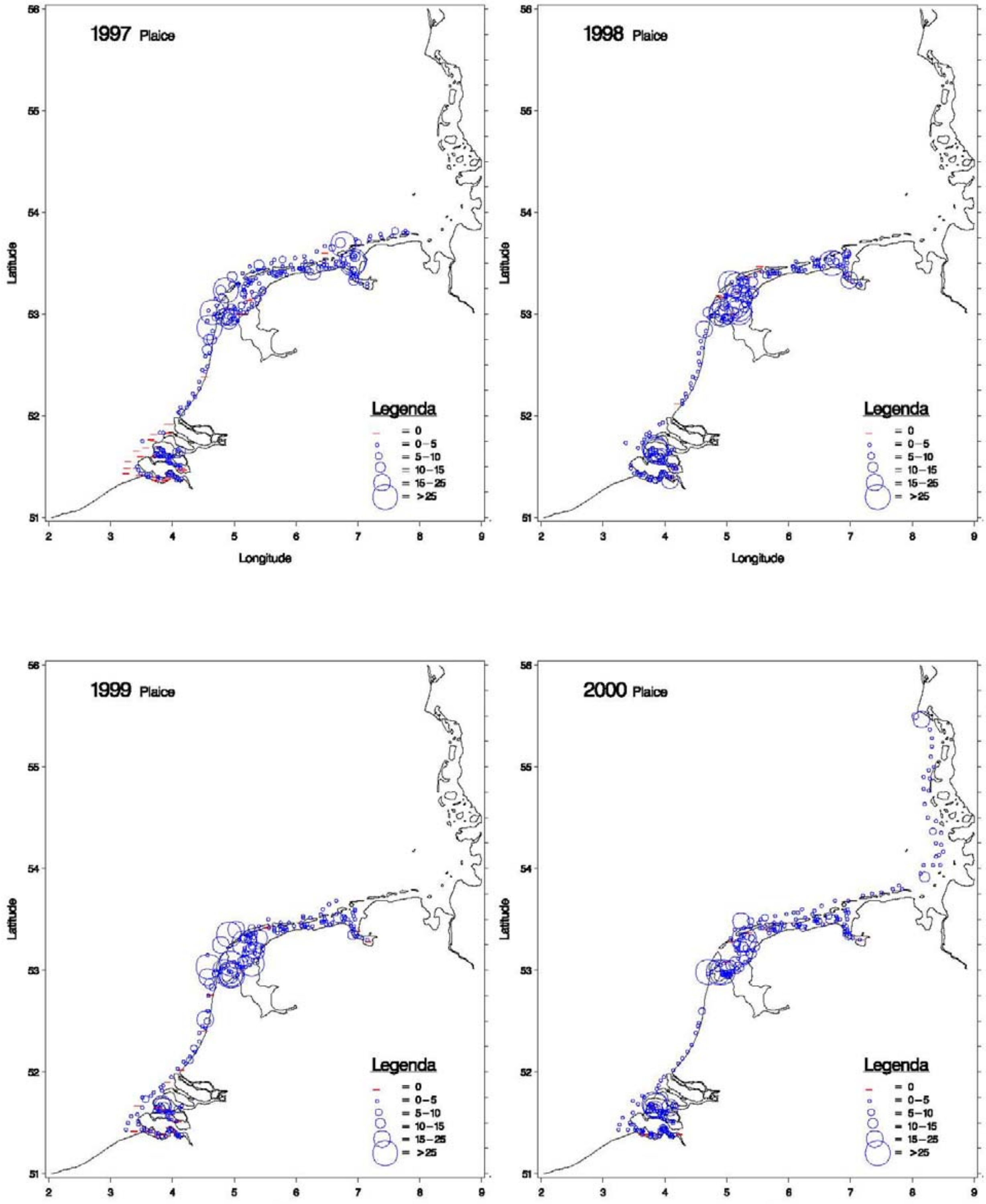

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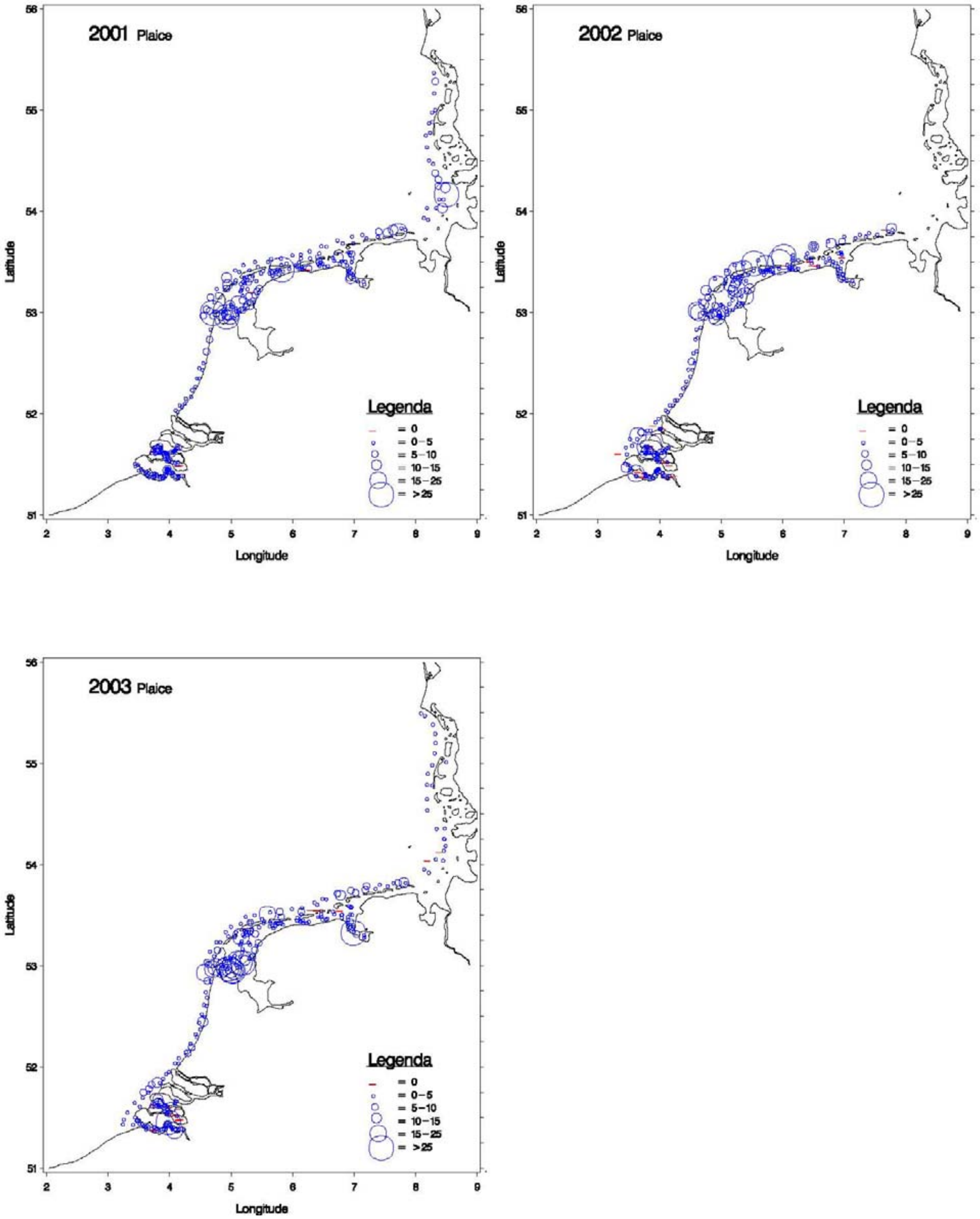

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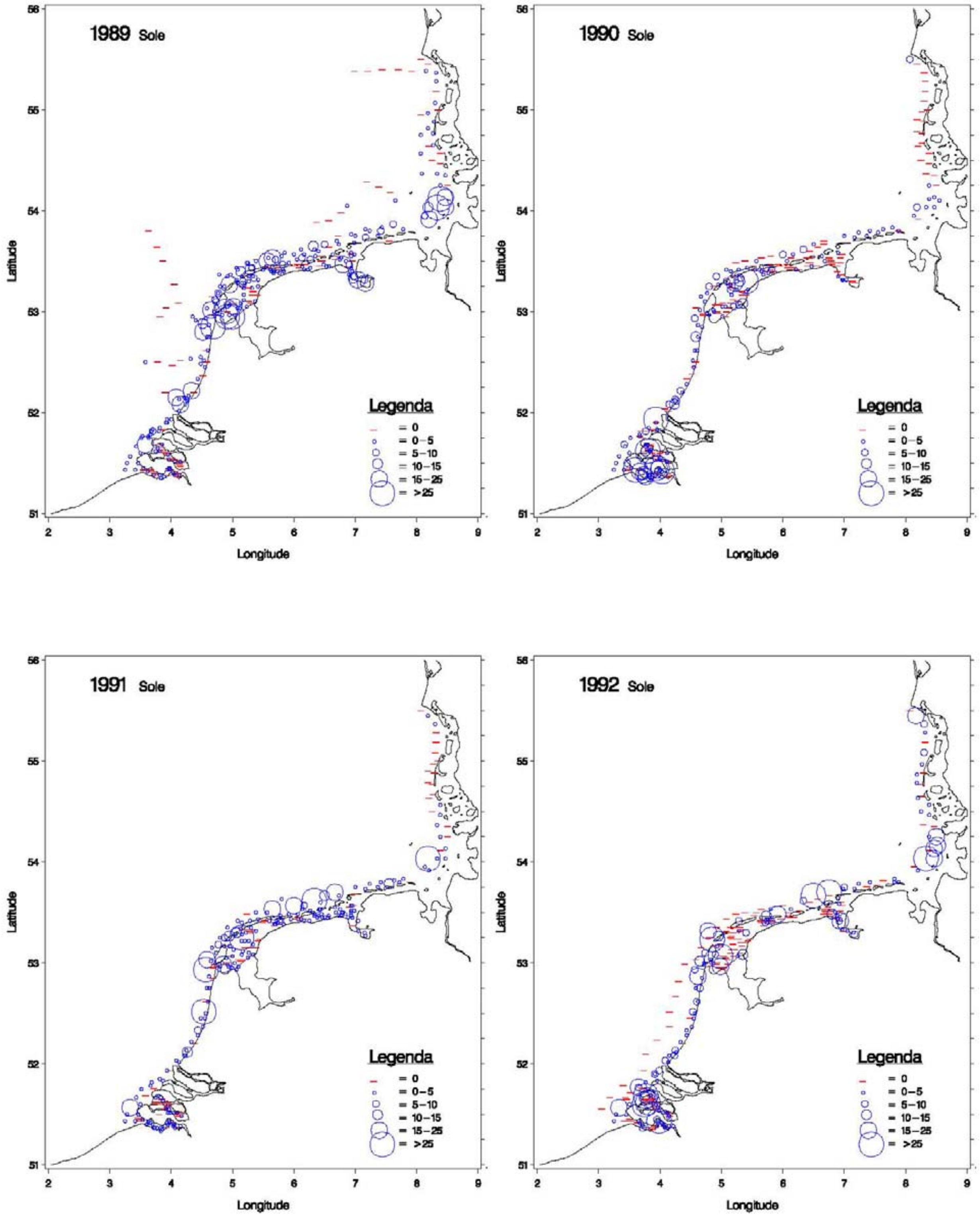


Figure 4. Spatial distribution of o-group sole in 1989 to 2004, number per 1000m^2 per haul.

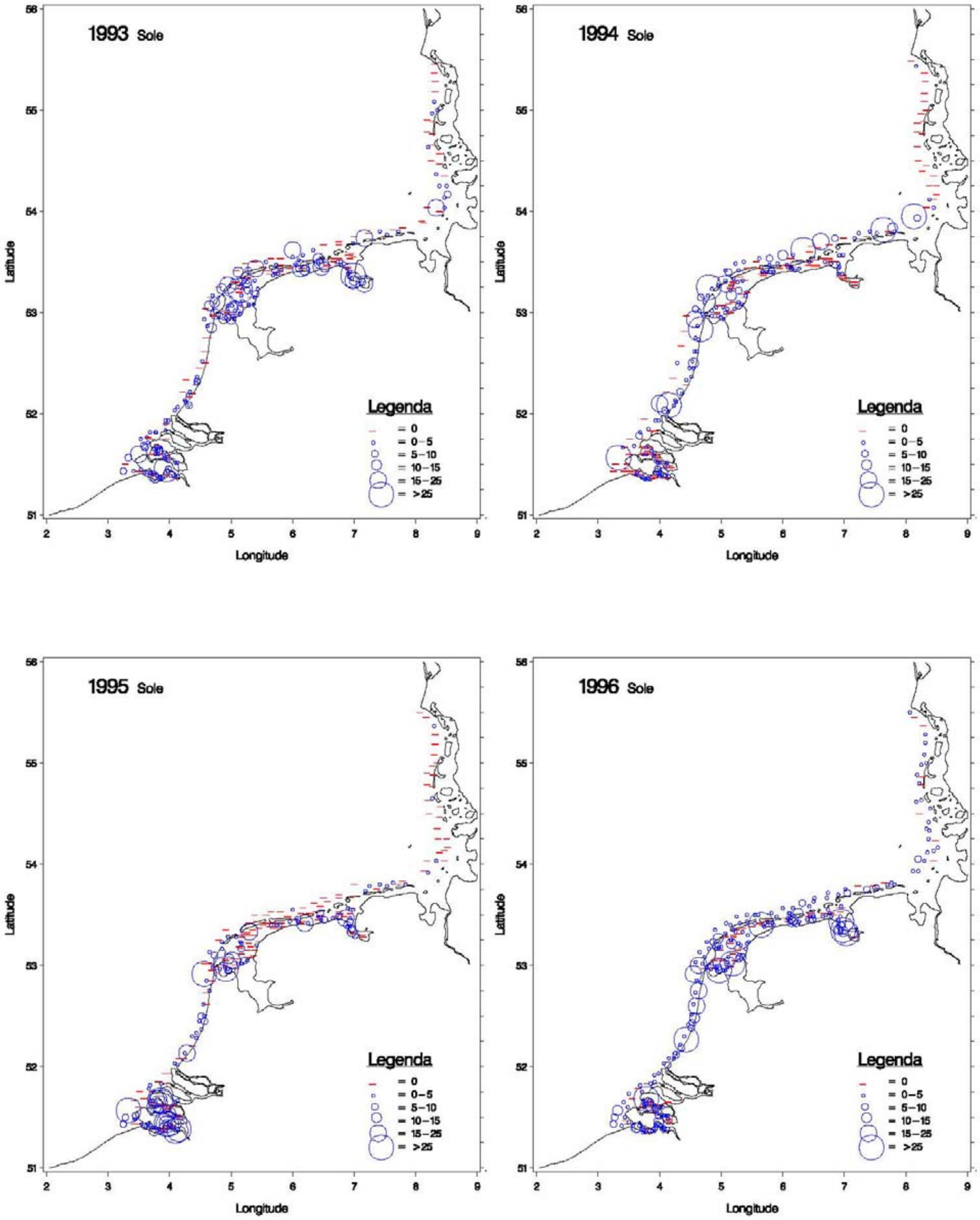


Figure 4. *continued*

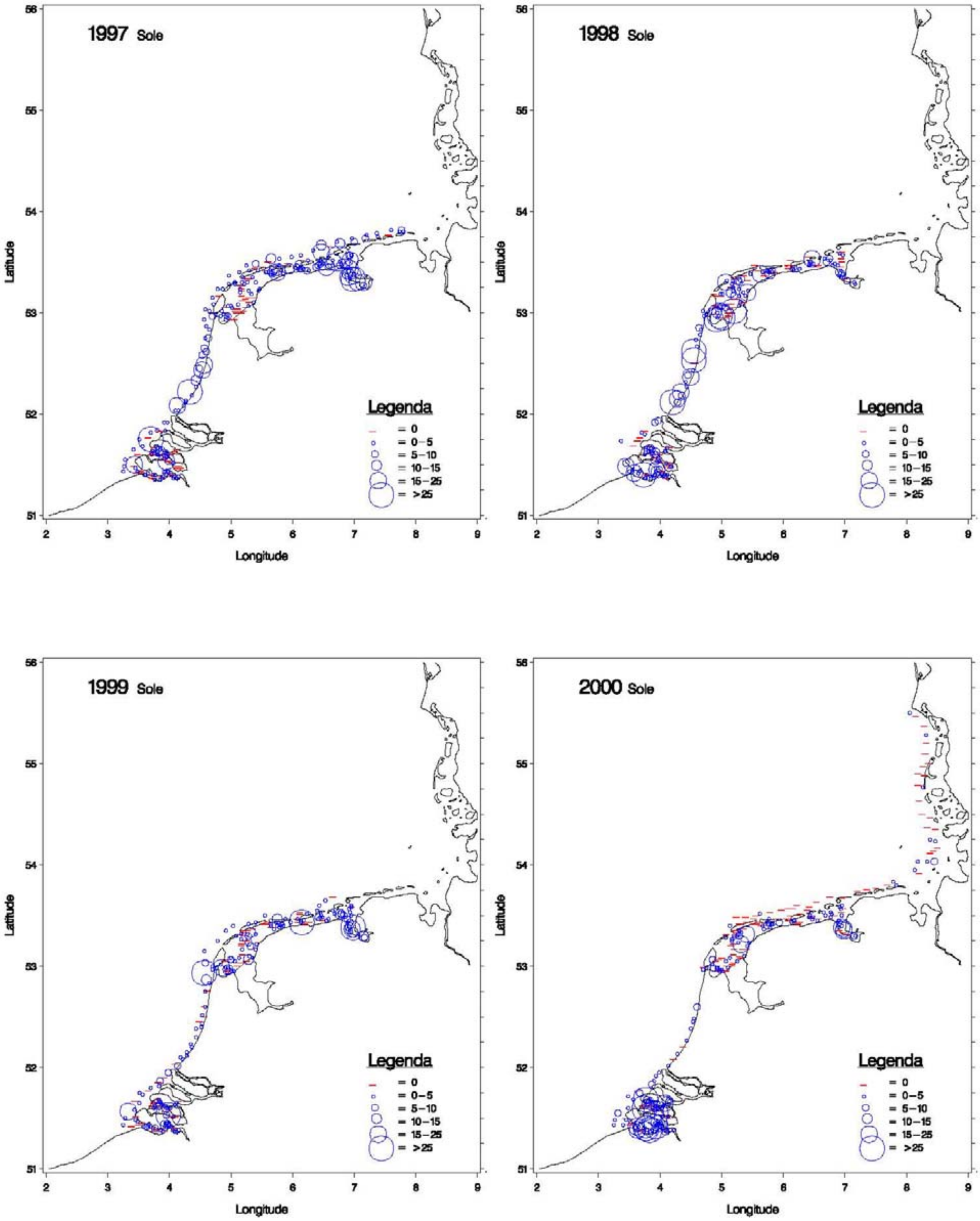


Figure 4. *continued*

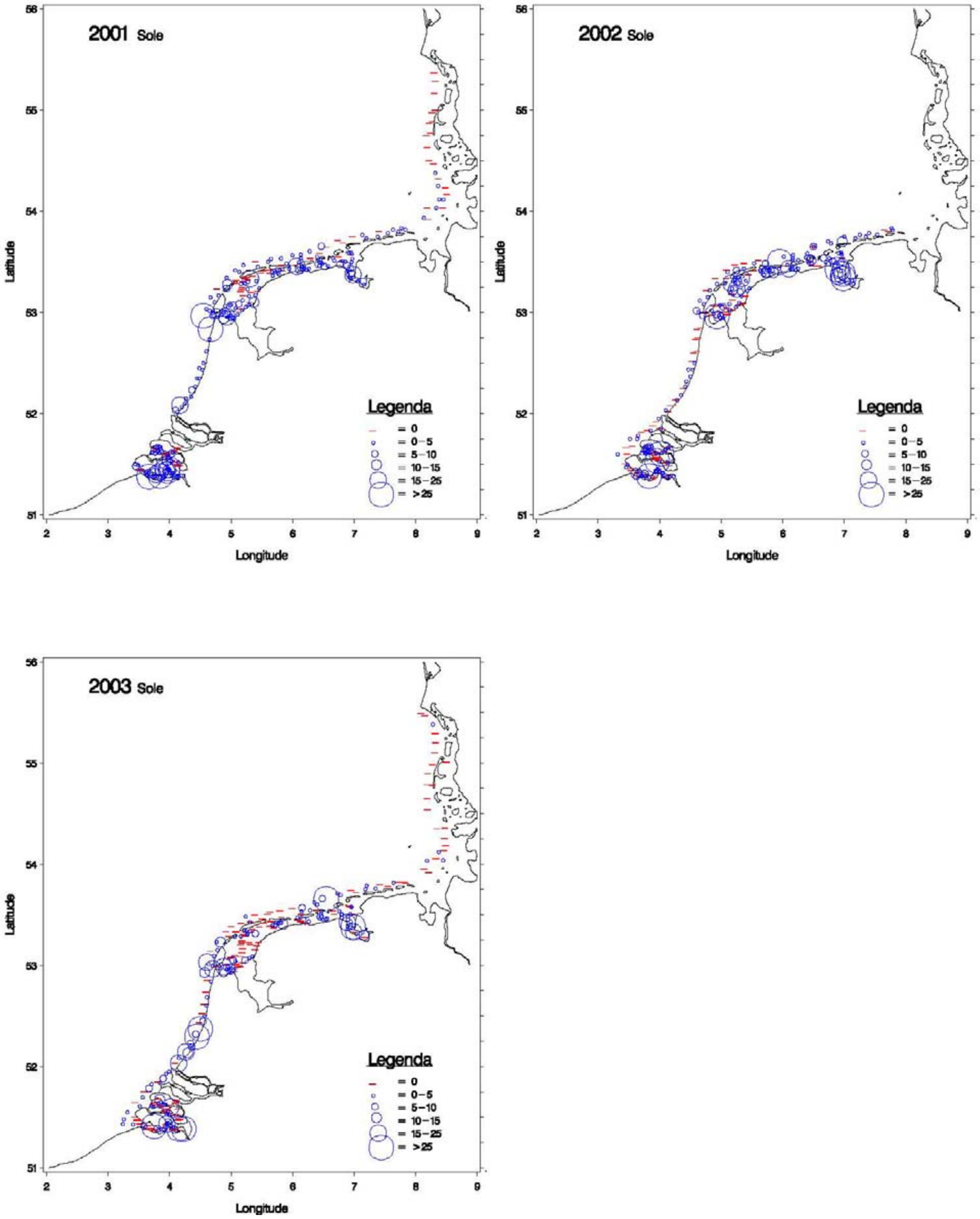


Figure 4. *continued*

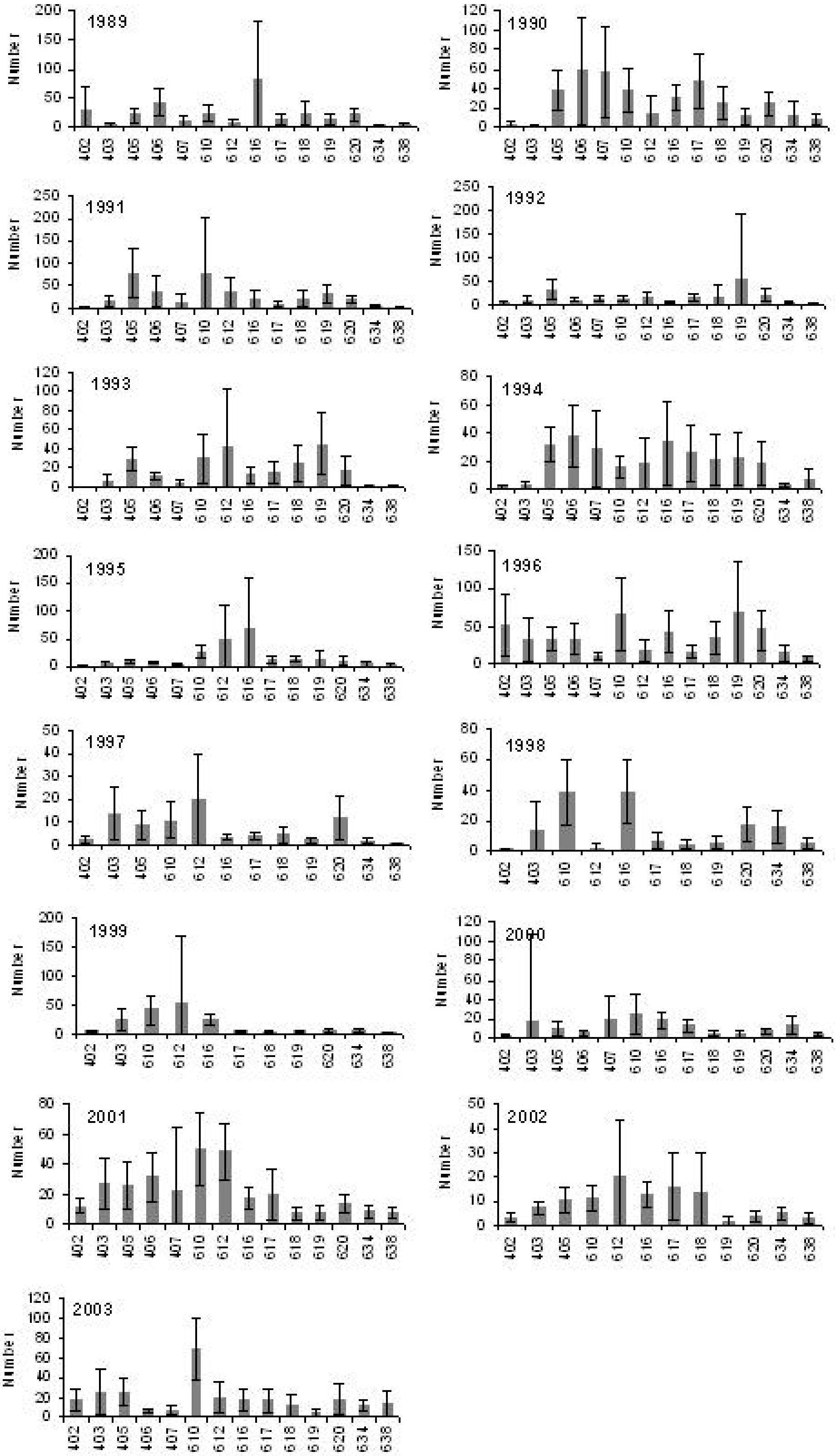


Figure 5. Abundance of 0-group plaice by area and year (y-axis: Number per 1000m2, x-axis: area). Vertical bars display standard deviation.

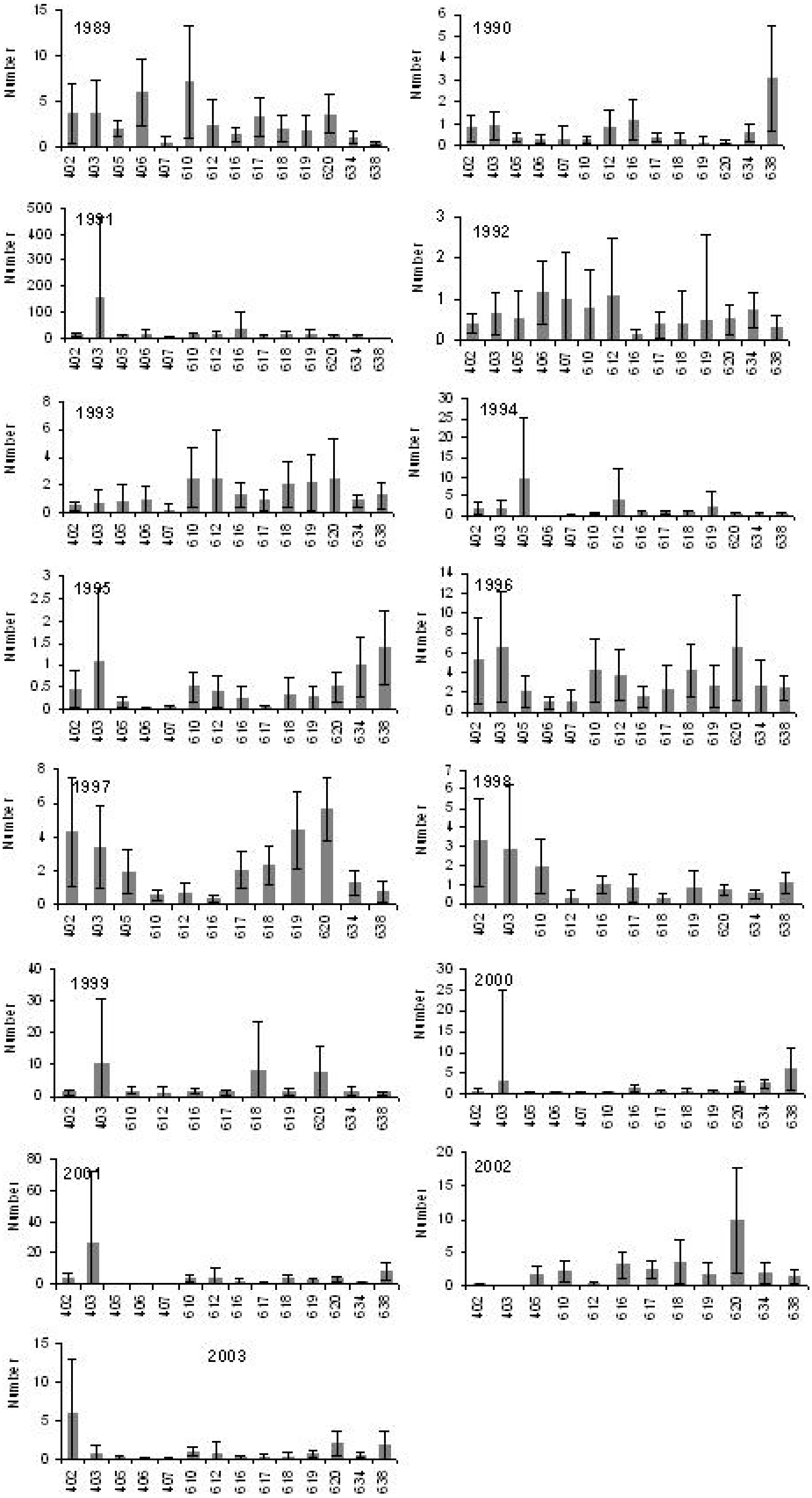


Figure 6. Abundance of 0-group sole by area and year (y-axis: Number per 1000m2, x-axis: area). Vertical bars display standard deviation.

2b Flyland surveys

Introduction

The effect of infrastructural works on the transport of fish larvae was also a point of concern in the time the government was investigating the possibilities of an airport in sea. Within this context a survey was carried out to describe the spatial distribution of recently settled and metamorphosing flatfish. The survey was funded by the Flyland project in 2002 and by R&D funding in 2003. The initial intent was to examine both the spatial as well as the seasonal distribution, but due to weather conditions (2002) and the fact that the Flyland contract was broken open (2003), insufficient number of cruises could be carried out to examine seasonal distributions. Ideally the survey should have focused on larvae, both demersal as well as pelagic. However, this was not possible as the larval sampling had to be combined with the sampling of juvenile and adult flatfish, which was carried out for another part of the Flyland project.

Materials and methods

Sampling

Sampling was carried out with the 6m-beam trawl that is used during the DFS. For the purpose of this study, a fine-meshed (1.4 mm) liner was placed in the cod-end. In 2002, 3 transects perpendicular to the coast were sampled: (Noordwijk, Egmond and Schulpengat). In 2003 an additional transect (Vlieland) was sampled. Each transect consisted of 10 stations, more or less at equal distances, but in 2002, only 8 of these 10 stations were sampled. Three cruises were carried out in 2002 and 1 in 2003 (see Table 1). Samples were conserved on board and sorted out in the laboratory. Species determinations were done according to Russell, 1976 and stage determinations according to Ryland, 1966.

Data treatment

The catch numbers were converted to number per standard haul (15 min.) These catch rates are either plotted by haul and sampling period (Figure 2), or averaged over the transects (Figure 1). The stage composition by station (Figure 3) was determined using all larvae caught within a year.

Survey results

How the timing of the cruises related to the peak in arrival of larvae is unknown. All that can be said is that the 2003-cruise and the second cruise in 2002 were within the period that plaice larvae arrived in the coastal waters, and the 3rd cruise in 2002 was within the sole influx period.

Plaice appeared to be most abundant on the Schulpengat transect in 2002, and on the Egmond transect in 2003. Sole seemed to be most abundant on the Noordwijk transect (Figure 1). In 2003 the plaice larvae appeared to be concentrated on the inshore stations, but this pattern was not clear in 2002 (Figure 2). No firm conclusions can be drawn on the spatial distribution patterns because the between-haul variability in catch rates is high and the number of hauls relatively low. The distribution pattern of plaice in 2002 was largely determined by 1 haul; a large number of plaice larvae were caught on station 9 of the Schulpengat transect (Figure 2). These results are indicative for a patchy distribution.

The youngest stage observed for plaice was 4b, whereas the youngest stage observed for sole was 4a. The stage composition by station (Figure 3) clearly shows that stage 5 larvae of both species are distributed further inshore than the others stages. Note that the largest catch of plaice larvae in 2002 was on station 9 (Schulpengat) and this catch consisted mainly of stage 4b larvae, and the largest catch in 2003 was on station 1 (Egmond) and consisted mainly of stage 5 larvae.

Literature

Russell, F.S. 1976. The Eggs and Planktonic Stages of British Marine Fishes. Academic Press, London. 524 pp.

Ryland, J. S. 1966. Observations on the development of larvae of the plaice, Pleuronectes platessa L., in aquaria. J. Cons. perm. int. Explor. Mer 30: 177-195.

Table 1. Number of hauls per sampling period and transect.

Year	Sampling period	Location transect				Total
		Noordwijk	Egmond	Schulpengat	Vlieland	
2002	5 Mar.		7			7
	25 Mar. – 28 Mar.	8	8	8		24
	3 Jun. – 6 Jun.	8	8	8		24
2003	17 Mar. – 20 Mar.	10	10	10	10	40
Total		26	33	26	10	95

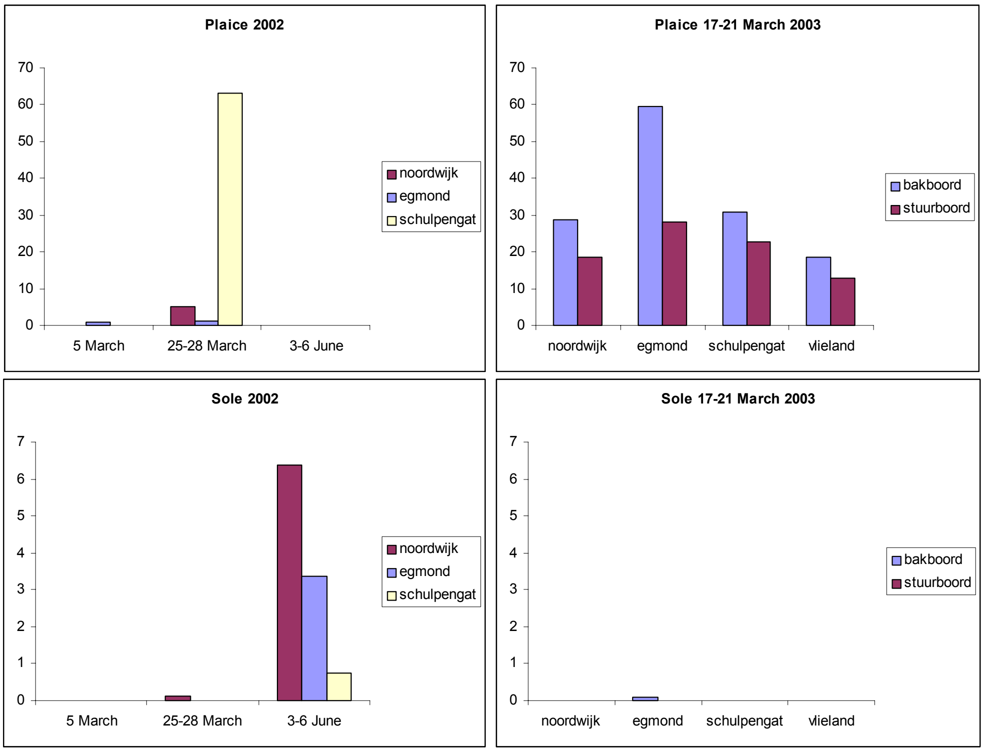


Figure 1. Average catch rates by transect and sampling period for plaice (top) and sole (bottom), in 2002 (left) and 2003 (right).

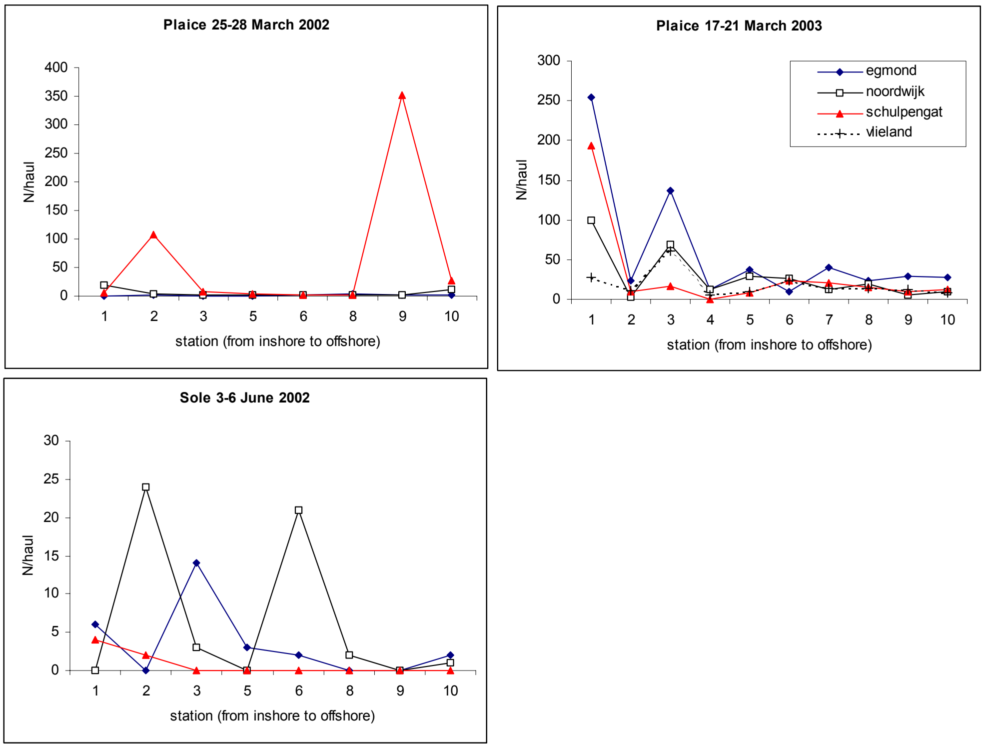


Figure 2. Catch rate by station and transect for plaice (top) and sole (bottom), in 2002 (left) and 2003 (right).

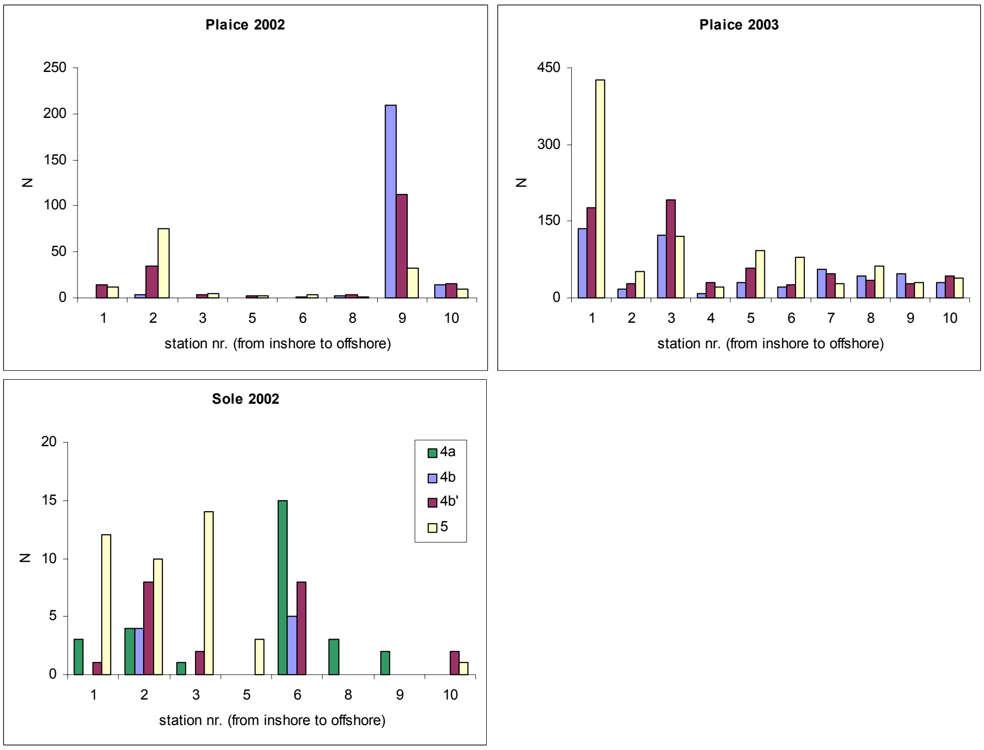


Figure 3. Stage composition by station for plaice (top) and sole (bottom), in 2002 (left) and 2003 (right).

2c Maasvlakte 2 survey

Introduction

In the MV2 baseline study for fish, a survey was carried out in which the area designated for land reclamation (MV2), the area designated for a marine protected area (MPA), and a reference area (Ref) were sampled (Figure 1). This survey was used as a platform to collect additional data on the distribution of recently settled and metamorphosing flatfish. The survey was expected to be within the period that sole larvae arrive in the coastal nurseries.

Materials and methods

Sampling

The same gear and procedures were used for sampling larvae as during the Flyland cruises (see Annex 2b). The survey was carried out in late May 2005 and the areas and sampling positions are illustrated in Figure 1.

Data treatment

The catch numbers per haul were converted to catch numbers per 1000m^2 (Table 1) and averaged by area (Table 2). The mean length per haul and area was calculated by applying a weighted-mean procedure, i.e. weighing length by number.

Survey results

The catch rates of plaice and especially sole were very low. This wasn't surprising for plaice as the main period of larval influx is past by May. The plaice caught in the MPA area were 3-3.7 cm, which no longer can be categorized as recently settled. For sole, higher catch rates were expected, but only 1 sole was caught during the whole survey. It cannot be concluded from this single survey whether the low catch rates are related to the place or the time of sampling.

The catch rates of recently settled dab were notably higher in the area designated for MV2 than in the other areas. It seems as if the same pattern occurs in the distribution of plaice.

Table 1. Densities (N/1000m^2) and mean length (in cm) by haul.

Haul	Area	Latitude	Longitude	***Dab***		***Plaice***		***Sole***	
				Dens.	Length	Dens.	Length	Dens.	Length
1	MPA	51.90	3.83	0		0		0	
3	MPA	51.91	3.86	0.8	1.2	0		0	
4	MPA	51.90	3.91	0.2	1.4	0		0	
5	MPA	51.90	3.93	0		0		0	
6	MPA	51.88	3.90	1.5	1.5	0		0	
7	MPA	51.88	3.93	0.6	1.6	0.6	3	0	
9	MPA	51.89	4.00	0		0		0	
10	MPA	51.86	3.99	0		0		0	
11	MPA	51.85	3.93	0		0		0	
12	MPA	51.84	3.94	0.2	1.4	0.2	3.7	0	
13	MPA	51.98	3.91	0		0		0	
14	MPA	51.86	3.93	0		0		0	
15	MPA	51.86	3.90	0.7	1.6	0		0	
16	MPA	51.88	3.89	0		0		0	
17	MPA	51.82	3.80	0.2	1.9	0		0	
18	MPA	51.79	3.80	0.9	1.5	0		0	
19	MPA	51.80	3.75	0		0		0	
20	MPA	51.82	3.66	0		0		0	
21	MPA	51.81	3.66	0		0		0	
22	MPA	51.80	3.66	0		0		0	
23	MPA	51.80	3.69	0.1	1.9	0		0	
24	MPA	51.78	3.67	0.1	1.5	0		0	
25	MPA	51.78	3.68	0		0		0	
1	MVII	51.98	3.94	0.6	1.4	0		0	
2	MVII	51.96	3.91	0.2	1.4	0		0	
3	MVII	51.97	3.96	0.2	1.6	0		0	
4	MVII	51.96	3.97	0.4	1.6	0.7	1.7	0	
5	MVII	51.96	3.99	0.6	1.5	1.2	1.9	0	
6	MVII	51.96	4.00	0.3	1.8	0.2	1.9	0	
7	MVII	51.94	3.99	0.2	1.3	0.7	1.9	0	
8	MVII	51.94	4.00	0.1	1.3	0		0	
9	MVII	51.94	3.94	0.2	1.6	0		0	
10	MVII	51.93	3.98	0.8	1.6	0		0	
11	MVII	51.93	3.97	1.3	1.4	0		0	
12	MVII	51.93	3.98	3.1	1.4	0		0	
13	MVII	51.94	3.99	0.3	1.5	0.1	1.8	0	
1	MVR	51.72	3.50	0		0		0	
2	MVR	51.70	3.47	0		0		0.1	0.9
3	MVR	51.69	3.46	0		0		0	
4	MVR	51.64	3.38	0		0		0	
5	MVR	51.63	3.41	0		0		0	
6	MVR	51.62	3.43	0		0		0	
7	MVR	51.59	3.44	0.1	1.4	0		0	
8	MVR	51.67	3.53	0		0		0	
9	MVR	51.67	3.55	0		0		0	
10	MVR	51.66	3.53	0		0		0	
11	MVR	51.64	3.55	0		0		0	
12	MVR	51.62	3.53	0		0		0	
13	MVR	51.65	3.64	0		0		0	
14	MVR	51.65	3.65	0		0		0	

Table 2. Mean densities (N/1000m2), mean length and number of non-zero observations by area.

Area	Number of hauls	*Dab*			*Plaice*			*Sole*		
		N>0	Dens.	Length	N>0	Dens.	Length	N>0	Dens.	Length
MPA	25	10	0.3	1.5	2	0.03	3.2	0	0	
MVII	13	13	0.54	1.5	5	0.25	1.8	0	0	
MVR	14	1	0.01	1.4	0	0		1	0.01	0.9

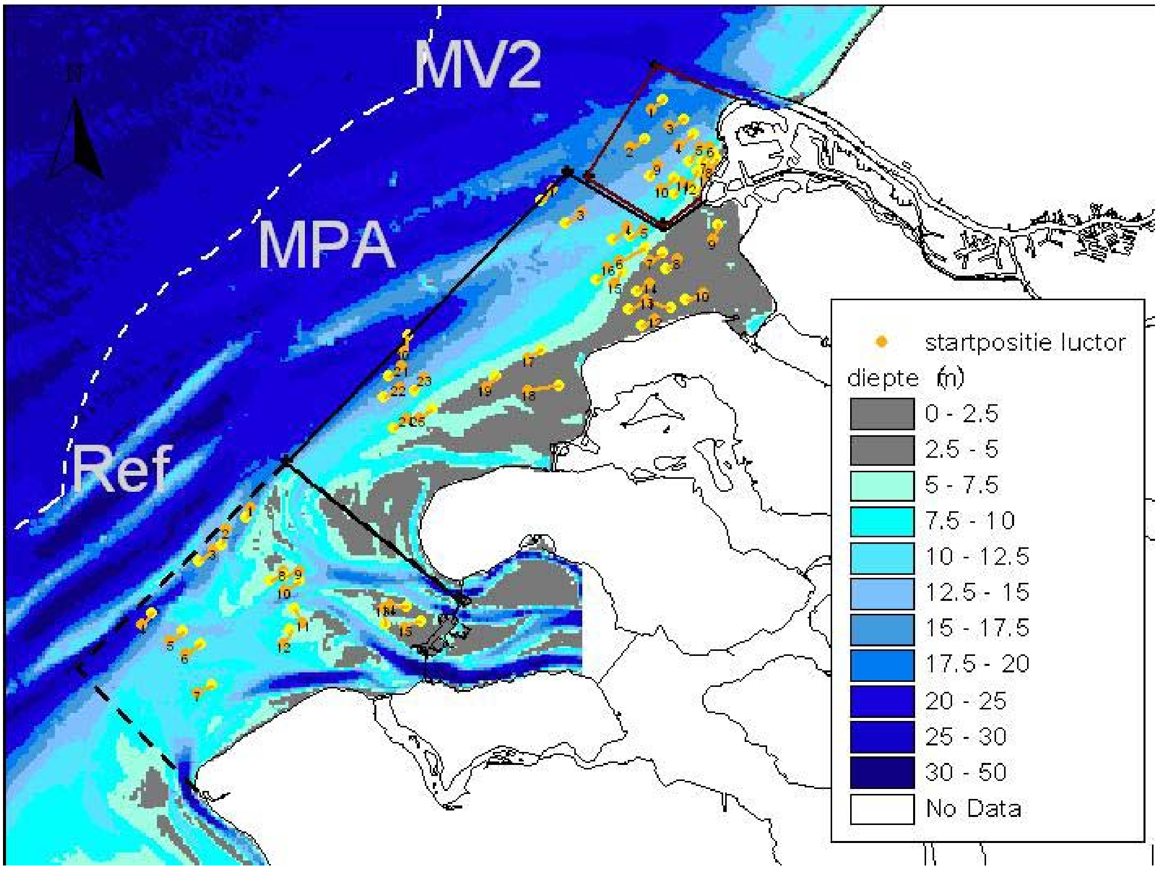


Figure 1. Geographical areas and sampling positions of the MV2-2005 survey

2d NIOZ data

Introduction

From 1993 to 2002, the Royal Netherlands Institute for Sea Research (NIOZ) has surveyed the abundance of 0-group plaice on the tidal flats in the western Wadden Sea (Balgzand), and from 1995 onwards otoliths were collected from the catches for day ring analyses. These data are of great value for the validation of the larval transport model. Firstly, they provide information on the seasonal pattern of plaice larvae entering the Wadden Sea. Secondly, because the day ring data provide information on larval stage durations of plaice settling in the Wadden Sea for the years included in the model simulations.

Part of these data has been published (Van der Veer & Witte, 1999; Van der Veer et al., 2000):

- Seasonal abundance (mean density by survey period) of 0-group plaice for the years 1993-1999 and of recently settled plaice for the years 1993-1998
- Day ring data converted to estimated hatch dates for the years 1995-1996

The following data were made available for the validation of the model study.

- Seasonal abundance (mean density by survey period) of 0-group and recently settled plaice for the years 1995-2002
- Larval stage duration prior to, and after metamorphosis (mean ±sd)

Materials and methods

The sampling procedures and the otolith analyses are described in detail in Van der Veer & Witte, (1999) and Van der Veer et al. (2000).

Results

Otolith day ring analyses provide an estimation of the duration between hatching and the onset of metamorphosis and between the onset of metamorphosis and the catch date. The catch date is presumed to be equal to the settlement date as only recently settled plaice were included in the otolith analyses. The day ring analyses suggest that, on average, plaice settle at more or less the same age every year (Table 1 and Figure 1).

The Balgzand survey data provide estimates of the timing of arrival and of the relative abundance at the time of settlement. Recently settled juveniles are distinguished from the rest of the 0-group by length (<15mm). Inter-annual variability in the timing of peak abundance is observed (Figure 2).

Literature

Van der Veer, H. & J.I.J. Witte. 1999. Year-class strength of plaice *Pleuronectes platessa* in the Southern bight of the North Sea: a validation and analysis of the inverse relationship with winter seawater temperature. Marine Ecology Progress Series 184: 245-257.

Van der Veer, H. W., Geffen, A.J., Witte, J.IJ. (2000). Exceptionally strong year classes in plaice *Pleuronectes platessa*: are they generated during the pelagic stage only, or also in the the juvenile stage? Mar. Ecol. Prog. Ser. 199: 255-262.

Table 1. Duration of the pelagic larval phase, duration since the onset of metamorphosis, and the total number of days since hatching.

	pelagic larval			metamorphosis			total age		
Year	N	mean	stdev	N	mean	stdev	N	mean	stdev
1995	108	33	9	138	17	8	108	50	10
1996	138	49	10	151	7	7	138	56	9
1997	122	50	6	122	10	6	121	60	8
1998	106	51	4	116	9	6	106	60	7
1999	133	47	5	131	11	4	131	58	6
2000	123	52	3	129	9	4	123	61	6
2001	101	47	7	103	8	5	97	55	9
2002	118	54	4	121	10	5	116	64	6
overall	949	48	9	1011	10	6	940	58	9

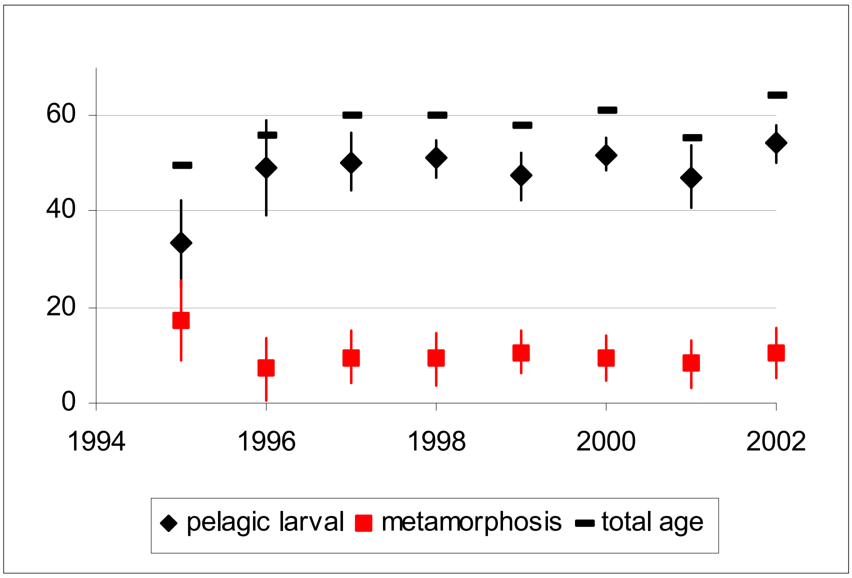


Figure 1. Duration (mean ± sd) of the pelagic larval phase, duration since the onset of metamorphosis, and the total number of days since hatching.

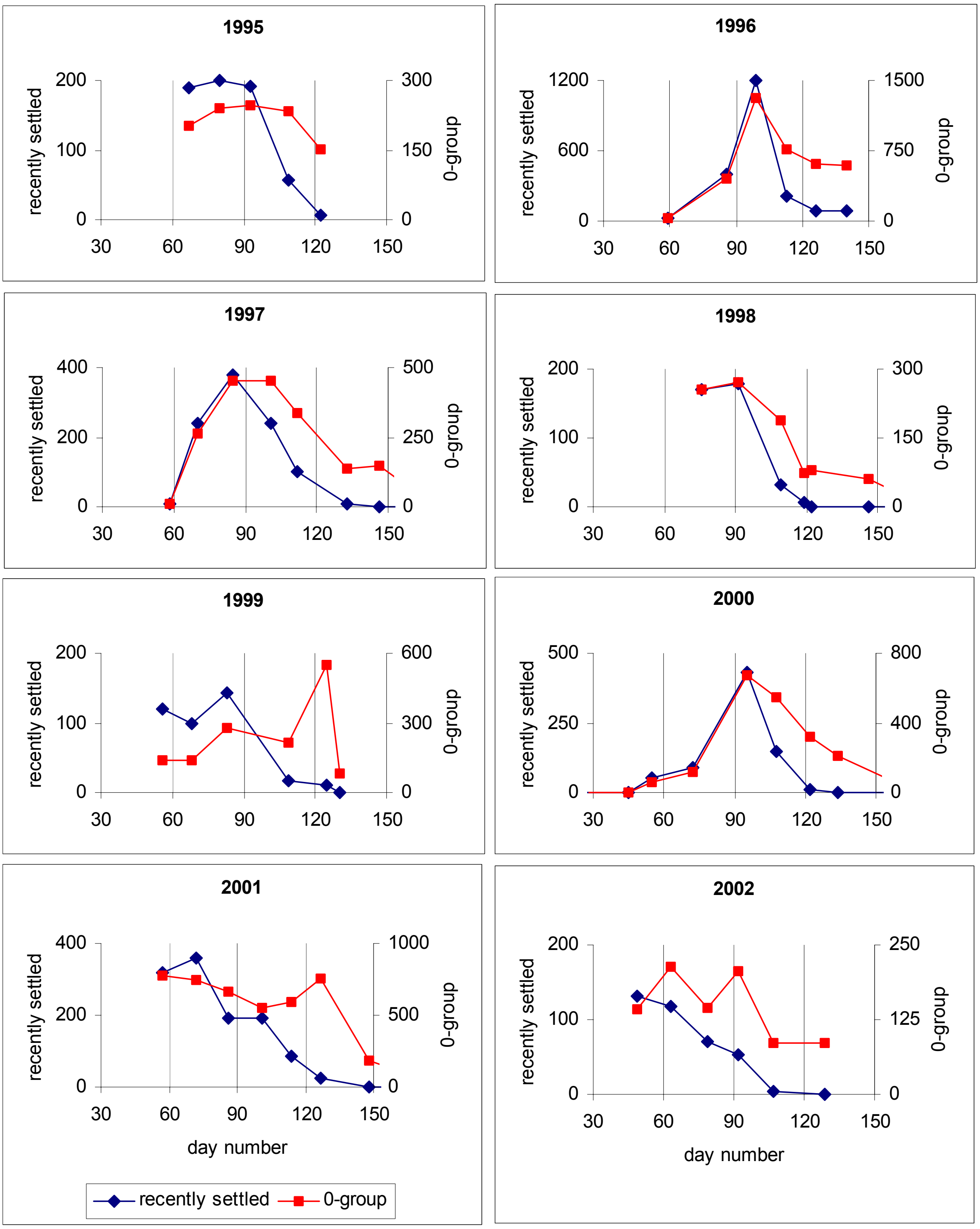


Figure 2. Seasonal abundance (N/1000m^2) of 0-group and recently settled (<15mm) plaice on the Balgzand tidal flats in the western Wadden Sea.

2e Stow net survey Western Wadden Sea

Introduction

The Wadden Sea is one of the major nursery grounds for plaice. Field data showed (Van der Veer *et al.*, 1990) that settlement of plaice larvae in the Wadden Sea, occurs from March until May. Delivery of larvae into the nursery grounds is influenced by the temporal and spatial distribution of spawning and by larval drift conditions. Altered currents, induced by MV2, may influence transport routes and thus also the final destination of fish larvae and the flux of plaice larvae into the Wadden Sea. To be able to assess the impact of MV2 after land reclamation, it is important to define current status of delivery rates and temporal variances in delivery of plaice larvae into the Wadden Sea.

The stow net survey in the western Wadden Sea provides quantitative estimates of larval abundance in the western Wadden Sea throughout the season. These data are used to quantify temporal distribution pattern and mean delivery of plaice larvae into the western Wadden Sea through two of the main inlets. Furthermore, a distinction could be made between influx of plaice larvae during ebb and flood tide.

Materials and methods

Sampling

From February to May 1988 and 1989 several stow net surveys were carried out in the western Wadden Sea. Sampling took place at a regular time interval (half monthly periods) in two of the main inlets to the western Wadden Sea (figure 1). The sampling gear consisted of an anchored plankton net with a circular mouth opening of 2 m diameter. In general the netting consisted of nylon “Monodur” with a mesh size of 1.40 mm. Total length of the net was 14 meter. The volume filtered was measured and the herring larvae were sorted out of all hauls and converted to numbers per 10.000 m^3 (Corten & Van de Kamp, 1979). In 1989, the flatfish larvae were only sorted out during a part of the survey. At inlet 1 (Marsdiep) flatfish was only sampled from March to mid April (3 cruises). At inlet 2 (Vliestroom/West Meep) flatfish was only sampled during one cruise in the first half of March.

Data treatment

Results from the surveys have been grouped into half-monthly standard periods. In order to calculate the mean number of larvae per haul for the entire cruise, first the mean number per haul and its variance were calculated for each individual sampling position. Next, the stratified mean and variance were calculated for the sampling positions combined. For estimation of the temporal distribution related to entrance of plaice larvae into the Western Wadden Sea, the average period (month) was calculated by applying a weighted-mean procedure and hence weighing period by number. Analysis of variance (ANOVA) was applied by SAS, GLM procedure, in order to test the correlation between number of herring and respectively total delivery and mean entrance period effects (alpha=0.05). Year and inlet-number were taken into consideration too. The effects of tide on mean delivery of larvae was tested following the same procedure.

Survey results

Delivery

Results show an increase in influx of larvae from March onwards to peak numbers in May (Figure 2). Larvae do not tend to enter the Wadden Sea through a specific passage to sea, since no significant difference (p=0.56) was found between number of larvae caught in respectively inlet 1 and 2 in 1988 (Table 1). In 1989 the abundance of larvae entering the

Wadden Sea through inlet 1 (Marsdiep) is much higher than in 1988 (Table 1), which suggest a large degree of interannual variability. Insufficient data are available for inlet 2 in 1989 for comparison with 1988.

Larvae entering the nursery ground are between stages 4a to 5. Figure 3 shows the relative abundance for each developmental stage per half monthly period per year. Stage 4b is the dominant stage at which larvae enter the Wadden Sea.

Temporal distribution

Figure 4 shows the average period when larvae of different stages enter the Wadden Sea for each year. Since the time series in 1989 is short for inlet 1 and consists of only 1 cruise (in month 3) for inlet 2, the 1989 data have been excluded from further analyses. Figure 5 shows the average timing in 1988 and demonstrates that more developed stages (stage 5) tend to enter the nursery grounds earlier than less developed stages (stage 4a). This is not conform the expectation that older larvae enter the nursery grounds later in season. The staging of larvae is subjective, which may have resulted in inaccuracies in the dataset. Another hypothesis for this pattern is that the larvae entering the Wadden Sea early in season originate from the English Channel spawning grounds and, compared to larvae from the Southern Bight spawning ground, are further developed by the time they reach the Wadden Sea.

Tidal effects

Field studies on plaice larvae (Rijnsdorp *et al.,* 1985) have demonstrated that pelagic catches were much greater during flood tide than ebb tide. They concluded that the onshore transport of plaice larvae is actively supported by behavioural features of the larvae: resting on the sea bed during ebb tide and rising into the water column during flood.

This phenomenon is also shown by results of this study (year=1988, figure 6). A significant difference ($p<0.0001$) between catches during ebb and flood tide was observed. During flood tide 16.5 larvae per 1000m ^{3} enter the Wadden Sea. This is almost four times higher than during ebb tide when entrance of larvae is only 4.2 per 1000m^3. Such tidal-related variations support the concept of selective tidal transport.

Literature

Corten, A & G. van de Kamp, 1979. Abundance of herring larvae in the Dutch Wadden Sea as a possible indication of recruitment strength. *International Council for the Exploration of the Sea (ICES)* C.M. 1979/ H:26 Pelagic Fish Committee

Van der Veer, H.W., Pihl, L., & Bergman, M.J.N. (1990) Recruitment mechanisms in North Sea plaice *Pleuronectes platessa*. *Mar. Ecol. Prog. Ser.*, **64**, 1-12.

Table 1. Average yearly abundance of larvae in the Western Wadden Sea, grouped by entrance position (Average number per 1000m^3)

	1988	1989
Inlet 1 (Marsdiep)	8.0	19.4
Inlet 2 (Vliestroom/West Meep)	15.8	13.8*
Average inlet 1 & 2	12.3	15.9

*Based on catches from one cruise only (first half March)

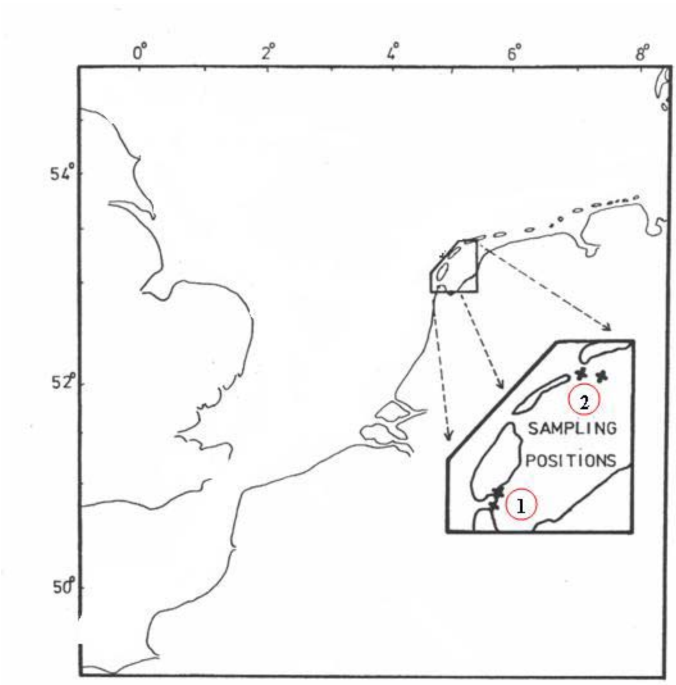


Figure 1. Overview of sampling stations of the Stow Net Surveys in the Western Wadden Sea (1988-1989). Inlet 1=Marsdiep, inlet 2=Vliestroom/West Meep (Source: Corten & Kamp, 1979)

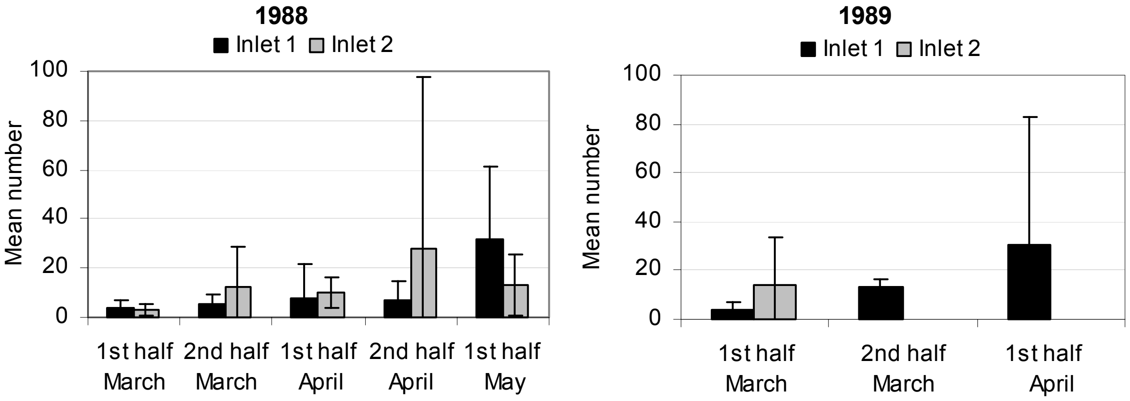


Figure 2. Mean influx of plaice larvae (number per 10.000m^3) into the Wadden Sea (1988-1989). Vertical bars disply Standard Deviation. Inlet 1=Marsdiep, inlet 2= Vliestroom/West Meep.

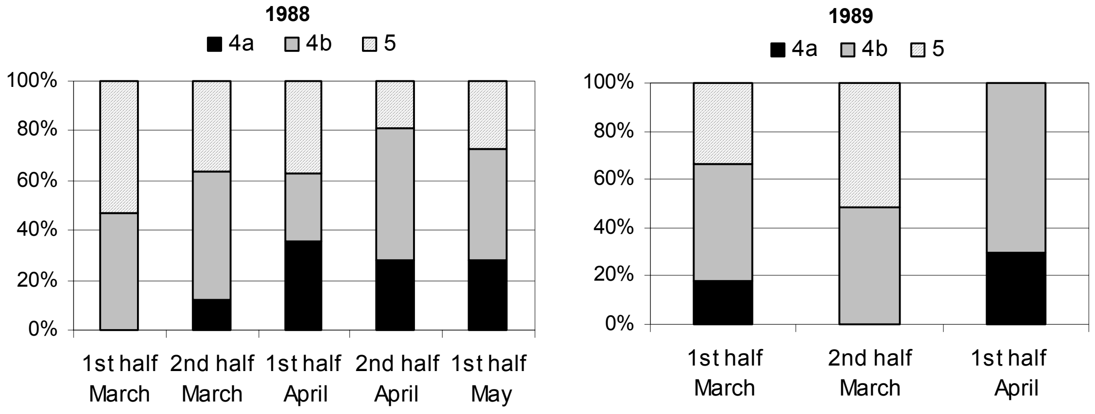


Figure 3. Relative influx of plaice larvae of different stages into the Wadden Sea (1988-1989). Average of the two inlets.

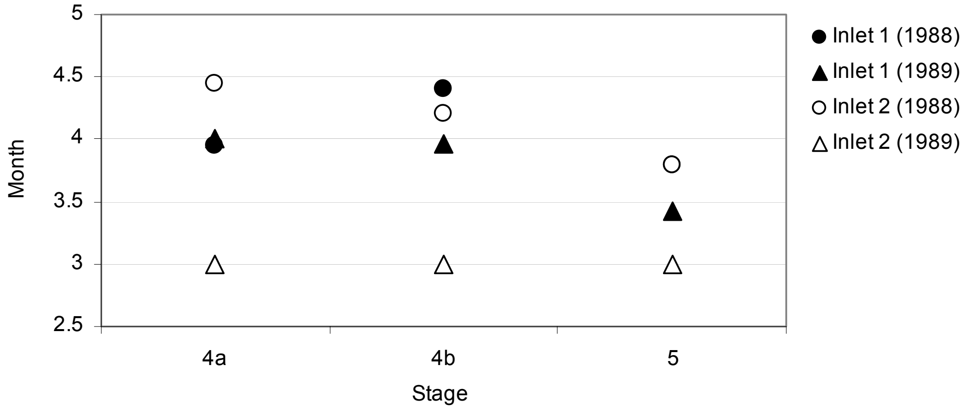


Figure 4. Timing of arrival (mean) of plaice larvae in the western Wadden Sea in 1988 and 1989. Inlet 1=Marsdiep, inlet 2= Vliestroom/West Meep. Month 3=1st half March, month 3.5=2nd half March, month 4= 1st half April, month 4.5=2nd half April and month 5=1st half May.

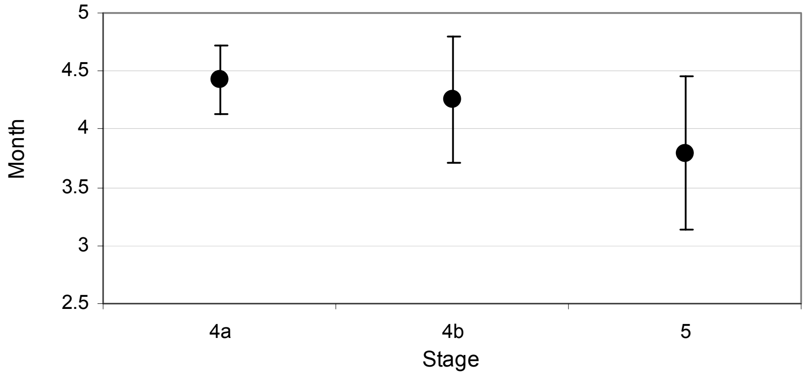


Figure 5. Timing of arrival (mean ± sd) of plaice larvae in the western Wadden Sea in 1988 (Marsdiep and Vliestroom/West Meep combined). Month 3=1st half March, month 3.5=2nd half March, month 4= 1st half April, month 4.5=2nd half April and month 5=1st half May.

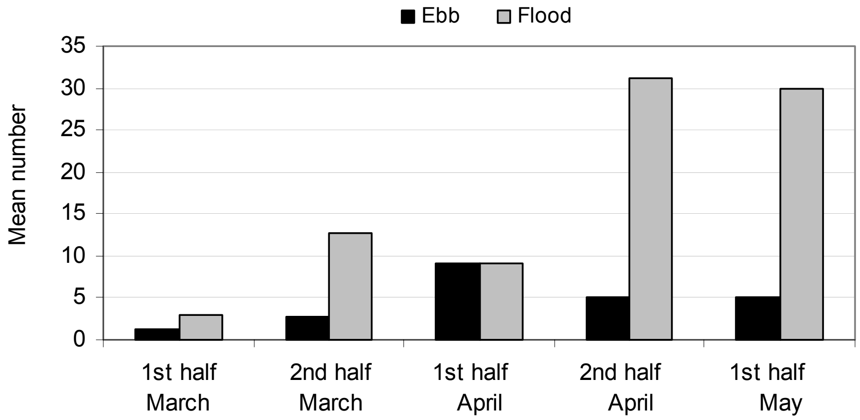


Figure 6. Tidal effects. Mean influx of plaice larvae during ebb and flood tide into the Wadden Sea (1988). Average of the two inlets (number per 10.000m^3).

Annex 3 – Herring Surveys

3a International Herring Larvae Survey

Introduction

The ICES programme of international herring larval surveys (IHLS) in the North Sea provides quantitative estimates of herring larval abundance. These data are used to quantify the spatial and temporal patterns in larvae abundance by length in proximity of their spawning grounds. These data provide useful information on both the spawning sites and the initial drift of larvae.

Materials and methods

Sampling

The International Herring Larvae Surveys are carried out in specific time periods and areas, following the autumn and winter spawning activity of herring from north to south. The herring larval abundance is surveyed in four different areas: the Orkney/Shetland area, the Buchan region, the Central North Sea and the Southern North Sea. Within this study only data from the Southern North Sea area used. (ICES, 2004)

In general a GULF type sampler is used to collect the samples. Immediately after hauling the sampler through the water column in a double oblique manner the samples are fixed in 4% buffered formaldehyde. Larvae remain exposed to the fixative for at least 48 hours before sorting to ensure proper fixation. The larvae are measured as total length and to mm below. Ideally all larvae are sorted and counted in all samples. However, if this is not possible sub sampling techniques are used. A sub sample of at least 200 larvae per station is measured. (ICES, 2004)

Data treatment

Catch data together with specific information like haul position, survey area etc. are reported to the ICES International Herring Larvae database annually. The database contains information about the surveys conducted since 1972 (ICES, 2004). For this study only data after the collapse in herring stock is used, therefore the years (/campaigns) from 1985 onwards are used

Larvae numbers per square meter are calculated for each year and position separately. For each year and standard position the measured larvae are aggregated into the following three length frequency distribution groupings:

- Length class 1: Larvae < 11 mm
- Length class 2: 11 mm >= larvae <= 16 mm
- Length class 3: Larvae >16 mm

In order to analyse the northward migration pattern of the larvae, the survey area is split in seven sub areas based on 0.5 latitude degrees (figure 3.1.1). Average location for each length class was defined by calculation of the mean area weighted by catch density. Analysis of variance (ANOVA) was applied by SAS, GLM procedure, in order to test the correlation between mean area of herring and respectively length class and year effects (alpha=0.05).

Survey results

Figure 3.1.2/3 and table 3.1.2 show that herring larvae of different length classes are randomly dispersed between the sub areas. Abundance of herring larvae of length class 1 (>11 mm) is highest in area 3.2 (table 3.1.2), however, the absolute value is relatively low in all sub areas (table 3.1.1). Since larvae hatch at 9 mm and have an average growth rate of 0.2 mm day, it is obvious that only a small fraction of the total larvae are in class 1. Abundance of length class 2 larvae (11-16 mm) was profound (figure 3.1.2 and table 3.1.1). Catch densities were 7 times higher than class 1 and class 3 was just a minuscule fraction of this length class. With an average location of 2.4, larvae of length class 2 are in general situated at locations more southwards than length class 1, which is not something you would expect from the larger migration pattern of downs herring. It appears that mortality of herring larvae mainly takes place after they reached 16 mm in length, since catch densities of length class 3 were very low. Abundance of length class 3 is highest in area 3.6.

Although a significant difference ($p<0.0001$, □=0.05) was found between mean area and length class, it can not be concluded that difference in migration pattern and spatial distribution of the herring larvae is caused by age/length (length class). As graph 3.4.1 indicates, difference in location can not be caused by migration/drift since location of length class 2 is more southwards then length class 1. It seems that larvae at this age (<50 days) do not yet start their drift from spawning site to the nursery grounds in the Wadden Sea. There is, however, a year effect ($P<0.0001$, □=0.05) which does explain the interannual variability (figure 3.1.4). Spatial distribution of downs larvae (<50 days) is therefore rather influenced by year effect such as weather conditions and currents than by age/length.

Since spatial distribution of herring larvae (<50 days old) is highly influenced by year effects, the impact of altered currents, influenced by MVII, will presumably not impact the initial drift of larvae from the spawning grounds in the southern North Sea towards the nursery grounds in the Wadden Sea.

Literature

Dickey-Collas, M., 2005. Desk study on the transport of larval herring in the southern North Sea (Downs herring). *Netherlands Institute for Fisheries Research, report no.*

ICES, 2004. Report of the working group for herring surveys. ICES Living Resource Committee. *ICES CM 2004/ G:05 Ref. D.* (Annex V)

Table 3.1.1 Mean catchdensity (number per m^3) of herring larvae of three length classes in the different areas.

	Length class < 11 mm		Length class 11-16 mm		Length class >16 mm	
	Mean	SD	Mean	SD	Mean	SD
Area 1	0.9	*5.8*	14.3	*114.4*	0.0	*0.2*
Area 2	2.5	*11.1*	24.4	*96.3*	0.1	*0.6*
Area 3	2.2	*9.1*	12.5	*54.7*	0.1	*0.5*
Area 4	2.1	*7.7*	10.4	*36.6*	0.1	*0.6*
Area 5	1.3	*5.9*	5.2	*24.3*	0.1	*0.4*
Area 6	1.1	*4.9*	2.5	*9.4*	0.1	*0.5*
Area 7	0.4	*2.6*	1.1	*7.1*	0.0	*0.2*

Table 3.1.2 Spatial distribution of herring larvae of three lengthclasses (1985-2004): Mean area per length class, and *standard deviation* (see also figure 3.1.3).

Campaign	Length class < 11 mm		Length class 11-16 mm		Length class >16 mm	
	Mean	*SD*	Mean	*SD*	Mean	*SD*
1985	2.6	*1.0*	3.0	*1.0*	2.3	*1.1*
1986	4.9	*1.6*	3.6	*1.4*	5.0	*1.3*
1987	3.6	*1.0*	3.7	*1.0*	4.1	*1.4*
1988	4.3	*1.5*	3.4	*1.6*	5.2	*1.1*
1989	2.7	*0.9*	1.9	*0.7*	3.3	*1.3*
1990	3.1	*1.0*	3.0	*1.1*	3.7	*2.0*
1991	4.3	*1.3*	3.6	*1.6*	3.8	*2.3*
1992	2.8	*0.8*	2.6	*0.7*	4.0	*1.6*
1993	2.6	*1.3*	2.6	*1.0*	4.8	*1.9*
1994	5.1	*1.2*	4.0	*1.3*	4.4	*2.2*
1995	3.0	*1.2*	2.7	*1.1*	5.3	*1.5*
1996	3.8	*1.4*	3.5	*1.5*	4.9	*2.0*
1997	2.1	*0.8*	1.4	*0.7*	3.1	*1.9*
1998	4.8	*1.7*	3.4	*1.6*	5.8	*0.8*
1999	4.4	*1.6*	3.0	*1.4*	5.8	*0.8*
2000	2.9	*1.7*	3.1	*1.9*	2.7	*0.5*
2001	4.7	*1.9*	3.4	*1.5*	3.8	*1.9*
2002	2.4	*1.1*	1.6	*0.8*	1.8	*0.8*
2003	3.2	*1.5*	2.5	*1.3*	4.5	*1.5*
2004	2.0	*1.4*	1.9	*1.4*	3.9	*1.5*
2005	3.4	*1.3*	2.3	*1.3*	4.3	*1.3*
Mean 1985-2005	3.2	*1.6*	2.4	*1.3*	3.6	*1.7*

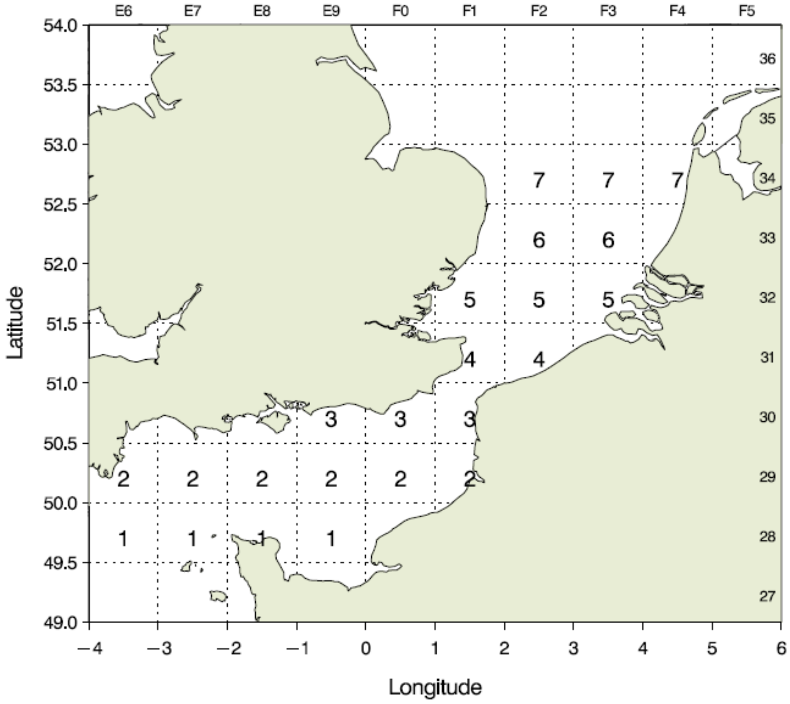


Figure 3.1.1 Geographical areas as defined within this study.

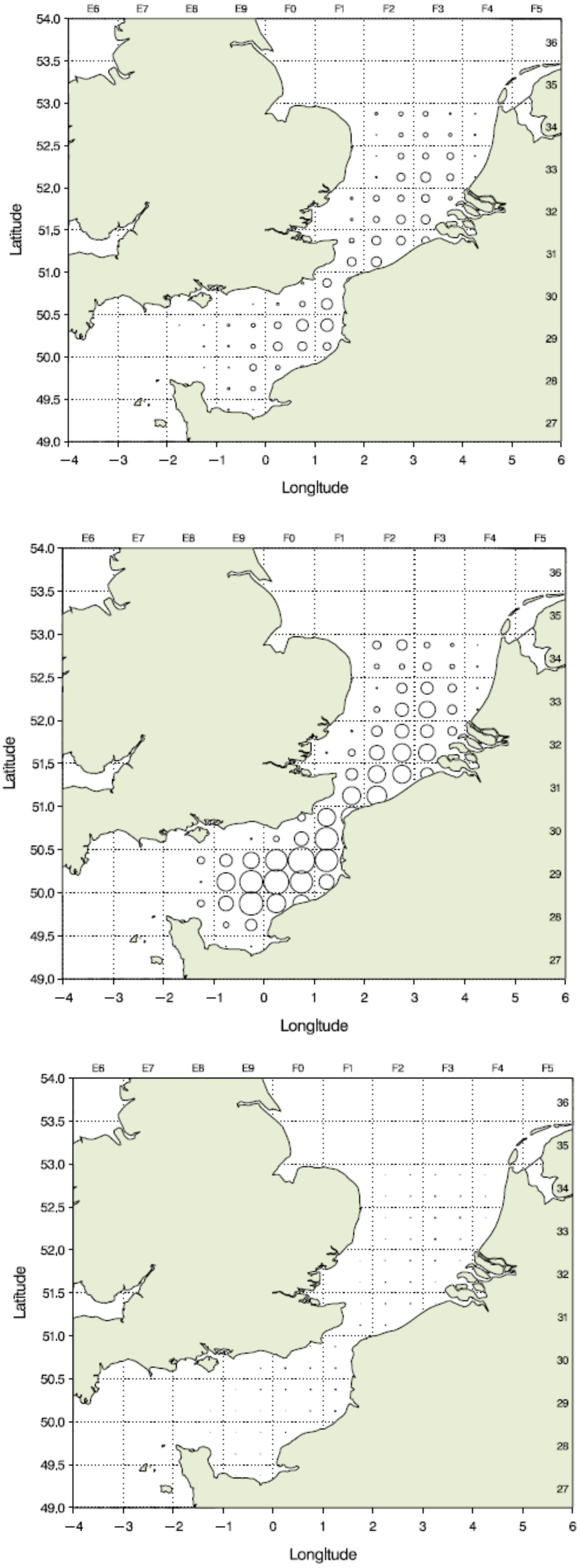


Figure 3.1.2 Spatial distribution of herring larvae: Mean catchdensity (number per m^3) of herring larvae of three length classes (1985-2004).

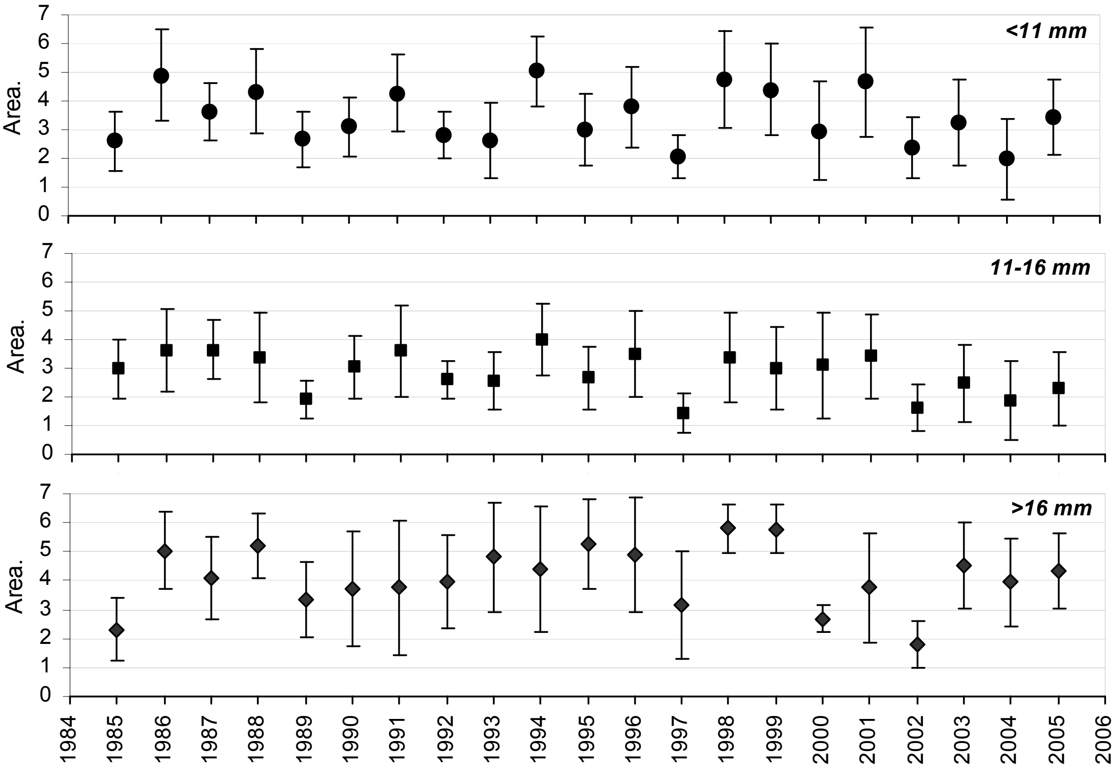


Figure 3.1.3 Spatial distribution of herring larvae of three lengthclasses (campaign 1985-2004); average area and variation (SD) per year.

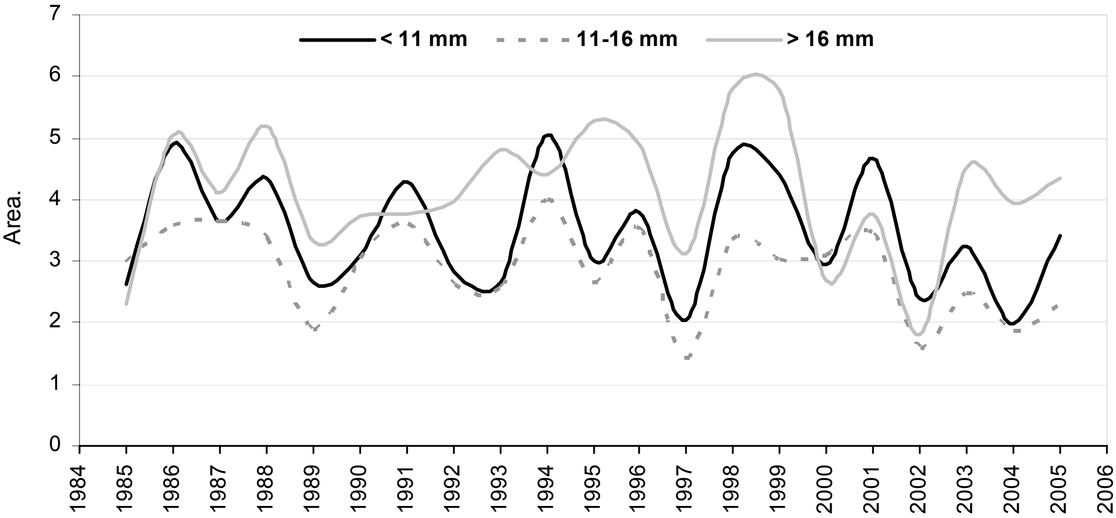


Figure 3.1.4 Spatial distribution of herring larvae of three lengthclasses plotted in 1 graph to show year effect (campaign 1985-2004).

3b International Bottom Trawl Survey (IBTS)

Introduction

The IBTS was originally designed to sample herring. It is very suitable for estimating the distribution and abundance of juvenile herring, hence the nursery grounds. Herring leave the nursery grounds between ages 1 and 3, depending on their growth and condition and join the adults in their migration from feeding grounds to spawning grounds (Mc Quinn, 1997; Brophy & Danilowicz, 2003).

Basic information of the spatial distribution pattern and interannual variability of juvenile herring during 1991-2003 is shown by field data of the International Bottom Trawl Survey (IBTS). These data are used for determination of nursery grounds of the Downs herring and also in order to achieve insight in the interannual variability of the spatial distribution pattern of the nursery grounds.

Materials and methods

Sampling

International research vessel trawl surveys are organised under the auspices of ICES, to map the distribution of juvenile herring *Clupea harengus* in the North Sea and to investigate the links between herring nursery grounds and the adult populations. The surveys are conducted annually. From 1991 to 1995 surveys have been carried out on a quarterly basis, herewith providing a full description of the seasonal distribution of the stock sampled. The following years (1996-present), the majority of vessels have only carried out surveys twice a year; a first quarter survey (Jan-Feb) and a third quarter survey (Aug-Sept). The stratification of the survey grid is based on ICES statistical rectangles (one degree longitude x 0.5 degree latitude). Each rectangle is usually fished by two ships of two different countries, so that at least two hauls are normally made per rectangle. The sampling method consists of a 30 minute haul with fishing speed of 4 knots using a GOV trawl net during daytime. (ICES, 2004)

After sorting the catch into species, a length distribution needs to be obtained. Length is recorded to 0.5cm below. Where the numbers of individuals are too large for them all to be measured, a representative sub-sample is selected of at least 75 fish. The otoliths are removed from the fish and stored for age determinations in the laboratory. (ICES, 2004)

Data treatment

Catch data together with specific information like haul position, survey area etc. are reported to the ICES IBTS database annually. The data are combined from all surveys and expressed as number per hour per haul. (ICES, 2004)

Since we are interested in the dispersion pattern between nursery grounds, the grid has been divided into 4 nursery ground areas (figure 3.2.1); the Central North Sea (1), German Bight (2), English coastal zone (3) and the Dutch coastal zone (4). Then, the average number per rectangle is calculated for each area, year and, when enough data were available (1991-1995), per quarter separately. The overall average was also calculated. Analysis of variance (ANOVA) was applied by SAS, GLM procedure, in order to test the correlation between number of herring and respectively area and year effects (alpha=0.05). Interference (area*year) was taken into consideration by testing the interaction between those parameters. Non-significant terms were excluded and the model was refitted with the remaining terms.

Survey results

In December/January of the first year following spawning (Q1), no juveniles are caught because mesh size of IBTS trawl nets is still too large. From the second quarter on, catches of juveniles have been recorded but full net selection still does not occur. Initially (Age-0, Q3) abundance is highest in Skagerrak, Kategat and German Bight region. Followed by a more continuous dispersion pattern between the nursery grounds later in season (figure 3.2.2).

Figures 3.2.3 shows the relative dispersion of juvenile herring between the four areas. The situation in quarter 3 does show a similar pattern for age-0 and age-1, while quarter 1 tells a total different story. In winter (Q1) fish have to deal with disturbance of their (nursery)habitat, caused by rough weather, food availability etc. In quarter 3, herring juveniles are less influenced by external factors and thus settle according to their preferences. Therefore fish are more dispersed in quarter 1, while in quarter 3 a more pronounced pattern is observed. The German Bight is by far the most important nursery ground for herring. Besides that, the Dutch Coastal zone also seems to be important for age-0 juveniles and showed peak values for age-0 in 1995, 2001, 2003 (Q3). The Central North Sea tends to be a major nursery ground for age-1 juvenile herring as well, which in some years even exceed the German Bight in total number of juveniles. In winter German Bight is still the major area for herring juveniles but the Dutch Coastal zone is an important nursery ground as well.

Absolute values show large interannual variability (figure 3.2.4), while relative value show more or less a stable pattern (figure 3.2.3, Q3). Although, no year effect was found ($p=0.11$, $\alpha=0.05$), a significant value ($P=0.0006$, $\alpha=0.05$) for the interaction between area and year was found.

The Dutch Coastal zone is not the major nursery ground for herring juveniles. Since herring are dispersed between the nursery grounds in winter time, it seems that they adapt to the surrounding circumstances.

Literature

Dickey-Collas, M., 2005. Desk study on the transport of larval herring in the southern North Sea (Downs herring). *Netherlands Institute for Fisheries Research, report no.*

ICES, 2004. Manual for the international bottom trawl surveys, revision VII. *The international Bottom Trawl Survey Working Group.*

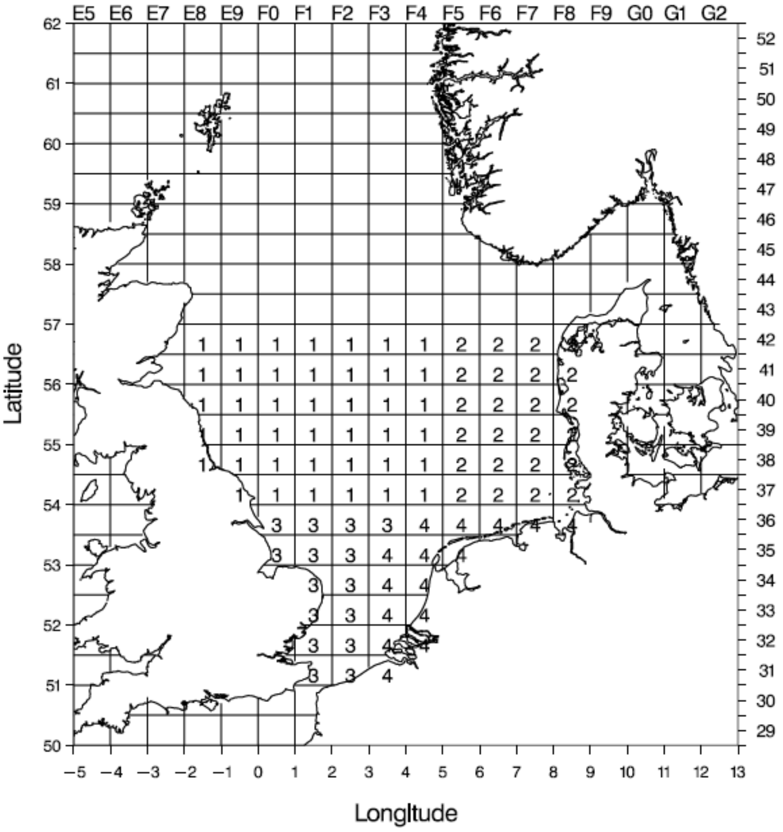


Figure 3.2.1 Geographical areas as defined within this study.
(Area 1=Central North Sea, Area 2=German Bight, Area 3=English Coast, Area 4=Dutch Coast)

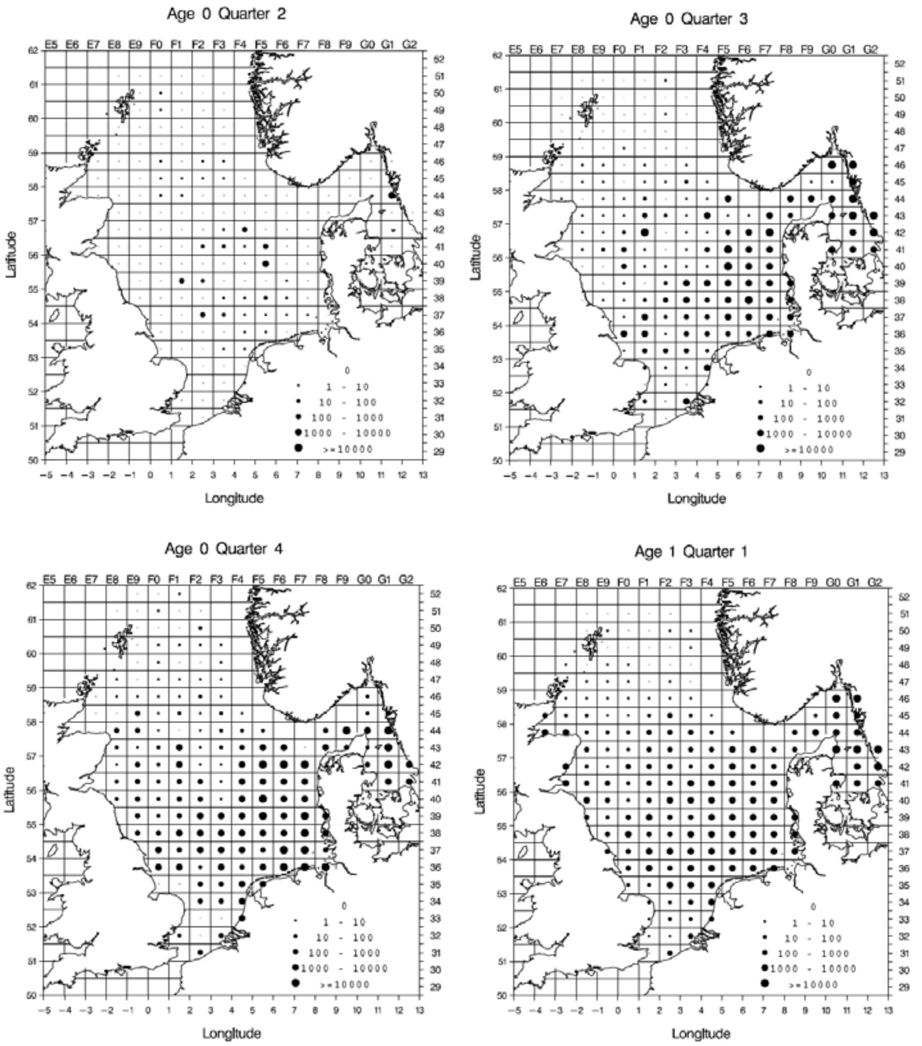


Figure 3.2.2 Drift of juveniles. Distribution of age 0 (Q:2,3,4) and age 1 (Q:1) herring, year 1991-1995. Abundance estimates (numbers per hour fishing) per ICES rectangle. Empty rectangles= no samples taken.

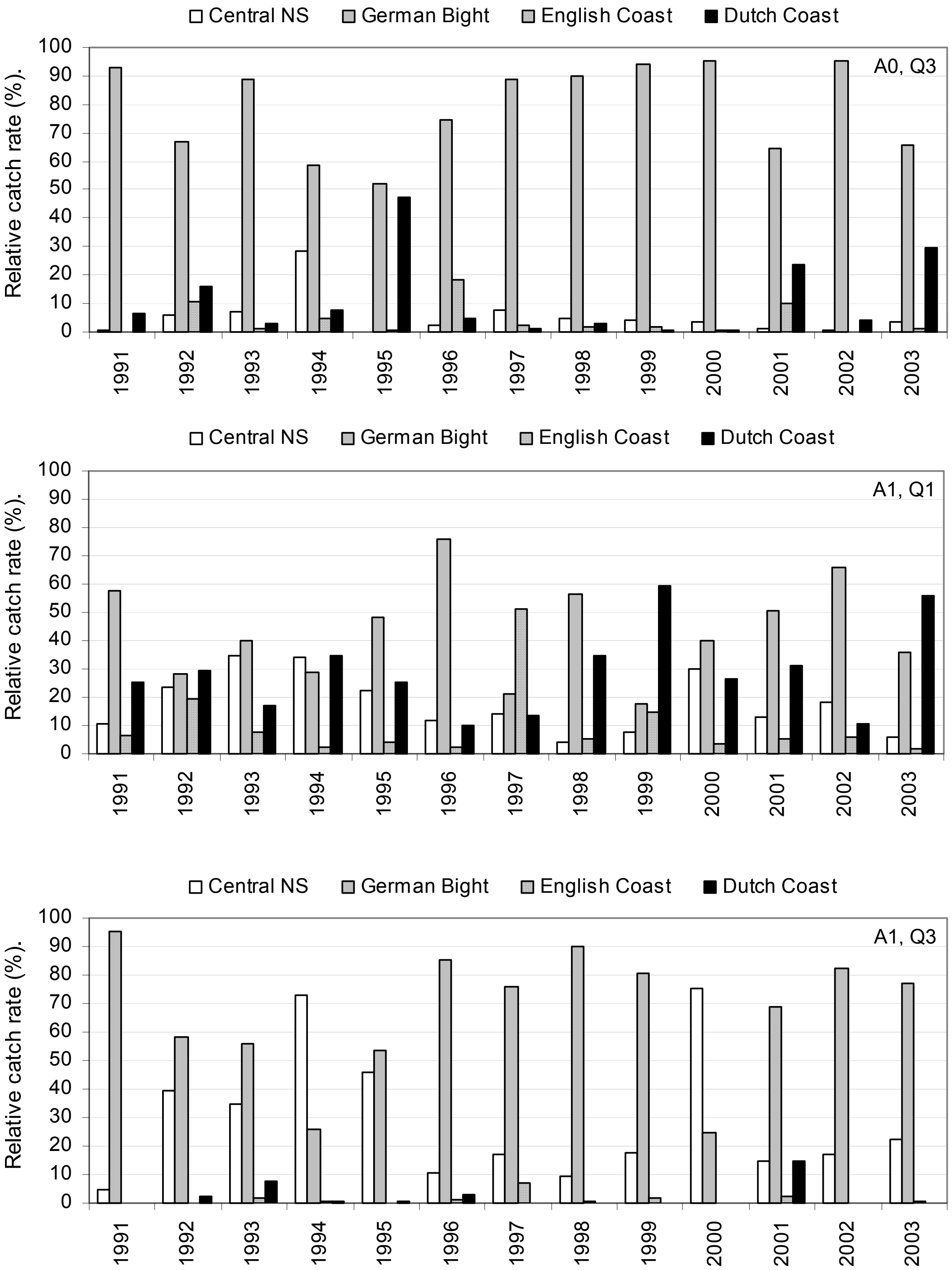


Figure 3.2.3 Spatial distribution: Relative catch rate between 4 nursery grounds (1991-2003). First graph describes Age-0 in Quarter 3, second graph Age-1 in Quarter 1 and the third graph Age-1 in Quarter 3

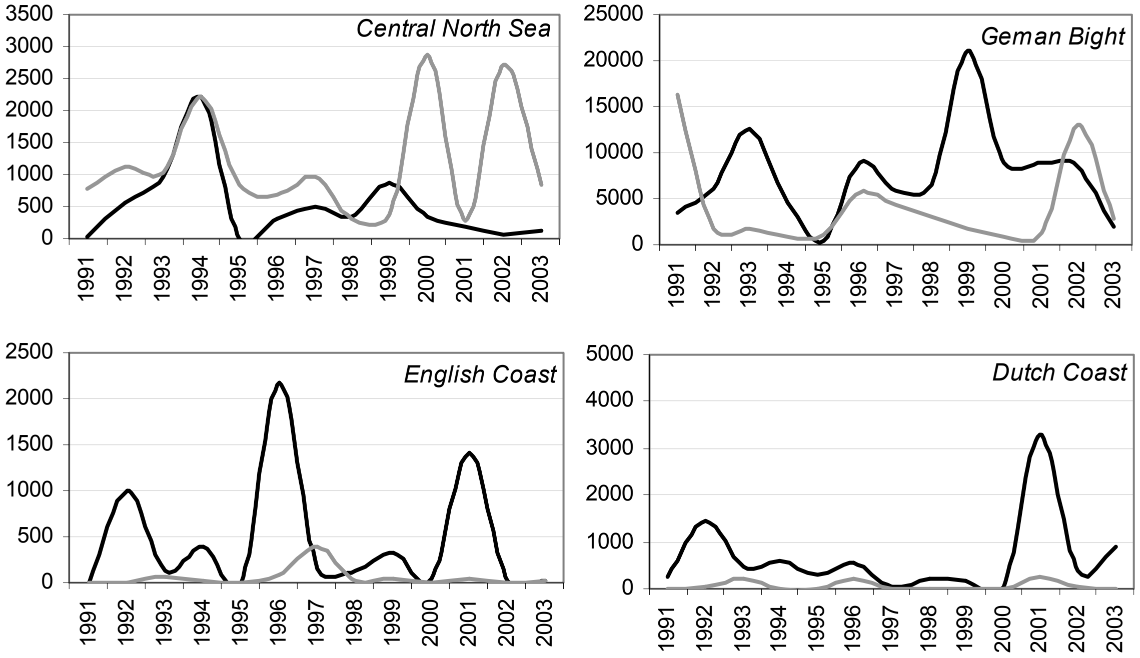


Figure 3.2.4 Average catch rate (number per haul per hour fishing) per ICES rectangle for the four areas (Q3, 1991-2003). (— Age-0 — Age-1)

3c Methot Isaac Kidd (MIK)-net data

Introduction

MIK-net data provides information about the first initial drift of herring larvae (3-4 month old) from the spawning grounds to their nursery habitats.

Materials and methods

Sampling

The Methot Isaac Kidd (MIK) net is a midwater ring trawl and is the standard gear for the sampling of fish larvae during the International Bottom Trawl Survey (Annnex 3b) in the first quarter. The net consists of a 1.6 mm mesh, 13 meter long black net. In the last meter a 5 mm net is inserted. The sampling method consists of a haul with fishing speed of 3 knots during nighttime. Duration and distance towed are recorded. (ICES, 2004)

The samples are preserved in either 4% formalin in fresh water or in 96% ethanol. Lengths of larvae are measured after preservation. Herring larvae are identified, and their standard length measured to the millimetre below. (ICES, 2004)

Data treatment

The MIK net-data are stored in a database at DIFRES. MIK net sampling in the southern North Sea and English Channel has traditionally been limited and hence the time series is not so useful for this analysis.

Survey results

There is great inter-annual variability in the abundance and distribution of these late stage larvae (Figure 3.3.1). The post larvae are found west of the Dutch and Belgium coast. The mean length of larvae caught in February also varies with year and ranges from 15 to 20mm (Table 3.3.1).

Table 3.3.1. Mean length per year

Year	Mean (mm)	SD (mm)
1995	16.19	3.46
1996	17.42	2.35
1997	19.33	6.24
1998	18.72	3.23
1999	18.83	3.85
2000	15.19	4.68
2001	18.00	3.42
2002		
2003	20.46	3.31
2004	19.69	3.09
2005	16.74	3.87

Literature

ICES, 2004. Manual for the international bottom trawl surveys, revision VII. *The international Bottom Trawl Survey Working Group.*

Figure 3.3.1. Herring. Abundance of herring larvae per m^2 in the southern North Sea in February, taken from the ICES MIK net surveys.

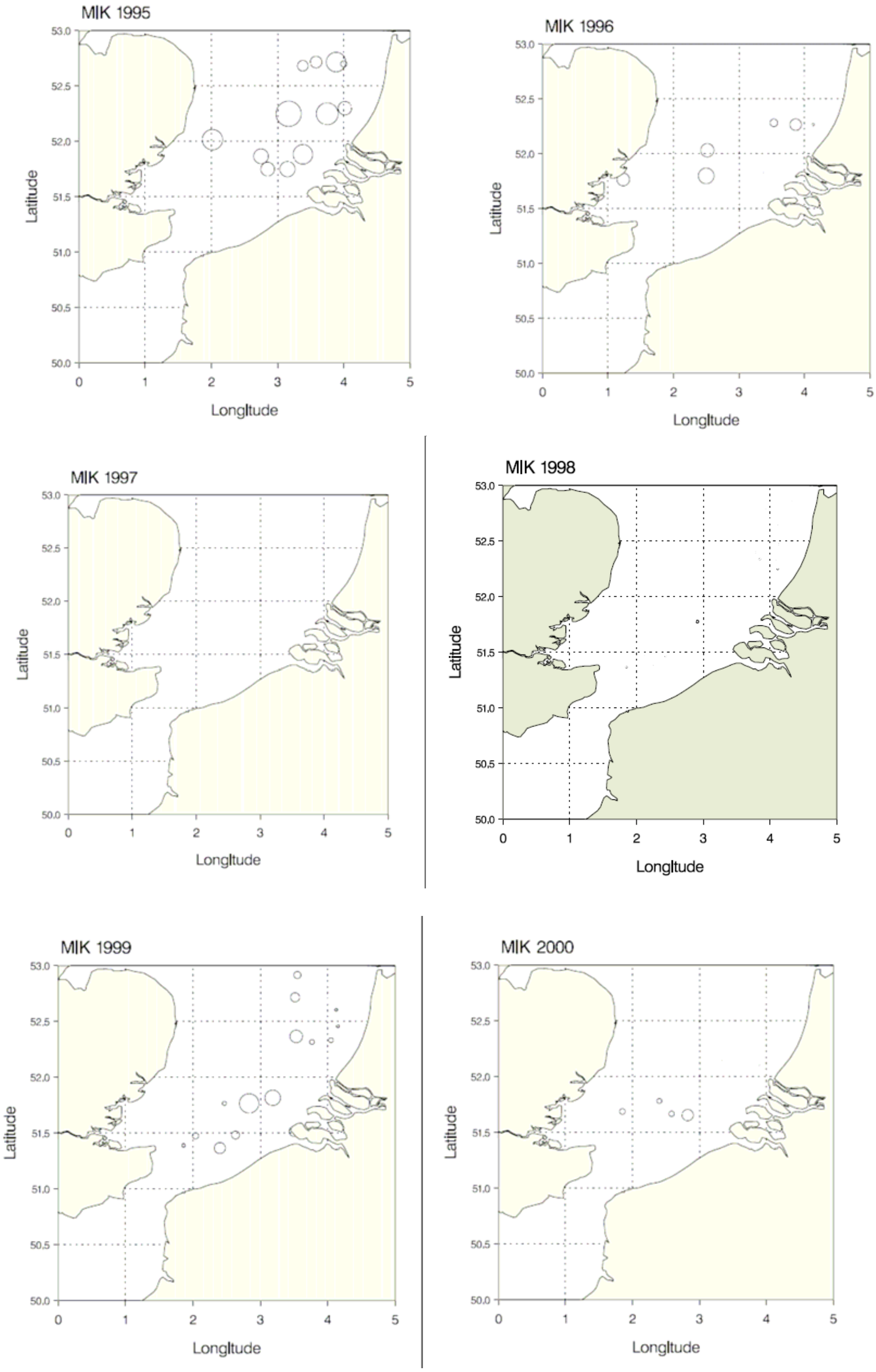
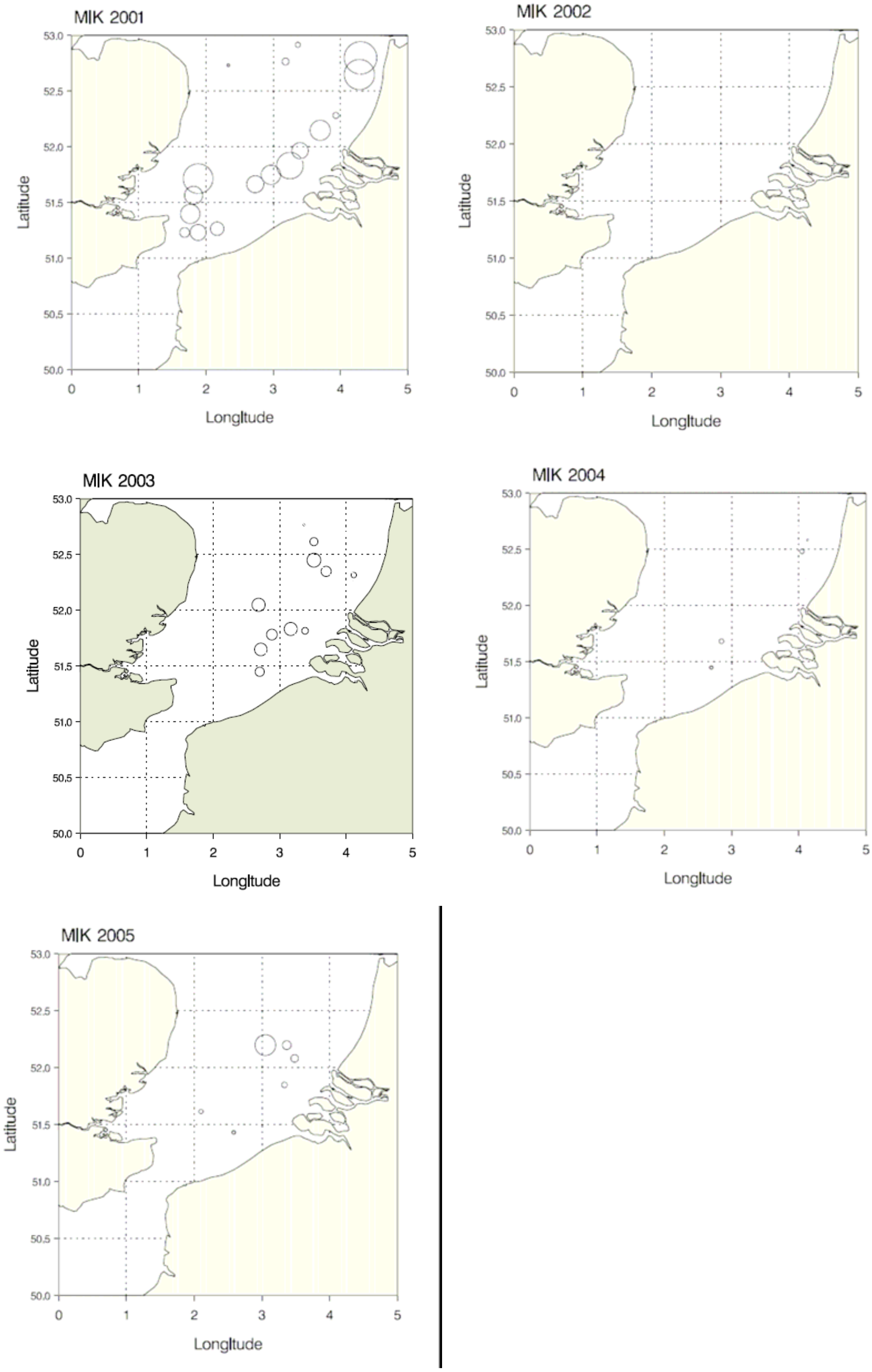


Figure 3.3.1. Herring. conitued



3d Stow net survey Western Wadden Sea

Introduction

The transport and drift from herring larvae from their spawning grounds is towards of the juvenile nursery grounds (Wallace, 1924; Burd, 1978). Post larvae of 3.-5 month old enter the Wadden Sea, which is one of the juvenile nursery grounds for herring.

Data from the SNS Western Wadden Sea survey provides information about quantitative estimates of herring larval abundance in the Western Wadden Sea throughout the season and between years. These data are used to quantify temporal distribution pattern and delivery of herring larvae into the Western Wadden Sea. Distinction is made between two groups of larvae, one originating from spawning grounds in the Central North Sea (Banks herring) and another group originating from spawning grounds in the Southern North Sea and the English Channel (Downs herring).

Materials and methods

Sampling

Each year from 1967 to 1989 in the period February-May several Stow net surveys were carried out in the Western Wadden Sea. Sampling took place at a regular time interval in two of the main inlets to the Western Wadden Sea (figure 3.4.1). The sampling gear consisted of an anchored plankton net with a circular mouth opening of 2 m diameter. In general the netting consisted of a nylon “Monodur” with a mesh size of 1.40 mm. Total length of the net was 14 meter. The volume filtered was measured and the catches of herring larvae were all converted to numbers per 10,000 m^3 water. (Corten & Kamp, 1979).

Data treatment

The results from the surveys have been grouped into half-monthly standard periods, in order to compare changes in abundance throughout the season and between years. Based on the length distribution of the larvae for each particular cruise, distinction was made between larvae originating from the Southern and Central spawning grounds. In order to calculate the mean number of larvae per haul for the entire cruise, first the mean number per haul and its variance were calculated for each individual sampling position. Next, the stratified mean and variance were calculated for the sampling positions combined. (Corten & Kamp, 1979)

For estimation of the temporal distribution of entrance of herring larvae into the Western Wadden Sea, the average period (month) was calculated by applying a weighted-mean procedure and hence weighing period by number. Total delivery of herring larvae into the Western Wadden Sea was calculated for each group and year separately by calculating the area underneath the graphs where total number was plotted against the time. Analysis of variance (ANOVA) was applied by SAS, GLM procedure, in order to test the correlation between number of herring and respectively total delivery and mean entrance period effects (alpha=0.05).

Survey results

Temporal distribution

Time of entrance into the Wadden Sea of southern (Downs) and central (Banks) herring larvae is not similar (figure 1.4.2). Banks larvae enter the Wadden Sea in March. Before 1980 the entry of Banks larvae occurred mainly in the first half of March, after 1980, however, a significant ($p<0.0003$, $\alpha=0.05$) move towards entry into the Wadden Sea in the second half of March was observed (table 3.4.1 and figure 3.4.3). Downs larvae enter the Wadden Sea in the first half of April. A slight, but not significant, shift towards earlier entrance time was found for herring spawning in the South of the North Sea (Downs) (table 3.4.1 and figure 3.4.3).

Delivery

The total number of herring larvae that enter the Wadden Sea differ each year. Larvae originating from the Central North Sea (Banks) show no significant ($p<0.19$, $\alpha = 0.05$) change in delivery amounts over the years (figure 3.4.4). Abundance remained at a constant low level, with one high outlier in 1986. The overall average from 1967 to 1989 was 9380 larvae per 10,000m^3 (table 3.4.2). The total herring population in the North Sea crashed, but from 1980 onwards the population increased again. This is best shown by the number of Downs larvae that enter the Wadden Sea. The total delivery per year changed significantly ($p<0.0001$, $\alpha = 0.05$) after 1980. Before 1980 the average delivery was 5429 larvae per 10,000m^3. From 1980 onwards the abundance of Downs herring larvae in the Wadden Sea has grown rapidly, followed by a more (high) constant level in the late eighties (figure 3.4.4). The average delivery of Downs larvae after 1980 was 39900 larvae per 10,000m^3 (table 3.4.2).

Corten and Kamp (1979) commented that shortcomings in the dataset, caused by irregular survey times especially in the first sampling years, might cause inaccuracies in the estimated larval abundance. They also commented that catches of post-larvae were extremely variable, both between and within sampling stations suggesting very patching distributions of larvae, and/or the entry of post-larvae into the Wadden Sea in waves.

Length

Length was used to divide the Banks from Downs herring, hence there is a difference between Banks and Downs larvae (figure 3.4.5). Downs larvae have most commonly a mean length between 30 and 34 mm, while Banks larvae are between 41 and 43 mm when they enter the Wadden Sea. Note that those data was only available for the period 1967-1978, so before the recovery of the herring stock occurred.

Literature

Corten, A & G. van de Kamp, 1979. Abunadnce of herring larvae in the Dutch Wadden Sea as a possible indication of recruitment strength. *International Council for the Exploration of the Sea (ICES)* C.M. 1979/ H:26 Pelagic Fish Committee

Dickey-Collas, M., 2005. Desk study on the transport of larval herring in the southern North Sea (Downs herring). *Netherlands Institute for Fisheries Research, reportnr.*

Table 3.4.1 Mean period (month) of entrance into the Wadden Sea of herring larvae originating from two spawning area.

	Banks herring larvae		Downs herring larvae	
	Mean	*SD*	Mean	*SD*
Mean period (month) (1967-1989)	3.6	*0.5*	4.2	*0.4*
Mean period (month) before 1980	3.4	*0.5*	4.3	*0.4*
Mean period (month) after 1980	3.7	*0.4*	4.2	*0.4*

Table 3.4.2 Mean delivery of herring larvae of two spawning areas into the Wadden Sea (number per 10,000m^3).

	Banks herring larvae	Downs herring larvae
Mean delivery (1967-1989)	9380.7	45329.7
Mean delivery before 1980	3563.9	5429.3
Mean delivery after 1980	5816.8	39900.4

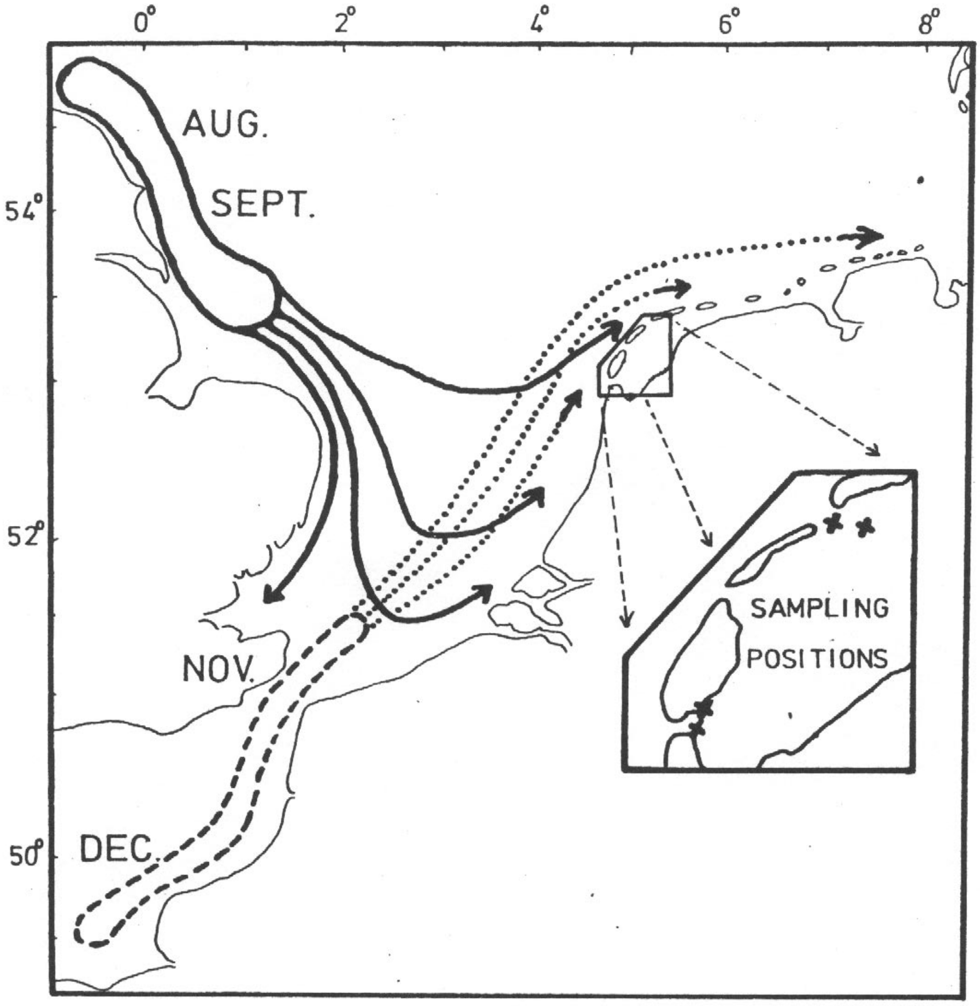


Figure 3.4.1 Overview of sampling stations of Stow Net Survey Western Wadden Sea (1967-1989)

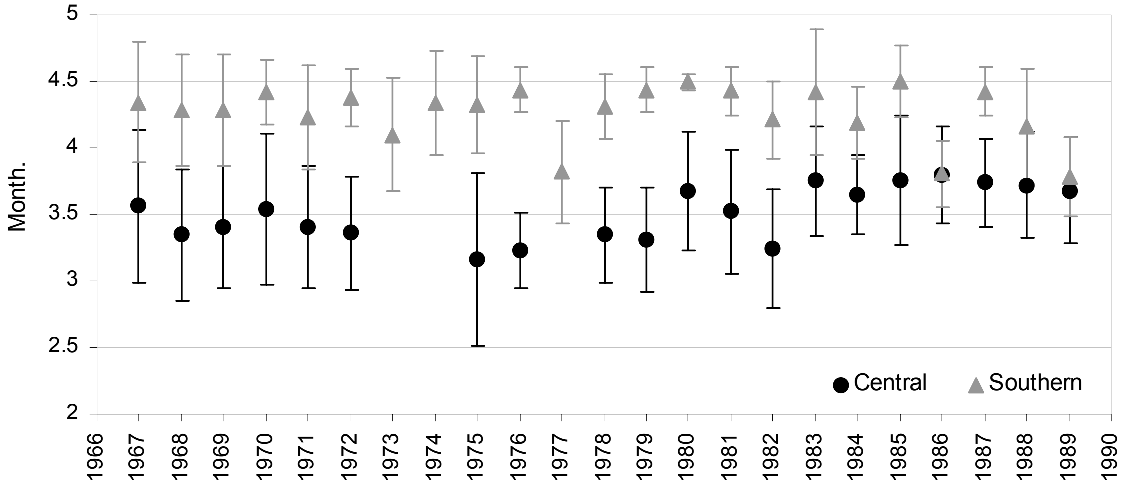


Figure 3.4.2 Temporal distribution of herring larvae (southern/Downs-▲ and central/Banks-●) into the Wadden Sea (1967-1989). Vertical bars display standard deviation (SD).

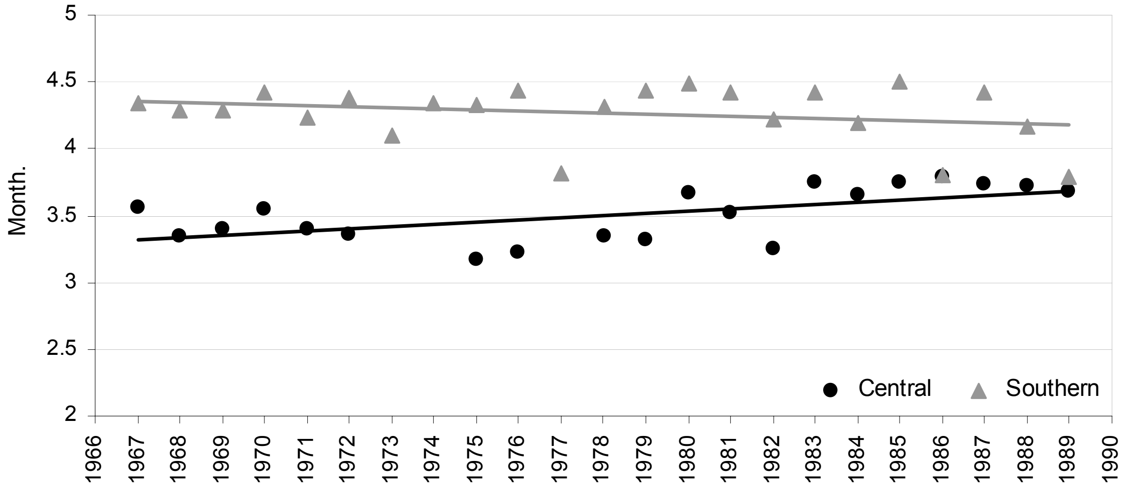


Figure 3.4.3 Trendline of temporal distribution of herring larvae (southern/Downs-▲ and central/Banks-●) into the Wadden Sea (1967-1989).

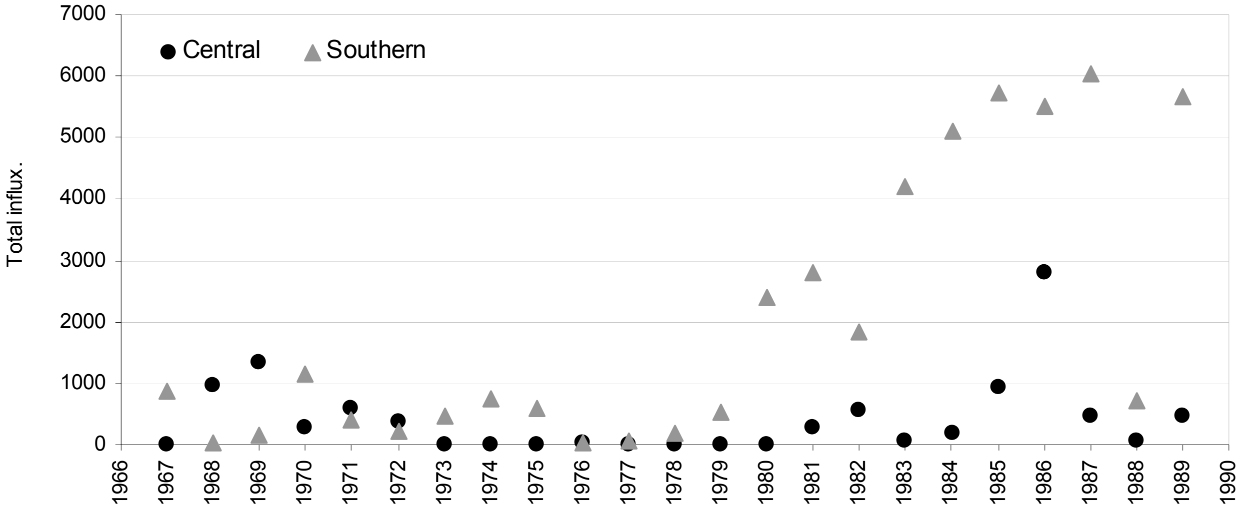


Figure 3.4.4 Total influx of herring larvae (number per 10,000m^3) into the Wadden Sea (southern/Downs-▲ and central/Banks-●) (1967-1989)

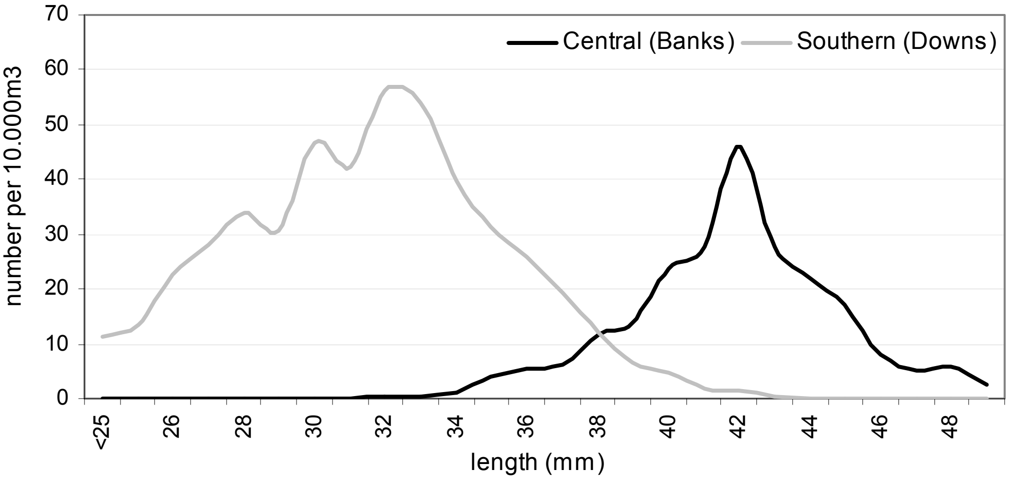


Figure 3.4.5 Length distribution of herring samples. Mean values for all surveys in the year 1967-1978