ICES SCRECVAP Report 2007

Report of the Study Group on Recruitment Variability in North Sea Planktivorous Fish (SGRECVAP)

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Contents

Executive Summary

The ICES Study Group on Recruitment Variability in North Sea planktivorous fish (SGRECVAP) met in early May 2007 to further consider the population dynamics (especially recruitment) of herring, sandeel and Norway pout in the North Sea. SGRECVAP first met in 2006, when worries were expressed about the apparent synchronous serial poor recruitment in those species since 2001. The second meeting of SGRECVAP in 2007 found that the residuals from the stock to recruit curves for Norway pout and herring still expressed similar trends despite the recent better recruitment in Norway pout, whilst there was no trend in the residuals of sandeel. A detectable change in the recruitment of herring and Norway pout in the North Sea was either caused by a reduction in productivity in the early 2000s or by a longer cycle of decline since the 1980s. There was only a biomass signal on the recruitment of sandeel. The productivity of all three stocks is low at present.

The lack of any properly funded research project on the recruitment of planktivorous fish in the North Sea meant that the activities of SGRECVAP were limited to list potential hypotheses, stimulate further investigations and carry out preliminary analysis. Data sets of environmental data were compiled to explore the hypotheses listed by SGRECVAP 2006. Specifically wind, temperature, water density, water colour, flow, copepods, chaetognaths, total zooplankton, nauplii, the ratio of *Calanus finmarchicus* and *Calanus helgolandicus* and the abundance of predatory fish were investigated.

A change in the North Sea environment has occurred at the same time as the poor recruitment in herring and the downward trend in Norway pout. It is likely that the poor recruitment in North Sea herring is a result of poor survival of larvae from the central and northern components of the stock. In the spawning areas of herring and Norway pout (in the central and northern North Sea) the sea temperatures have increased markedly, with a commensurate reduction in water density. The trend in herring recruitment since 1998 is similar to the trend in declining water density at the main herring spawning sites.

The zooplankton time series were investigated for spring, autumn and annual signals. The well known shift from *Calanus finmarchicu*s to *C. helgolandicus* was clearly seen, but process studies are required to determine whether this is important for the productivity of planktivorous fish. Overall from 1950 to the present, only the central North Sea shows large variability in the zooplankton community and the standing stock of chlorophyll. In the northern North Sea only the abundance of *Calanus* sp. copepodites showed a declining trend. However in the central North Sea, the total abundance of copepods, the abundance of adult *Calanus* sp. and *Calanus* copepodites all showed declining trends. The signals in the changes in the zooplankton were similar to those in the recruitment residuals of the fish (i.e. late 1980s and around 2000). Chaetognaths showed a declining trend until the 1980s.

There has been a recent increase in mackerel, horse mackerel, sardine and anchovy in the North Sea. Preliminary investigations suggest that mackerel and horse mackerel are not the cause of the poor recruitment as they do not overlap spatially and temporally with the larvae of herring or Norway pout. Spatial data on anchovy and sardine were not available to SGRECVAP, so this needs further exploration.

Suitable coupled bio-physical models are not currently available for North Sea herring, sandeel and Norway pout. Their development should be encouraged to investigate the mechanisms that determine year class strength and explain the commensurate signals seen in the environmental time series. SGRECVAP could not recommend any indices as predictors for trends in productivity. As the trends in productivity cannot be predicted, and there is no evidence to suggest a change in trend, the assumption that poor recruitment will continue is valid under the precautionary approach. Therefore stock projections should assume that the period of poor recruitment will continue.

1   Introduction

This is the second report of the ICES Study Group on Recruitment Variability in North Sea Planktivorous Fish (SGRECVAP). The first report (ICES, 2006) reviewed and documented the potential hypotheses for the serial poor recruitment in North Sea herring, Norway pout and sandeel (see Annex 1 for summary of SGRECVAP 2006). This 2007 report further investigates the recruitment dynamics of these species and begins the process of investigating hypotheses for the poor recruitment (Terms of Reference are given in Annex 2).

SGRECVAP 2007 was chaired by Mark Dickey-Collas (NL) with the following members Jürgen Alheit (Ger), Tone Falkenhaug (Nor), Alejandro Gallego (Scot, UK), Joachim Gröger (Ger), Emma Hatfield (Scot, UK), Priscilla Licandro (Eng, UK), Marcos Llope (Nor), Peter Munk (Den), Richard Nash (Nor), Mark Payne (Den), Christine Röckmann (NL) and Jörn Schmidt (Ger).

More information on herring, Norway pout, sandeel and the general ecosystem of the North Sea was either missed by SGRECVAP 2006 or has become available to the group since it last met. The updated time series of stock dynamics for the three target species have been lengthened (see chapter 2) and other new information is given below.

1.1   Sandeel banks

Since SGRECVAP met in 2006, additional information has become available on the distribution of spawning and fishing grounds. Sandeel in the North Sea comprises a group of five different species from which the lesser sandeel *Ammodytes marinus* and the small sandeel *Ammodytes tobianus* are the most abundant. The distribution of sandeel is highly patchy, limited by the availability of suitable habitat (Macer, 1966). Sandeel need a sandy sediment to bury, but avoid sediment where the weight fraction of silt/clay and very fine sand exceed 10%. Spawning of sandeel takes mainly place from December to January (Gauld and Hutcheon, 1990; Macer, 1966). As the main fishing on sandeels starts in March, the fishing grounds can be used as a proxy for the spawning grounds. The *ad hoc* group on sandeel presented a map with the fishing grounds derived from fisheries data of *A. marinus* (ICES, 2007c). As this map lacks information on areas where fishing is restricted or forbidden, the map was merged with information on the spawning grounds of the Fisheries Research Services of Scotland (FRS 2005) to fill the gap of information in the coastal areas of the Orkney and Shetland Isles (Figure 1.1.1).

1.2   Regional chlorophyll

The Phytoplankton Colour Index (PCI), which is derived from the greenness of the silk mesh in the CPR samples, is used as a proxy for phytoplankton biomass. Comparison of this visual assessment with SeaWiFS satellite data has shown that the PCI is a good indicator of phytoplankton standing stock (Raitsos *et al.*, 2005). In the North Sea a considerable increase in phytoplankton biomass (i.e. PCI) has been recorded since the mid-1980s in relation to increasing sea surface temperatures (Reid *et al.*, 1998; Edwards, 2000; Edwards *et al.*, 2001; Edwards *et al.*, 2007). In the same area an extension of the seasonal PCI maximum has also been recorded.

In terms of community structure, this regional climate variability has been related to an increase of dinoflagellates and a decrease of diatom abundance in response to warmer sea waters (Leterme *et al.*, 2005). The significant hydroclimatic changes that have occurred since the late 1980s and have continued to the present have resulted in an environment that favours the growth and earlier succession (Edwards and Richardson, 2004) of flagellates and dinoflagellates in the North Sea (Edwards *et al.*, 2006). In the North Sea, dinoflagellates are

positively correlated with the North Atlantic Oscillation (NAO) and SST, whereas diatoms are negatively correlated (Edwards *et al*., 2001).
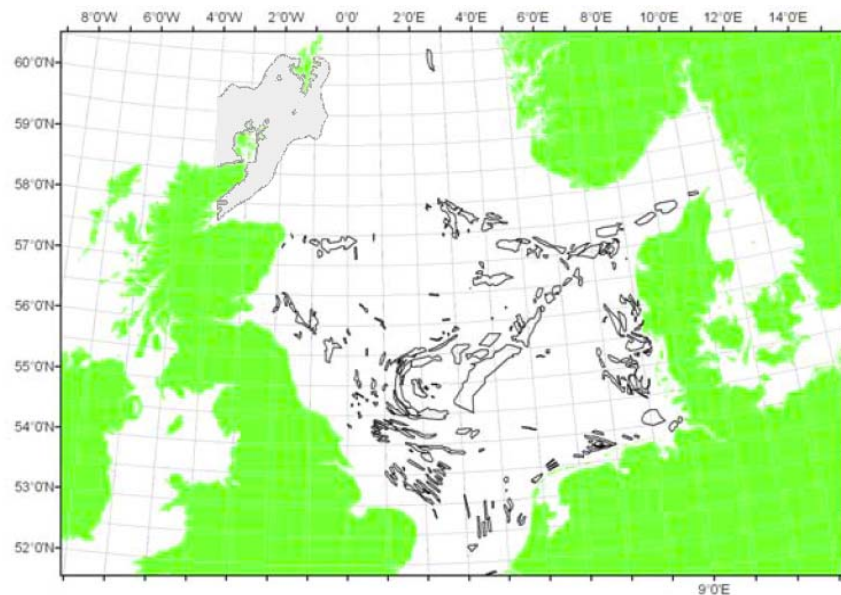

Figure 1.1.1. Fishing grounds of Sandeel in the North Sea (black lines); Spawning grounds of Sandeel in the Shetland/Orkney region (map redrawn from ICES, 2007c and FRS 2005).

1.3   Toxins

SGRECVAP 2007 received a working document from Foekema *et al*. (2007). Importantly it pointed out that the preliminary conclusions of SGRECVAP 2006 on the potential effect of anthropogenically produced toxins were based on ignorance, as acknowledged by SGRECVAP 2006. The effect of toxins can be species specific, and can also be delayed. In other words, toxins in an adult female can be passed into an egg and embryo. The embryo can then apparently develop in a normal manner, but the resulting larvae may die at a later time after hatch. This has been shown in amphibians and fish and mortality caused by toxins can impact at stages as later as metamorphosis. Therefore SGRECVAP cannot rule out the influence of toxins in the pelagic environment on the recruitment of planktivorous fish in the North Sea. However due to the make up of SGRECVAP, and the lack of information and data, further analysis was not possible.

1.4   Parasites

The last SGREVCAP did not consider the possibility of parasites. The incidence of cestode and digenean endoparasites in herring larvae has been noted from many regions around the North Atlantic (see Heath 1992 for a brief review). Heath and Nicoll (1991) found two main endoparasites to be present in the 1987 year class of herring larvae in the North Sea, the cestode *Scolex pleuronectis* (the collective name for larvae of tetraphyllidean cestodes) and the trematode *Hemiurus* spp. The data suggested that *S. pleuronectis* was only acquired beyond the length of 15 mm, and so would be particularly relevant for larvae during the overwintering period.

Rosenthal (1967) reported that laboratory reared larval herring fed *ad libitum* with wild plankton did not show increased mortality as a consequence of *S. pleuronectis* infection at intensities of up to 8 parasites per individual. However, in the field *S. pleuronectis* had a statistically significant impact on the incidence of prey in the intestines of larvae, and hence would be expected to affect growth rate and cumulative mortality (Heath and Nicoll, 1991). Ivanchenko and Grozdilova (1971) reported both growth rate reductions and mortalities among laboratory reared larval White Sea herring infected with trematodes.

The 1987 year class in the North Sea, for which there are existing parasitology data, showed high overwinter survival despite up to 45% prevalence of *S. pleuronectis*. However, the following sequence of three year classes (1988, 1989 and 1990) exhibited very low survival, comparable with that during the most recent recruitment failures, and also arose from high biomass of spawning stock. Hence, if parasite loading is involved in these periods of survival failure, then either a) the prevalence and intensity of infection during the poor survival winters must have been even higher than that measured in winter 1987/88 or, b) the parasite load may have exacerbated an environmental effect on survival such as scarcity of food. In either case, we would expect to find a difference in the pattern of prevalence and intensity of infection between the good and poor survival years.

1.5   Birds

Recent work has suggested that there are detectable links between the production of plankton in the North Sea and breeding success of sea birds via sandeels (Frederiksen *et al.*, 2006). However there are still no studies or time series to use that could allow the impact of birds on sandeel recruitment to be further investigated. There was no bird expertise present at SGRECVAP in 2007.

1.6   North Sea inflow events

Two marked shifts have been recorded in the North Sea since 1980 which have been linked to increased inflow of warm oceanic water into the northern North Sea (Reid *et al.*, 2001b, Holliday and Reid 2001; Reid *et al.*, 2003, Beaugrand, 2004). In 1988/1989 and 1998, higher rates of volume transport were observed in the Rockall Trough hydrographic section leading to an increased flow of oceanic water into the North Sea across a section between Orkney, Shetland and Norway in the winter months (Holliday and Reid 2001). These inflows seem to have caused changes in nutrient ratios and abundance and composition of plankton, benthos and higher trophic levels in the North Sea. In 1989 and 1998 oceanic species not normally found in the North Sea were observed there, suggesting pulses of oceanic water had entered the basin and triggered the subsequent ecosystem change. The inflow events in 1988 were related to North Sea regime shifts (Weijermann *et al.*, 2005) which seem to have changed environmental conditions in the North Sea. An inflow event occurred in the Norwegian Trench during the winter, November to February of 2000–2001 (Svendsen, IMR Bergen, pers com). Reduced herring recruitment has been observed in the post-inflow periods pointing to a potential link between the changed North Sea environment and fish larval survival. It is important to try and distinguish between inflow events and general warming caused reduced surface winter cooling (mild winters).

2   Recruitment signals

2.1 Stock recruitment relationships

2.1.1   Data sources

The most recent data describing the recruitment and spawning stock biomass (SSB) of herring, sandeel and Norway pout were obtained from the relevant ICES working groups. Time series for sandeel (1983–2005) and Norway pout (1983–2006) were obtained from SXSA analyses performed by the 2007 Working Group on the Assessment of Demersal Stocks in the North Sea and Skagerrak (WGNSSK) (ICES, 2007b). In both cases, annualised data at January 1st were obtained from the seasonal results by either summing over the year (fishing and natural mortalities) or by simply taking the first season's results as being representative of that year (weight in catch, weight in stock, stock number, and proportion mature). Annual time series of herring recruitment and SSB for the period 1960–2007 were obtained from the Herring Assessment Working Group (HAWG) (ICES, 2007a). Individuals were assumed to recruit to the fishery in the same year as spawning for sandeel and Norway pout, and in the following year for herring. Information from HAWG and SGREVAP 2006 (ICES, 2006, 2007b) suggests that the poor recruitment in North Sea herring is a result of poor survival of larvae from the central and northern components of the stock.

2.1.2   Stock-Recruitment (SR) relationships

Four well-known stock-recruitment relationships were examined as a data-exploration exercise. The models employed were the Ricker, Beverton-Holt, Segmented Regression (Hockey Stick) and Quadratic Hockey Stick (Figure 2.1.1). A segmented regression model shows a linear increase in R with SSB before reaching a break-point at SSB=β, beyond which the recruitment is independent of SSB. A quadratic hockey stick shows similar behaviour except for the region around the break point where the transition from linear dependence with SSB to constant recruitment is smoothed via the use of a quadratic function. The Beverton-Holt relationship shows a similar form, with recruitment gradually reaching a plateau with increasing biomass, but is based on theoretical considerations of recruitment being influenced by the finite carrying capacity of the environment. The Ricker relationship is the only functional form considered here that shows a reduced recruitment at high biomasses due to high-density effects reducing reproductive success.

These models were fitted to the available SSB and recruitment time-series for each species (subject to the appropriate recruitment lags) using the Fisheries Library in R (FLR) modelling system (Kell *et al.*, 2007). The parameters calculated are shown in Table 2.1. Using the Akaike information criterion (AIC) as a basis for comparing the quality of the fitted models, it can be seen that the "best fit" (lowest AIC) for herring is the segmented regression model, for sandeel it is the Ricker model, and for Norway pout it is Beverton-Holt. Unfortunately there is a different "best-fit" model for each species, potentially complicating the following analysis. However, the segmented-regression model is the second-best fit for both sandeel and Norway pout, and is the best fit when considered over all species (as determined by simply summing the individual AIC criteria). For reasons of consistency and simplicity, the segmented-regression model has been used across all three species; the impact of this simplification was examined briefly and an appreciable difference in the residuals was not readily observed.

The fitted stock-recruitment relationships (Figure 2.1.2), the time series of associated residuals, and the time series of the spawning stock biomass are shown for comparison purposes. Additional data points added to these relationships since the previous SGRECVAP report highlight the recent poor recruitment of herring, and the low stock levels of sandeel and Norway pout.

A clear trend can be seen in the herring residuals that appear to correspond closely with events in the fishery. From an initially productive state and high stock biomass in the early 1960s, the stock collapse in the late 1960s and into the 1970s can be seen in the corresponding sequence of negative residuals. Recovery of the stock in the late 1970s and early 1980s (following the closure of the fishery in 1978) is mirrored in the sequence of strong positive residuals during this period. The strong coupling between the dynamics of the fishery and the recruitment residuals from 1960 to the early 1980s reflects the recruitment overfishing that is the widely accepted explanation for the stock collapse during this period. It is important to note, however, that uncertainties in the stock assessment during this period are high due to uncertainty in the catches; care must thus be taken not to over-interpret these particular residuals.

After the peak in the residuals around 1980, three distinct periods can be identified. From 1980 to 1986 (inclusive) a sequence of high positive residuals is observed as the stock recovered from collapse and the fishing pressure was low. This is followed by a period from 1987 to 2000 of variable residuals distributed about the long-term mean of zero, during which time the fishing pressure was at moderate-to-high levels, in recent times (2001–2006), a sequence of strongly negative residuals has been observed, in spite of reductions in fishing pressure. The apparent decoupling of the residuals from the stock dynamics suggests a mechanism other than recruitment overfishing may be at play for this species.

A trend is also apparent in the Norway pout residuals, and mirrors the herring residuals trend observed in recent times. The residuals in the 1980s and early 1990s are largely positive, but have declined and become negative (with the exception of a single outlier) during the last 10 years. The recent sequence of negative residuals is also reflected in the stock dynamics, which has decreased appreciably during this time.

The residuals in the sandeel stock-recruitment relationship are evenly and randomly distributed around the mean value, and do not appear to reflect any obvious trends in the stock dynamics.

Ricker

$$R = \alpha \cdot SSB \cdot \exp(-\beta \cdot SSB)$$

Beverton-Holt

$$R = \frac{\alpha \cdot SSB}{\beta + SSB}$$

Segmented Regression (Hockey Stick)

$$R = \begin{cases} \alpha \cdot SSB & \text{if } SSB < \beta \\ \alpha \cdot \beta & \text{if } SSB \geq \beta \end{cases}$$

Quadratic Hockey Stick

$$R = \begin{cases} \alpha \cdot SSB & \text{if } SSB < \beta(1-\rho) \\ \alpha \cdot \left(SSB - \dfrac{(SSB - \beta(1-\rho))^2}{4\beta\rho} \right) & \text{if } \beta(1-\rho) \leq SSB \leq \beta(1+\rho) \\ \alpha \cdot \beta & \text{if } \beta(1+\rho) < SSB \end{cases}$$

Figure 2.1.1. Stock Recruitment Relationships. *R* is the number of individuals recruited to the fishery, *SSB* is the spawning stock biomass corresponding to the recruitment, and α, β and ρ are the parameters describing the relationship. Note that these equations are dependent on the units employed and thus the parameters must always be cited with their corresponding units.

Table 2.1. Results of fitting the stock-recruitment relationships for each species. α, β and ρ are given for the case where the spawning-stock biomass (SSB) is given in millions of tonnes (Mt), and the calculated recruitment (R) is given in billions of individuals. The Akaike information criteria (AIC) are also shown. Seg-reg is the segmented-regression model, Bev-Holt is the Beverton-Holt model, and Qhstk is the quadratic hockey stick model. [1] The quadratic hockey stick model for Norway pout gave the best fit when the curved (quadratic) section of the fit was minimised, so as to approach the segmented-regression model.

SPECIES	MODEL	α	β	ρ	AIC
Herring	Seg-reg	91.13	0.4489	-	94.08
	Ricker	120.97	1.0075	-	95.39
	Bev-Holt	56.39	0.3841	-	99.28
	Qhstk	94.10	0.4434	0.578	95.81
Sandeel	Seg-reg	1008.51	0.5334	-	52.49
	Ricker	1440.94	0.9334	-	51.02
	Bev-Holt	2123.31	2.2435	-	54.85
	Qhstk	1157.93	0.5049	0.999	53.82
Norway Pout	Seg-reg	584.91	0.1274	-	53.31
	Ricker	802.47	3.4560	-	53.46
	Bev-Holt	97.41	0.0630	-	52.51
	Qhstk	584.92	0.1274	0.001[1]	55.31
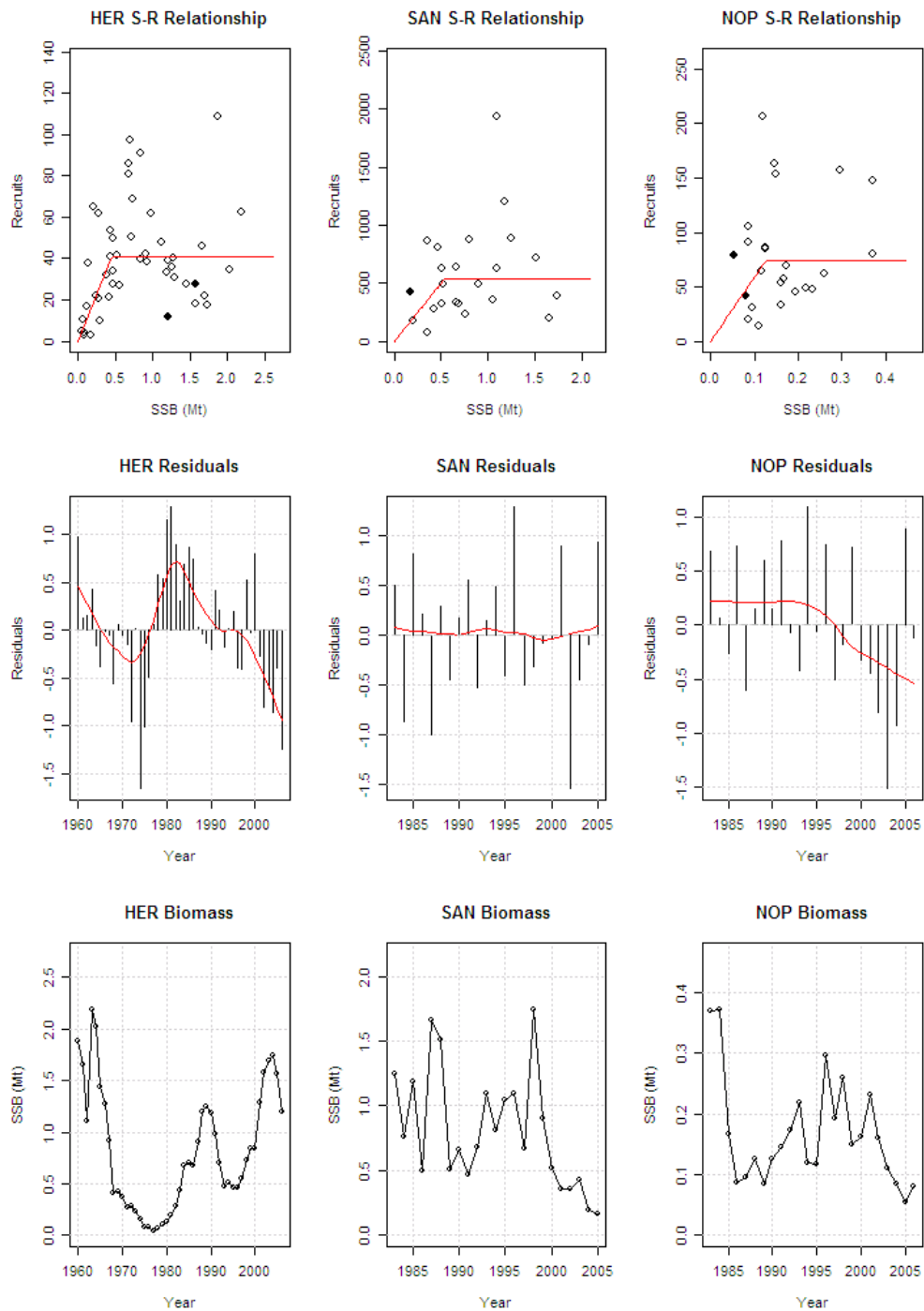
Figure 2.1.2. Herring (HER), sandeel (SAN) and Norway pout (NOP) stock-recruitment (S-R) relationships, biomass time series and recruitment residual time series. The top three graphs show the stock-recruitment data and the fitted segmented-regression models for each species. Data points that have become available since the first SGRECVAP report (two each for herring and Norway pout, one for sandeel) are plotted as filled circles on these graphs. The middle three graphs show the residuals (defined as the natural logarithm of the ratio of observed recruitment to recruitment estimated from the model) calculated from the segmented regression model for each species; a loess smoothing curve (in red) based on a 15 year smoothing window has been added to these plots to guide the eye. The bottom three plots show the spawning stock biomass time series. Years on both the residuals and biomass time series correspond to time at which the SSB is measured (and thus the year-class of the corresponding recruits).

2.2   Productivity of stocks

The North Sea herring stock, the North Sea sandeel stock and the North Sea Norway pout stock are examined for changes in productivity over their time series. The North Sea herring stock has been and well documented over a long time period in terms of its exploitation and related collapses and recoveries (Cushing and Bridger, 1966; Burd, 1985; Nichols, 2001; Simmonds, 2005). The main impact on its productivity was generally thought to be fishing, although the environment may also have had a major impact as well. Each habitat or ecosystem is thought to have a carrying capacity which varies in time (Jennings *et al.*, 2002). To account for the influence of the ecosystem on the productivity of the stocks two different methods were applied, extending the work of Dickey-Collas and Nash (2005) and Nash and Dickey-Collas (2005).

The data used in this analysis were derived from the assessment outputs from the HAWG in 2007 (2.1.1) for herring and from SXSA outputs from the WGNSSK (2.1.1) for Sandeel and Norway pout. The time series for herring was from 1960 onwards whereas for Sandeel and Norway pout the dataset started in 1983.

Recruit per spawner. First the recruit per spawner ratio was calculated. High ratios were assumed to represent a high production and low ratios a low production vice verse. These calculations formed the basis for the detection of periods of high and low production of the stock. Whilst this method is useful to compare the productivity between different stocks it assumes a linear relationship between stock and recruit.

Potential Production. Net and surplus production of the whole stock, including the recruits, the growth of all non-recruits, the natural and the fishing mortality, were calculated. To remove the influence of the fishery and its interaction through the spawning stock biomass, a stock recruit relationship was fitted and the year effect on recruitment retained. The hockey stick relationship was chosen to illustrate the assumption of minimal dependence of recruitment on SSB. The parameter values used to fit the models to data for the different species are given in Table 2.1. The residuals or deviations from the fitted S/R relationships were used to define the year effect for recruitment under the assumptions of the differing models. A constant exploitation pattern was generated based on an average selection over the last 10 years and a mean F that could be set at any level. For any chosen fishing mortality two new time series of recruitments were generated from: the initial starting stock for each of the three species, the recruitment deviations and the S/R relationships based on simulated SSB. The generated populations then represented potential production under different exploitation regimes. The stock size, net production and surplus production could be obtained without the effect of the SSB that was dependent on the original fishery.

Calculation of the surplus production Ps

Ps = Br + Bg - M

where Br is the biomass of the recruits, Bg the gain of biomass due to growth of all fish excluding the recruits, and M the removal du to natural mortality. The net production equals the surplus production minus the biomass due to fishing with the headline F and fixed selection pattern.

To investigate the influence of different headline F, all time series were used with F set between 0.5 and 1.5 (Figure 2.2.1 c).

All species showed variable production over time (Figure 2.2.1) that can be seen both in the recruit per spawner as well as in the net and surplus production estimates. In the North Sea herring the productivity increased markedly after the collapse in the late 1970s, supporting the recovery of the stock. In the middle of the 1980s the productivity fell to the level before the collapse and even decreased further during the last three years (Figure 2.2.1). It can be

assumed, that fishing must be reduced on this stock and to return to higher catches the productivity must increase again.

The sandeel stock showed high variability throughout the time series. However it had highest productivity in 1997 and 2002 both followed by a sharp decrease in the following year. In the most recent years there is again an increasing trend in productivity (Figure 2.2.1).

The Norway pout stock had a stable productivity in the first part of the time series with increasing productivity in the middle of the 1990s. However, also the variability increased. In 2001 the productivity felt to a historic low level and remained low until present (Figure 2.2.1).
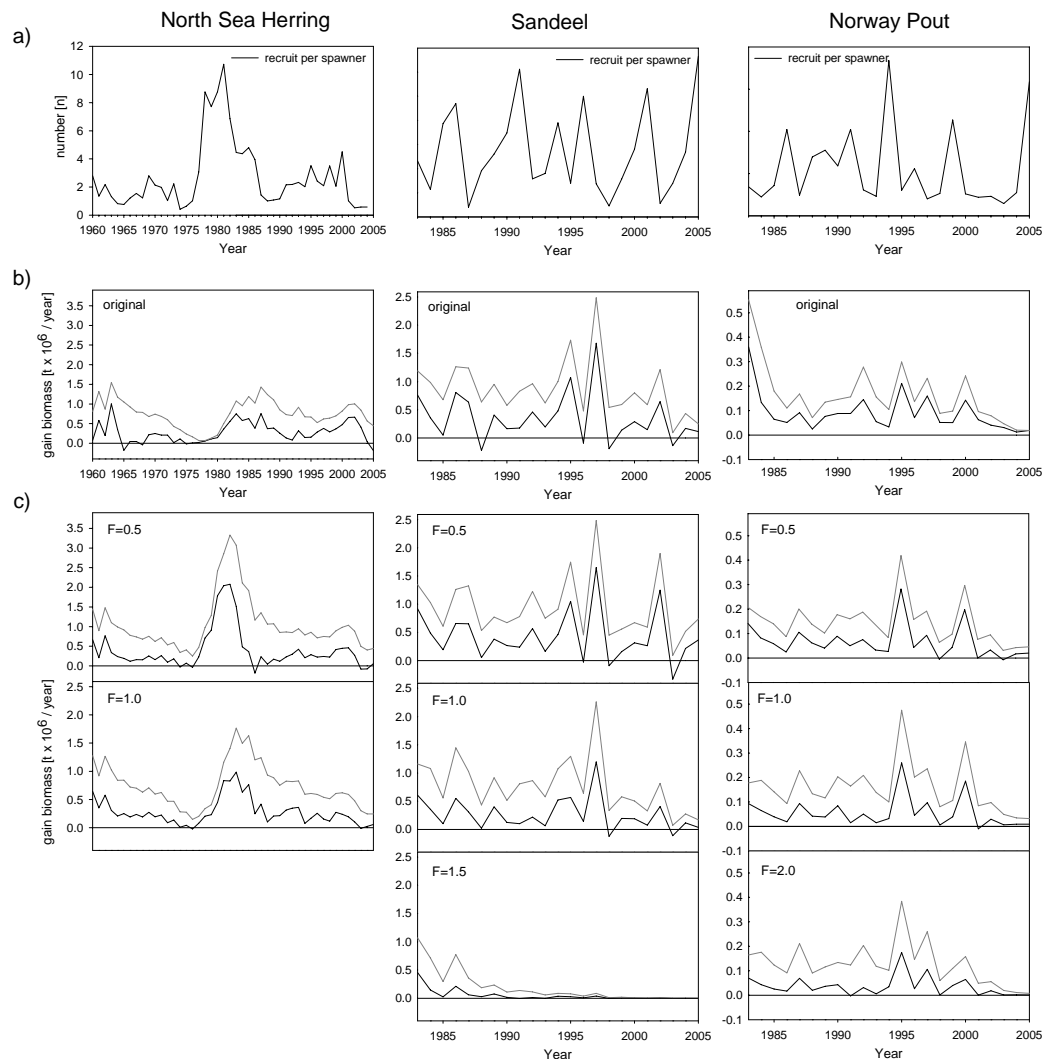
Figure 2.2.1. Productivity comparison of North Sea Herring, Sandeel and Norway Pout. a) The recruit per spawner ratio; b) the net and surplus production of the original data output of ICA final run 2006 for herring, SXSA output for sandeel and Norway pout and c) the hockey stick stock recruitment relationship adjusted to calculate the residuals of the recruits of each year used as a weighing factor for the calculation of the net and surplus production assuming different F; for North Sea herring the F of 1.5 was left out because it leaves no fish in the stock.

2.3   Traffic light approach

Analysis of the herring recruitment, Multiplicative Larvae Abundance Index (MLAI), Methot Isaacs-Kidd (MIK) and SSB time series using a traffic light plot (Figure 2.3.1) supports the notion of changes in the relationship between the recruitment indices and the SSB indices.

This supports the early studies using Paulik diagrams (Nash and Dickey-Collas, 2005; ICES, 2006). There is a clear change around the years 1988 and 2000; a rapid reversal is observed from a high-recruitment – low-biomass state to a low-recruitment – high-biomass state. The presence of a general negative correlation between the recruitment and biomass quintiles (20th percentiles) suggests the possible influence of density dependent phenomena in the system, but this was not analysed further by SGRECVAP, however, see working documents and the report of the ICES workshop on limit reference points (ICES, 2007d). Note that the time series shown is missing the 2006 data, with mean biomass and very low recruitment and does not show the 1 year lag between SSB and year class.

Year	R_ICAq	MIKq	MLAIq	SSBq
1977	20	20	20	20
1978	20	20	20	20
1979	20	40	20	20
1980	20	40	20	20
1981	40	60	20	20
1982	80	40	20	20
1983	80	60	40	40
1984	80	80	40	40
1985	100	80	60	40
1986	100	100	40	40
1987	100	80	40	60
1988	60	20	80	80
1989	40	20	80	80
1990	40	20	100	80
1991	40	100	60	80
1992	80	100	40	40
1993	60	40	40	40
1994	40	60	20	40
1995	60	40	20	40
1996	60	80	40	40
1997	40	20	40	40
1998	40	100	60	60
1999	80	60	40	60
2000	60	100	40	60
2001	100	80	80	100
2002	40	20	80	100
2003	20	20	100	100
2004	20	20	100	100
2005	20	40	100	100

Figure 2.3.1. Traffic light plot of the normally distributed 20th percentiles (i.e. quintiles) of the herring recruitment from ICA (R_ICAq), MLAI from IHLS (MLAIq), MIK from IBTS (MIKq) and SSB estimated from ICA (SSBq) from 1977 to 2005. The numbers in the cells display the quintiles in which the data for that year lies. The cells are coloured according to the quintile, from blue for 0–20% through green (20–40%), yellow (40–60%), and orange (60–80%) to red (80–100%). The dashed vertical line separates the two recruitment indices (R, MIK) on the left from the two spawning stock indices (MLAI, SSB). Note lag of 1 year between SSB and recruitment not accounted for.

3 Time series

3.1 Environmental variables

3.1.1 Data sources

SGRECVAP considered that it was important to investigate the existence of long-term trends in the environment that could be related to the trends in the planktivorous fish recruitment. To do this we examined several environmental variables and described their long-term trends. We used mainly two periods of the year (spring and autumn) and three areas (western, central and southern North Sea (see Figure 3.1.1 for the areas studied). These were chosen to broadly examine the herring and Norway pout spawning grounds and times, as no trend could be found in the sandeel stock to recruit residuals.

SST (Sea Surface Temperature): Reanalysis data from the HadISST (Global sea Ice Coverage and Sea Surface Temperature data) model developed by the British Atmospheric Data Centre, (BADC, http://badc.nerc.ac.uk/home/), Oxfordshire, UK.

Bottom Temperature, salinity and density: taken from the ICES oceanographic data base (www.ices.dk/ocean).

Wind Speed: Reanalysis data from the NCEP/NCAR Reanalysis Monthly Means (http://www.cdc.noaa.gov/cdc/data.ncep.reanalysis.derived.surface.html) developed by the Earth System Research Laboratory (Physical Sciences Division), NOAA, USA.

PCI (Phytoplankton Colour Index): winCPR (Continuous Plankton Recorder, http://www.network-research-group.org/wincpr/) run by the Sir Alister Hardy Foundation for Ocean Science (SAHFOS, http://www.sahfos.org/), Plymouth, UK.

Oceanic Inflow: NORWECOM (The NORWegian ECOlogical Model system), http://www.imr.no/~morten/norwecom, developed by Morten D. Skogen, Institute of Marine Research (IMR, http://www.imr.no), Bergen, Norway.

3.1.2 Long-term trend analysis

The trend characterization was done using Generalized Additive Models (GAMs, *Hastie and Tibshirani*, 1990; *Wood*, 2000) so that the trend is free to vary from the typical linear form to several degrees of non-linearity. This allows discrimination between linear and any other types of trends.

3.1.3 Long-term trends observed

SST: The long-term evolution of the autumn (Sep-Oct) and spring (Mar-Jun) SSTs for the western, central and southern North Sea (Figure 3.1.1 and 3.1.2). The first period corresponds with time of spawning of herring autumn spawners and the area covers the western and southern herring spawning areas as well as the area were the larvae are drifted after hatching.

Two different time periods are clearly distinguishable at the three areas and for the two seasons, before and after the late 80s. Before the late eighties, temperatures did not vary much from 1960 to the eighties and at some places it even showed a slightly decreasing trend. However, after the late eighties there has been a continuous increase.

Bottom temperature, salinity and density: These data show the pattern for the months Sep-Oct. The pattern shown by surface temperature is visible again in bottom temperature at Orkney and Buchan areas (Figure 3.1.3). The dynamics at Banks seem to be different as this warming period after the eighties is no longer evident. Note these empirical data compare well to the modelled SST data.

The temperature changes in the Orkney and Buchan areas apparently led to declining trends in water density, of which the trend in Orkney is significant ($p<0.05$). On the contrary only the Banks area showed significant salinity variation during the period. These patterns suggest that hydrographic changes differ between Orkney/Buchan and the Banks areas.

Wind speed: Wind speed (Figure 3.1.4) seems not to have significantly changed over the time period, only the central and southern areas showed significant patterns in autumn with a general increase around 1980.

PCI: Phytoplankton colour index, a proxy for chlorophyll (Figure 3.1.5), shows increasing trend northwards. The spring trend for the central North Sea resembles the temperature pattern.

Oceanic Inflow: An increase in the Atlantic inflow in the North Sea has been suggested as responsible for the late 80s regime shift. This is visible in the NORWECOM model flows both in the Orkney-Shetland transect and the Feie-Shetland eastern transect as an outflow (Figure 3.1.7). Although another important inflow event has been reported for the year 2000 it is not identifiable with this database (see Section 1.6, Weijermann *et al*., 2005). However, as the NORWECOM model is based on the atmospheric variability, it probably could not detect some changes in the shelf edge current (Reid *et al*., 2001b).
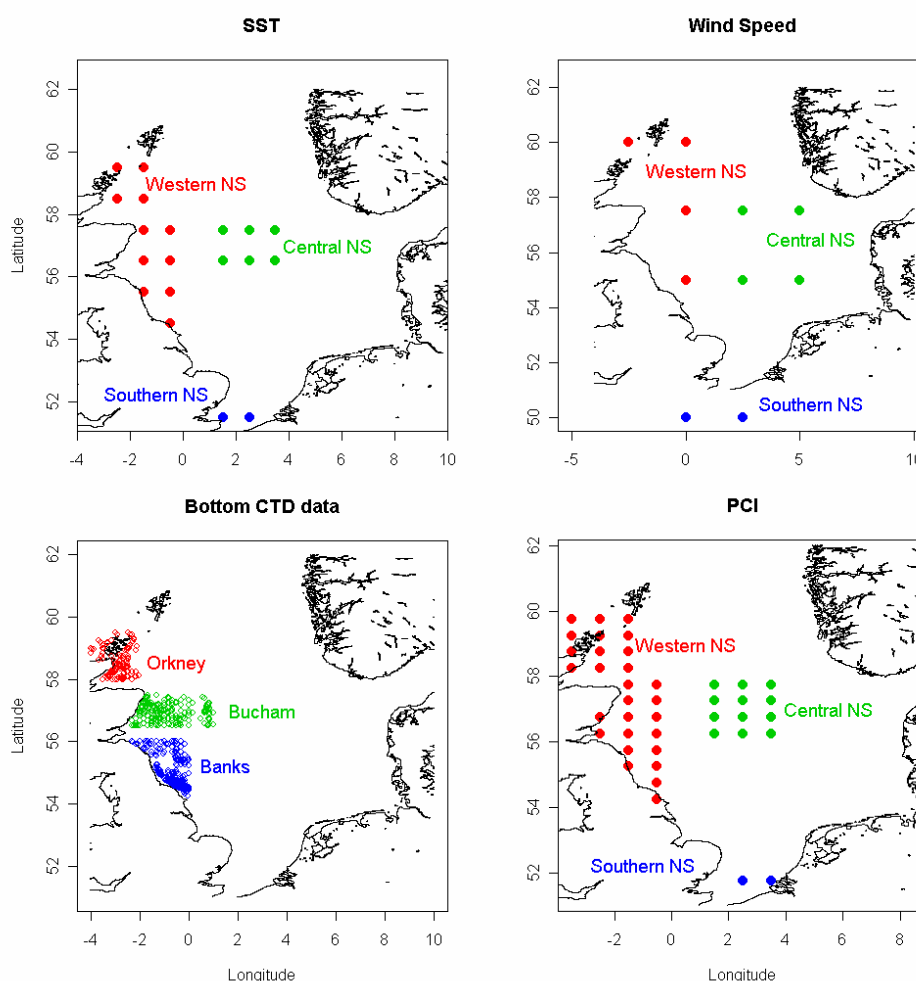

Figure 3.1.1. Location of the stations averaged for the 3 areas: eastern, central and southern North Sea in the case of SST, wind speed and PCI and the three regions from which CTD data were extracted: Orkney Islands, Buchan and Banks.
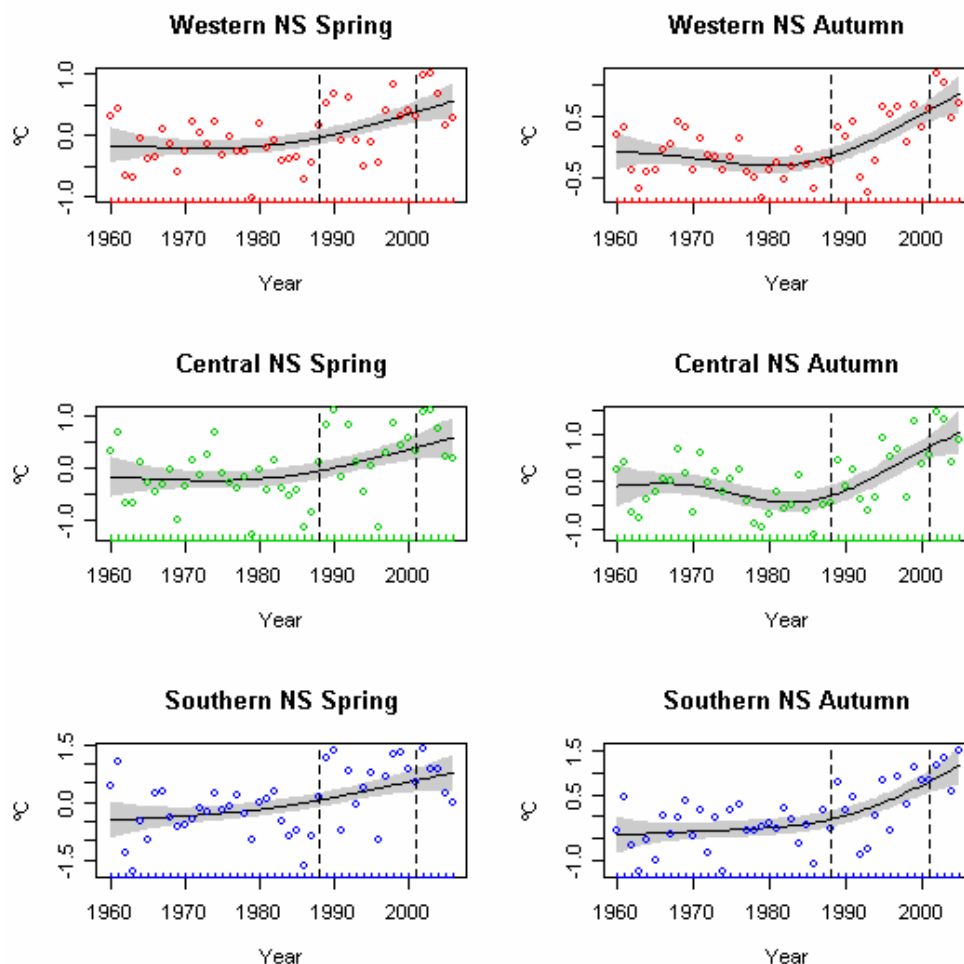
Figure 3.1.2. 1960–2006 SST trends for the eastern, central and southern North Sea (spring/autumn, left/right respectively). The grey shades are confidence bands (± 2 SE) around the mean prediction. All the trend smoothers were significant (p-value < 0.05).The vertical dashed lines correspond to the years 1988 and 2001.
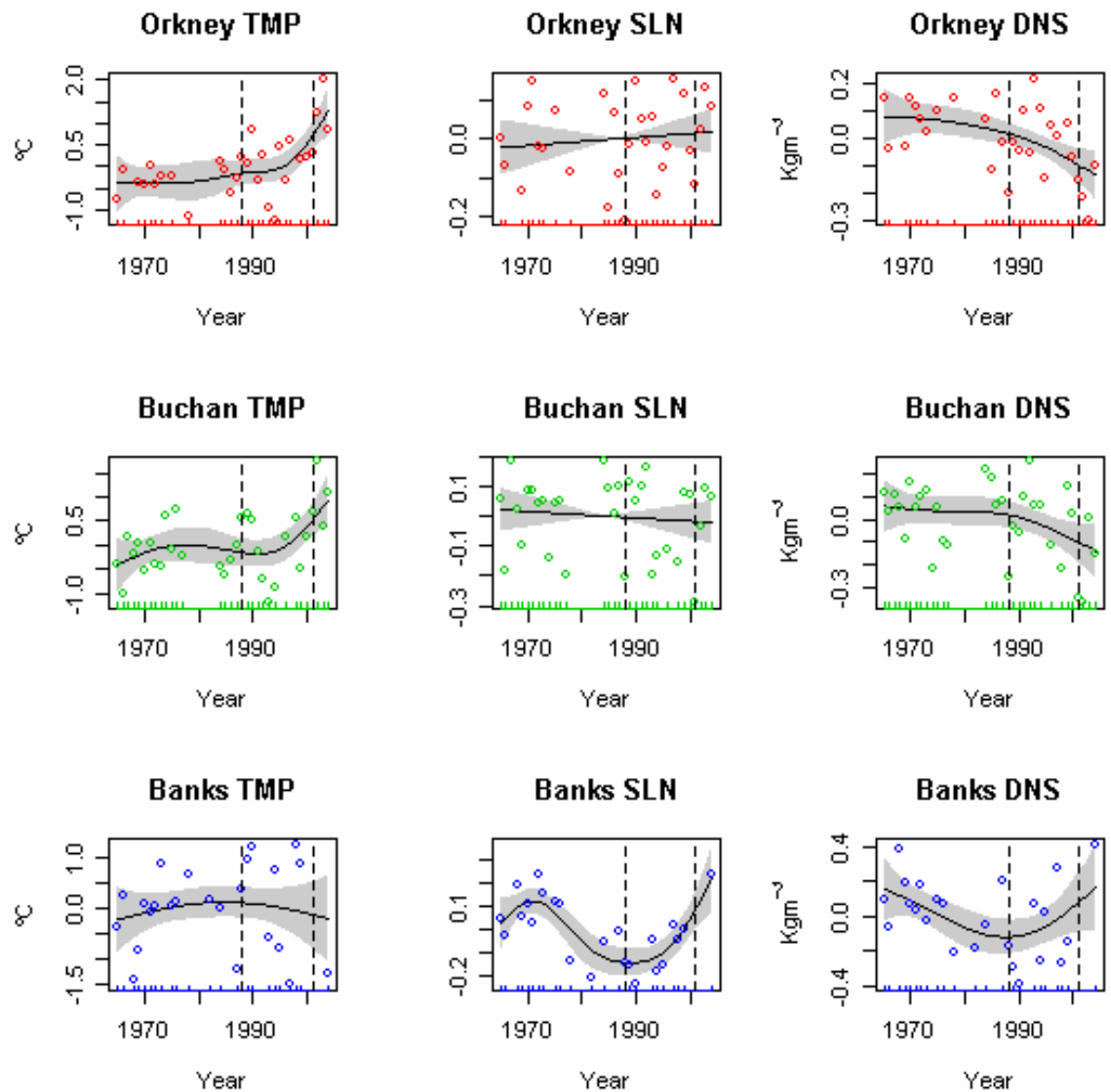
Figure 3.1.3. 1965–2004 trends of bottom temperature, salinity and density for the Orkney, Buchan and Banks areas during Sept-Oct. The grey shades are confidence bands (± 2 SE) around the mean prediction. Only Orkney TMP & DNS, Buchan TMP and Banks SLN trend smoothers were significant (p-value < 0.05).The vertical dashed lines correspond to the years 1988 and 2001.

Figure 3.1.4. 1960–2006 Wind speed trends for the eastern, central and southern North Sea (spring and autumn). The grey shades are confidence bands (± 2 SE) around the mean prediction. Only Southern and Central NS Autumn trend smoothers were significant (p-value < 0.05).The vertical dashed lines correspond to the years 1988 and 2001.
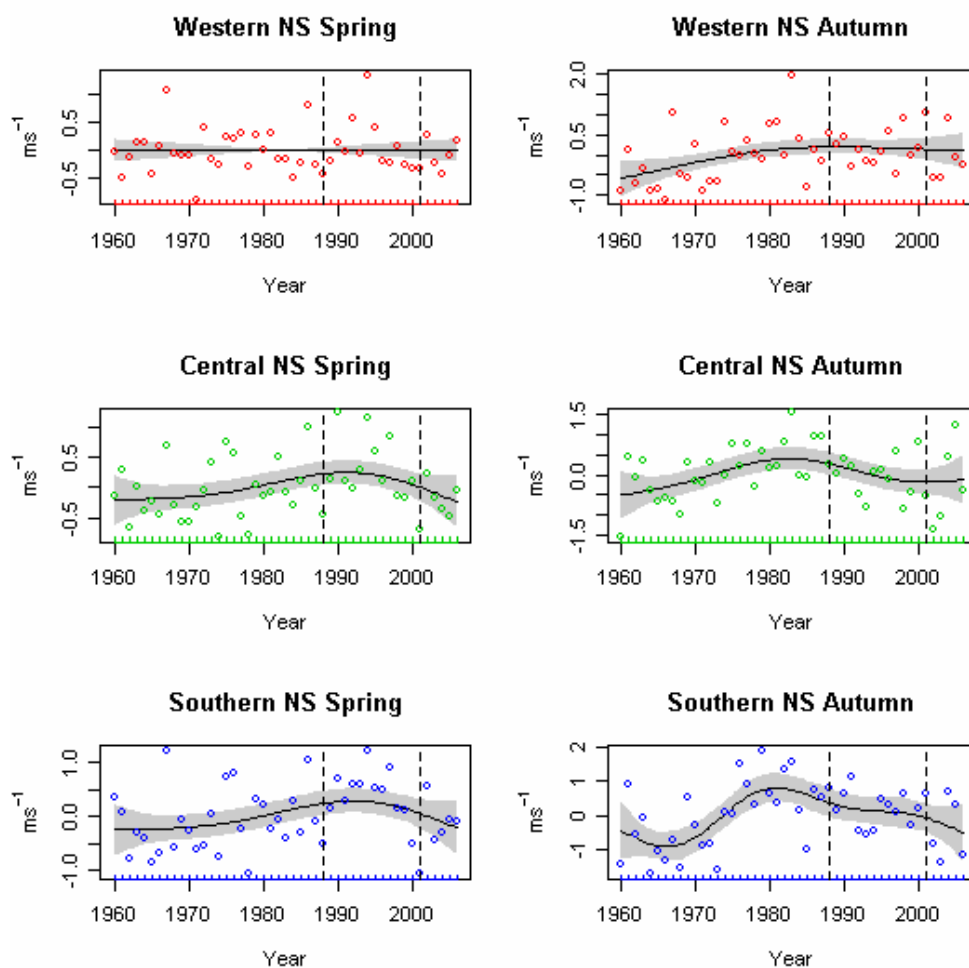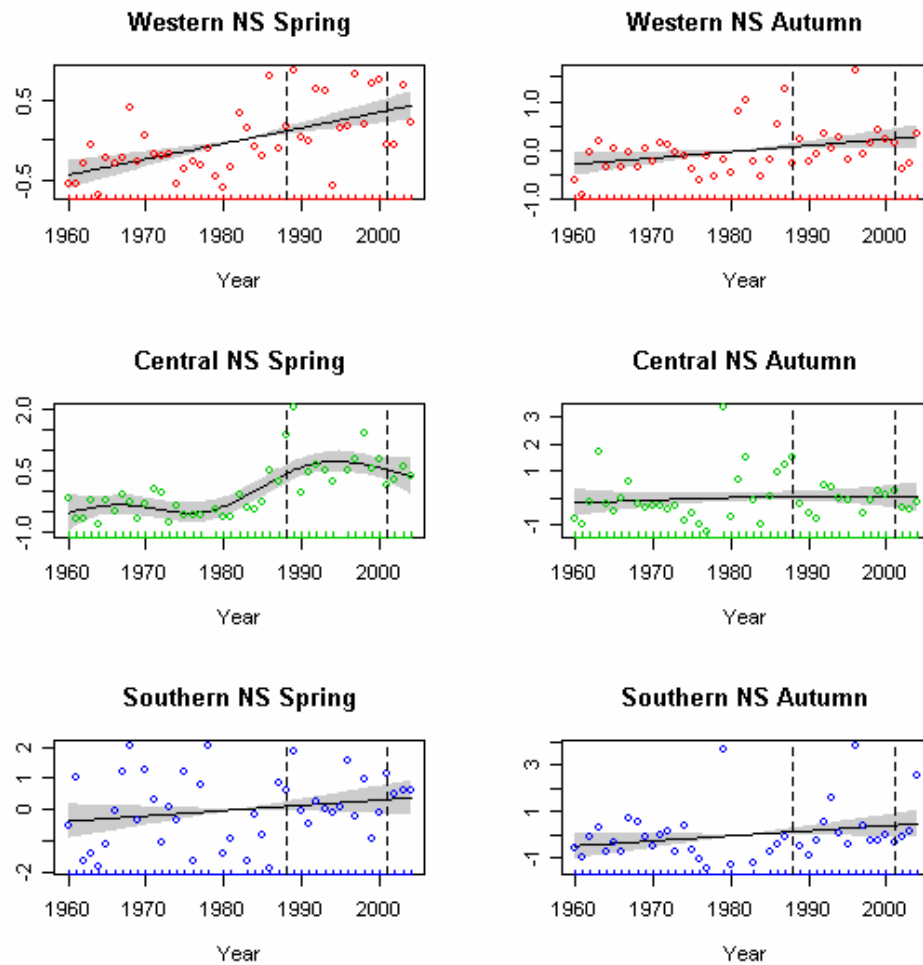
Figure 3.1.5. 1960–2006 PCI trends for the eastern, central and southern North Sea (spring and autumn). The grey shades are confidence bands (± 2 SE) around the mean prediction. Only western (spring and autumn) and Central NS spring trend smoothers were significant (p-value < 0.05).The vertical dashed lines correspond to the years 1988 and 2001.

Figure 3.1.6. Location of the transects across which the inflow/outflow of Atlantic waters was estimated.

Figure 3.1.7. 1960–2004 winter Inflow/Outflow of Atlantic waters in the North Sea (January-April). Positive values mean inflow while negative values mean outflow. Only the Orkney-Shetland trnsect shows significant long-term trends. The vertical dashed lines correspond to the years 1988 and 2001.

3.2   Zooplankton time series
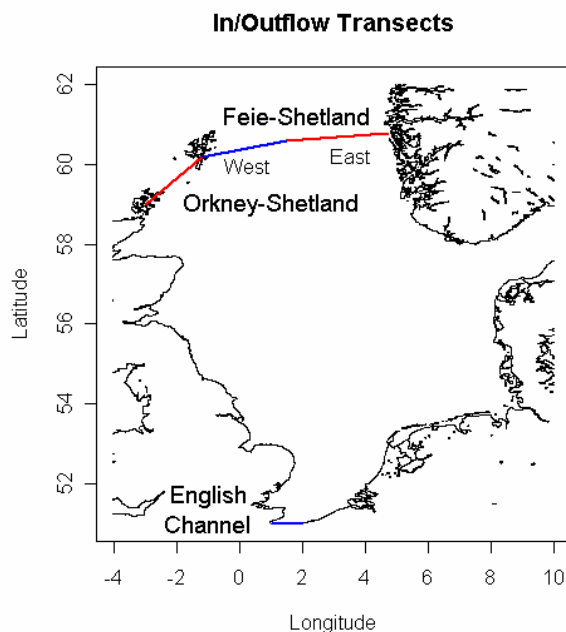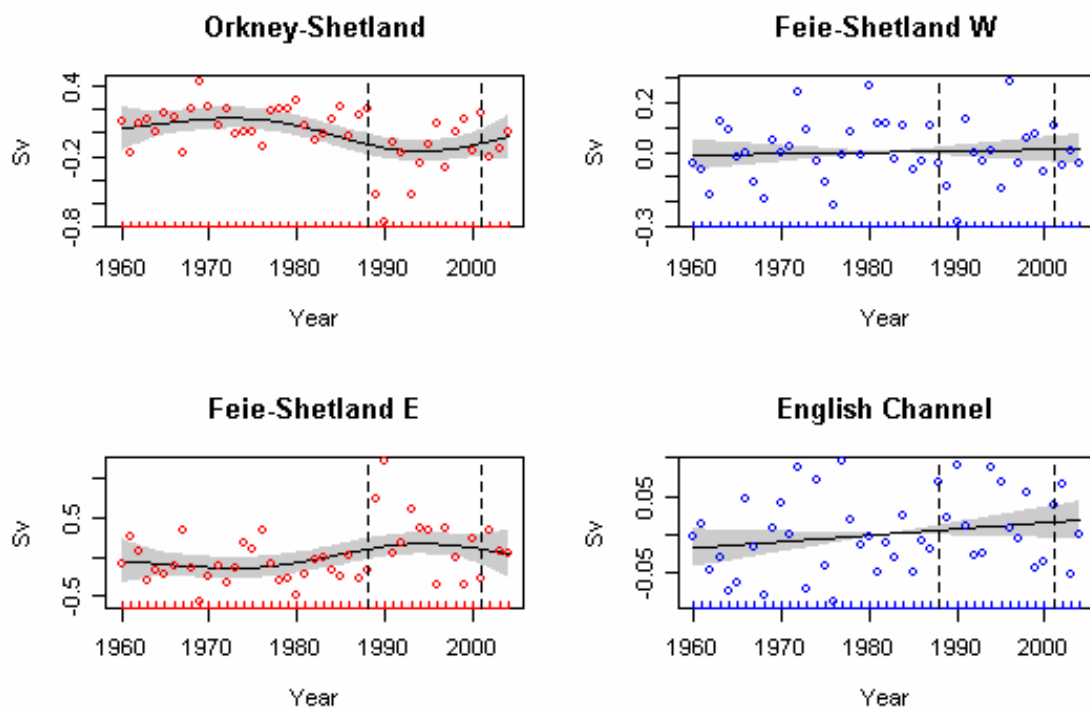
3.2.1   Data sources:

Zooplankton was collected by the Continuous Plankton Recorder (CPR), run by the Sir Alister Hardy Foundation for Ocean Science (SAHFOS, http://www.sahfos.org/), Plymouth, UK.

Long-term trends in the zooplankton were analyzed for two periods in three different regions of the North Sea. The two periods, spring (March-June) and autumn (September-October), corresponds to the periods of spawning and larval feeding. The three regions similar to the CPR regions of northern, central and southern North Sea correspond to the latitudinal extent of the three herring spawning grounds (Orkney, Buchan and Bank, Figure 3.1.1).

The following components in the zooplankton were chosen for analysis:

Total copepods

Total zooplankton, including meroplankton

Chaetognaths: A potential predator on pelagic fish eggs and larvae and also a competitor with fish larvae on the same food. Other gelatinous invertebrate predators/competitors, such as ctenophores and cnidarians (medusae) may be significant, but are not quantitatively sampled by the CPR.

Ratio of *C. finmarchicus/Calanus* spp: Since the two dominant Calanus species in the North Sea are *C. finmarchicus* and *C. helgolandicus*, this ratio will illustrate the relative abundance of the two species.

Calanus **sp I-IV in April-July** as a proxy for the abundance of nauplii in May-June. Copepod nauplii are considered as important prey for fish larvae, however nauplii are not sampled quantitatively by the CPR.

3.2.2   Observed long-term trends

Some quantitative changes have occurred in the zooplankton composition since 1948. Although changes can be seen throughout the three regions, the changes are greatest in the central region.

Total copepods have significantly decreased in the central North Sea (Figure 3.2.2, upper panels) both in spring and autumn. *Calanus* sp, which are the dominant species of copepods mainly in spring-summer, show a similar decreasing trend in spring and so do their early stages (CI to CIV). This general decreasing trend is not clear in the northern and southern regions (Figure 3.2.1 and Figure 3.2.3 respectively).

On the other hand, total zooplankton abundance shows the opposite pattern with a slight increasing trend mainly driven by a rise at the end of the series (Figures 3.2.2 and 3.2.3). This apparent inconsistency is explained by an increase in the meroplankton component, which although important in terms of numbers of individuals doesn't seem to have an important effect on biomass (Licandro, SAHFOS, com. per.).

An interesting trend is shown by the abundance of chaetognaths for the whole North Sea. These well known predators have significantly decreased since the beginning of the record and are now increasing again. Their importance in autumn is clearly demonstrated. Chaetognaths may act as both predators on and competitors with fish larvae.

Regarding food quality, the percentage of *Calanus finmarchicus* (assuming that this species may be considered high-quality food for fish) in relation to *Calanus helgolan*dicus (lower quality) shows a step-wise decrease in the late eighties. This shift is the direct consequence of the northward displacement of *C. finmarchicus* due to the increase in temperature (Planque and Fromentin, 1996; Edwards *et al*., 2006) and the subsequent increase in *C. helgolandicus*, of more meridional preferences (Figure 3.2.4).

C. helgolandicus usually occurs at lower maximum densities than *C. finmarchicus*, and the population reaches its maximum abundance later in the season. A decrease in *C. finmarchicus* will thus not only change the food quality, but also delay the timing of occurrence of prey (nauplii) in spring. This explains why the observed decrease in *Calanus sp.* is most pronounced in spring (Figure 3.2.2). This phenological effect needs further investigation as the shift in ratio between the two Calanus species may affect both food quality and match/mismatch of prey and predator.

Northern North Sea

Figure 3.2.1. Indices of zooplankton in the northern North Sea. Time series of CPR catches from spring (usually March to June, from April to July for *Calanus* I-IV) and autumn (September to October) from 1948 to 2004. Fitted line is a second order polynomial fit, with an r^2 indicator (denoted by * if significant).
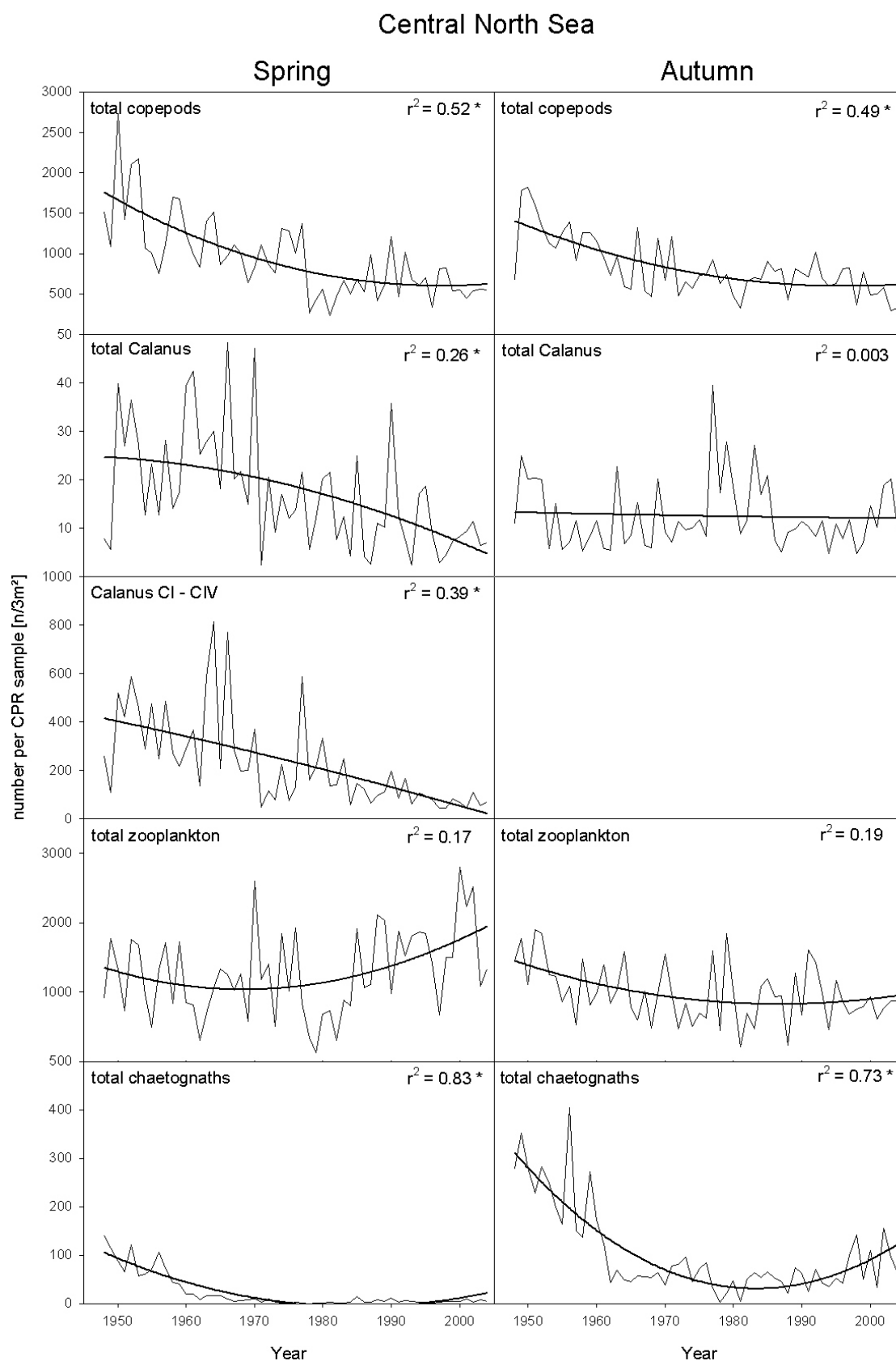
Central North Sea

Figure 3.2.2. Indices of zooplankton in the central North Sea. Time series of CPR catches from spring (usually March to June, from April to July for *Calanus* I-IV) and autumn (September to October) from 1948 to 2004. Fitted line is a second order polynomial fit, with an r^2 indicator (denoted by * if significant).
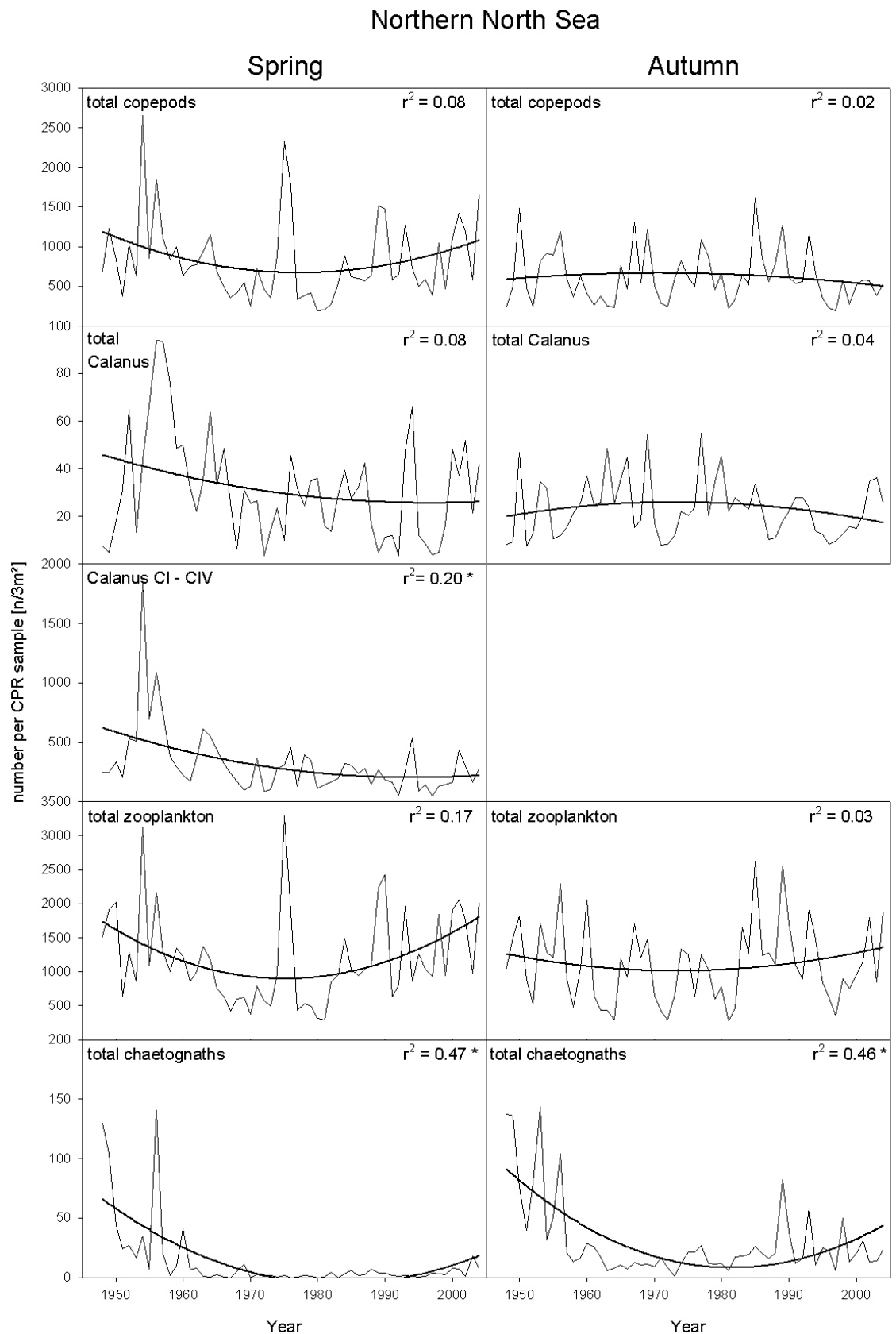
Figure 3.2.3. Indices of zooplankton in the southern North Sea. Time series of CPR catches from spring (usually March to June, from April to July for *Calanus* I-IV) and autumn (September to October)) from 1948 to 2004. Fitted line is a second order polynomial fit, with an r^2 indicator (denoted by * if significant).
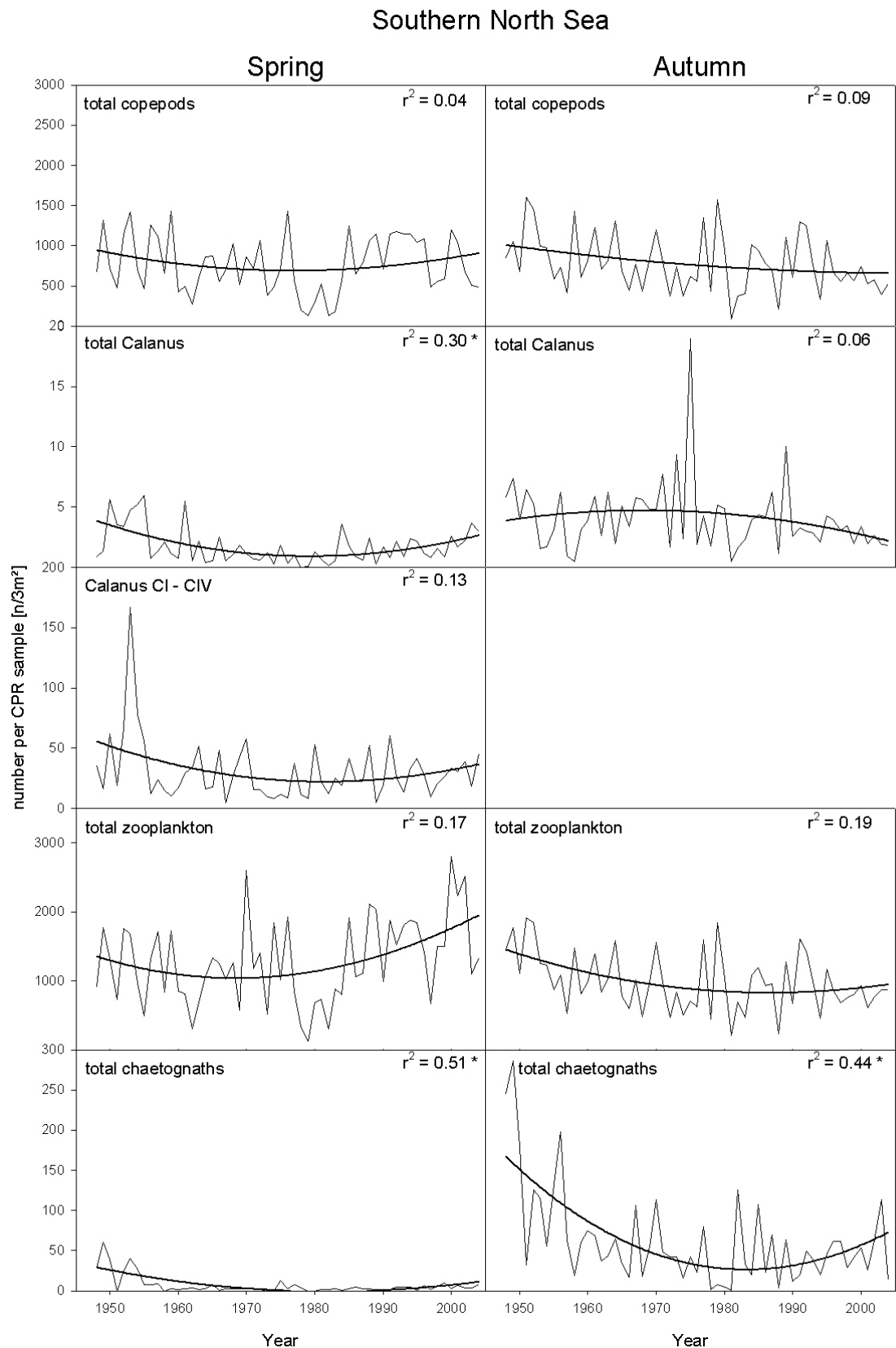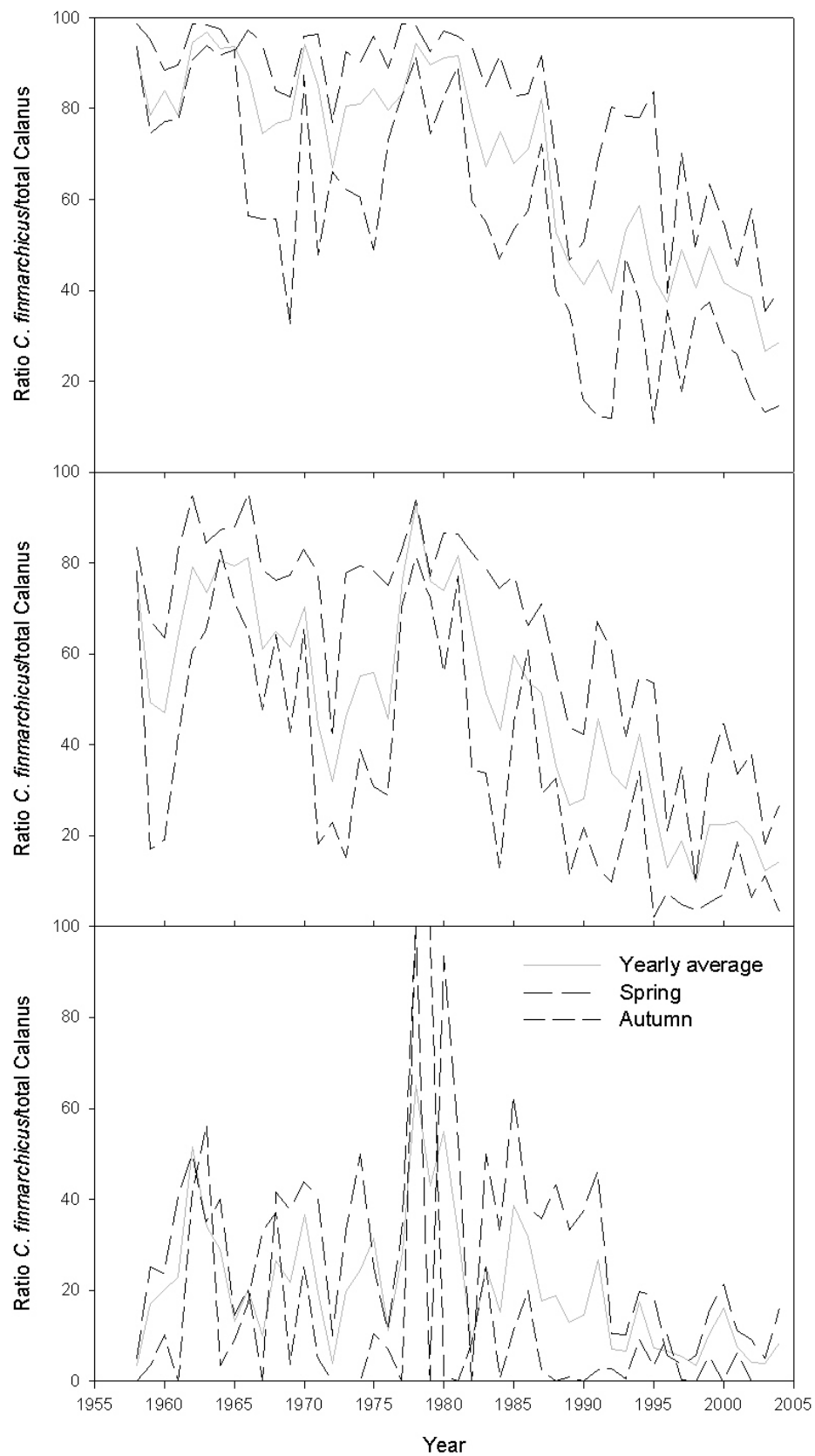
Figure 3.2.4. Indices of ratio of *Calanus finmarchicus* to total *Calanus* in the northern, central and southern North Sea in spring and autumn from 1956 to 2005.

3.3 Fish abundance time series

3.3.1 Data sources

A number of candidate species were identified in terms of their planktivorous and piscivorous behaviours. Anchovy and sardines may feed on planktonic fish eggs and larvae. Herring, sprat, Norway pout and sandeel are also planktivorous, but herring can also be piscivorous, preying on sandeel. Piscivorous predators include mackerel and horse mackerel, feeding on both postlarvae and juvenile fish.

Quarterly time series of spatially aggregated survey indices of herring, Norway pout, sprat and mackerel are available from the ICES datras website (ICES DATRAS indices 2007). These indices represent catch rate per hour during the NS-IBTS up to 2007 (Table 3.3.1). Indices for quarters 2 and 4 are only available for the years 1994–1996. Catch rates per hour of anchovy and sardine (NS-IBTS Q1) were available directly from ICES.

Spatially resolved survey catch rates per hour of herring, Norway pout, mackerel, horse mackerel, and sprat are available via the ICES Fish-map website (ICES Fish-map 2007). The indices represent catch rate per hour during the NS-IBTS. Indices for quarter 1 and 3 are available up to 2004. Indices for quarters 2 and 4 are only available for the years 1994–1996. The length of the individual time series available varies between species (Table 3.3.2). For mackerel and horse mackerel, spatially resolved time series of survey indices were available to the study group covering the period from 1983–2006.

No sandeel indices were available from either source.

3.3.2 Time series of predator abundance

The NS-IBTS quarter 1 indices were used to investigate trends in survey catch as a proxy for abundance for several fish species (Figures 3.3.1 and 3.3.2).

Spatially disaggregated data were not available for sardine and anchovy. The time series for these species were only available from 1985. In the 1980s and early 90s, virtually no anchovy or sardines were caught. From 1995 onwards, the catches of both species have shown an increasing trend, with peaks in 1995, 1998, 2003–2004 (sardine also in 2005) and 2007 (Figure 3.3.1). Similarly, there has been an increasing trend in catch rates of mackerel and horse mackerel in the 1990s (Figure 3.3.1).

The NS-IBTS quarter 1 indices for herring reflect the North Sea herring population dynamics with a low stock size in the late 1960s and during the 1970s after the stock collapse followed by stock recovery after the fishery had been closed from 1977–1980. Catch rates have fluctuated since, but show a decreasing trend during the recent years (Figure 3.3.2).

Sprat catch rates have fluctuated over the whole time period (Figure 3.3.2). However, catch rates have been largely stable over the last 10 years. Norway pout catch rates are variable. They peaked between 1997 and 2000, but since then catch rates have decreased (Figure 3.3.2). NB: In the herring and Norway pout data series, the first data points have been deleted due to concerns over erroneous survey values.

3.3.3 Spatial time series – distribution and potential overlap of larvae and predators

The MIK time series of post-larval abundance and spatial distribution of herring is available from 1977 to 2007 (Figure 3.3.3). There are no equivalent time series for sandeel or Norway pout. These samples are collected during the Q1 NS-IBTS. The abundance of these larvae is a reflection of year class strength (Nash and Dickey-Collas, 2005). Across the time series there have been three major periods of poor recruitment in herring: 1976–1978 (post stock collapse); 1988–1990 (poor survival of high larvae abundance); 2002–2006 (poor survival of

high larvae abundance). There have also been periods where either northern or southern components of herring have dominated, and periods of fairly uniform spatial recruitment. It needs to be remembered that the early stage larvae are distributed further west than late stage larvae (i.e. MIK). There is no quarter 4 North Sea IBTS. However, quarter 1 indices are available and can be used as a proxy for quarter 4 distribution.

Mackerel

Spatially disaggregated data are available for mackerel in the North Sea from 1983 to 2006 (Figure 3.3.4). As reflected in the time series, mackerel was absent, or present in only very low numbers until 1997. Its presence has been constant since then, to a greater or lesser extent. However, the predominant presence has not been in the north-western region where the herring larvae are distributed but in the north-eastern North Sea.

Horse mackerel

Spatially disaggregated data are available for horse mackerel in the North Sea from 1983 to 2006 (Figure 3.3.5). Horse mackerel has been present in the northern North Sea across the time series, with a decrease there in recent years. It has been present in the southern North Sea in reasonable numbers in only a few years (1986–1990 and 1998). Its period of abundance in the southern North Sea did not overlap with herring larvae as there was little production of the Downs herring component during those time periods. Its recent increase in abundance has been seen as a general increase across the entire North Sea.

ICES Fish-map data were available to compare Q1 NS-IBTS catch rates for different time periods for herring, Norway pout and sprat.

Herring

1 winter ringers, quarter 1

Juvenile herring in the 1st quarter are primarily distributed in the south-eastern North Sea and the Skagerrak/Kattegat (Figure 3.3.6). This is a reflection of their nursery areas and is similar for the 0-group herring in the previous quarter. There is therefore little spatial overlap between early herring larvae and juveniles.

2–5 winter ringers, quarter 1

The distribution of adult herring (2–5 wr) in the 1st quarter has shown little change over the time period (Figure 3.3.7). Adults are widely distributed throughout the North Sea in quarter 1. What change there has been is indicative of a slight easterly movement in recent years in the western North Sea, away from the areas of higher larvae abundance, suggesting that any opportunity for cannibalism of larvae has decreased in recent years

Norway Pout

In quarter 1, Norway pout is distributed in the western-central and northern North Sea, with its southern distribution limit running as a diagonal line from the Skagerrak across the North Sea to the English coast at around 54ºS (Figure 3.3.8). The spatial distribution has not varied much over the time period. There is the potential for overlap with part of the larval herring distribution in spatial terms. However, pout distribution is associated with deeper water. There appears to have been a reduction in the distribution to the southwest of the area in recent years. With the concomitant decrease in total abundance of Norway pout in recent years and different depth preferences it is unlikely that this species has been responsible for the decline in larval herring.

Sprat

Sprat is primarily distributed in the western and southern North Sea (Figure 3.3.9). It is found in association with juvenile herring in coastal areas, as well as in more central parts of the southern North Sea. There is the potential for overlap of adult sprat and herring larvae in the south-western part of the North Sea but not in the north. Over the time periods shown, however, there has been little change in sprat distribution and a stable abundance. There does not appear to have been an increase in sprat abundance in the western part of its range, which one might associate with an increased overlap with the Downs component (the relative importance of the Downs component has increased in recent years (Figure 3.3.3)).

Table 3.3.1. Indices of the NS-IBTS Q1.

	QUARTER	AVAILABLE TIME SERIES	SOURCE
Herring	1	1965(66)–2007	ICES NS-IBTS indices
Norway pout	1	1972(75)–2007	ICES NS-IBTS indices
Sprat	1	1974–2007	ICES NS-IBTS indices
Mackerel	1	1974–2007	ICES NS-IBTS indices and NS-IBTS Q1 spatial CPUE
Horse mackerel	1	1983–2007	NS-IBTS spatial CPUE
Anchovy	1	1985–2007	NS-IBTS spatial CPUE
Sardine	1	1985–2007	NS-IBTS spatial CPUE

Table 3.3.2. Spatial indices of the NS-IBTS via ICES Fish-map.

	AGE=WR	QUARTER	TIME SERIES	SPLIT INTO:
herring	1 wr	1	83–04	83–89 90–99 00–04
	2-5 wr	1	83–04	83–89 90–99 00–04
Norway pout		1, 3	83–04	
		2, 4	94–96	
Sprat		1, 3	83–04	
		2, 4	94–96	
Mackerel		1, 3	83–04	
		2, 4	94–96	
Horse mackerel		1, 3	83–04	
		2, 4	94–96	

NS-IBTS Q1 indices
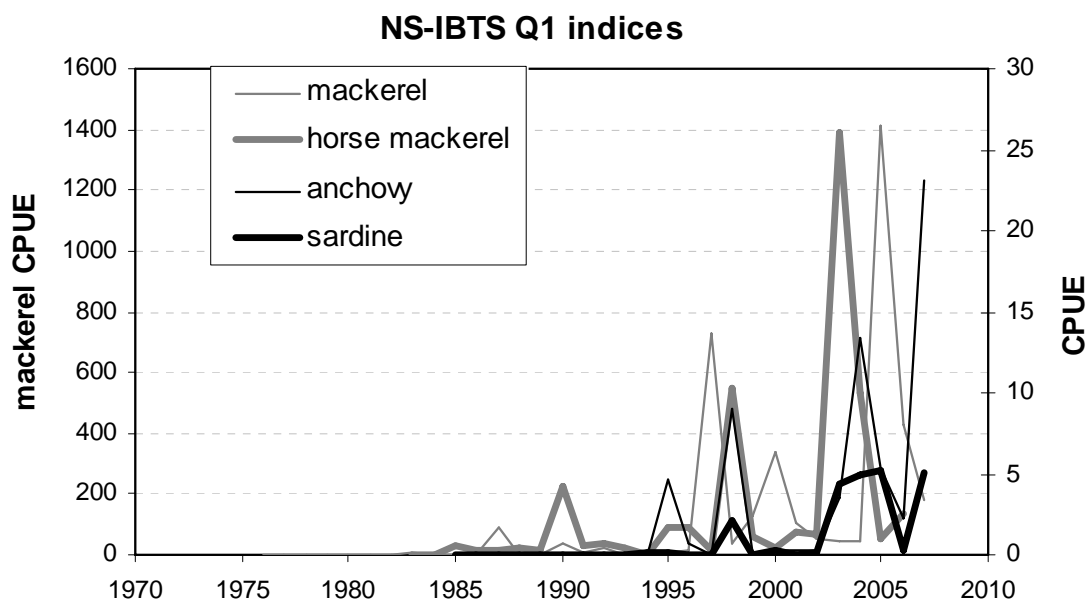
Figure 3.3.1. Survey abundance time series (CPUE) of mackerel, horse mackerel, anchovy and sardine during the 1st quarter North Sea International Bottom Trawl Survey (NS-IBTS). N.B. The time series of the individual indices/catch rates have different start dates: Mackerel: 1974 (ICES index), Horse mackerel: 1983, Sardine and, anchovy: 1985.
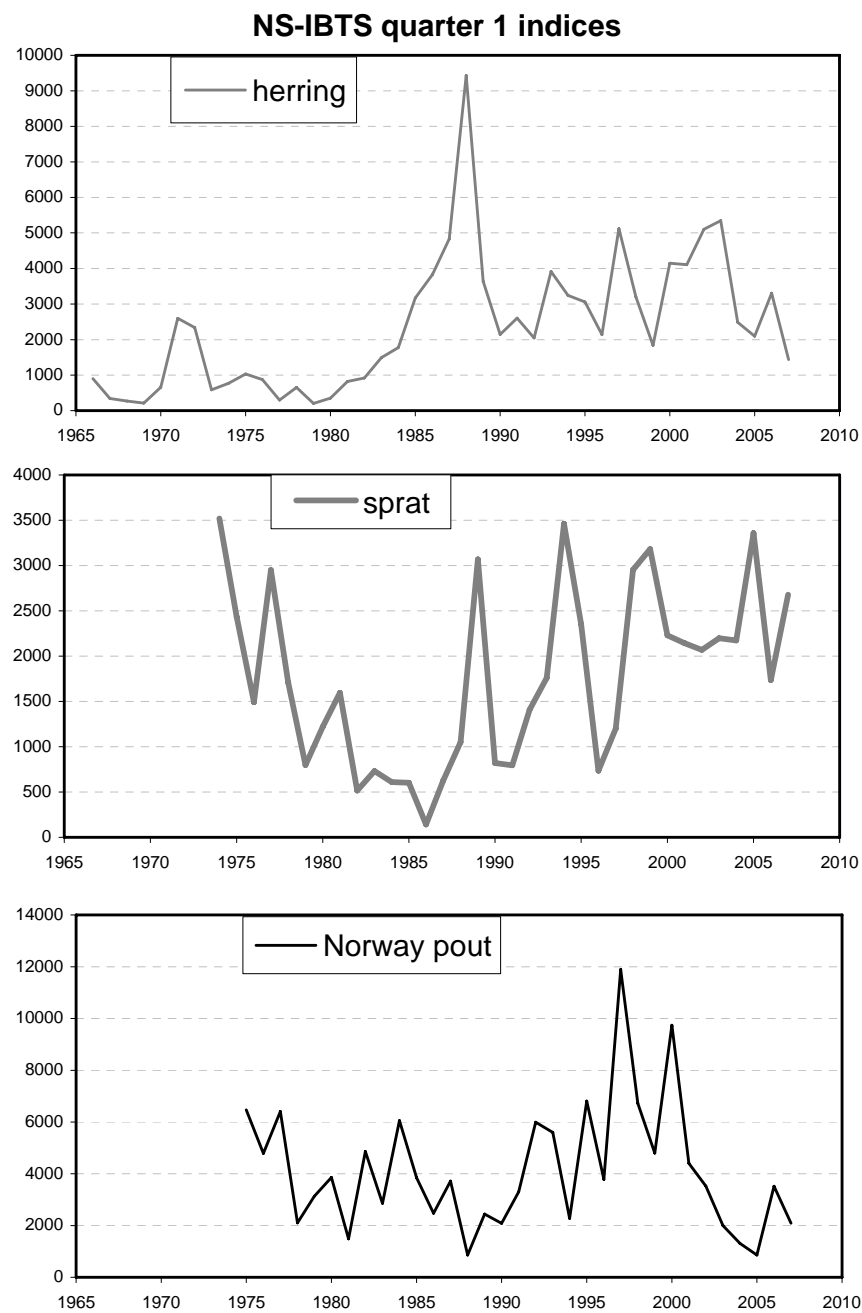
Figure 3.3.2. Survey abundance time series (CPUE) of herring, sprat and Norway pout during the 1st quarter NS-IBTS. N.B. In the herring and Norway pout data series, the initial data points were deleted due to concerns over erroneous survey values.
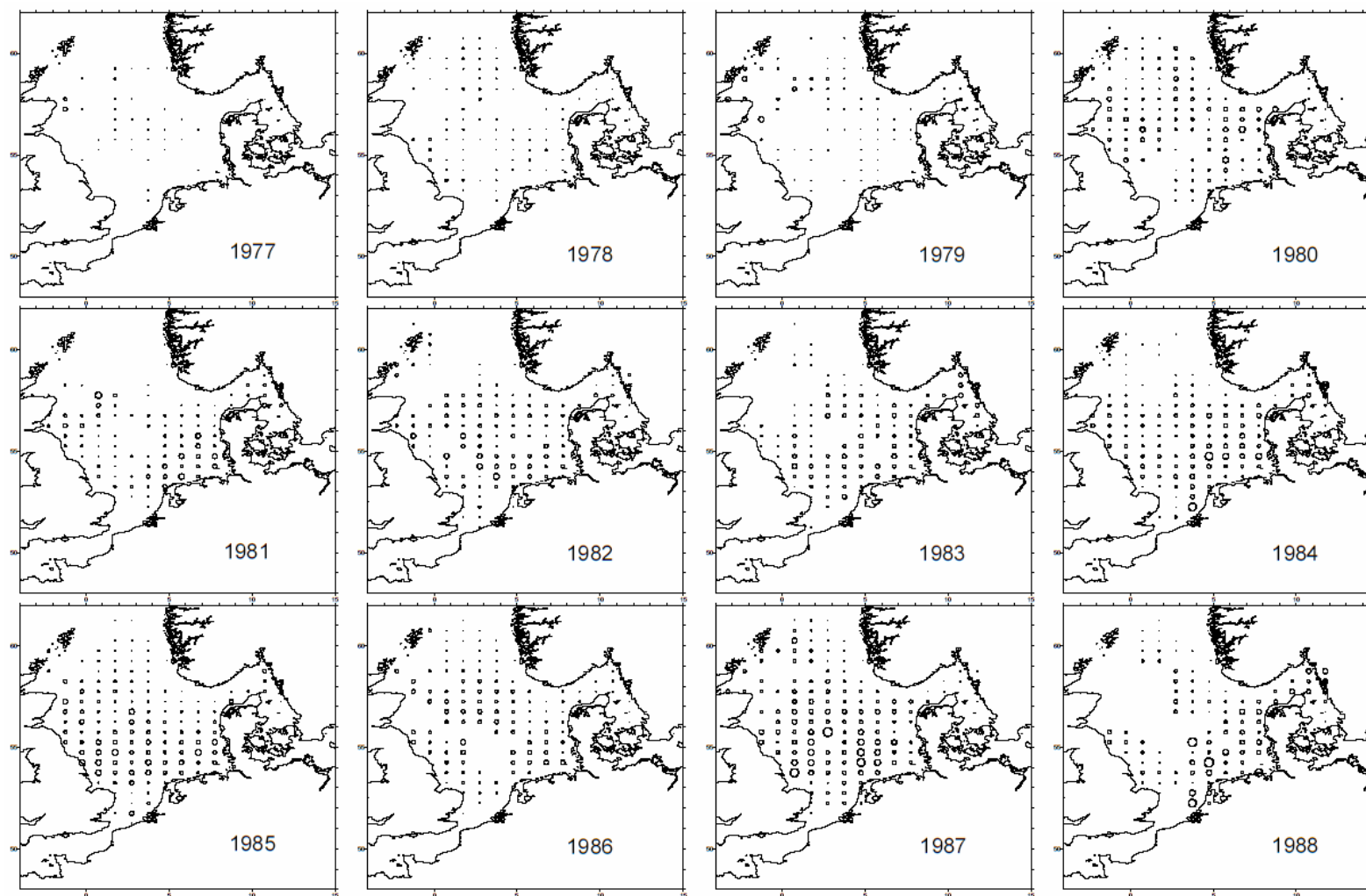
Figure 3.3.3. Spatial distribution of herring post-larvae from the MIKT net survey during the 1st quarter NS-IBTS, 1977–2007. (year class= survey year -1).
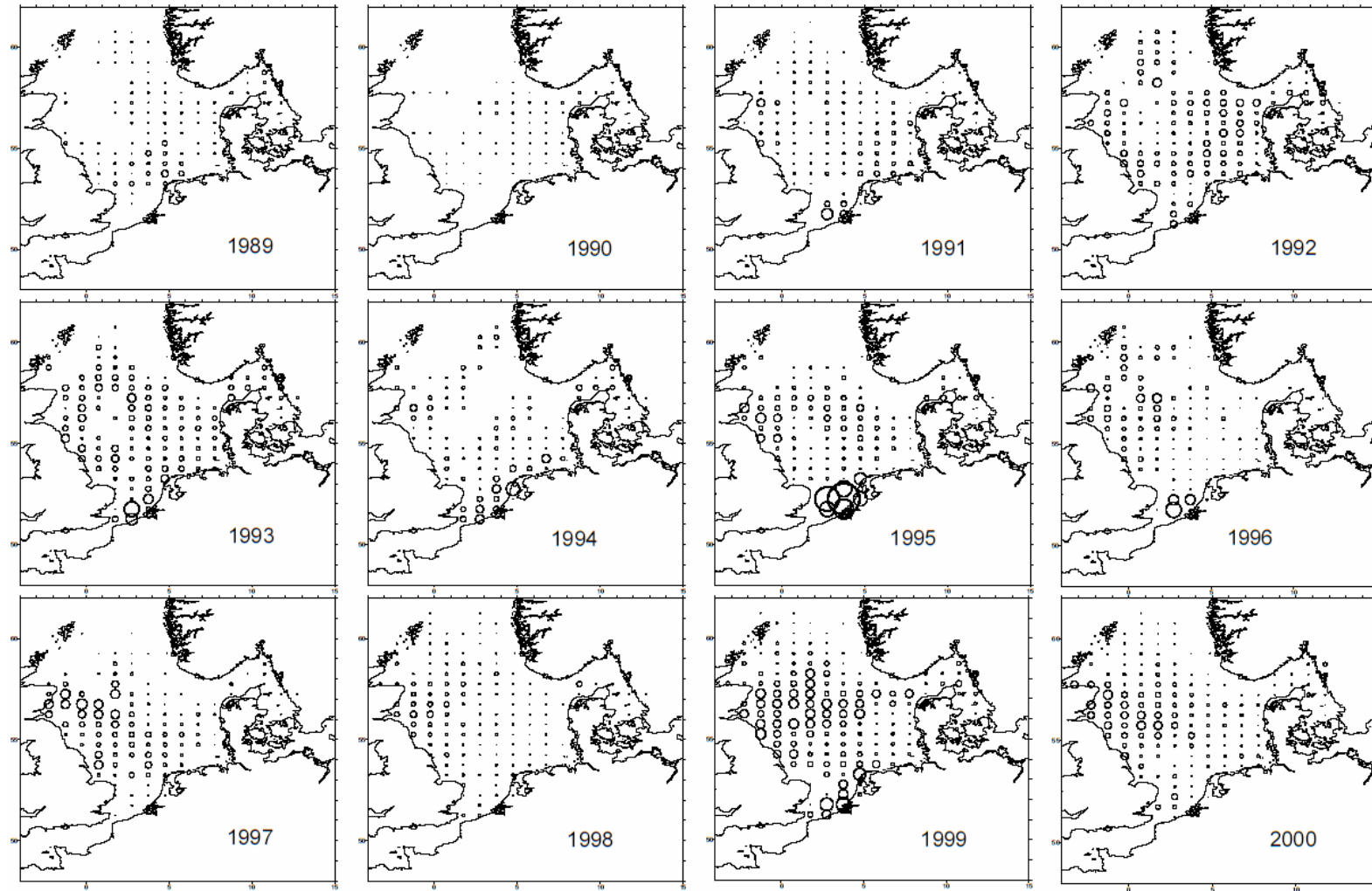
Figure 3.3.3 continued. Herring post larvae (MIK net).
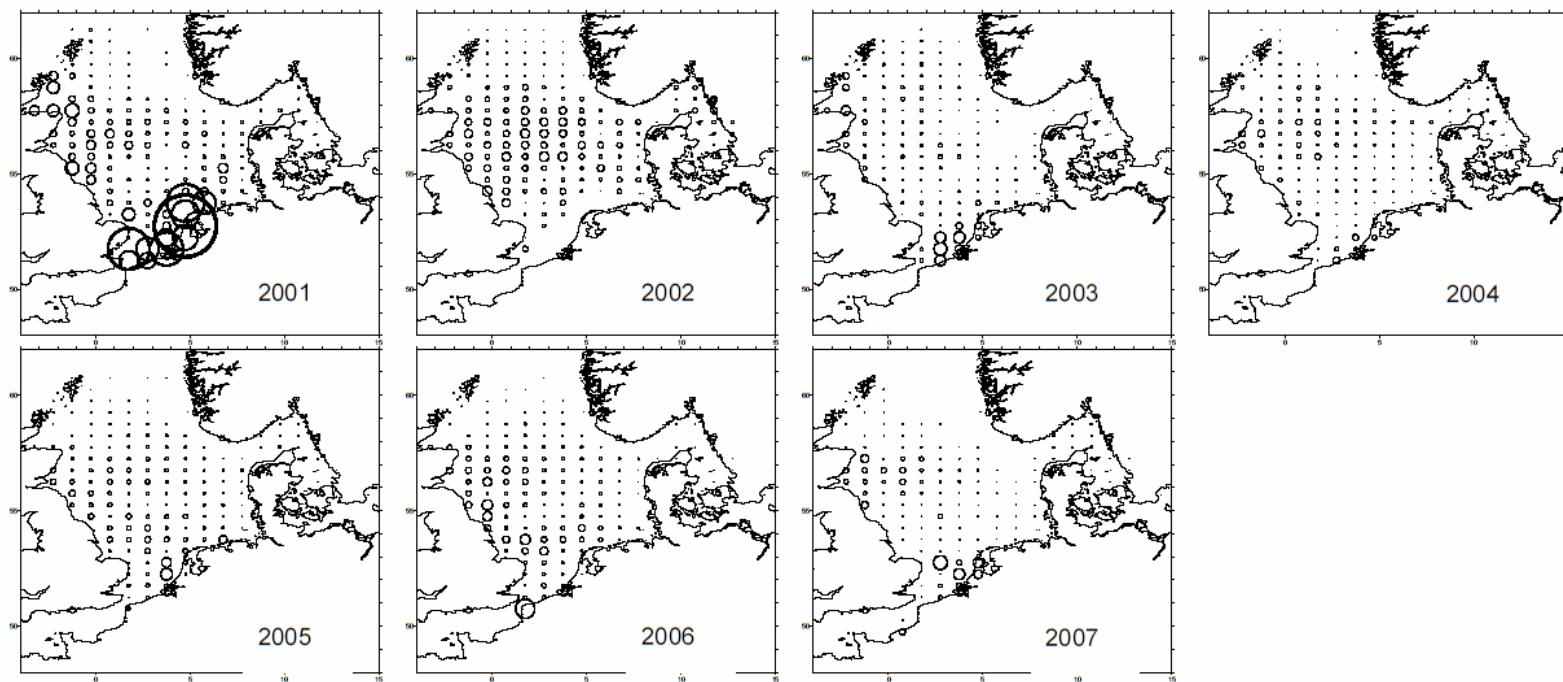
Figure 3.3.3 continued. Herring post larvae (MIK net).
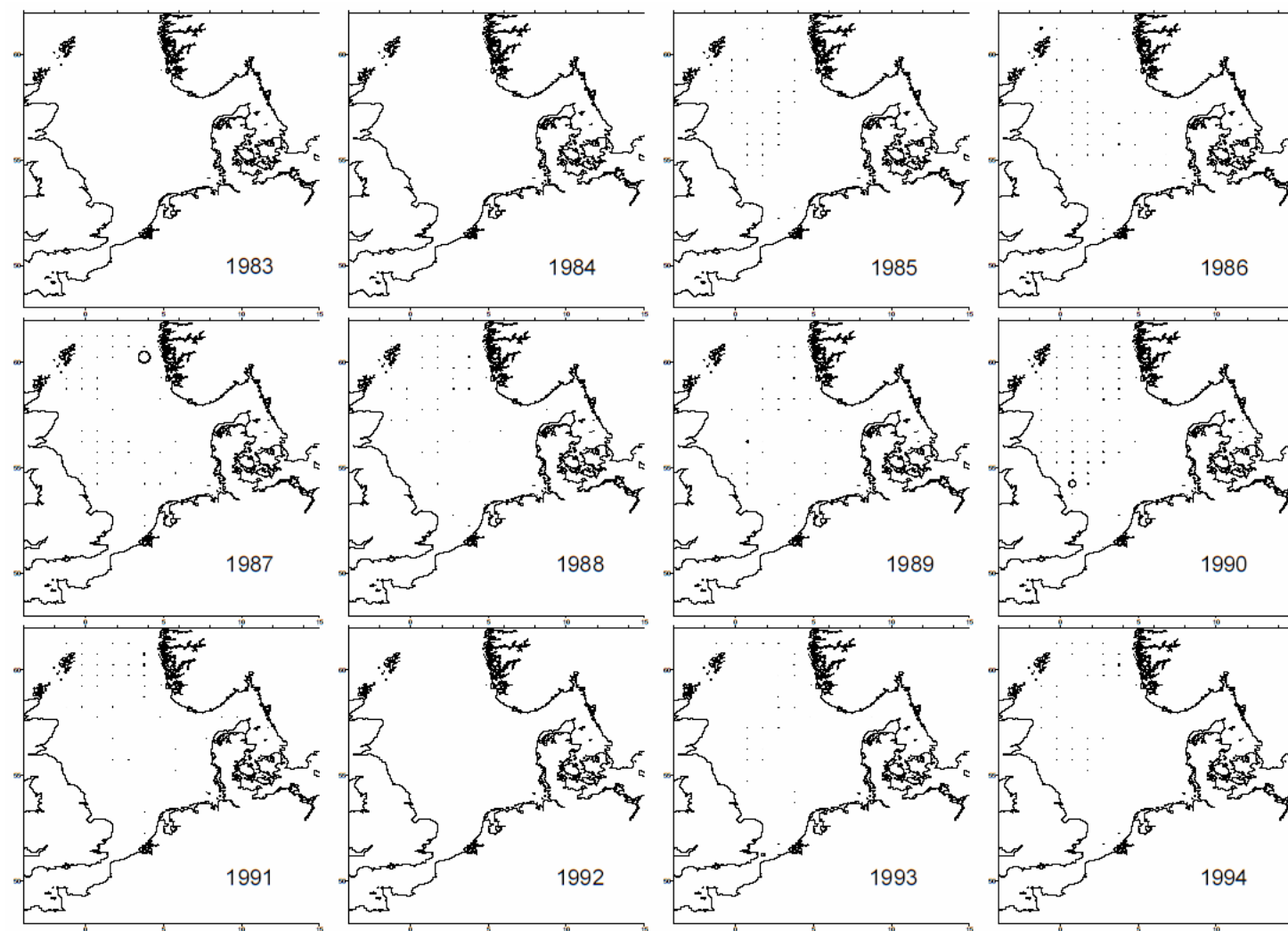
Figure 3.3.4. Spatial distribution of mackerel throughout the North Sea during the 1st quarter NS-IBTS, 1983–2006.
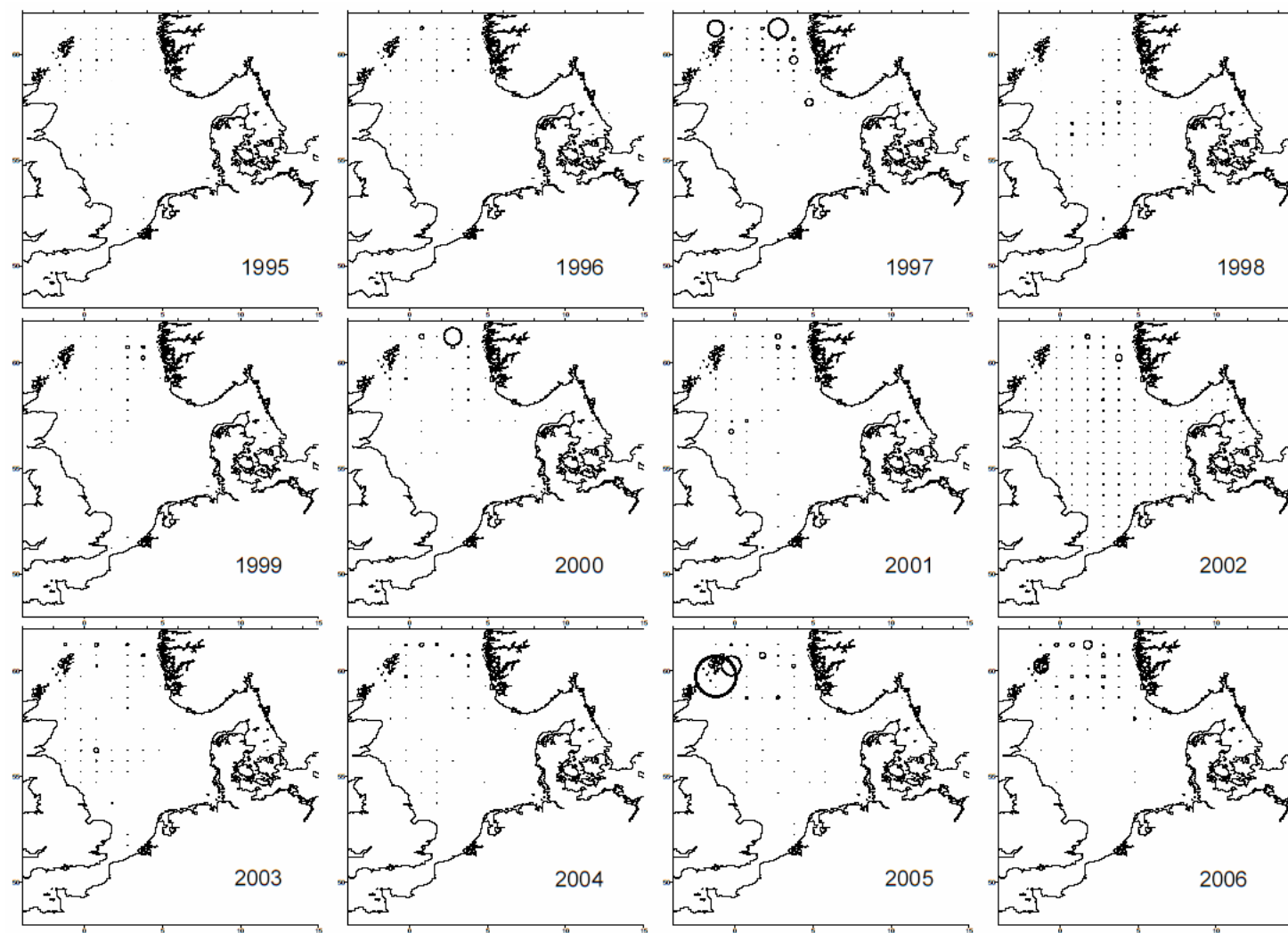
Figure 3.3.4 continued. Mackerel.
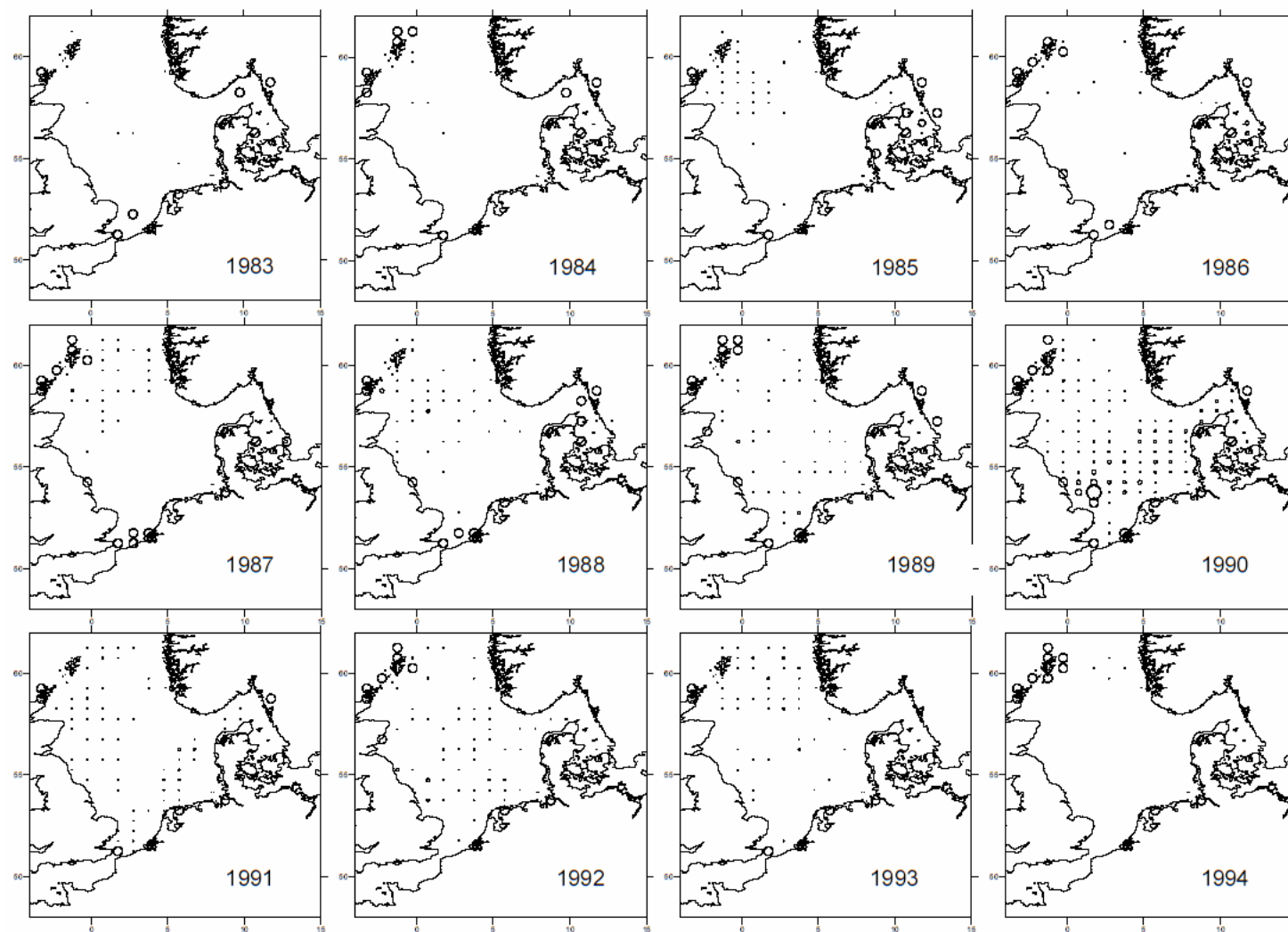
Figure 3.3.5. Spatial distribution of horse mackerel during the 1st quarter NS-IBTS, 1983–2006.
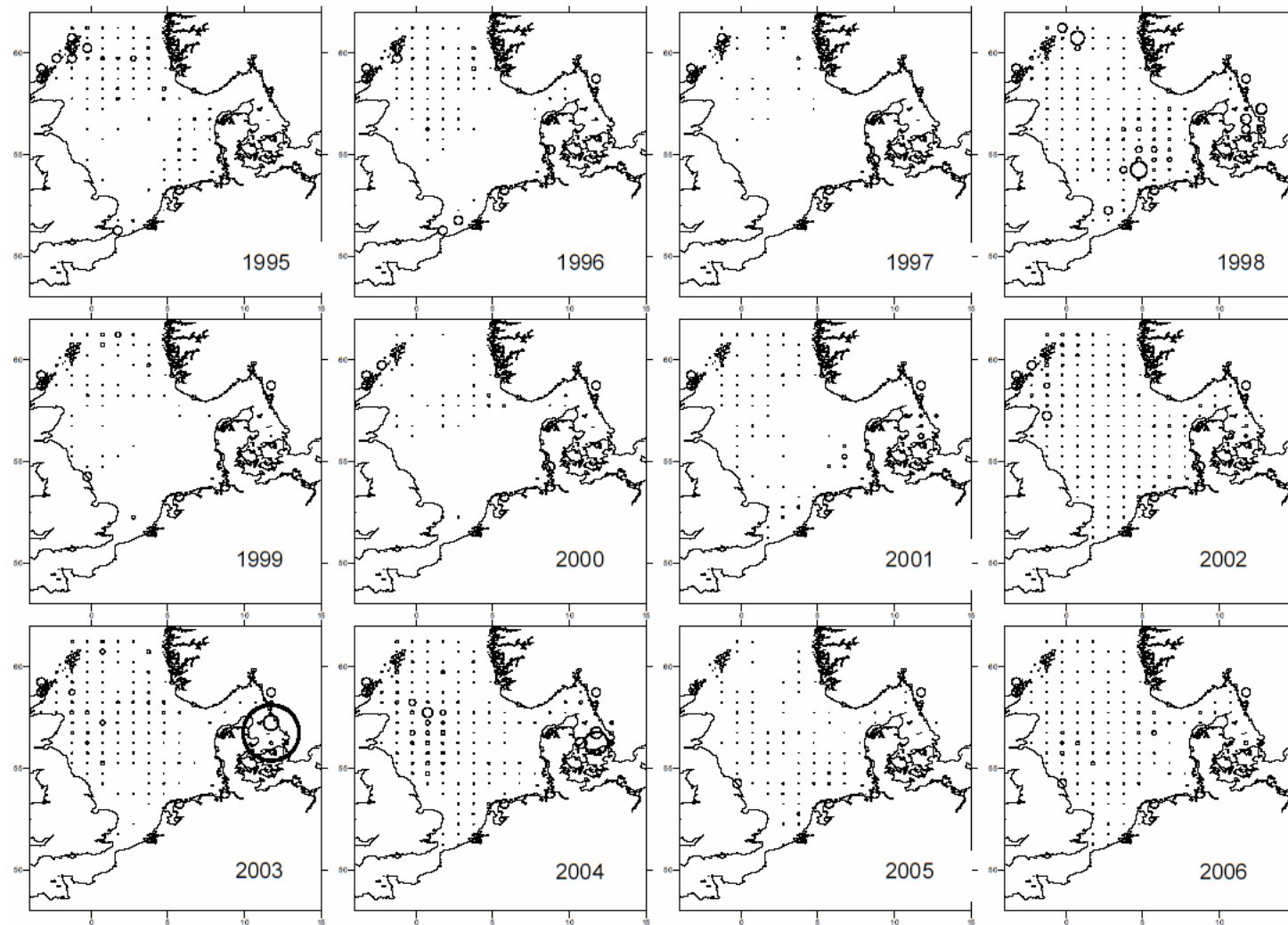
Figure 3.3.5 continued. Horse mackerel.

Herring 1 wr Q1

1983-2004

1983-1989

1990-1999

2000-2004
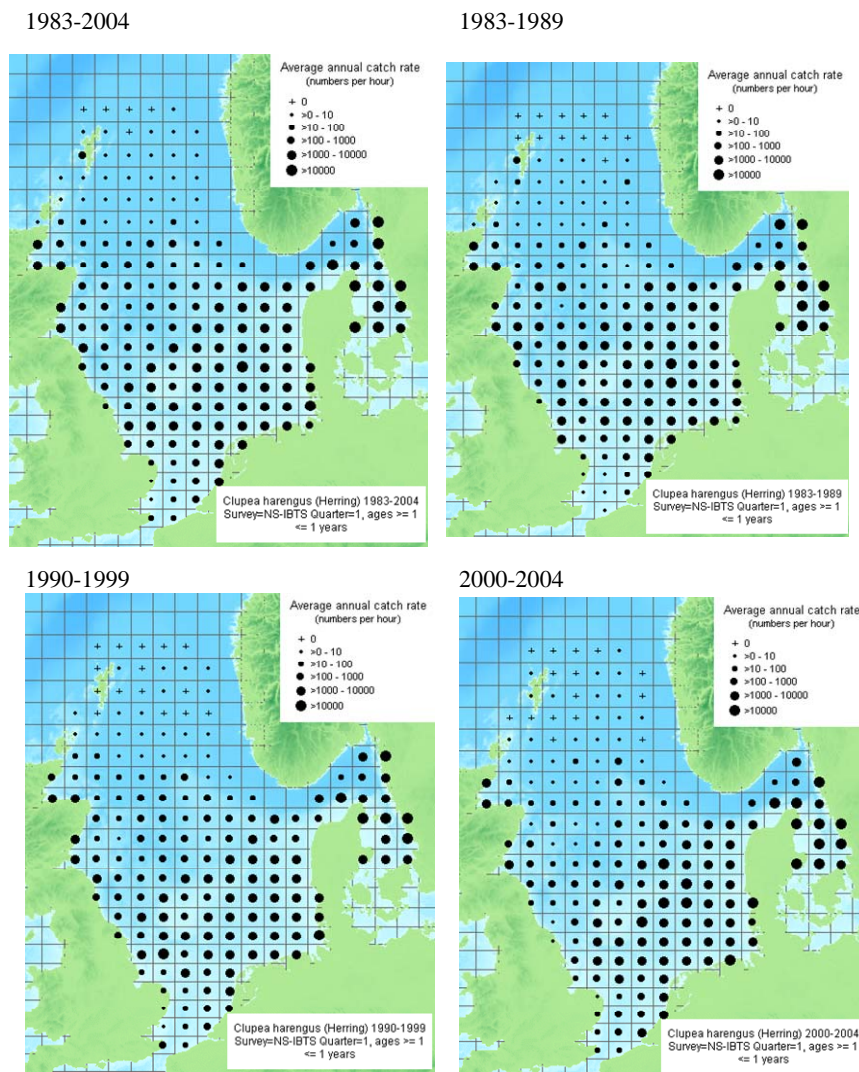
Figure 3.3.6. Herring 1 wr Q1. Survey abundance (catch rate per hour) during the 1st quarter NS-IBTS during four time periods.

Herring 2–5 wr Q1
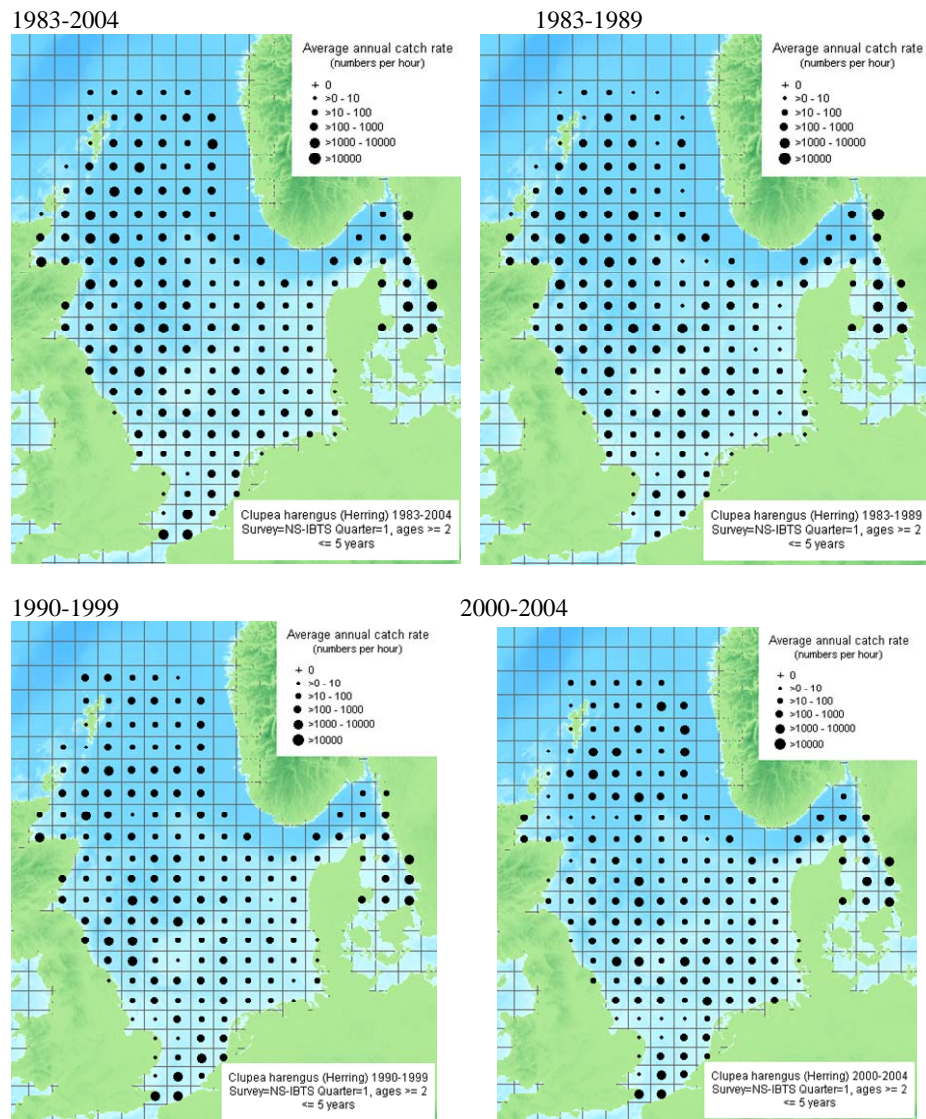
Figure 3.3.7. Herring 2–5 wr, Q1. Survey abundance (catch rate per hour) during the 1st quarter NS-IBTS during four time periods.

Norway pout Q1
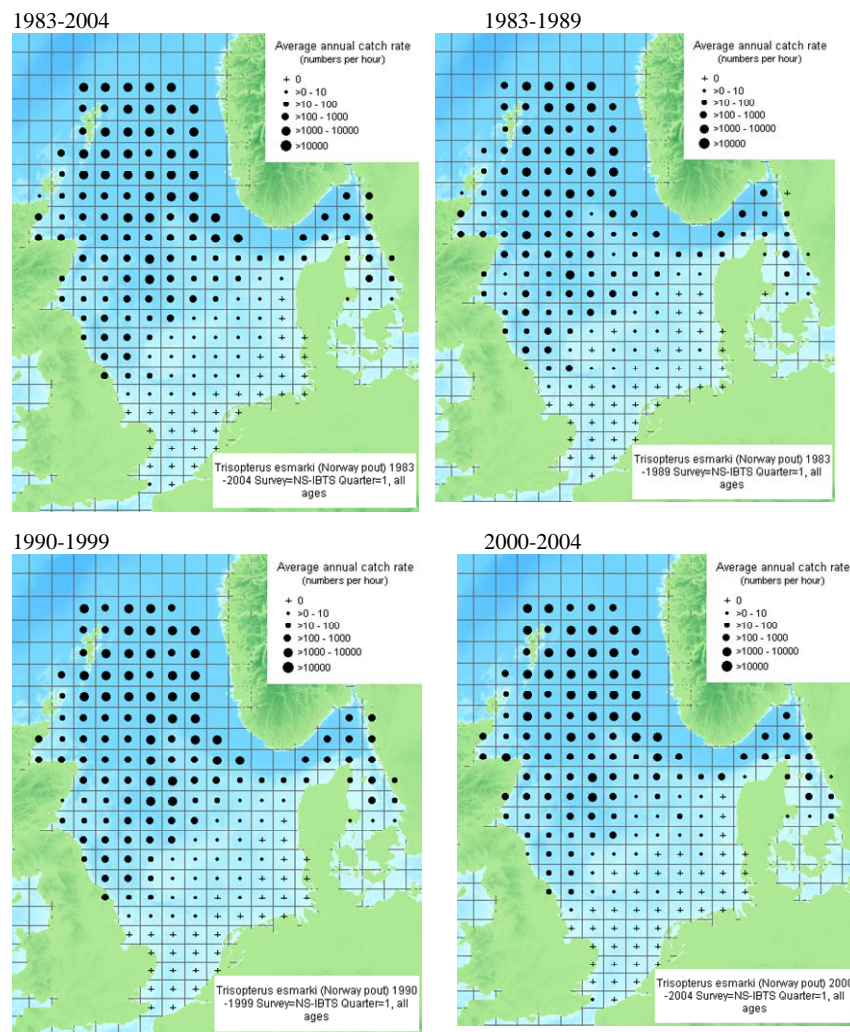
Figure 3.3.8. Norway pout (ages 0–4) Q1. Survey abundance (catch rate per hour) during the NS-IBTS during four time periods.

Sprat Q1
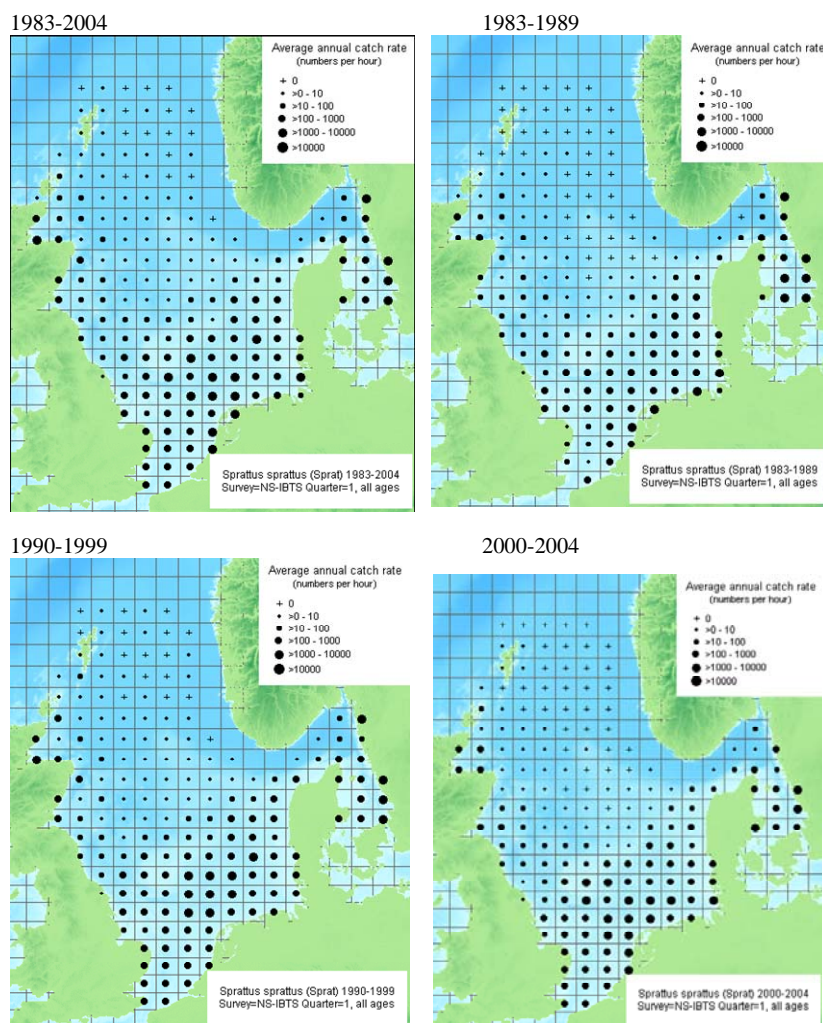
Figure 3.3.9. Sprat (ages 0–6) Q1. Survey abundance (catch rate per hour) during the NS-IBTS during four time periods.

4   Hypotheses

After reviewing many hypotheses during SGRECVAP 2006, and considering the constraints in expertise at the current meeting, the SGRECVAP 2007 looked specifically at hypotheses suggested in 2006 (Section 4.1 below) which involved hydrography, zooplankton and aquatic predators (see Sections 4.2 to 4.5 below). None of the hypotheses was fully tested. **Other potential hypotheses that involved toxins, birds, eutrophication and maternal effects on recruitment (see ICES, 2006) were not considered.** This chapter will consider the hypothesis in relation to their relative spatial scales.

4.1   Hypotheses suggested by SGRECVAP 2006

4.1.1   Changes in abundances of dominant species: *C. finmarchicus* and *C. helgolandicus* have effected recruitment.

a) There has been a significant decline in the abundance of *C. finmarchicus*: which has either affected the supply of nauplii in spring, or copepodites over the autumn or winter.

b) There has been a significant change in the ratio of *C. finmarchicus* to *C. helgolandicus*, which effects the feeding of adults or larvae.

4.1.2   Changes in plankton phenology (seasonal timing):

c) There has been a significant change in e.g. Phytoplankton colour, species composition, abundance (leading to shift in zooplankton productivity).

d) Competitors and predators (within the zooplankton) appear significantly later in the year.

e) There has been a significant increase in the spring thermal regime (SST)

f) There has been a significant increase in the autumn and winter thermal regime (SST)

4.1.3   Changes in the plankton community structure:

g) There has been a significant change in the composition of herbivores;

h) There has been a significant change in the composition of carnivores;

i) There is a significant change in the plankton community structure and this has resulted in a significant reduction in larval production, leading to low levels of recruitment.

4.1.4   Examination of predator interactions:

j) An increase in invertebrate predators on fish larvae over the last three years (2002–2004) has resulted in a significant reduction in larval production, leading to low levels of recruitment.

k) A change in predation pressure on larvae, initiated by changes in the density of the larvae.

l) There is increased spatial overlap of high concentrations of larvae and potential major predators (medusae, chaetognaths, adult herring, mackerel, horse mackerel). Spring (Sandeel and Norway pout), autumn/winter (herring).

4.1.5   Direct hydrographic events:

m) There has been a significant change in the hydrography in the spring and autumn leading to larvae not being in ideal areas or nursery areas.

n) There has been a significant change in the location of fronts and their intensity in the spring/ summer period.

o) There has been a shift in the salinity (density) regime in the spring early summer.

p) There has been an increase in the windspeed or storm frequency during the spring and early summer, also during the late autumn and winter period.

4.2 Evidence of North east Atlantic processes and influence of climate change

4.2.1 Large scale climate influences

Evidence has been accumulated that marine ecosystems undergo large-scale fluctuations, occurring over decadal time periods which seem to be driven by climate forcing (Stenseth *et al.*, 2002), as clearly demonstrated for the North Pacific (e.g. Hare and Mantua, 2000) and eastern boundary current systems (e.g. Chavez *et al.*, 2003; Alheit and Niquen, 2004). Shifts in climate regimes can reorganize marine communities and trophodynamic relationships and induce changes in the mix of dominating species over decadal time scales. An ecological regime shift in the North Sea in the late 1980s has been extensively described in a number of publications and been related to changes in the index of the North Atlantic Oscillation (NAO) (Reid *et al.*, 1998; Kröncke *et al.*, 2001; Reid and Edwards, 2001; Reid *et al.*, 2001a; Reid *et al.*, 2001b; Beaugrand and Ibanez, 2002; Beaugrand *et al.*, 2002; Reid and Beaugrand, 2002; Beaugrand, 2003; Beaugrand and Reid, 2003; Beaugrand *et al.*, 2003; Reid *et al.*, 2003; Beaugrand, 2004, Alheit *et al.*, 2005; Weijermann *et al.*, 2005). Interestingly, regime shifts have been suggested recently for the central Baltic Sea (Alheit *et al.*, 2005), the northwestern Mediterranean and European lakes coinciding with the North Sea shift in the late 1980s whereby the NAO appears to synchronize dynamics in the different ecosystems (Souissi *et al.*, 2007; Alheit and Bakun, subm.).

Dynamics of the NAO have been tracked backward for several centuries using a number of different proxies and it appears that historical fish population fluctuations have been forced by NAO dynamics such as the Bohuslän herring periods and alternating periods of herring and sardine populations in the NE Atlantic (Alheit and Hagen, 1998). However, there are a number of European fish populations where the dynamics do not seem to be associated with the NAO. Since the early part of the last century, fluctuations of anchovy and sardine populations seem to correspond to the dynamics of the Atlantic Multidecdal Oscillation (AMO). Also, large-scale biogeographical shifts of zooplankton (Beaugrand *et al.*, 2002) and fish (Quero, 1998; Brander, 2003; Poulard and Blanchard, 2005) have been reported for European shelf seas which have been related to the increasing trend in Northern Hemisphere temperature.

The residuals from a segmented–regression stock-recruitment model reveal a strong background periodicity (see Section 2.1, Figure 2.1.2), i.e. the residuals show a cyclic behaviour of positive and negative deviations. As residuals are ideally supposed to be white noise, this is a strong suggestion of external periodic factors that are not accounted for by the stock-recruitment model; hence the analysis of environmental time series. Cyclic patterns of this nature may be triggered by exogenous factors at a range of scales on either a regional or a global scale.

To identify and characterize the underlying cyclic pattern, spectral analysis was applied to both the recruitment residuals and the "raw" recruitment time series. Using Fourier decomposition and a Kappa test as part of a stepwise regression procedure significant periods and cycles can be found in the herring stock to recruitment time series, one of them is 7.6 years. It is of interest to note that the winter-NAO (North Atlantic Oscillation; Hurrell, 1995) also consists of a 7.6 year period. However SGRECVAP 2006 pointed out that the NAO does not provide a mechanism for recruitment variability itself, and is a proxy for change in the system. This apparent concordance between the periodicities requires further analysis.

4.3 Variability within the North Sea

Previous studies have shown long-term variability of abiotic and biotic factors in the North Sea, some of these changes appearing concomitantly in different sub-areas and at different time. In order to test some of the hypotheses suggested by SGRECVAP 2006, a common statistical approach has been applied to the datasets of planktivorous fish, zooplankton (i.e. the

food for the fish) and Sea Surface Temperature (SST), which has been chosen as a proxy of the environmental changes in the North Sea.

4.3.1 Fish, zooplankton and the environment

A chronological clustering has been applied to the following time series of fish, zooplankton and SST:

i) residuals of the time series of herring in 1960–2006; residual of the datasets of herring, Norway-pout and sandeel in 1983–2005;

ii) anomalies of the time series of total copepods, total *Calanus*, *Calanus* I-IV, chaetognaths and total zooplankton in the central North Sea in spring (March-June) and autumn (September-October) from 1960 to 2004. The juveniles of *Calanus* were used as proxy of *Calanus* nauplii. Thus for this group the yearly averages in April-July were considered;

iii) anomalies of SST in 1960–2005.

The chronological clustering confirmed the change in the time series of fish after 2001–2002, as already indicated by SGRECVAP 2006. During the same period a change was recorded in the zooplankton in autumn and spring, while no relevant change was observed in the yearly SST anomalies. A contemporary change in temperature, spring zooplankton and herring was observed in 1998.

The analysis of a more extended data set than in SGRECVAP 2006, pointed out other changes in the period previous 1983. In particular, a change in SST, autumn zooplankton and herring was recorded after 1972–1973, while a new temperature regime in 1978 corresponded to a change in the spring zooplankton.
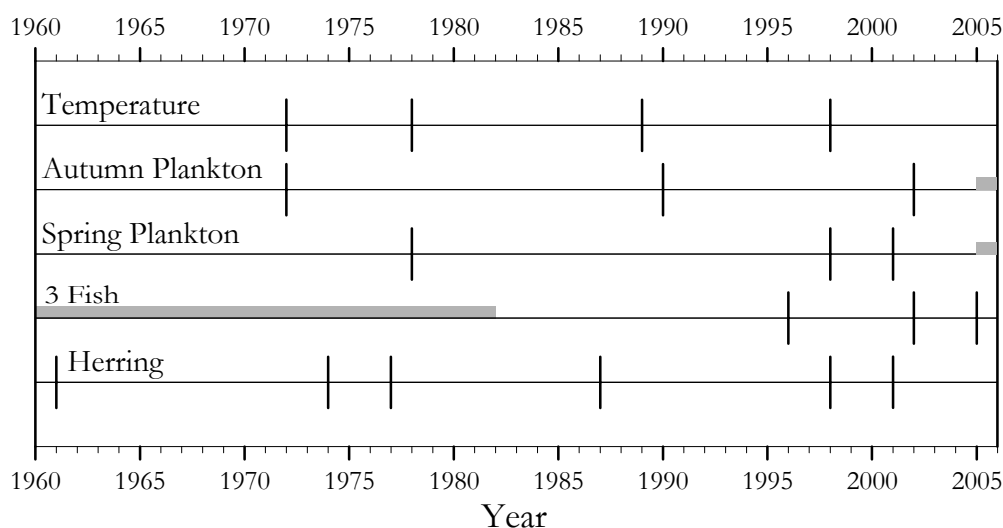
Figure 4.3.1.1. Chronological clustering of Sea Surface Temperature (SST), zooplankton and fish, based on a Euclidean matrix of distance between years (Q-mode analysis). The datasets are described in the text. The grey pattern means 'no data available'.

4.3.2 Fish

Herring, sandeel and Norway pout have planktonic larvae and are thus vulnerable to predation during this life-cycle phase. Fundamental to this process is the requirement for spatial overlap; the predator and the larval prey must obviously be in the same place at the same time for larval mortality to occur. Furthermore, concomitant with variation and changes in oceanic processes, both larval and predator abundances vary in time and space, and thus, changes in predator-prey overlap (match-mismatch) can result in changes in larval mortality.

To investigate this hypothesis, potential planktivorous and piscivorous predators were identified and time series of abundance indices were collated of planktonic larvae and potential planktivorous predators. It should be noted that SGRECVAP did not have expertise in this field, so this investigation is superficial. It is important to highlight that this approach is inherently asymmetrical in its conclusions. While the absence of spatial overlap is strong evidence against larvae predation effects, the presence of overlap does not prove that larvae predation is occurring and is significant. Care thus must be taken in the interpretation of these results.

Herring

Distribution of herring depends on their age. One winter ring (1-wr) herring are distributed in the south-eastern North Sea, from the German Bight into the Skagerrak and do not therefore overlap with the larvae in the western North Sea. In quarter 1 surveys, adult herring (2–5 wr) are distributed across the North Sea. For cannibalism to occur on larval herring one might expect to see an increase in adult abundance in larvae production areas. There has been no overall westerly increase in distribution. It even appears that there has been a decrease in adult abundance in western areas in the recent period.

Horse mackerel abundance has increased in recent years. It has been present in the northern North Sea over the entire time period. The periods in which it has been more abundant in the southern North Sea are not concomitant with periods of high Downs larval abundance. We do not therefore consider horse mackerel to be responsible for the decline in herring recruitment.

The predominant increase in mackerel in the North Sea has been in the north although there has been a spread across a wider area in some years. Mackerel abundance increased in 1997, decreased, then increased again from 2000 until the present. However, its distribution tends to be in the north-eastern North Sea, where larvae are not distributed. Its presence in 1997 did not appear to affect the abundant 1996 year class. There was a higher abundance around Orkney/Shetland both in 2005 and 2006 but there has been no consistent increase in that area in recent years. We do not therefore consider mackerel to be responsible for the decline in herring recruitment.

Norway pout spatial distribution appears to have remained stable across the time series. However, its abundance has decreased markedly since the mid-1990s. We do not therefore consider Norway pout to be responsible for the decline in herring recruitment.

Sprat numbers have remained fairly stable over the last 10 years or so. Sprat are certainly present in areas of herring larvae distribution in the western North Sea. However, their distribution pattern has been similar from the early 1980s to 2004. Like herring adults then, there has been no westerly increase in distribution that might be expected if predation were an important factor driving the increase in herring larval mortality.

Norway pout and sandeel

It is almost impossible to draw any meaningful conclusions for these two species. Data are only available from 2004 for larval distribution. There is certainly potential overlap for Norway pout larvae and therefore predation by adult herring, horse mackerel, mackerel and adult Norway pout. Potential sandeel larvae predators include herring, sprat and horse mackerel.

Conclusions

The IBTS indices are in accordance with findings by Heath (2005), suggesting an increase in gross production of planktivorous fish. These species all have the potential to prey on the larvae of herring, Norway pout and sandeel. However, from the broad brush, subjective analyses possible within this study group, it does not appear that any of these species are responsible for the increase in larval mortality.

4.3.3 Further analysis

Due to a lack of time, and limited statistical expertise further analysis of the time series was not possible at SGRECVAP. It is hoped that further analysis will occur in the months to follow, by individuals from the group.

4.4 Further analysis of Norway pout and sandeel

The smoothed trend in Norway pout is similar to that in herring, and considering the finding of SGRECVAP 2006, the trends are considered similar. However the conclusion of SGRECVAP 2007 is that there is no detectable trend in the stock to recruit residual in North Sea sandeel. In other words there is no signal to investigate. There is also a paucity of data on Norway pout to further investigate the trends at a process level. Therefore SGRECVAP could only investigate the trend in herring larvae, and as poor year classes are determined between hatch and metamorphosis, the work centred on the larvae of herring.

4.5 Local influence on North Sea herring larval productivity

4.5.1 Testing hypotheses linking hydrographic frontal processes to herring recruitment

Studies at the spawning grounds of North Sea herring suggest strong linkages between hydrographic fronts and the early life of the herring larvae (Kiørboe *et al.*, 1988; Munk *et al.*, 1986; Heath and Rankine, 1988). Owing to convergent flow towards the frontal zone both fish larvae and their prey are aggregated which will promote larval feeding and growth conditions and lessen larval dispersal. Further, the frontal jet-current plays in important role in larval drift towards the nursery grounds. Hence, recruitment might depend on frontal activity at the spawning grounds.

The fronts are basically found in the same areas year after year, but variability in their position and intensity has been observed, depending on freshwater outflow from land and influx of more saline water masses in the northern North Sea and the Channel area.

The present analysis of long term trends in hydrography shows significant inter-annual trends in water temperature and water density in areas covering important herring spawning sites (Section 3.1). Hence, if larvae are distributed in the same geographic areas year after year, then such a change in water mass characteristics would mean altered conditions to the larvae. SGRECVAP investigated the following hypotheses:

    i)   herring spawning has been geographically consistent during the period, and as
           a consequence;
    ii)   predominant parts of larvae populations have experienced water masses of
           declining densities;
    iii) in the area of distribution, a decline in bottom water mass density reflects a
           offshore displacement of the frontal zone.

For investigation of these hypotheses SGRECVAP used data from the IHLS surveys from the Orkney-Shetland spawning grounds. Information on standard oblique hauls for herring larvae with parallel information on surface and bottom temperature and salinity was available for the years 1998 to 2005 (no salinity for year 1999). The sampling was carried out transect-wise in longitudinal direction, and the first hypothesis was investigated by a looking for a year effect on larval longitudinal position (Figure 4.5.1.1a). This effect was insignificant (GLM, p>0.9), indicating that that there has been no spatial trend in herring spawning and distribution of larvae.

The second hypothesis, whether larvae during the investigated period were distributed in water masses of declining bottom water densities, was tested by a looking for the year effect on

experienced bottom water density (no data available for 1999, Figure 4.5.1.1b). This effect was highly significant (GLM, p<0.0001). The likelihood of frontal presence in the areas of low or high bottom water density is subsequently investigated by regressing the rate of bottom water density change with values of bottom water density. The rate of change is calculated transect-wise for a series of longitudinal transect in the dataset. A rate of change at a given station is expressed as the change in bottom density between this station and the neighbouring station (in offshore direction). The relationship between rate of change and bottom water density was significant (GLM, n=129, p<0.0001, Figure 4.5.1.2)).
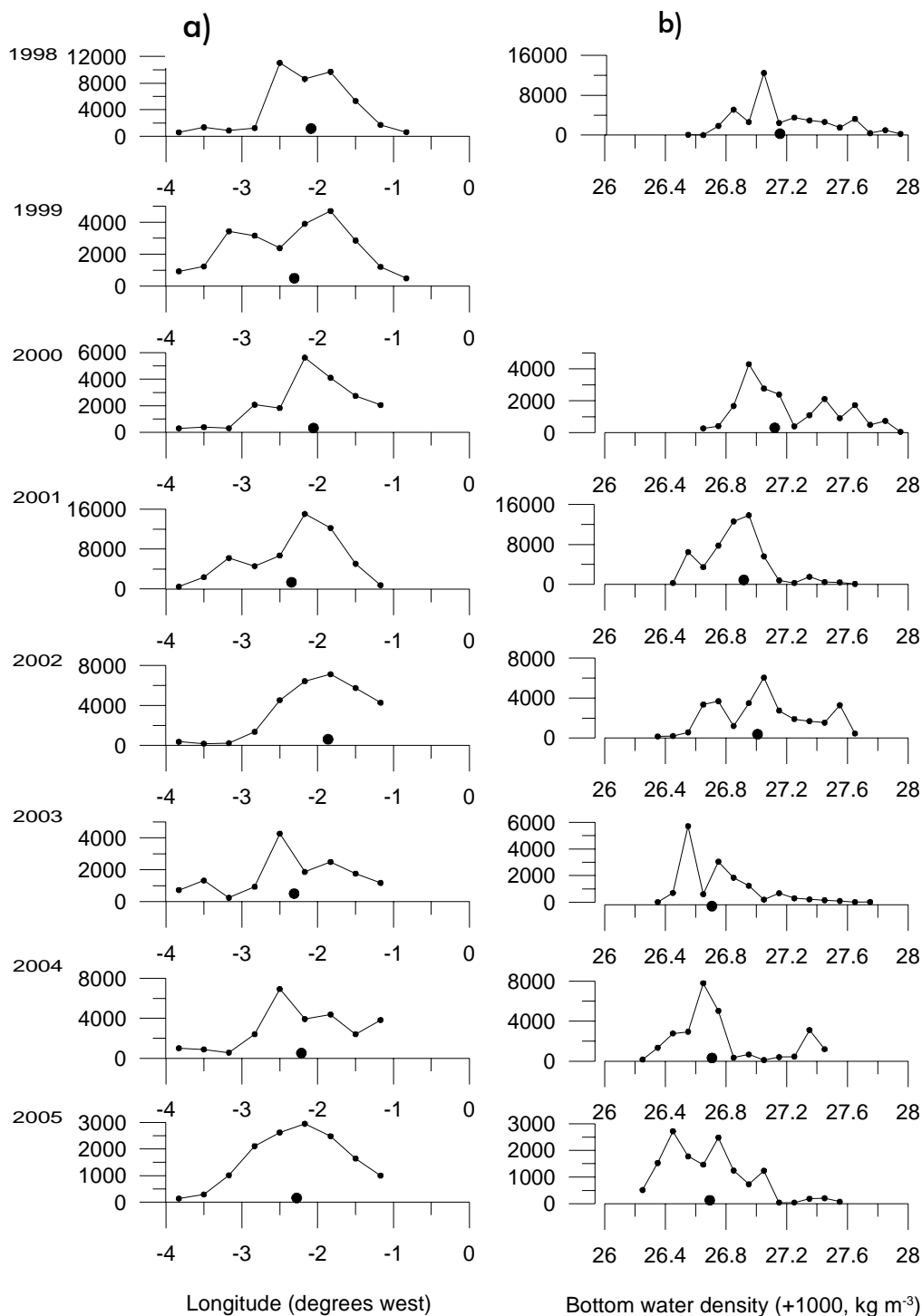
Figure 4.5.1.1. a) Plot of accumulated abundance of larvae versus longitudinal position, years 1998–2005. Large symbol indicate weighted average position. b) Plot of accumulated larval abundance versus bottom water density. Large symbol indicate weighted average position. No data available for 1999.

In conclusion this investigation indicates that the period of declining bottom water density (as observed as a general trend during the past decade, Figure 3.1.3) has also been a period of weakening of frontal processes at the herring spawning grounds. Hence, the hypothesis about a positive relationship between presence and intensity of frontal activity at the spawning grounds and subsequent recruitment success cannot be rejected. The study is limited to cover

the late period of recruitment decline, initiatives are been taken assemble further data, and extend the study to include the period of recruitment decline observed in the late 80s.
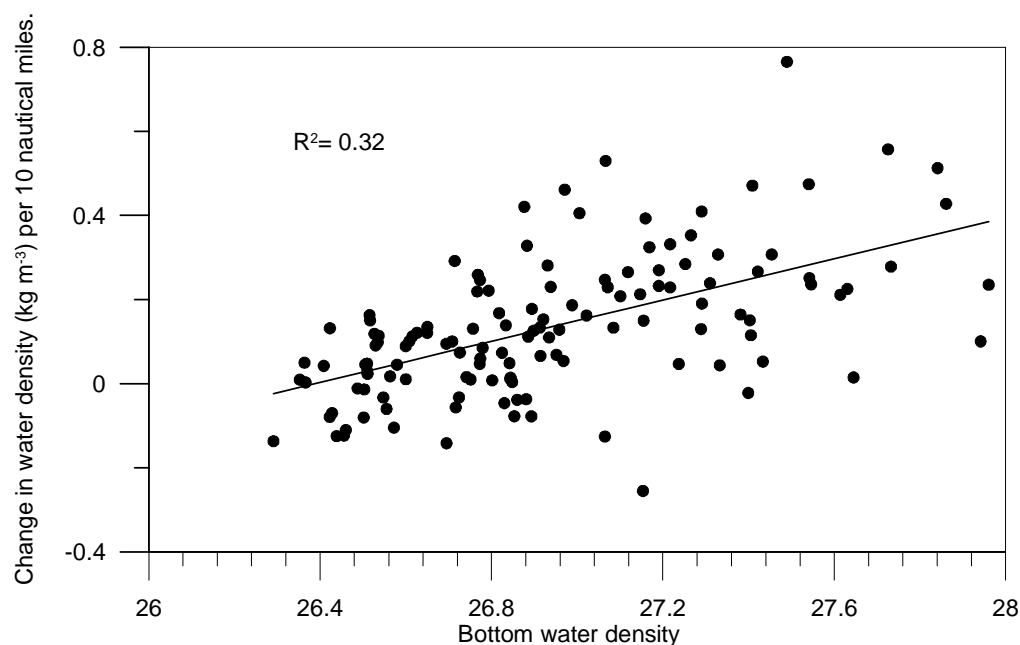
Figure 4.5.1.2. Regression of frontal intensity (measured by rate of change in water density) versus water density at station.

4.5.2 Potential spatial and temporal effects influencing the North Sea herring larvae production

The analysis below shows that larvae production is clearly influenced by the characteristics of the water (temperature and salinity) associated with the spawning area and length of spawning time.

The hypotheses investigated were:

1) Herring larval production is directly influenced by the spatial and temporal extent of spawning;

2) The spatial and temporal extent of spawning are associated with regional characteristics such as temperature and/or salinity.

While the spatial dimension may be characterized as the favourable space available on the spawning sites during the spawning period, the temporal effect may be characterized as the length of the favourable time slot available. The following will call the spatial dimension "spatial extension" and the temporal dimension "temporal prolongation". Both are difficult to observe and measure directly and thus two proxies were defined based on available information. The proxy for the spatial extension is defined here as the accumulated area by spawning ground where larvae were observed during surveys, weighted by the abundance of the larvae in the smallest unit of area applicable to the IHLS (International Herring Larvae Survey). The smallest unit of area thus consists of one 10 NM square as defined in the so-called "area file" of 1985. Due to its fixed shape, the area covered by this unit can vary, as it may overlap with land (islands, main land, bays, etc.). As a proxy for temporal prolongation we defined the standard deviation linked to the range of "occupied" length classes (in mm) weighted by their associated frequencies. In contrast to the number of length classes (19 classes) the standard deviation varies over time and, in contrast to the variance, has the same dimension as the mean, the median or the individual values. The trade-off is that it is partly

confounded with the survey timing. Annual time series the two proxies by spawning ground were determined is given in Figure 4.5.2.1 (with trend lines).

The analysis of larvae production (LP) is based here on two size groups: the smaller yolk sack larvae of size classes 5 to 9 mm (6 to 7 in the southern North Sea) (Larvae Abundance Index; LAI values) and the larger post-yolk sack larvae of size classes 10 to 24 mm (11 to 24 in the southern North Sea, Heath, 1993; Gröger *et al.*, 2001). This approach was employed as different larvae stages have different needs and thus can be expected to react differently to changes in environmental conditions. The annual development of the LAI values by size group and spawning ground is given in Figure 4.5.2.2 in which the spawning grounds are associated with different stock components and are coded as: B = Orkney/Shetland, C = Buchan, D = Central North Sea, E = Southern North Sea. Figure 4.5.2.2 indicates a change over time in the contribution of the different stock components towards the total herring larvae production in the North Sea.

Environmental effects were evaluated using the CTD data (1998 onward) that were taken along with the larvae data as part of the IHLS. Not all spawning grounds were sampled or at the same frequency. The CTD data consisted of surface and bottom temperature and salinity. To match the temperature and salinity data with the annual larvae data records we derived bottom and surface means and variances by spawning ground from these. As the lengths of the different time series were different, the analyses were carried out in two steps:

1) Linking the CTD data to the "spatial extension" and "temporal prolongation" proxies and investigating their association (correspondence) using correlative measures.

2) Investigating the direct effect of "spatial extension" and "temporal prolongation" on the larval production based on the two size classes of larvae (and thus indirectly the temperature and salinity effect) using correlation and regression.

Due to the short time span of the data sets, both analyses could not be undertaken on each spawning ground separately but were based on the entire survey area. The following results should thus not be considered as being final as they aggregate over physically different areas. However, they applicable to a general (global) pattern or trend.

The first analysis (1) revealed that based on 26 data points the spatial extension is positively correlated to the variance of the bottom temperature (R = 0.46, p = 0.0156). This is confirmed by a stepwise variable selection procedure in a multiple regression approach: assuming a causal direction from bottom temperature to spatial extension leads to a fraction of about 20% (p = 0.0206) of the variation in spatial extension being explained by the variability in the bottom temperature. In contrast to this the temporal prolongation is not only positively correlated with the variance of the bottom temperature (R = 0.57, p = 0.0018) but also to the mean surface temperature (R = 0.50, p = 0.0069) and the mean bottom salinity (R = 0.40, p = 0.0415). Applying a stepwise variable selection procedure by assuming a potential causal effect based on linear combinations of bottom temperature variance, mean surface temperature and mean bottom salinity explains about 50% (p = 0.0014) of the variation in temporal prolongation with all three factors included. This was significant at the 5% significance level. The variance of the bottom temperature represents its fluctuation and is indicative of the variability in the favourable environmental conditions.

The second analysis involves testing for correspondences between the two larvae size groups (5 to 9 and 10 to 24 mm) on the one hand and temporal prolongation as well as spatial extension on the other. This exercise was based on 286 data points and shows a clear correlation of small larvae abundances with temporal prolongation (R = 0.60, p < .0001) and spatial extension (R = 0.52, p < .0001), being more or less evenly distributed between the two. In contrast to this, the larger larvae are highly correlated with temporal prolongation (R = 0.79, p < .0001) and less strong with spatial extension (R = 0.56, p < .0001). Applying a

variable selection procedure and assuming a causal relationship between small larvae abundance and either one or both factors leads to a 2-factor regression model that explains 56% (p < .0001) of the variation of the larvae abundance. When both factors were included the relationship was significant at the 5% significance level. In the case of the larger larvae, 76% (p < .0001) is explained by a 2-factor regression model with both factors included being significant at the 5% significance level. A plot of the predicated versus observed larvae abundance for both larvae groups (Figure 4.5.2.3 illustrates the model fit for both larvae groups (left panel: small larvae; right panel: larger larvae) illustrates how well the model fits the data.
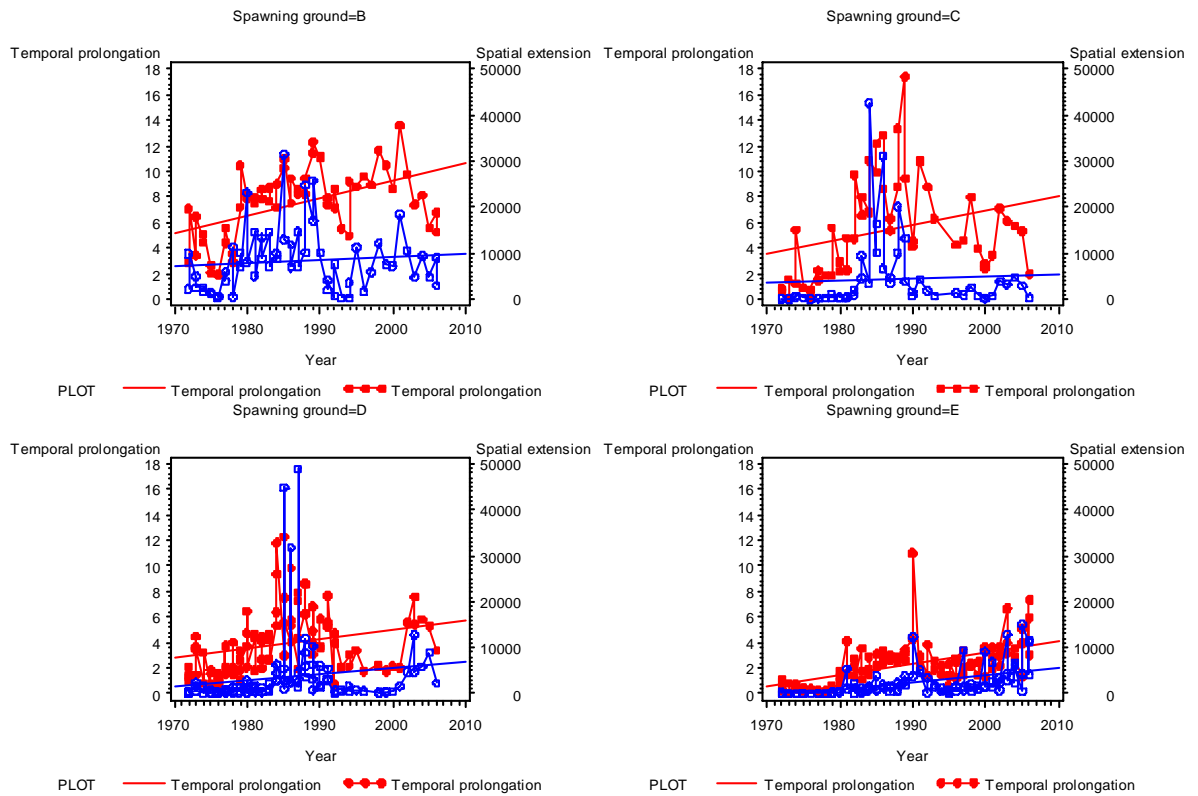
Figure 4.5.2.1. Time series plots of spatial extension and temporal prolongation by spawning ground – with linear trend lines (B = Orkney/Shetland, C = Buchan, D = Central North Sea, E = Southern North Sea). Red – temporal, Blue – spatial.
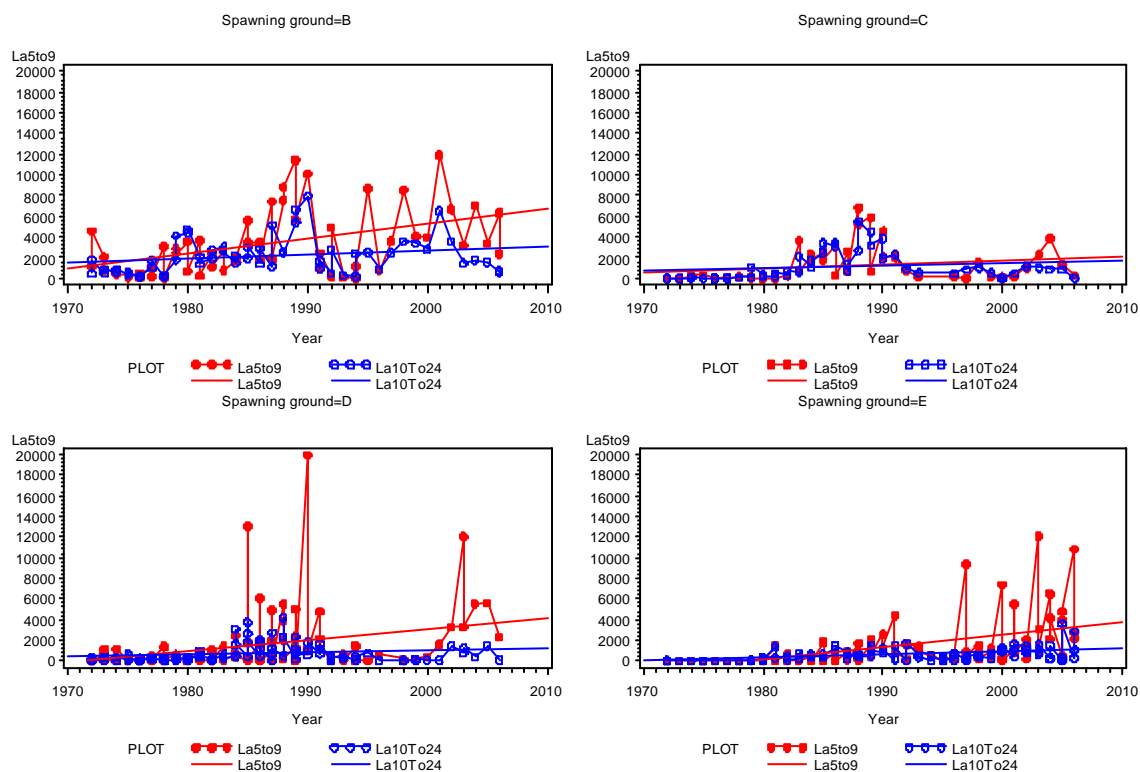
Figure 4.5.2.2. Time series plots of larvae abundance values (LAI values) for size groups 5 to 9 and 10 to 24 mm by spawning ground – with linear trend lines (B = Orkney/Shetland, C = Buchan, D = Central North Sea, E = Southern North Sea).
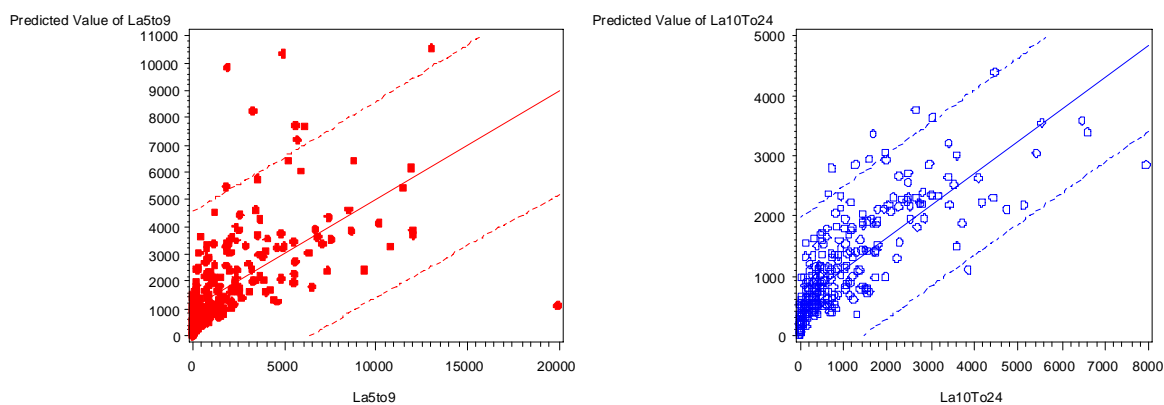
Figure 4.5.2.3. Quality-of-fit plots for small (5 to 9 mm) and larger larvae (10 to 24 mm); modelled were the larvae abundances as being affected by spatial extension and temporal prolongation. Both panels show the predicted versus observed values.

4.6   Summary

Trends in the physical and biological variability could be detected during the present analysis. The variability may be influenced by wider scale events, but effects can be seen at smaller scales (e.g. herring spawning sites and temperature). Linkages between changes in zooplankton and water characteristics and the recruitment variability in herring and Norway pout are indicated, however, the underlying mechanisms that actually create the recruitment variability are still unclear. Annual recruitment strength does differ between the different

spawning components of herring (ICES, 2007). Observations indicate that the recent declining trends are caused by a recruitment failure in the northern and central North Sea, where also water characteristics and zooplankton have shown the greatest change during the last decade.

The trends over decades seen in water temperature (and density) are probably not caused by one off inflow events (e.g. 1989 or the winter of 2000–2001 in the Norwegian Trench, Svendsen, IMR, Bergen pers com), although these can impact recruitment in a few years (see Section 2 and 4.3). It is likely that the longer trends in temperature and density reflect a general warming of the area (Holliday, SOC, UK, Brown, BODC, UK and Svendsen pers com.) since the late 1980s that has been caused by warming of inflowing Atlantic Water, warmer summers and reduced surface winter cooling (mild winters).

It appears unlikely that increased predation by mackerel or horse mackerel have caused poor recruitment. The potential for other factors such as maternal effects, toxins or parasites to influence recruitment have yet to be investigated.

5   Bio-physical modelling

The ToR was "to contrast this synthesis [ToR a)] with the results from bio-physical models hindcast through the same period (1980–2006) to determine if any further hypotheses can be ruled out as the cause of the poor recruitment of North Sea planktivorous fish".

Presently, the availability of bio-physical modelling (BPM) tools to carry out the work specified in the ToR is extremely limited. As far as we are aware, no BPM has been developed for North Sea Norway pout. In the case of Atlantic herring, a published study (Bartsch *et al.*, 1989) focused on a single year (the winter of 1987–1988), when the authors hypothesized anomalous circulation patterns in the northern North Sea resulting in atypical larval transport patterns. Some more recent models developed for North Sea sprat (Daewel *et al.*, submitted; Kühn *et al.*, submitted) are largely based on functional relationships developed for herring larvae, re-parameterised for sprat where possible. The equivalent model for herring will be developed in the near future, as part of on-going research (RECLAIM project, EU FP6 contract no. 44133) and used to produce time series hindcasts but these are not yet available. Recent investigations on the annual transport of Downs herring larvae between 1996 and 2005 showed that transport from hatching sites varied between years based on the hydrography and behaviour of the larvae (Dickey-Collas *et al.*, in prep). However, as the MIK indices for this area are at such coarse spatial resolution and there are no separate estimates of recruitment for the Downs component of North Sea herring, it was not possible to compare annual time series of transport with recruitment strength. Sandeel BPM's have been used to investigate various aspects of the ecology of the species in the North Sea but have either targeted a specific area of the North Sea (Gallego *et al.*, 2004) or left out some important, generally accepted spawning grounds in the area (e.g. banks in the central North Sea (Proctor *et al.*, 1998); spawning grounds off Orkney, Shetland and in the Moray Firth (Christensen *et al.*, (submitted)). Some of these studies considered annual time series (1955–1993, Proctor *et al.* (1998); 1970–2004, Christensen *et al.*, (submitted)). These studies have identified the importance of transport processes but the most recent work (Christensen *et al.*, submitted) has shown that both productivity (egg production and survival) and transport are approximately equally important and both should be addressed, a reason given by the authors for the variable success of past modelling exercises to explain sandeel recruitment in the North Sea.

The usefulness of "bio-physical models hindcasts", presumably of late larvae (in the case of herring and Norway pout) or settled juveniles (in the case of sandeel), i.e. until the stage when passive transport (or non-directed swimming) can no longer be reasonably assumed, is highly dependent on the characteristics of the BPM. For example, if the BPM does not incorporate any processes that are directly or indirectly affected by water temperature, comparing the model results with a water temperature time series is meaningless. Therefore, the BPM must incorporate all potentially relevant processes (although not necessarily explicitly). We have compiled a Table with some suggestions of processes/relationships that should be included into BPM's of the three species, and the current status of knowledge of each process/relationship (Table 5.1). Carrying out a comprehensive modelling exercise for all 3 species and a suitable time series of years, over the full geographical domain of the North Sea is a very significant task. However, the final development of the relevant tools is not far away so major advances in this field can be expected in the near future, as long as this modelling work attracts the necessary level of interest and funding by the scientific community.

Table 5.1. Listing of the data/relationship requirements to model each of the relevant processes within an individual-based bio-physical modelling framework, for the 3 species of interest. Notes: [1] **T required for a number of other processes (e.g. growth modelling) and S if any processes are modelled as a function of water density (e.g. buoyancy);** [2] **vertical patterns include ontogenetic vertical migration behaviour, DVM and buoyancy (of eggs and/or larvae);** [3] **settlement in the case of sandeels and metamorphosis in the case of herring and Norway pout;** [4] **growth can be modelled following a "holistic" approach, as a function of temperature and/or prey (food) availability, or using a mechanistic feeding and growth model, where a considerable number of functional relationships and parameters is required;** [5] **in its simplest form, mortality can be modelled as a function of larval size and/or predator fields, or a full mechanistic model can be used, in which case a considerable number of functional relationships and parameters is required.**

		SANDEEL		HERRING		NORWAY POUT	
PROCESS	REQUIREMENTS	AVAILABLE	SOURCE	AVAILABLE	SOURCE	AVAILABLE	SOURCE
spawning	location	Y	ICES (2007b); FRS (2005)	Y	ICES, 2007a	N	
	EP function	N?		~	(can be done rel. easily)	N	
	magnitude (population egg production)	Y	SSB + fecundity data	Y	SSB + fecundity data	N	
larval transport	hydrodynamics (flow, turbulence, T and S[1])	Y	Several HDM (ROMS, POLCOMS, HAMSOM, etc.)	Y	(same)	Y	(same)
	vertical patterns or behaviour [2]	Y	Jensen *et al.* (2003)	Y	Heath *et al.* (1988, 1991); Munk *et al.* (1989)	Y	Munk (unp.data)
	endpoint [3] (e.g. settlement, metamorphosis)	Y	spawning areas	Y	Gallego and Heath, 1994	~	Russell, (1976)
growth [4]	f(T)	Y (relationship) Y (T data)	Christensen *et al.* (submitted) Switek *et al.* (2005)	Y (relationship) Y (T data)	Folkvord *et al.* (2004); Munk *et al.* (1991)	Y ? Y (T data)	Munk (unp. observational data)
	f(prey)	N (relationship) Y (prey data)	Switek *et al.* (2005)	Y (relationship) Y (prey data)	Folkvord *et al.* (1997); Munk (1992)	N (relationship) Y (prey data)	
	mechanistic feeding and growth model	N		Y	Fiksen and Folkvord, (1999)	N	
mortality[5]	f(larval size)	N		Y	McGurk (1993); Kiørboe *et al.* (1988)	N	
	f(predators)	N		N		N	
	mechanistic mortality model	N		N		N	

6   Candidate early warning signals

Term of reference c requested that if SGRECVAP could establish plausible causative links for the poor recruitment, any candidate early warning signals that could be used to assist in determination of recruitment scenarios for short term projections of stock numbers should be reported. SGREVAP considered that the investigations are not far enough advanced to be able to recommend any indices as predictors for trends in productivity but hydrography and zooplankton show potential and should be further investigated.

The issue of whether the poor recruitment has occurred since 2002, or is part of a declining trend from the 1980s onwards is crucial to the analysis (see Section 2.1). The available evidence for either hypothesis is conflicting. SGRECVAP could not decide which trend was dominant. As mentioned by SGRECVAP 2006, many of the environmental signals (e.g. temperature and NAO) are correlated, sometimes with a lag, thus disentangling the dominant processes is complex and requires further investigation. It should be noted, that other than temperature, very few of the time series considered by SGRECVAP have a predictive ability as the data are collected within the same time frame as the MIK index for herring.

As SGRECVAP cannot predict the recruitment trends and there is no evidence to suggest that the current trend will change, the assumption that poor recruitment will continue is valid within the precautionary approach. Therefore stock projections should assume that the period of poor recruitment will continue.

7   Conclusions

The residuals from the stock to recruit curves for Norway pout and herring expressed similar trends despite the recent better recruitment in Norway pout, whilst there was no trend in the residuals of sandeel. A detectable change in the recruitment of herring and Norway pout in the North Sea was either caused by a reduction in productivity in the early 2000s or by a longer cycle of decline since the 1980s (which could also be described as a period of large positive residuals then a period of small residuals followed by a period of large negative residuals). There was only a biomass signal on the recruitment of sandeel. The productivity of all three stocks is low at present.

The lack of any properly funded research project on the recruitment of planktivorous fish in the North Sea meant that SGRECVAP was limited to list potential hypotheses, stimulate further investigations and carry out preliminary analysis.

A change in the North Sea environment has occurred at the same time as the poor recruitment in herring and the downward trend in Norway pout. In the spawning areas of herring and Norway pout (in the central and northern North Sea) the sea temperatures have increased markedly, with a commensurate reduction in water density. This may effect frontal development. The trend in herring recruitment since 1998 is similar to the trend in declining water density at the main herring spawning sites. The warming of the northern North Sea is associated with warmer Atlantic Water and less cooling over winter.

As mentioned in SGRECVAP 2006 there have been broad gradual change in the zooplankton community of the North Sea (ICES, 2006). SGRECVAP 2007 looked more specifically at areas of importance to larvae herring production, and probable Norway pout spawning. Overall from 1950 to the present, only the central North Sea shows large variability in the zooplankton community and the standing stock of chlorophyll. In the northern North Sea only the abundance of *Calanus* sp. copepodites showed a declining trend. However in the central North Sea, the total abundance of copepods, the abundance of adult *Calanus* sp. and *Calanus* copepodites all showed declining trends. The timing of the changes in zooplankton was similar to those in the recruitment residuals of the fish (i.e. late 1980s and around 2000). There

was a reduction in chaetognath abundance since the 1950s, with a slight increase in recent years, particularly in autumn. The well known shift from *Calanus finmarchicu*s to *C. helgolandicus* was clearly seen, but process studies are required to determine whether this is important for the productivity of planktivorous fish in terms of the quality of food or phenology (timing).

There has been a recent increase in mackerel, horse mackerel, sardine and anchovy in the North Sea. Preliminary investigations suggest that mackerel and horse mackerel are not the cause of the poor recruitment as they do not overlap spatially and temporally with the larvae of herring or Norway pout. Spatial data on anchovy and sardine were not available to SGRECVAP, so this needs further exploration. Parasites or anthropogenically produced toxins may also affect planktivorous fish recruitment.

Suitable coupled bio-physical models are not currently available for North Sea herring, sandeel and Norway pout. Their development should be encouraged to investigate the mechanisms that determine year class strength and explain the commensurate signals seen in the environmental time series.

Whilst the impact of toxins, parasites and maternal effects where not considered in detail, these factors may be playing a role in the serial poor recruitment of North Sea herring.

The investigations are not far enough advanced to be able to recommend any indices as predictors for trends in productivity but hydrography and zooplankton show potential and should be further investigated. As SGRECVAP could not predict trends in recruitment and there is no evidence to suggest that the current trend will change, the assumption that poor recruitment will continue is valid within the precautionary approach. Therefore stock projections should assume that the period of poor recruitment will continue.

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Annex 1: Executive summary of SGRECVAP 2006

The poor recruitment in recent years (2001–2004) in planktivorous fish in the North Sea has become cause for concern for fishers, managers, and scientists alike. It has lead to fishery closures and cuts in total allowable catches in sandeel, Norway pout, and herring. SGRECVAP met to investigate and describe the serial poor recruitment, and review probable mechanisms for the recruitment trends.

Time-series analysis showed that there was a common trend in the recent recruitment of all three target species. There was a strong negative trend in the stock-recruit residuals for herring and Norway pout, suggesting that the poor recruitment in those stocks is not related to spawning-stock biomass size. This was not the case in sandeel, where the situation was more complex. The common pattern of decline in recruitment seen in the planktivorous fish was not common to the major commercially exploited fish species in the North Sea. There was evidence for significant shifts of at least two periods of recruitment for the major commercial fish species exploited in the North Sea (1986 and 1996/1997). Specifically for the three target planktivorous species, SGRECVAP considered there was a significant shift in recruitment in 2001.

There was enough evidence to conclude that poor recruitment in herring was caused by a higher mortality of herring larvae before February of each year. The mechanisms for this were most likely poor larval feeding, predation or poor hatching condition and probably a combination of these. There was evidence that higher mortality of herring larvae can co-occur with high larval production.

Whilst herring, Norway pout and sandeel showed a common trend in recruitment, it cannot be assumed that the same mechanism was common for all three species. Owing to insufficient information on the production of each life history stage in Norway pout and sandeel it was not possible to determine the mechanisms driving recruitment. It was clear that the poor sandeel recruitment from 2002 occurred at low spawning-stock biomass (the stock was below Blim in 2000); this was not the case for Norway pout.

A well documented change in the planktonic community occurred in the North Sea after the mid 1980s. Change has continued to date, on a gradual basis, and is linked to the broader process of climate change/variability. Reponses at other trophic levels to this gradual change in the zooplankton may result in abrupt changes.

More exploration is needed to investigate the hypotheses presented in the report particularly targeting ecosystem interactions, especially in zooplankton (combined with hydrographic variability), predation, and quality/condition of adults, eggs, and larvae. The Study Group on Recruitment Variability in North Sea Planktivorous Fish (SGRECVAP) acknowledged that many of the proposed hypotheses could not be tested without extensive use of empirical data and individual and ecosystem modelling (biophysical models and spatial trophic modelling).

Annex 2: Terms of Reference, resolution 2006/2/LRC07

The Study Group on Recruitment Variability in North Sea Planktivorous Fish [SGRECVAP] (Chair: Mark Dickey-Collas, The Netherlands) will meet in Plymouth, UK from 7–11 May 2007 to:

a) produce a synthesis of quantitative estimates of the annual and seasonal anomalies of the following characteristics of the North Sea between at least 1980 to 2006 (at both the whole North Sea and sub region level) with access to the REGNS database:

    i) oceanic water inflow into the southern and northern North Sea.

    ii) hydrographic induced transport fluxes across the North Sea.

    iii) temperature and salinity by region, including water mass characteristics.

    iv) the relative strength and locations of frontal features.

    v) copepod biomass and abundance.

    vi) total zooplankton biomass and abundance.

    vii) mismatch index, as defined by SAHFOS.

    viii) the abundance and distribution of planktivorous fish larvae.

    ix) recruitment indices of planktivorous fish.

    x) spatial and temporal overlap of sprat, adult herring, mackerel, horse mackerel and seabirds with pre-recruits of planktivorous fish.

b) to contrast this synthesis with the results from bio-physical models hindcast through the same period (1980–2006) to determine if any further hypotheses can be ruled out as the cause of the poor recruitment of North Sea planktivorous fish;

c) if plausible causative links can be established, report on any candidate early warning signals that could be used to assist in determination of recruitment scenarios for short term projections of stock numbers;

d) report any evidence for the causes of the poor recruitment in recent years in North Sea herring to the HAWG meeting in 2008.

SGRECVAP will report by 30 August 2007 for the attention of the Living Resources Committee, and ACFM.

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Annex 4: SGRECVAP Terms of Reference for the next meeting

SGRECVAP was set up to meet twice in concurrent years (2006 and 2007). This has now occurred, and considering the recommendations of the study group, there is no proposed follow up meeting.

Annex 5: Recommendations

SGRECVAP has the following recommendations:

RECOMMENDATION	ACTION
1. That coupled bio-physical models be developed for North Sea herring, Norway pout and sandeel	National Labs/ EU
2. The national labs, the industry and/or the EU fund a specific project to investigate the serial poor recruitment in North Sea herring and Norway pout.	National Labs/ EU/ fishing industry
3. That the REGNS database be made more available to those who request data	ICES, JRC