ICES CM 2002/Q:08

Evidence for effects on the North Sea ecosystem due to varying oceanic inflow over the last 100 years.

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Oceanic inflow is estimated to contribute more than 90% of the nutrient input into the North Sea (NSTF, 1993). Variability in the volume, chemical properties, biological content and source of the inflowing water is thus likely to have a considerable effect on North Sea ecosystems. Changes seen in the plankton over the last 40 years, measured by the Continuous Plankton Recorder (CPR) survey, allow clear periods to be identified that appear to be associated with variability in inflow. Monthly estimates of inflow, outflow and netflow across a section between Orkney and Utsira in Norway, have been derived from runs of the NORWECOM model for two depth intervals: surface to 150m and >150m. A comparison is made between these modelled physical measurements and plankton results for the period 1958 to 1999. Distinguished plankton periods that appear to reflect changing inflow events are discussed in relation to hydrometeorological and fisheries variability and earlier plankton studies over approximately the last 100 years.

Keywords: Oceanic inflow, zooplankton, inflow modelling, hydrographic variability, atmospheric forcing, slope current, fisheries.

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Introduction

The volume and source of inflowing oceanic water to the North Sea, in terms of nutrient content, is likely to have a major impact on ecosystem productivity since it is estimated that 90% of the annual input of nutrients is derived from this source (NSTF, 1993). Variability in these inflows is thus likely to effect the carrying capacity for fish resources and in turn the composition and tonnage of fish landings. Early evidence demonstrating variability in the source and volume of inflowing oceanic water was shown from indicator plankton (Fraser, 1969) and from salinity (Dickson 1967; Dickson, 1971), but until recently this aspect of North Sea ecosystem modulation has been largely ignored as anthropogenic impacts from eutrophication, contamination and fisheries have been the main focus to explain ecosystem variability. Recent work from the Continuous Plankton Recorder (CPR) survey and 3D physical modelling, has helped to reinforce the importance of oceanic inflow as a driving force for changes in the North Sea (Edwards *et al.,* 2002; Reid and Edwards 2001). The work presented here is 'in progress' and was set as a target to contribute to this theme session. We present in sequence:

a. Changes in the abundance of two of the largest and most important copepods in the North Sea: *Calanus finmarchicus* and *Calanus helgolandicus* for the period 1958 to 2000 to demonstrate evidence for different 'biological periods' that may be related to inflow events.

b. A comparison between these findings and the results of the wind driven NORWECOM 3D model for measured inflow, outflow and netflow at two depth intervals 0-150m and 150-500m.
c. A retrospective analysis of evidence for other inflow events from 1900 to 1957 based on published information on biological, chemical and physical events.

Methods

Continuous Plankton Recorder (CPR)

A network of transects along which CPRs are towed monthly across the major geographical regions of the North Atlantic has been operated, with a break during the Second World War, since 1931. The CPR is a high-speed sampler (usually towed between 10-18 knots), sampling at a depth of approximately 10m. After the tow, the CPR is returned to the laboratory for routine analysis involving the recorded estimate of phytoplankton biomass (phytoplankton colour index) and the quantification of zooplankton and phytoplankton taxa (Warner and Hays, 1994).

The NORWEgian ECOlogical Model system (NORWECOM)

The wind and density driven circulation module of the NORWECOM coupled physical, chemical, bio-logical model system (Skogen *et al.,* 1995) has been used to calculate positive, negative and net transports across a west-east transect between Orkney and Utsira (Norway) in the northern North Sea. The model uses a 20km horizontal grid covering the whole shelf area from Portugal to Norway. Velocity fields were calculated for each pixel grid at 15-minute time steps over the period 1958 to 1999. Measurements were averaged to give a mean velocity field for each month in the time series over the whole North Sea. The transport components were calculated from these measurements normal to and integrated across the whole Orkney-Utsira section. The model was forced by six-hourly wind stress (determined from hindcast atmospheric pressure fields), four tidal constituents, where available monthly river runoff and a climatological Baltic inflow. For information on how heat fluxes, evaporation and precipitation, initial values for velocities, water elevation, temperature, salinity and boundary conditions are treated in the model see Skogen *et al.* (1995).

Comprehensive Ocean-Atmosphere Data Set (COADS)

Monthly means of scalar wind, U and V winds (south to north and east to west components of wind respectively) were averaged from COADS (Woodruff, 1987) one degree data for the area 55°N – 60°N, 5°W - 5°E over the period January 1958 to December 1999. The data were provided by the NOAA-CIRES Climate Diagnostics Center (Boulder, Colorado, USA).

North Atlantic Oscillation (NAO)

In the North Atlantic, the dominant mode of atmospheric variability is the NAO. An index of the variability of the NAO is derived from the alternation of atmospheric mass between subtropical, high-surface pressures (centred over the Azores) and sub-polar, low surface pressures (centred over Iceland) and accounts for more than one third of the total variance of sea level pressure in the North Atlantic (Dickson and Turrell, 2000). Decadal trends in this index influence regional temperatures and precipitation, and the degree of wind speed/direction over northern Europe (Hurrell, 1995).

Results

Results

Calanus and inflow

The abundance of the boreal copepod *C. finmarchicus* and warm temperate congeneric *C. helgolandicus* has shown a systematic alternation in abundance in the North Sea over the last 40 years (Figure 1). In part, this reflects the inverse correlations that the two species show with the NAO (Fromentin and Planque, 1996, Planque and Fromentin, 1996). Although the relationship between *C. finmarchicus* at least, has broken down since 1996 (Planque and Reid, 1997), a strong relationship with sea surface temperature (SST) is also evident for *C. helgolandicus* which in the North Sea can be considered as a biological thermometer (Lindley and Reid, 2002). When expressed in the ratio of *C. helgolandicus* to *C. finmarchicus* (Figure 2) the regime shift identified by Reid *et al.* (2001a), is clearly distinguished. This event was shown to be strongly related to increased inflow of oceanic water from the Atlantic (Reid *et al.,* 2001a) with a southerly source and that also appears to be linked to higher flows in the slope current to the west of the British Isles (Holliday and Reid, 2001; Reid *et al*., 2001b). The two peaks evident in the ratios also coincide with the two major incursions demonstrated by the intrusion of southerly plankton into the North Sea (Edwards *et al.,* 2001; Holliday and Reid, 2001).

If expressed in the reverse ratio of *C. finmarchicus* to *C. helgolandicus* two other periods are identified: a 'cold' biological event between approximately the years 1978 to 1982 and an earlier 'cold' event between ~1962 and 1967. In the earlier period *C. finmarchicus* was abundant in the North Sea. The two species were not distinguished in CPR analysis prior to 1958, but because *C. finmarchicus* is on average 10 times more abundant than it's 'sister' species, a comparison has been made between *C. finmarchicus* and total *Calanus* over the whole period 1946 to 2001. The relationship is very close (r= 0.85; p=0.01). Applying this relationship back to 1946 (Figure 3), it is clear that *C. finmarchicus* also dominated the plankton of the North Sea for the period 1946 to 1957.

If the relative abundance of these two copepod species is expressed in percentage terms (Figure 4), a clear trend in their relative abundance is evident with a notable change in the trend in the years 1978 to 1982 first identified in Reid *et al.* (2000). Then this 'cold biological event' was attributed to a 'top down' density driven modulation from the fishery. There may still be a density driven component during these years, but it would now appear that this change is physically forced (Edwards *et al.,* 2002; Reid and Edwards, 2001). The 1978 – 1982 event is also distinguished in the plankton by the presence in the North Sea and especially in the Norwegian trench, of a suite of plankton characteristic of boreal waters (*C. hyperboreus, Metridia longa, Navicula planemembranacea,* Reid and Edwards, 2001), plus a wide range of other associated changes in plankton, fish and hydrographic properties (Edwards *et al.*, 2002).

Characterisation of the ~1962-1967 period is less clear and has been less rigorously examined to date. It would appear to again represent a time of lower oceanic inflow with reduced penetration of 35 salinity (see Figure 9 of Reid *et al.,* 1992) water into the North Sea. Unpublished work by Beaugrand clearly distinguishes this period on the basis of calanoid copepod community composition and both local and large-scale hydro-climate parameters.

NORWECOM Modelled inflow/outflow

Wind and density driven forcing generates gradients at the surface of the North Sea. The model that is used for this analysis is primarily forced by wind data in real time derived from surface pressure. Density driven effects are not considered. External processes to the North Sea that might also generate inflow e.g. from the strength of the slope current are also not included in the model. Modelled inflow into the northern North Sea is shown in Figure 5a. A clear trend is evident over the period 1958 to 1999 to a shortened period of lower inflow in the summer with an increasing intensity and longer period of strong winds in the rest of the year. A similar plot for scalar/winds (Figure 5b) shows the same pattern demonstrating the clear linkage between wind and the model results.

Figure 6 shows the results for inflow and outflow in the same format as above for two depth intervals 0-150m and >150 to 500m. From the perspective of the model 500m represents the bottom of the Norwegian Trench. Clearly evident in the inflow and outflow plots for the upper water layer is the increased winter inflow post 1987 that corresponds with the regime shift identified by Reid et al., 2001. Outflow in this upper layer was minimal in the stratified summer months of the year. Enhanced outflow also occurred in most years subsequent to 1987 in the water layer 0-150m with low inflow especially in the first three months of the year in the layer below 150m . The 1978-1982 event is most evident in the reduced netflow in the upper layer (Figure 7) in the early months of the year and higher inflow and net flow at the same time in the water layer below150m (Figures 6,7). Netflows (Figure 7) in the upper layers appear to be generally lower in the first six months of the year and the reverse in the lower layer. The anomalously high inflow event of the autumn of 1972 (Figure 7) is also evident in the plankton with incursion of the doliolid *Dolioletta gegenbauri*. There is little evidence from the modelled transports for anomalous variability in the period 1961-1966 other than generally low inflow in the upper layer.

The modelled data used in this study were originally derived from flow averaged over four depth intervals, 0-30m, 0-50m, 0-150m and 0-500m. A Principal Component Analysis was carried out on all monthly flows over the period 1958 to 1999 for all depth intervals. The resulting First Principal Component was shown to be inversely correlated with the NAO ($r = -0.74$; $p=0.01$). Given the known high correlation between the NAO and scalar winds in the northern North Sea (Reid and Planque, 2000; Dickson and Turrell, 2000) this relationship is not surprising, but the correlation re-emphasises the important role that the NAO plays in hydrometeorological variability in the North Sea.

Historical evidence for inflow events in the Twentieth century

The Continuous Plankton Recorder (CPR) has systematically surveyed the North Sea on a monthly basis in both space and time since 1948. Records from the survey suggest that particularly high numbers of oceanic plankton species were recorded in the early 1950s, 1972, in the late 1980s, early 1990s and in 1997/98 (Reid *et al.,* 1992; Edwards *et al.,* 1999). Using historical evidence from early plankton and fishery research cruises, we have attempted to build a chronology of Atlantic inflow events that predate the CPR survey back to the beginning of the 20th century. The hydrobiological indicators include oceanic plankton (particularly thaliacea) and the presence of fish species in the North Sea that are normally characteristic of more southerly and shelf-edge habitats. Major swarms of thaliacea and southerly species recorded in the North Sea throughout the 20th century are shown in Table 1. Physical data was also examined to determine the areal extent of Atlantic water (>35 PSU) and major salinity anomalies in the North Sea. Whilst many historical records have been examined, the major sources of information come from work previously published by Fraser (e.g. 1961) and Dickson (1967). In Dickson's study, based on biological and physical evidence, he describes oceanic inflow events as 'Accelerated Atlantic inflow events'. Accelerated inflow events (pre 1950s) catalogued by Dickson (1967) include 1905-1909, 1920-1921, 1931-1935, 1937-1939 and 1949.

During the period 1900-1925 particularly notable inflow events evidenced by high salinity anomalies were recorded between 1903-1906 and from 1920-1923 (Lucas, 1946). Deep water specimens of the fish genus *Arnoglossus* were recorded in the northern North Sea 1904-

1906 suggesting a major inflow event (Dickson, 1967). And in 1904-1905 the Arctic-boreal euphausiid *Thysanoessa inermis* was common in the Norwegian Trench and Skaggerak. Other cold water species such as *Calanus hyperboreus* and *Metridia longa* were present throughout the North Sea between the years 1902 to 1906, at times even at the surface (Kramp, 1913). The Arctic species *Calanus hyperboreus* was also common in the bottom waters of the Faroe-Shetland Channel and was found as far south as 54°N 30'W in the North Atlantic at this time. Huge drifts of "distinctly" Atlantic salps (especially *Salpa fusiformis*) into the northern North Sea occurred in 1905 and "enormous shoals" of the warm water pteropod *Spiratella lesueri* (not recorded north of the Bay of Biscay before 1906) were reported entering the English Channel in 1906 (Fraser, 1961).

Dickson (1967) suggests that a minor accelerated inflow event occurred between the period 1912-1914. The only notable oceanic species that were recorded around this period was *Doliolum nationalis*, which was recorded in the Southern Bight in 1911 (Lindley *et al.,* 1990). The next major oceanic faunal invasion occurred between the period 1920-1923 when enormous swarms of *Salpa fusiformis* were noted in the northern North Sea (Fraser, 1949). Vast swarms of pteropods and radiolarians were also noted in the North Sea during this period (Hardy, 1923).

The only inflow event that stands out between 1926-1950 as exceptional was in the years 1931-1935. This period was marked by the presence of Mediterranean water in the Faroe-Shetland Channel and exceedingly high salinities in the Southern Bight in the autumn of 1933 (Dickson, 1967). Dickson also identified hydrobiological evidence for a major inflow event based on the incursion into the Baltic from the North Sea of horse mackerel (1932) and anchovy (1933) as well as noting a dramatic rise in the anchovy stock of the southern North Sea between the period 1930-1934 and the occurrence of unusual warm-water fish species. Lucas (1933) noted the presence of Atlantic thaliacea (*Dolioletta gegenbauri*) in the northern North Sea in 1933. Other evidence for unusual hydro-climatic conditions around this period included major phytoplankton blooms in 1933 and 1934 of *Rhizolenia styliformis* and *Biddulphia sinensis* covering 7,400 squares miles in the southern North Sea and the presence of *Sagitta elegans* in the Thames Estuary in 1933-1934 (Dickson, 1967). In summary, three major Atlantic faunal invasions and salinity anomalies occurred in the North Sea in the first half of the 20th century in 1903-1906, 1920-1922 and 1931-1935.

Discussion

From evidence collected by the CPR and other data sources it would appear that the plankton of the North Sea over most of the last century had a cold temperate character. The copepod *C. finmarchicus* dominated copepod assemblages certainly back to 1946 and from earlier CPR records would also appear to have been the dominant species in the 1930s. Information from other surveys indicates that colder conditions prevailed from the beginning of the 20th century.

On the above pattern are superimposed two short periods when the North Sea had a more boreal character with incursion of species usually found much further to the north. The most recent of these events occurred between approximately the years 1978 and 1982 and had a profound effect on North Sea productivity, apparently even leading to a reduction in the total biomass of North Sea fish stocks (Edwards *et al.*, 2002, Reid and Edwards, 2001). The earlier period occurred in approximately the years 1902 to 1906; at this time boreal species were extensively distributed and common in the North Sea and even extended well south in the North Atlantic to the west.

Two short warm events occurred in the years 1920-23 and 1931-35, the latter including evidence for a major incursion of horse mackerel into the North Sea, even extending into the

Baltic, as well as extensive and large blooms of phytoplankton. These events show some of the characteristics (e.g. extensive phytoplankton blooms) of the period, with warm temperate zooplankton, that has prevailed until present following the regime shift that occurred around 1988. However, a preliminary examination of evidence from the CPR survey in the 1930s suggests that the plankton of the North Sea at that time had a cold temperate character. In terms of observed effects and its length the present warm phase would appear to be unique in at least the last century. The regime shift has had a pronounced impact on North Sea ecosystems evident in a range of altered hydrodynamic characteristics, step-wise changes in nutrient ratios and pronounced changes in both the abundance and composition of the plankton, benthos and other higher trophic levels. The growing season of the plankton appears to have extended considerably, much of the phytoplankton appears to be ungrazed and settling to the bottom. Together these ecosystem changes are unfavourable to cold water demersal fish species such as the cod, are reinforcing the observed pronounced decline in their stocks and are complicating fishery management decisions that at present are based on models that do not take into account ecosystem variability.

The cold and warm biological events appear to be linked to increased (warm) and decreased (cold) inflows of oceanic water from the North Atlantic. In the case of the cold events the source of the colder water that is carrying the boreal indicator plankton derives from the Norwegian Sea via a deep inflow into the Norwegian Trench with the species subsequently undergoing vertical migrations and advection onto the shelf. The warm event after 1988 is highly correlated with modelled oceanic inflow and with higher oceanic inflows from the Slope Current that bring in water to the North Sea of a Lusitanian origin. The enhanced inflows are generated by both increased winds and a change in the pattern of wind distribution with an increase in westerlies. These events are shown in turn to be highly correlated with the NAO and reflect regional changes in the climate of North West Europe. The periodic strong inflows from the Slope Current accentuate the overall changes, but the timing of their occurrence does not appear to be directly linked to westerly winds or the NAO although time series data to check such a link is not available. Such inflows as occurred in 1988/9 and 1998 were followed by enhanced levels of phytoplankton biomass as measured by the CPR colour index. We expect that any future incursion of Lusitanian water into the North Sea will lead to a further enhancement in productivity and peak in the index of phytoplankton colour.

Fromentein and Planque (1996) showed that the abundance of *C. finmarchicus* was highly significantly, inversely, related to the NAO, a relationship that broke down in 1996 (Planque and Reid, 1998). This species overwinters in a diapause state in deep water of the Norwegian Sea (and possibly at times the Norwegian Trench) and is most likely introduced to the North Sea via this route (Heath *et al.,* 1999) in deep inflow events, especially in the first quarter of the year. Examination of Figure 6 shows that inflow of water below 150m in the first quarter failed in years after 1987, fitting exactly the observed decline in the abundance of this species in the North Sea. In these years there was also, in contrast to the normal pattern, a strong outflow in the first quarter of the year. Any vertically migrating copepods from depth would be likely transported out of the North Sea along the Norwegian coast.

A major incursion of oceanic water below 150m recurred in the spring of 1996 and should have led to a renewed influx of *C. finmarchicus* (Planque and Reid, 1998). But the expected recruitment did not happen almost certainly because of a major reduction of the overwintering stocks in the deep water of the Norwegian Sea (Heath *et al.,* 1999; Planque and Batten, 2000). Further factors that are likely to have contributed to the disappearance of this species in the North Sea are the considerable northward biogeographic shift of cold boreal species like *C. finmarchicus* that have occurred over the last 40 years, the unfavourable warm temperatures for a boreal species that have recently characterised the North Sea due to forcing by both the NAO and Northern Hemisphere temperatures (Beaugrand et al., 2002) and a strong and warm Slope Current possibly preventing incursion of *Calanus in the* spring onto the shelf (Reid *et al.,* 2001b).

This preliminary comparison of plankton time series measurements from the CPR and modelled fluxes of water into and out of the North Sea has revealed an at time close relationship between the plankton and hydrography. The ecology of *C. finmarchicus* appears to be intimately related to the normal pattern of deeper water in/outflow in the first half of the year shown by the model. A conclusion that can be made from the evidence for the occurrence of periodic warm/cold events is that they are key forcing variables on North Sea ecosystems and similar events are likely to occur in other shelf seas. The patterns of change observed must have importance in developing an understanding of variations in the fish stocks of the North Sea. Furthermore, an integration of monitored plankton data and modelled hydrographic information may be of value in developing environmental input to new approaches to the management of fisheries. The model results need to be validated by field measurements and the processes behind these previously undocumented variations in the patterns of vertically differentiated inflow and outflow examined. This study serves to reinforce the need to maintain long-term monitoring programmes of the plankton and the value of the standardised procedures applied over a long period of time by the CPR survey.

Acknowledgements

The CPR survey would not be possible without the co-operation of the agents, owners, masters and crews of the vessels that tow the recorders. The survey is supported by a consortium comprising: IOC, UNIDO, the European Commission and agencies from Canada, Denmark, France, Iceland, Ireland, the Netherlands, the United Kingdom and the USA.

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TABLES AND FIGURES

Table 1: Thaliacea in the North Sea from historical records between 1900-2000. ♀ noted as reproducing in North Sea. According to Fraser (1949) the presence of reproducing populations indicates large influxes of warm oceanic water into the North Sea.

Records of Thaliacea in the North Sea	**Year**	**Region**
Salpa fusiformis (dense swarms) ♀	1905	Northern North Sea
Doliolum nationalis ♀	1911	Southern Bight
Salpa fusiformis (dense swarms) ♀	1920-22	Northern North Sea 55 N
Salpa fusiformis (dense swarms) ♀	1925	Northern North Sea 55 N
Dolioletta gegenbauri ♀	1928	Northern North Sea 55 N
Dolioletta gegenbauri ♀	1933	Northern North Sea 57 N
Salpa fusiformis (dense swarms) ♀	1954-55	Northern North Sea
Dolioletta gegenbauri	1972	Northern North Sea 56 N
Doliolum nationalis	1989	German Bight
Doliolum nationalis	1997	German Bight, Skagerrak

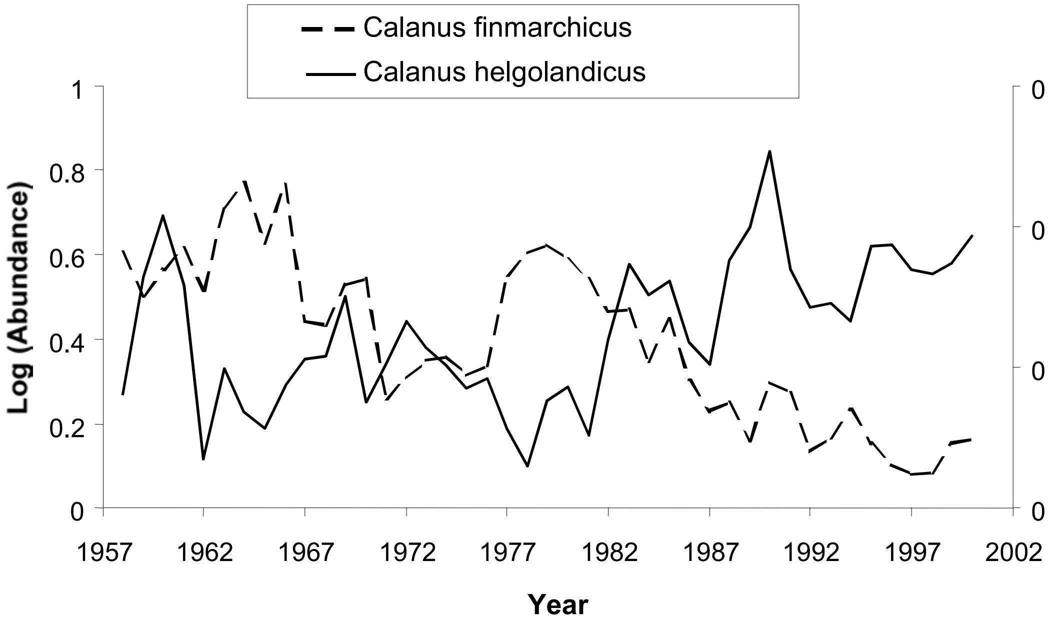

Figure 1. Graphs of the log abundance of *C. finmarchicus* (solid line) and *C. helgolandicus* (dashed line) averaged for the North Sea over the period 1958 to 2000.

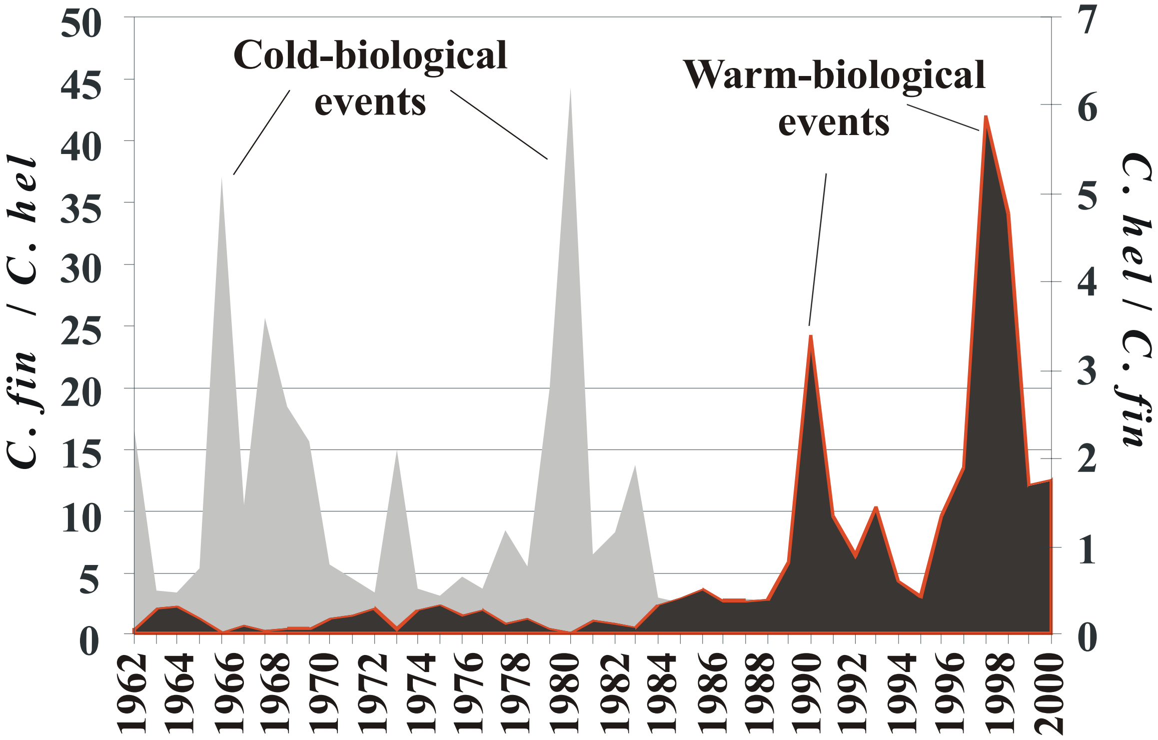

Figure 2. Plots of the relative ratios of *C. helgolandicus* to *C. finmarchicus* shaded in black and right axis and the reverse ratio, left axis and shaded in grey over the same period as Figure 1.

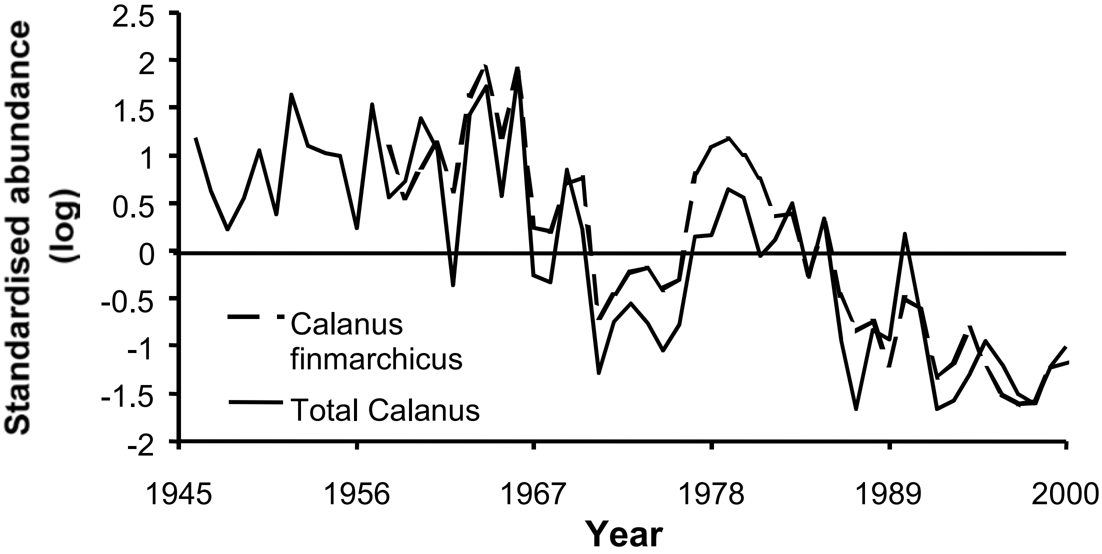

Figure 3. Standardized plots of the abundance of *C. finmarchicus* (solid line) with superimposed Total *Calanus* (dashed line) averaged for the North Sea between 1946 to 2000.

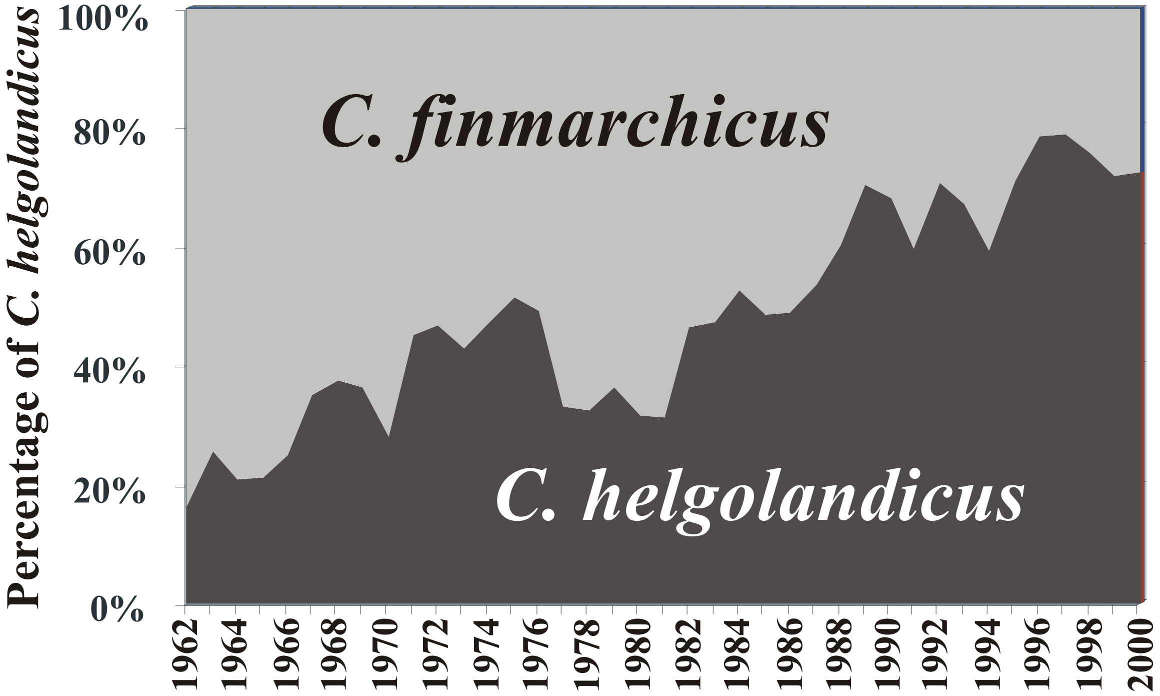

Figure 4. A plot of the relative % abundance of *C. finmarchicus* and *C. helgolandicus* (1962-2000).

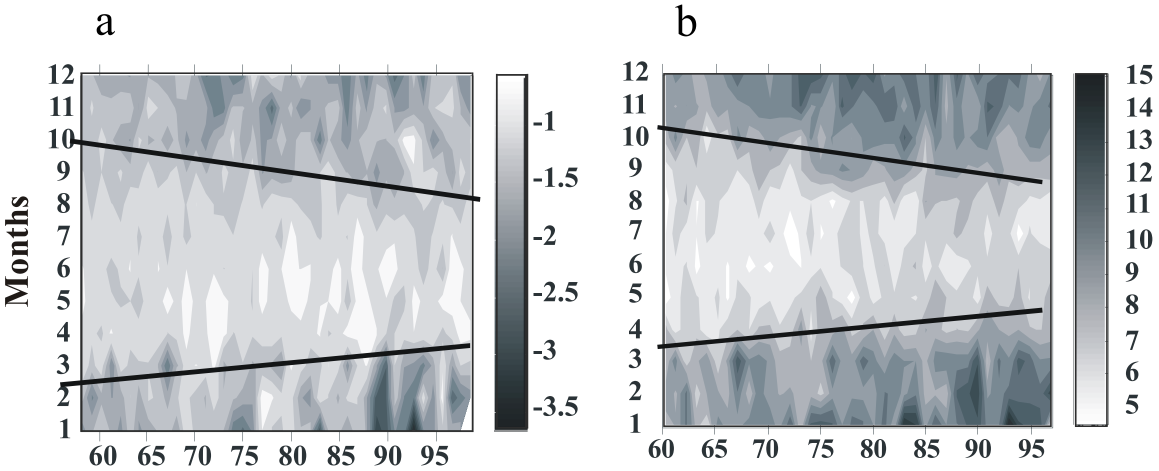

Figure 5a. A contour plot of modelled oceanic inflow into the North Sea across a section between Orkney in Scotland and Norway averaged for each month between 1958 and 1999 (Units Sverdrups). Left axis months. 5b. Scalar wind averaged for the area55°N 60°N 5°W 5°E, plotted as for 5a (Units m sec^{-1}). Lines have been delineated on the figures to emphasise the similarity in the seasonal changes seen in both parameters.

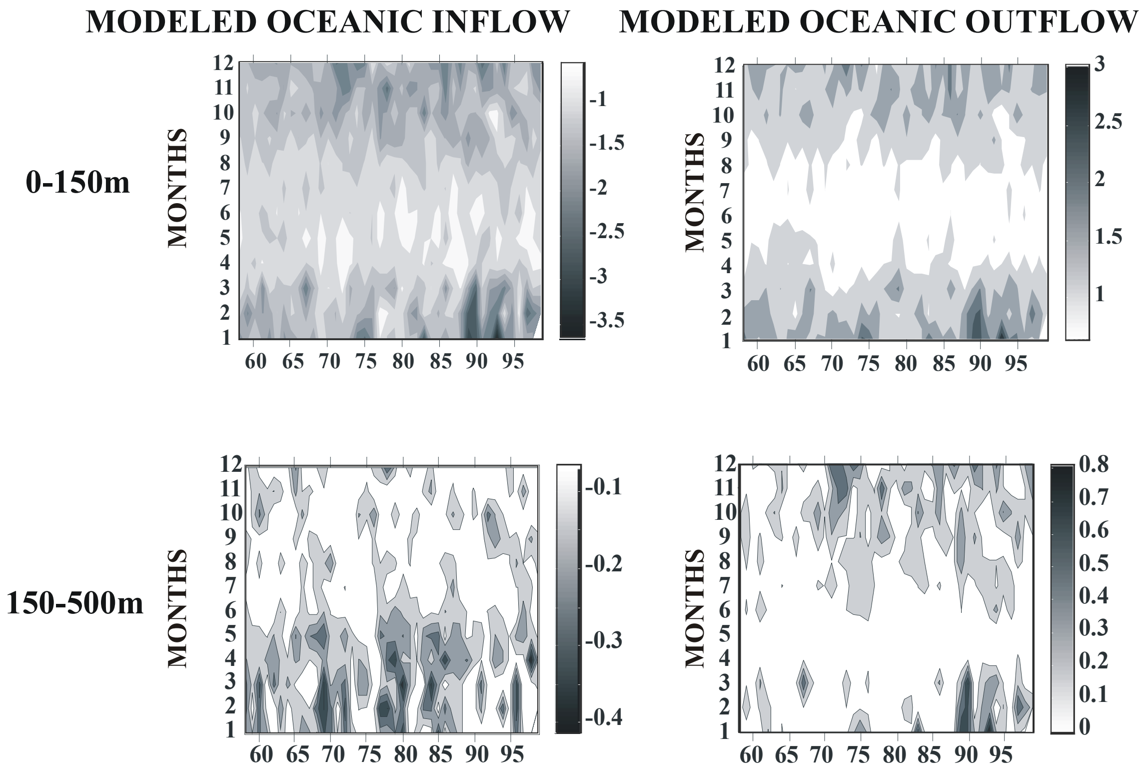

Figure 6. Contour plots as for previous figure with inflow (on the left) and outflow (on the right) for the depths 0-150m (upper panels) and 150-500m (lower panels).

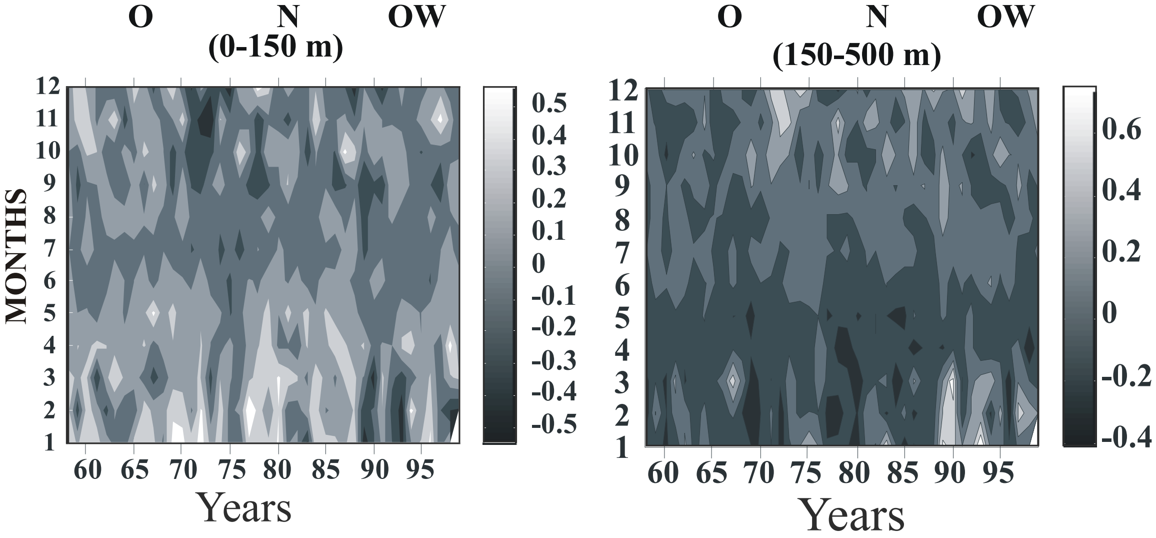

Figure 7. Long-term monthly means in modelled net flow for surface (0-150 m) and bottom (150-500 m).