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# Is there a connection between high transport of water through the Rockall Trough and ecological changes in the North Sea?

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Changes in the ecosystem of the North Sea may occur as pronounced inter-annual and step-wise shifts as well as gradual trends. Marked inter-annual shifts have occurred at least twice in the last two decades, the late 1980s and the late 1990s, that appear to reflect an increased inflow of oceanic water and species. Numerical modelling has demonstrated a link between altered rates of inflow of oceanic water into the northern North Sea and a regime shift after 1988. In 1989 and 1997 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 oceanic water has origins mainly west of Britain in the Rockall Trough, where the long-term mean volume transport is around 3.7 Sv northwards (1 Sv=$10^6$ $m^3$ $s^{-1)}$, but in early 1989 and early 1998 was observed to be more than twice the mean value, reaching over 7 Sv. These periods of high transport coinciding with the inferred pulses of oceanic water into the North Sea suggest a connection through the continental shelf edge current.



Key words: Rockall Trough, North Sea, interannual variability, zooplankton, phytoplankton, geostrophic transport, shelf edge current.

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## Introduction and Results

Evidence is growing that the North Sea periodically experiences changes in the physical and ecological conditions associated with different inflow rates of oceanic waters. Long-term monitoring has revealed ecological shifts of varying magnitude, effect and frequency (e.g. the late 1980s and late 1990s). In this paper we suggest that the sudden changes in the ecosystem are triggered by pulses of oceanic water entering the North Sea, that these pulses occur at the same time as unusually high transport of warm saline upper water through the Rockall Trough, and that it is the Scottish Shelf Edge Current that provides the connection between the two regions.

A significant event in the North Sea occurred around 1988, described as an ecological regime shift by Reid *et al.* (1998). There was a sharp rise in phytoplankton colour, a visual estimate of chlorophyll, from samples taken by the Continuous Plankton Recorder (CPR) and, in addition, many phytoplankton and zooplankton species showed changes in abundance (Figure 1) whilst the catches of horse mackerel increased substantially. Reid *et al.* (2000) employed a 3D numerical model of the northwest European shelf region forced by observed monthly wind fields to indicate that since 1988 the flow of oceanic water into the North Sea across a section between Orkney, Shetland and Norway had increased by around 50% (from 2 to 3 Sv in the model, 1 Sv=$10^6$ $m^3$ $s^{-1}$) in the winter months. They suggested that the increase in oceanic inflow brought about the observed regime shift. Further support for an increased inflow at that time is provided by observations of exceptionally high salinity in 1989–1991 west of Britain, in the English Channel and the North Sea. These changes were associated with higher transports leaving the North Sea (the Utsira section) and thus higher transports of inflow (Becker and Dooley, 1995).

A stepwise change observed in the macrofaunal benthic communities off Norderney (one of the Frisian islands) in the southern North Sea (Krönke *et al.*, 1998) approximately coincided with the changes observed in

 

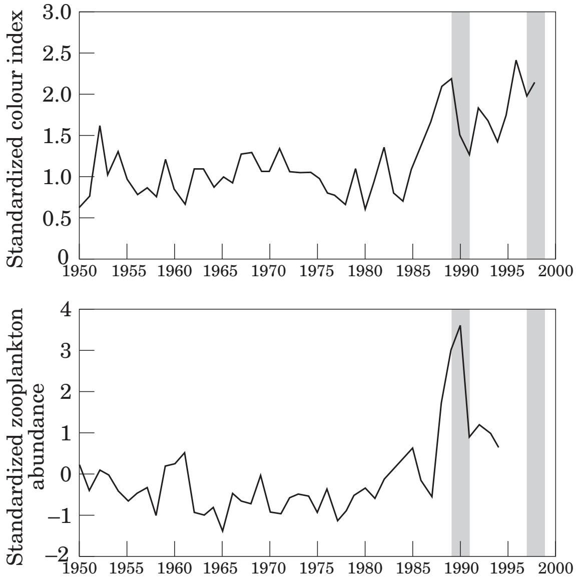


Figure 1. Time series of biological indicators in the North Sea. (a) Phytoplankton colour index (annual means averaged for the whole North Sea); (b) Zooplankton abundance (first Principle Component of variability in the North Sea from the CPR survey, data to 1994 only). Shaded boxes indicate the periods when oceanic doliolids were observed in the North Sea.

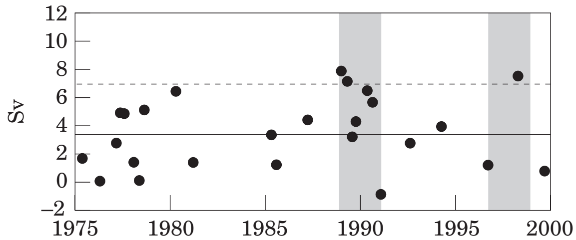


Figure 2. Transport estimates above 1200m through the Rockall Trough since 1975 (1 Sv=$10^6$ $m^3$ $s^{-1}$). Positive is northwards, solid line is the mean value (3.7 Sv) and dashed line is at 7 Sv. Geostrophic transports were calculated with a level of no motion at 1200 dbar, see Holliday *et al.* (2000) for full details. Shaded boxes as for Figure 1.

the plankton and hydrography. The mean biomass, abundance and species numbers of the macrofauna all showed changes around 1989/1990 that varied in degree depending on the season of the quarterly surveys sampled. The peak of the changes was, in general, centred on 1990, suggesting that the benthic response to the changes observed in the phytoplankton took from one to two years to take effect.

At the time of the 1988 ecological regime shift, further biological data implied that there had been an unusual incursion of oceanic water into the North Sea, but that the incursion was in the form of a pulse rather than a prolonged period of increased transport. The evidence came from the short-lived occurrence of doliolids (gelatinous zooplankton) normally found only in oceanic waters and not in the North Sea. From data collected in 1989, Lindley *et al.* (1990) observed the presence of doliolids in the German Bight and concluded that this was a result of exceptional inflow into the North Sea since doliolids are usually only found in oceanic waters to the west and southwest of Britain (Figure 1). A further incursion occurred in late 1997, again revealed by the presence of oceanic indicator species observed by the CPR survey (Edwards *et al.*, 1999). They noted that doliolids were found east of Scotland and between the Netherlands and Denmark in September 1997. At the same time copepods normally occurring west of the UK were found in the North Sea, for example the mesozooplanktonic copepods *Metridia lucens* and *Candacia armata*. These occurred first in September 1997 in the northern North Sea and reached the southern North Sea by December 1997. The spatial distribution of *C. armata* suggests that inflow occurred both from the north and through the Channel.

The pulses of oceanic water into the North Sea occurred at similar times to an unusual circulation in the Rockall Trough. Holliday *et al.* (2000) analysed a time-series of a hydrographic section across the northern Rockall Trough (located at 8–14°W 57–58°N, Figure 3) and showed that whilst the mean geostrophic transport of upper water (above 1200 m) is 3.7 Sv northwards, in some years it may be more than twice that amount (Figure 2). These periods of high transport (greater than 7 Sv) were observed in the sections occupied in early 1989 and spring 1998. No data were collected in late 1997 and the irregular temporal sampling prevents any estimate being made of the frequency of the increased transport periods. Around 50–80% of the net northward baroclinic transport is carried in the Shelf Edge Current (SEC), the remainder passes between Rockall and the Anton Dohrn Seamount (57.5°N 11.1°W), while around 1–2 Sv recirculates within the basin (Figure 3). The maxima in the total baroclinic transports are due to increased flow in a current west of the Seamount as well as increased flow in the SEC at 57°N. The SEC has a large barotropic component so the method of geostrophic estimation of transport does not account for all the flow. However, comparison of geostrophic shear with current meter records (Hill and Mitchelson-Jacobs, 1993) and recent sections across the shelf break with direct, instantaneous current measurements from Acoustic Doppler Current Profilers, suggest that the geostrophic technique can provide a reasonable estimate of the variations in transport in the absence of long-term observations of total transport.

## Discussion

There is compelling evidence that step-wise temporal changes in the ecosystem of the North Sea are strongly

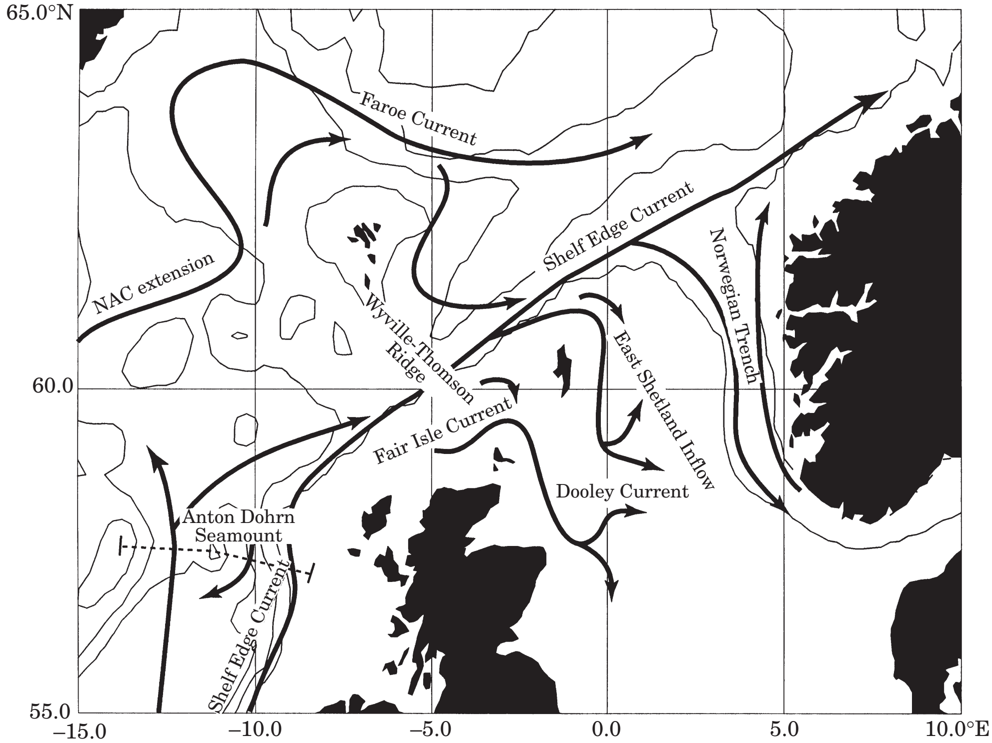


Figure 3. Schematic of upper ocean currents affecting the Rockall Trough and the northern North Sea (modified from Ellett *et al.*, 1986; Turrell, 1992, and Hansen *et al.*, 1998). NAC is North Atlantic Current. Dashed line indicates location of Rockall Trough hydrographic time series. Contours are at 200, 1000, 2000 and 3000 m.

connected to periodic pulses of inflowing oceanic water. The question then is what are the sources of the oceanic water and what may cause periodic incursions into the North Sea? The shelf sea waters of the North Sea are open to oceanic waters in the north between Orkney, Shetland and Norway and via the English Channel, with the total volume inflow of oceanic waters most recently estimated at around 1.7 Sv, with most (1.6 Sv) entering from the north (Huthnance, 1997). The oceanic water is usually referred to as "Atlantic Water" but Turrell *et al.* (1996) suggested that it contained influences from the water type "Eastern North Atlantic Water" carried in the SEC through the Rockall Trough, and also "North Atlantic Water" from the Iceland Basin (originating in the North Atlantic Current). It has been suggested by Reid *et al.* (1998), on the basis of biological evidence and model results, that higher flows have occurred in the SEC during periods with a high positive NAO Index, as has occurred since about 1988. The nature of interaction of the North Sea with the North Atlantic is still poorly understood and there are no published direct observations of the temporal variation of total inflow. We can, however, utilise the biological and model evidence to infer periods of increased oceanic inflow, even though it was not directly measured.

The SEC is the physical feature that connects the Rockall Trough with the North Sea. Theoretical consideration of the exchange process between the North Atlantic and the North Sea lead Huthnance (1997) to conclude that the SEC must play a significant role and that, in fact, it has a far greater impact than the larger North Atlantic Current. The possible contributory processes to the exchange arise through "forcing" around Scotland and salinity differences between the North Atlantic and North Sea. He suggested that the main factors are local density-driven flows, along-slope flows driven by density fields and winds, and tides. Exchanges through shear dispersion may be enhanced by topographic features such as the Norwegian Trench. Numerical models of the North Atlantic implemented under the "DYNAMO (Dynamics of North Atlantic Models)" project (DYNAMO Group, 1997) show currents flowing from the shelf-edge region into the North Sea via the Fair Isle current and north of the Shetlands (A. New, pers. comm.). Observations and models indicate that the northward flow through the Rockall Trough is divided into at least two branches that merge again in the northern part of the basin to flow over the shallow (500 m) Wyville–Thomson ridge and continue downstream as the SEC (Ellett *et al.*, 1986,

A. New, pers. comm.). Thus the baroclinic transport that includes the SEC observed through the Rockall Trough at 57°N has the potential to affect the flow north of the Wyville–Thomson Ridge. The downstream pathways of Rockall Trough water are not well established and it is feasible that during periods of high transport at 57°N there is increased flow westwards along the Wyville–Thomson Ridge, leading to increased flow into the Iceland Basin or west of the Faroes. In that scenario there may not be increased flow in the SEC north of the Ridge. However, the data presented here suggest that the baroclinic transport through the North Rockall Trough at 57°N is linked in some way to the rate of inflow into the North Sea, because the two indicators, observed at the former and inferred for the latter, show simultaneous periods of increased flow.

A direct connection between the flow of water in the Rockall Trough and the shelf edge north of Scotland requires a physical feature to link the two regions. Here we suggest that it is the SEC. Despite many observations of an SEC at numerous locations along the continental shelf break from North Africa to the Norwegian coast, it has not been conclusively proved from physical observations that there is a continuous current over that distance. There is direct evidence, though, that the SEC can be continuous along the western coast of the UK: drogued drifting buoys deployed in the SEC in the Rockall Trough have been observed to move rapidly along the shelf break, before leaving the SEC and turning into the North Sea in the Fair Isle Current between the Orkneys and Shetland and north of the Shetlands (Burrows *et al.*, 1999). Pingree *et al.* (1999) showed a similar transport of drogued Argos buoys in 1995 from south of Ireland on the shelf to north of Shetland via the SEC on the edge of the Malin Sea.

Biological data provide indirect evidence of at least periodic connections over a greater distance along the shelf edge; the habitat ranges of tropical species of fish west of Europe have recently extended further north than previously observed (Quero *et al.*, 1998). Species found on the shelf edge at depths of between 150–600 m are now found from southern Portugal to the north of Ireland. This northward range extension in the SEC has occurred over a period of 30 years for some species but as rapidly as six years for others. The authors interpret these observations as possible evidence of climatic change, with warmer conditions in the northern localities allowing the tropical species to survive. However the observations are also evidence that, at some periods at least, there must be a connection along the shelf edge between southern Portugal and west of the UK. This has been suggested before. Fraser (1962), for example, described the presence of a ''Lusitanian stream'' just beyond the edge of the shelf to the west of the British Isles containing plankton more typically representative of Iberian offshore or Mediterranean waters. Using oceanic indicator species to plot the extent of oceanic invasions into the North Sea, Fraser (1969) showed that marked variability occurred between years from virtual absence to strong representation in, for example, 1954 and 1955 when Lusitanian species spread far to the south of the North Sea. The events of the late 80s and 90s, respectively described here, are two further and even stronger examples of the penetration of ''Lusitanian water'' into the North Sea.

The suggestion of possible climate change being indicated by biological data warrants further investigation for the North Sea ecology also: the events in the late 1980s and late 1990s appear from the CPR survey data to be unusual in a time series of more than 50 years. Are they indicative of long-term change or are they stochastic events? To be able to answer these questions we need to address the processes underlying the exchange between the North Sea and the open ocean.

## Conclusion

We believe that the simultaneous occurrence of high baroclinic transport through the Rockall Trough and pulses of oceanic water flowing into the North Sea is evidence of a connection between the two regions. The Shelf Edge Current is of prime importance in the exchange between the open ocean and North Sea and may be the connecting feature between the Rockall Trough and the North Sea. However it is not clear from the observations whether the transport through the Rockall Trough is influencing the inflow into the North Sea, or whether they are both responding to common forcing conditions.

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