The North Atlantic: evidence for a change in ocean climate in recent years

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Plankton as an indicator of hydroclimatic variability

Physico/chemical sampling of the oceans has until recently been largely carried out by research cruises that typically are deployed irregularly without a synoptic sampling strategy in space or time. There are also few long-term measurements of current flow in the North Atlantic so that understanding of its changing hydrography and the consequences of climate change is at present built on a limited information base. It has long been known that planktonic organisms can be used to characterise particular water masses as 'indicator species'; data from the plankton can provide substantial additional evidence for changes in the hydrography of the oceans. This is especially so as the plankton appears to be able to integrate the varying meteorological and other factors controlling its growth and may provide evidence for change that is not clearly seen in the hydrometeorological environment. A monthly synoptic survey of the plankton, the Continuous Plankton Recorder (CPR) survey, has been carried out over a large area of the North Atlantic for more than fifty years providing a unique source of information to supplement hydrographic information. One of the unexpected findings from the CPR survey is the consistency of the patterns of change found in space and time considering the complexity of their living environment as witnessed from satellite observations. Highly significant relationships have been determined between CPR plankton and climatic indices such as the North Atlantic Oscillation (NAO) index and the Gulf Stream index providing additional evidence to suggest that the plankton is integrating its hydroclimatic environment.

The Continuous Plankton Recorder survey

On September 31 2001 the Continuous Plankton Recorder (CPR) survey will celebrate the 70th Anniversary of the first CPR tow by Alister Hardy between Hull and Bremen in the North Sea. The survey has operated over an extensive region of the North Atlantic between 37° and 64°N each month from January 1946 to the present and pre Second World War from 1931 to 1939 largely in the North Sea. Since 1931 close to 4 million miles of sea have been sampled and close to 180000 samples analysed (Figure 1). Both the sampling procedures and the methods of plankton analysis have changed little over the last fifty years (Warner and Hays, 1994). Phytoplankton and zooplankton are counted and identified into 450 taxonomic categories of which approximately one third are to species level. The results are stored in an Access database that, as of July 2001, contained 2103400 positive data points (zeros are not included) for the period January 1946 to June 2000 inclusive. The total dataset including zeros comprises ~ 81 million data points. Data from the prewar survey from 1931 to 1939 are presently held in paper form.

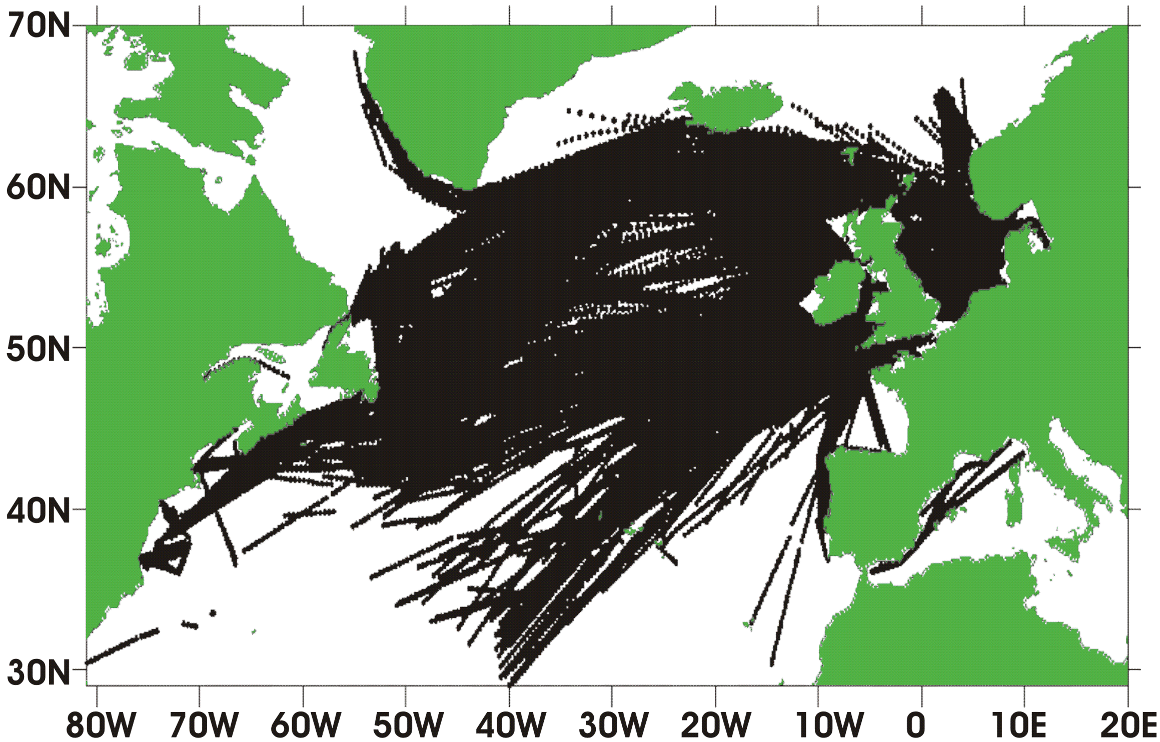

Figure 1: A map showing the positions of all CPR samples for the period January 1946 to December 1999. Each sample is represented by a small dot.

Long term trends

Results from the survey document long term trends and step-wise changes. Since the 1960s multivariate statistical analyses have been applied to CPR data to try and explain plankton variability. Colebrook first applied Principal Component Analyses to the data and the First Principal Component of the dominant zooplankton and phytoplankton taxa has been considered as characterising the dominant changes over time e.g. Colebrook et al. (1984). These analyses were last updated to 1996 and show for the North Sea a downward trend in zooplankton and phytoplankton until approximately 1980 since when there has been a moderate recovery whereas the trend has generally continued downwards in the Atlantic.

Phytoplankton Colour, a visual index of chlorophyll observed from the CPR filtering silks also shows pronounced and statistically significant trends over the last 50 years (Edwards et al., 2001). The colour index has shown a positive increasing trend in the North Sea and in an area off the shelf to the west of the British Isles whereas the pattern of change was the reverse in the eastern Atlantic to the north of 59°N and south of Iceland. Increases in the colour index have also been seen in the last decade in the western Atlantic over the Grand Banks and on the Newfoundland shelf (Figure 2 and Sameoto, 2001). The scale of the changes seen has been substantial in terms of an altered seasonal cycle and by implication in standing stock.

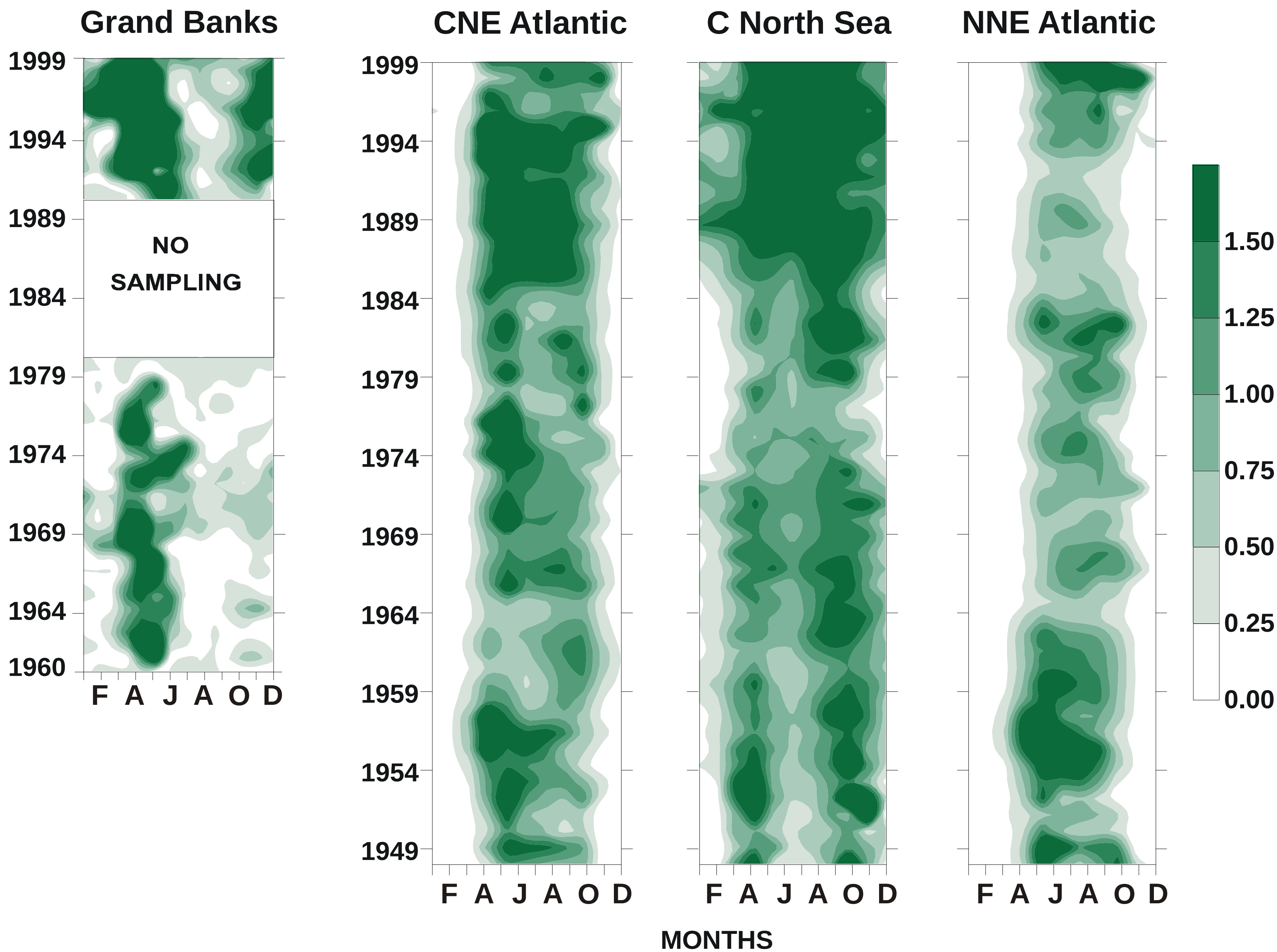

Figure 2: Contour plot of mean monthly Phytoplankton Colour during 1948-99 for the northwest Atlantic Grand Banks, central (C) North Sea, central northeast (CNE) Atlantic and northern northeast (NNE) Atlantic

The role of the North Atlantic Oscillation (NAO)

The NAO as the dominant mode of atmospheric variability in the North Atlantic is an alternation in the atmospheric pressure difference between the low pressure zone normally centred on Iceland and a counter high pressure centre over the Azores. The NAO plays a key role in the modulation of hydrographic variability in the area and in particular, the wind driven circulation, precipitation, sea surface temperature and deep convection in the Greenland Sea and to intermediate depths in the Labrador Sea. Reid et al. (1998) proposed two scenarios for changes in the circulation of the North Atlantic in high and low NAO index states (Figure 3). When the index is negative the North Atlantic current is northwesterly directed and strongly penetrates the Nordic Seas and deep convection is active in the Greenland Sea, but minimal in the Labrador Sea. In the opposite case of a positive NAO convection is halted in the Greenland Sea leading to a reduction in Norwegian Sea deep water and is enhanced in the Labrador Sea. At the same time the penetration of the North Atlantic current into the Norwegian Sea is reduced while flow in the subboreal gyre may have increased, but warmer waters penetrate in a narrow eastern margin current.

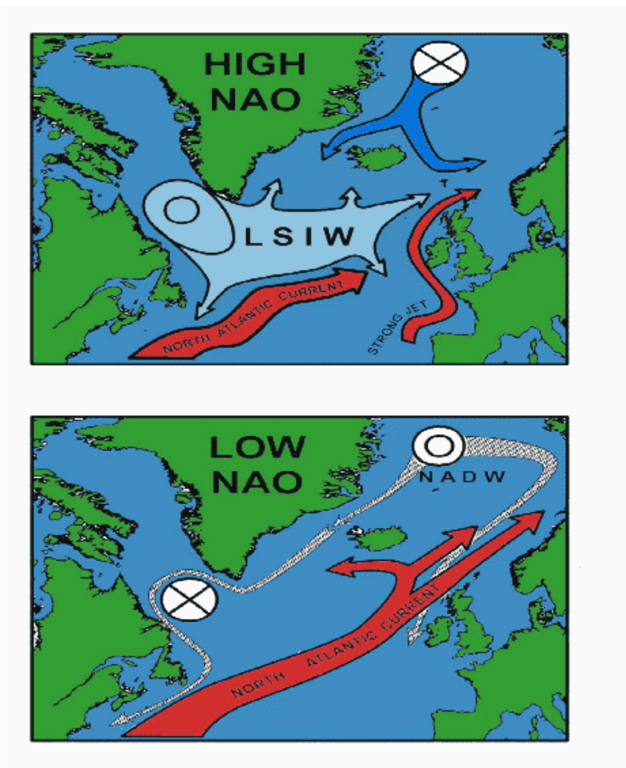

Figure 3: Hypothesized changes in the circulation of the North Atlantic in the alternative scenarios of a prolonged period of high (top panel) or low (bottom panel) NAO index. The bifurcating surface flow north of Iceland shown in the high NAO situation indicates outflow from the Fram Strait. LSIW=Labrador Sea intermediate water; NADW=North Atlantic Deep Water. The shaded lines indicate approximate directions of deep water flow. In reality the outflow from the Faroe Shetland Channel flows to the North towards Iceland eventually joining the deep western boundary current to the east of North America.

Plankton and the NAO

In the North Sea the pattern of change seen in colour is significantly correlated (5%) with the North Atlantic Oscillation (NAO) as is the copepod *Calanus finmarchicus* (negatively, 1%). Indeed for many areas of the eastern Atlantic the annual means for

Phytoplankton Colour and *C. finmarchicus* are inversely correlated. This is unlikely to be a trophic relationship because of the very different seasonal cycles of the two entities and the relationship is instead further evidence in support of the suggestion that they are integrating hydrometeorological variability and reflecting changes in the ocean climate of the Atlantic. The relationship between *C. finmarchicus* and the NAO described by Fromentin and Planque (1996) for the northern North Sea appears to have broken down around 1996; an event that also appears to be reflecting a change in the regional ocean climate of the Norwegian Sea. The volume of Norwegian Sea deep water has declined substantially in the 1990s and the upper surface of this water has deepened in consequence. The copepod *C. finmarchicus* vertically migrates off the shelf to this deep water to overwinter, the reduction in its overwintering habitat may be the cause of the decline of the species in the North Sea or it may have moved further north as the general warming seen in the area is likely to be unfavourable to this boreal species. In 1999 the abundance of the boreal copepod *C. finmarchicus* in the area defined by Fromentin and Planque had declined to 25% of the level observed in 1958. In contrast the congeneric warm water species *C. helgolandicus* increased in abundance by 48%.

North Sea regime shift

Other patterns of change seen in CPR results are more regionally defined. A change in the North Sea circa 1987/8 has been described as a regime shift as it is evident in biological, physical and chemical determinands (Reid et al., 2001a). The change is clearly evident in the increased length of the growing season of Phytoplankton Colour at this time (Figure 2). It is also evident in individual species of phytoplankton and zooplankton, fish catches (e.g. horse mackerel and red mullet) and modelled inflow into the North Sea. The total heat content of the North Sea has also increased since this time (Pohlman pers comm) and substantial increases have been recorded in the biomass of the benthos off the German coast and in the community structure of the benthos off England (Warwick and Clarke pers. comm.). Measurements of nitrate, phosphate, silicate and oxygen in the Skagerrak and German Bight showed pronounced step wise changes at the time of the regime shift. Subsequent to the change in regime the North Sea appears to have become more productive, a change that has coincided with the most consistent period of a strongly positive North Atlantic Oscillation (NAO) index since records began. The changes also suggests that there has been an increase in the quantity of detritus settling to the bottom and possibly changes in pelagic/benthic cycling and/or increased resuspension of detrital material by stronger winds.

Superimposed on the regime shift there is evidence for periodic increased inflow of oceanic water into the North Sea from the slope current to the west of the British Isles. The first of these events coincided with the beginning of the regime shift carrying with it unusual southerly Lusitanian plankton more characteristic of the Bay of Biscay and further south including the doliolid *Doliolum nationalis.* A second major incursion carrying this species appears to have occurred in 1998. Both of these events have been shown to coincide with evidence for increased geostrophic flow in the eastern boundary current in the Rockall Trough (Reid et al., 2001b). Satellite measurements of sea surface temperature along the European shelf edge suggest that pulses of warm water have extended north along the shelf over hundreds of miles. A number of fish species as well as warmer water plankton appear to have extended their northerly range as part of these events possibly as a response to the higher temperatures found in NW European waters in recent years.

Plankton changes in the western Atlantic

The routes operated by SAHFOS in the western Atlantic do not provide as extensive a coverage of this complicated hydrographic area as in the east and unfortunately the time series is shorter and discontinuous due to a termination of funding in the 1980s. It is however possible to make comparisons between the approximate period 1960 to 1980 and the recommenced survey from 1991. Pronounced differences are evident between the two periods. Since the early 1990s in the western Labrador Sea and over the Grand Banks there has been a sharp decline in small copepods and euphausiids at the same time as a marked rise in the Phytoplankton Colour index (Figure 2) and changes in the composition of the phytoplankton (Sameoto 2001). Small copepods form possibly the main food source for larval cod and the reduction in their abundance is likely to be a major factor in the decline of cod recruitment.

From the beginning of the 1990s there has been a pronounced increase in the abundance of polar planktonic taxa such as *C. glacialis*, *C. hyperboreus*, and *Ceratium arcticum* in the western Atlantic and in particular the Labrador Sea (Johns et al., in press). The highest numbers ever recorded in the CPR survey of the large copepod *C. hyperboreus* occurred in April and May 1999. The species also appears to be spreading further south being recorded below 40°N south east of Long Island in 1993, 1995 and 1998. These findings are consistent with evidence for an increasing southerly penetration of Labrador Sea intermediate water in the 1990s that coincides with a high NAO index period. These extreme southerly records in 1998 close to the slope edge may be recording increased southerly penetration of Labrador Slope water that is believed to intensify its southerly flow, with a lag, after negative NAO years (Drinkwater et al., 1999). This event in 1998 had a major impact on the community structure and biomass levels of the plankton over the Scotian Shelf and in the Gulf of Maine for a few years when the cold slope water progressively replaced the bottom waters on the shelf.

Plankton Biodiversity

Geostatistical and multidimensional statistical analyses have been applied to the CPR dataset to evaluate changes in the biodiversity of planktonic copepods. (Beaugrand et al., 2000). Recently these techniques have been used to develop nine indicator assemblages for the North Atlantic (Beaugrand et al., in press). This application has revealed pronounced changes in the plankton community structure through time at the scale of the North Atlantic and has reinforced the observation that warmer plankton is moving north with a retreat of colder fauna in the eastern Atlantic and the opposite situation in the western Atlantic.

Conclusions

The patterns of change seen in the plankton fit well observed hydrographic variability evident in the northern North Atlantic and Nordic seas and may be providing the first evidence of a reorganisation of ecosystems at an ocean basin scale as a consequence of global warming. Some of the changes observed are correlated with the NAO, but this does not explain all observed variability e.g. the pulsed increases in northerly flows in the eastern margin current. On the basis of projected rises in levels of CO_2 modelling results have suggested that the NAO is likely to remain positive for the next forty years. If so the deep water outflow from Nordic seas may continue to reduce with a consequent slow down in the Global Conveyor Belt.

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