Environmental influence on the spawning distribution and migration pattern of northern blue whiting (*Micromesistius poutassou*)

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Abstract

Postspawning blue whiting migrate from the spawning grounds west of the British Isles, past the Faroe Islands and into the feeding areas in the Norwegian Sea during the spring months March to early June. The changeable migratory route through Faroese waters, as inferred from fisheries statistics, is found to be closely linked to the hydrography along the Rockall Bank, as simulated by an ocean circulation model. A variable spawning intensity around the bank is suggested as the causal mechanism for this link. The observed variability is primarily governed by the strength and extent of the subpolar gyre. Utilizing apparent links between the atmospheric forcing and the subpolar gyre dynamics, the environmental spawning and recruitment conditions for the present (2007) season is forecasted.

1. Introduction

The northern stock of blue whiting (*Micromesistius Poutassou* Risso) migrates between the spawning grounds west of the British Isles and the feeding areas in the Norwegian Sea. After the spawning period in March – May the majority of the post-spawning fish pass the Faroes Islands either on the western side through the Faroe Bank Channel or on the eastern side through the Faroe-Shetland Channel (Fig. 1).

The blue whiting is a pelagic gadoid of great commercial importance, but due to the large population size, its considerable migratory capabilities and wide spatial distribution, much remains to be understood regarding the stock composition and dynamics. Accurate estimates of the stock size are difficult to obtain and the management of this species provides therefore a challenge.

One main uncertainty is the extent of the spawning distribution, which was first investigated by Schmidt (1909). He provided evidence for spawning along the European Continental Shelf and around oceanic banks between Iceland, the Faroe Islands and Spain. Others have reported spawning on the Reykjanes Ridge (Magnusson and Hallgrimsson 1965) and along the west coast of Northern Norway (Lopes 1979). Eggs and larvae information from the Continuous Plankton Recorder from the 1930s to the 1960s showed that the most intensive spawning was happening west of Scotland and along the eastern side of the Rockall Bank (Fig. 1) (Bailey 1974; Henderson 1957; Henderson 1961). Larvae from this region will either drift into the Faroe-Shetland Channel, or spread towards the region west of the Faroes (Fraser 1958; Henderson 1953; Henderson 1961).The spawning activity southwest of Ireland, around the Porcupine Bank, was moderate during the 1950s (Henderson 1957), but there was an upward trend after 1955 (Bainbridge and Cooper 1973). This trend continued and resulted in a southeastward shift in the spawning distribution from the near Rockall Bank region in the 1930-60s to the Porcupine Bank/Continental Shelf region in the early 1990s (Fig. 1). The most recent publications seem almost to have forgotten about the zonal dimension regarding the spawning distribution and do only discuss the dimension along the European Continental Shelf, with focus regions around the Porcupine Bank and along the Hebridean shelf (Ryan et al. 2005, Skjoldal et al. 2004).

The blue whiting is especially sensitive to both temperature and salinity during the spawning period and will only spawn in waters warmer than 8-9º C and salinities in excess of 35.2-3 (Henderson 1957). The average hydrography in the region east of the Rockall Bank is near these threshold values although the variations are considerable. The period

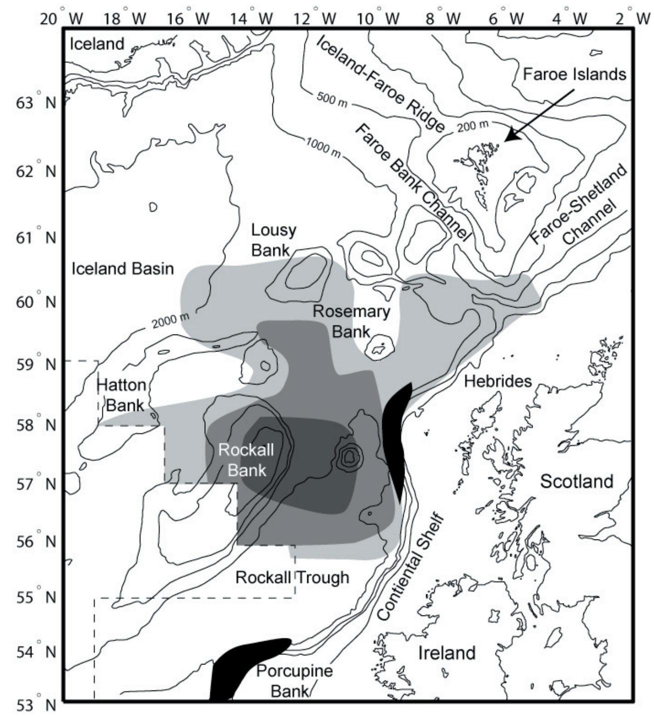

Fig. 1 Map of the study region, showing places referred to in the text. The grey contours show the mean density of blue whiting larvae during the years 1948-1956 as reported by Henderson (1961). The intensive spawning areas during recent years, as reported by Skjoldal et al. (2004), are shown in black.

in the 1930-60s, when the Rockall Bank region was the main centre of spawning, was also the warmest and saltiest period in the NE Atlantic during the 20th century (Turrell et al. 1993). Since then, temperatures and salinities have generally decreased, with additional marked decadal variability, until the early nineties when both temperatures and salinities were unusually low. The intensive spawning areas during this latter period, confined to the Continental Shelf Current (Skjoldal et al. 2004) (Fig. 1), have always temperatures and salinities above the mentioned threshold values.

A very rapid reversal happened in the marine climate around 1996 resulting in a hydrographic regime in 1998 comparable to that of the 1960s. This trend continued and the year of 2003 was the warmest and saltiest ever observed in the NE Atlantic (Hatun et al. 2005b), and this happened concurrently with a threefold increase in the spawning stock biomass of blue whiting, compared to the pre-1996 values.

The post-spawning fish are very weak and will probably follow the main currents at depths from 200 m to 500 m (Hansen and Jákupstovu 1992; Skjoldal et al. 2004). The flows passing the Continental Shelf spawning grounds at the Porcupine Bank and the Hebrides will transport planktonic objects (egg, larvae and exhausted fish) northeastwards through the Faroe-Shetland Channel, while the flow passing the eastern side of the Rockall Bank leads to the region south of the Iceland-Faroe Ridge (Ellett et al. 1986). There is a convergence of both the western and the Continental Shelf flows in the channels south of the Faroe Islands resulting in sharp hydrographic fronts, along which post-spawning blue whiting congregate. An intensive fishery has been taking place in this region during the spring periods from late April to early June since 1977.

To identify distinct periods when the main fish concentration passes east or west of the Faroes, on their way to their feeding areas in the Norwegian Sea, we use fisheries statistics. A state-of-the-art global general ocean circulation model is used to put the variable migration pathways in context of marked concurrent oceanographic changes in the subpolar and primarily Northeastern Atlantic Ocean.

The ocean model and the fisheries data are described in section 2. In section 3 the correspondence between the east-west proportion of the fisheries in the Faroese Channels (the Faroe-Shetland and the Faroe Bank channel) and the extent and strength of the subpolar gyre is outlined. The link between the variability in the gyre and in the hydrography and currents in the Rockall-Faroe region are discussed in section 4. This is elucidated for two three-year periods pre- and post-1996, which represent the largest change in both the east-west proportion and in the total spawning stock biomass seen in observational records. A discussion on the significance of the east-west distribution asymmetry in the Faroese Channels and the possibility for forecasting is given in section 5. A brief conclusion is given at the end.

2. Material

The main impediments for the understanding of the blue whiting population dynamics are the vast dispersion, the rapid migration and the changeable environmental and biological conditions. Data from the fisheries and simulations from a realistic ocean model are used in an attempt to overcome these challenges. We have preferred data from the fisheries before acoustic-abundance surveys because the acoustic-abundance is mostly available in the North-South dimension along the Continental Shelf and the acoustic-abundance is only a quasi-synoptic snapshot from a limited and variable coverage of research vessels.

Fishery information

Under the NEAFC (North Eastern Atlantic Fisheries Commission) scheme, vessels report to their respective (national) Contracting Parties and this information is shared via the NEAFC Secretariat's database. The blue whiting catch statistics applied here are obtained from this database. The data are available as monthly values of the total catch gridded onto 0.5º latitude x 1º longitude rectangles and differentiated for each national fleet. Information on the blue whiting fisheries extends back to 1977 and all years are included in the present analysis. Data are exclusively used from the Norwegian and the Faroese fleets as these give the best representation of the post-spawning fisheries in the Faroese Channels.

Ocean Model

Hydrographic observations from the study area are sporadic, while the hydrographic changes can be pronounced. Being in need of three dimensional hydrographic fields during the spawning periods and spanning the spawning regions from 1977 to present, the only viable approach is to use a model. The employed model is the NERSC version of the Miami Isopycnic Ocean Circulation Model (MICOM) (Bentsen et al. 2004; Furevik et al. 2002). It covers the North Atlantic and the Nordic Seas from 30ºN to 78ºN and the distance between grid cells is on the order of 27 km in the study region. The model is driven at the ocean surface by the atmosphere represented by daily mean NCAR/NCEP re-analyses (Kalnay et al. 1996) of freshwater, heat and momentum (Bentsen and Drange 2000). Through its boundaries the model is driven by a global version of the same model, but with a coarser grid resolution. The model is isopycnal, which means that the vertical coordinate is density rather that depth, and this gives a more physical representation of the water masses which tend to move isopycnally rather than along planes of constant depth. Only the upper 12 isopycnal layers of the 26 layers in total are used in this study, because these represent the water masses in the Rockall-Faroe region which post-spawning blue whiting occupy. The average depth of these layers is shown horizontally in Fig. 2 and vertically in Fig. 3. All presented fields and values from this model are thus vertical averages over these 12 isopycnal layers in addition to being temporal averages over the post-spawning period from week 9 (late February) to week 25 (early April).

It has previously been demonstrated that the model gives a realistic representation of the hydrography in the NE Atlantic (Hatun et al. 2005b; Hatun et al. 2005a)(Sandø and Furevik, submitted), the transport across the Iceland-Faroe Ridge (Nilsen et al. 2003), processes in the Northwestern

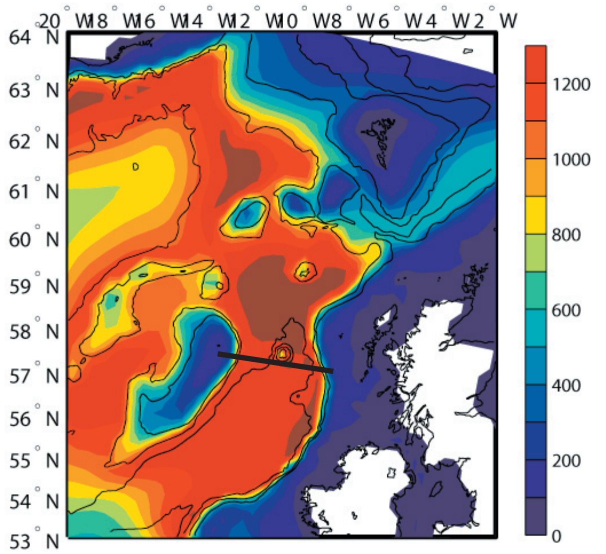

Fig. 2 Mean depth (meters) of the upper 12 isopycnal model layers which are employed in this study. The black line illustrates the section shown in Fig. 3

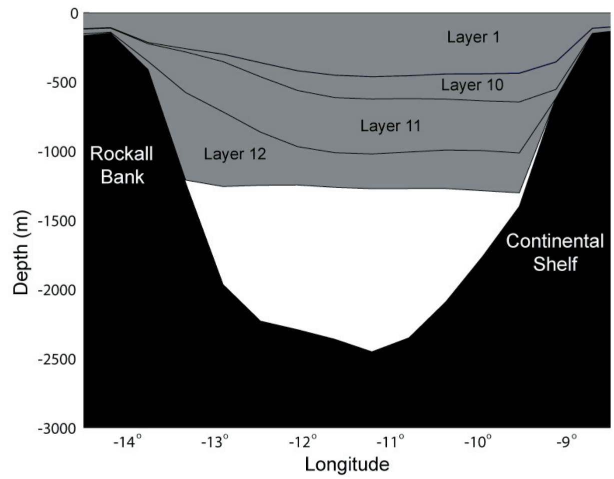

Fig. 3. A cross-section from the Rockall Bank to the Continental Shelf along the black line shown in Fig. 2. The mean depths of the employed isopycnal model layers are shown in gray and the sea floor is shown in black.

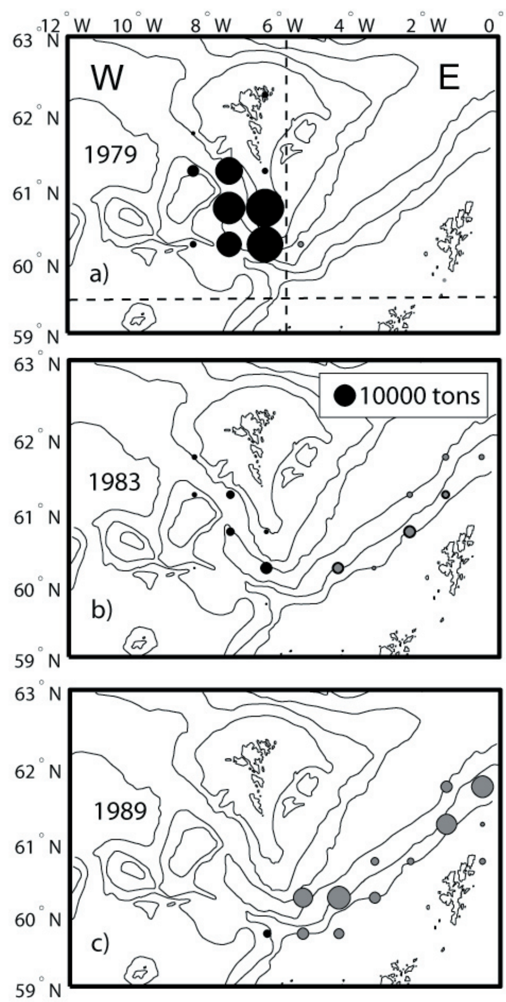

Fig.4 Reported catches of blue whiting during May in: a) a western year, b) an intermediate year and c) an eastern year. The black dashed lines in a) are the dividing lines that define the subregions W and E. The catches within each subregion are shown as black (W) and gray (E) dots, and the area of each dot is proportional to the amount of blue whiting fished with in a 0.5° latitude x 1° longitude rectangle centered on the dot.

Atlantic (Deshayes, 2006) and the general dynamics in the North Atlantic (Hatun et al. 2005b; Mauritzen et al. 2006). More technical details on the model can be found in (Bentsen et al. 2004).

3. Fisheries and subpolar gyre indices

Hansen and Jákupstovu (1992) have previously shown that the fisheries in the Faroese Channels have clearly different geographical distributions from year to year, and that this can be used as a reliable proxy of the distribution of northward migrating blue whiting. The approach of these authors will be adopted here, although the analysis will be extended both in space and time by including the Norwegian fleets in addition to the Faroese fleet.

The East-West distribution

When the fishery takes place on the western slope of the Faroe Plateau the fishable concentrations are confined to a narrow and often dense band along the shelf edge which also is associated with sharp hydrographic front. When, on the other hand, the fishery takes place in the Faroe-Shetland Channel the shoals are more dispersed and less ‘fishable’.

Seeking an index for the east-west proportion of the northward migrating blue whiting, a region bounded by 16ºW, 4ºE and 59.5ºN has been selected. This region is again divided along the 6ºW meridian, into a western (W) and an eastern (E) subarea as shown in Fig. 4a. Summing the catches in each subarea during May and comparing these, each year will be categorized as either *western* or *eastern*, depending on which value is larger. The month of May is chosen since almost all catches within the study area are made during this month.

Catches during pronounced western and eastern years are shown in Figs. 4a and 4c, respectively, and a less determinable year is shown in Fig. 4b for comparison. For most years this east-west division is clear and variability on 5 to10-

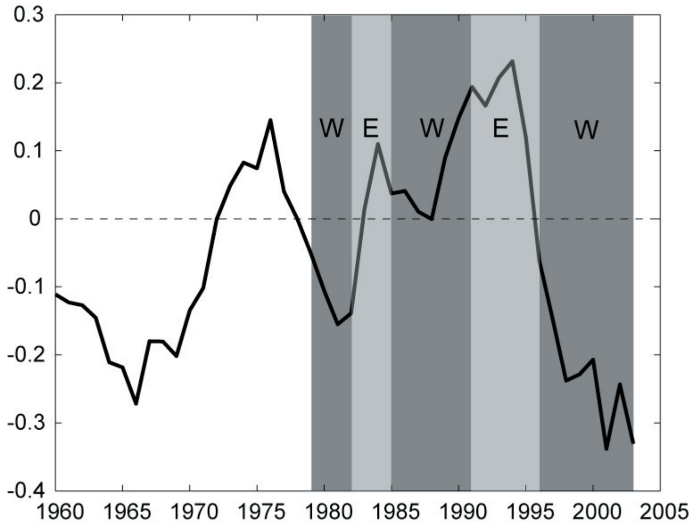

Fig. 5. Periods of eastern years (light gray) and western years (dark gray), shown together with the gyre index (black line).

years time-scales is discernable (Fig. 5). Less determinable years can occur during the switch from a period with say persistent western years to a period with persistent eastern years.

The fishery in the Norwegian Trench was excluded from the above analysis since it does not reflect the migration dynamics of the spawning stock, and no northern limit has been applied to the study region, because no fishery is present north of the Faroes during May. The subareas could be skewed to enhance the east-west division, but we have chosen to use rectangular regions in order to be compatible with the previous work of Hansen and Jákupstovu (1992). These authors had positioned the southern limit at 59ºN, but the limit at 59.5ºN should decrease the risk of including fish, that actually migrates through the Faroe-Shetland Channel, into the western subarea (see Fig. 4). The presented results are, however, not very sensitive to these details. The fishery reports are not complete, but assuming that similar errors are being made for the fisheries in the two subareas, this should not influence the geographical distribution.

Source water masses for the Rockall Trough

In order to better understand an apparent link between the migration pattern of blue whiting and the dynamics in the subpolar North Atlantic Ocean, a short review of the general oceanography of the Rockall region will first be given.

The main source water masses that enter the Rockall Trough from the south are the Western North Atlantic Water (WNAW) carried by the North Atlantic Current (NAC) and the Eastern North Atlantic Water (ENAW) which is drawn from the 'intergyre region' between the Azores and the Bay of Biscay (Holliday 2003; Pollard 1996) (Fig. 6). The ENAW, which is influenced by Mediterranean Water, is relatively warm and saline compared to the other water masses in the Rockall region, and it carries its distinct plankton fauna (Fraser, 1961). The WNAW is both colder and fresher than the ENAW due to admixture with very cold and fresh water masses from the adjacent subpolar gyre. The NAC carries large volumes of water towards the Porcupine Bank, but most of it retroflects back towards west and continues in the Iceland Basin were it constitutes the eastern border of the subpolar gyre. The Rockall Plateau acts as a divide for the NAC and a variable amount of this relatively cold and fresh water flows into the Rockall Trough where it continues northwards primarily along the eastern flank of the Rockall Bank. The relative influence of the NAC around the bank has pronounced implications for both hydrography and currents in this region. The subpolar gyre is a main regulator of this inflow (Hatun et al. 2005b), and its dynamics should therefore be expected to be important for the spawning distribution and thereby for the east-west migration pattern in the Faroese Channels.

Covariability with the environment

The east-west distribution of blue whiting in the Faroese Channels was discussed in context of the local hydrography by Hansen and Jákupstovu (1992). Using a general circulation ocean model, the east-west distribution will here be put into a broader spatial context.

The western and eastern years obtained from the above analysis are compared to a so-called *gyre index* (Hatun et al. 2005b) in Fig. 5. This gyre index is obtained from the simulated sea surface height over the entire North Atlantic Ocean, and it reflects the shape and strength of the subpolar gyre.

High values of the gyre index are associated with cold and fresh conditions in the NE Atlantic and this seems to coincide with eastern years (Fig. 5), while low gyre index values, associated with warm and saline condition, seem to result in western years. The correspondence is quite close, although not perfect, so a closer inspection of the causal relationships is warranted.

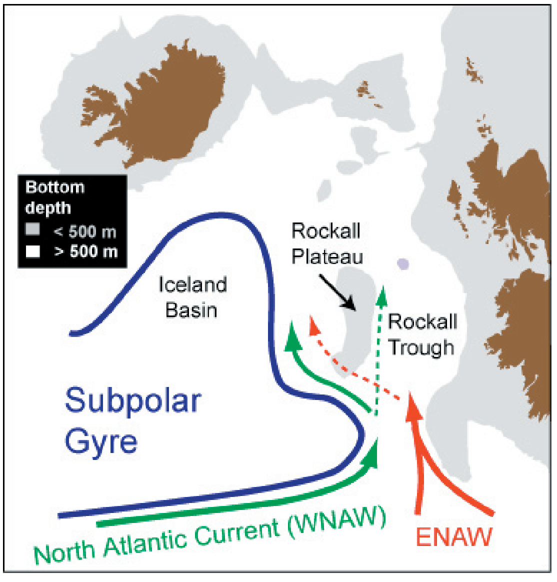

Fig. 6. A sketch of the source flows to the Rockall Trough. Dashed flow arrows indicate that the currents are very variable.

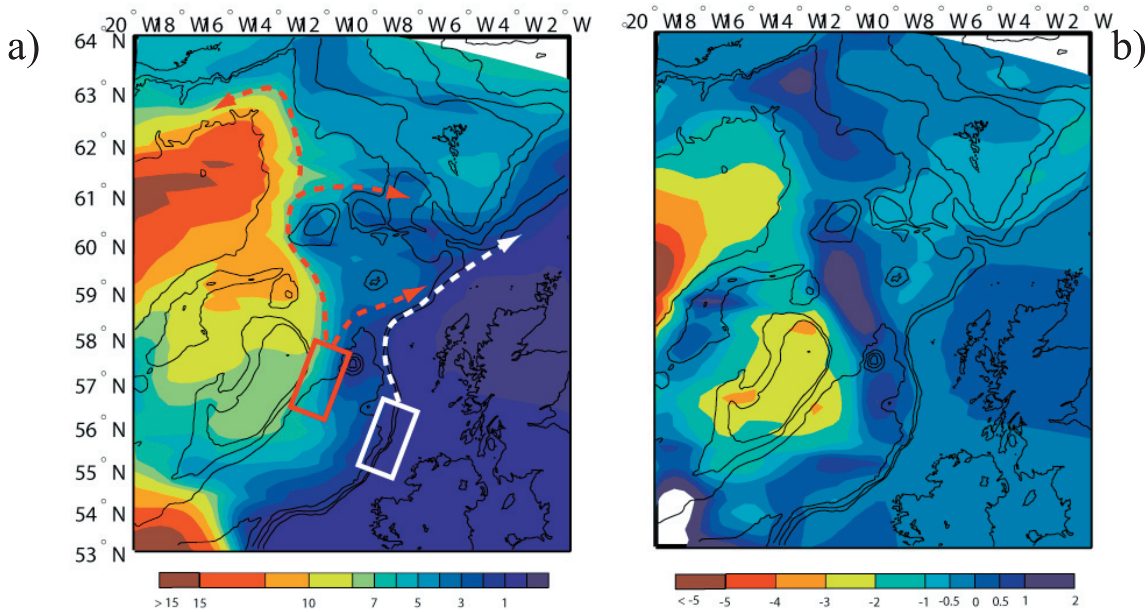

Fig. 7 Streamlines representing a) the simulated average flow field (1977-2003), and b) the changes from three cold and fresh years 1993-1995 to three warm and saline years 1996-1998. The fields are vertically averaged over the uppermost 12 isopycnal model layers (see Figs. 2 and 3), and temporally averaged over the spring period from week 9 to week 25. The colors show the transports in 10^6 m^3s^{-1} (Sverdrup), as represented by the colorbars. The red and white dashed arrows in a) show the downstream drift from a region near the Rockall Bank (red rectangle), and from a region near the Continental Shelf (white rectangle), respectively.

4. Means and the mid 1990s changes

The early 1990s were characterized by very strong westerly winds across the subpolar Atlantic Ocean and large heat losses to the atmosphere. The North Atlantic Oscillation (NAO) index is directly related to the westerlies through the sea level pressure difference between Iceland and the Azores-Gibraltar region, and this index showed record high values during the early 1990s (Hurrell 1995). This resulted in a relatively fresh (Curry et al. 2003), strong (Curry and McCartney 2001) and inflated subpolar gyre, and the subarctic front was moved far eastwards into the NE Atlantic (Bersch et al. 1999; Bersch 2002). The spawning-migration waters between Rockall and the Faroes were fresh and cold during these years and the blue whiting stock was small (Skjoldal et al. 2004). The extreme reversal in the NAO index in winter 1995-1996 was followed by a dramatic decline of the subpolar gyre (Hakkinen and Rhines 2004), westward shift of the subarctic front (Bersch et al. 1999), temperature and salinity increase in the spawning-migration region (Hatun et al. 2005a), replacement in plankton community (Hatun et al., 2007, submitted), a threefold increase in the blue whiting spawning stock biomass, and a clear shift from persistent east years to a period of persistent west years (Fig. 5). The associated changes in currents and hydrography in the spawning-migration area from three low gyre index years 1993-1995 to three high gyre index years 1996-1998 will here be illustrated using simulated fields.

Flow field

The flow field is a vectorial field constituting of zonal and meridional velocities *u,v* who again vary with longitude, latitude and depth. Such fields are more difficult to illustrate than are scalar fields like temperature and salinity. The blue whiting stock will only populate the upper waters in the Rockall Trough, which in the model are represented by the uppermost 12 isopycnal layers (Fig. 3). The flow in these layers can be considered non-divergent, meaning that water masses can not leave nor enter these layers. This enables us to circumvent the complexity of a vector field by using a so-called *stream function* φ which is given as the horizontal integral of the depth integrated velocity components *U,V*.
By starting at the eastern boundary (the British Isles or Norway) and then integrating the meridional flow component, *V*, towards the west, we obtain the simulated scalar stream function. This has been done for the time-averaged flow field over the period 1977-2003 as shown in Fig. 7a. The stream function is given in units of millions of cubic meters of water per second or *Sverdrup* relative to the eastern boundary, and the flow will follow isolines. This means that particles (eggs, larvae or passive fish) seeded near the eastern flank of the Rockall Bank (red rectangle in Fig. 7a) will drift partly towards the Faroe-Shetland Channel to the south of Rosemary Bank, but the larger portion will drift towards Lousy Bank. From Lousy Bank particles will drift both towards the Faroes and towards Iceland (Fig. 7a). Particles seeded near the Continental Shelf (white dashed arrow and dark blue isolines) will remain near the shelf and be advected through the Faroe-Shetland Channel. This simulated flow pattern is in gross agreement with reported currents based on observations (Ellett et al. 1986; Hansen and Østerhus 2000) although the anticyclonic near-bank circulation around the Rockall Bank (Dooley 1984) and the Faroe Plateau (Hansen 1992) is not realistically represented.

The post-1995 changes in the flow pattern are shown in Fig. 7b. Main features to notice are a significantly reduced cyclonic circulation around the Rockall Bank, a massively reduced circulation in the Iceland Basin and reduced flow through the Faroe-Shetland Channel.

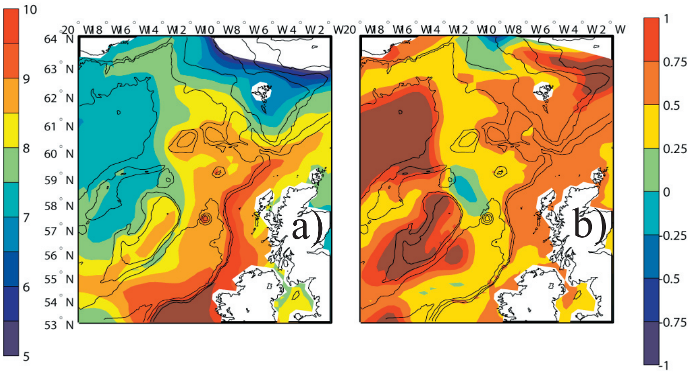

Fig. 8 a) Simulated temperatures averaged over the period 1977-2003, and b) the changes from three cold years (1993-1995) to three subsequent warm years (1996-1998). The fields are vertically averaged over the uppermost 12 isopycnal model layers (see Figs. 2 and 3), and temporally averaged over the spring period from week 9 to week 25.

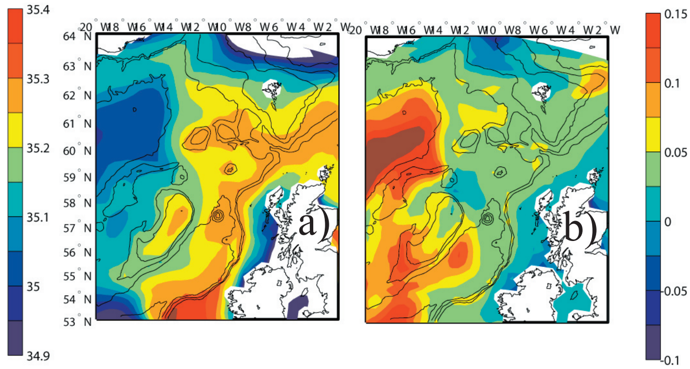

Fig. 9 a) The simulated salinity averaged over the period 1977-2003, and b) the changes from three fresh years (1993-1995) to three subsequent warm years (1996-1998). The fields are vertically averaged over the uppermost 12 isopycnal model layers (see Figs. 2 and 3), and temporally averaged over the spring period from week 9 to week 25.

Hydrography

The mean simulated temperature and salinity fields (Figs. 8a and 9a) show characteristic high values in the Continental Shelf Current. The Porcupine Bank is always embedded in warm and salty water, while the waters along the eastern flank of the Rockall Bank (red rectangle in Fig. 7a) have temperatures and salinities near the threshold values of 8-9ºC and 35.2-3 tolerated by spawning blue whiting (Henderson 1957). The westward flow to the south of the Rockall-Hatton Plateau, northwestward flow to the north of the plateau and the flow through the Faroe-Shetland Channel are all associated with protrusions of warm and saline waters.
There was a general increase in both temperatures and salinities after 1995 in the Rockall-Faroe region. The reduced influence of the NAC along the eastern edge of the Rockall Bank and the reduced circulation in the Iceland Basin resulted in a large regional temperature and salinity increases. This reflects the reduced influence of sub-arctic water masses from the high gyre index years 1993-1995 to the low gyre index years 1996-1998.

5. Discussion

The east-west distribution of the northward migrating blue whiting is important as this influences the school density and thus the "fishability" in the Faroese Channels, and as it determines the entrance to the feeding grounds in the Norwegian Sea. More importantly the east-west asymmetry could be a proxy for the spawning distribution and support for this hypothesis will be given below.
Five mechanisms could explain the east-west asymmetry: 1) changes in the frontal dynamics south of the Faroe Plateau (Hansen and Jákupstovu 1992), 2) changes in the currents between the spawning regions and the Faroese Channels, 3) changes in the hydrography between the spawning regions and the Faroese Channels, 4) the food availability along their migration route and 5) east-west variability in the spawning distribution. In lack of information on the spawning distribution and its variability, many studies on post-spawning blue whiting have assumed a fixed distribution (Bartsch and Coombs 1997; Skogen et al. 1999). The east-west distribution will firstly be discussed under such an assumption (the first four mechanisms) and then in the more realistic scenario of a variable spawning distribution.

Constant spawning distribution

Mechanism 1) relies upon the additional assumption that post-spawning blue whiting are passively drifting with the currents because of exhaustion (Hansen and Jákupstovu 1992). A subsurface front south of the Faroes, acting as a 'trap door' guiding the flow at ~400 m depths either into the Faroe-Shetland or into the Faroe Bank Channel, was suggested to be the governing mechanism by Hansen and Jákupstovu (1992). There is indeed a strong front south of the Faroes, but we find it doubtful that this will lead a majority of the slope current from the Scottish Shelf into the Faroe Bank Channel. Having studied the regional hydrography (not shown), no clear 'trap door' mechanism was found that mimics the variability in the east-west asymmetry of the fishery distribution. Although the blue whiting primarily reside around 400 m depths in this region, they perform diurnal vertical movements. They will thus partly reside in shallower waters which are persistently moving into the Faroe-Shetland Channel. Mechanism 1) cannot be disregarded, but it is probably not the full explanation for the east-west asymmetry. If this is correct, it means that the migrating fish can only reach the western Faroe region by somehow entering the western main flow, as represented by the light blue streamlines and the red dashed arrow in Fig. 7a.
Mechanism 2) does also rely in passively drifting post-spawning fish. The only way the currents between the spawning regions and the Faroese Channels could cause the east-west asymmetry, is through a variable exchange between the western flow and the slope current already in the area near the Porcupine bank. This is because Continental Shelf Current is tightly guided by the slope between Porcupine Bank and the Faroe-Shetland Channel, and drifters that are once entrained in this current will remain over the slope (Ellett et al. 1986).
A significant exchange between the Porcupine Bank and the Rockall Bank is, however, unlikely according to Fraser (1958).

Mechanism 3 allows for swimming ability so that the post spawners remain in preferred hydrographic conditions during their northward migration. This means that the westward

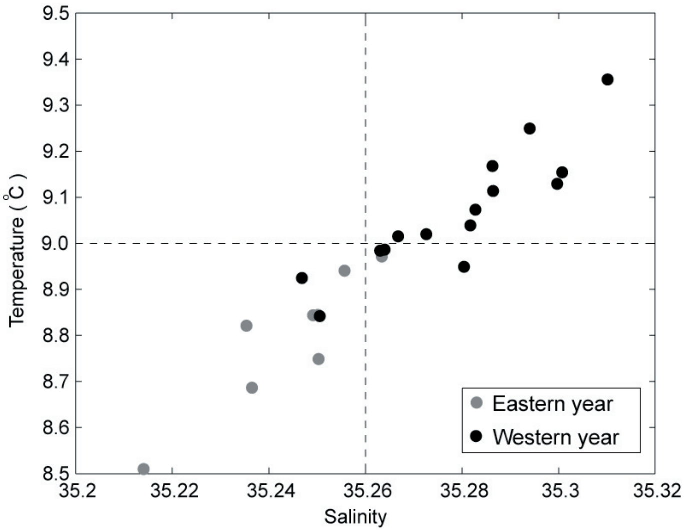

Fig. 10 The simulated temperatures and salinities along the eastern edge of the Rockall Bank (see the region in Fig. 7a), separated into western years (black dots) and eastern years (grey dots).

swimming could be more persistent during warm and salty years (low gyre index) than during colder and fresher years, and the probability of ending up in the western flows would therefore be larger during a low gyre index period. This would probably require better swimming ability than the post-spawners possess, but the process can not be disregarded.

The blue whiting is reported not to feed during spawning, but will gradually resume its normal feeding habits, and it remains unclear how the exchange in the plankton fauna (i.e. mechanism 4), associated with the variability in the source water masses (Fraser 1961), will influence the migration.

Variable spawning distribution

The spawning distribution from the late 1930s to the late 1960s (Bailey 1974; Henderson 1957) was clearly different from the recently reported spawning distribution (Skjoldal et al. 2004) (Fig. 1). During warm and saline periods, eggs, larvae and exhausted fish will be embedded directly in the western flows that mainly lead towards the Faroese banks and Plateau (red rectangle in Fig. 7a). The sensitivity of spawning fish to the ambient hydrography is the most obvious factor that can regulate the spawning activity near the Rockall Bank (Henderson 1957; Schmidt 1909). This could be trough a direct thermal effect on the metabolism, but the hydrography could also be a proxy for the amount and species of zooplankton, which is primary food source for the larvae (Bailey, 1982)(Bailey, 1974)(Conway, 1980)(Cooper 1973)(Seaton 1968)(Bainbridge and Cooper 1973).
Under the assumption that spawning intensity and hydrography are interlinked, the hypothesized relation between the east-west asymmetry and the spawning distribution (mechanism 5) can be tested. The simulated temperature and salinities from the earlier centre of spawning (Fig. 1) have been separated into eastern and western years as shown in the TS-diagram in figure 10. The hydrography is averaged over the red rectangle in figure 7a, which is an overlap between the region of maximum egg and larvae concentration in the 1930-60s and a region which in the simulated flow field clearly belongs to the western branch in the Rockall Trough. A statistical T-test shows that the temperatures and the salinities are significantly higher during western years than during eastern years, and the significance for salinity ($p < 0.001$) is higher than for temperature ($p<0.005$).

We thus propose that spawning activity within the western current branch is the most efficient mechanism for entraining post-spawning fish into this flow and thereby causing a significant fishery along the western side of the Faroe Plateau.

Support from observations

The Norwegian fleet has participated in the blue whiting fishery since its commencement in the late 1970s. This fleet has not been limited much by political regulations in the Rockall Trough region, and is therefore a good indicator for the dynamics of this fishery. The annually averaged catches by this fleet during two 7-years periods before and after the large changes in the mid 1990s are calculated and shown in Fig. 11. A clear increase and northwestward shift of the catches is evident after 1996-97. Byrkjedal *et al.* (2004) conclude that a “range extension” hypothesis cannot be favored before a “sample artifact” hypothesis due to limitations in hydrographic and acoustic survey data. More modern and efficient ships joined the fleet in the mid 1990s and one could also ascribe the changed fisheries patterns to this.

If the spawning grounds still are largely limited to the near Continental Shelf locations (Skjoldal et al. 2004) (Fig. 1) after 1997, then a more efficient fleet would show increased catches in these places, and not the observed slight reductions (Fig. 11). The record high catches on the Rockall-Hatton Plateau (Fig. 11a) would also be very unlikely under such a scenario. There is therefore little doubt that a significant spawning activity is taking place on the plateau after 1997, and no doubt that post-spawning fish are migrating northwards within the western flows in these later years (Fig. 7a).

It could again be argued that the northward migration within the western flows has been taking place there all the time, but it has been unnoticed by the more limited fleet before 1997. Search for fish and some fishery by the Russian fleet did, however, take place on the Rockall-Hatton Plateau before 1997. The excellent fishability on the plateau and south of the Faroese banks experienced after 1997 (Fig. 11b) would probably have been spotted and exploited before, even by a smaller fleet.

The traditional acoustic surveys have largely been limited to a strip along the Continental Shelf and these data can therefore not reveal zonal shifts in the spawning distribution (Byrkjedal et al. 2004). The fishery statistics employed here does not carry this restriction. We therefore claim that the observed shift in the fishery is not only a “sample artifact”, but displays a real shift in the spawning distribution supporting the conclusions in the previous section.

Interestingly, the largest increase in the catches of blue whiting happens south and west of the Rockall Plateau, which is the region where very large simulated circulation and hydrographic changes are seen (Figs. 7-9). This is the region which before 1997 was dominated by the relatively cold and

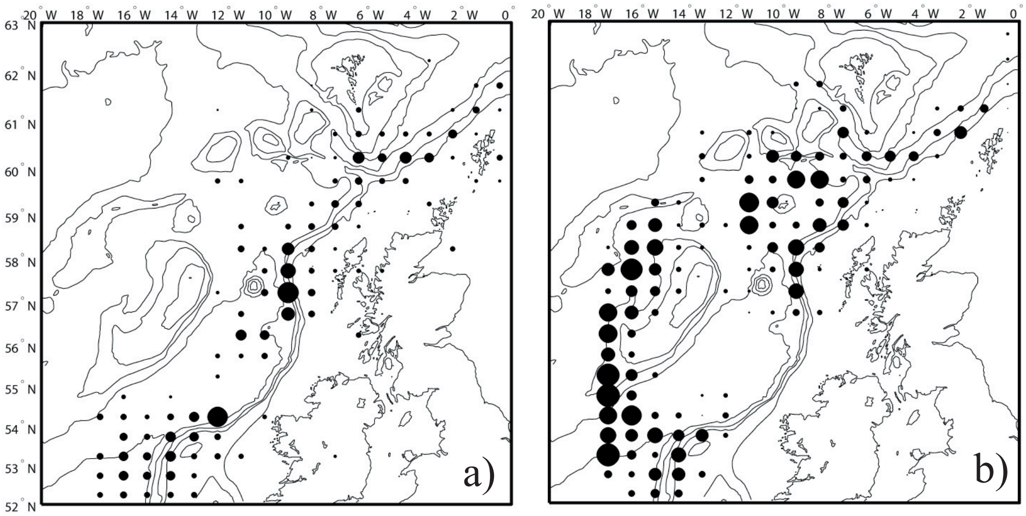

Fig. 11 The reported catch of blue whiting by the Norwegian fleet averaged over a) the eastern years from 1989 to 1996 and b) the western years 1997 to 2005. The area of each dot is proportional to the amount of blue whiting fished within a 0.5º latitude x 1º longitude rectangle centered on the dot.

fresh WNAW (Fig. 6), but which subsequently became flooded by the warmer and more saline ENAW.

The total spawning stock biomass

The estimated threefold increase in the biomass of blue whiting happening concurrently with the major changes in the marine climate and the shift from eastern to western years during the mid 1990s indicates a possible connection. But one event is not enough to prove a causal relation, and it has also been speculated whether or not the estimated large increase in stock size estimate is a result of larger fishing and sampling effort (Byrkjedal, 2004).

The blue whiting fishery was good during the late 1970s and early 1980s, but declined thereafter. The year 1982 produced a good year class, but the recruitment in 1983 was markedly weakened. The observed anticyclonic circulation on the Rockall Bank was strong in 1982, but much weakened in 1983 and temperatures on the bank dropped considerably (Dooley 1984). The strength of the simulated and relatively fresh and cold NAC branch along the eastern edge of the bank did indeed increase during this period as reflected by the gyre index (Fig. 5), and a shift from western years to eastern years followed. The largest catches are reported in the western subarea (Figs. 4a), and this happened during the late 1970s-early 1980s period and during the post-1995 period (see also Fig. 11b) when the gyre index was low (Fig. 5). It therefore seems likely that warm and saline western years are associated with a larger blue whiting stock, although this is just a tentative inference.

Forecasting potential

The present model is only forced by reanalyzed atmospheric fields and it is therefore possible to back-track the gyre index variability to processes in the atmosphere to some degree. We will here identify the most plausible links between the atmospheric forcing and the oceanic response and use these links to forecast the environmental condition for this years (2007) spawning season.

The most discussed forcing mechanisms for the subpolar gyre dynamics are buoyancy loss to the atmosphere (cooling) and wind stress curl (Eden and Willebrand 2001; Hakkinen and Rhines 2004). The buoyancy loss, particularly near the Labrador Sea, induces deep convection which again maintains a cold gyre core which lighter water masses circulate. An efficient buoyancy loss, or heat loss as discussed here, generates a strong subpolar gyre circulation. Increased wind stress curl west of Ireland will also cause a stronger horizontal subpolar gyre circulation. The physical process behind this is more complex and the oceanic response is expected to lag the atmospheric forcing by 2 to 3 years (Eden and Willebrand 2001). As the lagged oceanic response to both heat and wind stress curl forcing is similar, it is difficult to differentiate between them and to present one as the principal driving force. Instead of giving a physical description of the mentioned forcing mechanisms, simple statistical regression analyzes are performed between the gyre index and each of the atmospheric fields in order to display their regions of possible action, and to determine the strength of their links. The heat loss is averaged over the winter months December to March when deep convection takes place and the wind stress curl is averaged over the full year, before performing the regressions. The patterns showing significant correlations are located in the Labrador Sea for the heat loss (Fig. 12a) and south of the Rockall Plateau for the wind forcing (Fig. 12b), as expected. Maximum correlations were found when the atmosphere leads the ocean by 1 year, and this reveals a potential for forecasting.
To utilize this potential, spatial averages are calculated over a ~ 55 km x 55 km rectangle within each center of air-sea interaction (white rectangle in Figs. 12a and b) in order to produce indices of the heat forcing and the wind stress curl, respectively. These indices are plotted against the gyre index,

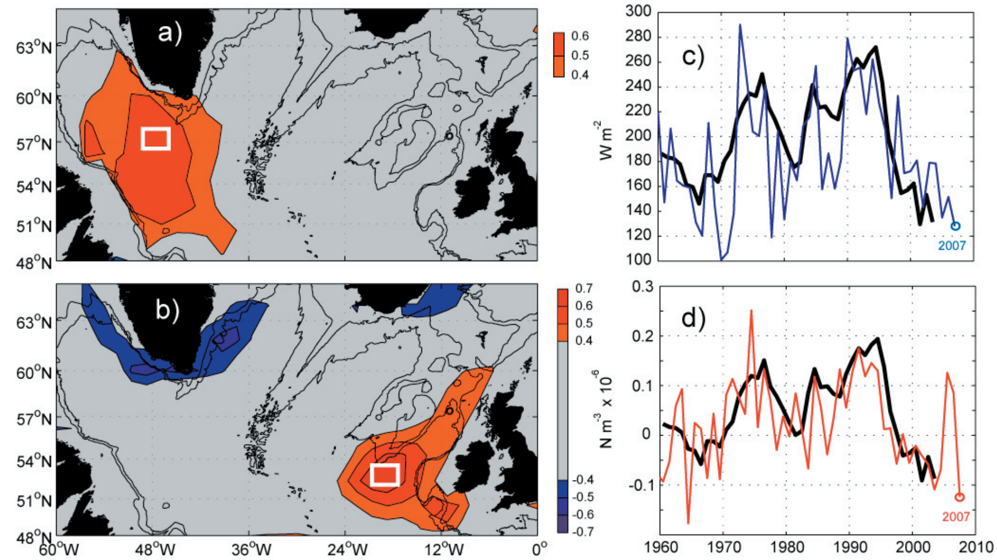

Fig. 12 Multiple regressions between the gyre index and the a) air-sea heat flux and the b) wind stress curl. The gyre index lags the atmospheric forcing by one year and only significant correlations are shown. Time series of the heat flux and the wind stress curl within the white rectangles shown in a) and b) are plotted together with the gyre index in c) and d), respectively.

but shifted one year ahead of time in figures 12c and d. The atmospheric indices appear noisier than the oceanic index, but a closer fit is found by smoothing in time (not shown). Smoothing in time can, however, not be performed when prediction for the upcoming year (2007) is desirable. Both atmospheric indices agree upon the large reduction in forcing intensity around the mid-1990s, but while the heat forcing shows a steady decline until present, the wind stress curl displays a rapid intensification in 2004 and 2005, which should be transferred into the ocean in 2005 and 2006. Both atmospheric indices predict a weak circulation in the subpolar gyre in 2007, and thus good spawning and recruitment conditions for the blue whiting in the Rockall Trough this year.

Climate change and global warming can however alter the hitherto observed decadal to multi-decadal variability in the North Atlantic Ocean climate and shift threshold temperature and salinities northwards and westwards. The discussed dynamics of the blue whiting could thus be altered accordingly.

Conclusions

The migration route of blue whiting from the spawning grounds west of the British Isles to the feeding areas in the Norwegian Sea are shown to vary between a western path over Iceland-Faroe Ridge and an eastern path through the Faroe-Shetland Channel. This variability is shown to mimic the variability in circulation strength and the extent of the subpolar gyre. The causal mechanism is that the oceanic conditions influence the spawning distribution. A strong subpolar gyre results in colder conditions in the spawning area, a spawning distribution that is confined to the European Continental Shelf, a migration path through the Faroe-Shetland Channel and possibly a smaller total fish stock. A weak gyre results in warmer conditions, a spawning distribution that extends over the Rockall-Hatton Plateau, a migration route west of the Faroe Islands and possibly a large stock. The forecasting potential for this dynamics is promising, suggesting that the oceanic condition for spawning and recruitment were favorable during the 2007 spawning season.

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