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The Mean Sea Level Pressure (MSLP) Gradient across the Denmark Strait as Index for the Oceanographic Conditions in North Icelandic Waters.

by

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ABSTRACT

The oceanographic conditions in Icelandic waters are closely related to atmospheric forcing. In the present paper winter means of the atmospheric sea level pressure gradient across the Denmark Strait are correlated to a time series of temperature at station S3 off North Iceland. These data show that variations in North Icelandic shelf waters are closely related to the gradient. The correlation between 3-years moving averages of the gradient and the temperature at S3, one year delayed, was 0.73. This climatic relation clearly reflected the abrupt change from Atlantic to Arctic conditions on the North Icelandic shelf in the 1960s and the variability since then. Further, the effects of the variations on water mass properties in the southern Norwegian Sea are discussed. Biological effects have been observed on all levels in the food web. Various authors describe related biological variations, from the primary production level to cod and herring. The cod responded to the climatic variability and the associated narrowing habitat with a decline in abundance. The stock of herring that earlier was grazing north of Iceland, changed its migration pattern, and has not yet returned.

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Introduction

Areas that are of importance for the present study are the Irminger Sea and the southern Iceland Sea. In the Irminger Sea the Irminger Current carries Atlantic water, deriving from the North Atlantic current, northward along the west coast of Iceland. Off northwest Iceland, where the current meets the Greenland-Iceland Ridge, it is constrained to split into two branches. The northern one, the North Icelandic Irminger Current, turns around Horn, the north-western corner of Iceland, to flow eastward over the North Icelandic shelf. The other branch turns toward southwest, and follows the east coast of Greenland toward Cape Farewell. There it flows parallel with and underneath the Arctic and Polar waters of the East Greenland Current (Figure 1).

The oceanographic conditions in the upper layers off North Iceland are mainly characterized by two quite different water masses. The relatively warm and salty Atlantic water of the North Icelandic Irminger Current flows eastward North of Icelandi. North of the Denmark Strait the East Icelandic Current diverges from the East Greenland Current and carries cold and relatively fresh Arctic waters eastward over the North-Icelandic slope. Hence, as these two quite different water masses flow eastward, they mix with each other along the shelf edge. This mixing considerably modifies the water masses, especially during winter when seasonal cooling creates convective mixing. According to Stefansson (1962) this mixing during wintertime forms a local water mass: the North Icelandic Winter Water. This water mass merges into the East Icelandic Current as it flows into the south-western Norwegian Sea. As the current proceeds eastward over the northern slope of the Faroe-Iceland Ridge, the mixing and modification continues. In this area Read and Pollard (1992) defined the mixing product as Modified East Icelandic Water. Proceeding further toward east, these waters originating from north of Iceland, flow into the southern Norwegian Sea and Faroe-Shetland Channel. In this area most of these waters occur as an intermediate Arctic water mass, but particularly during summer, its less dense versions may mix into the Atlantic waters in the surface layers of the Norwegian Atlantic Current (Blindheim et al., 2000).

Based on computation of geostrophic current in the hydrographic repeat sections north of Iceland, Stefansson (1962) assessed the volume flux of Atlantic Water in the North Icelandic Irminger Current to be 0.6 Sv. Later Kristmannsson (1998) assessed the eastward warm water transport off Kögur. This was based on a 5-year long series of current measurements near the core of the North Icelandic Irminger Current over a bottom depth of 250 m. The transport computations were based on only one mooring with two current meters, which possibly gave too few data to obtain reliable result, but they are supported by later results based on measurements at three mooring sites (S. Jonsson, Personal information). The measurements by Kristmannsson revealed both seasonal and longer-term variations. The seasonal cycle showed two maxima: one in May through August and a second in November through January. The mean monthly variations ranged from 0.9 Sv in March to 2.0 Sv in May, while longer-term variations varied between 0 Sv, in February/March 1990, and 2.8 Sv in January 1987. The long-term variations agree with observed hydrographic conditions in North Icelandic waters during this period, showing strong Atlantic influence during 1984 – 1987 and, accordingly, more Arctic conditions in 1989 – 1990 (Malmberg and Kristmannsson, 1992).

These variations in the volume flux of Atlantic Water into the North Icelandic region are of great importance for both oceanographic and biological conditions in the area. It has been shown that the temperature and salinity in the North Icelandic standard section off Siglunes were drastically reduced during the late 1960s (Malmberg, 1969 and 1986; se also Malmberg and Kristmannsson, 1992). This was the beginning of the “Great Salinity Anomaly” (Dickson et al., 1988). Biological effects are described by many authors, for example Thordardottir, 1977; Astthorsson at al., 1983; Stefansson and Olafsson, 1991; Jakobsson and Østvedt, 1999).

It was early claimed that the variations in oceanographic conditions north of Iceland were associated with atmospheric forcing. For example Stefansson and Gudmundsson (1969) showed a distinct relation between the atmospheric pressure distribution in spring and the hydrographic conditions in summer. Malmberg and Kristmannsson (1992) found a positive correlation between the wind stress curl west and north of Iceland and the water mass distribution in North Icelandic waters 6 to 9 months later. Working on data from 1956 –1998, Olafsson (1999) concluded that the hydrographic regime responded to shifting between local southerly and northerly winds. He further found that the North Atlantic Oscillation does not explain observed hydrographic variations in North Icelandic water. In 5-years moving averages of the data from the Siglunes Section, however, Malmberg and Valdimarsson (in press) found some relation to 5-years means of the NAO in three parts of the period, beore, during, and after the ice years 1965-71.

Here we will relate hydrographic conditions north of Iceland to a 100-year long series of atmospheric mean sea lever pressure (MSLP) gradients across the Denmark Strait, and further, we will briefly discuss some biological effects

Data

The atmospheric pressure data are from Frich et al. (1996) and Schmith et al. (1997). Data from Stykkisholmur on the west coast of Iceland (65°05´N, 22°44´W) and Angmagssalik on the east coast of Greenland (65°36´N, 37°38´W) are of special interest as these stations have a series of observations during the period from 1895 to 1995, although with some gaps in the series from Angmagssalik. Shorter series of MSLP data from two station further north on the East Greenland coast, Scoresbysund (70°29´N, 22°00´W) and Danmarkshavn (76°46´N,18°46´W), are also used to indicate the temporal variations in the atmospheric high pressure cell over Greenland. The oceanographic data are observed in spring on the Icelandic Siglunes standard section along 18° 50´ W across the North-Icelandic shelf to 1000 m depth (Figure 1).

Results and discussion

Figure 2 shows 5-years moving averages of winter MSLP, averaged over the months December through March, from three stations on the east coast of Greenland: Angmagssalik, Scoresbysund, and Danmarkshavn. Although the series of observations are of different length, it is clearly indicated that they have similar large-scale variations. Further it is seen that there were fairly constant differences between the stations, and that the MSLP was increasing northward along the coast. The difference in pressure during winter between Scoresbysund and Angmagssalik was on average 6.5 hPa (hecto Pascal), with a standard deviation of 0.7 hPa. Although it should be considered with caution, it is therefore reasonable to conclude that the differences between the stations would be similar during the whole century. In spite of the moderate variations in the difference between Scoresbysund and Angmagssalik, there was a clear trend, the difference decreasing from 1948 to 1964, and later, increasing from1969 to 1992. More in general, Figure 2 shows that the MSLP over Greenland increased from the late 1890s to the late1960s. Since then the trend has been toward lower MSLP.

Figure 3 shows that also the MSLP variations in the Iceland Low, here represented by the time series from Stykkisholmur, were very similar to the fluctuations in the Greenland High. In Figure 3 these are represented by the time series from Angmagssalik. Normally the MSLP at Angmagssalik was higher than at Stykkisholmur, but this was not always the case. Particularly in the period 1947-1954, Stykkisholmur had higher MSLP than Angmagssalik. For the whole period the difference in MSLP between Angmagssalik and Stykkisholmur varied between –3.6 hPa (1948) and 6.9 hPa (1912) with an overall average of 1.82 hPa, and a standard deviation of 2.32 hPa. This is further demonstrated by the gradient of winter MSLP between Angmagssalik and Stykkisholmur over the period 1895-1995 shown in Figure 4. The gradient indicates the average wind pattern during the different winter seasons in the Denmark Strait area, values above zero representing prevailing northerly winds.

Although gaps in the data from Angmagssalik break the series during some intervals, it is seen that the highest winter means occurred around 1910, while the longest period with negative gradient occurred during the late1940s and the first half of the1950s. These years which formed an extreme for the whole century-long period, fell within the period from about 1920 to the 1960s that had relatively low values. This period with moderate atmospheric forcing resulted in high Atlantic influence in North Icelandic waters, as also described by Stefansson (1969) based on a long series of sea surface temperatures from the island of Grimsey near the Siglunes section. The end of this period, with an abrupt increase in the gradient across the Denmark Strait from values near or below zero in the early 1960s to a high level, around 4 hPa, at the end of the decade seemed to have great consequences.

The oceanographic effects are demonstrated by the conditions in North Icelandic waters. The correlation coefficient between the winter MSLP gradient across the Denmark Strait and the temperature the same spring at 50 m depth at station S3 (Figure 1) during the period 1950 – 1995, was $r = 0.56$. The highest correlation, $r = 0.73$, was obtained between the 3-year moving averages of the winter MSLP gradient and identical averages of the temperature at 50 m depth at Station S3, one year delayed. This is further illustrated in Figure 5 where 3-years moving averages of the S3 temperatures are compared with 3-years moving averages of the MSLP gradient between Angmagssalik and Stykkisholmur one year earlier. For the comparison the values of the gradient are inverted and entered in hPa.These results may look somewhat in contrast to earlier findings, concluding that wind conditions west and north of Iceland affect the oceanographic conditions north and east of Iceland three months later (Stefannsson, 1962;

Stefansson and Gudmundsson, 1969; Olafsson 1999). This may, however, not be the case if the difference in spatial scale is taken into consideration. The atmospheric pressure gradient between Angmagssalik and Stykkisholmur will reflect rather large-scale variations in the Irminger Sea and in the Denmark Strait. Besides reducing the volume flux of Atlantic Water in the Irminger current as a whole, prevailing northerly winds will further promote increased supply of Atlantic Water into the East Greenland Irminger Current. The supply of Atlantic Water to the North Icelandic Irminger Current will be reduced accordingly. It is shown that the wind conditions have similar effects as far south and west as on the former Ocean Weather Station A at 62° N, 33°W in the Irminger Sea (Blindheim, 1968).The delay of variations on the shelf north of Iceland in relation to the winter MSLP gradient across the Denmark Strait may, therefore, be reasonable as it has regional rather than local effects. The correlation given above is, however, only based on oceanographic data from spring and the delay may, therefore, not be exact.

On decadal time scales, the graph of the winter MSLP gradient in Figure 4 indicates that there was low supply of Atlantic Water to the North Icelandic area during the first two decades of the 20th century, which is in fair agreement with the findings of Stefansson (1969). This was followed by an approximately 30-year long period with larger Atlantic influence. Within this period, the years around 1950 seemed to be favoured by the century's greatest supply of Atlantic Water to the shelf north of Iceland (Stefansson, 1962). In contrast, the strong northerly winds when the high pressure over Greenland peaked during the late 1960s led to years with cold conditions north of Iceland and drift Ice blocking the north and east coasts of country (Malmberg, 1969). This also coincided with the period when the NAO winter index was at its lowest.

Most of the waters carried by the North Icelandic Irminger Current mixes into the East Icelandic Current and flow into the south-western Norwegian Sea where it forms a cold tongue of Arctic character as first described by Helland-Hansen and Nansen (1909). The position of the Arctic Front between this water and the Atlantic waters of the Norwegian Atlantic Current may vary from year to year (Shevchenko and Isaev, 1985; Monstad and Blindheim, 1986). Further to the east, the Arctic water also occurs at intermediate depths underneath the Atlantic Water in the southern Norwegian Sea and the Faroe-Shetland Channell. As described by Blindheim et al. (2000), the narrowing of the Norwegian Atlantic Current, or in other words, the eastward shift of the Arctic Front, since the 1960s was associated with fluctuations in the NAO. Also the cooling and freshening in the upper layers of the western Norwegian Sea were ascribed to the same wind forcing. This effect shall, of course, not be ignored, but variations in the properties of the waters carried into the area by the East Icelandic Current may also be of importance. These characteristics, and possibly also the amount of the Arctic waters, may wary with the conditions north of Iceland. The variability in the inflow of Atlantic Water into the North Icelandic shelf area may thus be reflected in the properties of the waters flowing into the southern Norwegian Sea.

The difference between 1958 and 1997 in extent of water deriving from north of Iceland is demonstrated in Figure 6. This figure shows two sections, worked in spring of both years, extending from 62°21'N off the Norwegian coast, across the Norwegian Sea, and into the Iceland Sea southwest of Jan Mayen. In 1958 Modified East IcelandicWater was observed only in an area in the central Norwegian Basin, southeast of the small volume of Atlantic Water over the western slope of the basin. (This Atlantic water is carried southward by the cyclonic circulation in the basin). It was characterised by a slight minimum in salinity, close to 34.90, at temperatures between 2 and 3°C. Only between 3 and 5°W, where it extended from the surface to about150 m depth, its salinity was slightly below 34.9 as indicated in Figure 6.

In 1997, however, Arctic waters occupied the upper layers to almost 1000 m depth across the whole Norwegian Sea, in the eastern part of the section as an intermediate layer between the Atlantic Water and the deep waters below. The deeper component of this water is known as Norwegian Arctic Intermediate water and derives from both the Iceland and Greenland Seas. In this section the Modified East Icelandic Water was observed in about the same area as in 1958, but in 1997 it was fresher and of a larger volume. It was mainly observed as a salinity minimum around 200 m depth although it extended from the surface in the central basin. The lowest salinities were below 34.8, and associated with temperatures mainly ranging from 2 to 4°C.

The section from 1958 was, as shown in Figure 4, occupied in the period when the gradient across the Denmark Strait was at a low level and conditions on the North Icelandic shelf were characterised by Atlantic Water (Figure 5). On the other hand, 1997 was within the period with high gradients and, accordingly, low Atlantic flux in the North Icelandic Irminger

Current. These conditions may be a component in the mechanism behind the difference between the two sections in Figure 6.

Biological effects

Biological effects of the drastic change toward colder conditions in North Icelandic waters during the late 1960s have, as already mentioned, been described by many authors and are well known. Here are mentioned only some of the main features to illustrate the connection to the climatic factors that are described. The biological effects could be observed at all levels of the food web. Hence, during the ice years (1965 – 1971) primary production dropped to a low level (Thorardottir, 1977) and in the next turn this affected higher trophic levels. In zooplankton this could be observed both with regard to abundance and species composition (Astthorsson et al., 1983).

Cod in the northern North Atlantic is dependent on moderately warm oceanographic conditions and nutritionally rich areas. These areas have continental slopes and shelves to the right of the current direction and derive waters from oceanic cyclonic current systems. The current transports the eggs and larvae from spawning areas into the nursery and feeding grounds. Off Iceland the cod spawn mainly in relatively warm waters south of the country. The currents carry eggs and larvae around the west coast to nursery and feeding areas in North Icelandic waters, and some years also westward towards Greenland. These warm current systems meet cold waters along the Arctic Front where mixing improves living conditions.

As stated above, variations on various time scales occur in the environmental conditions, resulting in warm and cold periods. Hence, during the 1960s and 1970s the area in the Northern North Atlantic under Arctic influence, expanded along the Arctic front all the way from the Barents Sea to Newfoundland waters, thus narrowing the cods habitat. During this period the temperature and salinity in the Irminger current decreased to levels considerably lower than those in the period 1920-1960, and in spite of a slight increase since the late 1960s it has not yet reached the level of the 1950s. Also, since the mid 1960s, variations of time scales ranging from one to a few years have been more frequent than earlier. As seen in Figure 7, the abundance of the Icelandic cod frequently fluctuated in phase with these variations.

More in general, during the period of climatic deterioration since the late 1960s, most cod stocks in the Northern North Atlantic declined (se for example Jakobsson, 1992; Malmberg and Blindheim, 1994). It may often be disputed that the stock reductions results from a heavy fishing load. Most probably this has also been the case for the overall decline from the mid 1950s to 2000 shown in Figure 7, despite relatively good recruitment from time to time. As already mentioned, the shorter-term variations shown in the figure may be associated with the environment. In this aspect one should bear in mind that the fishing load can be steered, but not environmental variations.

The hydrographic variations also affect the capelin around Iceland although it grazes in Arctic waters. The distribution of grazing capelin is often difficult to relate to the environment, but its growth is correlated with the temperatures in North Icelandic waters (Vilhjalmsson, 1994).

The possibly most important biological effect of the climatic changes was the disappearance of the stock of Norwegian Spring Spawning Herring from North Icelandic waters. Although intense fishery reduced this stock considerably, the changes in its distribution could not occur because of over-fishing. These changes include its total absence from the Norwegian Sea during approximately two decades from 1969, and, in particular, its still lasting absence from North Icelandic Waters.

Thorough investigations on the stock were initiated in 1950 (for example Jakobsson, 1980; Jakobsson and Østvedt, 1999). These investigations showed that during the period 1950 – 1962, the summer feeding grounds were mainly in the Iceland – Jan Mayen area and after the grazing period the stock was found in a concentrated wintering area at around 10°W east of Iceland. From 1963 a portion of the stock, and from 1967 the whole stock, left the area north of Iceland to graze in the northern Norwegian Sea, but its wintering area east of Iceland was mainly retained. After 1969 no grazing herring were observed in the Norwegian Sea (Dragesund et al., 1980).

This evacuation from North Icelandic waters coincided with the period when the oceanographic conditions in North Icelandic waters changed from an Atlantic environment to a rather Arctic one with ice formation during winter and drift ice blocking the north and east coasts of Iceland during spring and early summer. This was associated with an increase of the MSLP gradient across the Denmark Strait from a very low level in 1964 to a very high level in 1966 (Figure 4), and it has remained at this high, although variable, level during the following decades.

From a reminiscence of the herring stock that found habitat in northern Norwegian fjords and adjacent coastal waters, it was rebuilt to abundance during the 1980s and early 1990s, and the stock has again been feeding in the Norwegian Sea. It has, however, hardly been as far west as to the Icelandic EEZ. Its most western distribution was observed in 1994, but since then the herring has mainly found grazing areas east of the Arctic Front in the Lofoten Basin northeast of Jan Mayen.

This is clearly associated with the variable, but on average high values of the MSLP gradient across the Denmark Strait and the resulting low flux of Atlantic water, and accordingly, high Arctic influence in North Icelandic Waters since the late 1960s. Furthermore, it cannot be expected that the herring return to North Icelandic waters before the MSLP gradient across the Denmark Strait has stabilised at a lower level for more than 5 years. The period with relatively low values from 1982 to 1986 was apparently not sufficient although it was at a similar level as the period before 1960 when herring was abundant in North Icelandic Waters during summer. It seems that the dominating character of the waters and their nutritional capacity needs some years to be established.

It has been shown that also grazing blue whiting have responded to variable extent of waters from the East Icelandic Current in the southern Norwegian See (Shevchenko and Isaev,1985, Monstad and Blindheim, 1986).

The effects mentioned above show that the climatic variability related to the pressure gradient between the Greenland High and the Iceland Low has effects not only in Icelandic waters, but also far into the Norwegian Sea, particularly during the extraordinary 1960s.

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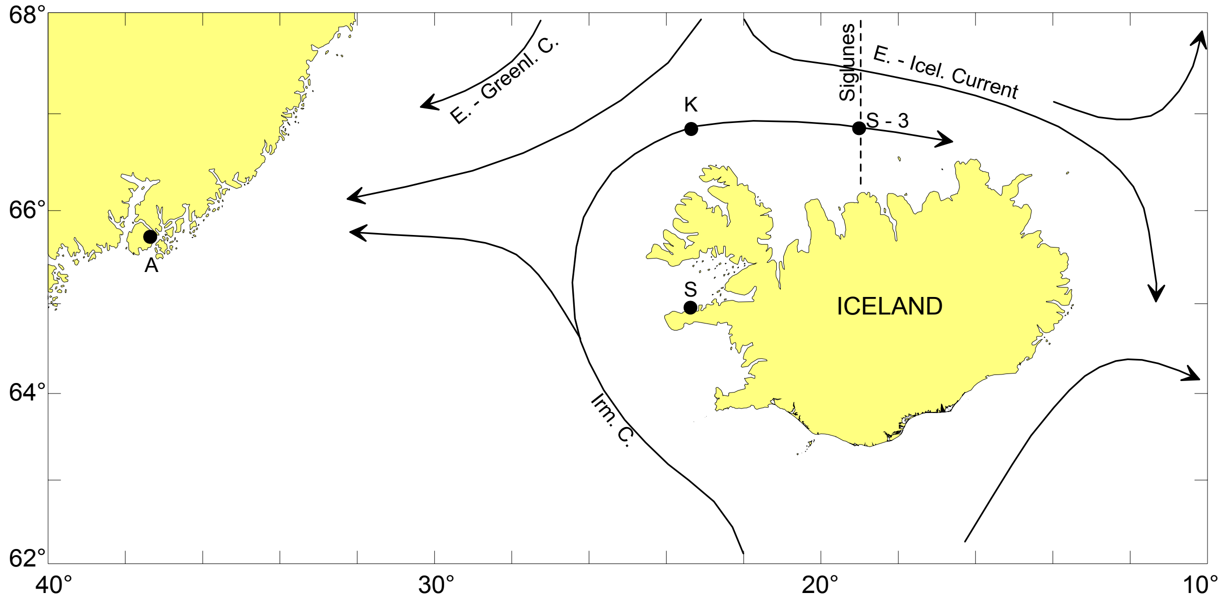


Figure 1. Schematic main ocean currents in Icelandic waters and stations referred to in this paper: A) Angmagssalik, S) Stykkisholmur, K) Køgur, S-3) Station 3 on the Siglunes Section.

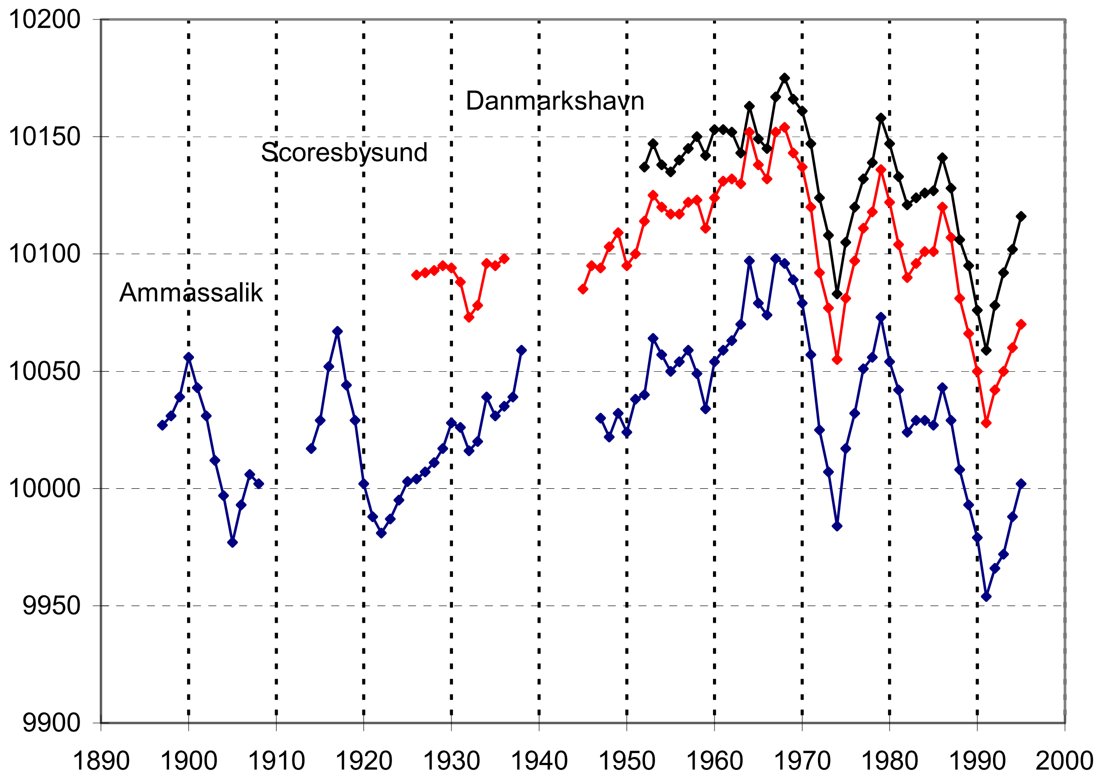
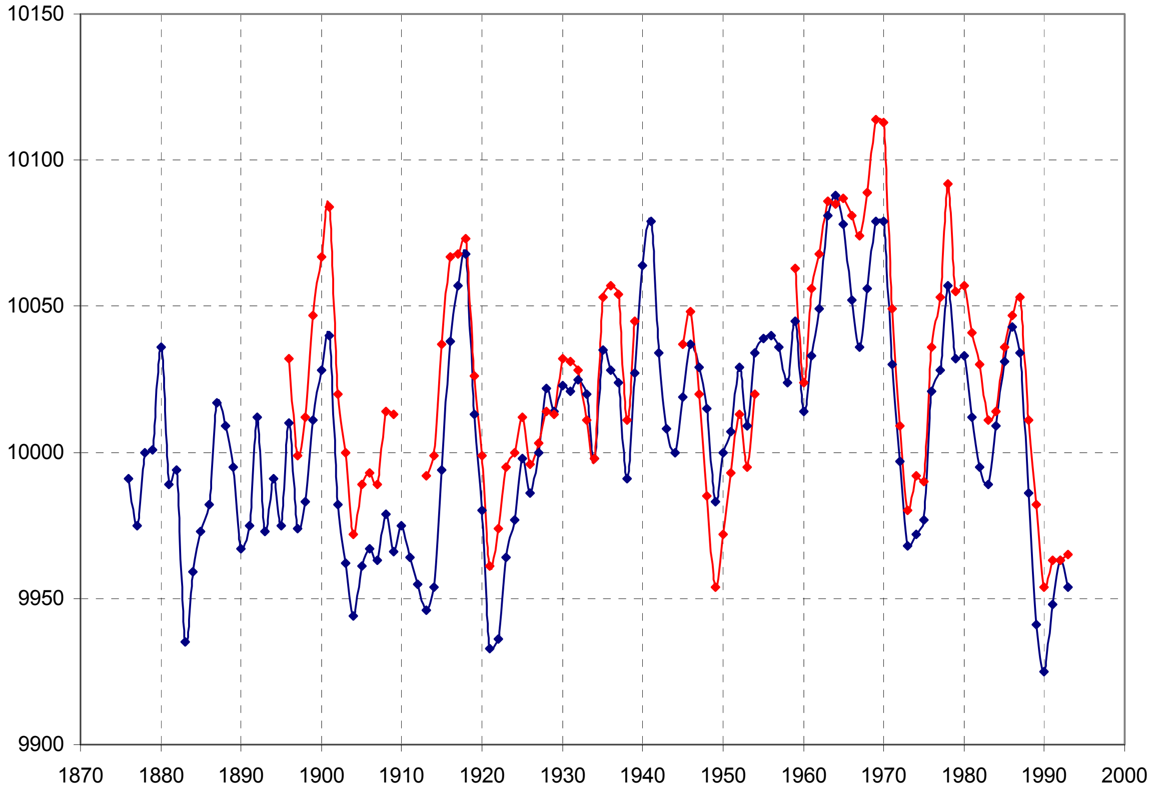


Figure 2. Five-years moving averages of mean sea level pressure, hPa *10, December through March, at Angmagssalik, Scoresbysund, and Danmarkshavn, East Greenland during the 20th century.



Figur 3. Mean sea level pressure, hPa*10, December through March at Angmagssalik (1895-1995) and Stykkisholmur (1874-1994).

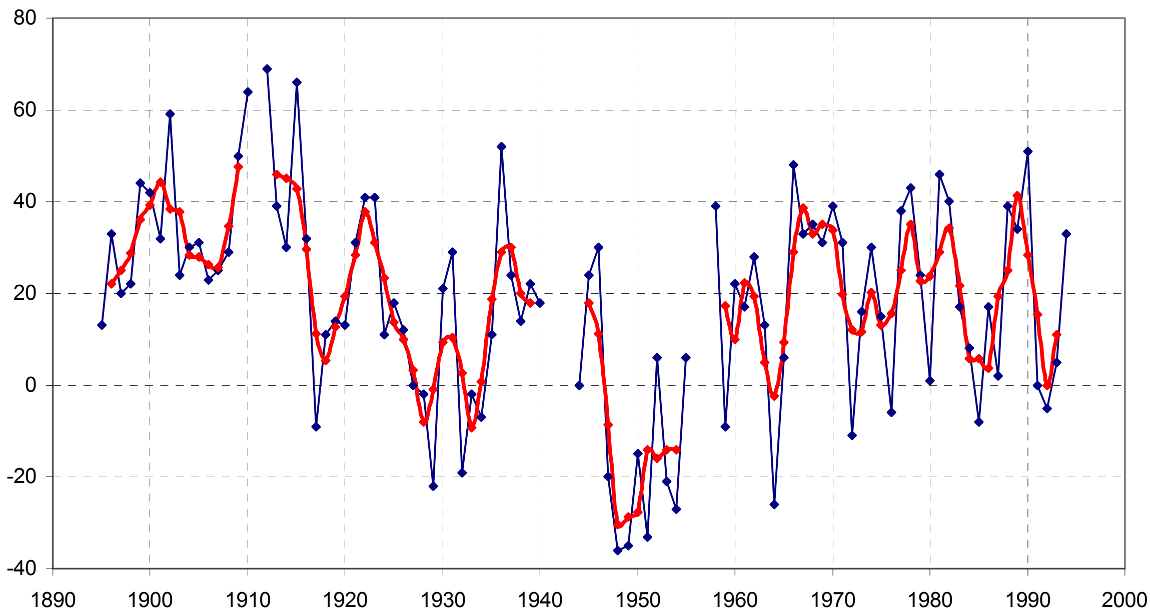


Figure 4. Mean sea level pressure gradient (hPa*10) between Angmagssalik and Stykkisholmur with 3-years moving averages (red).

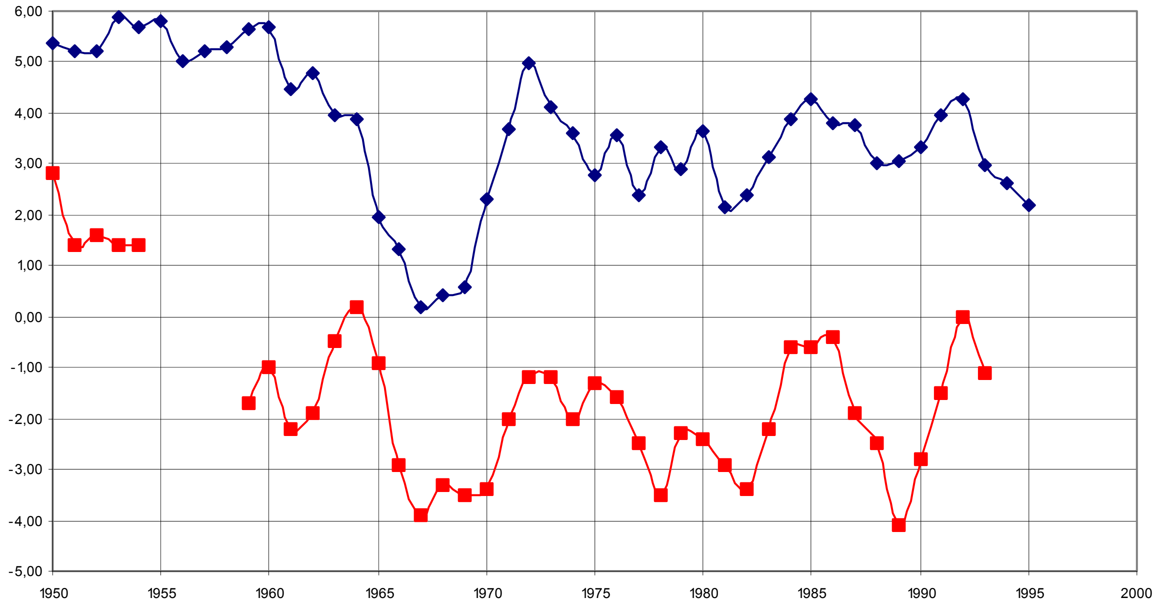


Figure 5. Three-years moving averages of temperature at 50 m depth, Station S-3, in spring 1950 to 1995 (blue) and inverse MSLP gradient (hPa) between Angmagssalik and Stykkisholmur one year earlier (red).

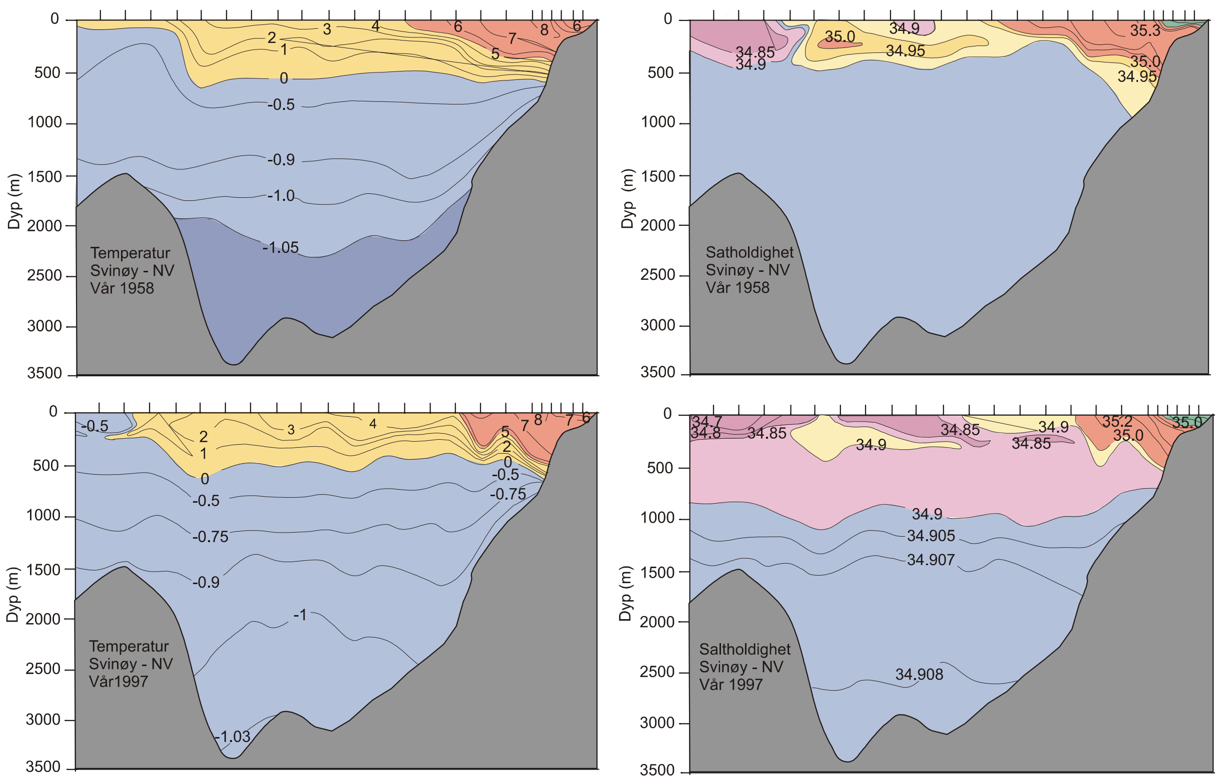


Figure 6. Potential temperature and salinity in a section between 61°21’N, 04°40’E off the Norwegian coast and 67°43’N, 10°53’W, southwest of Jan Mayen, worked in spring in 1958 and 1997.

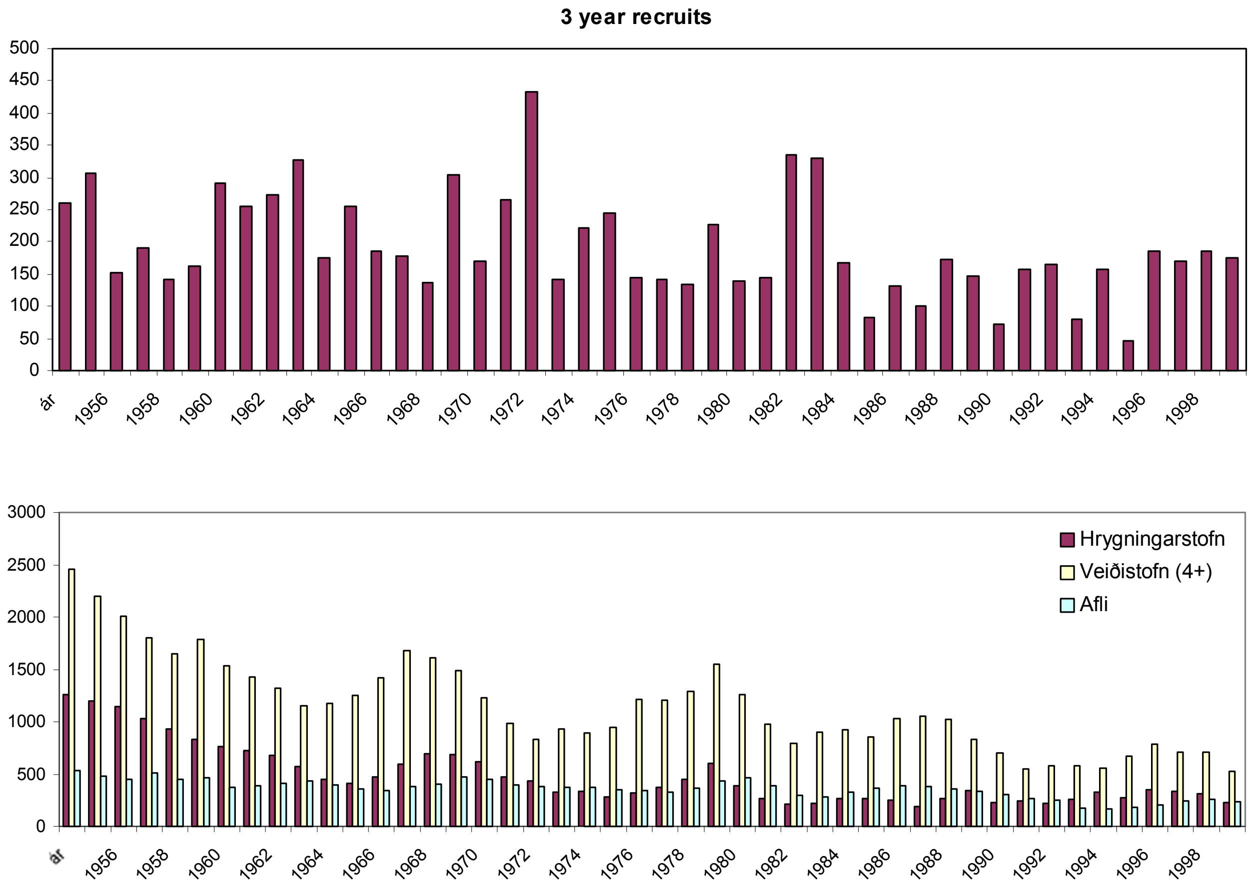


Figure 7. Yearclass strength, n*10^6, of three-years old cod (upper panel), fishing stock, spawning stock and catches of Icelandic cod 1954 – 2000, in thousands of tonnes.