Geographical distribution and abundance of Northeast Arctic haddock (*Melanogrammus aeglefinus*) in a fluctuating climate

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Abstract

Northeast Arctic haddock (NEA haddock) is an important commercial fish species, distributed along the Norwegian shelf and in the Barents Sea, bordering the Arctic areas in the northeast. Large inter-annul to multi-decadal temperature fluctuations characterise the marine climate in the area. During recent decades the long-term trend has shown an increase in temperature. Understanding how NEA haddock reacts to these climatic changes is important when developing management strategies for maintaining a sustainable stock, however few studies have addressed this question. The main aim of this thesis is to analyse how the temperature changes have affected the abundance and distribution of NEA haddock in the period 1981-2011, focusing on age groups from 0-group to 9-year old fish. The study is based on time series of trawl and temperature data from the Barents Sea collected annually in surveys since 1981, extracted from the FishExChange database. Results indicated that high temperature have been necessary, but not sufficient to get a strong year-class, further the abundance appear to have responded to temperature on both a short and long time scale. The ambient temperature was decreasing with increasing age between 1 and 3 years of age, and thereafter, ambient temperature was increasing with increasing age between 3 and 9. This pattern appears to have been independent of the absolute temperature in specific years. The 0-group and 1-year old fish were found further east in warm years, contrary there were weak relations between location of distribution centres with temperature for older age groups. However, the distribution centre for age groups between 2 and 6 correlated with abundance. Since the temperature trend showed an increase in the period studied, the results can be used when speculating how a further temperature increase by global climate change may affect the abundance and distribution of the NEA haddock stock.
1. Introduction

For the Barents Sea fish stocks temperature changes are believed to have large impact on both year-class strength and geographical distribution, and for the Northeast Arctic (NEA) cod there are extensive studies as documentation for this issue (e.g. Nakken and Raknes, 1987; Ottersen et al., 1998; Sundby, 2000). However, for other important gadoid fish, like the NEA haddock, few studies have addressed this question. NEA haddock is one of the most important commercial fish species in the Barents Sea (Olsen et al., 2010). The stock is characterized by extreme fluctuations in recruitment (Olsen et al., 2010). Historical catch levels have fluctuated from as low as approximately 21 000 tons in 1984, to the record high levels of almost 250 000 tons in 2010 (ICES, 2011). Understanding how the NEA haddock stock reacts to climatic fluctuation and changes is important for developing management strategies for maintaining a sustainable stock.

Haddock is demersal, gadoid fish species, with stocks situated around western and eastern shelf areas in the North Atlantic. The NEA haddock stock is distributed in the boreal areas along the Norwegian shelf and in the Barents Sea, but border the relatively colder arctic areas in the eastern and northern parts of the Barents Sea. Spawning occur along the slope between the continental shelf of northern Norway and the Norwegian Sea, between March and June, at depths between 300 and 600 meters (Olsen et al., 2010). Pelagic eggs and larvae have limited moving abilities and drift north-eastwards with the currents, and show large spatio-temporal variation in abundance and distribution (Bergstad et al., 1987; Olsen et al., 2010). By August-September, the distribution of the pelagic juveniles extends over most of the Barents Sea south of the Polar Front before they settle to the seabed in August-October (Bergstad et al., 1987; Stiansen et al., 2009; Olsen et al., 2010). Juveniles use the Barents Sea as a feeding area (Olsen et al., 2010), and up to the age of 3, no regular seasonal migration is observed (Sonina,
1969 cited in Bergstad et al., 1987). They become mature at the age of 4-7, and are then distributed in the central and southwestern parts of the Barents Sea as well as in the coastal areas of the Norwegian Sea (ICES, 2011). They recruit to commercial fisheries after the age of 3 (ICES, 2011).

Substantial inter-annual to multi-decadal temperature fluctuations characterise the marine climate in the Barents Sea (e.g. Loeng and Drinkwater, 2007). During the past three decades the long-term trend has shown an increase in temperature likely related to increasing phase of the multi-decadal oscillations (Loeng and Drinkwater, 2007), but possibly amplified by anthropogenic forcing (IPCC, 2007). The relationship between the physical and biological conditions in the Barents Sea have been discussed in several papers (e.g. Sætersdal and Loeng, 1987; Loeng and Drinkwater, 2007). Investigations have shown that physical conditions are important indicators/proxies for recruitment, distribution and growth of many important commercial fish species as reviewed by Loeng and Drinkwater (2007), including NEA haddock (Ottersen and Loeng, 2000). Specifically, eggs, larvae and juveniles of NEA haddock are sensitive to external factors, which directly and indirectly influences growth and survival (Ottersen and Loeng, 2000). The distribution of NEA haddock is affected by temperature, where cooling of water masses have been reported to lead to a more westerly distribution (Sonina, 1969 cited in Bergstad et al., 1987).

A lot of the knowledge on NEA haddock is based on grey literature, such as survey reports and ICES Working Group documents (Olsen et al., 2010). Compared to NEA cod, few studies have analysed climate impact on NEA haddock, especially regarding the temperature effect on older age groups, or addressed potential differences in the response to temperature between the age groups.

The main objective of this master thesis is to study how the abundance and distribution of NEA haddock have been affected by temperature fluctuations in the period 1981-2011. Since the temperature has been steadily increasing during this period it gives us a unique opportunity to study the changes in abundance and distribution during a period which might have similar features with what could be expected under global climate change.
The focus of this study will be on NEA haddock from 0-group to 9-year old fish. The study is based on time series of trawl data from the Barents Sea collected annually in winter surveys since 1981. Only winter data will be considered in this study (except for the 0-group where data are collected August-September). The biological data will be analysed together with spatial temperature data, which gives the opportunity to compare local distribution with local temperature condition. The age-divided data makes it possible to compare the different age groups of NEA haddock with each other, and quantify whether they show different responses to the temperature fluctuations. Additionally, the results will be compared with similar results on NEA cod in search for previously unknown similarities and differences between the two gadoid species. Further, since the temperature is generally increasing in the period studied, the results could be helpful when predicting how a further potential temperature increase (e.g. climate change) may influence the abundance and distribution of the NEA haddock stock.

This will be investigated by answering the following research questions:

- How strong were the correlations between temperature and abundance, both for 0-group and the age groups between 0 and 9, and have these relations changed throughout the period?
- What has been the thermal habitat for the different age groups, and are there inter-annual variations in thermal habitat related to temperature fluctuations within this period?
- Have the location of annual distribution centres for the various age groups been affected by temperature fluctuations in this period? And if so, have abundance been more important than temperature for the location of the annual distribution centres?
2. Background

2.1 Life history of NEA haddock

Haddock is a demersal, gadoid fish species with populations distributed on western and eastern shelf areas in the North Atlantic (Gjøsæter, 2009). The NEA haddock population is located in the Barents Sea and on the continental shelf along the Norwegian coast. The NEA haddock may live for up to 20 years, and grow to 19 kg and 110 cm (Olsen et al., 2010). Most NEA haddock mature at ages 4-7 and at lengths between 40-60 cm (Olsen et al., 2010). However, the maturation rate is variable and depends on age and length as well as other factors such as cohort and sex (Korsbrekke, 1999). The NEA haddock is generally restricted to water masses warmer than 2ºC, with highest densities found in areas with 5-6ºC (Bergstad et al., 1987).

The mature part of the NEA haddock stock start spawning migration in January-February, however, large inter-annual variation in timing and extent of the migration is observed (Bergstad et al., 1987). Spawning occur along the slope between the continental shelf and the Norwegian Sea and off the coast of northern Norway (Fig. 2.1b). The most important spawning grounds seem to be on the western side of Tromsøflaket on the banks outside Røstbanken, Vesterålen, the outer part of Vestfjorden and Møre-Romsdal (Olsen et al., 2010). However, spawning areas have not been properly investigated, and their exact location are diffuse (Olsen et al., 2010). Spawning occurs in March-June, but most intensively in April-May (Bergstad et al., 1987). The eggs are pelagic and usually spawned at depths between 300 –600 meters in temperatures between 4 and 6ºC (Olsen et al., 2010). After spawning the NEA haddock return back to the feeding grounds in the eastern Barents Sea in late summer (Bergstad et al., 1987).
The eggs hatch after approximately 14 days (Gjøsæter, 2009). Eggs and larvae drift northward with the currents. Their distribution as 0-group in August-September extends over most of the southern and western Barents Sea south of the Polar Front, but also along the western coast off Spitsbergen (Olsen et al., 2010). Both inter-annual and long-term variation in their distribution occur, mostly associated with changes in the water mass distribution and climate conditions (Bergstad et al., 1987). The pelagic juveniles settle to the seabed during August-October in temperatures warmer than 1°C (Bergstad et al., 1987). They have then grown to 30-130 mm. The long spawning period is the main reason behind this large variation in size (Gjøsæter, 2009). Juveniles use the Barents Sea area as feeding ground. Up to the age of 3, no regular seasonal migration is seen. However, juveniles (2-4 year) can live pelagic lives during summer (Bergstad et al., 1987). After the age of 3, they show seasonal migration between eastern and coastal feeding areas in summer and western overwintering areas in deeper waters (Bergstad et al., 1987). The mature fish also perform more extensive vertical migration than juveniles, and is therefore generally found higher in the water column (Bergstad et al., 1987; Olsen et al., 2010).
Figure 2.1: The distribution of NEA haddock eggs, larvae, juveniles, adult and spawning areas, as well as their main migration patterns by (a) first quarter, (b) second quarter, (c) third quarter, and (d) fourth quarter (from Olsen et al., 2010).
2.2 Physical description of the Barents Sea

The Barents Sea is a continental shelf sea, located between 70 and 80 degrees north, and connecting with the Norwegian Sea to the west and the Arctic Ocean to the north (Stiansen et al., 2009). The average depth is approximately 230 meters.

The climate in the area is to a large extent determined by the distribution of three water masses; Atlantic Water, Coastal Water, and Arctic Water. Each of them is associated with specific current systems; the Norwegian Atlantic Current, the Norwegian Coastal Current, and the Arctic current systems, respectively (Loeng, 1991). Simplified, Coastal Water flow north and eastward along the Norwegian coast, relatively warm North Atlantic water flow eastward in the southern parts of the Barents Sea, while cold Arctic water flow southwestwards in the northern part (Fig. 2.2a) (Ellingsen et al., 2008). The oceanic polar front, characterised by a strong temperature gradient separates the warm Atlantic water (boreal areas) from the cold Arctic water (arctic areas).

The temperature is reflected by the current conditions and the distribution of the water masses with different temperature characteristics (Fig. 2.2b). The temperature have shown substantial variations ranging from inter-annual to multi-decadal (Atlantic Multidecadal Oscillation) (e.g Loeng, 1991; Loeng and Drinkwater, 2007). This is displayed in the Kola-section temperature time series (Fig. 2.3) which shows inter-annual to decadal scale variations as well as a multi-decadal signal with two cold, and two warm periods throughout the 20th century. The variability is partly caused by spatial and temporal fluctuations in the physical properties and amount of inflow of relatively warm Atlantic water (Loeng, 1991; Ingvaldsen et al., 2002) entering the Barents Sea in the south western areas. Warm periods are in general associated with a high heat flux into the region due to both higher temperature in, and larger volume inflow of the relatively warm Atlantic water (Loeng, 1991). Focusing on the past 25 years, the climate has fluctuated with a 7-10 year period, with a superimposed overall trend showing an increase in temperature.

The relative shallow depth causes the bottom topography to have high influence on the current conditions and the distribution of water masses (Sundby, 1984). This also becomes
clear from the positioning of the polar front. The front is particularly sharp in western areas due to topographic stability, but difficult to trace on the eastern side (Loeng, 1991; Harris et al., 1998). The ice edge follows the polar front during winter and early spring, and is therefore relatively stable in the western parts, but show large inter-annual variation on the eastern side (Loeng, 1991). The polar ice reaches its maximum extent into the Barents Sea around March (Loeng, 1991).

Figure 2.2: (a) Main circulation and bathymetry in the Barents Sea and surrounding seas, (b) average temperature at 100 meters depth, based on observations during August-October for the period 1977-2007 (from Stiansen et al., 2009).

Figure 2.3: Inter-annual to multi-decadal fluctuations in the average annual temperature between 0 and 200 meter depth in the Atlantic part of the Kola section (Bochkov, 1982) (from Stiansen et al., 2009).
2.3 Features of NEA haddock in relation to the Barents Sea ecosystem

Within an ecosystem, species respond to climate fluctuations, and species interact with each other. Hence, both the physical and biological aspects of the Barents Sea ecosystem need to be considered in order to understand the mechanism responsible for the observed variability in abundance and geographical distribution of NEA haddock.

The high-latitude Barents Sea ecosystem consists of fewer fish species than typical low-latitude and tropical ecosystems (Sakshaug, 2009). Around 200 fish species have been caught in trawls in the area, 100 occur regularly (ICES, 2011), and only 9 fish species constitute approximately 90% of the total abundance (Stiansen et al., 2009). NEA haddock is one of the most abundant species, together with NEA cod, polar cod, redfish, Greenland halibut, long rough dab, European plaice, capelin and Norwegian spring-spawning herring. Despite few species, the Barents Sea region is among the highest productive area in the Arctic and subarctic realms, particularly in the warm south western parts (Sakshaug, 2009).

2.3.1 Impact of physical aspects on production

The temperature and its fluctuation are found to have impact on the biological production in the area, as reviewed by Loeng and Drinkwater (2007). The temperature affect all trophic levels of the ecosystem, e.g. the time of overlapping between phytoplankton and zooplankton, distribution of zooplankton, and the growth rate of fish larvae are found to be affected by temperature.

The Barents Sea ecosystem is a spring-bloom system with a short duration of high-productive phytoplankton bloom compared to other ecosystems of the world oceans. In accordance with the match-mismatch hypothesis of Cushing (1990), the synchrony in productivity from phytoplankton to zooplankton and larval fish is of importance for successful survival of the early vulnerable life stages of fish. A good match will transfer the production to higher trophic levels, whereas a mis-match will result in low survival of the larvae. In warm years, there are larger temporal overlapping in time between the zooplankton and the phytoplankton.
bloom than in cold years (Orlova et al., 2005), and in the timing between the occurrence of the larvae fish and the zooplankton prey (Ellertsen et al., 1989).

*Calanus finmarchicus* is the dominant zooplankton species in the Norwegian Sea and the western part of the Barents Sea, and is the main food resource for larvae and early juvenile stages of NEA cod (Sundby, 2000; Dalpadado et al., 2009) and NEA haddock (Dalpadado et al., 2009) as well as other fish species (Stenseth, 2002). Krill is also an important and abundant prey item (Dalpadado et al., 2009). Advective processes and related temperature changes may influence the distribution and abundance of zooplankton species in the Barents Sea (Dalpadado et al., 2003). A high inflow of the relatively warm Atlantic water masses normally implies a high advection of zooplankton into the Barents Sea from the Norwegian Sea, and also higher local production due to the related increase in temperature (Sundby, 2000). Therefore, variability in the Atlantic inflow cause large inter-annual variations in zooplankton biomass in the southern Barents Sea and further, through this, inter-annual variations in recruitment of fish which depend on these zooplankton as prey. Hence, the temperature is considered to be a proxy for the for food abundance during the early stages (e.g. Sundby, 2000).

Additionally, high temperature related to high inflow of the relatively warm Atlantic water is found to affect growth rates of the fish larvae (Ottersen and Loeng, 2000). Ottersen and Loeng (2000) found a positive correlation between the fluctuating temperature during early life stages, growth rate at early life stages and further the strength of corresponding year-classes of cod, haddock and herring. Higher temperature directly increase the growth rate, which will under sufficient food supply decrease the duration of the high-mortality and vulnerable juvenile stages. Fluctuations in the Atlantic inflow are therefore believed to be, through food availability and growth rates, a driving mechanism behind the varying recruitment of many Barents Sea fish species (e.g. Ottersen and Stenseth, 2001; Loeng and Drinkwater, 2007). Many of the Barents Sea fish stocks show a strong recruitment when temperature is high, as for example for NEA cod (Sætersdal and Loeng, 1987; Ellertsen et al., 1989).

Fluctuations in fish recruitment in the Barents Sea are evident from Figure 2.4. Large
temporal fluctuations in NEA haddock stock size driven by strong year-classes appearing in a cyclic pattern have characterized the dynamics of this stock historically (Olsen et al., 2010). NEA haddock show higher variability in recruitment than other fish species in the region. A strong year-class can exceed a weak year-class by a factor of 60 (Bergstad et al., 1987). Thus, estimates of the NEA haddock stock size has varied between 66 000 tons and 600 000 tons between 1950 and 2007 (ICES, 2011) (Fig. 2.5). The total stock biomass was estimated to more than 1 200 000 tonnes in 2009 and 2010 (ICES, 2011). Input of exceptionally large year-classes in 2004, 2005 and 2006 is the main reason behind the observed record high levels of the NEA haddock stock in these recent years (Olsen et al., 2010).

However, the relation between temperature and fish recruitment do not hold for all fish species in the Barents Sea ecosystem. Competition for food and the size of the stock that act as predators must also be taken into account. For instance, Dingsøyr et al. (2007) found a negative correlation between temperature and 0-group abundance for capelin, probably linked to changes in capelin spawning grounds to areas with increased number of predators. Further, the size and age structure of the spawning stock of the fish species is also of importance for fish recruitment (MacKenzie et al., 2003). For NEA haddock it has been observed that strong year-classes are observed when the temperature is favourable, and the spawning stock is large and dominated by older age groups (ICES, 2011). For haddock, capelin, herring and cod there are no strong year-classes occurring during periods with low spawning stocks biomass (SSB), indicating that SSB is an important factor for successful recruitment (Eriksen et al., 2010).

2.3.2 Distribution of NEA haddock in relation to other fish species

The current features and the distribution of the water masses divide the Barents Sea ecosystem into a cold northeastern part with Arctic water, and a warmer south western part with Atlantic water masses. It influences the ecosystem structure with a typical Arctic ecosystem in the cold part and boreal ecosystem in the warmer part. NEA haddock is a boreal species, confined to the boreal and arcto-boreal ecosystem with its specific species of zooplankton and fish. However, NEA haddock may also occasionally utilize the bordering regions to the Arctic for feeding excursions.
Figure 2.4: Abundance indices for 0-group in millions of individuals from the Barents Sea ecosystem survey. Not corrected for catching efficiency (from Stiansen et al., 2009).

Figure 2.5: Green curve are landings, red bars show SSB and blue bars show the total stock biomass of age 3 and older (from Stiansen et al., 2009).
The boreal part of the Barents Sea serves as a nursery area for the offspring of several fish stocks spawning along the western and northwestern coasts of Norway, including haddock, herring, cod and saithe (Olsen et al., 2010). The 0-group of capelin, herring, cod and haddock are distributed over most of the Barents Sea, but with highest biomass in the central areas and at the entrance of the Atlantic water inflow (Eriksen et al., 2010; Eriksen et al., 2012). The circulation pattern structure the spreading and transport of eggs and larvae from the spawning grounds to the Barents Sea. The main distribution of 0-group NEA haddock and NEA cod overlapped largely with areas of high biomass of zooplankton (Dalpadado et al., 2009).

Important factors determining distribution of older fish are the distribution of different water masses with different properties, bottom type and depth (Stiansen et al., 2009). Distribution of food is also of importance, however, the distribution of zooplankton affects the pelagic species more than the benthic species. Since the fish species have different preferences they are not evenly distributed. Shifts in distribution and spawning areas related to temperature changes have been found (Sundby and Nakken, 2008).

Figure 2.6 shows the general distribution of the most abundant fish species in the Barents Sea. Redfish (Sebastes mentella), saithe (Pollachius virens) and especially cod (Gadus morhua) have largely similar distribution as NEA haddock, both when it comes to spawning area, winter area an feeding area. NEA cod has in general a more northern and eastern distribution than NEA haddock. Greenland halibut (Reinhardtius hippoglossoides) has also a similar distribution, especially the adults, but their spawning areas are located along the continental shelf west in the Barents Sea, only overlapping with the NEA haddock spawning area in the south. The juvenile area of the herring (Clupea harengus) also overlap with the distribution area for NEA haddock, however the feeding area of adult herring is situated in the Norwegian Sea. The capelin (Mallotus villosus) stock, which is one of the most important prey species for top predators (Bergstad et al., 1987; Olsen et al., 2010), is situated in the central parts of the Barents Sea. They spawn along the coast of northern Norway, and their larvae and 0-group distribution overlap with the distribution of NEA haddock in the southern areas. Polar cod (Boreogadus saida) is situated in the northeastern parts of the Barents Sea, not overlapping with NEA haddock.
Figure 2.6: General distribution of some of the most abundant Barents Sea fish species (from Stiansen et al., 2009).


2.3.3 Trophic relations associated with NEA haddock

During the vulnerable larval and early pelagic juvenile stages, the timing in abundance between the feeding fish and its prey is of large importance to recruitment (Cushing, 1990). In May, first-feeding larvae are dependent on food of suitable size which during this period is eggs and nauplii of copepods. As they grow they switch to larger food items. In June-July the diet of pelagic juvenile NEA haddock is dominated larger copepodite stages, krill and appendicularians (Dalpadado et al., 2009). After the larvae have settled they feed mostly on benthic organisms (Olsen et al., 2010), such as polychaetes, krill, amphipods, fish larvae and capelin (Gjøsæter, 2009). There is a shift in diet towards fish as the 0-group grows larger (Dalpadado et al., 2009). NEA haddock prey on capelin and capelin eggs during the capelin and haddock spawning season. In times of low capelin abundance or little overlap, other fish species becomes more important as a food source, such as herring (Stiansen et al., 2009). However, it should be noted that less than 7 % of the NEA haddocks’ diet composition is fish species (ICES, 2011). After the age of 2, they eat echinoderms, molluscs, prawns and capelin. Cannibalism is not common, and constitutes only 0.2 % of the diet composition (ICES, 2011).

Through the competition of food at early life stages, species interactions become important when analysing recruitment variability in the NEA haddock stock (Dingsør et al., 2007). The observed synchrony in the year-class strength of cod, haddock and herring in the Barents Sea related to their response to temperature fluctuation may lead to increased competition for food between these species (Ottersen and Loeng, 2000; Dingsør et al., 2007). In general, the diet of NEA cod and NEA haddock do not overlap, except for the smaller size groups of both species, which both feed on krill during spring and fall (Burgos and Mehl, 1987). The competition for food at larval and juvenile stages can explain why high densities of 0-group cod may lead to a reduction in the survival of 0-group NEA haddock, and why the survival of 1-year old fish is found to be density dependent at high temperatures (Dingsør et al., 2007).

In addition to be competing species for food at juvenile stages, NEA cod is the most important fish predator on NEA haddock. In 2005, NEA haddock constituted 10 % of the diet composition of NEA cod older than 2 years old (ICES, 2011). It is the juvenile stages of NEA haddock that is most exposed to predation from NEA cod, with the numbers eaten decreasing
considerably when the NEA haddock reaches the age of 2. In some years, NEA cod eat large numbers of juvenile NEA haddock, which likely impacts the survival of young NEA haddock significantly, although the absolute effect has not been quantified (Olsen et al., 2010). Long rough dab and adult saithe also prey on young NEA haddock (ICES, 2011). Adult NEA haddock is rarely preyed on by other Barents Sea fishes, however, marine mammals such as harp seals, minke whales and killer whales, who prefer to eat capelin, do take NEA haddock and other gadoids as part of their diet when capelin abundance is low (Bergstad et al., 1987; Stiansen et al., 2009).

2.3.4 NEA haddock fisheries
Humans are part of the Barents Sea ecosystem through fisheries, removing roughly 1/3 of the total NEA haddock biomass each year (ICES, 2011). Fisheries should therefore be considered when investigating changes in NEA haddock abundance, especially on older age groups. NEA haddock is the second most important commercial fish species among the demersal fish species in the Barents Sea (Gjøsæter, 2009). NEA haddock enters the fisheries at the age of 3, and is by then harvested throughout the whole year (ICES, 2011), with an average annual catch of 125 000 tonnes based on the past 60 years (Olsen et al., 2010). NEA haddock aged between 4 and 6 are most heavily fished on, but this varies depending on the age distribution of the year-classes present in the stock (ICES, 2011). Historically, the exploitation rate of NEA haddock has been variable (Fig. 2.5). Lowest landings (less than 50 000 tons) occurred in the periods 1982-1985 and 1990-1991, and highest landings (more than 200 000 tons) were recorded in the period 1972-1974. The strong 2004-2006 year-classes which recruited to fisheries in 2007-2009 can explain the high landings in 2009 and 2010 (also above 200 000 tons).
2.4 Comparisons of NEA haddock and NEA cod

Similar to haddock, cod (*Gadus morhua*) is a gadoid, demersal fish species distributed in the Barents Sea, and adjacent water (Olsen et al., 2010). NEA cod has throughout history been the most important fish resource taken in the Barents Sea (Gjøsæter, 2009). Due to its importance, it is one of the most studied fish species in the Barents Sea, contrary, much less is known about NEA haddock. NEA cod and NEA haddock largely have similar life history (Tab. 2.1) and distribution area in the Barents Sea (Fig. 2.6) (Bergstad et al., 1987). Thus, their familiar similarities may give us reason to believe that also behaviour and reaction to changes in physical properties might have similar features, suggesting that features regarding the abundance and distribution of NEA haddock in relation to climate can be made based on current knowledge on NEA cod.

Maturity of NEA cod is reached at the age of 6-8 years (Olsen et al., 2010), which is older than NEA haddock who reach maturity at the age of 4-7. Similar to NEA haddock, the mature portion of the NEA cod stock undertakes spawning migration from the Barents Sea to the western coast of Norway (Nakken and Raknes, 1987). Spawning migration of the NEA cod starts in December, earlier than that of NEA haddock. The main spawning areas for NEA cod are at Vesterålen, Røstbanken, and Vestfjorden, but also in coastal areas farther north and south. These spawning areas are largely similar to that of NEA haddock, however the haddock tend to spawn further away from the coast closer to the shelf break. NEA cod spawn in March-April and the hatched larvae are advected northwards mainly with the Norwegian Coastal Current into the Barents Sea. NEA haddock larvae are transported in the same direction but farther offshore and to a larger extent by the Atlantic Current (Castaño-Primo, 2012). In August-September both NEA haddock and NEA cod larvae are distributed over most of the Barents Sea area south of the polar front (Olsen et al., 2010). NEA haddock grows faster than NEA cod during the first years of life (Bergstad et al., 1987). The highest abundances of both 0-group NEA cod and NEA haddock are found in the Atlantic water masses, located in central and western parts of the Barents Sea. These areas overlap with high biomass of zooplankton (Dalpadado et al., 2009). Time of settling for both species is unclear, but literature states that NEA haddock settle between August and October, while NEA cod
settle in late autumn (Bergstad et al., 1987). The 0-group of NEA cod tends to be distributed further east compared to NEA haddock (Bergstad et al., 1987). This is probably related to their horizontal difference in spawning location, hence a difference in direction of drifting. NEA cod eggs are spawned closer to the coast, and follow the Norwegian coastal current (Vikebø et al., 2005), while NEA haddock eggs and larvae are in general spawned further away from the coast and therefore drift with the Norwegian Atlantic current. The spatial difference between the species also occurs for the older age groups, with NEA cod generally distributed further northeast than NEA haddock (Bergstad et al., 1987). Consequently, NEA cod has colder temperature habitat than NEA haddock. The Barents Sea is during summer used as feeding area for all age groups of NEA cod and NEA haddock, and seasonal migration between shallow feeding areas, and deeper wintering areas are performed (Bergstad et al., 1987).

NEA cod is substantially more abundant than NEA haddock. For comparison, the average biomass of the NEA haddock stock has been estimated to 350 000 tonnes between 1950 and 2008, while the stock size of NEA cod has on average been estimated to 2 000 000 tonnes for the same period (ICES, 2011). This trend is already evident at early stages with the abundance of 0-group NEA cod being much higher than that of 0-group NEA haddock (Dalpadado et al., 2009). Laurence and Rogers (1976) experimentally found that cod embryo and newly hatched larvae may have slightly better chances for survival than haddock, when exposed to different temperature and salinities.

Inter-annual variations in stock size is observed for both species. While the NEA haddock stock size has varied between an estimated 66 000 tonnes and 600 000 tonnes between 1950 and 2008, the NEA cod stock has on the average varied between 0.8 and 4 million tonnes for the same period (ICES, 2011). These inter-annual variations in stock size have been related to climatic variability, with temperature positively correlating with recruitment (e.g. Sætersdal and Loeng, 1987; Ottersen and Loeng, 2000). However, recruitment of NEA cod and NEA haddock showed no significant correlation with temperature in the period 1993-2009 (Eriksen et al., 2010).
Nakken and Raknes (1987) analysed the NEA cod distribution in relation to bottom temperature. Their study showed a westward displacement of NEA cod with increasing age of the fish. While the distribution pattern of 1-year old NEA cod still is influenced by the previous year's 0-group pattern, the older fish seem to adjust their distribution relative to each other in a systematic manner within the temperature field. Despite this distinct distribution pattern, large inter-annual variations appeared for all age groups (Nakken and Raknes, 1987). For instance, in some years the 2-year old NEA cod is located slightly further east than the 1-group, possibly caused by variation in predation on these small fish (Ottersen et al., 1998). This has also been observed for juvenile NEA haddock, where the 2-year old fish is in general distributed further eastward compared to the 1-year old fish (Bergstad et al., 1987). Less is known about how the older age groups of NEA haddock are distributed in relation to each other, but it is of great interest to investigate whether they might behave similar to cod, with the older age groups generally being distributed in warmer water further west. For NEA cod, an easterly distribution of the 0-groups will lead to a similar distribution for the 1-year old fish in the succeeding year, and possibly the corresponding year class at older ages. However, the connection between the distributions at age 1 and 2 and older NEA cod is generally weaker (Ottersen et al., 1998).

The inter-annual variation in geographical distribution have been related to water temperature conditions (e.g. Nakken and Raknes, 1987; Ottersen et al., 1998; Eriksen et al., 2012). Eriksen et al. (2012) analysed how climatic changes influence their spatial distribution of 0-group NEA cod and NEA haddock, and found that the distribution area increase from cold to warm years. Higher temperatures are found to shifts the distribution of all age groups of NEA cod east and northwards (e.g. Ottersen et al., 1998). Less is known about the temperature effect on distribution on older age groups of NEA haddock.

In addition to the temperature effect on distribution, the abundance of NEA cod is also found to affect their distribution (Ottersen et al., 1998). The centre of mass is found to extend eastward during high abundance, independent on the temperature. This was evident in 1993 and 1994 when the temperature decreased and westward shift in NEA cod distribution towards warmer water was expected to compensate for the low temperature. However, the
centre of mass for 3-year old NEA cod shifted towards the east into even colder water, most likely due to a high stock abundance (Ottersen et al., 1998). It can be hypothesised whether NEA haddock behave similar.

Table 2.1: Comparison of life history traits between NEA haddock and NEA cod (Bergstad et al., 1987; Olsen et al., 2010).

<table>
<thead>
<tr>
<th></th>
<th>NEA haddock</th>
<th>NEA cod</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spawning migration</td>
<td>January-February</td>
<td>December-January</td>
</tr>
<tr>
<td>Spawning</td>
<td>March-June</td>
<td>March-April</td>
</tr>
<tr>
<td>Settling</td>
<td>August-October</td>
<td>late autumn</td>
</tr>
<tr>
<td>Maturation age</td>
<td>4-7</td>
<td>6-8</td>
</tr>
<tr>
<td>Maximum age</td>
<td>~22</td>
<td>~30</td>
</tr>
<tr>
<td>Maximum length</td>
<td>~110</td>
<td>&gt;130</td>
</tr>
<tr>
<td>Maximum weight</td>
<td>~19</td>
<td>&gt;30</td>
</tr>
</tbody>
</table>

2.5 The Barents Sea winter survey

Data on abundance and distribution of NEA haddock (older than the age of 1) are gathered from the annual Barents Sea winter survey. The Institute of Marine Research (IMR), Norway, have since 1981 performed yearly bottom trawl and acoustic surveys of demersal fish in the ice free part of the Barents Sea, The main aim is to map the spatial distribution and obtain indices of abundance of NEA cod, NEA haddock and other species (Jakobsen et al., 1997). In most years there have been 3 vessels participating, normally between 1. February and 1. March (Aglen et al., 2008). The Polar Research Institute of Marine Fisheries and Oceanography (PINRO) in Russia, has partly participated in the survey since 2000 (Johannesen et al., 2009). In addition to biological data obtained trough trawling and acoustics, hydrographic data are collected with a CTD (Jakobsen et al., 1997), and water samples are taken. Reports are made after each survey. References to yearly survey reports
from 1981-2007 are given in (Jakobsen et al., 1997).

2.5.1 The purpose and use of the survey
The survey purpose is to map the species diversity in the Barents Sea, as well as obtain abundance indices of length and age for haddock, cod, deep-sea redfish, golden redfish and Greenland halibut, as well as mapping the geographical distribution of those fish stocks. Weight and age at maturity is also estimated. Additionally, stomach samples from cod are collected and analysed for estimating the predation by cod on important species, e.g. capelin, haddock and cod (Aglen et al., 2008; Jakobsen et al., 1997).

Research projects at IMR and PINRO use the data from the winter survey. At IMR, the data are used in projects related to monitoring abundance of Barents Sea demersal fish stocks, mapping fish distribution in relation to climate and prey abundance, estimating consumption and growth, and studying species diversity, composition and interaction in the fish community (Aglen et al., 2008; Johannesen et al., 2009). The assessments of NEA haddock (and NEA cod) are heavily dependent on these results. The abundance indices and weight-at-age data are used directly in the ICES stock assessment (Jakobsen et al., 1997), and further in fisheries management.

2.5.2 Methods
A Campelen 1800 research trawl with mesh size of 22 mm, 40 meter sweep wires, strapping and Rockhopper gear is used. The duration of trawling is 15 minutes, but can be reduced to 10 minutes in the case of large catches. The trawling height, contact with the bottom, trawling speed, and the spread and opening of the bottom trawl doors are measured with sensors attached to the trawl (Johannesen et al., 2009). Roughly 350 bottom trawl hauls are made each year (Aglen et al., 2008). The positioning of the bottom trawl stations are chosen prior to the survey. The station density varies with the expected concentration of haddock and cod. A detailed description on the bottom trawl methodology is given in (Jakobsen et al., 1997).

All fish species caught are sorted, and total weight for each species is registered with
electronic weights. In addition to measurements of fish, catch weighs and catch numbers of
king crab and shrimp are also recorded. A minimum of 20 individuals per species is length
measured with electronic measuring board. Individual samples such as individual weight, age,
sex, and stage are always taken from a certain amount within a length group of the target
species (haddock, cod, deep-sea redfish, golden redfish and Greenland halibut), additionally
for pelagic species (capelin, polar cod, blue whiting and herring) if resources are available.
Stomach samples are additionally taken from cod (Johannesen et al., 2009). Sub sampling is
done if the catches are large. A guideline with general description of the sampling procedures
is updated yearly.

All biological data are transferred into the software “regfisk” where the data are stored
together with the station information such as the positioning, exact time of trawling, and data
from the trawling sensors (Johannesen et al., 2009).

In addition to the planned traw stations, pelagic trawls (and sometimes bottom trawls) are
made based on the acoustic registration to quantify the species detected by the acoustic
measurements (Johannesen et al., 2009). The acoustic method in use is based on observing
and recording integrated echo intensities. Mathematical models are applied to estimate fish
density, amounts of fish and distribution of length, weight and age (Jakobsen et al., 1997).
The system currently in use is the Large Scale Survey System (LSSS) (Korneliussen et al.,
2006).

CTD measurements are made at approximately every 3 trawling stations. These observations
give an indication of the inter-annual variability in the ocean winter climate in the Barents
Sea.

2.5.3 Changes over the period
The survey area and methodology has undergone development over the years, which may
affect the quality of the data. The main changes between 1981 and 1996 are detailed in
Jakobsen et al. (1997) and later changes discussed by Johannesen et al. (2009). The potential
for using the survey to study changes in the Barents Sea fish community, and for single species has been evaluated by Johannesen et al. (2009), who concluded that the data should be used with caution, especially when comparing old and new data (Johannesen et al., 2009).

Figure 2.7 shows the changes in survey area for some years. From the start the area surveyed was smaller than today, and a randomised sampling design was employed. The area was fixed between 1981 and 1992. Survey area was extended north and eastwards in 1993. This was done to cover the increased distribution area for NEA cod, which increased due to improved climate and increasing stock size in the early '90s. Since then there has been an aim to cover the whole distribution area of the NEA cod outside the ice border. Coverage may be limited due to unusually large ice extent, as was the case in 1999 (Aglen et al., 2008). The Norwegian vessels access to the Russian EEZ has been limited, especially in 1997 and 1998. The surveys were conducted without participation from Russia before 2000. Between 2001-2005 Russian vessels covered important parts of the Russian zone. In 2006 and 2007 Russia did not participate, and in 2007 Norwegian vessels did not get permission to carry out the survey in Russian zone. However, since 2008 the Norwegian survey vessels have received permits to enter the Russian zone (ICES, 2011).

The most drastic changes in methodology were changes in gear and trawl mesh size, procedures for handling of the catch, introduction of electronic weights and measure board and reduction in trawl time from 60 minutes to 30 minutes in 1987 and later from 30 to 15 minutes (Jakobsen et al., 1997; Johannesen et al., 2009). In the beginning, both commercial vessels and research vessels were used, despite the fact that commercial vessels were more poorly manned, and the work conditions and equipment poorer (Johannesen et al., 2008). Figure 2.7 illustrates the gradual decrease in the use of commercial vessels. Documentation of bicatches of species other than the traditional target species (cod, haddock, redfish and Greenland halibut) has previously not been well prioritized, due to lack of resources (Johannesen et al., 2009). Now, all fish species (including kingcrab and shrimp) are recorded, counted and total weight registered. The acoustic measurement systems have been continuously improved since the survey started and several generations of echo sounders and echo integrators have been in use (Jakobsen et al., 1997; Korneliussen et al., 2006).
Figure 2.7: Survey area in 1983, 1993, 2003 and 2006. Blue dots are stations with research vessels, while red dots are stations conducted by commercial vessels (from Johannesen et al., 2009).
3. Material and Methods

Interpolated spatial temperature data and time series of temperature from the Fugløya-Bjørnøya section (FB-section) have been used together with spatial age-divided abundance data on NEA haddock (between the age 0-9) in order to address the research questions. The biological and physical data were collected by IMR and PINRO on annual surveys in the Barents Sea during the period 1981-2011 (Chap. 2.5).

The analyses were divided into three parts (corresponding with the research questions addressed in Chapter 1):

• time series analysis using the index data on abundance and temperature to study the relation between temperature and abundance,
• thermal distribution histograms were made using spatial data on temperature and abundance to analyse the temperature habitat of the different age groups,
• maps of distribution were made to study variations in age groups distributions with local temperature and abundance. Here, both index and spatial data were used.

Additionally, the results were compared and discussed together with similar results on NEA cod.
3.1 Data description

Table 3.1 shows a schematic overview of the spatial and non-spatial physical and biological data used in this study.

Table 3.1: Schematic overview of data used in this study. All data represent the period 1981-2011.

<table>
<thead>
<tr>
<th>Data Type</th>
<th>non-spatial (from SJØMIL)</th>
<th>spatial (from FEC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>annual mean temperature from the 50-200 meter depth layer at the FB-section</td>
<td>interpolated pelagic temperature from the 0-45 meter depth layer in August-September</td>
</tr>
<tr>
<td></td>
<td></td>
<td>interpolated bottom temperature collected in January-March</td>
</tr>
<tr>
<td>Abundance</td>
<td>0-group in August-September</td>
<td>age-divided data for 1- to 9-year old NEA haddock in January-March</td>
</tr>
<tr>
<td></td>
<td>SSB estimates from the ICES fish assessment from 2011</td>
<td>age-divided data for 1- to 9-year old NEA haddock from bottom layer in January-March</td>
</tr>
</tbody>
</table>

3.1.1 Physical data

The temperature and salinity in the FB-section have fluctuated in the period 1981-2011 (Fig. 3.1a). T-S diagram (Fig. 3.1b) shows how temperature and salinity are positively correlated in the period (R=0.65). The positive correlation have previously been shown for the same section, as well as for other sections in the Barents Sea (Loeng, 1991). The correlation between these water properties indicates that a change in temperature represents a change in water mass, and therefore possibly a change in other characteristic properties as well. Temperature as a climate component will therefore be the main focus in this thesis.

The temperature indices from the 50-200 meter depth layer at the FB-section between 1981 and 2011 have been used. The section is situated in the western part of the Barents Sea, and chosen due to its location in the core area of the NEA haddock stock, and also where the main Atlantic inflow takes place. Ottersen et al. (1998) analysed temperature variations in the Barents Sea area and found that inter-annual temperature variations are in synchrony in the
different areas in the Barents Sea. It can therefore be assumed that the temperature in the FB-section is representative for the temperature variations in the whole area.

Figure 3.1: Top: Approximate location of the hydrographical section Fugloya-Bjørnøya. Bottom, left: Annual mean temperature (blue) and salinity (red) from the 50-200 meter depth layer at the FB-section for the period 1981-2011 (made at www.imr.no/sjomil/index.html), corresponding T-S diagram (bottom, right).
The temperature at the FB-section has been monitored 6 times per year since 1977. Figure 3.2 shows how the annual fluctuations and fluctuations from the different months have been in synchrony throughout the period. For the purpose of this study, the annual mean was chosen because it represents the integrated temperature that the fish actually experience throughout the year in a better way than the temperature in a single month. Additionally, annual mean was more correct to use in combination with the biological data which were collected at different time of the year.

In addition to the annual mean temperature indices from the FB-section, spatial temperature data obtained in surveys from two different depths and seasons were used; bottom temperature in January-March, and pelagic temperature in August-September. The deepest temperature measured with the CTD, (maximum 20 meters from the bottom with 70 % of the measurements between 5-15 meters from the bottom) previously interpolated into a horizontal grid (Westergård et al., 2010), was used as bottom layer temperature. The pelagic temperature layer was defined as the mean of the spatially interpolated temperature from 5 different depths layers between 0 and 45 meters from the surface.

![Figure 3.2](image)

Figure 3.2: Temperature from the 50-200 meter depth layer in the FB-section from 1981 to 2011. The thick black line shows the annual mean, while the coloured lines represent different months.
3.1.2 Biological data

Spatial distribution data on 0-group NEA haddock have annually been collected with pelagic trawl in the Norwegian-Russian ecosystem survey (encompassing the previously known “0-group survey”) in August-September (Eriksen et al., 2010). NEA haddock older than 0-group has annually been collected with bottom trawl in the annual Barents Sea winter survey in January-March (Jakobsen et al., 1997; Johannesen et al., 2007; Chap. 2.5.2). The data are age-divided based on otolith analyses. Fish older than 9 years old was not included in the analyses. Time series of non-spatial index data on abundance calculated from the spatial data for NEA haddock between 0 and 9 were also used. These abundance data are represented as numbers of fish per square nautical mile within 25 x 25 km squares.

Additionally, spawning stock biomass (SSB) estimations from the ICES fish assessment from 2011 were used.

3.1.3 Databases

The non-spatial temperature and abundance indices, as well as the estimated SSB were taken from the SJØMIL database, public available at www.imr.no/sjomil/index.html. SJØMIL is a database for aggregated time series, containing data series from the IMR monitoring programme, as well as ICES fish assessment data.

All spatial data where imported from the FishExChange (FEC) database, where the physical and biological data are stored into the same spatial grid cells system, simplifying merging of the biological and physical data. Storing it in this way makes it easy accessible for further analysis using statistical packages such as R or GIS systems. The FEC database contains geographical referenced physical and biological data gridded into cells with 25x25 km resolution. Description of the FEC database can be found in Westgård et al. (2010) and at www.imr.no/prosjektsiter/fishexchange/nb-no.
3.2 The analyses

In all analyses, the 0-group data were linked with the pelagic temperature (since the 0-group are pelagic until August-October), while the bottom temperature was used together with the data on age groups older than 0-group (since these older age groups are demersal).

3.2.1 Abundance

To address the questions regarding the effect of temperature on abundance only the non-spatial index data were used for both temperature and NEA haddock abundance.

Graphs were made showing how temperature, abundance of individual or merged age groups, and SSB have varied over the period 1981 to 2011. Further, plots were made which showed how the abundance of individual age groups has varied with the temperature. Due to the large range in abundance, logarithmic abundance was used (ln (abundance+1)). Regarding the temperature used in these plots, two different approaches were made: (i) the temperature used was the annual mean sea temperature from the survey year; (ii) the temperature used was the annual mean sea temperature from the year they were spawned. The first approach was made to see whether the abundance of a specific age group in a certain year is directly linked to the temperature that year, while the second approach was evaluating the importance of temperature during the first year of life on the abundance as they become older. A similar set of plots were made where data from three periods (1981-1989, 1990-1999 and 2000-2011) were separated with coloured areas.

Correlation coefficients were calculated for all the plots using the Spearman rank method. This correlation method was used to avoid extreme values dominating the coefficient. P-values classified the significance of the correlations (p-value < 0.05 indicate significance).

The graphs, plots, and correlation coefficients were made/found with R, version 2.10.1 (R Development Core Team, 2009).
3.2.2 Thermal habitat
To quantify whether the age groups have different ambient temperature, weighted histograms (weighted by abundance) were made, each showing the frequency of occurrence for one age group within temperature intervals for the whole time period. The spatial temperature and abundance data were used for this purpose. Abundance and temperature data from the same grid cells were merged together to create the histograms. A temperature histogram showing the frequency of all temperature registrations was added to each histogram. Temperature percentiles (2.5, 50 and 97.5) were calculated for each age group.

To study inter-annual differences in thermal habitat for the age groups, another figure was made showing the thermal habitat for the different age groups for 5 different years; three cold (1981, 1986 and 1996) and two warm years (1991 and 2006). These years were categorised into cold and warm based in visual inspection of the annual mean temperature in Figure 3.2. Similar figures have been made for NEA cod by Nakken and Raknes (1987) and Ottersen et al. (1998).

The histograms, plots and percentiles were made/calculated with R, version 2.10.1 (R Development Core Team, 2009). The weighted histogram was made with the plotrix-package, and the weighted percentiles were found with the Hmisc-package.

3.2.3 Distribution
Maps showing the distribution of all age groups (0-9) for all the years (1981-2011) were made to get an overview over where the different age groups of NEA haddock have been spatially distributed. The distribution is represented with dots, where the size of the dots are proportionate to the size of the catch. The numbers of fish that the dots represent are found in Table 3.2.
Table 3.2: The exact and approximate abundance that the size of the dots in the distribution maps represent. A is abundance represented as as numbers of fish per square nautical mile within a 25 x 25 km.

<table>
<thead>
<tr>
<th>Dot Size</th>
<th>Exact</th>
<th>Approximate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small dot</td>
<td>$\ln (A+1) &lt; 7$</td>
<td>$A &lt; 1000$</td>
</tr>
<tr>
<td>Medium sized dot</td>
<td>$7 &lt; \ln (A+1) &lt; 10$</td>
<td>$A &gt; 1000, A &lt; 22 000$</td>
</tr>
<tr>
<td>Large dot</td>
<td>$\ln (A+1) &gt; 10$</td>
<td>$A &gt; 22 000$</td>
</tr>
</tbody>
</table>

Further, maps with the centre of distribution were made, one for each age group showing where the annual centre of distribution, weighted by abundance, had been located in the period studied. The centre of distribution was found by calculating the average longitude and latitude, following the same procedure as Ottersen et al. (1998):

$$
\bar{\text{lon}} = \frac{\sum (N(x, y) \cdot \text{lon}(x, y))}{N(x, y)}, \text{ and}
$$

$$
\bar{\text{lat}} = \frac{\sum (N(x, y) \cdot \text{lat}(x, y))}{N(x, y)},
$$

where $N(x,y)$ is the number of fish estimated in the square located around position $(x,y)$. For the age groups between 6 and 9 there are some years without catches, hence no distribution centre can be found. This occurs for 6-year old group in 1986 and 1987, 7-year old group in 1987, the 8-year old group in 1981, 1988 and 1989, and the 9-year old group in 1981, 1983, 1986-89 and 1996.

In the maps, the annual distribution centres are symbolized to represent the temperature and the abundance of the age group in question in that particular year. The annual mean temperature at the FB-section was used to categorise the temperature in a specific year into average (long-term mean temperature ± 1 standard deviation), cold (below average) and warm (above average). Note that this categorisation is different from the temperature categorisation described previously, regarding the abundance analyses, which was only based on visual inspections. The age-divided abundance indices from SJØMIL were used for categorising the abundance in a specific year into low, medium or high. A year with medium abundance was
for 0-group defined as the long-term average abundance of 0-group ± one standard deviation. The abundance for the groups 1-9 were skewed, making standard deviation a poor measure for defining the categorisations, therefore the semi interquartile range was used instead of standard deviation. In other words, for the age groups between 1-9, the average abundance was defined as the long-term average of the individual groups ± one semi-interquartile range. For all age groups the low and high abundance were defined as being under or above the corresponding average, respectively.

In addition to the maps, graphs were made showing the time development of the average longitude and latitude for the age groups between 0 and 9. The annual mean temperature in the FB-section and the abundances were also included in the graphs.

Maps were made using Quantum GIS, version 1.7.1 (Quantum GIS Development Team, 2012), while R, version 2.10.1 (R Development Core Team, 2009) was used to make the plots and calculate correlation coefficients. Pearson product-moment correlation coefficient was used, except for correlations with abundance where the Spearman rank method was used, to avoid extreme values from dominating the coefficient.
4. Results

4.1 Temperature effect on abundance

Temperature and abundance have fluctuated throughout the time period 1981-2011 (Fig. 4.1). In general, the temperature was relatively low in the '80s, with more abrupt fluctuations apparently with a decadal-scale pattern compared to the '90s. After year 2000, the temperature was steadily high throughout the decade, with a record high peak in 2006. The overall trend for the entire period has been an increase. Figure 2.2 shows how this increase was a part of a natural multi-decadal oscillation. The abundance was dominated by a few strong year classes, with three periods of high abundances appearing in the period. In general, the peaks in abundance correspond with the temperature peaks, with a time lag equivalent to the age of the age-group in question. This was especially clear following the temperature peak in the early '80s and around 1990. However, this pattern was not as clear for the next two temperature peaks in 1999 and 2006. See appendix a) for individual graphs on the abundance in relation to temperature for the age groups 0-9.

The 0-group stands out from the other age groups because it has not fluctuated like the abundance of the other age groups. The 0-group abundance was low throughout the '80s and '90s, with only small peaks in the years with temperature peaks. In fact, for some years the abundance of 0-group fish was less than that of 1-year old fish in the succeeding year, indicating that the survey does not capture the entire 0-group distribution vertically and/or horizontally. The low abundance was followed by one large peak in the period 2004-2006 (Fig. 4.1). Despite the surprisingly low 0-group abundance followed by a large abundance peak around 2005, the abundance of 0-group correlated significantly (R=0.67) with the annual mean temperature from the FB-section for the years 1981-2011 (Fig. 4.2).
Figure 4.1: Temperature (thick black line) and abundance of 0-group to 5-year old NEA haddock (represented with different colours) in the period 1981-2011. The temperature is the annual mean in the 50-200 meter depth layer at the FB-section. The abundance data are observational data in numbers of fish in millions.

Figure 4.2: Relation between logarithmic abundance of 0-group in number of observation in the period 1981-2011 (in millions) and annual mean temperature from the FB-section. The numbers represent the year, and lines are drawn between succeeding years.
For the older fish, there was not a relation between the temperature from the survey year and the abundance (with an exception for the age groups 1, 7 and 8). This can be seen in the first column in Figure 4.3, where the logarithmic abundance of 0-, 3- and 8-year old NEA haddock are plotted against the temperature from the survey year. On the other hand, there was a positive correlation between the logarithmic abundance of various age groups of NEA haddock with the annual mean temperature at the FB-section the year they were spawned (second column Fig. 4.3; Tab. 4.2). This indicates that temperature during their first year of life was important for the year-class strength. However, visual inspection of the plots shows a weakening of this pattern as they become older.

In the third column in Figure 4.3 the abundance is plotted non-logarithmically, contrary to the other two columns. From these plots it becomes evident that strong year classes always occurred in relatively warm years, while no strong year classes occurred in cold years. Weak year classes have occurred in both cold and warm years. Plots equivalent to those in Figure 4.3 for all age groups are found in Appendix b.
Figure 4.3: Logarithmic (first and second column) and non-logarithmic (third column) observational abundance indices (in millions) of 0-, 3- and 8-year old NEA haddock, plotted against annual mean temperature in the 50-200 meter depth layer at the FB-section from the survey year (first column) and the year they were spawned (second and third column). Abundance is on the y-axis and temperature is on the x-axis. Lines are drawn between succeeding years. Be aware that the y-axis changes with the age.
The trend in both temperature and abundance has increased in the period 1981-2011. This can be seen in Figure 4.4 where the abundance of 0-group NEA haddock is plotted against the temperature, and where colour-shaded areas represent data from three periods (1981-1989, 1990-1999 and 2000-2011). It was established earlier that there was a significant correlation between the abundance of 0-group and temperature, however, Figure 4.4 shows that it does not seem to be a relation between the two at shorter time scales.

From Table 4.2 it appears that there were some significant correlations between abundance and temperature within the shorter periods. In general, the correlations were significant in the '80s, but non-significant in the '90s and the 2000-2011 period. During the '80s, the correlation coefficient was on average 0.79 for the ages 0-9 (all being significant). For the '90s only the 2-year old NEA haddock shows significant correlation (R=0.68), while for the period 2000-2011 there was only significant correlations between temperature and abundance for the age groups 5-7.

Plots equivalent to Figure 4.4 for each age group between 1 and 9 are found in Appendix c.
Figure 4.4: Observational abundance indices of the 0-group plotted with the annual mean temperature in the 50-200 meter depth layer at the FB-section. The year next to each point represent the year class. Points from the period 1981-1989, 1990-1999 and 2000-2011 are shown in blue, yellow and red, respectively. The coloured areas show where the points from the three different periods are placed, with colour in according to the respective period.

Table 4.2: Correlation coefficient (Spearman rank method) between the observational abundance of different age groups and the average annual temperature at the FB-section the year they were spawned, for three time periods. Star indicates significance, with p-value < 0.05. Red numbers are not significant.

<table>
<thead>
<tr>
<th></th>
<th>0-group</th>
<th>age-1</th>
<th>age-2</th>
<th>age-3</th>
<th>age-4</th>
<th>age-5</th>
<th>age-6</th>
<th>age-7</th>
<th>age-8</th>
<th>age-9</th>
</tr>
</thead>
<tbody>
<tr>
<td>1981-1989</td>
<td>0.57*</td>
<td>0.77*</td>
<td>0.85*</td>
<td>0.75*</td>
<td>0.87*</td>
<td>0.83*</td>
<td>0.88*</td>
<td>0.8*</td>
<td>0.85*</td>
<td>0.7*</td>
</tr>
<tr>
<td>1990-1999</td>
<td>0.05</td>
<td>0.31</td>
<td>0.68*</td>
<td>0.51</td>
<td>0.43</td>
<td>0.47</td>
<td>0.39</td>
<td>0.39</td>
<td>0.38</td>
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</tr>
<tr>
<td>2000-2011</td>
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<td>0.36</td>
<td>0.26</td>
<td>0.41</td>
<td>0.38</td>
<td>0.83*</td>
<td>0.84*</td>
<td>0.98*</td>
<td>-0.32</td>
<td>-0.5</td>
</tr>
</tbody>
</table>
4.2 Thermal habitat

4.2.1 Thermal habitat for the whole time period

Thermal habitat histograms for each age group between 0 and 9 are shown in red bars in Figure 4.5, while the interpolated temperature from the entire Barents Sea is shown as green bars. Data from the whole period studied (1981-2011) are used in these histograms. The 0-groups experience a higher temperature than the older age groups, as they were collected in August-September in the upper part of the water column and therefore represents the warmest time of the year. Contrary, the older age groups were caught in January-March, hence for these groups the histograms represent their thermal habitat during winter. Since the red bars (showing where NEA haddock is located within the temperature field) are within the green bars (showing the temperate in the whole area), it appears that the coverage of NEA haddock in the surveys have in general been good throughout the time period. However, the histograms do not indicated whether the coverage have been sufficient within single years. In fact, some of the years showed that the distributions were partly outside the Barents Sea temperature range, especially during years with high abundance (Fig. 4.7; Appendix d). The coverage was especially insufficient for younger age groups, on the eastern, western and northern limits. For the older age groups the coverage tended to be good in the northern and eastern parts, but not in the western areas.

As mentioned, the 0-group was confined to the warmest water, with 95 % of the fish being between 3.5°C and 9.8°C degrees, with the median temperature at 7.5°C (Tab. 4.3). Thereafter, visual inspection of the histograms (Fig. 4.5), Table 4.3 and Figure 4.6a show that the NEA haddock inhabited colder water between the ages 1 and 3 (especially between 1 and 2). The median for the age groups 1, 2 and 3 are 3.85, 3.18 and 2.87 degrees, respectively. Further, they inhabit warmer water after the age of 3. The temperate median temperature increased from 2.9°C for the 3-year old fish, to 4.5°C for the 9-year old fish. The 2.5 and 97.5 percentiles also follow this pattern (Fig. 4.6a).
Figure 4.5: The thermal habitat for the 0-9 age groups of NEA haddock in the period 1981-2011 (1981-2008 for 0-group) (red bars). Green bars show histogram of the interpolated temperature from the whole sampling area for the period 1981-2011. Temperature from the 0-50 meter depth layer collected in August-September was used together with the 0-group abundance data, while bottom layer temperature collected in January-March was used with the abundance data for the 1-9 age groups.
Table 4.3: Percentiles (0.025, 0.5 and 0.975) of the thermal habitat for the age groups between 0 and 9 of NEA haddock.

<table>
<thead>
<tr>
<th>Age</th>
<th>0.025 percentile</th>
<th>0.5 percentile</th>
<th>0.975 percentile</th>
</tr>
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<tbody>
<tr>
<td>0</td>
<td>3.44</td>
<td>7.52</td>
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<tr>
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<td>1.26</td>
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</tr>
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<td>1.86</td>
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</tr>
<tr>
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<tr>
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<td>6.31</td>
</tr>
<tr>
<td>9</td>
<td>2.14</td>
<td>4.52</td>
<td>6.22</td>
</tr>
</tbody>
</table>

4.2.2 Inter-annual variability in thermal habitat

Figure 4.6b shows the median temperature for each age group between 1 and 9 for three cold (1981, 1986 and 1996) and two warm (1991 and 2006) years. Compared with the average median temperature for the whole period (Fig. 4.6a), the patterns are similar for the individual years, i.e. the thermal habitat is coldest for the 3-year old NEA haddock (2-year old fish in 1996 and 2006), and warmer with increasing or decreasing age. The ambient temperature was highest during the warm years compared to the cold years, but the shape of the curves is largely similar for all years. Another feature that is evident from Figure 4.6b is that the inter-annual variation in thermal habitat is largest for the younger age groups and declines substantially towards 9-year old fish.
4.3 Distribution

4.3.1 Distribution area

Inter-annual variation in the distribution area for the different age groups occurred during the period 1981-2011 (Appendix d). The maps in Figure 4.7 shows the distribution of 0-, 3- and 8-year old NEA haddock for years with high and low abundance. The area of distribution appears to have been larger during years with high abundances. Further, the maps indicate the spatial limitations in survey coverage. For instance, the 0-group surveys in 1991 and 2001 do not seem to capture the northernmost distribution at the northern edge of Svalbard. Moreover, the winter survey in 2009 did probably not capture the entire distribution of 3-year old fish, neither in the eastern or western areas (Fig. 4.7). In general, the survey coverages appear to have been insufficient in all directions during years with high abundance, especially for younger age groups. There has also been a tendency of poor coverage in the western areas for older age groups. Maps for all age groups (0-9) for all years can be found in Appendix d.
Figure 4.7: Distribution area for 0-, 3- and 8-year old NEA haddock in years with high abundance to the left, and low abundance to the right. Black dot indicate that there were NEA haddock in the surrounding area, with the size of the dot being proportionate to the numbers of NEA haddock (Tab. 3.2). Red dots show areas where no NEA haddock within that age group were caught in the trawl.
4.3.2 Annual distribution centre

The location of the annual distribution centres differed among the age groups (Fig. 4.8). The annual distribution centres for the 0-group were much further north compared with the older age groups. However, this might be related to differences in survey coverage; the coverage has been larger and further north for the 0-group survey compared to the coverage at the winter survey catching 1- to 9-year old fish. The 1-year old fish was more westerly distributed than the 2-year old group, while the distribution centres for the age groups between 2 and 4 have been in more or less the same area. After the age of 5, the annual distribution centres were gradually shifting westwards as they became older.

Inter-annual variations in the location of the centre of distribution within the age groups were seen for all the age groups. In general, the age groups between 0 and 4 showed a larger variation in the north-south direction, compared to 5- to 9-year old fish, who showed largest variation in the east-west direction (Fig. 4.8).

In the maps in Figure 4.8, the size and colour of each distribution centre dot represents the relative abundance and temperature for that particular year. The location of annual distribution centres for 0-group significantly correlated with both temperature and abundance (Tab. 4.4). The 0-group is the only age group (together with the 5-year old fish) where average latitude is significantly correlated with both temperature and abundance (Tab. 4.4). For the 1-year old fish, there was a relation between the location of annual distribution centre with temperature, but not with abundance. The distribution centre for ages between 2 and 6 showed a relation with abundance, but not with temperature (except for 5-year old fish) (Fig. 4.8; Tab. 4.4). Specifically, for these age groups the distribution centres tended to be further west during years with high abundance, compared to years with low abundance. Distribution centres for the age groups older than 6 did not show any pattern with neither temperature nor abundance (Fig. 4.8; Tab. 4.4).

Fluctuation in temperature and abundance of the age groups between 0 and 5 were shown in Figure 4.1. Here we revisit these fluctuations together the fluctuations in annual distribution centre, or more specifically; average latitude and average longitude. Graphs showing these
temporal fluctuations are given in Figure 4.9 for the age groups 3 and 8, and equivalent graphs for all age groups between 0 and 9 year are found in Appendix e.

The average latitude and longitude of the annual distribution centres are negatively correlated (Fig. 4.9; Tab. 4.4), which implies that the changes in location of the distribution centres occurred mainly in the southeast/northwest direction. For simplicity, the focus will further be on average longitude as a proxy for distribution centre.

For the 3-year old NEA haddock. The peaks in average longitude were aligned with peaks in abundance, and not with peaks in temperature. This trend, where the average longitude correlates with abundance – and not with temperature – is also evident for the age groups between 2 and 4 shown in Appendix e. For the 8-year old NEA haddock, it was no significant correlation between average longitude with temperature or abundance (Tab. 4.4). Similar result for the age groups 6-9 are found in Appendix e.
Figure 4.8: Annual distribution centres for the 0-9 age groups of NEA haddock in 1981-2011. The size and colour of the dots indicate the abundance and temperature in that particular year, respectively. Red, purple and blue dots represent warm, average and cold years. Small, medium and large dot size represents small, medium and high abundance. The centres of distribution is not included in some years for age group between 6 and 9 because of no fish in that age group in that particular year. This occurred for 6-year old fish in 1986 and 1987, 7-year old fish in 1987, 8-year old fish in 1981, 1988 and 1989, and 9-year old fish in 1981, 1983, 1986-89 and 1996.
Figure 4.9: Time development in the period 1981-2011 for the average annual temperature in the 50-200 meter depth layer at the FB-section (blue lines), logarithmic abundance of NEA haddock based on observations (in millions) (red lines), average longitude (black lines) and average latitude (yellow lines), for the 3-year old NEA haddock (top) and 8-year old NEA haddock (bottom). The average latitude and longitude are from January-March. The shaded area in the graph for 3-year old NEA haddock, shows where peaks in abundance are aligned with peaks in the average longitude. Note that due lack of data on 8-year old NEA haddock in 1981, 1988 and 1989, these average latitude and longitude are not shown correct in the figure for these years.
Table 4.4: Correlation coefficient between; TB: temperature and average latitude (Pearson product-moment method), TL: temperature and average longitude (Pearson product-moment method), MB: abundance and latitude (Spearman rank method), ML: abundance and longitude (Spearman rank method), and LB: latitude and longitude (Pearson product-moment method). Star indicates significance, with p-value < 0.05. Red numbers are not significant.

<table>
<thead>
<tr>
<th>Age group</th>
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<th>TL</th>
<th>MB</th>
<th>ML</th>
<th>LB</th>
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</tr>
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</tr>
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</tr>
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</tr>
<tr>
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</tr>
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</tr>
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</tr>
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</tr>
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<td>-0.16</td>
</tr>
<tr>
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<td>0.18</td>
<td>-0.08</td>
<td>-0.73</td>
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</tbody>
</table>
5. Discussion

Temperature fluctuations ranging from inter-annual to decadal are observed in the Barents Sea in the period 1981-2011, with the general trend showing an increase throughout the period. The increase is linked with the Atlantic Multidecadal Oscillation, fluctuating with approximately 70-year periods (Fig. 2.2; Chap. 2.2) (Sutton and Hodson, 2005; Sundby and Nakken, 2008). The increase may also have been amplified by anthropogenic forcings (IPCC, 2007). The temperature fluctuations have had an influence on the abundance and distribution of the NEA haddock stock, which is one of the most abundant fish species in the Barents Sea ecosystem, and one of the most important commercial species in this area (Gjøsæter, 2009).

5.1 Effect of temperature on abundance

The results demonstrated a positive correlation between temperature and the 0-group abundance of NEA haddock for the period 1981-2011 (Fig. 4.2), supporting results from previous studies on 0-group NEA haddock (Ottersen and Loeng, 2000; Eriksen et al., 2012), as well as other species in the Barents Sea, such as NEA cod and herring (Sætersdal and Loeng, 1987; Ellertsen et al., 1989). For NEA haddock older than 0-group there were no relation between temperature from the survey year and abundance, with exception from the 1-, 7- and 8-year old fish (Fig. 4.3; Tab. 4.1). As for the 1-year old NEA haddock, the correlation might be due to a combination of strong correlation between 0-group abundance with temperature, and relatively small temperature change between succeeding years. As for the 7- and 8-year old fish, the correlation is probably related to the 7-8 year period in the temperature oscillations. The weak correlation between abundance and temperature from survey year for older fish indicate that abundance of the older age groups are more determined by the year-class strength in previous years, and not by the temperature in the survey year.
On the other hand, there was a strong correlation between the abundance of the age groups between 1 and 9 and the temperature the year they were spawned (Fig. 4.3, Tab. 4.1), which is in accordance with results from an earlier time periods (Bergstad et al., 1987). These correlations were expected given that the natural mortality is exponentially decreasing with increasing age (Houde, 2002), causing strong year classes at 0-group stage to stay strong as the corresponding year class becomes older. These results emphasize the importance of temperature during their first year of life on the 0-group abundance, but also the abundance of the corresponding year class as it becomes older. However, the correlations weaken as the NEA haddock becomes older (second column Fig. 4.3), which is probably related to fishing mortality given that NEA haddock is a commercially important stock recruiting to the fisheries at the age of 3.

Strong year classes appeared only during warm years and never during cold years, while weak year classes occurred in both warm and cold years (third column Fig. 4.3). Consequently, high temperature appears to have been a necessary but not sufficient condition for getting a strong year classes of NEA haddock. This is similar to what was found for NEA cod (Ellertsen et al., 1989). Underlying mechanisms behind the correlation between temperature and recruitment of fish stocks in the Barents Sea has been the subject of many investigations (e.g. Ottersen and Loeng, 2000; Sundby, 2000). Temperature has been found to be a proxy for food abundance (Ellertsen et al., 1989; Sundby, 2000), and has also been shown to be positively correlated with the growth and hence survival of the larvae (Ottersen and Loeng, 2000; Chap. 2.3.1). High growth rates in the early vulnerable stages are beneficial for survival in combination with enough food (Ottersen and Loeng, 2000). The reason behind the poor recruitment observed for some of the warm years could be related to changes in food abundance, because the inflowing water might not necessarily be accompanied by high zooplankton biomass in all warm years (Sundby, 2000). To clarify, note that “recruitment” is hereafter the abundance within the 0-group stage (“recruitment” is also defined in literature as abundance recruiting to fisheries at a certain age, e.g. 3 years old). Alternatively or additionally, low recruitment in some of the warm years could be due to a low SSB. The importance of the SSB on fish recruitment has been discussed and confirmed in several
studies (e.g. Ottersen and Sundby, 1995; Dingsør et al., 2007; Eriksen et al., 2010). It was found that the SSB correlates with recruitment only in warm years (MacKenzie et al., 2003), implying that a low SSB limit recruitment even if temperature conditions are favourable. This can also be seen in the present results. The fact that there were no strong year classes of NEA haddock following the temperature peak in the end of the ‘90s was probably the result of low SSB during this period (Fig. 5.1).

The present results showed a significant correlation between 0-group abundance and temperature (Fig. 4.2). However, separation into shorter periods resulted in significant correlations only for the period 1981-1989 (Fig. 4.4; Tab. 4.2). The lack of correlations between temperature and recruitment during recent years are in accordance with results from Eriksen et al. (2012). The '80s were cold, probably causing temperature to be the main limiting factor on recruitment during this decade. Contrary, the temperature was generally high and stable in the last two periods, and therefore probably more beneficial for recruitment, causing factors other than temperature to be limiting on recruitment. The fact that high temperature is a necessary but not sufficient condition for strong year classes explain the lack of temperature correlations in the warm periods. In warm periods with only high temperatures there is both strong and weak year classes, i.e. no correlation with temperature. Additionally, the difference in correlation could be related to the different temperature ranges and the varying rate of temperature changes in the periods. The temperature in the '80s had the widest temperature range, with relatively abrupt changes in temperature compared to the following periods. This probably enhanced the correlations. As for the last two periods where no significant correlations were found between temperate and abundance, the range in temperature was smaller and the changes in temperature less abrupt, making a possible correlation harder to detect.

Further, the fact that the correlations between temperature and recruitment were lower /not significant on shorter time scales (Fig. 4.4) are in accordance with results from Sundby and Nakken (2008), who analysed the long-term shift in spawning areas for cod. They found no relation between shift in spawning areas with temperature on decadal and shorter time scales, however it was a significant correlation for larger time period, i.e. the multi-decadal variation.
It was concluded that the type of response of fish stocks to climate variability and change depends on the periodicity of the climate variations. The difference in correlation for the different time periods in the present results can be explained by recruitment having a fast and a slow response to temperature. The fast response are related to how temperature have an effect on growth rates during the early vulnerable stages (Ottersen and Loeng, 2000), but also how temperature is a proxy for food abundance (Sundby, 2000). The slow response is probably related to how temperature has an effect on the SSB of the NEA haddock, which is as mentioned also important for their recruitment. Spawning stock features are shown to have a multi-decadal response time to temperature changes (Sundby and Nakken, 2008), and may therefore be less dependent on the temperature fluctuations during a relatively short time period. This can explain why the present results showed no significant correlation between temperature and abundance on the shorter decadal scale periods, but did show a correlation on the longer period between 1981 and 2011.

Figure 5.1: Estimated SSB for NEA haddock in tonnes from the ICES 2011 assessment (orange line), annual mean temperature from the 50-200 meter depth layer at the FB-section (black line), and observational abundance of 3 different merged age groups of NEA haddock in numbers of fish (in millions) (red, blue and green line). All variables are shown for the period 1981-2011. Note: this figure is different from Figure 4.1 because some of the age groups are merged together and SSB is included.
5.2 Effect of temperature on distribution and thermal habitat

Highest densities of immature and adult NEA haddock during feeding season (in summer) are found in areas with 5-6°C (Sonina, 1969 cited in Bergstad et al., 1987). The results from this study showed that the median ambient temperature during winter for the age groups 1-9 was between 3.9°C and 4.5°C (Tab. 4.3). The general trend in thermal habitat for the age groups between 1 and 9 showed that the 2-year old NEA haddock was on average distributed in colder water compared to the 1-year old fish, and further that the 3-year old fish was in colder water than the 2-year old fish, i.e. a shift towards colder water between the age of 1 and 3 (Fig. 4.5, 4.6; Tab. 4.3). The fact that the 2-year old fish was found in colder water than the 1-year old fish is in accordance with results from previous periods (Sonina, 1969 cited in Bergstad et al., 1987). However, the shift towards water with even lower ambient temperatures for the 3-year old fish has not been shown previously. In general, the temperature in the Barents Sea decreased eastwards (Loeng, 1991). Consequently, the decrease in ambient temperature between the ages 1 and 2 implies a more easterly distribution of 2-year old fish than 1-year old fish, which is in accordance with the distribution maps in Figure 4.8. The maps do not show a clear difference in the centre of distribution for 2- and 3-year old NEA haddock, even though the thermal habitat histograms indicated a slightly colder habitat for the 3-year old fish compared to the 2-year old fish. The underlying reason for the observed shift into colder water up to the age of 3 is unclear. Possible mechanisms might be related to prey and predator distribution fields, growth, or density dependency.

For NEA haddock older than 3, the ambient temperature showed an increase with increasing age (Fig. 4.5, 4.6; Tab. 4.3). This is in accordance with the distribution centres in the maps (Fig. 4.8), which generally showed a more westerly distribution for older fish. Similar results have been found for NEA cod, with older age groups generally being distributed further west compared to younger age groups (Nakken and Raknes, 1987). The more westward distribution of age groups older than 3 is probably related to spawning migration towards warmer areas in the south-west undertaken by the mature parts of the stock (older than 4-7). Spawning migration typically starts in January-February (Bergstad et al., 1987), which overlaps with the timing of the winter survey. The fact that age difference in distribution is
probably related to spawning migration, makes it difficult to expand these results to a general hypotheses on distribution if the age groups for the rest of the year. Data from other seasons, when spawning migration is not an issue, must be analysed to confirm this specific pattern on how the age groups are distributed in relation to each other.

The results showed that warm years resulted in a warmer thermal habitat than during cold years for all age groups (Fig. 4.6b), implying in general that the age groups only to a small degree adjust their distribution to maintain the same ambient temperature. However, there are to a certain extent age differences. Age groups older than 5 year seem to compensate more than the younger age groups (Fig. 4.6b). Figure 4.8 showed how the distribution centre of young age groups varied more in the north-south direction, as opposed to the distribution centres of the older age groups which largely varied in the east-west direction. Since the east-west temperature gradients are smaller than north-south temperature gradients, this might explain why inter-annual variations in thermal habitats for 0-group to 4-year old fish are larger than inter-annual variations in thermal habitats for 5- to 9-year old fish (Fig. 4.6b). The similarity between the shapes of the curves in Figure 4.6b for the different years indicate how the age groups are similarly placed in relation to each other in cold and warm years, and that a change in temperature do not seem to affect this pattern.

Results showed that the 0-group in general was distributed further east in warm years (Fig. 4.8; Tab. 4.4). Three mechanisms can explain this pattern: (i) stronger inflow of Atlantic water in warm years, transporting the 0-group further east, (ii) higher survival of 0-group in the eastern parts of the Barents Sea in warm years (due to the temperature itself, food, or both), (iii) a northward shift in spawning areas in warm years, which has been found for cod (Sundby and Nakken, 2008), resulting in a shorter drifting distance to the eastern parts of the Barents sea. These possible mechanisms are most likely acting together. Contrary to the results from this study, Eriksen et al. (2012) found that 0-group NEA haddock remained in the central areas of the Barents Sea despite a varying temperature regime, indicating a relatively strong coupling to a specific area, concluding that observed variation in spatial distribution of 0-group was not governed by local temperature variations.
Further, the distribution of 1-year old NEA haddock also correlated with temperature (Fig. 4.8; Tab. 4.4). This might be related to how the distribution of 1-year old NEA haddock is influenced by their distribution pattern in the previous year when they were 0-group, as has been found on NEA cod (Nakken and Raknes, 1987). The distribution of older age groups did not show significant correlation with temperature, except for a low correlation for the 5 age group (R=0.37). This indicated that the distribution of these age groups is most likely driven by other mechanisms, possibly food abundance, or by spawning migration. Abundance was found to be an determining factor for distribution for some of these older age groups (Chap. 5.3). Given the temperature effect on abundance (Fig. 4.2, 4.3; Tab. 4.1), it could be hypothesised that temperature will have an indirect effect on distribution through its effect on abundance, however this effect would then be acting on a longer time scale.

The results showed that the long-term trend in location of the distribution centres for the various age groups seem to have increase throughout the study period (Fig. 4.9; Appendix e), which speculatively could be related to the increase in temperature.

Since only winter data were considered in this study (except for the 0-group where data are collected in the late summer/fall), it must be kept in mind that the distribution of NEA haddock is different during summer. No regular season migration is observed up till the age of 3, while the 3-year old fish and older show seasonal migration between eastern and coastal feeding grounds in summer, and the southern and western wintering areas (Sonina, 1969, cited in Bergstad et al., 1987).

5.3 Abundance affecting distribution
The annual distribution centres of the age groups between 2 and 6 did not correlate with temperature, but they did show a positive correlation with abundance (Tab. 4.4). The fact that abundance influences the distribution could also be seen on the maps in Figure 4.7, where the area of distribution is larger in years with high abundance. This density dependent distribution is observed for many species (Gaston et al., 1997). When the abundance of a species is high,
they will be distributed over a larger area. For NEA haddock the increase in distribution will mainly occur in the eastern direction which is more suitable compared to areas further west which is the area in the deep-sea region beyond the continental shelf. It should be mentioned that the density-dependent distribution could be an artefact created by the fact that there is a higher probability for catch as abundance increase (Gaston et al., 1997).

Abundance of 0-group will most likely lead to a strong abundance of the age groups of the corresponding year class as they become older (Fig. 4.3; Tab. 4.1). Consequently, it is likely that strong year classes will be distributed further east during their whole life, compared to weak year classes. In other words, the eastward distribution in years with high abundance is probably not related to an active movement that year for the age group in question, but on the other hand related to a more easterly distribution of all age groups within a strong year class.

There were no relation between abundance and distribution centre for NEA haddock older than 6. This could be related to fewer fish at these age groups, causing density dependency to be less important.

5.4 Comparison with NEA cod

Cod is a gadoid, demersal fish species distributed in the Barents Sea, and adjacent water (Fig. 2.5) (ICES, 2011). It is one of the most studied fish species in the Barents Sea, while much less is known about NEA haddock. NEA cod and NEA haddock have largely similar life history and distribution area. During the egg, larval and pelagic juvenile stage they share similar parts of the water column and will probably also share similar kind of prey items. In addition they would probably be exposed to similar kinds of predators. However, they have different prey preferences after settlement to the bottom, and NEA haddock is generally more confined to the bottom layers than NEA cod. The two species have many common features and are expected to react similar to changes in physical properties (Chap. 2.4).
5.4.1 Abundance

Results from this study showed that high temperature is necessary but not sufficient for getting a strong year class of NEA haddock (Fig. 4.3). This is in accordance with results on NEA cod (Ellertsen et al., 1989). Sætersdal and Loeng (1987) found that, similar to the results on NEA haddock, NEA cod tend to produce strong year classes in warm years and poor year classes in cold years, which have been related to higher abundance of *Calanus finmarchicus* in warm years (Sundby, 2000). However, it has later been found that temperature may have an asymptotic effect on NEA cod abundance, thus a further increase in temperature may give no further gain in the 0-group abundance (Eriksen et al., 2012). On the other hand, the abundance of 0-group NEA haddock shows a positive correlation with increasing temperature (Bogstad et al., 2012; Fig. 4.2).

Contrary to the NEA haddock 0-group, extreme low abundance of 0-group cod is rare (Fig. 4.1). This is probably related to their difference in spawning locations. The NEA cod eggs are spawned closer to the coast and drift with the coastal current into the Barents Sea (Vikebø et al., 2005). NEA haddock is on the other hand being spawned closer to the shelf break and therefore transported with the Atlantic current, probably spreading the 0-group of NEA haddock over a larger area, with the possibility that parts of the 0-group are lost for recruitment out in the deep sea beyond the shelf break (Castaño-Primo, 2012).

5.4.2 Thermal habitat

The median ambient temperature for NEA haddock between the age 1 to 3 is lower with increasing age (Fig. 4.5, 4.6; Tab. 4.3). The opposite is generally true for NEA cod, with a warmer temperature habitat with increasing age for NEA cod between the age 1 to 3 (Nakken and Raknes, 1987; Ottersen et al., 1998). Speculatively, these differences could related to the difference in growth, or to their difference in food or habitat preference. For age groups older than 3, the thermal habitat are warmer with increasing age for both species (Ottersen et al., 1998; Fig. 4.5, 4.6; Tab. 4.3). Moreover, age groups of NEA cod older than 2 are distributed in relation to each other in the same way in the temperature field, independent on the absolute temperature (Nakken and Raknes, 1987; Ottersen et al., 1998). This is in accordance with the
present results for NEA haddock (Fig. 4.6b).

5.4.3 Distribution centre

Distribution centres for NEA haddock have in Figure 5.2 been compared with similar results for NEA cod from Ottersen et al. (1998). The distribution centres of NEA cod between 1 and 6 years of age are gradually further westwards with increasing age. Contrary, the distribution centres for the same age groups of NEA haddock were located more or less in the same area. Their differences in eastwest movement with age could be related to a difference in temperature preferences or bottom preferences with age, or possibly be related to food. As opposed to haddock, cod have a strong cannibalistic behaviour (ICES, 2011). It can be questioned whether younger age groups of NEA cod are distributed further away from the older age groups to avoid the risk of being eaten. NEA haddock is on the other hand not cannibals, which could explain why the age groups between 1 and 6 appear to be located in the same area.

Previous studies have found that NEA cod are distributed further east than NEA haddock (Bergstad et al., 1987). Figure 5.2 indicates that this is only the case for the youngest age groups, where the 1- and 2-year old NEA cod appear to be distributed further east compared to the 1-and 2-year old NEA haddock. However, after recruiting to fisheries (after the age of 3), NEA cod appear to have a more western distribution than NEA haddock. It must be mentioned that the data coverage on NEA haddock is limited, especially in the western direction. Consequently, the NEA haddock stock might have a more western distribution than what the data used in this study indicates.

Further, two plots compared in Figure 5.2 are based on data from different periods. The data on NEA cod are from a shorter period 1988-1995 than the data used in this study. The longer period for NEA haddock results in a wider range in both temperatures and abundance and therefore possibly also a wider range in distribution centre for NEA haddock. These large amounts of data might camouflage whatever westward movement the NEA haddock might actually undertake.
Further, the results on NEA haddock showed that the average longitude was related to abundance for age groups between 2 and 6 (except for 1-year old fish), and not to temperature (Tab. 4.4). Similar results have been found for young NEA cod, extending further east if number are high, independent of temperature (Ottersen et al., 1998).

Figure 5.2: Areas encircling the centres of distribution for 1- to 6-year old NEA haddock in 1981-2011 (top) and 1- to 6-year old NEA cod in 1988-1995 (from Ottersen et al., 1998) (bottom).
5.5 Sources of errors related to data coverage limitations

Horizontal and vertical limitations in the sampling coverage, as well as inter-annual changes in data coverage may lead to data that poorly represents the actual abundance and distribution of the stock.

Figure 4.1 shows how the 0-group index is relatively low in the '80s and '90s and dominated by one high peak in the period between 2000 and 2011, and therefore standing out from the abundance indices of the other age groups which showed a more fluctuating pattern. A low 0-group index be related to limitations in the data caused by the use of pelagic trawls in August-September combined with the time of 0-group settling in the period August-October (Olsen et al., 2010), possibly resulting in an underestimation of the 0-group. Additionally, it could be explained by how the ecosystem survey is probably not covering the whole distribution area of the 0-group (Eriksen and Prozorkevich, 2011; Appendix d). In most years since the survey started there has been found 0-group NEA haddock all the way out to the western limit of the surveyed area, which is in accordance with maps from Eriksen et al. (2010) (see maps on 0-group distribution in Appendix d). This sharp western limit of distribution is highly unlikely, indicating that the 0-group is distributed further west in the Norwegian Sea. To support this hypothesis, 0-group NEA haddock has been observed in the mackerel survey in the Norwegian Sea (K.R. Utne, personal communication, 2012). The hypothesis have also been tested in modelling studies, showing how location of spawning location affect the 0-group distribution, and further that not all of the 0-group end up in the Barents Sea (Castaño-Primo, 2012).

Further, the high peak of 0-group abundance around 2005 contrasting with the low abundance in earlier periods do not necessarily indicate a larger abundance of 0-group during these years. It could simply be caused by variation in the currents. Hypothetically, the currents in the '80s and '90s might have transported the 0-group further west in the Barents Sea, resulting in a poor overlap between the distribution of 0-group and the survey coverage. While the currents in the '2000s carried the 0-group further east into leading to a larger fraction being caught in the survey.
As for the older age groups, parts of the mature NEA haddock do not return to the Barents Sea after spawning, but stay in the Norwegian Sea (ICES, 2011). These will not be caught in the winter survey. Further, the winter survey do not cover areas around Svalbard where there has been found 0-group in August-September, and possibly also older NEA haddock during winter. In addition to these horizontal limitations, diurnal migration of all age groups up into the water column (Bergstad et al., 1987; Olsen et al., 2010) (Chap. 2.1), may lead to underestimations of the abundance of the 1- to 9-year old NEA haddock when only bottom trawls are applied.

Temporal changes in methods and survey areas can also question the credibility of the data (Chap. 2.5.3). For instance, the winter survey area is limited by the ice border, which is directly related to water temperature. Warm years might therefore result in higher catch numbers, not necessarily due to the temperature but because of the larger area surveyed these years (Dingsør et al., 2007), since larger ice free areas allow larger survey area.

The centres of distribution are based on data from the 1981-2011, a period with a gradually increase in temperature and abundance of NEA haddock. The coverage on the winter survey also increased throughout the periods, drastically in 1992. Separating whether changes in location of annual distribution centre location are due to temperature, abundance or simply coverage changes could be an issue. The changes in coverage in the winter survey, combined with a changing temperature and abundance might even give artificial results. For instance, since there was on average lower abundance before the survey extensions, this will presumably enhance the difference between distribution centres in year with few or many, and therefore weaken the conclusion on how the distribution of the age groups between 2 and 6 were correlated with abundance. However, years with small abundance of the age group between 2 and 6 also showed a more westward distribution after the coverage extension in 92, indicating that this pattern is probably not just an artefact created by the differences in area covered in the survey. Changes in coverage for the survey catching 0-group have not been as drastic, and the distribution centres for this group are not as affected by this.
5.6 Effects of future climatic changes on the NEA haddock stock

The temperature in the Barents Sea is expected to increase with approximately 1-2°C by 2050 (Hanssen-Bauer et al., 2009). Predicting the biological responses to such future climatic changes are challenging, and it can be helpful to study how responses have been to temperature changes in the past. The temperature trend showed an increase in the period analysed in this study, hence the results could be used when speculating how a further temperature increase may affect the abundance and distribution of NEA haddock.

The results showed how abundance of NEA haddock increased during the period with warming in the Barents Sea (Fig. 4.2, 4.2, 4.4). A further increase in abundance might therefore be expected given a further temperature increase (Fig. 5.3). The NEA cod have already shown an asymptotic response in recruitment to the temperature increase, thus, an increase in temperatures may give no further gain in the 0-group abundance of NEA cod (Eriksen et al., 2012). Similar responses for NEA haddock could occur if the temperature continues to increase. Alternatively, the abundance of NEA haddock decreases.

The effects of a possible temperature increase on distribution are easier to predict. It is expected that the NEA haddock stock will, like many other species, show a shift in distribution with a change in temperature (Mueter et al., 2009). The temperature is expected to have the highest increase in the eastern parts of the Barents Sea (Hanssen-Bauer et al., 2009). In other words, there will be an eastward shift in the boundary between the relatively warm boreal areas and the cold arctic areas, resulting in a larger suitable environment for NEA haddock further east. This study showed how the distribution of 0-group tend to be further east in warm years, which strengthens this theory. A northward shift in distribution may also be expected. The distribution of juvenile NEA haddock is found to have extended further north in recent years (Olsen et al., 2010), possibly related to the temperature increase in the Barents Sea. Results from this study do not show a northward shift with increasing temperature, but that is probably related to poor survey coverage in the northern most regions. Consequently, an increase in suitable habitats might be favourable for survival and cause a higher abundance.
Further, the present results showed how the age groups of NEA haddock are located in relation to each other in a systematic pattern, apparently independent on the absolute temperate. Based on this it could be hypothesised that a temperature increase is not likely to change how the age groups are distributed in relation to each other. However, the predicted temperature increase is expected to be larger in the eastern areas than in the western areas. Given that the age groups of NEA haddock showed different and distinct temperature habitats (Fig. 4.5, 4.6; Tab. 4.3), the spatial difference in temperature increase may change how they are geographically distributed in relation to each other.

For a more accurate prediction, the stock must be considered in an ecosystem perspective. The responses on abundance and distribution of the NEA haddock stock is related to how other stocks, acting as predators or prey for NEA haddock, are affected by the temperature increase.

![Figure 5.3](image)

Figure 5.3: Similar plot as in Figure 4.4 showing (abundance indices of the 0-group plotted against temperature). Additionally, the predicted temperature by 2050 is marked with an arrow and a question mark.
5.7 Suggestions for further work

In this study the temperature effect on the abundance and distribution of NEA haddock during the period 1981-2011 was considered. It would further be interesting to take a more cohort approach, and through this test the temperature effects on distribution and abundant following a year class. An interesting question regarding this is whether the 0-group distribution affects their distribution as they become older, and if/how temperature plays a role in this potential pattern.

The rate of warming could be taken into account, mapping whether there are different effect on recruitment or distribution if the temperature changes fast or slow. This would be possible to answer given that both fast and slow warming have occurred in the period 1981-2011.
Conclusions

The main conclusions can be summarised as follows:

• The temperature in the year the NEA haddock were spawned was positively correlated with the abundance of the corresponding year class as they became older. However, this pattern weakened with increasing age, probably related to fishing mortality.

• High temperature has been necessary but not sufficient for getting a strong year class of NEA haddock. Low SSB was mentioned as a possible explanation for the weak year classes in some of the years with apparently favourable temperatures.

• Abundance appear to respond to temperature on a long time scale. The long-term response on abundance is probably related to the temperature effect on the SSB.

• The median ambient temperature was gradually lower with increasing age between 1 and 3 years of age, but gradually higher with increasing age between 3 and 9 years of age. This was observed in both cold and warm years, indicating that the age groups were similarly distributed in relation to each other independent on the absolute temperature.

• The 0-group was more easterly distributed in warm years. This could be explained by a higher inflow, higher survival in the east, or a more northward spawning area in warm years.

• Distribution centres of NEA haddock older than 1 year did not show a relation with temperature. However, the location of annual distribution centre for the age groups between 2 and 6 correlated with abundance. Hence, temperature may have influenced the distribution through its effect on abundance.

• There are horizontal and vertical limitations in the sampling coverage of the winter and ecosystem survey.
• Due to the temperature increase in the period analysed in this study, the results could be used when speculating how a further temperature increase may affect the abundance and distribution of NEA haddock.
Bibliography


**Database webpages:**
SJØMIL -  www.imr.no/sjomil/index.html
FishExChange - www.imr.no/prosjektsiter/fishexchange/nb-no
Appendix

a) Graphs on temperature and abundance
Graphs displaying temperature (blue lines) and abundance (red lines) of 0-group to 9-year old NEA haddock in the period 1981-2011. These graphs are made with data from the SJØMIL database directly at the IMR-webpage (www.imr.no/sjomil/index.html). The temperature used is the annual temperature from the 50-200 meter depth layer at the FB section. The abundance data are from fish observations from annual surveys in the Barents Sea (Chap. 2.5).
b) Plots on temperature and abundance

Logarithmic (first and second column) and non-logarithmic (third column) observational abundance indices (in millions) of 0-group to 9-year old NEA haddock plotted against annual mean temperature in the 50-200 meter depth layer at the FB-section from the survey year (first column) and the year they were spawned (second and third column). Abundance on the y-axis and temperature on the x-axis. Lines are drawn between succeeding years.
c) Temperature when spawned VS abundance divided into decadal periods
The plots show the relation between annual mean temperature at the 50-200 meter depth layer at the FB-section the year they were spawned on the x-axis and the logarithmic abundance of the age groups between 0 and 9 on the y-axis. The coloured filled areas represent data from different decades, blue is 1981-1989, yellow is 1990-1999 and red is 2000-2011.
d) Distribution maps

Observed distribution of NEA haddock for all age groups (0-9) for all years in the studied period (1981-2011). Due to the difference in time of sampling, the maps on 0-groups distribution are shown together, while the distribution maps for the age groups between 1 and 9 are sorted by year. The size of the dot black dots are proportionate to the size of the catch (Tab. 3.2). Red dots show areas where no NEA haddock within that age group was caught in the trawl.
1981

age-1  age-2  age-3

age-4  age-5  age-6

age-7  age-8  age-9
1983

age-1  age-2  age-3

age-4  age-5  age-6

age-7  age-8  age-9
1985

age-1  age-2  age-3

age-4  age-5  age-6

age-7  age-8  age-9
1986

age-1  age-2  age-3

age-4  age-5  age-6

age-7  age-8  age-9
1990

age-1  age-2  age-3

age-4  age-5  age-6

age-7  age-8  age-9

96
1991

age-1  age-2  age-3

age-4  age-5  age-6

age-7  age-8  age-9
1992

age-1

age-2

age-3

age-4

age-5

age-6

age-7

age-8

age-9
1993

age-1  age-2  age-3

age-4  age-5  age-6

age-7  age-8  age-9
2000

age-1  |  age-2  |  age-3
age-4  |  age-5  |  age-6
age-7  |  age-8  |  age-9
2002

age-1  age-2  age-3

age-4  age-5  age-6

age-7  age-8  age-9
2004

age-1  age-2  age-3

age-4  age-5  age-6

age-7  age-8  age-9

110
2008

age-1

age-2

age-3

age-4

age-5

age-6

age-7

age-8

age-9

114
2009

age-1  age-2  age-3
age-4  age-5  age-6
age-7  age-8  age-9
2010

age-1

age-2

age-3

age-4

age-5

age-6

age-7

age-8

age-9
2011

age-1

age-2

age-3

age-4

age-5

age-6

age-7

age-8

age-9

117
e) Fluctuations in latitude, longitude, abundance and temperature

The graphs show time development in the period 1981-2011 for the average annual temperature in the 50-200 meter depth layer at the FB-section (blue lines), average abundance of NEA haddock based on observations (red lines), average longitude (black lines) and average latitude (yellow lines), for the 0-group to 9-year old NEA haddock. The average latitude and longitude are from August-September for 0-group and January-March for the other age groups. Note that for the age groups between 6 and 9 there are some years without catches, hence no distribution centre can be found. This occurs for 6-year old group in 1986 and 1987, 7-year old group in 1987, the 8-year old group in 1981, 1988 and 1989, and the 9-year old group in 1981, 1983, 1986-89 and 1996. Due to lack of data on some of the age groups during these years, these corresponding average latitude and longitude are not shown correct in the figure for these years, but values for the previous or succeeding year was used.