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From single species surveys towards monitoring of the Barents Sea ecosystem

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ABSTRACT

The Barents Sea, a large, high-latitude shelf sea, has been monitored and investigated for more than a century. More than 1800 occasional expeditions have been organized both by Norway and Russia, and since the1960s the collaboration between the Institute of Marine Research (IMR, Bergen) and the Knipovich Polar Research Institute of Marine Fisheries and Oceanography (PINRO, Murmansk) has been strengthened by developing and carrying out joint surveys. Monitoring changes in the Barents Sea fish stocks and collecting information needed for stock assessments and advice for fisheries management were the driving forces behind the increased effort spent on marine research. This triggered the development of sampling and observation methodology, the design of scientific research vessels for using various equipment and gear, and the development of new technologies for processing several types of samples. Increased data collection generated a need for the development of complex database systems and software that, could analyze larger data sets. Joint large-scale monitoring over the last 50 years, together with joint management of living marine resources during the last 20 years, resulted in high stock biomasses of commercially important fish stocks and thus the successful development of fisheries in the Barents Sea. Here, we describe the development of Barents Sea monitoring from single species (or fishery) surveys that were focused on target species/groups to integrated ecosystem surveys that aim to describe the status and main changes in the Barents Sea ecosystem.

1. Introduction

The Barents Sea is a high-latitude shelf ecosystem in the northeastern Atlantic. It is a productive marine ecosystem with more than 200 species of fish, thousands of benthic invertebrate species and diverse communities of plankton, seabirds and marine mammals inhabiting or visiting the area (Jakobsen and Ozhigin, 2011). Only a limited number of species are of commercial interest. Nonetheless, these species provide the basis for some of the largest fisheries in the world, and in the 2000s, the total annual catches of capelin, polar cod, cod, haddock, redfish, Greenland halibut and shrimp were reported to be close to 1.1 million tonnes (averaged for the period of 2000–2014, Stiansen et al., 2008) and was the highest in 2002 and 2011 (1.5 million tonnes). Human activities such as shipping, tourism, and oil and gas exploration are also influencing the ecosystem.

The Barents Sea has been monitored and investigated for more than a century. Norway and Russia have carried out more than 1850 occasional expeditions during this period. Just after 1900, the countries built their first specially equipped research vessels, and thus, fishery expeditions became more regular (Alekseev et al., 2011). The oceanographic section “Kola meridian” has been observed annually (and in some periods several times per year) since 1903 and has the world’s longest continuous record of sea temperatures and salinity along a hydrographic section (Fig. 1). Research on the Barents Sea fish stocks was carried out during the first half of the 20th century; however, collaboration between Norway and Russia was limited from 1914 to 1954. Since then, collaboration between the Institute of Marine Research (IMR, Bergen) and the Knipovich Polar Research Institute of Marine Fisheries and Oceanography (PINRO, Murmansk) has been renewed and strengthened. Since 1965, these institutions have jointly planned and carried out annual fishery (or single species) surveys. Triggered by sharp declines in some of the major fisheries that were caused by overfishing and ecological events during the late 1960s to the mid-1980s, it became evident that a broader view of the ecosystems was necessary to avoid such devastating events in the future. From the beginning of the1980s’ multi-species and ecosystem considerations

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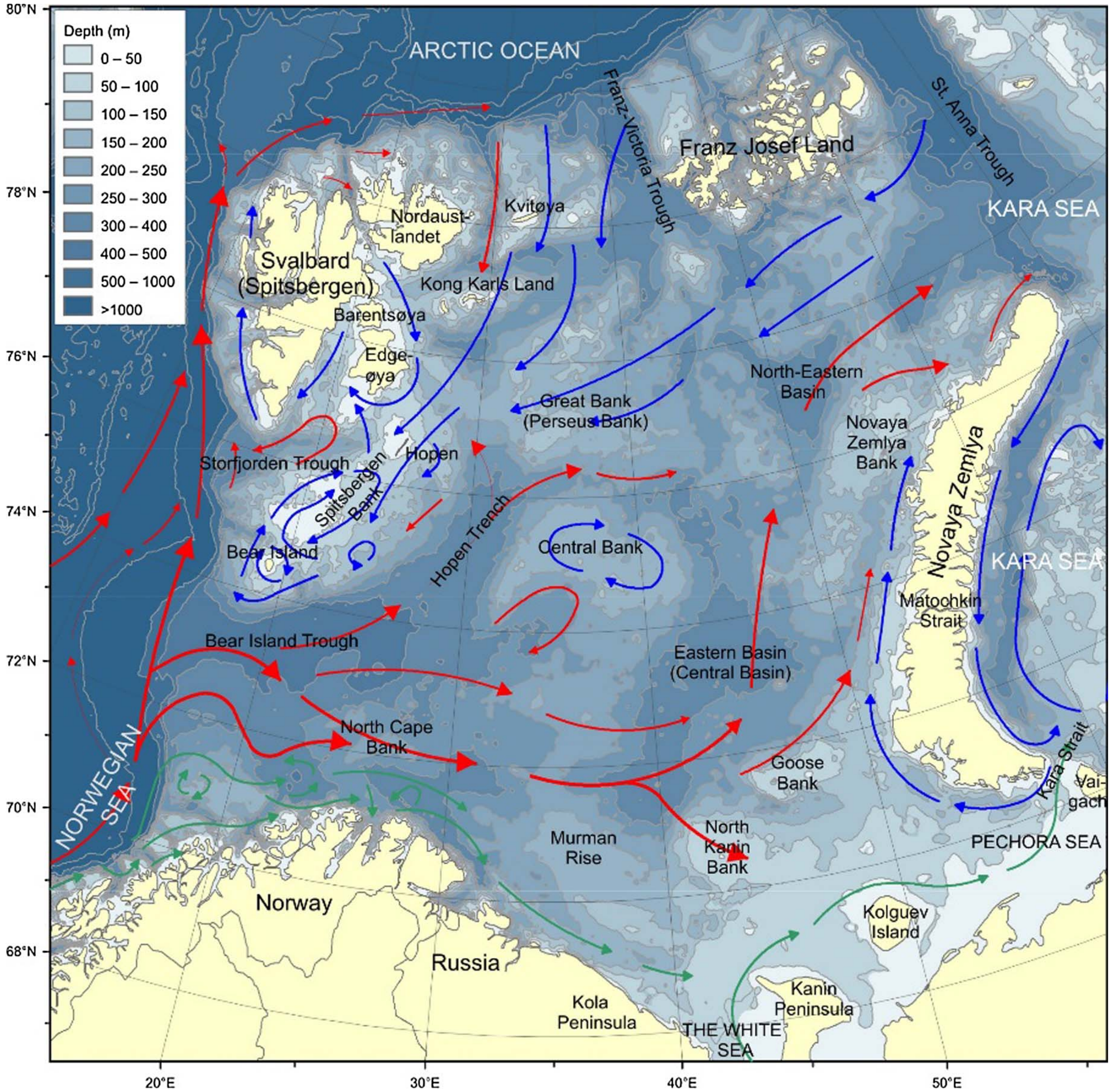

Fig. 1. The Barents Sea. Red arrows show Atlantic water currents, blue arrows Arctic currents and green arrows currents of coastal waters. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

have been gradually added to the aim of various surveys to increase our knowledge about the ecology of the commercial species and later, the ecosystem structure and dynamics. Thus, more than 50 years of a collaborative effort between Norway and Russia has provided an extensive knowledge base for this marine ecosystem (Røttingen et al., 2007; Sakshaug et al., 2009; Jakobsen and Ozhigin, 2011; Hammer and Hoel, 2012). Monitoring of the ecosystem is vital for operative, up-to-date fishery science to support the principles and criteria for the precautionary, ecosystem-based and bio-economically viable management approaches laid down by the Joint Norwegian-Russian Fishery Commission (Alekseev et al., 2011). The successful fisheries management of the Barents Sea is based on comprehensive monitoring (Røttingen et al., 2007; Hammer and Hoel, 2012).

Right from the beginning, the expeditions to map and monitor the large commercial fish stocks in the Barents Sea were based on the need to maximize the output from the fisheries. An increasing demand for healthy seafood as well as a need for a stable outcome for the high number of fishers inhabiting northern Norway and Russia led to this monitoring becoming high priority. Monitoring changes in the stocks and the collection of information needed for stock assessments for fisheries management advice were the driving forces behind the increased effort spent on marine research. The monitoring surveys were rather specialized, predominantly considering only one target species at a time, and they were devoted to the most abundant fish species. The main reason for that was that neither the research vessels at that time nor the fishing vessels occasionally used for research purposes could operate several types of trawls, seines, nets, or other equipment on a day-to-day basis. Alongside this surveying, much effort was spent on developing sampling methods and gear to match the data demands for these important fish stocks. Analytical stock assessments require data on the status and biological parameters of a stock (abundance indices, length and age composition of catches, mean weights at age of stock and catches, and proportion of mature individuals at age).

In recent years, there has been an increasing focus on the effects of human activities other than fisheries on the ecosystem. This research has been driven both by legislation, such as the protection of biodiversity, and global challenges, such as climate change and ocean acidification. The need to investigate additional ecosystem components (water quality and pollution, biodiversity and abundance of phyto- and zooplankton, pelagic and demersal fish, benthos, marine mammals and seabirds) and processes led to the use of a range of methods and gear to simultaneously observe various ecosystem components, such as several plankton nets, trawls and grabs, DeepVision and human observers. Observations of fish diet and fish health (occurrence of pollutants and diseases) by visual observation or chemical analyses were also added (Michalsen et al., 2013). Planning and carrying out such complex ecosystem surveys (more types of gear, new sampling techniques, larger crew and more scientific experts) must seek the best trade-offs between the demands of each discipline and maintain the overall data quality needed to detect changes across the ecosystem components, while adhering to budgets and available ship time. The expansion of the objectives of surveys from a single species to ecosystem monitoring has increased the knowledgebase considerably, but the longevity of the surveys and the total cost have substantially increased.

In this paper, we document the changes in the monitoring activities in the Barents Sea and assess the associated trade-offs involved in developing ecosystem monitoring. We describe some of the challenges associated with integrated surveying, and we hope that the experiences from the Barents Sea monitoring might be of some help when considering monitoring of other areas.

2. The Barents Sea ecosystem

The Barents Sea is a large shelf area (approximately 1.6 million km^2) located at high latitudes between 66.7 °N and 82.5°N, north of Norway and Russia (Fig. 1). The mean depth is 220 m (Gorshkov, 1980), and the maximum depth in the western Barents Sea is approximately 500 m. The bottom topography, with its banks and basins, steers the currents and governs the distribution of water masses (Loeng, 1991). The ocean currents in the Barents Sea are dominated by Atlantic Water flowing into and across the Barents Sea. The flow of Atlantic Water across the western boundary is influenced by the atmospheric pressure and winds. South-westerly winds tend to strengthen the inflow, while north-easterly winds tend to slow the inflow and may even reverse it and cause outflow events, particularly in the northern portion of the western entrance to the Barents Sea (Ingvaldsen et al., 2003). There is also an inflow of Atlantic Water from the West Spitsbergen Current to the northern Barents Sea through the deeper parts of the northern shelf (Lind and Ingvaldsen, 2012). Cold Arctic Water is found overlying the Atlantic Water in the northern Barents Sea. Some of the Arctic Water of the northern Barents Sea possibly circulates around the archipelagos, both Svalbard and Franz Josef Land. There is probably also exchange of the Arctic Water between the northern Barents Sea and the adjacent Nansen Basin of the Arctic Ocean. The inflowing Atlantic Water is relatively warm and gives boreal conditions in the western and southern part of the Barents Sea, while the Arctic Water is cold and gives sub-arctic and arctic conditions in the northern part (Ozhigin et al., 2011; Smedsrud et al., 2010, 2013). The boreal and Arctic regimes are separated by a sharp oceanographic polar front in the western part of the Barents Sea (Ozhigin et al., 2011).

Most of the sea ice in the Barents Sea is moving first-year pack ice that forms seasonally, but multi-year ice is found in the northern Barents Sea where it is partly advected in from the Arctic Ocean (Vinje, 2001). Ice cover varies seasonally and interannually. Ice coverage is at a minimum in September, when an average of 5% of the Sea is covered with ice. The extent of the ice varies widely depending on the weather conditions; in extremely warm years, there is no ice in August–September, while in cold years, drifting ice covers approximately 30% of the area. Maximum ice cover is in April and ranges between 35 and 85%, with an average of approximately 60%. The long-term yearly mean ice overage is close to 40% (Ozhigin et al., 2011). Climate and the extent of ice cover have varied during the total observation period, and in recent years, there has been a warming trend (Drinkwater et al., 2011).

The seasonal growth of phytoplankton is different in ice-covered and ice-free areas. In ice-covered regions, the growth is highly influenced by ice melting, causing vertical stability and thereby driving a short spring/summer phytoplankton bloom with low (approximately 50 g C m^{-2}) primary production (Skjoldal and Rey, 1989; ICES WGIBAR, 2016). By contrast, the spring blooms in the Atlantic water mass are driven by seasonal warming and are therefore slower and prolonged, but with considerably higher primary production (about 100 g C m^{-2} per year (Skjoldal and Rey, 1989). Thus, in the Atlantic water masses there is a more effective coupling to the next level in the pelagic food web, with more time for grazing zooplankton to exploit the phytoplankton production. In the ice-covered regions, due to the shorter-lived ice edge blooms, there is more sedimentation of ungrazed production as energy input to deeper water and benthos (Skjoldal and Rey, 1989). As the fraction of the Barents Sea covered by Atlantic water masses is higher in warm years compared to cold years, there is a higher overall production and a stronger coupling to the next level in the food web during such years.

Most fish species in the Barents Sea are living at or are associated with the bottom. In general, small demersal fish species feed largely on benthic invertebrates; larger demersal species feed more on small fish, while pelagic species feed predominantly on zooplankton. The pelagic species capelin, herring and polar cod are mainly plankton-feeders and constitute important links between lower and higher trophic levels in the Barents Sea ecosystem (Skjoldal and Rey, 1989; Dolgov et al., 2011a, 2011b; Stige et al., 2014; Ciannelli et al., 2007). Atlantic cod, Greenland halibut and long rough dab are mainly piscivorous with a variety of fish species in their diet (Dolgov et al., 2011a). Capelin is a main prey species for cod in the Barents Sea and it is also important in the diet of several fish species, marine mammals and seabirds. However, these species also feed on invertebrates. Capelin abundance in the ecosystem fluctuates, but when abundant it is by far the dominant pelagic species in terms of biomass, while Atlantic cod is dominant among the demersal fish species (Johannesen et al., 2012a). It should be noted that both species are important commercial species and that their numbers also depend on the intensity of fishery.

All the major fish stocks have seasonal migrations within, and in some cases, also outside the Barents Sea. The migrations give spatial closure to the life cycles in relation to the main current systems that transport larvae from the spawning grounds to the nursery areas. The general pattern of migrations is south- and westward towards warmer water (or avoiding cooler water) for wintering, 'upstream' for spawning in the spring, and east- and northward for feeding in the summer. There is also a large variation in the diet composition over time and space, reflecting the dynamic changes in the Barents Sea ecosystem. The migrations may be dictated by the large-scale physical regime in terms of currents and water masses (for the purpose of spatial life cycle closure), but they are also influenced by the migrations of other species that constitute their prey (and possibly predators). For example, plankton-feeders, such as young herring, capelin and polar cod, have large-scale feeding migrations where they spread out and feed on the zooplankton that grow and develop in the upper water layer of the subarctic and low-arctic waters during the short summer season.

The total biomass of fish in the Barents Sea can reach as high as 10–12 million tonnes (Stiansen et al., 2008; ICES WGIBAR, 2016).

3. Historical overview of single species surveys

Table 1 shows the most historically important survey series carried out in the Barents Sea. This list of surveys is not complete; both IMR and PINRO carried out additional surveys, but the surveys that we describe here are the main long-term and large-scale surveys and those were focused on target species/groups and led to integrated ecosystem monitoring (Table 1, more detailed information of the Barents Sea surveys is given in Supplementary material 1).

IMR and PINRO have mostly used their own vessels for surveys, which deliver data for stock assessment and advice for commercially important species (capelin, cod, haddock, redfishes, Greenland halibut, wolffishes, and saithe) in the Barents Sea, but hired fishing vessels have also been used for, such as surveys like the groundfish surveys in the

Table 1
General information and abbreviation for main Barents Sea surveys.

Survey	Time	Coverage area	Target species/groups	Abbreviation	Years
Norwegian-Russian winter survey	February–March	Central, west, east, south	Demersal fish species	NRWS	1981–
The Russian survey of mature capelin stock	January–March	Southern Barents Sea	Capelin spawning stock	RMCS	1987–
Norwegian spawning cod survey	March–April	Lofoten (Norwegian coast)	Cod	NSCS	1985–
Russian Ichthyoplankton surveys	April–July	South-western Barents Sea	Fish eggs and larvae of demersal fishes	RIS	1959–1993
The international ecosystem survey in the Nordic Seas	May–June	South-western part	Herring	IESNS	1995–
Norwegian shrimp surveys	April–September	Barents Sea and Svalbard	Shrimp	NRSS	1980–1997
Joint Norwegian-Russian 0-group fish survey	August–September	Whole Barents Sea	Offspring of demersal and pelagic species	NR0GR	1965–2003
Norwegian Greenland halibut survey	August–September	Continental slope and north of Svalbard	Greenland halibut and redfish	NGHS	1995–2003
Joint Norwegian-Russian capelin survey	September	Whole Barents Sea	Pelagic species	NRCS	1972–2003
Norwegian cod survey	September–October	Svalbard (S) and Bear Island - Hopen Island (BS)	Cod	NCS	1985 (S)–1995(S + BS)–2003
Russian late autumn-winter survey	November–December	Whole Barents Sea (excluding north-eastern part)	Demersal fish species	RAWS	1956–
Norwegian-Russian surveys for king crab	April–October	Norwegian and Russian waters since 2000	King crab	NRKCS	1994–(2000)–

summer (NCS), surveys that deliver data for stock assessment of king crab, whales and seals, and occasionally, in other cases, surveys that were conducted when it was not possible to allocate time on one of the research vessels.

4. The need for more integrated observations

When establishing the Convention on Fishing in the North-East Atlantic in 1959, Norway and Russia agreed on paying special attention to the conservation and sustainable use of marine living resources and the coordination of research in the area. A strong decrease in the Northeast Arctic cod stock in the late 1950s-early 1960s and a collapse of the Norwegian spring spawning herring in the 1960s led to a dramatic decrease in catches. To avoid similar situations in the future, the ICES Herring Committee recommended starting a survey to investigate the early stages of commercial fish species. Data on pre-recruit stages were seen as essential, which resulted in the establishment of the NR0GR described above. In 1972, the development of new acoustic methods allowed for surveys aimed at measuring the absolute biomass of pelagic stocks, such as capelin. Since the 1980's, many different surveys have been conducted to provide data on stock size and the structure of different stocks, see above. The scheduling of these surveys was decided based on the target species' biology/ecology and seasonal stock distributions, while the survey design was based on the possibility to cover the target stock(s) and the data needed for assessment. However, the survey series described above were by no means static; they were augmented with additional sampling and with better equipment and instruments when they became available. Process studies on recruitment, predation and consumption were added to some of the surveys when become clear that such information was needed to be able to develop better methods for stock assessment, prognoses and management advice. A good example is the joint Norwegian-Russian stomach sampling program of cod and other predatory fishes that was started in 1984. At that time, it was realized that such data was needed to get a better understanding of the food web, and in particular, how cod predation on capelin would affect the amount of capelin available for fishing. Stomach sampling of cod was introduced in various surveys, and after a few years, the results were included in the prognosis model for capelin.

5. The road towards integrated monitoring of the ecosystem

The change from several specialized surveys to a few integrated surveys (later termed ecosystem surveys) was not abrupt and is better described as an evolution rather than a revolution. Some of the specialized surveys were gradually merged, and at the same time, they took new fields of research on board. For instance, the capelin survey (which, from the beginning, included polar cod inside the capelin distribution area, but mainly concentrated on the mature part of the capelin stock needed for fishery advice purposes) was expanded to cover the south-eastern parts of the Barents Sea, where the young stages of capelin were found, and it gradually included other pelagic stocks, such as the young stages of herring and blue whiting. After that, it covered most of the ice-free parts of the Barents Sea and provided acoustic estimates of capelin, herring, polar cod and blue whiting; it was termed the "Barents Sea pelagic fish survey" for some years. Still, it was a specialized survey, where the survey design was optimized for acoustic surveying, although more and more stations in predetermined positions for oceanographic and plankton work were included. The major change in the survey came when bottom trawling for groundfish was introduced. Now, the survey design had to be shifted from an acoustic transect design to a combination of acoustics and predetermined stations along the transects. This resulted in a need for many more experts taking part in the survey and much more time being spent on stations. Gradually, the focus shifted from information gathered while the ship was moving to information gathered while the ship was stationary.

The process described above was partly self-propelled and partly influenced by the decisions taken by the relevant institutions, IMR and PINRO. At IMR, a committee with a mandate to consider the merger and integration of various surveys in the Barents Sea was established (Nakken et al., 2002). The stated motivation for this work was the need for more integrated surveys to provide relevant information about the whole ecosystem, but economic arguments related to better coordination of the monitoring were also important. Based on the report from this committee, a formal resolution was later made by IMR and PINRO to merge several surveys in the autumn period into one Barents Sea Ecosystem Survey (BESS, Nakken et al., 2002). The included surveys were the augmented NRCS (which had developed into a pelagic fish survey in the meantime), the NR0GR, the NGHS, and the NSHS (see Table 1 and Supplementary material 1). The plankton investigations were also intensified compared to previous surveys. Shrimp investigations were included from 2005 onward. In addition, Nakken et al. (2002) recommended that all surveys in the Barents Sea should be made more "ecosystem oriented", for instance, by including capelin and polar cod work during the NRWS and including stomach sampling of both piscivorous and planktivorous fish and plankton sampling where appropriate. At present, there are three ongoing monitoring surveys in the Barents Sea: BESS, NRWS and RAWS. The latter two still focus on important commercial species only, while the BESS is an ecosystem survey.

6. Challenges with integrated ecosystem surveys

The coordination of a multi-ship, multipurpose survey like the BESS is a tremendous task. Planning, implementation, and reporting are based on a highly functional international collaboration between Norway and Russia, that takes place by correspondence, annual co-operative meetings between IMR and PINRO in March (planning), post-cruise meetings (reporting), and through and exchange of scientists and technical personnel on the vessels during the survey.

6.1. Survey design

As mentioned above, each of the specialized surveys included in the BESS had their own design based on the purpose of the survey and the type of survey. The challenge was to harmonize these designs into one that would fit all purposes and maintain a synoptic coverage. This was not a trivial task, and it soon became evident that one design would not fulfill these criteria and the chosen design would have to be a compromise between various options. In practice, the cruise tracks and stations were planned based on a regular grid, taking the availability of ships and time into consideration, rather than on the basis of theoretical considerations of an optimal design. A regular grid of acoustic transects were laid out, where the stations were placed at equal distances along these transects. These stations were so-called ecosystem stations, and they included a demersal trawl haul, a pelagic trawl haul (0-group-type), one or more vertical phyto- and zooplankton nets, and CTD probe with water bottles rosette, etc. When the ship was moving, data from echo sounders, Acoustic Doppler Current Profilers (ADCPs), weather stations, and marine mammals and seabird observations were recorded. However, some deviations from this regular grid were implemented; for instance, to the north and west of Svalbard, the continental slope is rather steep, and depths of 2000–3000 m are found not far from the coast. In these areas, a combination of regular stations for 0-group fish and a depth-stratified grid for bottom trawl stations were implemented, combining the design of the surveys that had previously covered that area (NGHS, NRSS, NCS). Another adjustment to the survey design was made when the shrimp survey was included in 2005. The distance between the ecosystem stations adopted for the BESS was found to be too large to determine the length, sex-, and maturity stage- composition of the shrimp stock in the main shrimp areas south east of Svalbard. Therefore, additional trawl hauls for shrimp were conducted between the ecosystem stations. Similarly, the experts on acoustic surveying the capelin found that the grid of acoustic transects in the main capelin area was too distant to give capelin abundance estimates with sufficient precision for stock assessment purposes (Tjelmeland et al., 2011). In 2013, acoustic transects with only 15 nautical miles in between were implemented in the main capelin area and west of Franz Josef Land (Fig. 2).

The large area that needs to be covered during the BESS resulted in limited spatial resolution, with 35 nautical miles between stations. Thus, the survey data based on stations do not resolve processes that occur at finer spatial scales, including smaller scaled hydrographic processes. Spatial distribution patterns observable by acoustics, reflecting, e.g., prey aggregative behavior and predator avoidance, or predator aggregative responses may be observed along acoustic transects. Other designs, such as the random stratified design used in the winter surveys, have also been considered for the BESS. This design would give higher precision of the abundance indices based on trawl samples and would minimize the variance, if the strata were correctly defined. The main challenge with such designs for a multipurpose survey is that there are different optimal stratifications for the many species that are targeted, such that a survey design that is optimal for monitoring one process or ecosystem component is suboptimal for another process or component. Hence, the choice of a regular grid with regional adaptations is a highly pragmatic choice. However, so far, this design meets the required precision of the main deliveries. It requires, however, a thorough knowledge of the survey design from the data users to properly adjust the data analyses to reflect regional variations in resolution.

In addition to “ecosystem stations”, consisting of CTD probes, pelagic and demersal trawls and plankton nets, pelagic trawling targeting the pelagic fish observed on the echosounders is conducted for the allocation of acoustic signals to species and biological samples of capelin, herring and polar cod. In some cases, demersal trawling is also carried out in response to aggregations of demersal fish close to the bottom (Michalsen et al., 2011; Eriksen and Gjøsæter, 2013).

Another challenge with a combination of regular sampling and acoustic sampling is synoptic coverage, since the time allocated to station work may delay spatially acceptable synoptic coverage for migrating pelagic stocks (such as capelin, herring and blue whiting). If the vessels are progressing too slowly through the distribution areas the fish movements and migrations negatively impact the precision of abundance estimates, effectively setting limitations to the number of stations and the number of monitoring activities on each station.

To conclude, the survey design of the BESS results from many different considerations and trade-offs regarding data use: the need for acceptable levels of uncertainty (low variance, CV) on data for stock assessment for specific species, the need to cover a large geographic area; the need to address large depth differences, the need to cover important spatial processes; the need for synoptic coverage in space and time, and the need to maintain a long-time series.

6.2. Ships

As mentioned above, the first generations of research vessels were not designed for multi-purpose work, but were specialized; for example, they were specialized for bottom trawling, pelagic trawling, or oceanographic work. The first Norwegian research vessel built for ecosystem surveying was the “new” “G.O. Sars” in 2003, which replaced the G.O Sars from 1970. With double sets of trawl winches and trawl doors, it can operate several types of trawl without the extra work of changing trawl doors, etc., and, with an instrument hangar placed mid-ship, many different types of instruments and sampling gear can be deployed. The vessel accommodates approximately 45 people, and is the most silent research ship ever built. In Russia, three research vessels were built in 1985–1988 (“Professor Marti”, “Fridtjof Nansen” and “PINRO”), which were specialized for bottom trawling, pelagic trawling and conduct ecosystem research. Since 2004, Russia been also using a modernized fishing vessels with double trawl systems for bottom trawling, pelagic trawling. Today, two research vessels operate operates several types of gears for conducting the joint ecosystem investigations.

Each vessel participating in the BESS conducts the survey in a given area, and Norwegian vessels mostly cover the Norwegian economic zone and the Fisheries protection zone around Svalbard, while Russian vessels cover the Russian economic zone. Multipurpose surveys can obviously be carried out with less outfitted research vessels, but it takes much more time on the stations and some types of sampling gear cannot be used on all vessels. Thus, the possibility of efficiently performing multipurpose surveys demands research vessels that are designed for such work. The recent generations of research vessels are increasingly designed for multiple purposes, and this development must be taken even further in the future.

6.3. Sampling equipment and observation methods

A wide range of methods and gears have been used on the BESS, including various types and sizes of pelagic and demersal trawls for catching fish and large plankton, plankton nets designed to catch phyto- and zooplankton in vertical hauls, benthos grabs, beam trawls and

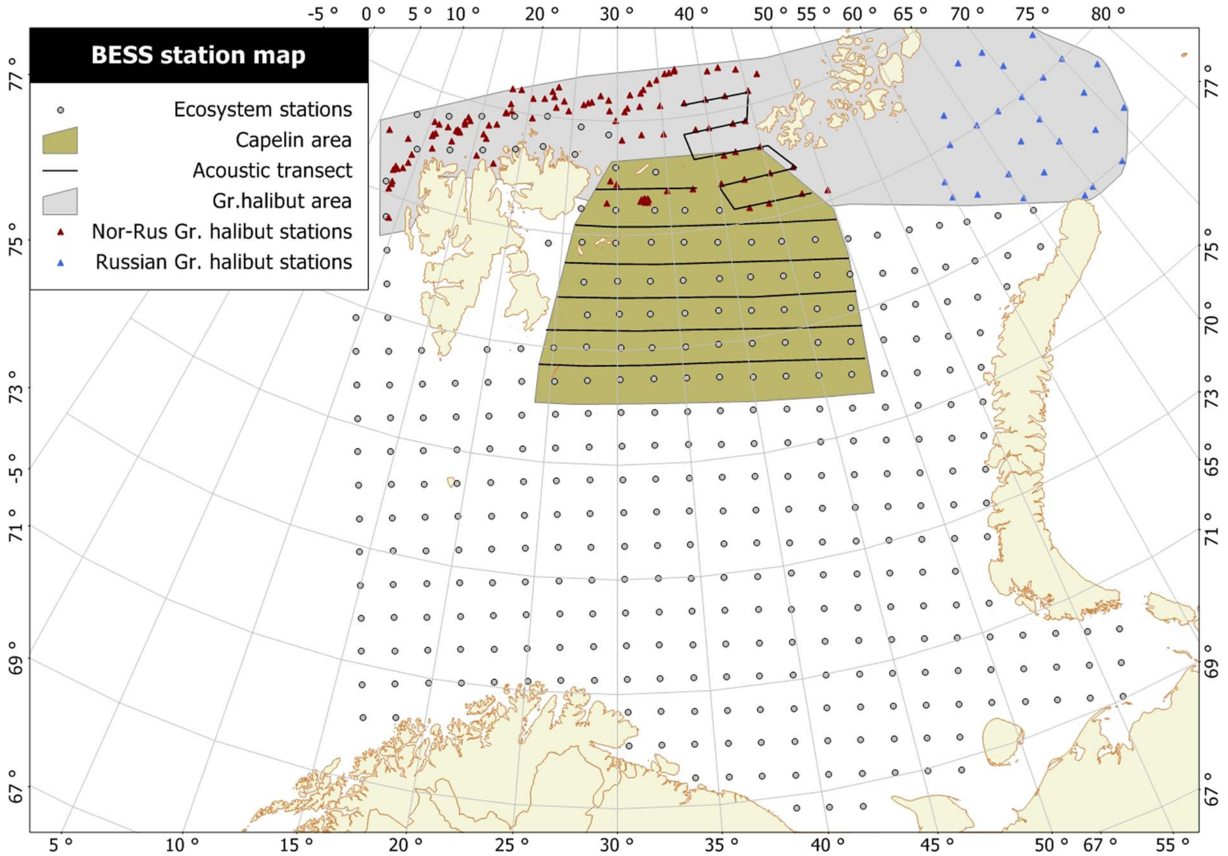

Fig. 2. Map of the standard BESS survey. With ecosystem stations means stations where a demersal trawl haul, a pelagic trawl haul, one or more vertical phyto- and zooplankton nets, CTD probe with water bottles rosette were taken at same location. Capelin area shown with green area and additional acoustic transect shown with black lines. Depth stratified Greenland halibut station shown with triangles (brown for Norwegian-Russian, while blue for Russian stations) and conducting of these stations varied between years. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

sledges, sediments corers, CTD-probes with water bottles to record water physics and chemistry, echo sounders used for mapping and calculations of fish abundance and biomass, and ADCPs for measuring current profiles. The standardization of equipment and observation methods is vital for proper monitoring, and therefore a common set of survey manuals was developed and used on board the Norwegian and Russian ships. The survey manual for the BESS is updated as appropriate and is normally one of the topics discussed during the planning meeting between the PINRO and IMR scientists.

6.4. Intercalibration of equipment

Even though the standardization of equipment and methods has been strived for, a doubt always remains as to whether identical or similar equipment used on different vessels gives identical data. Consequently, intercalibration exercises, where two or more ships work side-by-side and compare their results, were mandatory during the early years of the multi-ship cooperation, particularly when vessels from two nations were involved. For instance, during the capelin surveys in the 1970s and 1980s, the survey normally started with an intercalibration of the acoustic equipment in which three or more vessels sailed side-by-side for several nautical miles to compare their output from the echo integrators. The vessel, that was considered to have the most stable echosounders was taken as the standard, and intercalibration factors were calculated for the other vessels. In recent years, all vessels have digital echosounders with modern transducers that are calibrated using standard spheres at regular intervals. When measurements were found to be very stable from year to year, such intercalibrations were conducted more seldom. Additionally, a division of the survey area between Norway and Russia, where the Norwegian vessels cover the Norwegian EEZ and the Fishery Protection area around Svalbard, while the Russian vessels cover the Russian EEZ, makes working side-by-side complicated.

Additionally, fish trawls and plankton nets have been intercalibrated in the past, but for the reason mentioned above, such work has been discontinued in more recent times. This situation is not satisfactory, and ways to overcome this problem have been on the agenda several times during the planning of the BESS. However, it is challenging to find time and resources for calibration when ship time is limited.

6.5. Development of new sampling equipment

Over the years, the need for replacing old equipment with newer equipment often emerges, but it is always a trade-off between continuing with the old equipment, to maintain a time series or replacing it to be more efficient and get more realistic results. IMR and PINRO scientists are currently developing a new pelagic trawl that may solve some of the limitations with the standard Harstad trawl (Nedreaas and Smedstad, 1987). This trawl was designed to capture small fish and has been used in NR0GR since 1980 (Anonymous, 1980; Eriksen and Gjøsæter, 2013). The new trawl should meet the following criteria: maintain a constant geometry at all depths and a well-defined catch area, and avoid clogging or loss of organisms. PINRO and IMR have recently tested a modified Harstad trawl and a new pelagic trawl, and the results indicated that a ruffled small mesh blinder prevents the clogging of organisms, squared meshes in front of the trawl keep the trawl opening in a constant shape, a modified design of the cod-end prevents fish from escaping during hauling, and the trawl captures organisms from macroplankton (krill and amphipods > 15 mm) to small and large fish. After further refinement of the prototype and testing it is likely that this new trawl will soon replace the Harstad trawl in the BESS.

Various kinds of multiple opening and closing net systems have been tested for several years to get a better vertical resolution of plankton and fish catches. The MOCNESS (Wiebe et al., 1976), carrying 8 nets that can be opened and closed from the ship during a vertical profile tow, has been standard equipment on the Norwegian vessels during the BESS. A similar system for fish trawls has been used occasionally, and it normally carries three separate cod ends that can be opened and closed from either a signal from the ship or after programmed time intervals. This equipment has not been standardized, but it provides additional information that is useful for allocating nautical area backscattering coefficients (NASC) from the echo integrators to species.

An alternative technique to the increase vertical resolution of captured species caught and their size distributions has been tested recently: the "DeepVision". This stereo camera equipment was developed and mounted in the trawl, and tested during the BESS (Jørgensen and Rosen, 2012). The "DeepVision" takes pictures of all organisms passing through the extension of the trawl (Rosen et al., 2013). Individuals ranging from macroplankton including krill, amphipods and jellyfish, to 0-group and adult fish could be identified and measured in the images. Fine-scale patchiness, species distributions and overlap can be documented both vertically and horizontally along the cruise track (Underwood et al., 2014). However, currently the images need to be processed manually, as the automatic species identification of some fish is difficult due to several factors, including similar body shapes. For the routine use of "DeepVision" in ecosystem monitoring of the Barents Sea, these limitations are crucial. Thus, the further development of "DeepVision" and software for automated image analyses (species identification, length measurement and object counting) should be prioritized in the future. To obtain continuous records along trawl tracks, a choice can be made to either bring the total catch on board the vessel or just trawl with an open trawl and rely solely on the species and size distribution obtained from "DeepVision". A combination is also possible, where one or several cod ends can be closed whenever something is seen in the pictures that should be taken on board for further sampling and analysis.

There has been a tremendous development of acoustic instrumentation in recent years, and the postprocessing software for acoustic data has been steadily enhanced. Acoustic probes that are lowered through the water masses in the same manner as a CTD-sonde, carrying several echosounders of various frequencies that can either look sideways or downwards, are a recent development with huge potential; for instance, they can provide a depth profile of plankton and fish aggregations. The higher resolution that can be obtained with such equipment compared with hull-mounted transducers allows for using acoustics for smaller organisms, such as macro-zooplankton and mesozooplankton. These methods will probably give more accurate estimates of plankton abundance in the future, compared with the net-samples applied hitherto for plankton abundance estimation.

Another development that will be routinly used in 2017 is broadband acoustics. Compared to the systems in use today, which emit signals from three or four narrow frequency bands, a broadband echosounder will emit signals within broad frequency bands, resulting in more detailed frequency response analysis, a higher resolution of scatterers and a decreased width of the acoustic dead zone near the sea floor.

6.6. *Timing*

The BESS survey occurs in August–September, when the Barents Sea is more or less ice-free. Hence, the total distribution area of most stocks, except those associated with ice, can be properly covered. Autumn is also a period when organisms have minimal migration, as it is late in the feeding season and prior to migrations to wintering areas. As such, the survey monitors the ecosystem *after* the productive spring and summer season, and allows an assessment of the *outcome* of the annual production, by measuring the gain in length and weight of the various stocks in the current year. This is also a period when the 0-group of commercially and ecologically important fish is large enough to be effectively caught by trawls, at the same time settlement processes of the 0-group of demersal species has not begun.

The autumn period is ideal for abundance estimation of the capelin stock. The feeding season is approaching its end, and the northward feeding migration has mostly ceased. Most capelin are found in areas that are not too shallow (to escape over the hull-mounted transducers) and not too close to the sea floor (to escape in the acoustic dead zone) and in small schools and scattering layers that are well-suited for acoustic abundance estimation. Additionally, this timing is well suited for assessing the mature part of the stock with the purpose of giving quota advice for the winter fishery, which takes place on prespawning capelin that approach the coast to spawn in March. This is a reasonably short period for stock prognosis prior to the spawning season; this prognosis is needed to give advice within a spawner escapement framework. Capelin stock is one of the few examples of a stock where the acoustic measurement is taken as an absolute measurement of stock size and is not calculated by mathematical models based on catch statistics and stock size indices. A successful survey estimate during the BESS is consequently a prerequisite for giving quota advice for this species.

Nevertheless, autumn may not be the most ideal time for monitoring adult groundfish (cod, haddock, redfish, and Greenland halibut), shrimp and others. For instance, an analysis of cohort tracking in the swept area abundance indices for cod has revealed that the data from the BESS cannot match the accuracy obtained during the more specialized winter surveys. The reasons for this discrepancy are not completely clear, but both fish behaviour and a more optimal stratification during the more specialized surveys could are probably involved. Acoustic indices of cod and haddock have not been calculated from the BESS, although the data for making such indices are available, and with the availability of a more automated and less cumbersome calculation software for abundance indices (StoX, Totland et al., 2011), such calculations are now feasible.

The BESS survey lasts for two months and usually starts along the Norwegian and Russian coasts and works northwards. In August-early September, vessels cover the southern and central areas, where 0-group fish are distributed, and thus, it covers these fish before settlement. In mid and late September, vessels move northwards and cover capelin when they reach the northern distribution border and have less migration. Two months' difference between the start and end of the survey may introduce spatial and temporal variability, but it is representative for the season.

The weather conditions during the August–September period are normally much better than during other times of the year. This makes serious delays due to bad weather less likely during this period than for instance during the winter months.

6.7. *Development of sampling protocols*

During the BESS a huge number of samples are collected and processed and evaluations of whether less samples would be satisfactory have been undertaken (Pennington and Helle, 2013; Eriksen and Gjøsæter, 2013). Eriksen and Gjøsæter (2013) recommended the optimization of the survey effort by reducing of sample sizes for the 0-group and non-commercial fish species from 100 to 30 due to small length variations, a recommendation that was based on the analyses done by Pennington and Helle (2013, Fig. 3). The number of individual pelagic fish sampled for age, maturity, etc. has also been reduced from 100 to 30 in recent years, as the increased accuracy associated with taking 100 specimens was small (Mjanger et al., 2011). Simultaneously, improving the efficiency of plankton sampling by reducing the frequency of

Fig. 3. Norwegian research vessel "G.O. Sars" designed for multi-purpose surveys and build in 2004.

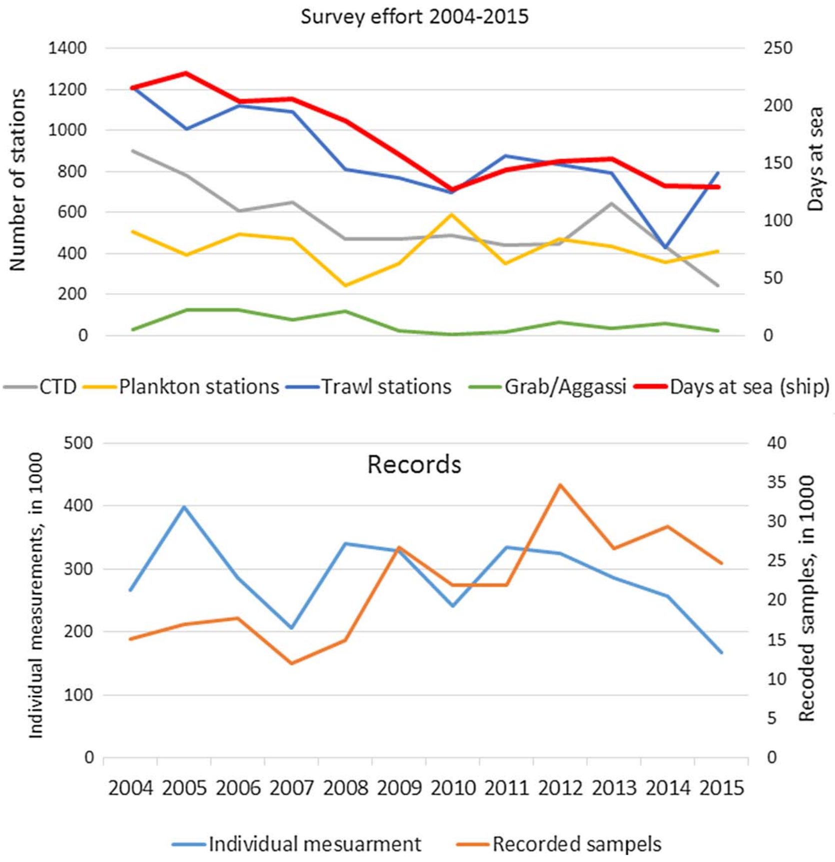

Fig. 4. Survey effort presented by ships days at sea (red line) and different type of samples taken by CTD (water properties, gray line), plankton net (meso- and macroplankton, yellow line), trawl (covering pelagic and near-bottom biota, blue line) and grab/Agassiz trawl (benthos, green line). Survey effort shown for the period from 2004 to 2015. Below, the number of individual measurements and number of samples processed at fish lab are given for the same period. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

vertical hauls with WP-II nets from 300 to 100 while increasing MOCNESS/Multinet or similar equipment were suggested (Eriksen and Gjøsæter, 2013), to obtain a better vertical resolution of plankton data, making the interpretation of acoustic data easier during the survey and providing useful data for ecological studies.

7. Additional challenges associated with survey complexity

7.1. Prioritizing among target species and other aims and tasks

Any survey needs to have a main goal. For an integrated ecosystem survey, there should also be a priority list between the different components in case the survey is hampered for some reason. For the BESS the main goal is stated as: "*The aim of the ecosystem survey is to monitor the status and changes of the Barents Sea Ecosystem to support scientific research and management advice.*"

One of the most challenging undertakings when planning a multi-purpose investigation like the BESS is prioritizing the various tasks that are part of the survey. As with all surveying in the field, work is sometimes delayed by bad weather, the break-down of equipment, sickness among the ship crew, etc. Although the planning accounts for some loss of working days, situations occur where the survey co-ordinator will have to reallocate ship time and give priorities to the most important tasks. However, when doing this, care should be taken with the choice of priorities, since these changes can deviate from the main idea of an ecosystem survey, which is synoptic sampling across key groups and species.

Considerations about which are the most important tasks vary among the participating scientists, so any *ad hoc* decisions are likely to be protested by some of the personnel involved. A priority list should be completed before the survey starts; it should be supplied by responsible persons at the participating institutions and preferably agreed upon by all the scientists involved in the cooperation. For the BESS, it has been decided that the highest priority is to obtain complete coverage of adult capelin stock and a capelin stock size estimate that is precise enough to serve as a basis for prognosis and quota advice. The annual capelin stock assessment relies 100% on this stock size estimate and is carried out less than a week after the survey is finished, so a failure in obtaining a capelin abundance estimate means that no advice can be given.

Apart from this top priority task, it has been difficult to agree on a priority list; to compensate, ample time for unaccounted events is set aside when the survey plans are made.

7.2. Resources vs objectives

The BESS is probably one of the most comprehensive surveys in the world, and IMR and PINRO have achieved between 127 days (2010) and 228 days at sea (2005) (Fig. 4). Michalsen et al. (2011) suggested that for the BESS, the survey effort should be at a level of 150–200 ship days to get sufficient coverage of the Barents Sea. However, while the ship time decreased, the survey area has increased due to increased ice-free areas and an increased number of other included investigations. Eriksen and Gjøsæter (2013) concluded that the decreased ship time, increased survey area and increased number of tasks can have a negative influence on the quality of the collected data and the working conditions on board, and therefore they recommended that the leaders of IMR and PINRO should evaluate and decide on a priority list for monitoring and should allocate adequate resources.

The survey is manned by technicians/scientists with diverse expertise, including oceanography, hydrochemistry, biochemistry (some years), acoustics, zooplankton, fish and benthos taxonomy, parasitology (some years), and marine mammal and sea bird observers (Eriksen and Gjøsæter, 2013). The number of person days at sea varied between years, and was 350–700 (Russian coverage) and 1300–1700 (Norwegian coverage) and was related to the monitoring effort. During the BESS period, several taxonomy seminars were held to improve the taxonomic determinations during the processing of samples on board. It is vital that the institutes have a sufficient amount of the right expertise to properly take care of samples, and the manning of individual surveys must be adapted to the tasks. If expertise is lacking, the committees should rectify this lack by employing new experts or upgrading the staff. At IMR, an in-house “Institute of Marine Research Academy” was recently founded with the aim of developing among the employees the knowledge and skills needed for the current and emerging tasks.

7.3. Storage, handling and retrieval of data

The BESS aimed to monitor the status and changes of the Barents Sea ecosystem to support scientific research and management advice and covered several aspects of the ecosystem from physical and chemical oceanography, pollution, phytoplankton and zooplankton to fish (both young and adults), sea mammals, benthic invertebrates, birds and interactions. Eriksen and Gjøsæter (2013) described in detail what species, areas, processes, etc. should be monitored during which seasons and what data products (assessments, etc.) should be the outcome of those investigations. Various kinds of data generated during BESS enter into the IMR and PINRO databases. All acoustic data (including raw data) are stored for later reference, but only scrutinized data (backscattering from zooplankton and fish along the acoustic transects) are stored in databases for easy access and further compilation. Chemical data, mostly emerging from water samples, are entered into a database for ocean chemistry, while physical data like temperature and salinity are stored in a database for ocean physics. Biological data are presently stored in various databases; measurements taken on fish sampled from trawl catches are stored in one database, while for instance information from plankton sampling are stored in another, and data from sighting of sea mammals and seabirds in still another. All data contained in the national databases are exchanged during and after the surveys. For more detail, see Supplementary material 2. Most data will complement existing time series, while some data belong to special investigations of limited duration. Joint data are owned by IMR and PINRO, and this joint ownership is realized through a full exchange of data during and after each survey. The storage of data types differs between IMR and PINRO, but even though the structures of the databases are different, it is possible to store practically all the data that are sampled in both database systems, and transport formats have been developed to ease the exchange of data. Although the data are split on several databases in both institutes, for instance, there is a database for acoustic data, one for biological data, another for physical and yet another for chemical data, they are linked through a common overarching database and a common user interface and use a common reference data-base. A framework including all aspects of data flow, from measurements to safe storage in databases, quality assurance and easy retrieval of data for use in estimation program has been developed at IMR through the project Sea2Data (Huse et al., 2015). Old databases are replaced by this new family of databases. This process may increase the use of data from different data sources in ecological studies.

8. Integrated ecosystem assessments and other application of data

A major output from the survey is the stock sizes of commercial and ecologically important species in the BS ecosystem. Additionally, time series of abiotic (area of Atlantic, Mixed and Arctic waters masses) and biotic (biomass of meso- and macroplankton for different water masses, non-commercial and ecologically important fish species or groups, and bio-geographical information about fish and benthos species) parameters were developed based on the BESS (reviewed by Michalsen et al., 2013).

The monitoring performed during these surveys is essential when reporting status of climate and living marine resources to the ICES working groups (Oceanic hydrography working group, Arctic Fisheries working group, working group for Northern Pelagic and Blue Whiting, working group for Regional Ecosystem Description and others), the Norwegian Management Plan for the Barents Sea, and the Joint Norwegian-Russian environmental status report (e.g., Stiansen et al., 2008). A new ICES expert group of integrated ecosystem assessment for the Barents Sea (WGIBAR, established in 2013) seeks to develop an integrated ecosystem assessment by using data from the BESS, other surveys, and 3-D physical and ecological modeling (ICES WGIBAR, 2016). In 2016, a working group for the integrated assessment of the Arctic Ocean was established by ICES in cooperation with the biodiversity working group of the Arctic Council (CAFF), the ICES/PAME Working Group on Integrated Ecosystem Assessment for the Central Arctic Ocean (WGICA). Although that group will concentrate on the central Arctic Ocean, data from the gateways from the sub-arctic seas to the Arctic Ocean are highly relevant as a basis for their work, and data from the BESS will obviously make up parts of their data in the future.

During the fourteen years of the BESS, a better understanding of the ecosystem components and processes has been obtained. In later years, this knowledge has been documented in more than 150 scientific papers and 14 survey reports. This knowledge, together with other sources of information, has been assembled in the book “The Barents Sea ecosystem, resources, management. Half a century of Russian-Norwegian cooperation” (2011, ISBN 978-8251925457). Therefore, the BESS has a high level of dissemination of results in the form of reports, stock assessments, management plans, and scientific publication. The results are also widely used in internal and external projects.

9. Summary and conclusions

The monitoring of living marine resources in the Barents Sea is a joint effort between Norway and Russia, and collaboration between the two countries has been ongoing on a regular basis since 1956. Traditional marine monitoring programs have generally focused on collecting data for the commercial fish stocks and are used in stock assessments as a basis for producing fishery management advice (recommended quotas, etc.). Stock assessment in the narrow sense (analytical assessment) is a quantitative assessment of the size of a fish stock expressed as the numbers and weights of fish in different age groups. This limits the possibilities for including additional data from the ecosystem in the stock assessment. However, the total allowable catch (TAC) is set for 1–2 years after the primary data are collected, and this requires a prognosis for stock development one to two years ahead of time in which assumptions have to be made regarding population dynamics, including recruitment (for short-lived species), growth and mortality. Management advice is based on these prognoses, and it might use relevant information about environmental biotic and abiotic aspects in the ecosystem. We know empirically that physical forcing (through changes in currents and water masses) has a strong influence on the recruitment, distribution and dynamics of fish populations. Such information can therefore, in principle, help us make better interpretations based on valid assumptions and projections.

Ecosystem monitoring (BESS) allows for ecological studies that increase the understanding of the processes at play in the Barents Sea ecosystem. The BESS is well-established and is the most comprehensive survey (spatial coverage, number of ecosystem components covered and resources used) in the world. During the 14 years of the BESS, we have obtained a better understanding of the ecosystem components and processes and knowledge has been documented in more than 200 scientific papers and 13 survey reports. During this period, many changes in the ecosystem have been documented, including changes in fish community structure (Fossheim et al., 2015), functional diversity of fish (Wiedmann et al., 2014), food web structure (Kortsch et al., 2015; Dolgov, 2016) and productivity (Eriksen et al., 2017). ICES working groups on integrated ecosystem assessment for the Barents Sea (WGIBAR) and the Arctic Ocean (WGICA, established 2016) mainly use the BESS-data, stock assessment data, and 3-D physical and ecological modeling to describe the status of the ecosystem, and based this long-term time series and knowledge, they try to explain current changes and predict further development of the ecosystem.

As mentioned above, the shift from single species to ecosystem monitoring greatly expands the knowledge base of the ecosystem. This monitoring has produced many data sets and has given us a much better understanding of the state of the Barents Sea ecosystem. Particularly, coverage of the benthic part of the ecosystem has become much better. This knowledge has yielded many scientific papers that would otherwise not have been possible (Gjøsæter et al., 2009, 2015; Fossheim et al., 2015; Jørgensen et al., 2015; Johannesen et al., 2012a, 2012b; Haug et al., 2017; Kjesbu et al., 2014). However, the broadening of the data collection comes at a cost related to increased survey time and decreased spatial resolution compared to the specialized surveys that formed the basis for the BESS. The increased survey length and decreased spatial resolution will increase the uncertainty in the fish stock estimates for all involved stocks. Both PINRO and IMR have responsibilities outside the Barents Sea, and since ship time is a limiting factor, there will always be a competition between survey activities in the Barents Sea and other areas. It is therefore important to trade off these issues in the design of the monitoring schedule and in the evaluation of activities.

It should also be emphasized that "holistic monitoring" of the Barents Sea demands more than one annual survey. Holistic monitoring implies that both spatial and temporal processes are properly resolved, to meet different needs. Such needs may be managers' need for updated annual advice on resource utilization, long-term research needs for studying trends, other researchers' need to study ecosystem processes on a finer time or spatial scale, such as seasonal variations or day/night variations, and so on. These different needs could partly be met by including additional platforms during the existing survey, but to capture seasonal variability additional surveys would have to be arranged. Additional platforms could be satellites, current rigs, drifting or stationary buoys equipped with for instance acoustics, flying drones, autonomous vessels, etc. However, surveys are still the best platform for the coverage of many components of the ecosystem, especially because no other platform has the capability to investigate such a broad range of ecosystem components at the same time.

A future monitoring program needs to utilize a combination of all these platforms, as well as numerical modeling, to be able to resolve ecosystem status and changes in the full temporal and spatial domains. In addition to ecosystem surveys, which give a better understanding of the changes in the ecosystem, we will need single species/group surveys that are dedicated to assessment purposes to obtain much higher precision for some stock estimations. Barents Sea monitoring has shown that the combination of ecosystem surveys with smaller, dedicated surveys gives the necessary support to scientific research and management advice.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.pocean.2017.09.007.

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