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Transport Programme Phase 2
Final Report

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Sammendrag / Summary

The Transport Programme Phase 2 was designed to make recommendations on monitoring in the Barents Sea region. This report provides a summary description of work performed by participating institutes and final recommendations from the programme.

Emneord:	Key words: Norwegian Arctic Contaminant transport Biological resources Monitoring

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Table of contents

1 Introduction

The main goal of the Transport Programme Phase 2 is to make recommendations on 1) where monitoring should take place and 2) what sample types (e.g. water, sediment, ice) should be collected. These objectives are a logical follow-up to the extensive work carried out during Phase 1 of the Transport and Effects Programme. Phase 2 is largely based on the background information and data resources assimilated during Phase 1. Participants from five institutes (3 Norwegian and 2 Russian institutes) have collaborated together to carry out Phase 2, supplying expertise on various aspects of this multi-disciplinary project.

The 2 main objectives were:

1. Identify key areas in the Kara and Barents Seas where priority contaminants accumulate in the environment. These areas will be identified through the use of models simulating contaminant transport under a variety of climatic conditions and source scenarios.
2. Identify monitoring locations/compartments in accordance with where contaminant pathways intersect with the primary habitat areas for polar bear, cod, and glacous gull habitats.

As a follow-on activity the project will further harmonise the locations/compartments selected in this project for the persistent organic contaminants with other ongoing monitoring programs carried out by Norway in the Kara and Barents Seas (i.e. the Norwegian Radiation Protection Authority programme to monitor radioactivity in northern seas and the Institute of Marine Research fisheries monitoring programme). This work will be described in a future report after completion.

The recommendations developed through this programme include built-in flexibility in recognition of the current lack of data on all aspects of the Arctic and the fact that the system itself is subject to a variety of short- and long- term perturbations (e.g. North Atlantic Oscillation, global change etc.).

2 Project Description

Project activities have been carried out by five organizations as summarized in Table 1. A brief description of the associated activities of each main partner is given below as well.

Table 1: Summary of project partners and activities.

MAIN PARTNERS	Contacts (Capacity & Role)
Akvaplan-niva (APN)	JoLynn Carroll, habitat assessment, assessment of HCH's, project integration
Norwegian Polar Institute (NPI)	Vladimir Pavlov, sea ice contaminant transport pathways
Institute of Marine Research (IMR)	Paul Budgell, ocean modelling of contaminant transport
Murmansk Marine Biological Institute	Dimitry Matishov, habitat assessment
Arctic and Antarctic Research Institute	Water exchanges and circulation patterns - historical data evaluation

1. <u>Assessment of HCH's and habitat assessment (APN)</u>

Data on hexachlorocyclohexanes were collected and evaluated for use in model validation studies carried out by IMR. A large body of research was collected from literature sources for the evaluation of Arctic Ocean HCH budgets. The evaluation of the data included assessments of the behaviour (transport pathways and loss terms) and distribution patterns (temporal trends, spatial trends, vertical resolution, basin-wide distribution). The results of the investigation were summarised in a comprehensive report and provided to IMR together with the compilation data set on HCH concentrations in the region of interest.

Information on the core habitat areas for selected species (polar bear, cod, glacous gull) were assembled from available sources. The primary data resources used for the compilation include routine national monitoring programmes and nature conservation assessments. These data were used to define relationships between critical habitats and major pathways of contaminant transport in the region of interest.

2. Sea ice fluxes and contaminant pathways (NPI)

In this work we estimate sea ice area flux through the boundaries of the Arctic Seas and calculate trajectories of sea ice transport from regions of potential pollution sources in the Arctic Ocean using velocity vectors of ice drift and ice concentration that obtained as a result of modelling. The Ice Statistical Model (ISMO) was used to the estimation of the ice flux through the all main straits of the marginal seas of the Arctic Ocean. These estimates are based on the modelling results for ice concentration and ice drift during the period 1966-2000. We applied ISMO to the simulation of the seasonal and interannual variability of the ice conditions in the Arctic Ocean. Implementation of this model allows us to simulate ice conditions not only for the period when satellite observations were available, but also for the decades when such observations were absent. It was shown that the estimation of sea ice exchange between the Arctic seas and Polar Basin obtained from the ISMO calculations can be used in a simulation of the transport of pollutants by sea ice. To estimate the approximate drift route of the sea ice from the areas containing potential sources of pollution in the Arctic Ocean, trajectories of the ice drift from several locations were simulated. These calculated trajectories allow us to evaluate the character of pollutant transport and the areas of their release and redistribution. For these simulations the reconstructed ice drift data for the period 1899-2000 were used. Based on an analysis of the most probable routes of ice drift from all selected potential sources of pollution, the most representative places for monitoring contaminants were proposed.

3. Ocean modelling of contaminant distributions (IMR)

Simulations of contaminant transport in the northern seas were conducted for a 55-year period using archived circulation and ice fields in an off-line version of the Regional Ocean Modelling System. 99Tc and α-HCH concentrations were computed for a region including the North Atlantic and Arctic Oceans.

4. Habitat assessment 2 (MMBI)

Murmansk Marine Biological Institute assisted APN in the collection, analysis and interpretation of data on biological habitats with particular emphasis on Russian data sources and information.

5. Assessments of archived oceanographic data (AARI)

Two investigations in support of the other modelling activities were conducted. The purpose of these investigations was to use real-time historical records to ground-truth the results of the various model simulations. Project 1 focused on an evaluation of data records collected by and archived within AARI for selected areas of the Arctic Ocean and Nordic Seas in order to look at the spatial and temporal variations in water mass characteristics and volume exchanges in selected areas. Project 2 used AARI data records to examine seasonal and multi-year variability of water thermohaline characteristics in the Greenland Sea. The results of both projects were used to evaluate and improve the model results obtained by IMR and NPI.

3 Results

Detailed results from each of the individual project components are presented as separate reports prepared by the individual institutes. A brief description of the main results from each project component is presented in Table 2 below.

Table 2: List of project reports from all partners.

MAIN PARTNERS	ACTIVITY	REPORT
Akvaplan-niva (APN)	Assessment of HCH/Habitat assessment	1
Norwegian Polar Institute (NPI)	Sea ice flux and contaminant transport	2
Institute of Marine Research (IMR)	Oceanographic contaminant transport	3
Murmansk Marine Biological Institute	Habitat assessment	4
Arctic and Antarctic Research Institute	Historical data interpretation	5

1. Assessment of HCH's and habitat assessment 1 (APN and MMBI)

Assessment of HCH's

A large body of research has been compiled on the existing HCH budgets for the Arctic Ocean and when identifying entry pathways and loss terms. A summary of relevant review articles for HCH modelling of the Arctic Ocean waters was compiled within this part of the project. This assessment indicates the following:

- HCHs are relatively volatile, partition into the dissolved phase of seawater (low bio-accumulation potential), but accumulate to some degree in sediments (highly productive areas). For first order modelling purposes, they can be regarded as conservative tracers.
- Arctic water HCH concentrations are a magnitude higher than in the source waters. This is a result of that HCH volatilises soon after application, and is transported pole-ward along the 'cold condensation' route.
- Oceanic HCH concentrations increase pole-ward and from the Canadian Basin towards the Canadian Archipelago. The enhancement effect is a result of water mass residence times, and the effect of ice coverage on air-sea exchange.
- Since the ban in usage of technical HCH, a considerable drop in atmospheric α-HCH has been observed. The drop is step-wise, once in the 1982/1983 and in 1990/1992. A similar but less pronounced trend is observed for γ-HCH. This is due to present usage of lindane as insecticide.
- Ocean surface levels of α- and γ-HCH concentrations have remain stable over the same time period. Vertical profiles show a rapid decline in concentration with depth.

- As a result of decreased atmospheric levels of α-HCH, Canadian arctic waters are now believed to be a source of α-HCH to the atmosphere, while α-HCH fluxes in waters of Atlantic origin are in near-equilibrium. γ-HCH appears to be in equilibrium between the reservoirs in the Arctic Ocean as a whole.
- Ratios of α-HCH/γ-HCH and α-HCH/β-HCH together with concentrations of each isomer are useful source indicators. The ratio in technical HCH lies between 3-7 and 5-11 for α-/γ-HCH and α-/β-HCH, respectively. The α-/γ-HCH ratio is observed to increase pole-ward, only to decrease on the Atlantic side as a result of present usage of lindane in this region.
- Enantiomeric ratios between (+)- and (-)-α-HCH, i.e. ER(+) and ER(-), are useful tracers for distinguishing between abiotic and biotic processes. The ratio is altered as a result of biological modification, but remains unaffected by purely abiotic processes. Not enough quantitative data available as yet.
- HCH enters the Arctic Ocean via atmospheric and oceanic transport and with river runoff.
- Loss terms for HCH are: 1) Through outflow of water masses through Fram Strait, the Canadian Archipelago and the Barents Sea, 2) Air-sea gas exchange, 3) Hydrolysis and microbial degradation, and 4) Ice export via the water exit routes. Though a net reversal in gas exchange across the air-sea interface has occurred in later years, volatilisation is regarded a minor loss-term. Ice export is also regarded a minor loss-term.
- The physical-chemical properties govern the fate of HCH in delivery and transformation processes.
- The key physico-chemical properties governing the fate of HCH are 1) Vapour pressure, 2) Henry's law constant, 3) Partitioning coefficients (K_{oa}, K_{ow}, K_{oc}). The properties are temperature dependent, a factor that needs to be taken into account in modelling work.

Habitat Assessment

a) Glacous gull- data were provided by the Norwegian Polar Institute[1]. These birds are found throughout the Barents Sea region and colonies have been identified on all surrounding landmasses of the Barents Sea.

b) Atlantic cod are important to commercial fisheries in the Barents Sea and the stocks are monitored on a regular basis by the Institute of Marine Research. Critical areas for Atlantic cod are the spawning grounds and larval distribution areas, particularly during the April-July time period. These areas are located along the entire northern coast of Norway, from the Lofoten Islands northward.

c) Polar Bear- The habitat of the Polar Bear is based on assessments of nature conservation at Svalbard. Polar Bears roam the entire northern and eastern Barents Sea region. Critical denning areas have been identified on Svalbard.

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[1] SCRIB 2004. Seabird Colony Registry of the Barents and White Seas. Unpublished database. Norwegian Polar Institute.

2. Sea ice contaminant pathways (NPI)

Comparison of the ISMO results with the observational data and simulating results obtained from the other models have shown that ISMO gives quite realistic estimations of the sea ice conditions in the Arctic Ocean and Nordic seas, and can also be used for reconstruction of the vectors of ice drift and ice concentration.

Based on the reconstructions of the sea ice drift and sea ice concentration for the period 1966-2000, seasonal and interannual variability of the ice fluxes through the main straits of the Arctic Ocean were simulated and analysed. The sea ice flux through the all straits has a strong seasonal variability. The maximum amplitude of the annual cycle is in Fram Strait (about 2500 km^2/day), and the minimum is in the strait between Svalbard and Franz Josef Land (270 km^2/day). In almost all the straits the ice fluxes are sharply decreased in the summer time but keep their direction during the whole year. Ice flux from the Chukchi Sea has opposite directions in winter and summer.

The difference between the annual mean ice fluxes through Fram Strait estimated by ISMO and most previous estimations is 0.1-30 %. The difference between estimations for Transects 2, 3 and 4 ranges from 2 to 21 %. Analysis of interannual variability has shown that only in the East Siberian and Chukchi seas is there a change in the direction of ice flux during the simulation period. Such changes in the Chukchi Sea occurred every 5-7 yr. In the others straits winter ice flux does not change its direction.

The calculated trajectories of ice drift from areas of potential sources of pollution allow us to evaluate the character of pollutant transport and the areas of their release and redistribution. The simulation of backward trajectories allows us to reveal the probable area of the origin of a contaminant. From the results of the ISMO simulation we can conclude that sea ice from most potential sources of contaminant can reach the open Polar Basin and Fram Strait. Contaminated sea ice from potential sources in the Kara and Laptev seas can reach Fram Strait within 2-4 yr, and from the East Siberian, Chukchi and Beaufort seas within 6-11 yr. Analysis of the interannual variability of the sea ice travel time, for example from the Mackenzie river to Fram Strait has shown a significant positive trend in the last century.

The results of the simulation can also give useful information for the selection of the most representative areas for monitoring contaminants in the Arctic Ocean. Based on simulated trajectories from different potential sources in the Arctic Ocean we can conclude that most important region for monitoring of contaminants are Fram Strait and Barents Sea Opening.

3. Ocean modelling of contaminant distributions (IMR)

The simulated ^{99}Tc distributions are quite realistic and provide us with some confidence that the transport portion of the model system is performing well. Results could be significantly improved by using higher resolution velocity fields, such as from the 20-km hindcast simulation that is now underway. Radionuclides discharged into the marine environment in northern Europe will likely have their strongest signature in the narrow, jet-like, portion of the Norwegian Coastal Current in the vicinity of the Lofoten Islands. Thus, that area is a good candidate for radionuclide monitoring.

The α–HCH simulation provides useful insight into possible transport pathways in the northern seas, but does not, at present, provide realistic concentration levels for that contaminant. Uncertainties in the atmospheric and boundary forcing are probably contributors to the lack of agreement between model and observations. Both model and observations indicate that α-HCH concentrations are low in the Barents Sea. However, the model simulation indicates the presence of a very strong seasonal cycle during most years with winter values typically 5 times those in summer. Because of this, it is recommended that POP monitoring programmes in the Barents Sea include winter sampling.

4. Assessments of archived oceanographic data (AARI)

Data from 427 871 oceanographic stations for the years 1894-2001 were integrated into an electronic archive for the years 1894-2001. Statistical calculations of the thermohaline characteristics were conducted further for each region separately for determination of the cold and warm seasons. Graphs were constructed of interannual variations of temperature and salinity, and heat content for the warm and cold seasons separately for each region. TS-diagrams of dispersion and average statistical TS-curves were constructed for each region.

Analysis of the within-year variability of temperature and salinity within the limits of the regions allows us to make the following conclusions:

- Gradual deepening of the kernel of the Atlantic waters happens in the process of their movement to the North, their temperature and salinity decrease;
- Temporal temperature distribution within the layer of the Atlantic waters is characterized by a clearly pronounced bimodal distribution, i.e. presence of two temperature maximums and three minimums;
- While moving along the Atlantic water stream to the North, the winter – spring temperature maximum shifts from March to February;
- While depth increases, the summer – autumn temperature maximum (salinity minimum) shifts from August at the surface horizons, to September at the subsurface ones and to October – November and even December at more deeper horizons;
- Phenomenon of separation of the temperature and salinity kernels of the Atlantic waters is registered; maximum salinity values are always located deeper than temperature maximum for 50 – 250 m.

Analysis of the within-year mean multiyear temperature and salinity variability within the limits of the regions exerted by influence of the stream of the Arctic surface and reverse Atlantic waters allows us to make the following conclusions:

- Polymodal temporal temperature distribution is typical for these regions, i.e. presence of several minimums and maximums.
- Two minimums are marked out in salinity distribution – in May and the main one in September-November.

Analysis of the within-year mean multiyear temperature and salinity variability within the limits of the so called “cupola” of the bottom waters allows us to make the following conclusions:

- The most interesting specific features of this region are a cupola-shaped rise of the bottom and deep waters of the Greenland Sea and processes of convection and ventilation of the near-bottom layers related with this rise. The rise of the bottom and deep waters is supported by the barotropic cyclone circulation that is characterized by strong within-year variations caused by seasonal variability of atmospheric circulation and energy redistribution processes between the atmosphere and ocean.

- The thermohaline characteristics of all the waters in this region are subjected to significant changes depending on season and are very complicated.
- One minimum and one maximum can be marked out at the spatial-temporal temperature section in the surface layer. The minimum has extreme on the surface (temperature less than -1.3°C) in March. A spatial-temporal heterogeneity is marked out in the layer 200 – 300 m related with the income of cold freshened waters. Salinity minimum is marked out in July at 20-30m.

Multi-year trends for the winter and summer seasons were calculated for the continuous and partly restored series. Analysis of the trend temperature variations allows us to make the following conclusions:

- Temperature increased in all the regions under consideration in summer. Thickness of the surface layer with temperature growth depended on region. Temperature increased in the entire water column from the surface to bottom in regions 6, 11, and 15 during the whole period of observations.
- While going from summer to winter, sign of the temperature trend in the surface layers varied to the opposite one in the regions related with propagation of the Atlantic waters. Temperature decreased during the whole period of observations.
- Maximum values of the positive temperature trend varied from 0.96°C to 2.39°C. They equal 1.59°C on average.
- Maximum temperature fall in regions 5, 8-9, and 12 was in the layer 750 – 800 m. It was equal on average -0.54°C. Maximum temperature fall in region 7 was at 250 m, and in region 13 – at 5 m.
- The negative temperature trend in region 13 in the surface layers can characterize, in our opinion, temperature tendency in the stream of the Arctic surface waters (we were not able to construct the temporal series for these regions).

Combined analysis of the spatial-temporal sections of temperature and salinity in the regions of propagation of the Arctic surface and Atlantic waters testifies that:

- The GSA, which kernel was registered on the surface in region 13 in 1965 manifests itself twice in the region of the Atlantic water propagation (region 12), after 2 years in 1967, and after 10-14 years in 1974 and 1979.
- The GSA of the 80-90s resulted in the significant freshening of the surface waters appeared in region 13 in 1985 – 1993, and its appearance in region 12 was registered in 1988 – 1989 and in 1993 – 1998 (kernel in 1997).
- Delay of beginning of the both salinity anomalies in region 12 in respect to region 13 testifies that the salinity anomalies in the 60-s and 80-90-s came into the Greenland Sea from the Arctic Basin.
- Duplicated manifestation of the large-scale spatial-temporal anomalies in the region of the Atlantic water propagation testifies that there are two routes of the recycling: the short one within the North European Basin, and the long one – within the limits of the North Atlantic (9-14 years).

- Probable explanation is obtained for manifestation of the quasi-cyclic variations of the thermohaline characteristics in the Greenland Sea; latent periodicities in parameter variations are formed depending on the passage route of the anomalies of different sign.
- The maximum multi-year variability of the parameters is concentrated in the surface layers, its intensity significantly decreases with depth increase, and it does not practically manifest itself at greater depths.

4 Discussion

The results of this project provide a basis for making recommendations for the design of a long-term marine monitoring programme for the Barents Sea. Key monitoring areas are to be identified where priority contaminants are likely to accumulate in the environment and where monitoring should therefore take place. With respect to the abiotic environment, conclusions for monitoring locations/compartments are based on (1) modelling of pollutant transport in water and ice in order to simulate contaminant transport under a variety of climatic conditions and source scenarios and (2) through a comparison of the modelling results with the locations of key habitat areas for important species. This assessment of the above diverse sources of information has resulted in the following key findings:

1. The habitat of Atlantic cod, glacous gull and polar bear extends throughout the Barents Sea region. Areas where the rearing of young occurs are important. For cod, this corresponds to the coastal region along northern Norway, north of Lofoten Islands. For glacous gull this corresponds to colonies located along all perimeter coastlines of the Barents Sea. Polar bears dens are observed on the island archipelago of Svalbard as well as on Novaya Zemlya.
2. Sea Ice produced in areas along the Russian coastline is a purveyor of contaminants. The primary source of sea ice into the Barents Sea is along a pathway originating in the Kara Sea. The Fram Strait region, west of Svalbard is the main exchange pathway into and out of the Arctic Ocean. Sea ice from source regions throughout the circumpolar Arctic Ocean are transported along trajectories ending in the Fram Strait. Thus Fram Strait is a major convergence zone for sea ice and the melting of sea ice in this region leads to the release of particles and water with associated contaminants. For the Barents Sea therefore, the region northwest of Novaya Zemlya and between Northern Greenland and Svalbard are focus areas for the transport of contaminants by sea ice.
3. Sea ice is also important due to the formation of Marginal Ice Zones (MIZ). MIZ areas are associated with some of the most productive ecosystems in the world. In the Barents Sea, the MIZ occurs across a vast area (see Figure 1). Its location is a function of large interannual variations in sea ice extent. High bioproduction in the Barents Sea is due to several factors including (1) high annual primary productivity in close association with the receding ice edge, (2) advection of large herbivorous zooplankton from the Norwegian Sea into the Barents Sea, and (3) transport of ice fauna by the Transpolar Drift from the Arctic Ocean into the Barents Sea.
4. Numerical simulations of contaminant transport in the Northern Seas indicate that α-HCH concentrations are relatively low in the Barents Sea region. However, concentrations can be 5 times higher during winter than in summer in the Barents Sea.

5. Trend variations of salinity and temperature with depth and from season to season exhibit highly variable and complex patterns. Thus it should be expected that time series of monitoring data will reflect the large interannual variations in oceanographic conditions.
6. The trends of long series temperature and salinity reflect climate variations. Observed positive temperature trends in the surface layers reflect general climate warming in the Northern hemisphere and the well-known intensification of incoming water of Atlantic origin during the 80s – 90s.

5 Recommendations

Appropriate monitoring locations for abiotic environmental compartments are suggested based on,

- knowledge of key habitats for polar bear, glacous gull, and Atlantic cod,
- contaminant concentrations are found in low levels throughout the Barents Sea,
- main transport pathways into and out of the Barents Sea
- zone of high productivity located in the marginal ice zone.

1. We recommend a minimum of 10 monitoring stations every 3 years during spring for regular monitoring (See map below).
2. Regular monitoring should be performed on seawater, bottom sediments, air and sea ice.
3. Because concentrations of volatile persistent organic pollutants are higher during winter than in summer in the Barents Sea, monitoring of volatile POPs should be periodically performed during the winter season. We recommend a minimum of 3 monitoring stations every 6 years for this purpose. Seawater and air samples should be collected.
4. A list of specific contaminants is not presented in this report as the decision should correspond with contaminants chosen for biological samples.
5. For sediment sampling stations, we recommend that grain size analysis and organic carbon content be carried out. Sedimentation rates should be determined at each monitoring station the first year and thereafter, every 3rd sampling time period (e.g. every 9 years). Salinity and temperature measurements should be made for water samples and a CTD profile should be collected at each monitoring station during sampling expeditions.
6. Methods to be used for all analyses should be taken from appropriate international guidelines with priority of the Arctic Monitoring and Assessment Programme. See also the report at: http://npolar.no/transeff/Effects/Monitoring/Monitoring-APN.htm