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1. Executive summary

The overall objective of AMOC was to develop and design an acoustic system for long-term monitoring of the ocean temperature and ice thickness in the Arctic Ocean, including the Fram Strait, for climate variability studies and global warming detection. The background for testing acoustic propagation for climate monitoring in the Arctic Ocean is the results from climate modelling studies which suggest that the Arctic region will show the strongest atmospheric warming in response to increased greenhouse warming (i.e. Manabe et al., 1992). This can furthermore cause a melting of sea ice (Vinnikov et al., 1999; Johannessen et al. 1999) and warming of the Atlantic water which flows into the Arctic ocean. Evidence for reduction of the Arctic sea ice over the last few decades have been presented by Johannessen et al. (1999) based on satellite data analyses and by Rothrock et al., (1999) who have analysed submarine ice draft data. Acoustical techniques can be used to observe average temperature changes over large distances in the Arctic Ocean. This has been demonstrated in the pilot Transarctic Acoustic Propagation experiment (TAP) where long range propagation (2600 km) across the Arctic Ocean was carried out using a low frequency source of 20 Hz (Mikhalevsky et al., 1999).

AMOC is feasibility study based on climate and acoustic model experiments and is complementary to the real experiments carried out in TAP. The approach of AMOC was to study detection and quantification of warming in the Arctic Ocean, using gyre scale acoustic long range propagation for measuring basin wide ocean temperature and ice thickness changes. Predicted climate change scenarios until 2050 have been used as input to acoustical models in order to assess the capability of using acoustical travel time to measure small changes in average temperature expected in the next few decades in the Arctic Ocean. Acoustic propagation, which has been successfully tested for climate monitoring in other oceans (Munk et al., 1995), can be an important component in detection of global warming because the method gives an average estimate of temperature change in the area between source and receiver. A future acoustical monitoring system should consider the following recommendations:

- Propagation paths between source and receiver must avoid shelf areas and other bathymetric effects at water depths shallower than 1500 m.
- Sufficient signal to noise ratio, which does not require post processing, can be achieved by using a transmission level of 160 db in Fram strait and 180 - 195 db in the interior of the Arctic, depending on frequency.
- Deployment depth of source is a crucial factor for successful transmission. In the Arctic Basin relevant source deployment depths should be at 500 m or deeper to capture mode 2 and 3 waves propagation through the Atlantic water masses. Shallow source deployment in the upper water masses will not capture the expected warming of the Atlantic water which is predicted by the climate model simulations.
- For the Fram Strait our result shows that both a deep and a shallow source will provide information about the mean temperature of the water masses. A deep source gives the best results for long term monitoring of the climate, while the shallow source will provide information about the seasonal changes in the upper water masses. Due to strong mesoscale eddy activity, it can be difficult to separate arrival times of the different rays for every transmission. However the simulations show that there are enough deep going rays which can be recognised to observe long-term changes in temperature.
- Choice of frequency must be adapted to the parameters to be observed. For ocean temperature observations 20 Hz can be used for propagation across the whole Arctic with minimum influence of sea ice. To observe ice thickness frequencies from 100 to 5000 Hz can used to obtain regional estimates. In the Fram strait it is possible to use higher frequencies, especially in the ice-free part (West-Spitzbergen Current).

The project has demonstrated that acoustic transmission data can be used to observe long-term changes in temperatures in the Arctic Ocean. The acoustical system should be used in combination with remote sensing from satellites, in situ observations and ice-ocean models.

2. Introduction

The overall objective of AMOC was to develop and design an acoustic system for long-term monitoring of the ocean temperature and ice thickness in the Arctic Ocean, including the Fram Strait, for climate variability studies and global warming detection.

The unique combination of underwater acoustic propagation, investigated in the AMOC project, satellite remote sensing and ocean climate modelling offers an innovative solution to monitor and predict climate change. AMOC consists of three main elements: use of existing ice-ocean data for the Arctic, climate simulation modelling and use of several acoustical models and methods.

Task 1: Data compilation and analysis: Compilation and analysis of existing ocean and ice data (i.e. temperature, salinity and speed of sound fields, ice thickness, concentration and extent) from the Arctic Ocean for use in climate and acoustic models. The work has been carried out by Nansen Environmental and Remote Sensing Center with contribution form the other `

Task 2: Climate and ice modelling: Simulation of present and future ocean temperature, salinity and speed of sound fields, ice thickness, concentration and extent in the Arctic Ocean, caused by natural variability and global warming scenarios, to be used as input to acoustic modelling. The work was carried out by the Max Planck Institute of Meteorology.

Task 3: Acoustic modelling of the Arctic basin: Simulation of present and future basin-wide acoustic propagation using natural variability and global warming scenarios (from climate and ice modelling) to investigate the sensitivity of acoustic methods for global warming detection Institute. The work has been carried out by Nansen Environmental and Remote Sensing Center with contribution from Scott Polar Research Institute

Task 4. Acoustic modelling of the Fram Strait: Simulation of present and future acoustic propagation in the Fram Strait to investigate the sensitivity of acoustic methods for monitoring heat and volume fluxes in an area of strong mesoscale eddy activity. The work has been carried out by Nansen Environmental and Remote Sensing Center with contribution form Nansen International Environmental and Remote Sensing Center in St. Petersburg, Russia..

Task 5: Design of a long-term monitoring system for the Arctic Ocean: an optimal acoustic monitoring system for climate change detection in the Arctic Ocean and the Fram Strait is proposed based on the results from tasks 1 - 4. This system is recommended for testing in a future project. This work is carried out by Nansen Environmental and Remote Sensing Center.

The links between the tasks of AMOC are shown in Fig. 1. Task 1 has compiled and delivered input data for model runs in the other tasks. A selection of high quality data was prepared as input for underwater acoustic propagation models, and was made available to analysts and modellers working on the project. Input from other data sources were also used, such as atmospheric forcing fields which were used to drive the climate model in Task 2. The output fields from the climate model (ice extent and thickness, ocean temperatures, salinity, speed of sound) were used as input to the various acoustical models which were used in the Arctic Ocean (Task 3) and in the Fram Strait (Task 4).

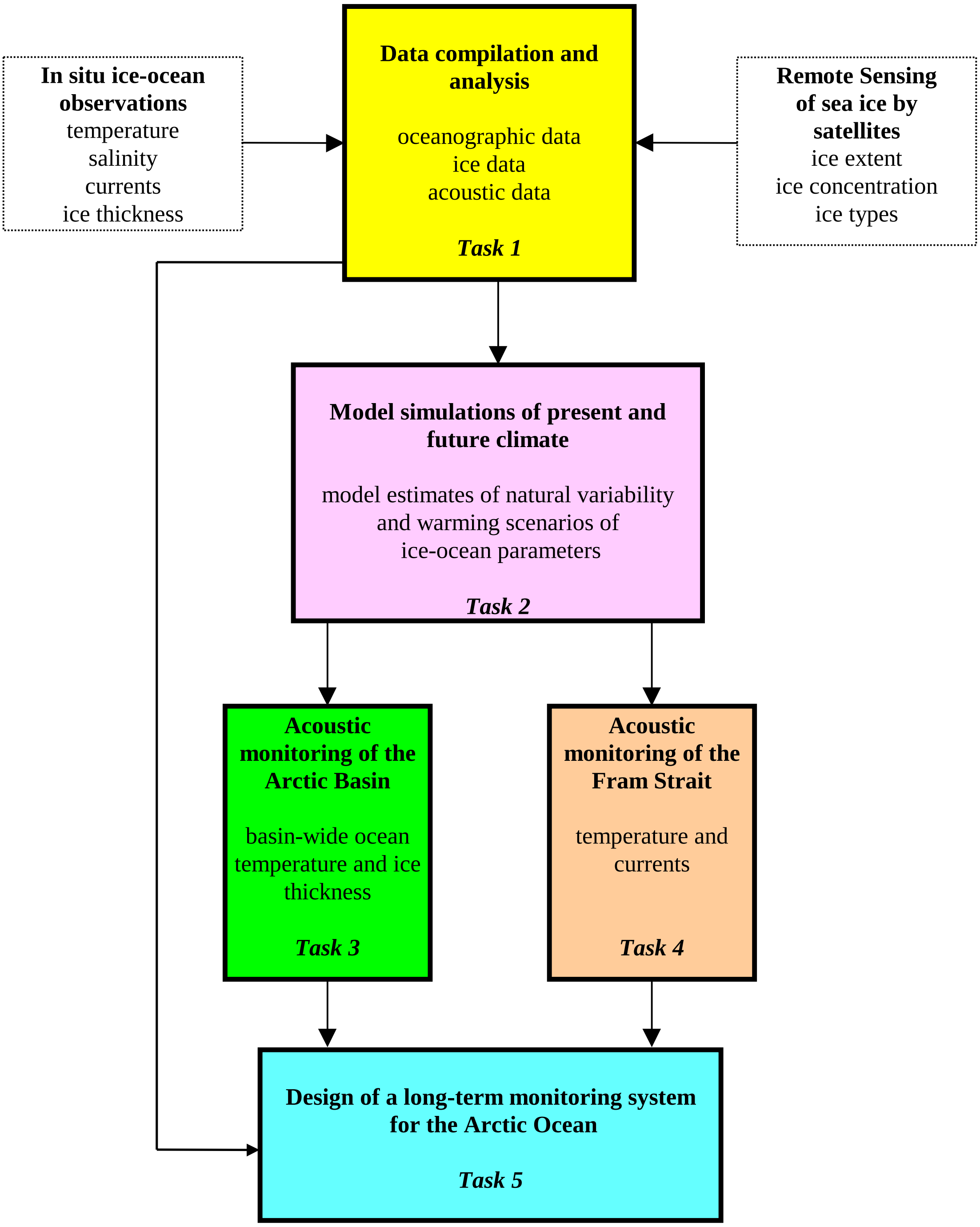


Figure 1. The links between the tasks of AMOC

3. Data compilation and analysis (Task 1)

The goal of this task has been to

4. Collect and document available data on ocean temperature, salinity, density, speed of sound, ice thickness, ice concentration, ice extent and acoustical in the Arctic Ocean and the Fram Strait
5. Generate input data for the numerical modelling work in Task 2, 3 and 4

The most important oceanographical data sets used in the study is the Joint US - Russian Atlas of the Arctic Ocean which contains temperature, salinity, density, mixed-layer depth, dynamic height and bathymetry from hydrographical stations over the period 1950 - 1990 (Environmental Data Group, 1997, 1998). Example of surface data are shown in Fig. 2.

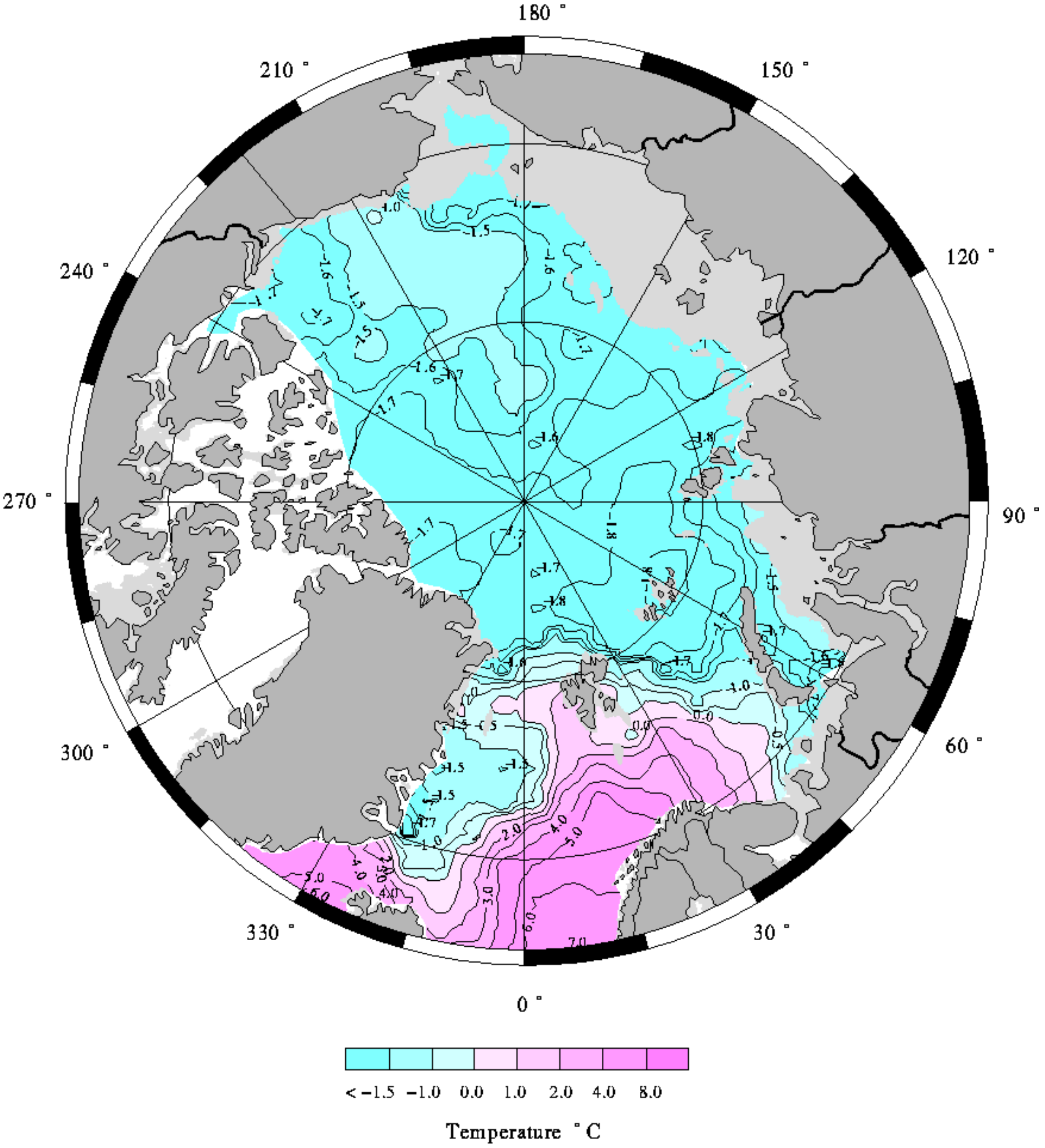


Figure 2. Example of ocean temperature data at 50 m depth from the Environmental Working Group Joint U.S. Russian Atlas of the Arctic Ocean. The data, which are presented

in 100 x 100 km grid, are mean values for the winter months of the from the 1980s.

The data are available in grids from 50 to 200 km, averaged over decades for winter (March - May) and summer (July - September). Supplementary data have been the CEAREX database, which mainly covers the Fram Strait and Greenland Sea area (Eastern Arctic Ice, Ocean and Atmospheric Data, 1991), and the high-resolution sections obtained by towed Seasoar on R/V Håkon Mosby in the Fram Strait area (Johannessen and Jensen, 1997a,b). Examples of averaged vertical profiles of temperature are shown in Figure 3 for the Fram Strait and North Pole area, respectively. A characteristic feature in both regions is the core of warm Atlantic water between 100 and 600 m depth. It is also noteworthy that the variability of temperature is much larger in the Fram Strait compared to the interior of the Arctic Ocean, which has important impact on the acoustic transmission in the two regions.

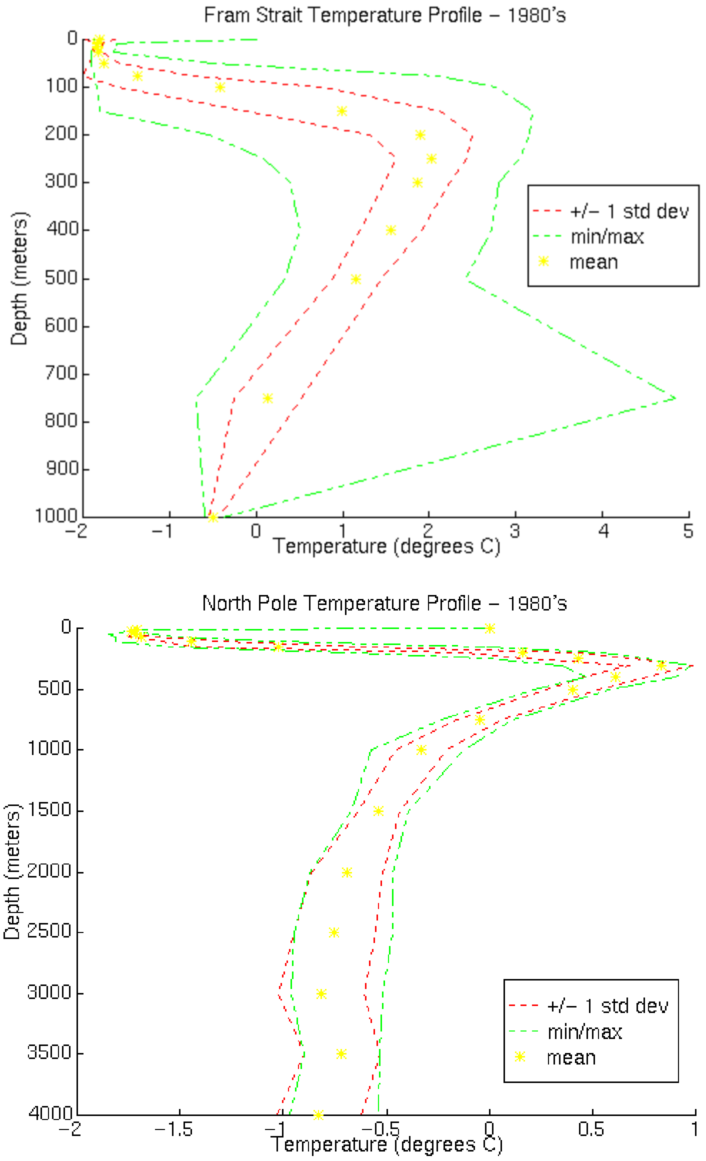


Figure 3. Examples of vertical temperature profiles the Fram Strait (upper) and the North Pole area (lower) Data are taken from the Environmental Working Group Joint U.S. Russian

Atlas of the Arctic Ocean.

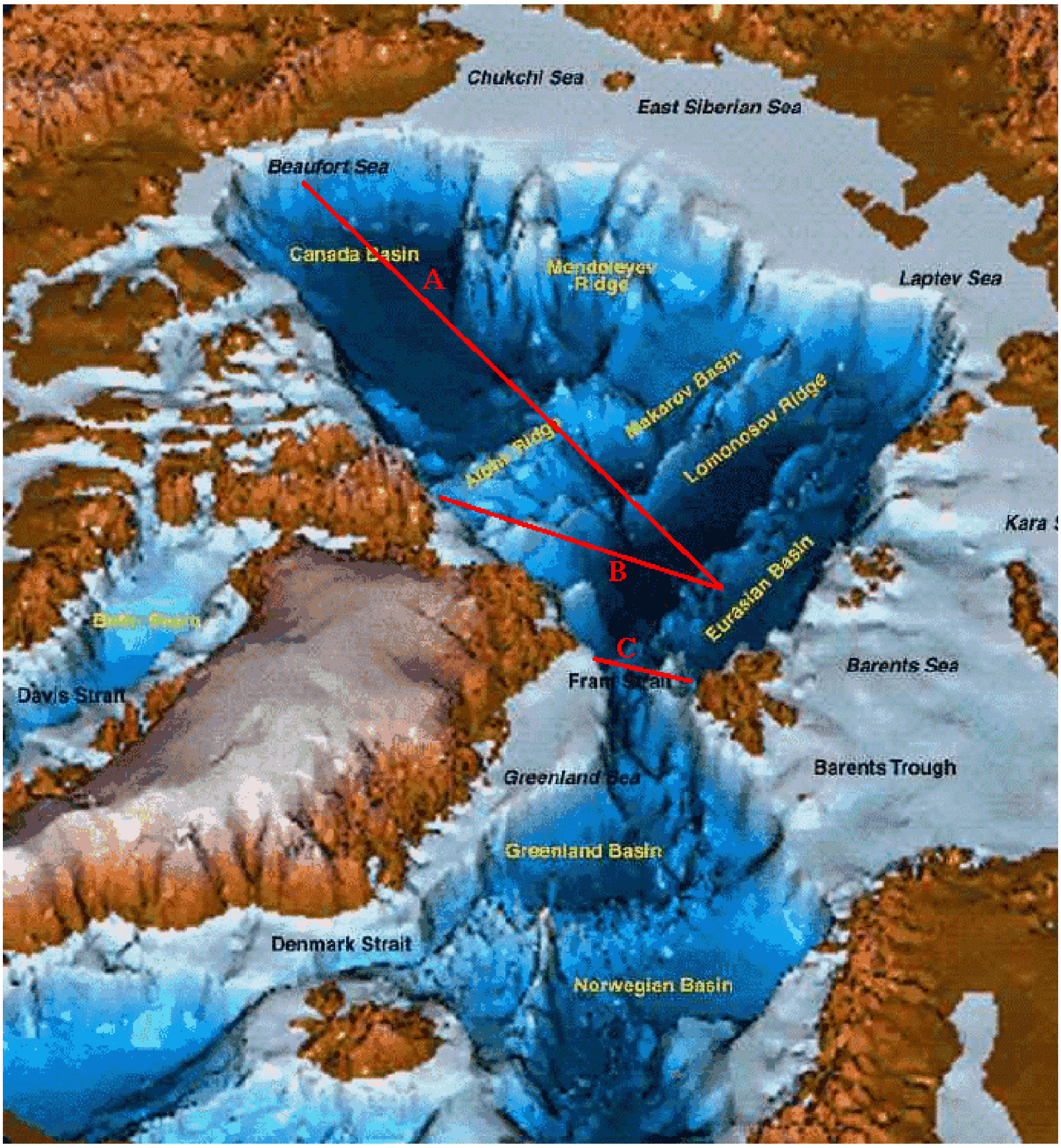


Figure 4. Bathymetry of the Arctic Ocean with the surrounding seas. Profiles TAP-A, B and C are overlaid as red lines.

Ice thickness data have been obtained from submarine cruises (Wadhams, 1998), while atmospheric fields have been obtained from NCEP/NCAR Reanalysis Project (NCEP, 1997). Bathymetry data are important for modelling of the acoustic propagation. The shallow shelf areas around the deep Arctic Ocean, with bottom depths of 200 m and less, is not suitable for long-range acoustic propagation because of reflection loss by bottom sediments. Therefore, the acoustical modelling has focused on three sections, all of them are located in the deep parts of the Arctic Ocean, along the lines marked A, B and C in Fig. 4.

4. Simulation of present and future Arctic Ocean climate (Task 2)

The goal of this task has been to establish 3-D fields of present and future climate scenarios in order to 1) estimate the expected warming in the Arctic Ocean and Fram Strait up to 2050; and 2) use these fields as input to acoustic propagation modeling in Task 3 and 4.

The climate modeling work has been performed at Max Planck institute using the high resolution Hamburg Ocean Primitive Equation (HOPE) model. The model has been used with typically 50 km resolution and 40 vertical levels in the Arctic Ocean. Simulations have been run for 100 years (1950 - 2050) using an anthropogenic forcing scenario with prescribed increase in greenhouse gases, and a control run with fixed concentration of greenhouse gases at 1990 level. The forcing fields are taken from the existing ECHAM/OPYC coupled simulations. The coupled ice-ocean model contains a sea ice model using Hibler's viscous-plastic rheology. The overall model output from the 100 year simulations is of order 30 Gbyte for each run after producing monthly means. Input data to the acoustic modelling have been taken along a few vertical sections: one in the Fram Strait and some crossing the deep Arctic Basin.

An example of model output is annual mean ice volume and extent for the 100 year period, shown in Fig. 5. The anthropogenic forcing experiment shows a trend of reduction in ice volume and extent from about 1980 until the end of the experiment in 2050. The control run shows interannual variability but no significant trend. The reduction of about 2.5 % per decade from 1978 - 1998 is in good agreement with satellite ice observations showing about 3 % reduction per decade (Johannessen et al., 1999).

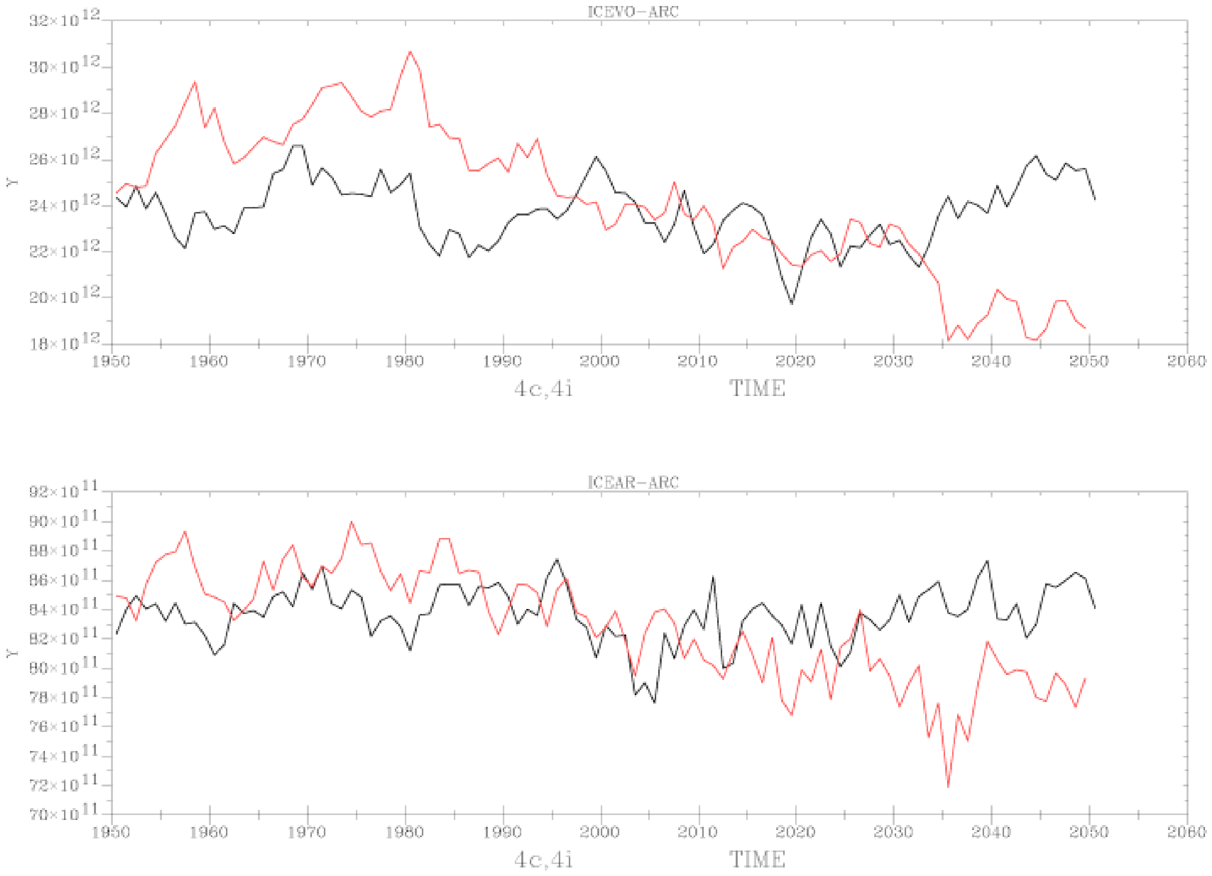


Figure 5. Time series of annual mean ice volume (upper)in units of m^3 *and ice extent (lower) in units of* m^2 *of the Arctic sea ice. Black line corresponds to the control run, red line is for*

the anthropogenic forcing experiment.

The regional distribution of the predicted decrease in ice extent can be studied by estimating the difference in mean annual ice concentration between 2020-2039 and 1980-1999 for each model grid and plot the results on a map (Fig. 6). The most significant reduction is found in the Greenland and Barents sea region (- 30 %). Also the Kara Sea region, Bering Sea and Sea of Okhotsk show reductions of more than 30 %. In general the reduction is strongest in summer and close to the ice edge. The interior of the Arctic Ocean shows no significant reduction. The control run shows no clear changes in ice concentration, except for a decrease in the Barents Sea (- 10%) and an increase around Greenland (+ 10%).

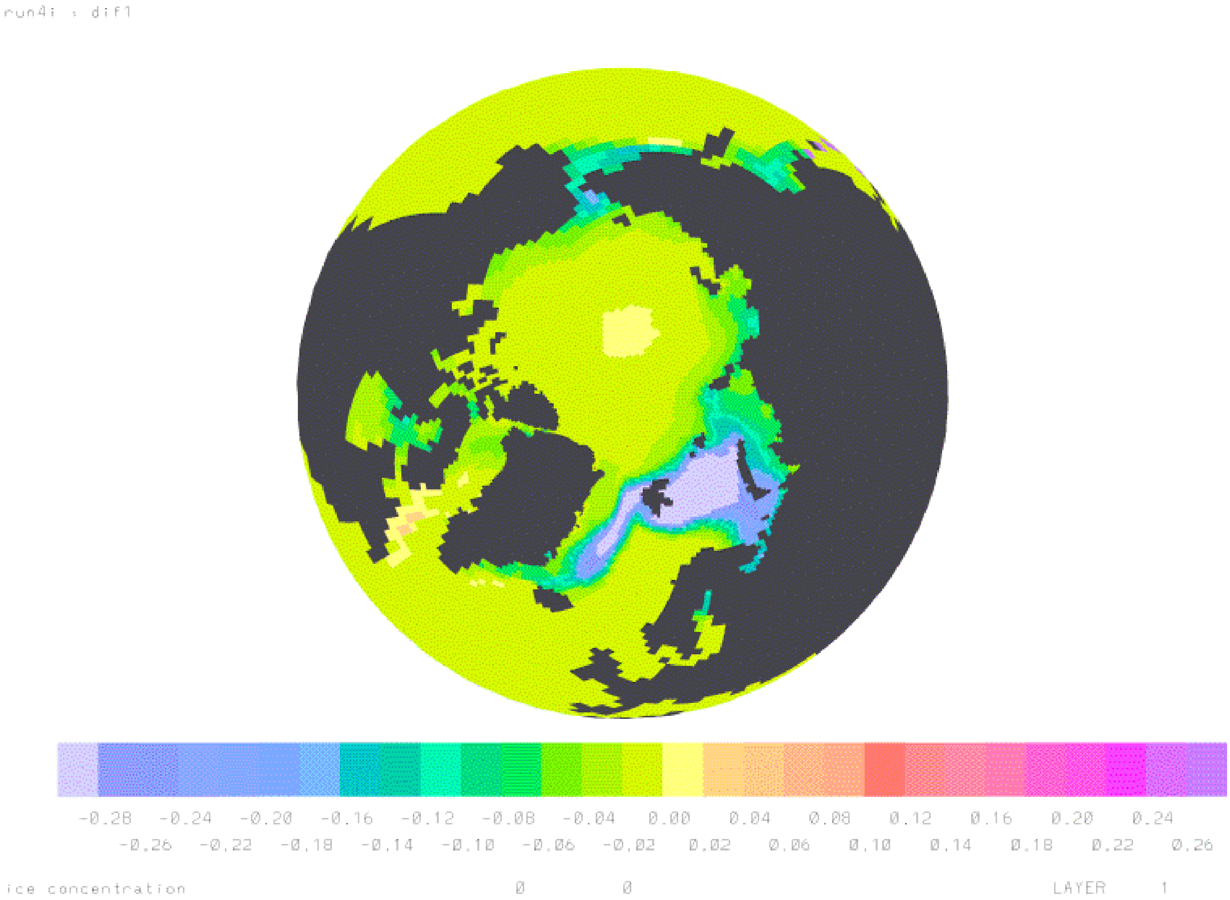


Figure 6. Differences in mean annual ice concentration distribution between the period 2020-2039 and 1980-1999 for the anthropogenic forcing scenario.

Predictions of ocean temperature fields will be discussed under presentation of acoustic modelling work for the Arctic Ocean (Task 3) and the Fram Strait (Task 4). Monthly mean values of temperature and salinity from the model simulations have been used to calculate vertical sections of sound speed along selected paths across the Arctic Ocean (i.e. TAP-A and -B) and the Fram Strait. These data have furthermore been used to calculate acoustic travel times, transmission loss and other acoustical parameters along these paths.

5. Acoustic propagation modelling in the Arctic Ocean (Task 3)

The goal of the acoustic modelling in Task 3 is to study the sensitivity of detecting climate change by acoustic propagation across the Arctic basin.

The approach has been to use existing acoustic models such as OASES (wave number integration model), RAY (Ray trace model), SUPERSNAP (normal mode) and RAM (parabolic equation), to perform the sensitivity study by using data from Task 1 and model results from Task 2 as input. Prior to the sensitivity study software had to be established

- to efficiently produce realistic environmental input to the acoustic models of the data delivered from Task 1
- to interface the acoustic models with the large amount of climate modelling results from Task 2
- to organize the large amount of input data and results
- to present the results from the long term simulation of acoustic propagation parameters

5.1 Acoustic propagation models

The acoustic propagation model OASES was for the first time implemented on a supercomputer to do simulations for more than 1000 km long tracks. Simulations have been done for a 400 km long track in the Fram Strait and two more than 1000 km long tracks in the interior of the Arctic basin.

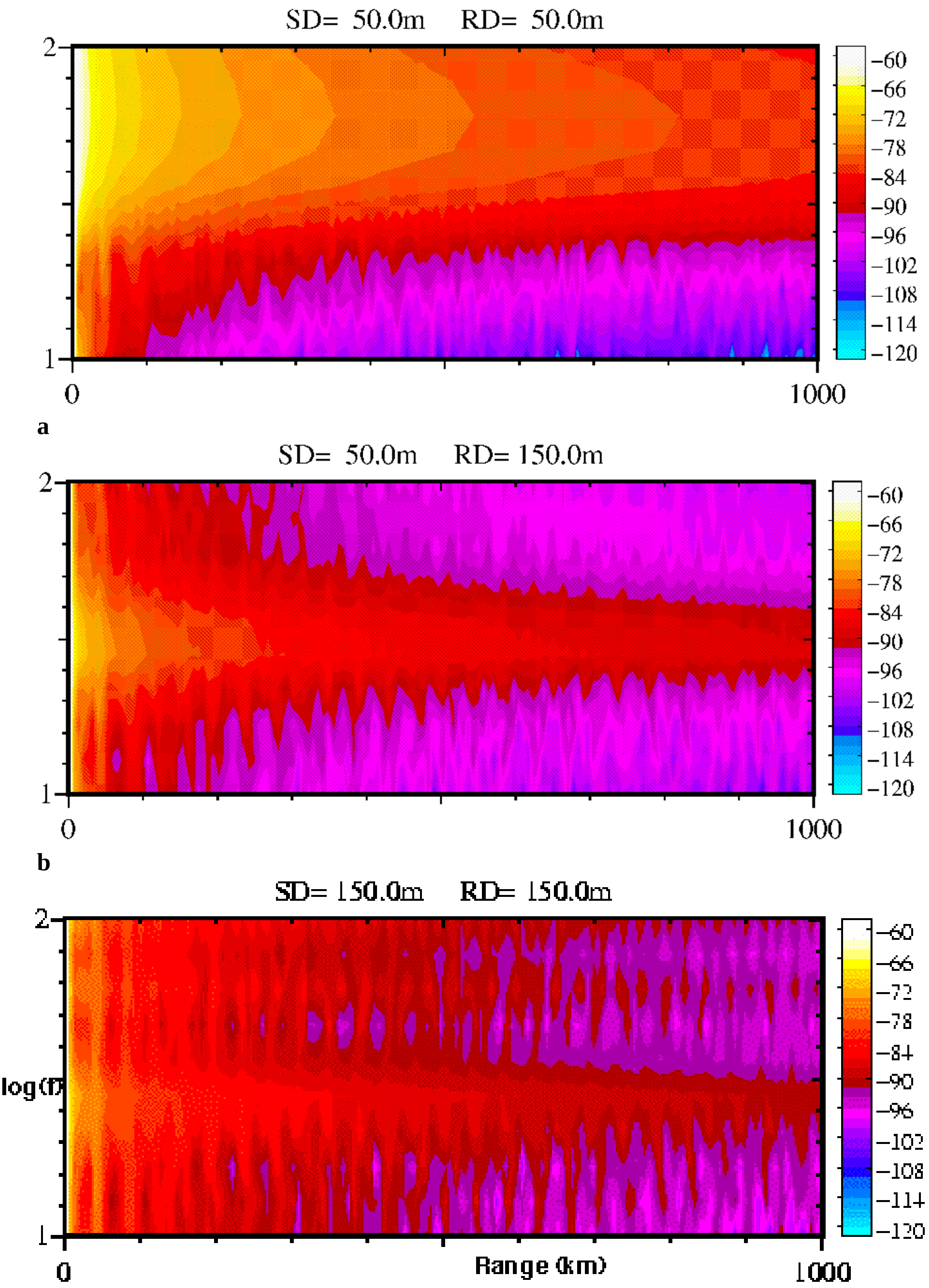
The OASES model was not used for the Arctic Ocean temperature sensitivity test (neither for travel time nor intensity) due the heavy computer demand. On the other hand the OASES model was used to document the optimum frequency of propagation and essential for sea ice sensitivity study. The RAY model was used for the travel time calculations and RAM for the transmission loss calculations. SUPERSNAP has been used to interpret the results. An overview of the acoustical models used in the project is given in Table 1.

The OASES model has been used to calculate the transmission loss as function of range and frequency (Fig. 7). In the interior Arctic Ocean it is often assumed small horizontal gradient in the oceanographic parameters, and therefore the ocean model is considered range independent in these simulations. The sea ice is modelled as a homogeneous thin and smooth elastic plate. Comparing the results show that the optimum frequency of propagation is most sensitive to the depth of the receiver relative to the surface duct and less sensitive to the position of the source. When both the source and receivers are positioned within the surface duct (as in the upper plot) the centre of optimum frequency domain of propagation is 65 Hz. If a receiver below the surface duct is concerned the optimum frequency is around 25 Hz. The same optimum frequency is found when source and receiver is below the surface duct the optimum frequency. Within the optimum frequency domain the transmission loss is around 84 dB 1000 km from the source, while at frequency outside the domain the transmission loss is more than 96 dB.

Table 1. Overview of acoustic models used in AMOC

Model	Theory	Range dependent	Ice ?	Elastic bottom?	Comments
OASES	Full wave	Yes	Yes	Yes	The effect of sea ice
SUPERSNAP	Normal mode	Yes	No	No	Only used as a supplement
RAY	Ray trace	Yes	No	No	Coupled to the climate model
RAM	Parabolic	Yes	No	Yes	Study the insonification

	approximation				of the ocean.



a

b

c

Figure 7. Transmission loss as a function of frequency and range for different source and receiver depths

5.2 Acoustic insonification of the Arctic Basin

The acoustic insonification of the Arctic Basin for the selected tracks have been studied by calculating the transmission loss as function of depth and range. The RAM model was used for a frequency of 20 Hz and two source depths (60 m and 500 m). The transmission loss for the TAP-A and TAP-B sections are shown in Fig. 8 and 9, respectively. The figures show that the transmission loss is significantly different for the two source depths. If a relatively shallow source depth is used the acoustic energy is generally trapped within the 200 m thick surface duct. Whereas for a deep source the energy is more concentrated between 300 and 1000 m, allowing these water masses to be monitored. On the other hand the shallow source should be excellent for monitoring the surface water layer.

The transmission loss at deeper depths are less influenced by the position of the source and more related to changes in the bathymetry. The part of the acoustic field which penetrates to the deeper part of the basin is very influenced by the topographical conditions, while the acoustic field in the upper part of the ocean is less influenced. In order to avoid influence by the sea floor on the important part of the acoustic field (which probes the 250-1500m water masses) one should keep the receiver array away from shelves and other shallow water regions. For the TAP-B track one should be aware that positioning a receiver array in shallow water (around 500 m) will cause additional transmission loss of the modes/rays which goes through the water masses between 250-1500m.

It was found that deployment of the source at 500 m depth instead of 60 m gave better insonification of the Atlantic Intermediate Water (AIW). Furthermore, the simulations showed that the selected tracks for monitoring the AIW should avoid shallow water regions, which will effectively filter away the part of the acoustic field that penetrates AIW water masses. This will have strong impact on how a long-term monitoring system should be designed with regard to source and receiver configuration.

5.3 Sensitivity to sea ice

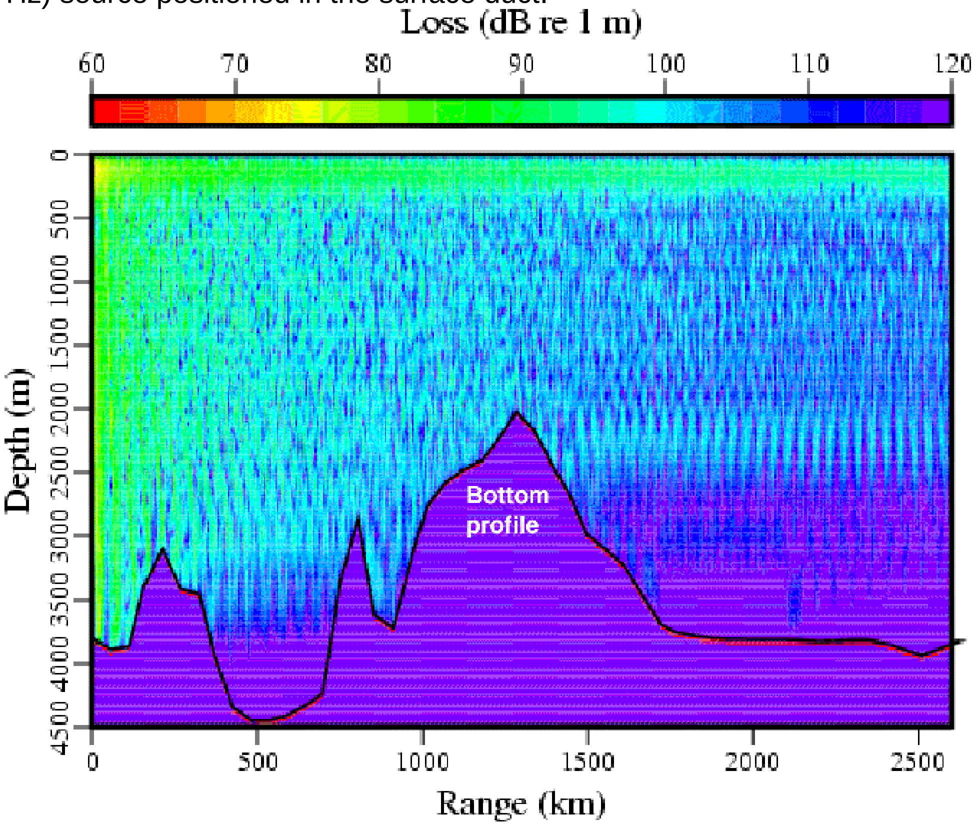
In order to use these open ocean models within ice covered regions at low frequencies asensitivity study to sea ice was performed at low frequencies. The result of this work showed that changes in ice thickness will not cause any travel time change compared to open water conditions if a low frequency (20Hz) source is used. This result is obtained under the assumption that changes in sea ice thickness was either caused by pure melting/freezing of sea water or that in case of a snow fall the corresponding mass of water “flows away” (corresponding to the mass conservation). Furthermore, we found that roughness, as it is treated in the OASES model, does not cause significant changes in travel time.

The reflection loss at frequencies below 100 Hz is insensitive to ice thickness, while it is slightly sensitive to changes of the under ice roughness. On the other hand the reflection loss as function is very sensitive to ice thickness at frequencies above 100 Hz, as shown by the model simulations in Fig. 10. Our study has clearly illustrated that a thinning of ice will cause a reduction of reflection loss at increasing frequencies.

The conclusions of this sensitivity study are that

- low frequency propagation can be modelled by using open water models like RAM andRAY without corrections for ice. This will make the basin wide calculations, for studying the effect of temperature/salinity changes in the Arctic Basin, much less computer demanding.
- basin wide estimates of mean ice thickness can not be provided by a low frequency source

- Regional estimates can potentially be provided by inversion techniques based ontransmission loss (and travel time) using signals from a broad band or coded (100-5000 Hz) source positioned in the surface duct.



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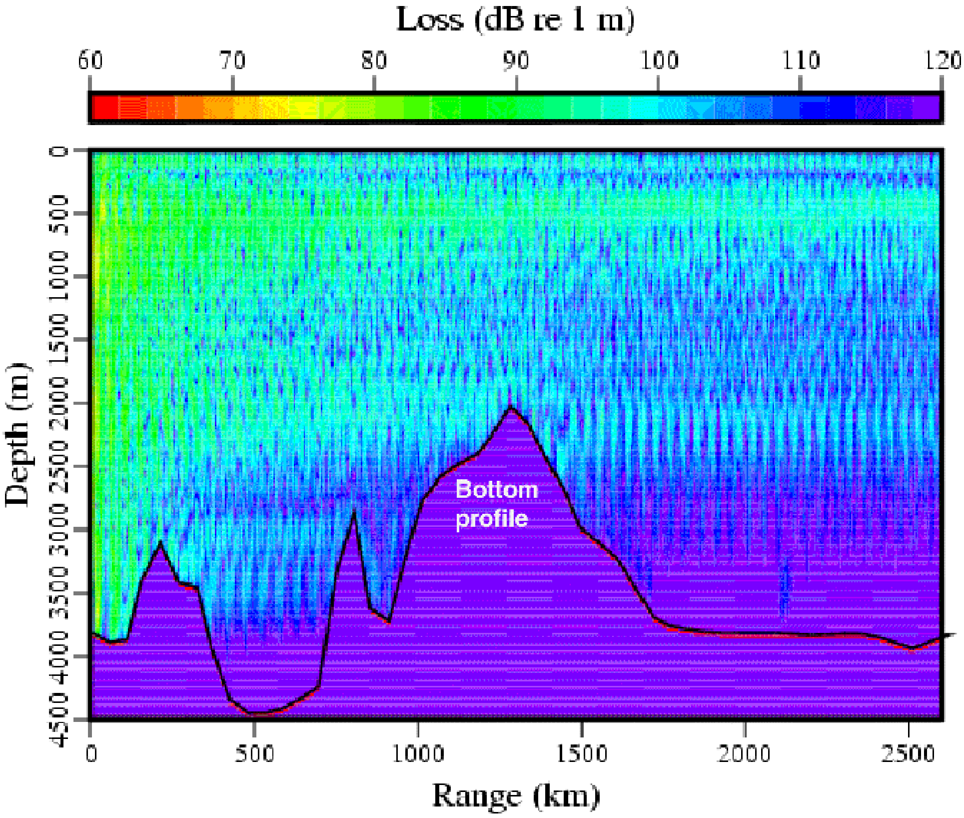

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Figure 8. Transmission loss calculated for TAP-A using mean oceanographic conditions of winters in the 1980s obtained from the US-Russian data Atlas. Source depth is 50 m in the upper plot (a) and 500 m in the lower plot (b). Source frequency is 20 Hz.

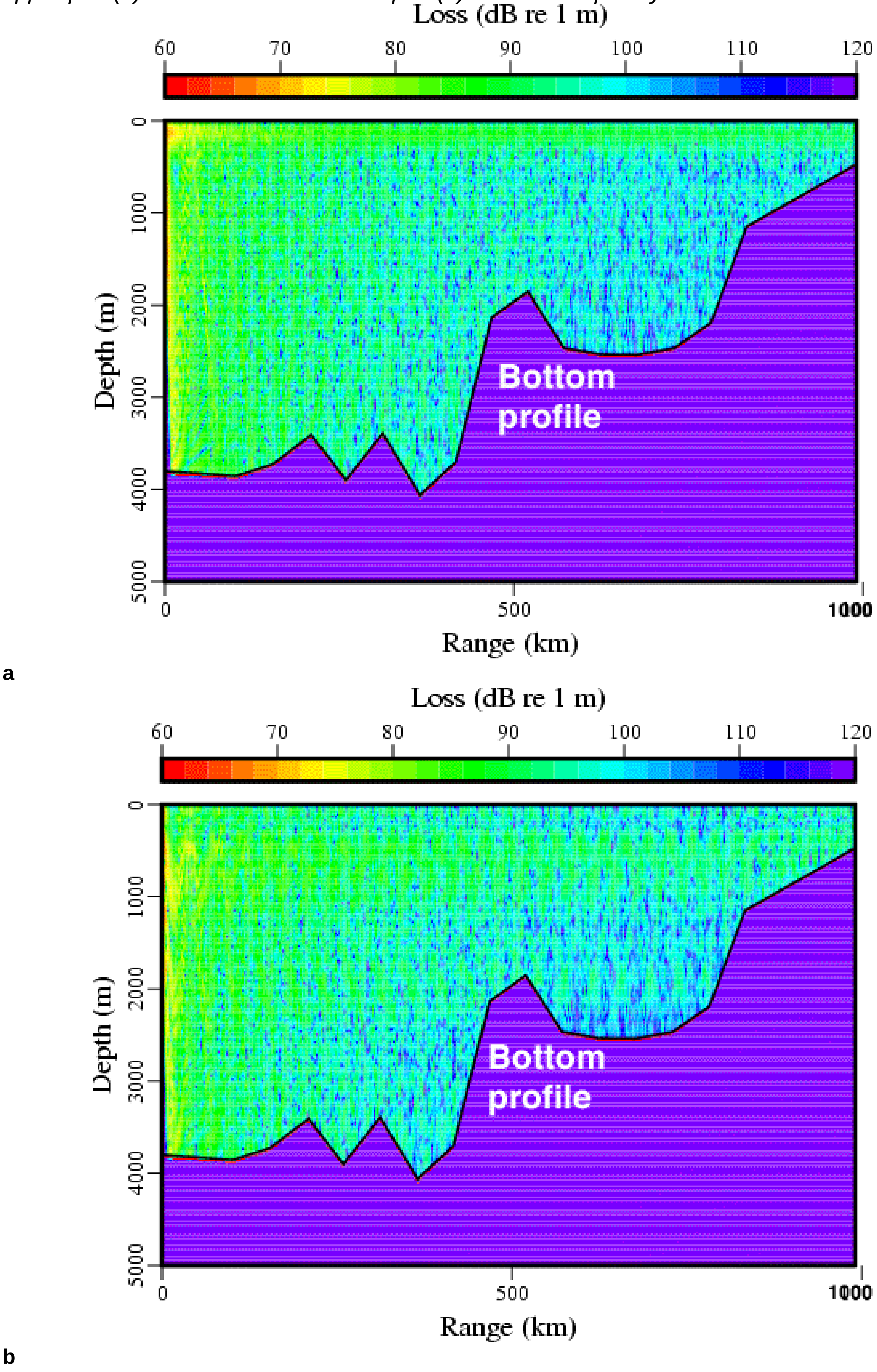


Figure 9. Transmission loss calculated for TAP-B using mean oceanographic conditions of winters in the 1980s obtained from the US-Russian data Atlas. Source dept is 50 m in the upper plot (a) and 500 m in the lower plot (b). Source frequency is 20 Hz.

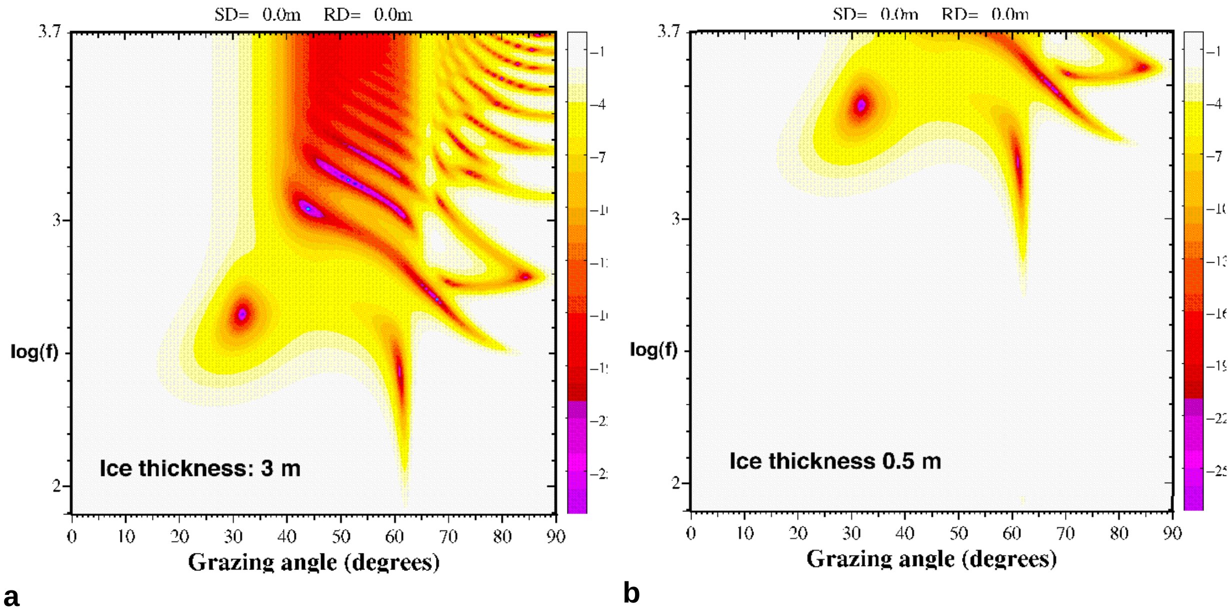


Figure 10. The reflection loss as function of frequency and grazing angle calculated for ice thickness of 3 m (a) and 0.5 m (b). The material constants are Cc=3600 m/s, cs=1800 m/s, ac=1.0 dB/wavelength as=2.5 dB/wavelength, density=0.92 g/cm^3. Sound Speed in water is set to 1440 m/s. Critical angle of reflection for the compressional waves are 61.3 degrees, and critical angle of shear waves 36.9 degrees.

5.4 Sensitivity to ocean temperature and salinity

As a rule of thumb the sound speed dependency of temperature, pressure and salinity is: 4m/sincrease per °C, 1.5 m/s increase per 100 m depth and 1m/s increase for a salinity increase of 1.0 ‰. In the Arctic Ocean the temperature in the upper 50-80 m is constant and close to freezing (about -1.8 ^{0}C), while a strong vertical gradient in temperature occurs at a depth between 80 and 200 m. This defines the surface duct of the Arctic Ocean, which trap much of the acoustic energy close to the sea ice cover. Using salinity around 31 ‰ gives a sound speed close to 1436 m/s. The direct path between a source and receiver separated with 2600 km within the duct corresponds to a travel time of 32.3 minutes.

Historical data

The historical data from the US-Russian data Atlas for tracks corresponding to TAP-A and –B were extracted and used as input to the RAY model to do acoustic experiments with different depths for sources and receivers. This study showed that there have been no trend changes in the oceanographic fields neither for TAP A, TAP-B nor the Fram Strait during the period from 1950 till 1989. Furthermore these simulations showed that in order to monitor the intermediate water depths from 200-1500 m one should deploy the source at 500 m. If the source is deployed at 60 m below the surface, as was done in the US long term Acoustic experiment, the major acoustic energy is confined in the surface duct and less energy goes into the intermediate water masses.

Climate model simulations

Two anthropogenic scenarios (including doubling of CO_2) and corresponding control runs have been provided from Task 2. Each scenario provided monthly mean ocean data over 100 years where the first 25 years is spin up for the climate model. The monthly averaged temperature and salinity profiles along the three tracks are used to calculate corresponding sections of sound speed to be feeded into the acoustic model. In Fig. 11 the averaged temperature along the TAP-B (700 km) has been plotted as function of time for the anthropogenic scenario from 1950 to 2050.

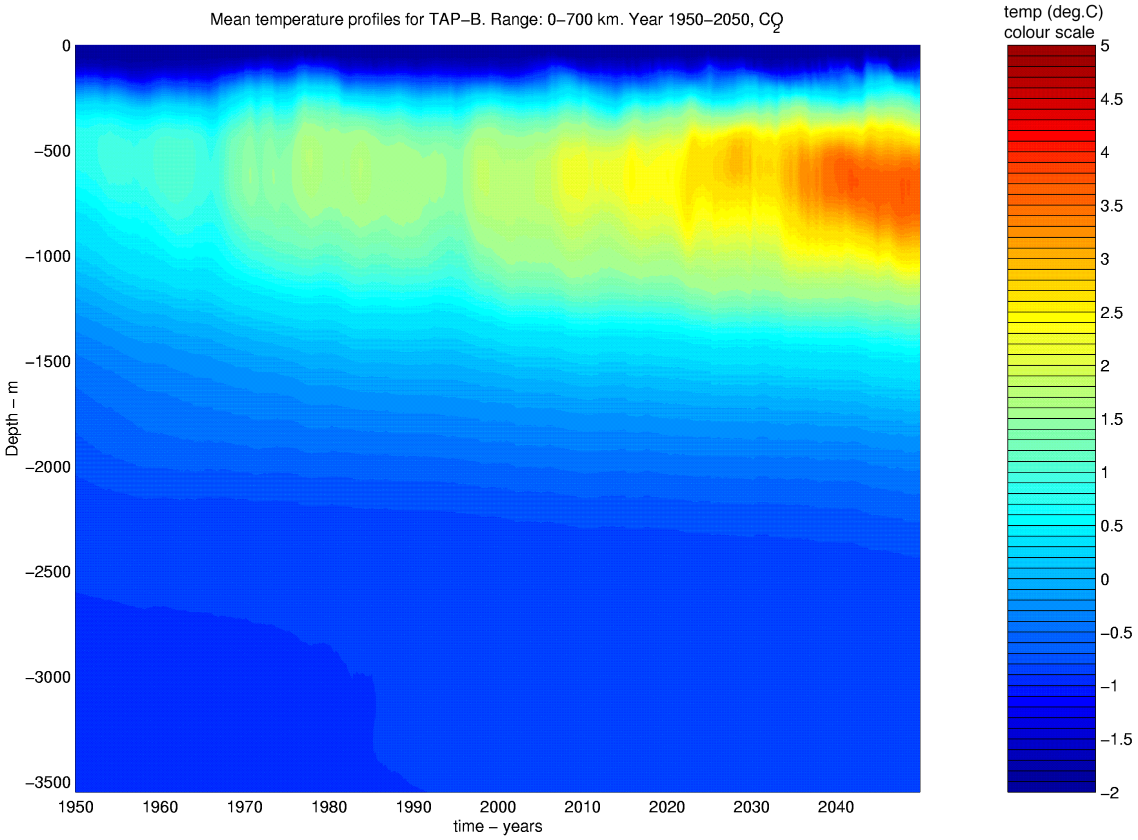
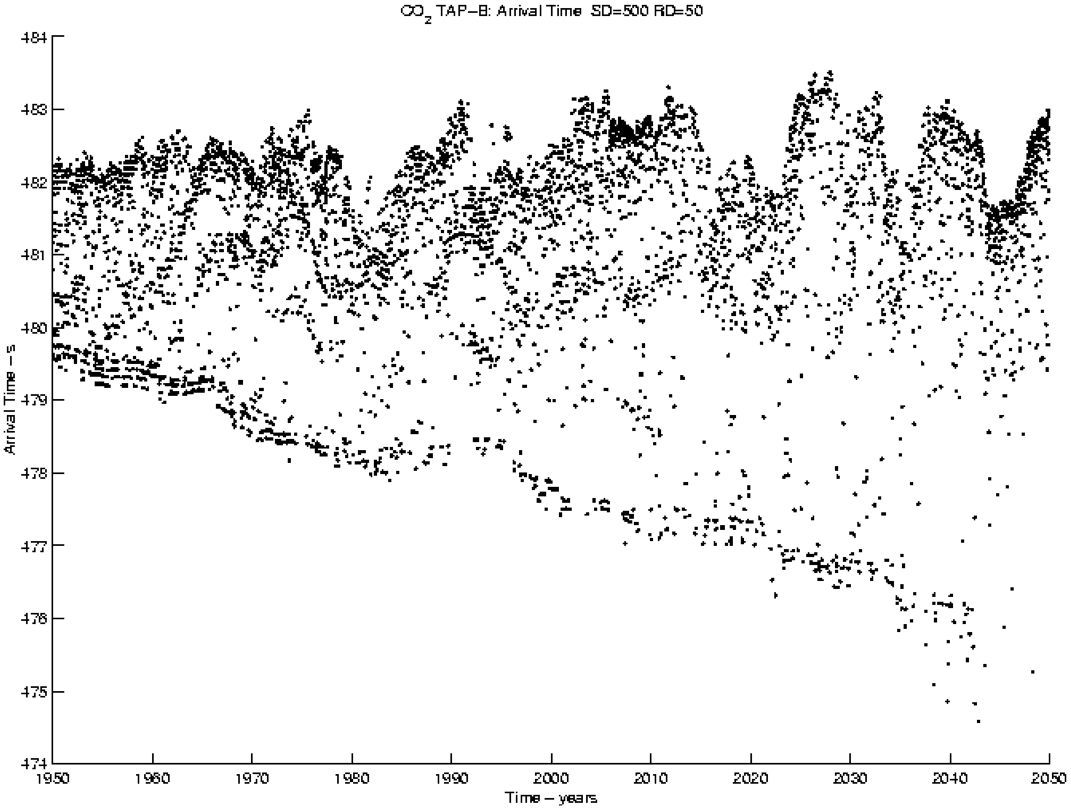


Figure 11. Vertical temperature averaged over TAP-B from 1950 to 2050 based on the anthropogenic scenario. The spin-up period for the climate model is from 1950 to 1975.

The water masses from 200 m down to 1500 m will increase temperature by 2.5 ^{0}C from the1980s to the 2050 in the, while no strong changes in the salinity (not shown) is found in the climate simulations. Relatively large interannual variability in temperature can be observed in the upper 1000 m.

In each acoustic experiment the eigenrays for a source located either on 60m or at 500 m and six receivers are calculated using RAY. Each acoustic simulation took around 2.5 months for the TAP-A (2623 km), roughly 3 weeks in the case TAP B (700 km), while in the case of Fram Strait the acoustic calculations took around 8 days (200 km). Each scenario provided monthly mean ocean data over 100 years. First the 100 years of monthly averaged temperature and salinity profiles along the three tracks were used to calculate corresponding sections of sound speed, which were fed into the RAY model. The Ray model calculated the eigenrays and eigenfronts for each source/receiver configuration. The travel times for each eigenray found for each “acoustic shot” are plotted against time for a deep source as seen in Fig. 12.



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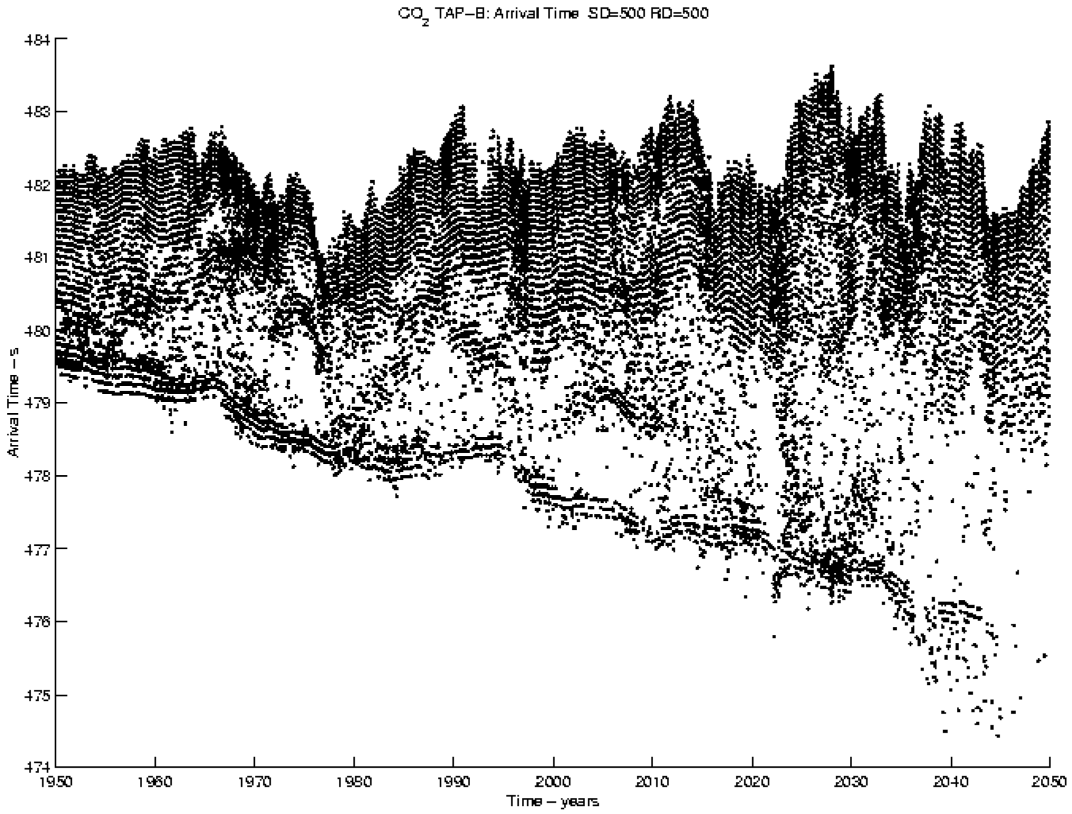

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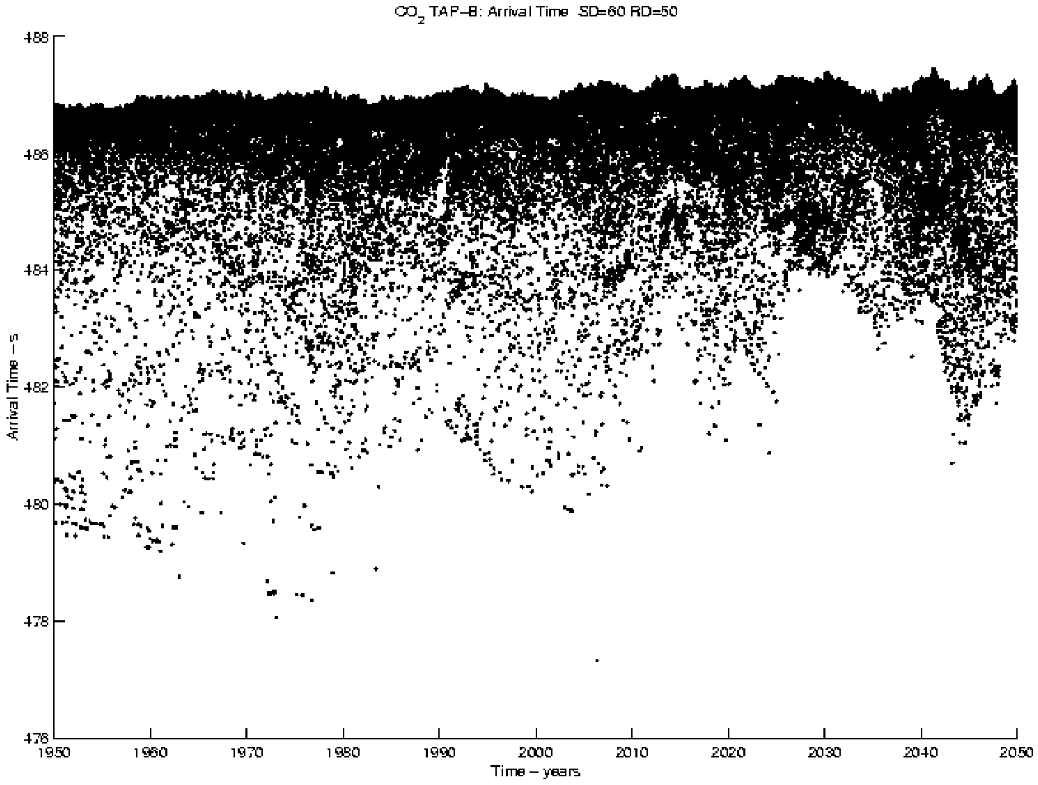
Figure 12. Travel time for each eigenray found for source depth of 500 m and receiver depth of 50m (a) and 500 m (b) as function of time for a 700 km long part of TAP-B using the anthropogenic scenario from Fig. 11.

In the case of source depth (SD) of 500 m and receiver depths (RD) varying from 50-100-200-300-400-500m the first arrivals at all the receivers, which corresponded to the deeper penetrating eigenrays, were relatively stable to monthly and inter-annual changes. A clear decrease in travel time of 4.5 s was found as the mean temperature from 200-1500 m increased by about 2.5° C. The late arrivals corresponded to the surface ducted eigenrays which were not related to the warming of the deep water masses. The first arrival time was correlated with mean temperature in the 0-200m, 200-1500 and 0-1500, showing a negative correlation of about 0.7 at the deepest receiver. At the other receivers the correlation was still negative but decreasing in value.

In Fig. 13 the travel time for each eigenray is plotted for the experiments with shallow source depth (60 m) and receiver depths of 50m and 500m, respectively. The results show that the strongest part of the signal are due to the rays which are trapped in the surface duct only a few rays penetrates deeper part of the ocean and these rays are very unstable from month to month. Furthermore, the number of deeper going rays are reduced with time and the arrivals become steadily later as the temperature increases in the water masses between 200-1500 m. This is caused by a strengthening of the vertical temperature gradient as the temperature increases in the water masses below the surface duct while the temperature in the duct is constant with time. This causes an acoustic intensification within the duct. On the other hand the acoustic signal contains increasingly less information about the temperature below the duct.

Using a shallow source at 60 m depth there is no climate signal present at any of the receivers. In the ongoing Russian/American ACOUS experiment (Mikalevsky et al., 1999) a source depth of 60 m has been used, and according to our results this experiment does not contain optimal information about the changes in the AIW. The changes observed by this system are generally found to be related to decadal oscillations in the upper water masses (0-500 m). By positioning the acoustic source at 500 m depth and the receiver array 700 km away the climate change occurring in the water masses between 200 and 1500 m is easily detected.



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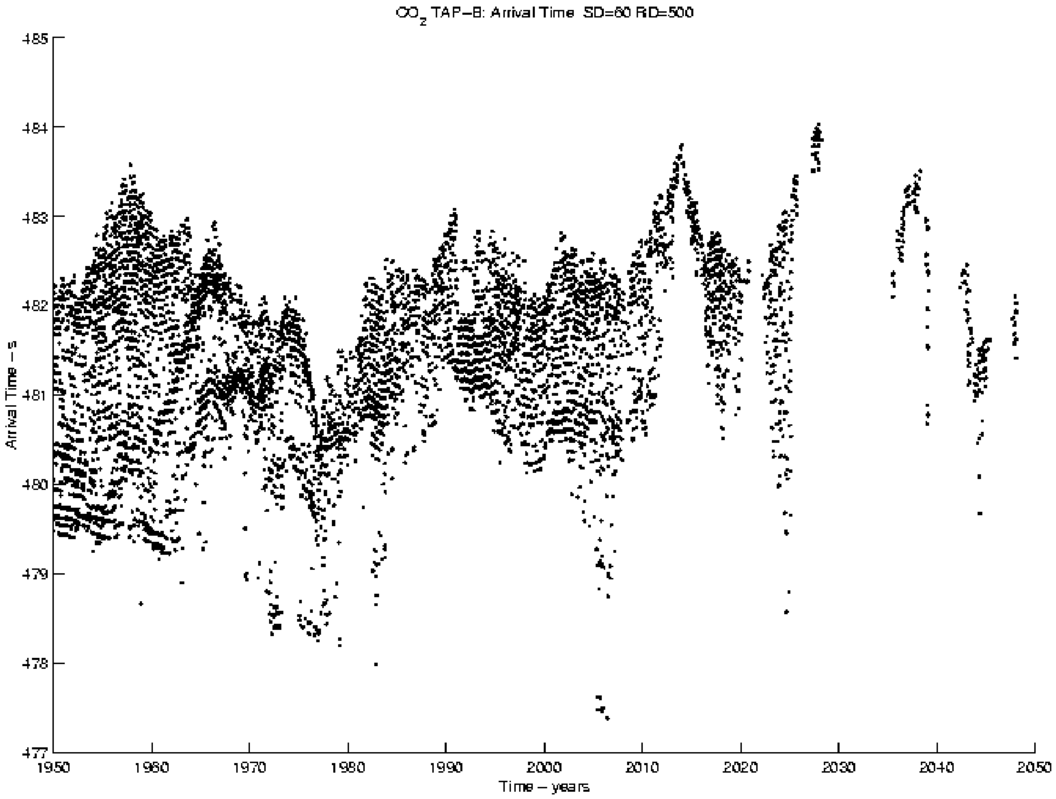


b

Figure 13. Travel time for each eigenray found for source depth of 60 m and receiver depth of50m (a) and 500 m (b) as function of time for a 700 km long part of TAP-B based on the anthropogenic warming scenario in Fig. 11.

6 Acoustic propagation modelling in the Fram Strait (Task 4)

The goal of task 4 was to study the feasibility of using acoustic monitoring in a strait where the temperature, currents and ice conditions vary considerably due to mesoscale eddies. In the Fram Strait it is important to observe both temperature and currents in order to estimate volume and heat flux. The Fram strait is dominated by warm water flowing northwards into the Arctic Basin on the eastern side and sea ice and cold surface water flowing southwards on the western side of the strait.

6.1 Modelling of optimal source and receiver configuration

The first part of Task 4 has bee to study the topographical influence on the acoustic insonification of the Fram Strait for optimal receiver and source configuration (Subtask 4.1). Simulations have been carried out across a 450 km long section the strait at 79^{o}N using OASES, RAM and RAY models. Input data to the models have been decadal mean sound speed fields for summer and winter of 1950s, 1960s, 1970s and 1980s. Example of sound speed field is shown in Fig. 14.

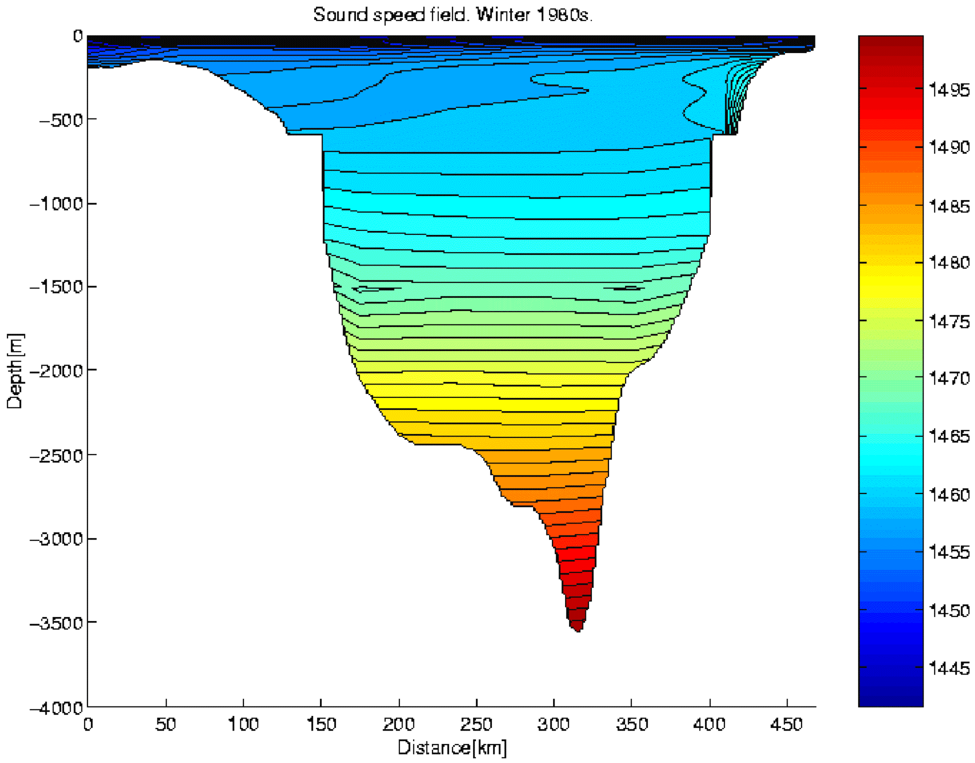


Figure 14. Mean sound speed field across the Fram Strait at 79°N based on winter data from the 1980s.

Numerical experiments have been carried out for different source depths (18 - 50 m), different frequencies (20 - 500 Hz) and different source/receiver positions (on shelf and off shelf). The results of the simulations show that

- For the source at the shallow shelf location the best signal to noise ratio is obtained when the sourceis positioned at 122 m depth.
- The sources/receivers positions should be off the shelf in order to avoid that the deeper going part ofthe acoustic field is influenced by bathymetry.
- A deep source gives a better insonification of the water masses at high frequencies.
- Calculation of the transmission loss as a function of the depth and range show that acoustic transmission of high frequency can be used for monitoring oceanographic changes.
- Sedimentation significantly influences on acoustic propagation when the source is located at the shallow shelf.

With respect to a good enough signal to noise ratio for low frequency receivers should be positioned in the upper 1000 m of the ocean while for high frequencies in the upper 500 m. An example of transmission loss as function of depth and range is shown in Fig. 15.

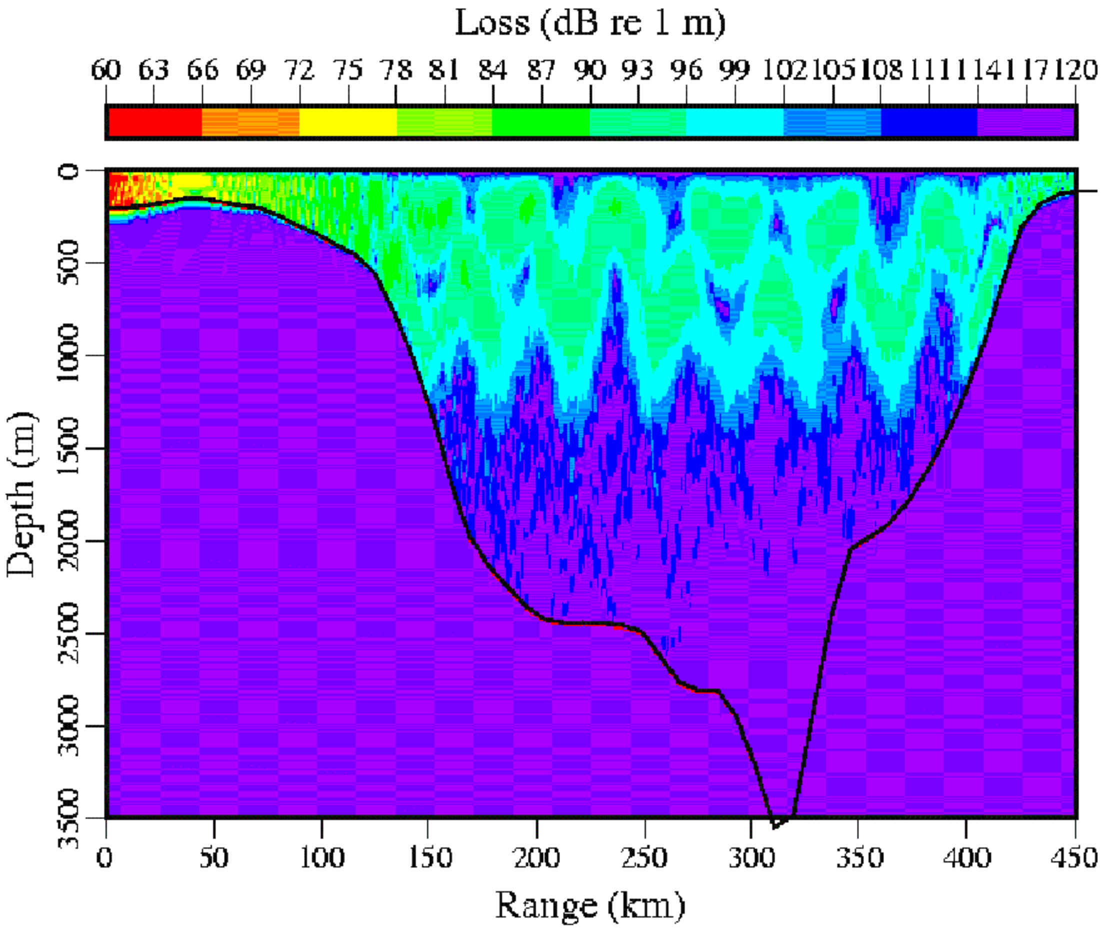


Figure 15. Transmission loss as function of depth and range for mean winter conditions across the Fram Strait, using source located on the western shelf at depth of 122 m.

6.2 Sensitivity of acoustic propagation to temperature changes

In Subtask 4.2 simulations have been carried out to study sensitivity of acoustic propagation to temperature changes. The RAM model has been used to calculate eigenrays and travel times of the eigenrays across the deep part of the strait at 79°N. Input data to the models have been decadal mean sound speed fields for summer and winter of 1950s, 1960s, 1970s and 1980s. Source and receiver depths have varied from 60 to 500 m and the distance between source and receivers was 240 km.

A compilation of travel time estimates for frequencies and temperature fields, using source depth of 60 m, is shown in Fig. 16. Rays passing through the colder upper water masses are slower than the rays passing through the lower warmer water masses. This is also reflected in the difference between summer and winter travel times. For deeper receiver deployments (250 and 500 m) the seasonal difference in travel times is reduced.

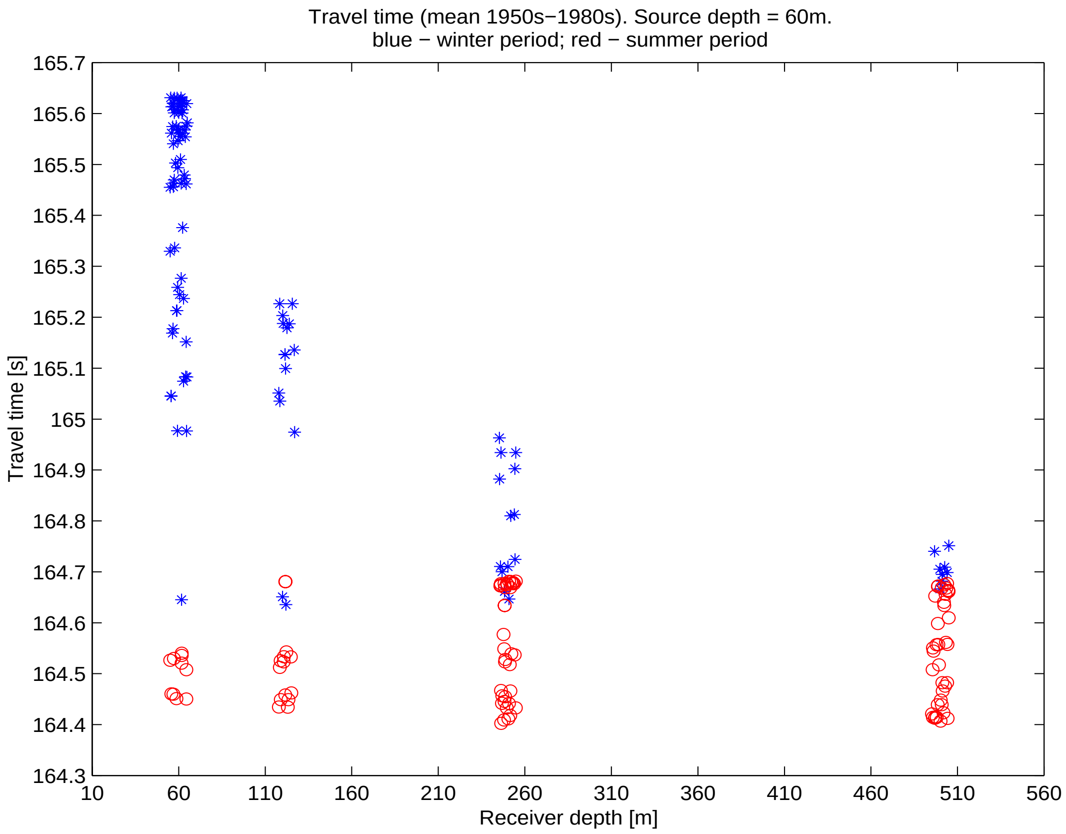


*Figure 16. Arrival times for eigenrays found at 240 km distance from the source for different receiver depths and averaged winter (*) and summer (o) temperatures.*

The simulations showed that for a shallow source deployed at 60 m:

- The seasonal variations (implying temperature and salinity variations) are clearly observed at all selected receiver depths (60, 122, 250 and 500 m).
- Less variations seen for the lowest receiver (at 500m depth).
- Summer conditions are more stable than the winter conditions.

For a deep source deployed at 500m the results show:

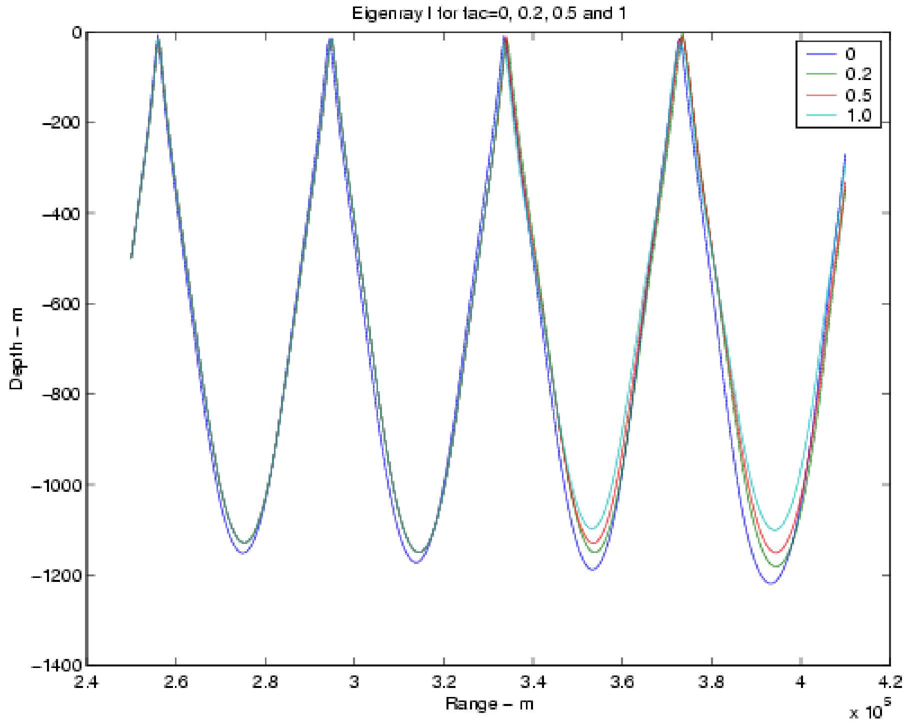
- Some seasonal variation seen for the shallow receivers (at 60 and 122 m depths).
- More stable situation with respect to seasonal changes is observed for the deep receiver locations (at 250 and 500 m depths).

In conclusion, travel time variations can be used for monitoring temperature and general structure changes in water mass structure expressed by the sound speed field.

The stability of rays in the Eastern part of the Fram Strait (the ice-free part of the strait) has been studied using RAY with respect to seasonal environmental variations and passages of meso-scale eddies. The main results of the work was:

- Although there are large changes during passing seasons and eddies, some of the rays show remarkable stability, and ought to be recognisable in an experimental situation for more than 50 % of the time. Furthermore, these rays are the deepest going rays, typically down to 0.8 - 1 km, and accordingly map the most important part of the West Spitsbergen current (Fig. 17, 18).
- In an experimental situation it is advisable to use a vertical receiving array, with receivers covering depths between 200 - 700 m, perhaps arranged in pairs so that the direction of

received rays can be established at different depths.



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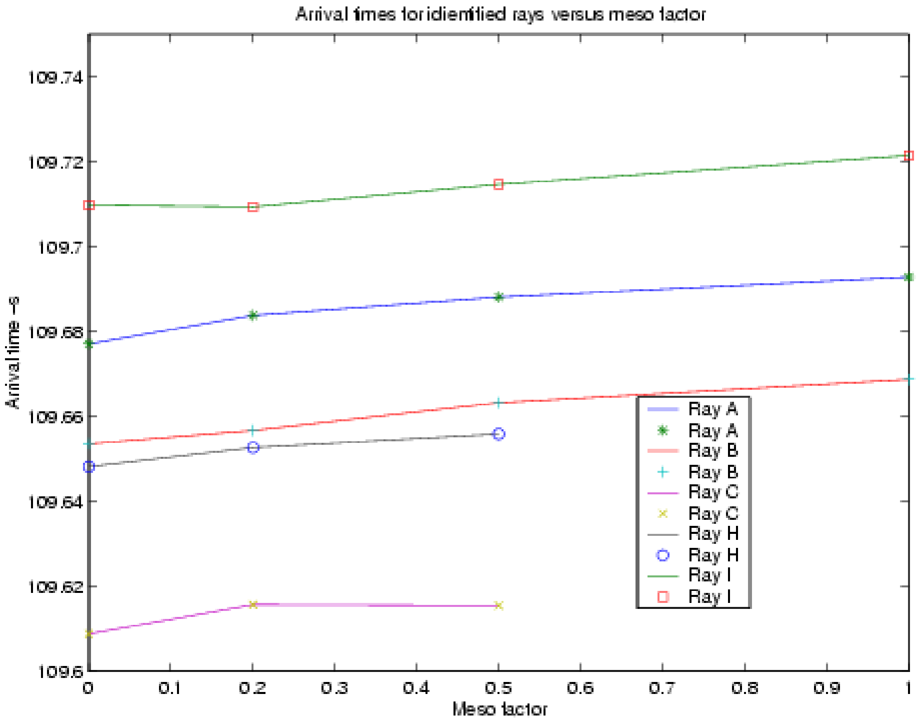


b

Figure 17. (a) Influence on one identify eigenray (denoted I) by varying amplitude of the mesoscale eddy, using factors of 0, 0.2, 0.5 and 1.0; (b) arrival times for different identified rays as function of mesoscale factor.

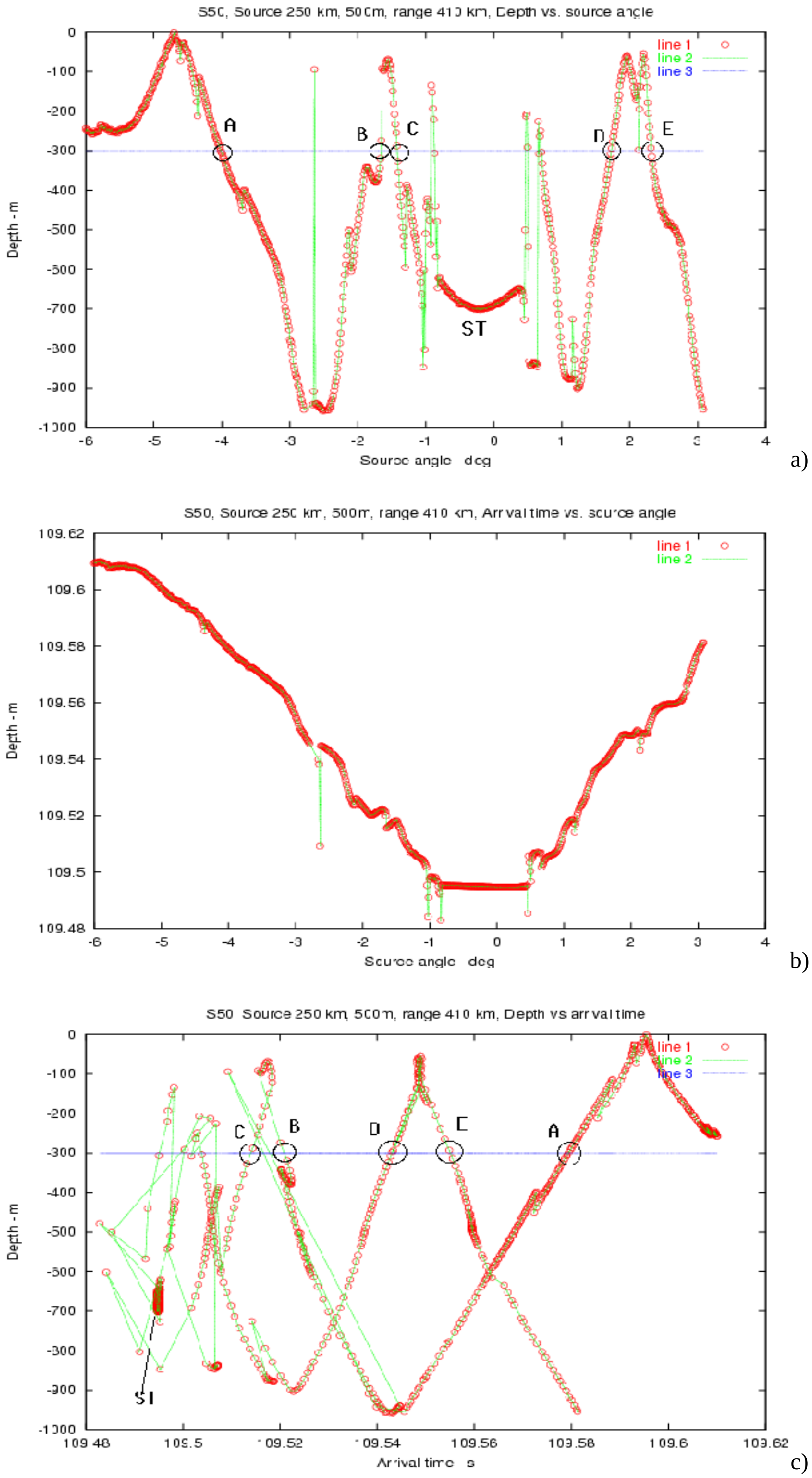


Figure 18. Ray fan results for summer 1950s data using source at depth 500 m and located 250 km east of 79°N 11°W: (a) Depth versus source angle, (b) arrival time versus source angle, and (c) depth

versus arrival time.

Figure 18 show examples of ray fan results from the RAY model by launching a great number of rays at the source and record their depth and travel time at the receiver range. The blue line indicates a receiver at 300m depth, and the circled intersections with the curve show the locations of eigenrays. Those denoted A, C and D are of the stable type.

The arrival time fluctuations have also been investigated for changing oceanographic data by shifting the entire sound-speed pattern horizontally with respect to the transmitter-bottom-receiver configuration for a distance essentially larger than the scale of ocean turbulence spatial correlation. For the isotropic ocean turbulence in each horizontal plane, when the spatial scale of correlation of random oceanographic inhomogeneities is the same in any direction in the horizontal plane, we obtain the *rms* travel time fluctuations for the 5s-ray arrival close to 30 ms. This value is noticeably larger than signal fluctuations due to surface scattering and ice cover influence. The temperature influence on the stable arrivals was estimated as a gradient of 29 ms/°*C* for the 4s-ray arrival and 37 ms/°*C* for the 5 s-ray arrival.

Two methods called CUMSUM (cumulative sum) and CAT (Collective Arrivals Time) have been tested. CUMSUM is based on the stable arrivals selection and determination of travel time variation. CAT consists of defining the trend in the whole signal-arrival spectrum caused by the temperature changes, and computing average parameters of the arriving signal ensemble. By the second method the collective sum of signal arrivals were estimated. The temperature dependence of the arrival-pattern duration leads to variation of the slope of the cumulative sum regression line. The advantage of this approach is that it is based only on relative measurements of arrivals. Measurement of the regression line slope does not require sophisticated instrumentation to match the receiver and the source clock, which is required for travel time measurements. The cumulative time procedure presents the possibility of determining the average temperature along the acoustic path in the ocean without considering arrival features in detail. Statistical approach applied for travel time calculation for the signal propagated across the Fram Strait through the decades reveals some trends, which could be related with temperature change in upper layer of the ocean mostly in winter environment conditions. Estimated travel time variations are shown in Fig. 19. The CUMSUM method is sensitive to the temperature variation in depth (baroclinic dependence), whereas CAT is most sensitive to barotropic temperature variations. In conclusion, 0.1°C per a year or 0.06°C per decade sensitivity can be reached permanent seasonal acoustical monitoring of temperature in Fram Strait.

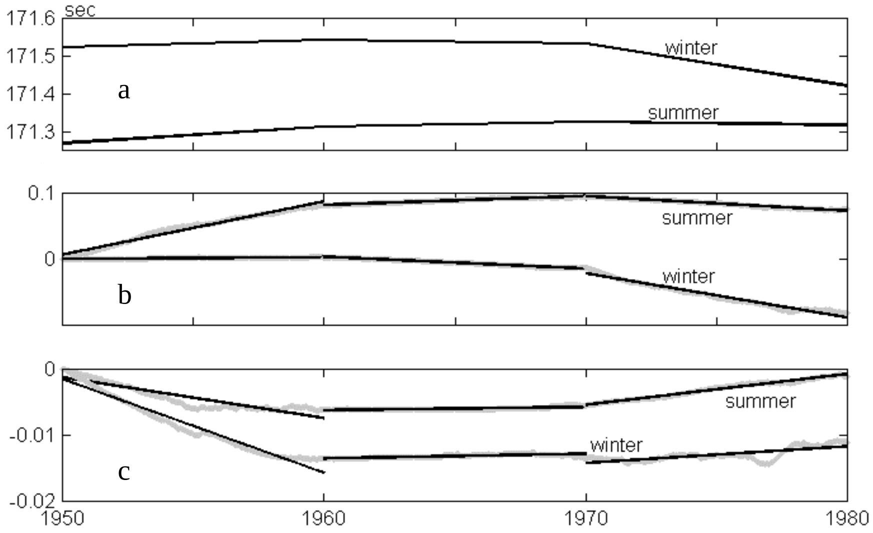
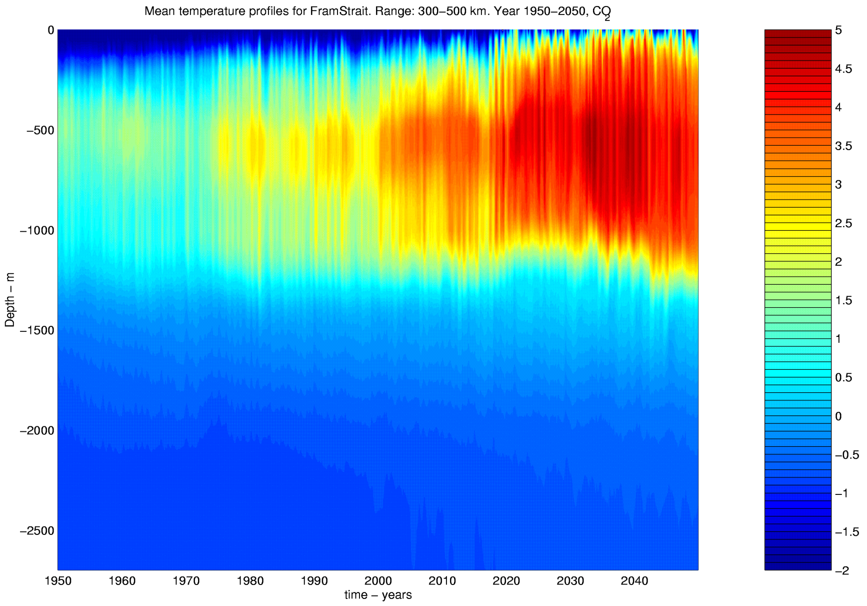


Figure 19. Travel time variations across the Fram Strait using decadal temperature data from 1950s to 1980s: (a) time propagation change along th eray stable through the decasdes and seasons, (b) collective arrival times in seconds, (c) cumulative sum changes in seconds. Shadow lines are values calculated from interpolated data, while solid lines are from least square regression.

A separate study used data from the climatic simulations in Task 2 as input to ray tracing model (RAY) for simulations across the eastern Fram Strait where the core of warm Atlantic water is a dominant feature. Data both from the anthropogenic (Fig 20 a) and the control run (Fig 20 b) were used. Seasonal as well as longer term variability is observed in both the anthropogenic and the control run. The anthropogenic simulation shows a stronger warming signal compared to the control run from 2000 to 2050.



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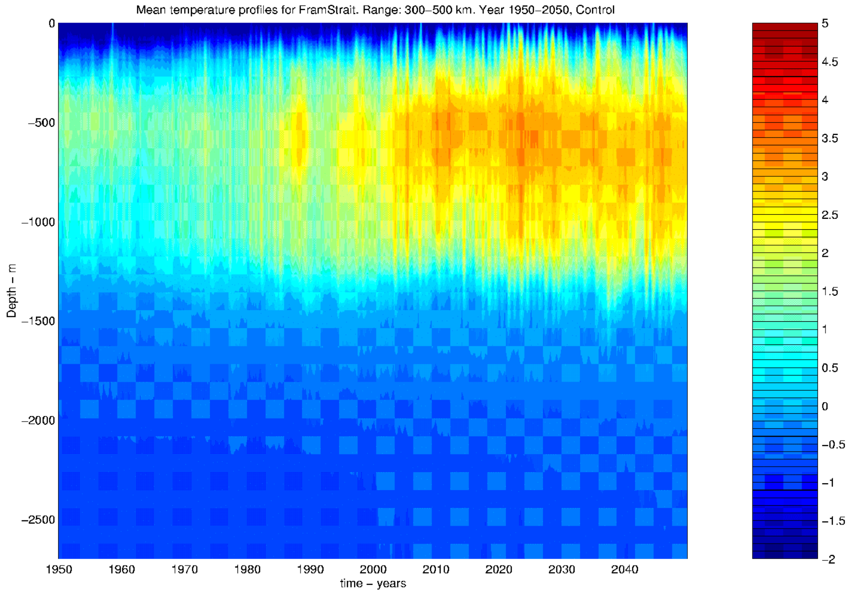

b

Figure 20. Mean Temperature across the eastern part of the Fram Strait as function of depth and time for Anthropgenic (a) and control run (b) for the period 1950 - 2050. The lower panel shows the arrival times as function of time.

The acoustic simulation shown in Fig. 21 suggests a clear decrease in the travel times but the travel timesare less stable (due to strong seasonal effects and decadal variations). This indicates that an averaging of the arrivals has to be performed to pick up the climate signal earlier than when considering the “raw” data. This has to be considered more in detail when developing the inversion techniques. By correlating the first arrival, mean arrival time and last arrival with mean temperature in 0-200m, 200-1500m and 0-1500m a negative correlation factor between 0.7 and 0.94 is found. This is a good relation between increase in temperature and decrease in travel time.

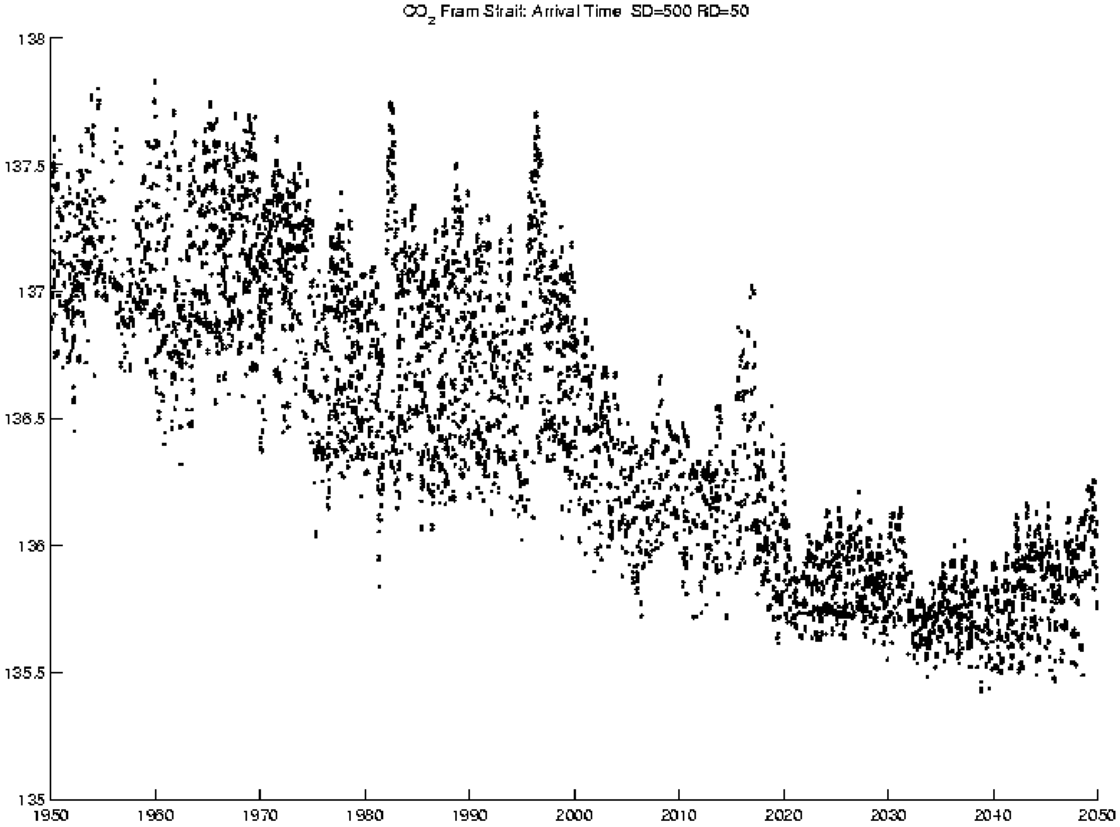

Figure 21. Travel time across 200 km of the eastern Fram Strait based on anthropogenic warming scenario in Fig. 20, using source depth of 500 m. The reduction in travel time over the 100 year period is 1.65 sec.

Travel times from the RAY model have also been estimated with measured environmental data (1950s - 1980s), shown in Fig. 22, which are comparable with the simulations in Fig 21. Propagation runs have been conducted along a 200 km section at 79°N. The travel times for the winter data (blue dots) are shifted slightly compared to the summer data (red dots) in Fig. 22 to clarify the seasonal difference.

The main results are:

- Comparison of ray travel times simulated with climatic models and measured mean environmental data shows a very good correspondence, i.e. the travel time over a distance of 200 km is about 136 seconds.
- For the sound tracks used in this study the climatic simulations indicate an expected decrease in travel time of 6 ms/year.
- The measured environmental data for the period 1950-1989 show no systematic change in the mean water temperature in the Fram Strait, but the seasonal difference was more

pronounced in the 1950s compared to the following decades.

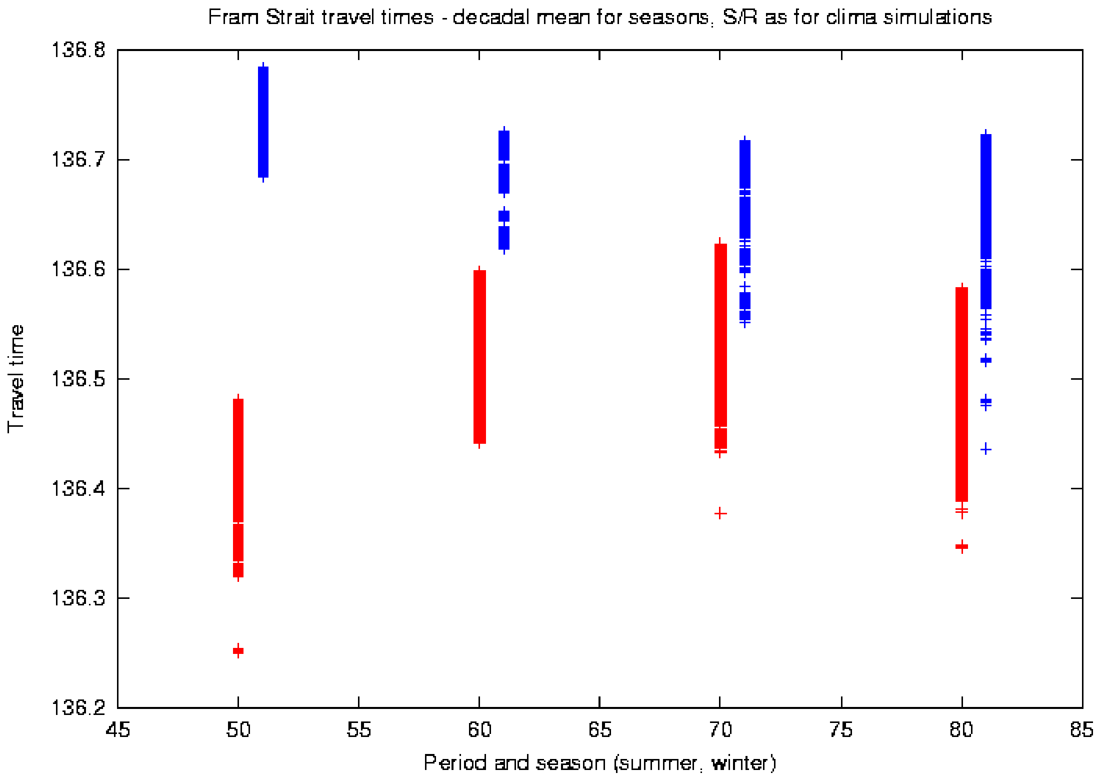

Figure 22. Travel time from RAY simulations across a 200 km section of the Fram Strait based on winter (blue dots) and summer (red dots) climatological temperature and salinity data for each decade.

6.3 Sensitivity of acoustic propagation to current velocity

In subtask 4.3 the sensitivity of acoustic propagation to current velocity changes was studied. Space-timescintillation analysis offers a promising method of remote acoustic sensing of current in the ocean. The evolution of the scintillation pattern is related to the advection of the inhomogeneous medium through the sound beam, thus providing a basis for flow velocity measurement. Simulation experiments were carried out using an array of 4 sources and receivers on each side of the Fram Strait, which defines 16 paths across the strait (Fig. 23). An example of current profile retrieved by the scintillation method is shown in Fig. 24.

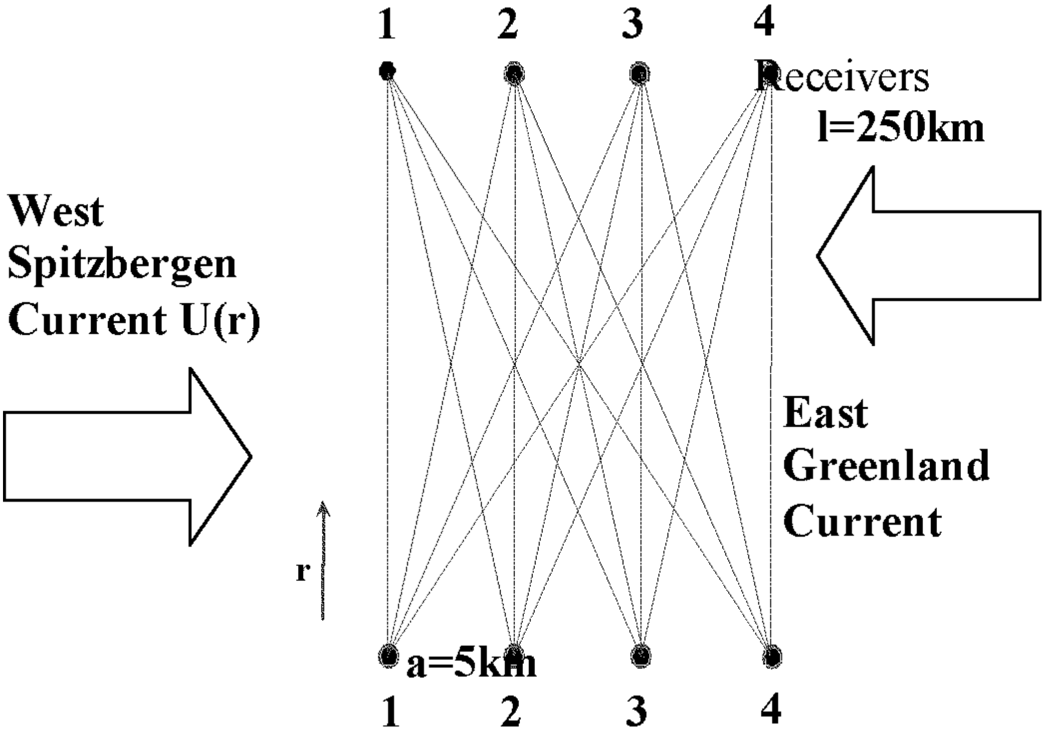

Figure 23. Scheme of tomography array across the Fram Strait. The distance between array elements alongthe current direction is 5 km, while the distance across the strait is 210 km.

The sensitivity study of acoustic propagation to current velocity changes resulted in the following conclusions:

- Signal scintillation approach was developed to retrieve current profile in Fram Strait cross section in small aperture tomography scheme. Both CAT and Stable Ray approaches have been considered for application of signal scintillation procedure. 10 % accuracy can be in inversion procedure for 4´4 array of 15 km aperture for 210 km path. Double frequency signal scintillation method was considered to transverse advection velocity detection. This method can be regarded as a “frequency-domain” version of the scintillation approach based on the measurement of correlation of the signals transmitted from the source to two receivers separated in space and can be developed to realise ‘one path tomography scheme’.
- Preliminary estimations of bottom autonomous system has been done for the small aperture tomography scheme in Fram Strait cross section, as shown in Figure 24.

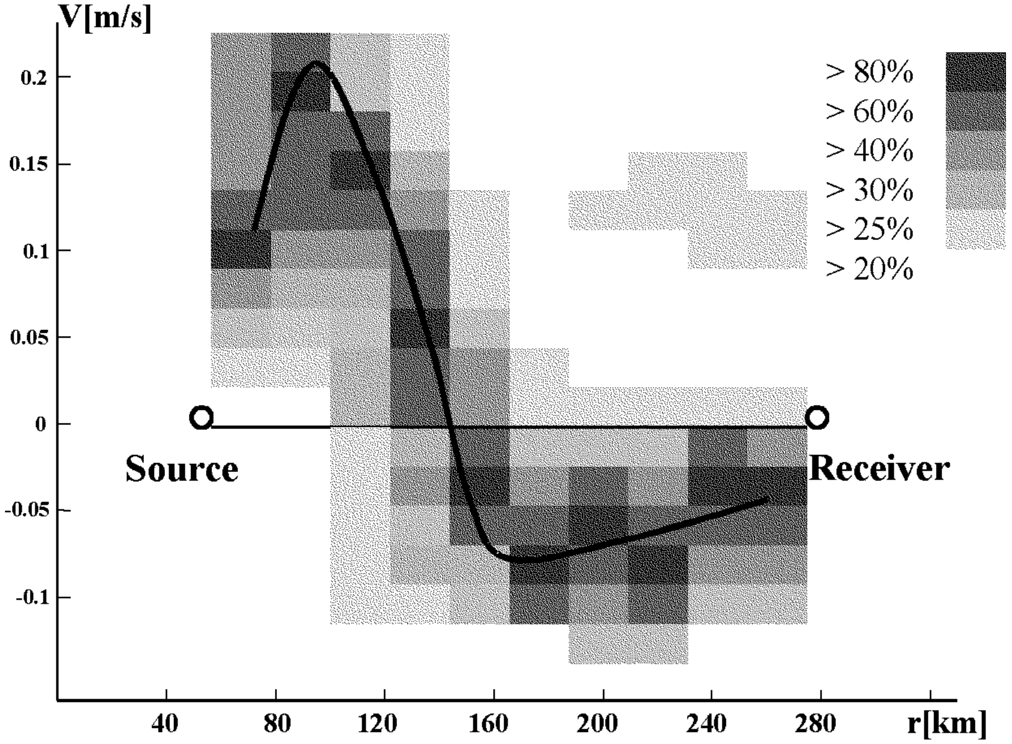

Figure 24. Example of current profile retrieval where the solid line shows the initial current profile across the Fram Strait and the shadow areas show the relative value of array tuning in accordance with the time lags defined by the geometry of the array.

7 Design an acoustic monitoring system (Task 5).

A monitoring system for the central Arctic will require frequencies from 20 to 40 Hz for averaged ocean temperature and from 100 to 3000 Hz for retrieving information about the ice cover using transmission loss data. Therefore we have to consider one monitoring system for changes in ocean temperature, and another monitoring system for changes in the sea ice thickness.

7.1 Monitoring averaged ocean temperature

The acoustic monitoring system for averaged ocean temperature in the Arctic has to fulfil the following requirements

1) ***The signal to noise ratio must be as good as possible without having to use too energetic acoustic sources.***

The results in Task 3 show that there is no difficulty in obtaining good enough signal to noise ratio (approximately 20 dB) for low frequency sources (20-40 Hz) in the central Arctic. This is because of low transmission losses (80-90 dB) at these frequencies, and due to the generally low ambient noise levels in the central Arctic (80-90dB). This has also been demonstrated by the TAP experiment in 1994 where the source strength was 196 dB.

2) ***The acoustic signal must travel though the regions and water layers where significant changesin ocean climate are predicted by climate modelling or historical data***

The simulations show that a source positioned at 500 m depth gives a better insonification of the AIW layer than using a shallow source as used in the TAP and ACOUS experiments. This is also seen in the ray trace simulations, where more eigenrays were found to travel through these water layers, at all deeper receiver depths considered using a deep source.

It is also clear that positioning of the receivers in regions with relatively shallow water (<1000-1500 m) will reduce the possibility to pick up information about the Arctic Intermediate Water, because rays passing through these water masses will be rapidly damped due to bottom interaction. Information about the surface water, on the other hand, is obtained from rays which are trapped in the surface water layer and therefore not affected by shallow water conditions. A deep source are more influenced by the bottom since more energy goes into the higher and deeper penetrating modes than in the case of a shallow source. However, the influence of the bathymetry can be avoided by selecting tracks that do not cross over shallow water areas.

3) ***The effects of averaged temperature changes should be separated from the effects caused by changes in the ice conditions.***

In Task 3 it was found that low frequency sound is insensitive to the ice properties both in travel time and transmission loss. According to this, a low frequency concept will contain a clean ocean temperature/salinity information.

From the above we recommend to use a deep low frequency source and receivers which are positioned so that the tracks do not pass shallow water regions (<1000m). A system to measure changes in averaged temperature measurements will be based on travel time measurements using vertical receiver arrays. The travel time has to be measured with an accuracy of a few ms. Such measurements require an accurate positioning of sources and receivers down to a couple of meters. This can be obtained most easily by fixing the receivers and source to the bottom, but on the other hand this may cause the climate signal to disappear due to increased bottom interaction, and it is therefore not recommended to positioning the source or receivers close to the bottom. Another more realistic concept is to moor the source and the receivers to the bottom. Receivers could also be moored below drifting sea ice. With the today's technology, using differential GPS, position can be provided with a accuracy down to 1-2 m. In travel time measurements this represents errors of the order of 1 ms. By using moored instruments, errors in positioning will be introduced because the arrays moves in response to the currents. This is a well-known problem in acoustic tomography, which is discussed in detail by Munk et al. (1995). For practical implementation of a moored system we have to consider technologies which take care of these positioning problems. One can assume that this problem is less in the Arctic basin than in the Fram Strait and other areas with strong currents due to mesoscale eddies. Other important questions that have to be considered are clock precision, and storage and retrieval of data including the possibility to obtain near real time data. This has to be taken care in detailed planning of a future experiment.

7.2 Monitoring averaged ice thickness

The modelling studies have shown that travel time measurements at low frequencies are not ableto pick up any information about the sea ice thickness or internal properties. A sensitivity study has shown that the acoustic signal is sensitive to the sea ice thickness at frequencies above 100 Hz. In the case of monitoring ice thickness by active acoustics two measuring concepts can be selected: 1) travel time and 2) broadband transmission loss. In addition a passive method based on ambient noise can be used.

Travel time measurements

Travel time changes due to ice thickness changes are introduced due to beam displacement at the sea ice interface. In a theoretical work by Jin et al. 1993 the travel time concept was described and studied for a center frequency of 250 Hz. According to this work the travel time changes requires an accuracy of at least 1 ms to retrieve information about the sea ice changes using a center frequency of 250 Hz and ranges of 120 km. This can be very hard to obtain by existing technology.

Transmission loss measurements

In AMOC the main focus has been on investigating if and how transmission loss measurements can provide ice thickness information. By using a broadband source and by measuring frequency dependent transmission loss one can obtain information about the frequency filtering processes caused by the sea ice. An inversion scheme based on such measurements will relay on the frequency dependent attenuation of the acoustic energy caused by the signal interaction with the water-ice interface as described with by the modulus of the complex reflection coefficient (reflection loss). The reflection loss depend on the sea ice thickness, elastic properties of the ice (compressional and shear wave speeds and corresponding wave attenuation rates) and sea ice roughness. The sensitivity in frequency filtering of the acoustic signal to elastic properties and roughness is less than the sensitivity to sea ice, but has to be investigated in more detail when developing new ice thickness inversion algorithms. One also has to consider the effect of a non-homogeneous ice plate. From our results it is most likely that future inversion schemes will need additional information about ice extent and ice classification (available from remote sensing from space) and corresponding elastic properties of the different classes of ice (detailed measurements are required).

Basin wide ice thickness averages from acoustics are not realistic, but the method can provide more regional averages over typical distances of 200-300 km. In order to get the best ?averagedice signal" the source and receiver should be positioned within the duct, and furthermore we propose to use one source and several receiver arrays in different directions (ex. star pattern). This method benefits from the strong ducting of acoustic energy in the surface duct, and the continuous interaction with the sea ice.

Furthermore, this method is less dependent on an accurate positioning than previously suggested travel time measurements. On the other hand the travel time concept would, at least theoretically provide a more accurate measure of the sea ice thickness. From the results available now, it seems that broad band transmission loss measurements will be the best and most robust approach to get regional sea ice information.

Ambient noise measurements

Another method discussed in the beginning of Task 3 (Sagen, 1998) is based on the observed correspondence between averaged ambient noise in the frequency band from 20 Hz up to 5 kHz with ocean stratification and sea ice properties. This makes the monitoring of changes in broad band ambient noise characteristics very interesting as additional component in future acoustic monitoring concepts in the Arctic Ocean. Ambient noise measurements have several benefits. First of all it produces no additional man-made noise in the Arctic ocean. Secondly, receiver arrays are much cheaper than configurations using large, low frequency acoustic sources. Thirdly, ambient noise recording systems needs much less energy supply and can also easily be mounted at the sea bottom or under the ice. Finally, the ambient noise can be used in a variety of ways both to identify dynamic processes causing break up, swell, ridging and to retrieve changes in averaged ice parameters and ocean stratification.

8. Overall conclusions and future perspectives

The conclusion from the modelling studies is that acoustic monitoring of the ocean climate is possible both in the Arctic Basin and in the Fram Strait using a deep source (500 m). A deep source gives the best results for long term monitoring of the climate, while the shallow source will provide information about the seasonal changes in the upper water masses. A shallow source (60 m) does not provide the climate signal. For TAP-A and TAP-B the first (early) arrivals at all receivers will contain information about the climate warming. For the Fram Strait one should consider the mean arrival time at receivers between 200-700 m.

An acoustic monitoring system must satisfy the following requirements:

- Propagation paths between source and receiver must avoid shelf areas and other bathymetricaleffects at water depths shallower than 1500 m.
- Sufficient signal to noise ratio, which does not require post processing, can be achieved byusing a transmission level of 160 db in Fram strait and 180 - 195 db in the interior of the Arctic.
- Deployment depth of source and receiver is a crucial factor for successful transmission. In theArctic Basin relevant deployment depths should be at 500 m or deeper to capture mode 2 and 3 waves propagation through the Atlantic water masses. Shallow deployment in the upper water masses will not capture the expected warming of the Atlantic water, which is predicted by the climate model simulations. A similar configuration can be used in the Fram Strait. Due to strong mesoscale eddy activity, it can be difficult to separate arrival times of the different rays for every transmission. However the simulations show that there is enough rays which can be recognised to observe long-term changes in temperature.
- Choice of frequency must be adapted to the parameters to be observed. For ocean temperatureobservation 20 Hz can be used for propagation across the whole Arctic with minimum influence of sea ice. In the Fram strait it is possible to use higher frequencies (100-250 Hz), especially in the ice-free part (West-Sptizbergen Current). To observe ice thickness frequencies from 100 - 3000 Hz can used to obtain region estimates. New inversion methods need to be studied.

The modelling work in this project should be continued by performing field experiments and more studies of inversion schemes both for ice thickness, temperature and current The above show that acoustic techniques can be used more or less as stand alone ocean climate monitoring concept. Another, but similar approach, is to use acoustic measurements in combination with ocean circulation models. The technique of using advanced assimilation of ocean parameters derived from acoustic measurements into ocean models has previously been suggested and recommended as a future method by Munk et al. (1995). In a recent study performed by Park and Kaneko (2000) coastal acoustic tomography data was assimilated into an ocean circulation model using ensemble Kalman filtering (Evensen, 1999). We propose as future investigation to develop assimilation schemes of acoustically sensed ocean parameters (current and ocean temperature) along key tracks in the Nordic Seas (eq. Fram Strait) into ocean circulation models to improve the ocean forecast results.

9. Acknowledgement

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Appendix: AMOC publications and reports

Published articles:

Authors	**Title**	**Publication**
Naugolnykh, K. A., E. C. Shang, Y-Y Wang, Esipov, I. B., Johannessen, O. M.	Numerical Simulation of the Parametric Array Application for Ocean Monitoing In the Fram Strait Environment.	Acoustical Physics, No. 3, Russia Academy of Science, 1999.
Naugolnykh, K. A., Johannessen, O. M., Esipov, I. B , Ovchinnikov, O. B., Tuzhilkin, Yu. I., and Zosimov (1998).	'Numerical simulation of Remote Acoustical Sensing of Ocean Temperature in the for the Fram Strait Environment	J. Acoust. Soc. Am**.** **104** (2), pp. 738-746, 1998.

Published reports, proceedings, abstracts, presentation at conferences:

Authors	**Title**	**Publication**
Johannessen, O.M.	Acoustic Monitoring in the Arctic,	In the Proceeding of European Climate Science Conference, Vienna, Austria, October 1998
Sagen, H.	Ambient Noise in the Marginal Ice Zone	Doctoral dissertation, 1998.
Johannessen, O.M, K. Hasselmann, P. Wadhams, L. Bobylev	AMOC First 6 Month progress Report. 1 Nov. 1997 - 30 Apr 1998	NERSC Special Report no 60.
O. M. Johannessen, K. Hasselmann, P. Wadhams, L. Bobylev	AMOC: Annual Progress rep. no. 1 1 Nov. 1997-30 Oct. 1998	NERSC Special Report no 61
O. M. Johannessen and V. J. Haugen	AMOC 1997. Seasoar and CTD data in the Fram Strait.	NERSC Special Report no 62
Hamre, T. et al.	AMOC: Technical report Task 1	NERSC Technical Report no.162
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