The Fram Strait acoustic tomography system

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The Fram Strait between Greenland and Spitzbergen is the main exchange gate for water masses, sea ice and heat flux between the Arctic Basin and the sub-Arctic seas. Although major resources are invested in measurements of current and temperature in the strait, the flux estimates still have significant deficiencies and errors. New observing technologies are now under testing and preparation for use in the Fram Strait. As part of the DAMOCLES Integrated Project (Developing Arctic Modeling and Observing Capabilities for Long-term Environmental Studies), a first step acoustic tomography system is to be installed in the Fram Strait in August 2008. An extended acoustic system serving both tomography and glider navigation is planned to be implemented in 2009 under the ACOBAR project (Acoustic technology for observing the interior of the Arctic Ocean). We will present the specification of the tomography systems; the experimental plan, and plans for data analysis, including data assimilation.

1   Introduction

In September 2007 the Arctic sea ice showed a record minimum which has not been observed since satellite monitoring of sea ice started in 1978 (Fig. 1). This minimum ice extent was more dramatic than the general trend over the last three decades where the reduction in ice area has been about 3 % per decade. In the recent "Arctic observation integration workshop" in New York in March 2008, the sea ice reduction and its consequences for future Arctic observing systems was a key issue.
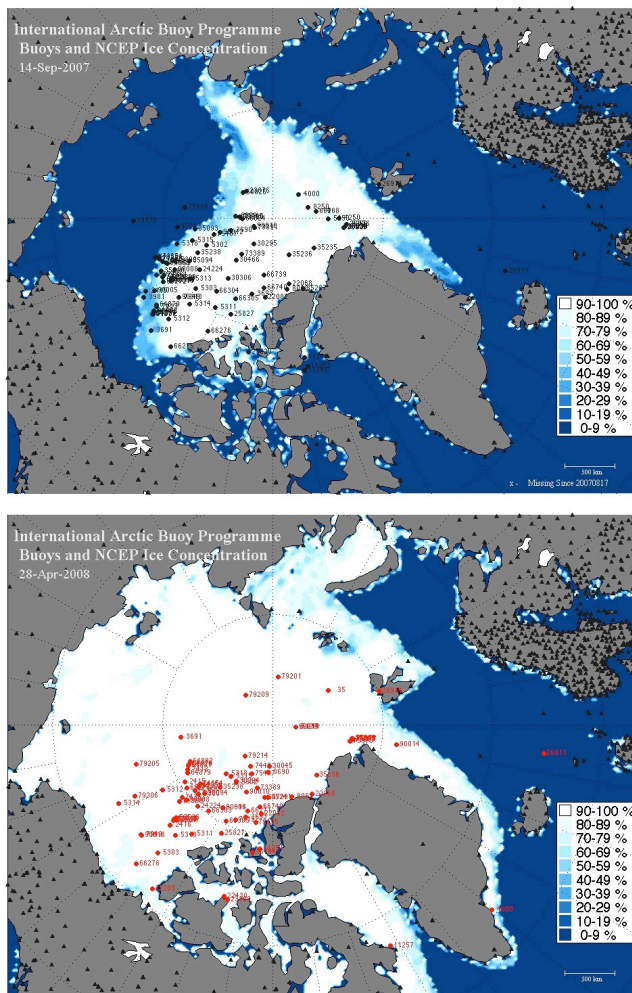

Fig. 1. Sea ice concentration maps from satellite passive microwave data including positions of buoys in the International Arctic Buoy Programme. The maps show minimum ice extent in September 2007 (upper figure) and the ice extent in April 2008 (lower figure)
(http://iabp.apl.washington.edu/)

A reduction in sea ice extent and thickness has been observed the last decades, e.g. [1], [2]. The sea ice reduction is a response to the warmer atmosphere observed in the Arctic as well as to changing water masses and fluxes in sub-Arctic and Arctic seas [3]. In the next years a larger portion of the sea ice during winter-time is expected to be thinner first year ice with larger seasonal and annual variability. Furthermore, the workshop participants concluded, that the ongoing transformation of sea ice conditions in the Arctic must have impact on how we design and implement sustainable components of Arctic Ocean Observatories in the future.

The International Arctic Buoy Programme maintains a number of ice buoys in a network providing meteorological and oceanographic data in real time available at http://iabp.apl.washington.edu/. This programme is a very important component of an Arctic Ocean Observatory. However, the ice buoy need the presence of thick and stable ice floes to survive in the Arctic over seasonal and inter-annual time scale. The reduction of multiyear ice in the Arctic in recent years introduces a bias in the data set towards the Canadian and Greenland sectors of the Arctic (Fig.1). In 2007, the summer ice minimum was associated with above average sea ice export in the Fram Strait.

The challenges of monitoring regions with a relatively thin and dynamic sea ice cover have been considered in the marginal ice zones (MIZ) of the Arctic Ocean over several decades. In the MIZ, including areas such as the Fram Strait, the solution has up to now been to deploy and maintain a dense array of anchored moorings. The limitations of conventional mooring systems are lack of real time data provision, under-sampling of dynamic regions with high meso-scale activity, and high costs associated with maintaining a large number of moorings.

One of the largest challenges is to obtain ocean data in real time or near real time from underwater installations. There are several methods under development such as winches or buoyancy platforms bringing data to the surface for satellite transmission; chains of acoustic modems to reach a central unit that can surface in open water, and use of pop-up buoys. A small chain of acoustic modems sending data to a surfacing unit are currently being tested in the icefree part of the Fram Strait as part of the DAMOCLES project (Fahrbach and Beszczynska-Moeller pers. comm., 2008). Acoustic modems are less efficient than standard modems used in telecommunication, but there are extensive efforts to improve the efficiency of acoustic modems both in range and the data rate.

Gliders provide a possibility to obtain a wide range of ocean data with a very high spatial resolution, only limited by weight and power consumption. The gliders can move

with a speed of around 1 km/hour along a saw tooth trajectory over large distances ($\approx$ 4000 km) [4],[5]. However, the gliders have problems with navigation in regions where the speed of the glider is of the same order as the ambient current velocity. Furthermore, the gliders cannot navigate by surfacing and using the GPS system in ice-covered areas as it does in open ocean. Use of gliders in the Arctic depends on development and implementation of short range and long range acoustic navigation systems [6].

While a glider spend 8 - 14 days to cover a 200 km, sound pulses travel the same distance within 138 s. Together with appropriate inversion techniques acoustic tomography/thermometry can provide unique, synoptic and integrated measures of internal ocean temperature at an accuracy of 0.01°C along the acoustic tracks [7]. Alternatively, the acoustic measurements can be assimilated directly into ocean circulation models. In acoustic tomography, increased resolution in the horizontal and vertical is obtained by increasing the number of acoustic tracks. Acoustic tomography has previously demonstrated its capability in the Arctic to study the ocean processes in the Greenland Sea [8], Barents Sea [9] and the Labrador Sea [10].

While tomography is superior to the glider technology in temporal resolution the glider provide ocean data at a much higher spatial resolution. A region with strong mesoscale activity requires both high temporal and spatial resolution of the observations. Therefore, we have proposed to establish a integrated data and model system combining acoustic tomography, gliders, point measurements and high-resolution ice-ocean modelling with data assimilation techniques to improve the accuracy of the heat, mass and freshwater transport estimates through the Fram Strait..

An upgraded Fram Strait Observatory will consist of conventional moorings and profiling moorings in the shelf areas, whereas gliders and acoustic tomography will cover the deeper part of the Fram Strait. Gliders and tomography system will be implemented in two EU projects, the ongoing DAMOCLES and the upcoming ACOBAR project. This paper presents the DAMOCLES Fram Strait acoustic system to be deployed in 2008, the integrated data and modeling system and the extended Fram Strait acoustic system to be deployed in 2009 as part of the ACOBAR project.

2 DAMOCLES: Fram Strait tomography experiment

In the last 10 years or so, an array of 14-17 moorings have been in operation in the Fram Strait along the 78° 50' N [11]. The Alfred Wegner Institute and the Norwegian Polar Institute have maintained the array, which consists of about 40 oceanographic instruments. Although major resources are invested in the measurement system the flux estimates still have significant deficiencies and errors [3].

An acoustic tomography system for monitoring of the fluxes through the Fram Strait was proposed by O.M. Johannessen in the mid 90s. A detailed numerical study was carried out within the EU project Acoustic Monitoring of the Ocean Climate in the Arctic - AMOC [12],[13], [14]. Based on numerical results from this project the Fram Strait tomography system was designed and implemented as part of the DAMOCLES project (Fig. 2).

2.1 Acoustic tomography system

The low frequency source to be used is a sweeping source from Webb Research Corporation, USA [20]. The source can produce a sweep from 190 Hz to 270 Hz with adjustable time duration of the transmissions. The source can also easily be programmed to produce CW signals or RAFOS signals. On axis maximum level is 190 dB // 1 µPa at 1 m from the source. To obtain accurate clock and positioning of the source in the water column, the sound source is integrated with STAR electronics in one pressure housing as one unit. The sound source will be located 400 meters under the sea surface.
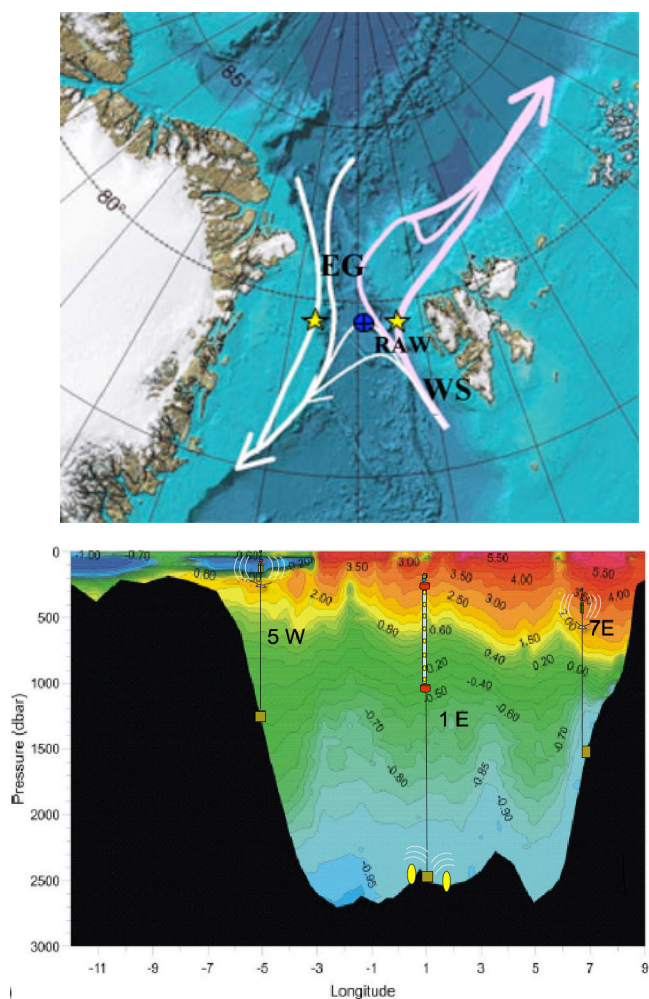

Fig. 2. (a) Map over the Fram Strait with the two sources (yellow stars) and the vertical array in the middle of the strait. The pink arrows show the West Spitzbergen Current (WSC). A Return of Atlantic Water (RAW) takes place in the centre of the strait, and Arctic water masses and sea ice is transported south by the East Greenland Current (EGC).

(b) Temperature section from CTD data and the tomography system across the Fram Strait at 78° 50' N.

The *Simple Tomographic Acoustic Receiver* (STAR) technology is developed by Scripps Oceanographic Institution. A standard STAR comes win a tube containing the electronics and lithium batteries and cable with hydrophones spaced by 1.5 wavelength. The standard STAR provides a precise clock, using a two-oscillator system (MCXO plus Rubidium). This time keeping concept provides a precision/stability better than 3 ms over a year. Furthermore, the STAR system with four acoustic transponders surrounding each mooring location provide a

long-baseline acoustic navigation system to measure the position of the control unit with an accuracy of 0.5 - 1 m. The four transponders will be deployed 0.5-1.0 km away from the anchor position of each mooring.

In DAMOCLES a long aperture is chosen to increase the amount of information available for the inversions and assimilation. A 686 m long vertical receiver array is obtained by joining two individual STARs tail –by – tail, where the hydrophones on each STAR are spaced by 96 m.

Acoustic modems, produced by Aquatec are attached to each STAR and to the sources. The STARs can be programmed to process reception data from each of the 8 hydrophones. The 20 dominant peaks will be identified and provided along with 7 points around each peak. Data can be downloaded on request with a modem deck unit from ship.

2.2   The acoustic experiment

A first attempt to deploy the tomography system was done in October 2007, however the deployment was interrupted due to strong winds and heavy sea. A new deployment is planned in August 2008 using R/V Håkon Mosby. The source mooring will be positioned at 78 45 N and 7 E, and the vertical receiver array will be positioned at 78 45 N and 1 E. The separation between the moorings is 129.7 km. Source depth will be 400 m, and the receiver array will have its upper hydrophone depth at 300 m. The source will transmit 60 s long sweeps every third hour. The receivers are scheduled to record for 80 s, providing 10 s before expected first arrivals and 10 s after last arrivals. A second field operation is planned in September 2008 using the KV Svalbard in order to position the transponders, obtain bathymetry and oceanographic data between the to stations, download first set of acoustic data using the acoustic modems, and listen to the source at different locations inside and outside the ice edge.

2.3   Integrated data and model system

The TOPAZ model system is an operational real time ocean monitoring and forecasting system covering the Atlantic and Arctic Oceans with spatial resolution of 10 to 16 km (http://topaz.nersc.no, [15]). The model system consists of an ocean circulation model, the HYCOM model [16], and an ice model based on the Elastic Visco Plastic (EVP) rheology for the dynamic part. The thermodynamic part uses a simple parameterization with a single ice thickness class. The ocean model is forced by atmospheric data with a resolution of 0.5x0.5 deg, available from the European Center for Medium range Weather Forecasting (ECMWF). Advanced data assimilation techniques are used to incorporate near real-time observations into the coupled ocean sea-ice model. The near real-time observations assimilated in TOPAZ are Sea level anomalies (SLA), sea surface temperatures (SST) sea-ice concentrations and soon in-situ T/S profiles from XBT and Argo floats.

However, a model resolution of 10-16 km, as in TOPAZ, is too coarse to resolve properly the mesoscale circulation in the Fram Strait. Therefore, a regional high-resolution (2 - 4 km) Fram Strait model has been implemented with nesting to the TOPAZ system. Nesting means that the high-resolution model takes its boundary conditions from the coarser, large-scale model. The Fram Strait model will run during the acoustic experiments, and receive its nesting conditions from the latest available TOPAZ system.

2.4   Data Assimilation.

The assimilation of data from the acoustic tomography array into ocean circulation models was originally recommended by Munk et al., [7] Studies of this topic have been carried out by for example [17] and [18]. In the present project we will use the Ensemble Kalman Filter (EnKF), which is described in detail in [19]. Its Monte-Carlo formulation makes it very convenient for assimilation of integrated (and nonlinear) ocean parameters such as acoustic travel times. EnKF has previously been applied to assimilate acoustic data into a barotropic ocean circulation model using very simple ray theory [17]. Although a very simplified ray model was used the results were promising, showing better result than using traditional acoustical inversion techniques.

Our approach will be to assimilate the measured acoustic travel times, corrected for clock drift and mooring motion, directly into the ocean model. We plan to use the "full" acoustic arrival time pattern, as described by the around 20 most pronounced peaks with intensity above a given signal to noise ratio, from all the 8 hydrophones. The Ensemble Kalman Filter (EnKF) is based on the Kalman Filter analysis scheme and is written as

$$\mathbf{A}^a = \mathbf{A}^f + \mathbf{K}\left(\mathbf{d} + \mathbf{D} - \mathbf{H}\mathbf{A}^f\right) \text{ where}$$

$$K = \mathbf{P}^f \mathbf{H}^T \left(\mathbf{H}\mathbf{P}^f \mathbf{H}^T + \mathbf{R}\right)^{-1} \tag{1}$$

A is a multi –dimensional matrix holding all the ensemble members (ocean states), K is referred to as the Kalman gain; index a refers to analyzed ensemble of ocean states, f refers to the ocean forecast; **d** is the acoustic observations, and **D** is a synthetic perturbation of the acoustic observations **d** (mean(D)=0). P^f is the forecasted error covariance matrix and R is the observation error covariance matrix. The acoustic observations are related to the ocean through a functional **H**, which contains interpolation of oceanographic fields to a regular grid, the conversion from temperature- and salinity fields to sound speed and the acoustic propagation model. This functional is used to establish the modelled observations (HA^f) used in the analysis. From Eq. 1 we see that it is the difference between the measured travel times and modelled travel times that impose corrections to the ocean model.

Modelled ocean states. After some test runs carried out with the Fram Strait model, it became clear that this model is too computationally demanding to assimilate acoustic data (or any other data) into the EnKF scheme. The EnKF scheme requires that 100 ensemble members are integrated forward in time both for the outer model (TOPAZ) and for the nested high resolution model. Our approach in DAMOCLES is therefore to assimilate the acoustic data into the coarser TOPAZ model.

In parallel, the high-resolution model will be run as a single member forward integration during the acoustic experiment. We will use the modelled high-resolution oceanographic fields to calculate the expected arrival times and compare these both to the observed travel times and to the modelled arrival times from TOPAZ. This will provide necessary information if we will gain any improvement by increasing the resolution of the ocean model and if we should proceed with another assimilation scheme for the inner model.

Corresponding to this, the ocean states, used in our work comes from the TOPAZ system, which is based on the Hybrid Coordinate Ocean Model (HYCOM) [16]. The vertical discretization algorithm in HYCOM chooses the optimal hybrid layer distribution at every time step: The hybrid coordinate is isopycnal in the open, stratified ocean, but makes a dynamically smooth transition (via the layered continuity equation) to a bathymetry-following coordinate (sigma-layer) in shallow coastal regions or to a depth coordinate (z-layer) in the mixed layer and/or non-stratified seas. As acoustic models (usually) requires data on a regular vertical axis the model data has to run through an interpolation scheme. Un-smoothed oceanographic fields may cause unwanted acoustic effects such as diffraction from artificial sharp edges in the ocean. A summer student project, carried out by Camille Marini, tested several interpolation schemes and based on this study it was found that a special second order interpolation gave the best result. As input to acoustic models we will need sound speed profiles. Several empirical relations establish connection between ocean temperature, salinity and pressure (depth). We have used the Mackenzie, K.V. "Nine-term Equation for Sound Speed in the Oceans", J. Acoust. Soc. Am. 70 (1981), 807-812. All sound speed data are provided on a grid having 500 m resolution in the horizontal, 2.0 m in the upper 1000 m of the ocean and 20 m from 1020 m and down to the sea floor. The student study also showed clearly that the interpolation scheme and the choice of grid that the modelled oceanographic fields are interpolated to have a large impact on modelled arrival time structure.

Acoustic model. A large number of acoustic models of various complexities exist. As the acoustic model will be run once for each ensemble member it should not be too computationally demanding. It is also essential that the model is able to generate the main characteristics of the arriving signal and to account for range dependency in ocean and bathymetry. Ray trace models are usually the most efficient codes in range dependent environments, and our first choice is therefore the RAY model, which is based on traditional ray tracing. The model use range dependent sound speed profiles and bathymetry as input and calculate eigenrays and corresponding travel times (and intensity) for a given source depth and the required number of hydrophones. This will simulate the measured registrations of acoustic travel times.

3   ACOBAR: Fram   Strait observatory

As part of the recently funded project ACOBAR an extended acoustic system will be implemented for tomography and for navigation of gliders and floats in the Fram Strait. Deployment is scheduled in September 2009. The first outline of the system is described in Fig. 3. The system will consist of three transceivers formed as a triangle and the long mooring array in the middle of the triangle.
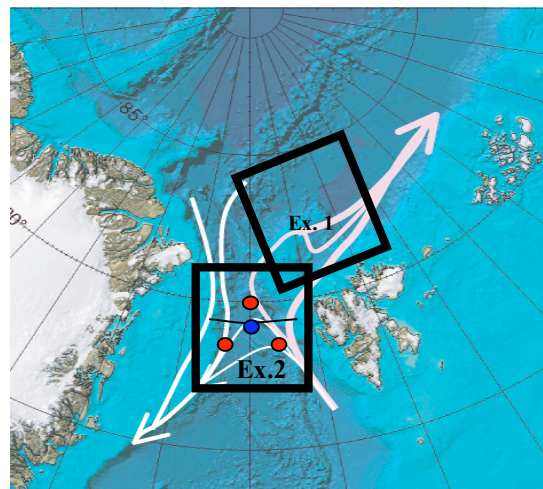

Figure 3. The Experiment areas of the ACOBAR project. Ex. 1 is the Arctic component where modified AITPS will be deployed and Ex. 2 is the Fram Strait observatory where the tomography and the gliders will be deployed.

4   Marine mammals issues

The propagation range for the Fram Strait tomography array is ~130-200 km. This range can be covered with a source level a few dB lower than the maximum level of 190 dB // 1 μ Pa at 1m. These source levels and frequencies have previously been used in several other experiments in the Labrador Sea [10] and the Greenland Sea [8], without any report on effects on marine mammals. Large marine mammals produce sounds up to 186 dB at frequencies between 200-1000 Hz, which is of the same order that the sweep source will produce. According to this, the impact of the transmissions is expected to be minimal. The transmissions will follow the Norwegian regulations for use of acoustic sonars, which have been formulated based on an extensive Environmental Assessment study. Furthermore, external and independent experts will carry out an environmental assessment within ACOBAR project and a marine mammal expert will sit in the project steering committee.

5   Conclusion

The Fram Strait tomography experiment under DAMOCLES has been prepared and will be implemented in August 2008. The first data obtained by acoustic modems will be available in October 2008. An extended acoustic system is planned to be deployed in September 2009 as part of the new project ACOBAR. The extended system will support both 3 D tomography and navigation of gliders and floats in the Fram Strait.

Acknowledgments

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