Spatial and temporal variability of currents and transport of warm waters towards the Arctic Ocean with focus on the flow towards the Greenland-Scotland ridge and the through flow area at the eastern side of the Fram Strait: Analysis and synthesis

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Preface

This synthesis and collection of papers constitute a thesis in partial fulfilment of the requirement for the degree philosophiae doctor (PhD) in oceanography at the Geophysical Institute, University of Bergen, Norway.

I want to thank my supervisors, Harald Svendsen, Svein Østerhus and Tom Rossby for all the help and the support they provided during the years of work on this thesis. Thank you for always taking time and having patience with me.

During this work, I have had two stays abroad of three months duration each. The first was at the Graduate School of Oceanography in Rhode Island, USA, where I worked together with Tom Rossby on the first analysis of the ADCP data.

The second was at Laboratoire d' Oceanographie Dynamique et des Climatologie in Paris, where I worked together with Gilles Reverdin on data from expendable bathythermographs and altimetry.

Pierre Jaccard has been a valuable source on information on ADCP setup and processing of data, and Bogi Hansen has contributed in discussions on analysis of the ADCP data.

I also want to mention the great student interrelations at the Geophysical Institute, which has been an inspiration through the years. Finally, thanks to family and friends for support along the way.

List of papers

Paper I

Søiland, H., P. Budgell, and Ø. Knutsen, (2008) The physical oceanographic conditions along the Mid Atlantic Ridge north of the Azores in June-July 2004, Deep-Sea Research II 55 (2008) 29-44, doi:10.1016/j.dsr2.2007.09.015

Paper II

Knutsen, Ø., H. Svendsen, S. Østerhus, T. Rossby, and B. Hansen (2005) Direct measurements of the mean flow and eddy kinetic energy structure of the upper ocean circulation in the NE Atlantic, Geophys. Res. Lett., 32, L14604, doi:10.1029/2005GL023615.

Paper III

Knutsen, Ø., H. Svendsen, G. Reverdin, S. Østerhus, and B. Hansen, Direct observation of volume and heat transport in the NE North Atlantic, manuscript.

Paper IV

Knutsen, Ø., H. Svendsen, and F. Nilsen, Circulation and cross-shelf exchange on the shelf off West-Spitsbergen, conditionally accepted for publication in Polar Research.

Contents

1. Introduction and outline

1.1 Introduction

The advection of warm subtropical waters east- and northward along the Subpolar Front and its transport routes through the Nordic Seas towards the Arctic Ocean, plays a central role in moderating the climate of the European subcontinent and the Arctic, reflecting the fact that the northern North Atlantic is much warmer than any other ocean at corresponding latitudes. Further, it is known that there exist low frequency (seasonal to decadal) variations in the circulation and hence poleward transport of mass and heat (Bersch et al. 1999). Studies of past climate using paleodata suggests that large and rapid climate changes have occurred throughout history and that changes in the thermohaline circulation of the ocean play a major role in many of these cases. Some of these rapid changes occurred over a period as brief as decade, whereas we tend to think of significant climate change as occurring over centuries or millennia. The third assessment report of the intergovernmental Panel on Climate Change (IPCC) released in 2001, discussed the potential slowdown of the North Atlantic thermohaline circulation under a global warming scenario (http://www.ipcc.ch/). The new U.K. Rapid Climate Change Programme (RAPID) is in part, a response to such concerns. Unfortunately, the lack of accurate information on currents (currents and transports are rarely measured, they are inferred from the density field) has made this variability difficult to define and quantify. Nonetheless, growing evidence from a wide range of hydrographic studies in recent decades suggests that the ocean does respond to changing atmospheric conditions. Using the atmospheric pressure difference between Portugal and Iceland as a measure of the strength of the westerlies (expressed in terms of an index known as the North Atlantic Oscillation or NAO index), it has been shown that heat losses to the atmosphere are large in the Labrador Sea when the NAO is high, whereas heat losses are more pronounced in the Norwegian and Greenland Seas when the NAO is low (Dickson et al. 1996). What is not so clear is how the ocean circulation responds to these decadal long variations in atmospheric forcing. For example, the Nordic WOCE program has recently reported that, at the present time, the heat transport into the Nordic Seas does so in like amount to both sides of the Faroes Islands. But there is considerable debate about how these waters approach the Greenland-Iceland-Faroes-Scotland ridge (Hansen and Østerhus 2000). Some studies (Krauss 1995) suggest that an eastern branch of the warm waters flowing north along the Reykjanes Ridge is responsible, other studies suggest that the waters approach the Iceland-Faroes ridge from the southeast. Perhaps both views are, in some sense, correct, but apply at different times depending upon the prevailing winds at the time. It is therefore an interesting fact that even today our knowledge about how warm waters are transmitted north towards the Greenland-Iceland-Faroes-Scotland ridge tends to be communicated in terms of sketches, rather than as quantitative statements about the mean circulation and its variability. The reasons for this can be traced to uncertainties associated with the dynamic or geostrophic method, which depends upon assumptions about the velocity field at some depth. There are ways to work around this limitation using inverse methods, data assimilation into dynamical models, or by integrating the equations of motion given the mean density field, and average forcing at the surface (e.g. Bacon 1997). But these estimates differ by quite a bit, and depend upon varying assumptions about forcing, the relative roles of advection, diffusion, baroclinicity and bathymetry. Out of these diverse approaches, there was a growing recognition that we need to measure the currents directly.

Our knowledge about the transport routes north of Greenland-Iceland-Faroes-Scotland ridge is somewhat better. In the last decade several studies based on direct measurements of currents and CTD-sections, also combined with modelling, have been carried out in the Nordic Seas and in the Arctic. Thus, our knowledge about transport routes and variability of the warm and saline Atlantic water flowing northwards through the Nordic Seas and through the Fram Strait into the Arctic Ocean, has been improved the last years (see e.g. Hansen and Østerhus 2000; Orvik and Niiler 2002; Orvik and Skagseth 2005; Hátún et al. 2005, Walczowski and Piechura 2006).

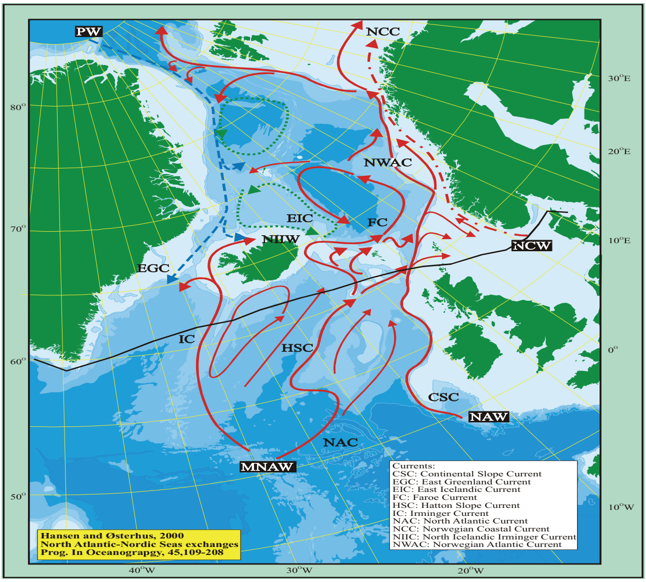

Figure 1 Map of the North Atlantic-Nordic Seas exchanges. The black line shows the ship route. Figure from Hansen and Østerhus 2000.

Topographic steering seems to have a decisive influence determining the transport routes, starting where the zonal eastward flowing North Atlantic current at about 52°N splits into two branches: a western branch through the Iceland Basin and further along the shelf slope of east Iceland and entering the Norwegian Sea through the Iceland-Faroe gap, and an eastern branch guided through the Rockall Trough and along the Irish-Scottish shelf and further through the Faroe-Shetland Channel into the Norwegian Sea.

Measurements indicate that the inflowing Atlantic water appears to maintain the twin-branch structure throughout the Nordic Seas towards the Fram Strait (Poulain et al. 1996; Orvik and Niiler 2002; Orvik and Skagseth 2005). The pathway of both branches is predominately determined by topographic steering. The eastern branch follows the Norwegian shelf slope and is named the Norwegian Atlantic slope Current (NwASC). This current branch continues along the western boundary of the Barents Sea, Barents Sea opening, (BSO) where it bifurcates southwest of the Bear Island into the North Cape

Current flowing eastwards in the Barents Sea, and one branch heading northwards along the BSO into the Fram Strait (the Svalbard branch), Figure 1 (Loeng et al. 1997). The western branch, which is named the Norwegian Atlantic Current (NwAC) tends to follow the slope of the Vøring plateau (Polain et al. 1996) towards Jan Mayen, then north-eastward along the eastern slope of the Mohn Ridge and farther northward west of Bear Island following the Knipovich Ridge toward the Fram Strait. In the Fram Strait the western branch has been traced northwards in the strait in a number of hydrographic sections. Schlichtholz and Goszczko 2006 analyzed a hydrographic section at $76^{o}30$N and found that the western branch reveals a clear signature at this latitude. Even in the northern Fram Strait the western branch has been recognized (Walczowski et al. 2005; Walczowski and Piechura 2006). The merged Svalbard branch and the Knipovich branch of the inflowing saline and warm Atlantic water along the shelf slope off West-Spitsbergen (e.g. Schauer et al. 2004) is named the West Spitsbergen Current (WSC). This current, studied first in-depth by Helland-Hansen and Nansen 1912, is therefore the northernmost extension of the Atlantic inflow to the Nordic Seas. On its way through the Fram Strait the WSC finally submerges and partly enters the Arctic Ocean below the less dense Arctic surface water and partly turns westward and constitutes a strongly modified AW which adds into the southward East Greenland Current under the Polar Water and is also mixed with the AW coming back from one of its longer loops in the Arctic Ocean.

Several studies show that the Atlantic Water is strongly modified during its transport through the Nordic Seas and the Fram Strait especially due to interaction with adjacent shelves. For example in the Fram Strait barotropic instabilities in the geostrophic constrained WSC cause significant onshore transport of Atlantic water manifested as numerous remnants of mixed AW and the Arctic type water (ArW) on the shelf. Related to these remnants is a heat loss from the WSC of the order of 1000 W m^{-2} (Saloranta and Haugan 2001).

Given the enormous importance of the region to the northern European and Arctic climate, the overall objective of this thesis is to improve our understanding of the spatial and temporal variability of currents and transport of warm water towards the

Nordic Seas and the Arctic. This is important in its own right, but also for ground-truthing satellite altimetric techniques for inferring surface currents, and as input to and verification of the many numerical studies underway.

1.2 Outline of the thesis

This thesis focuses on transport of warm waters through the North Atlantic towards the Nordic Seas and also on the outflow from the Nordic Seas along the eastern side of the Fram Strait. The thesis consists of two main parts. In the first part two papers are based on a data set collected by the container vessel Nuka Arctica, owned by the Royal Arctic Line A/S, which operates between Aalborg in Denmark and Nuuk on the west coast of Greenland, and one paper is based on field data collected during the MAR-ECO expedition along the Mid-Atlantic Ridge June-July 2004. The second part, paper four, is a combined model and field study and is based on simulations with the SINMOD model and data sampled on cruises carried out in September with R/V Håkon Mosby in the three years 1998, 1999 and 2000.

2 Objectives and methods

2.1 Focus

The primary focus is put on the following:

1) Determine the mean velocity field and eddy kinetic energy levels between Scotland and Cape Farewell. 2) Quantify the volume transport in the various current branches in the North Atlantic. 3) In conjunction with sea surface temperature and XBT profiles estimate the poleward heat transport and its seasonal variability. 4) Exchange of the warm Atlantic Water with adjacent shelves with special focus on the role of wind and topography.

2.2 Principles of ADCP

ADCP is short for Acoustic Doppler Current Profiler and it is an instrument commonly used within oceanographic communities. Our model is the first Vessel-Mount ADCP (VM-ADCP) developed by RD Instruments (RDI, now Teledyne RD Instruments) and released in 1983, and it is a farther development of the older Doppler speed log designed to measure ship velocity through water or over ground. The ADCP transducer emits pulses of ultrasonic sound at 150 kHz [1] which is scattered by particles (mostly zooplancton) floating with the water. A key assumption is that the particles on average float with the water and has no motion on its own. When particles move toward the ADCP, the sound is Doppler shifted to a higher frequency, both before the pulse hits the particle and after the particle has reflected the sound toward the ADCP. The amount of the frequency shift is proportional to the relative velocity between the particle and the ADCP and is given by the equation

$$F_D = 2F_S\,(V/C)\,cos(A) \qquad (1)$$

where F_D is the Doppler frequency shift, F_S is the frequency of the sound when everything is still, V is the relative velocity between the sound source and the sound receiver, C is the speed of sound and A is the angle between the relative velocity vector and the line between the ADCP and the reflecting particle. The number, 2, reflects that the Doppler shift happens twice, in transmitting and receiving of the sound signal. Figure 2 illustrates schematically this point.

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[1] Different models emit at different frequencies, from 38 kHz to 1200 kHz

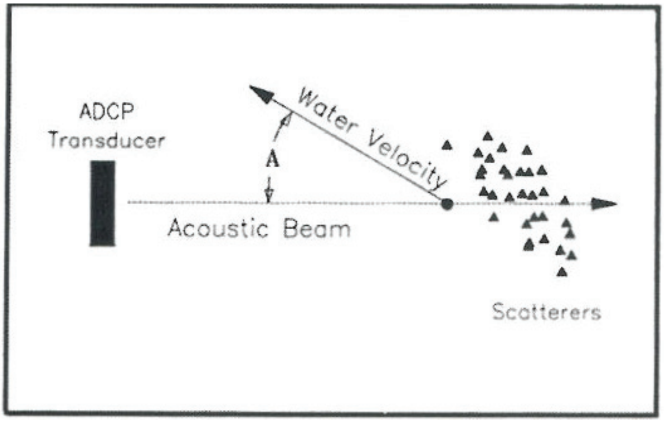


Figure 2 Illustration of the system of ADCP and scatterers. From RD Instruments 1989.

An ADCP has four such acoustic beams, which in our case have a 30° angle out from the vertical. Each beam measure a velocity component, and each of the beam pairs of two opposing rays measure one horizontal velocity component and one vertical. Assuming horizontally homogeneous currents (the same in all four beams), one get the two-dimensional horizontal flow and two estimates of the vertical component. The difference between the two vertical components is defined as the error-velocity.

As the beams have an angle to the vertical, the area of the reflecting particles is not a square, but a diamond. This gives more reflective area in the middle of the bin than the upper and lower part, and hence the velocities of the bins are biased towards the middle. Due to this skewness of the reflecting area, the bins are overlapping and thus not independent.

While the ADCP emits signals on one frequency, the backscattered signal is distributed over a range of frequencies with amplitude decreasing away from the Doppler shifted average. The midpoint in the returned bell curve of frequency distribution represents the Doppler frequency average. The width of that bell curve represents the spectral broadening and much of this spectral broadening is caused by the short duration of the transmit pulse. Reducing the transmit pulse by a factor 2 doubles the spectral width. This is related to the measurement uncertainty, where a doubling of the spectral width implies a doubling of the uncertainty in the estimate of the Doppler frequency, which translates directly to uncertainty in the velocity measurement. Other causes of spectral broadening are turbulence and acoustic beam width.

The uncertainty of the single ping velocity measurements is too large to be used directly, so many pings are averaged as an ensemble to improve the measurement quality. This method reduces the random error of the measurements, but not the bias. Ensemble averaging reduce the standard deviation of the velocity error by the square root of the number of pings in the ensemble (N); *sd* proportional to $N^{-1/2}$.

Bias is the long-term error that is present after enough averaging has been done to essentially eliminate random error, and is typically on the order of 0.5 - 1 cm/s. It depends on temperature, mean current speed, signal/noise ratio, beam geometry errors, etc, and is not yet possible to measure nor remove in post-processing.

The ADCP measure currents relative to itself, so it is necessary to correct the data for attitude (pitch, roll and heading) and motion (ship velocity) of the instrument. A gyrocompass is used for heading and a vertical gyro for pitch and roll. The heading from the gyrocompass is reliable but not accurate enough, so the heading is farther improved by correction of a four-unit GPS-system. Heading from GPS (Ashtech compass) is more accurate but less stable.

There are three ways to measure ship velocity; bottom tracking, navigation and assuming a layer of no motion. Bottom tracking is used over shelves where the depth is less than about 300 m. This is the preferred method because the current profiles and the bottom tracking data are measured in the same coordinate system. The advantage is that many of the largest errors are the same for the profiles and the bottom-tracking, which cancel out in the subtraction of the ship velocity. Over deeper water in the Labrador Sea, the North Atlantic and in the Norwegian Trench the navigation is used for ship velocity.

2.3 Setup of the ADCP-system on board

The ADCP transducer is mounted in a sealed-off sea chest and the electronic deck unit is placed on deck 3. The deck unit controls the transducer and receives the Doppler shifted signals. The computers are installed on the bridge (deck 12) and receive and store data from the deck unit and the navigation system. When in port in Aalborg, the data is written to disks and sent to the University of Bergen for processing. A detailed description of issues on setup of a vessel mounted ADCP system is found in Flagg et al. 1997.

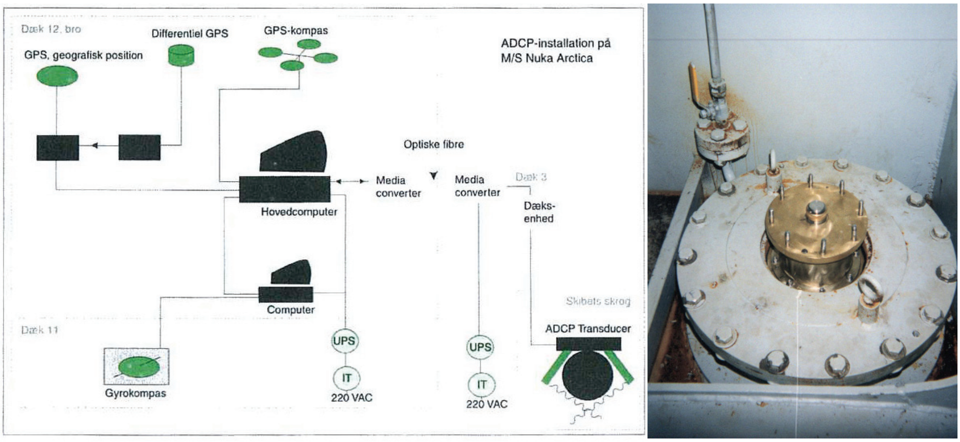


Figure 3 Left: Sketch of the setup of the ADCP system on board Nuka Arctica. Figure from Geologisk Nyt 5/1999. Right: The transducer mounted in a sea chest. A cable is connected at the back of the transducer and the vent pipe allows escape of trapped air. (Photo: Pierre Jaccard)

2.4 Processing of ADCP data

The 5-minutes averages pingdata output from the ADCP system was processed on a unix platform using the CODAS (Common Ocean Data Access System) developed by Eric Firing's group at the University of Hawaii, with additional functionality written by Pierre Jaccard at Geophysical Institute, UoB (now at NIVA). CODAS consists of code in C, Matlab and scripts that can run on a variety of platforms and can process data collected by VmDAS by Narrowband or Broadband ADCP or Ocean Surveyor (all by Teledyne RD Instruments).

The acquisition program (DAS2.48) writes binary files to the disk. There are actually no ocean velocities in the files as the ADCP reports current measured along each of its beams. These currents must be transformed into earth coordinates, and the motion of the ship taken out. Additional information such as heading and position are used to extract the ocean velocity from the measured velocities.

CODAS performs calibration routines to estimate the heading misalignment from bottom track data. This misalignment is used for the nearest part of water track data, typically the misalignment from the North Sea is used for the Atlantic on the same crossing. In occasions of significant difference in misalignment angle between the North Sea and the Greenland shelf we interpolated the angle for use in the Atlantic part of the section. CODAS also performs the correction of the gyro based on the GPS heading. In addition, CODAS makes it possible to edit out bad velocity profiles before any processing takes place.

2.5 Theory of detiding ADCP data

When observations of currents over a few days are available at a given location, it is always possible to represent them by a function of the form:

$$u(t) = u_0 + \Sigma_{i=1}^{N} a_i \cos(\omega_i - \theta_i);$$

$$= u_0 + \Sigma_{i=1}^{N} \{ b_i \cos(\omega_i t) + c_i \sin(\omega_i t) \}, \qquad (2)$$

where

$a_i = (b^2_i + c^2_i)^{1/2}$;

$\theta_i = \tan^{-1}(c_i/b_i)$,

u(t) is the time series of observed eastward current component at a given location, u_0 is its mean over the observation interval, and ω_i; a_i and θ_i are the frequency, amplitude, and phase of the ith tidal constituent, of which there are N included in the representation. The tidal variability from the current record can be removed by projecting the observations onto equation 2, using a least squares requirement on the residuals. This procedure is not directly applicable in the case where the data is also a function of the horizontal coordinates (x; y), as is the case with ship-mounted ADCP data. Therefore we let u_0; v_0; b and c be functions of x and y. We try to resolve the spatial variability with the aid of arbitrary spatial interpolating functions. Equation 2 is then written

$u(r; t) = u_0(r) + + \Sigma_{i=1}^{N} \{ b_i(r) \cos(\omega_i t) + c_i(r) \sin(\omega_i t) \}$,

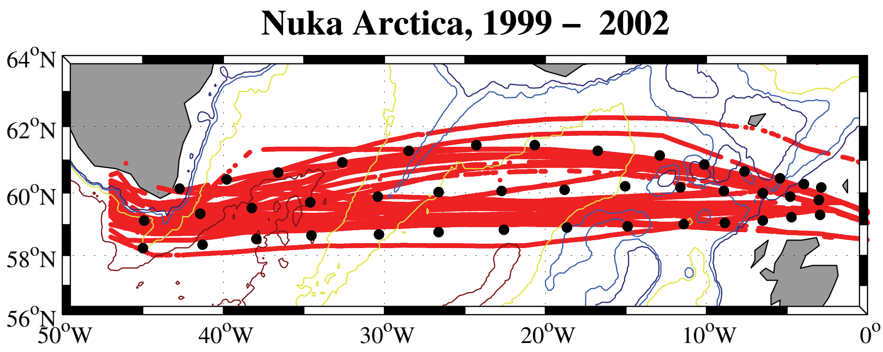
where r is the position vector. The $u_{0,}$ b_i and c_i spatial coefficients are represented as a series of Gaussian basis functions centred at specified locations called knots, see Figure 4.

The aim is not to fit the data exactly at every measurement point, but rather to minimize some mean of the deviations of the approximating functions to the actual data values. This is done by reducing the number of model parameters used, or by arbitrarily specifying *K* locations (*xj* called knots) in and/or near the surveyed area, with *K* less than total number of observations. By doing this, we end up with an overdetermined system of equations that can be solved by imposing a least squares requirement. The interpolating function so obtained is a smoothed version of the common spline fit. However, the resulting interpolation is dependent not only on the number (*K*) but also on the actual locations of the knots.

The system of equations to be solved is of the form *Ac* = *d*, where *A* is a

(m x n) model matrix which depends on the basis functions chosen, m number of observation points and n the model order, c is an n column vector of known coefficients, and d is an m column vector containing the measurements. There will be separate systems of equations for the u and v components, with identical A but different c and d.

The Matlab routine to extract and subtract tidal currents was supplied by Charles Flagg at Brookhaven National Laboratory, NY, USA. The method was developed by Candela et al. 1992, Wang et al. 2004, and Dunn 2002, and farther details can be found in any of those papers.


Nuka Arctica, 1999 – 2002

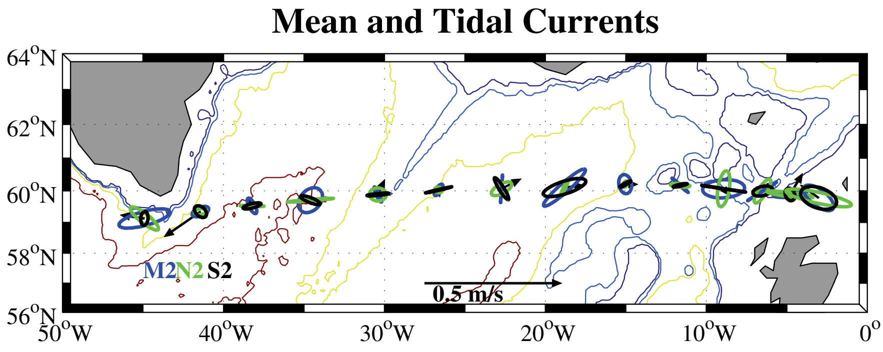

Mean and Tidal Currents

Figure 4 Overview of the position of the knots used for the detiding routine (upper panel) and tidal ellipsis and mean current (lower panel).

2.6 The numeric model

The hydrodynamic numerical model SINMOD used in this study is described in detail in Slagstad 1987 and Støle-Hansen and Slagstad 1991. The model is a 3D, finite-difference, z-level model, based on the continuity equation and the primitive Navier-Stokes equation of motion. The model uses 21 layers in a nested setup, where the model areas and forced flow across boundaries are given in Figure 5. Information on the model setups are given in Table 1 and Table 2 for the large and small model, respectively.

The driving forces are pressure gradients, gravity, friction and the Coriolis force, in addition to the forced flow across the boundaries. The prognostic equations are solved by finite differencing in an Arakawa C-grid. Computational demands are reduced by mode splitting of the fast barotropic mode and the slower baroclinic mode (Berntsen et al. 1981). Farther details can be found in Knutsen et al. in prep.

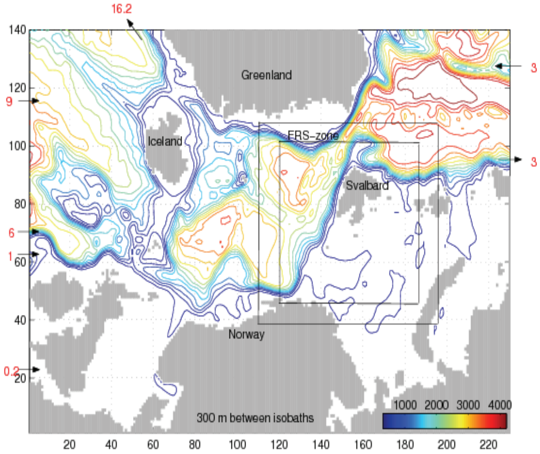


Figure 5 Large and small model area. The numbers on the open boundaries are forced transport in Sv. Figure from Knutsen et al. in prep.

Table 1 Model setup, large model

Depth of layers	10,5,5,5,5,5,5,10,25,25,50,50,100, 100, 100,200,300,500,1000, 1000,1000, [m]
Horizontal grid	20 km
# horizontal grid point	230 x 140
Barotrop time step	1800s:29 = 62.069 s
Barocline time step	1800s = 30 minutes

Table 2 Model setup, small model

Depth of layers	10,5,5,5,5,5,5,10,25,25,50,50,100, 100, 100,200,300,500,1000, 1000,1000, [m]
Horizontal grid	4 km
# horizontal grid point	320 x 300
Barotrop time step	300s:24 = 12.5 s
Barocline time step	300s = 5 minutes

3 Brief summaries of papers

Paper I:

The Physical oceanographic conditions along the Mid Atlantic Ridge north of the Azores in June-July 2004.

Søiland, H., P. Budgell, and Ø. Knutsen

During the MAR-ECO expedition in June and July 2004, 39 deep CTD stations were occupied with uneven spacing along the Mid-Atlantic Ridge between 41°N and 61°N. The CTD stations coincided with the biological sampling stations and thus gave a detailed vertical description of the water properties at these locations. Many different water masses were identified. However, using the predominant water mass in the upper 500 m, four different hydrographic regions were identified. Stations in the vicinity of the Reykjanes Ridge north of 57°N were dominated by Modified North Atlantic Water (MNAW). Stations south of 56°30'N and north of the Sub Polar Front (SPF) were dominated by Sub-Arctic Intermediate Water (SAIW). CTD data combined with along track continuous surface temperature and salinity measurements, satellite sea level anomaly data and sea surface temperature (SST) and along track current data (ADCP data) showed that the position of the SPF was at about 52°N, at the southern edge of the Charlie-Gibbs Fracture Zone (CGFZ). South of the SPF a Frontal Region with both North Atlantic Central Water (NACW) and SAIW present was observed, and south of about 50°N the predominant water mass in the upper 500 m was NACW. A ship-mounted RDI 75kHz ADCP was operated during the cruise and yielded high quality data during the first leg. The currents showed large variations over short distances and were strongly affected by topography. The ADCP data was be used to describe the mesoscale eddy field along the MAR and to detect three jets in the North Atlantic Current (NAC). Data from a current meter mooring left for 10 months after the cruise at a seamount just to the south of Charlie-Gibbs Fracture Zone showed how dominant the tidal currents are in the area. Typical spring tidal currents were about 0.15 ms^{-1} and the mean flow an order of magnitude smaller, about 0.03 ms^{-1}. A short term mooring on a seamount farther south showed tidal currents of 0.3 ms^{-1}. Binned 8-day, 4-km sea surface temperature (SST) satellite imagery were collected and processed for 2004. The SST data were analysed, and showed characteristic frontal structures in the MAR-ECO region

Paper II:

Direct measurements of the mean flow and eddy kinetic energy structure of the upper ocean circulation in the NE Atlantic.

Knutsen, Ø., H. Svendsen, S. Østerhus, T. Rossby, and B. Hansen

The upper ocean circulation in the sub-polar northeast Atlantic has been a challenge to quantify due to strong and variable wind-forcing, and strong and variable deep currents that lead to large uncertainties in the use of the standard dynamical method. Since 1999 we have been operating an acoustical Doppler current profiler on a container vessel that operates between Denmark and Greenland to repeatedly sample upperocean currents across the northeast Atlantic. Individual transects exhibit a highly energetic mesoscale variability, but ensemble-averaging of the sections reveals a striking organization of the mean field along the Reykjanes Ridge: a distinct southward flow along its eastern slope and two clearly defined peaks with seasonal modulation flowing to the north along its western slope. Higher values of eddy kinetic energy (about 150-600 cm^2s^{-2}) are observed along the transect, O(1.5) greater than surface drifter estimates.

Paper III:

Direct observation of volume and heat transport in the NE North Atlantic.

Knutsen, Ø., H. Svendsen, G. Reverdin, S. Østerhus, and B. Hansen

The Nuka Arctica is a container vessel that has an ADCP installed and operates between Denmark and Greenland on a three week schedule. The 58°N-62°N repeated sections of the Nuka Arctica provide a boundary for the northern part of the subpolar gyre, Nordic seas and Arctic Ocean, where a large part of the transformations of upper into deep waters involved in the meridional overturning circulation of the Atlantic sea take place. There are no time series of the heat and mass transport at that latitude estimated from data. From late 1999 this vessel has sampled the upper ocean currents with an ADCP, and here current data from 1999 throughout 2002 is analysed and discussed together with altimetry data (absolute dynamical topography), NCEP reanalysis data, hydrological climatology and XBT data from 2000 to 2005.

The intention with the present work was to calculate the variability of the total volume and heat transport across 60°N based on the ADCP data and XBTs collected between Denmark and Greenland by the Nuka Arctica. A thorough analysis of the data and comparing with data that has been collected in other projects and with other equipments and methods revealed however that the ADCP data sampled at the eastern part of the section probably is of such a bad quality that they are unsuitable for our purpose. Instead we have used the ADCP data in the part of the section where the quality is satisfactorily to estimate the volume and heat transport of the current branches across the section.

We discuss fluxes of volume and heat across the sections based on data from ADCP and XBT's collected from the Nuka Arctica, altimetry data from Aviso, and NCEP reanalysis data in relation to previous estimates. We find good agreement to other direct measurement in the Faroe-Shetland Channel with transport of 3.1 Sv and 106 TW in the upper 400m. The transport of the Irminger Current is estimated to 4.6 Sv and 130 TW, the southerly transport on the eastern side of the Reykjanes Ridge is 2.1 Sv and 65 TW and the North Atlantic Current is 2.2 Sv and 71 TW for the upper 350 m. Transport estimates based on absolute dynamic topography generally fit well to the ADCP measurements for the large scale currents.

Paper IV:

Circulation and cross-shelf exchange on the shelf off West-Spitsbergen.

Knutsen, Ø., H. Svendsen, and F. Nilsen

The Arctic type water (ArW) in the current heading north along the coast off West-Spitsbergen is separated from the Atlantic Water (AW) in the West-Spitsbergen Current (WSC) along the shelf slope off West-Spitsbergen by a temperature-salinity front. The impact of topography and wind on this current system is studied with special focus on exchange and mixing between ArW on the shelf and AW along the shelf slope. The study is mainly based on numerical model simulations and a few observed sections of hydrography and currents which are also used to evaluate the model. The results reveal that the WSC is forced to follow the shelf slope northward towards the Arctic Ocean. Even the effect of strong wind does not change the main flow pattern along the slope. Our study confirms the assumptions of earlier works from the shelf area that frontal instabilities initiated by the combined effect of wind forcing and topographic steering and varying cross-shelf density gradients may cause significant cross shelf exchange. It is argued that on the shelf is it only in the troughs that the impact of topographic steering on the circulation pattern dominates the effect of the wind-driven current component. The wind force has its strongest effect over banks and close to the coast, especially near the northern and southern tip of West-Spitsbergen. The effect of bottom friction, convectively driven mixing and the tide on the circulation and exchange processes are discussed, but the model resolution prevents a detailed investigation.

4 Future perspectives of the Nuka Arctica

The old logging system of the ADCP was replaced with a new one in May 2004. The old system could only operate on 386-computers, while the new one now runs on Pentium-computers with Linux installed. The new software stores all the single ping data instead of only the 5-minute ensembles. This gives more possibilities during the processing, and increase the likelihood of getting good data. Furthermore, the Linux-on-Pentium system is assumed to be far more stable than the Windows-on-386, and thus the acquisition will likely be more successful.

The processing system used for the Nuka ADCP data have been the CODAS which was developed by the group of Eric Firing at the University of Hawaii in the late 80s. There are some important limitations with this software; it requires a lot of time to understand and use, it is no longer continuously maintained and has not been updated since the early 90s, it is mainly developed for instrumentation and data sets from University at Hawaii, it is difficult to extend and it is not appropriate for automatic data acquisition.

At present, there exists no functioning replacement processing system to the old CODAS. However, it has been the intention to develop such a system that provides high quality ADCP processing that is more user friendly. A customized version of this package will then be developed for the Nuka Arctica. In the mean time, a routine for transferring new Nuka ADCP data to the old CODAS format has been developed, and is in a testing phase at present. The intention is to get a preliminary overview of the data collected after May 2004, and the processing will be performed at the University of Rhode Island, USA.

In a more long term perspective, a new 75 kHz ADCP should be installed. This instrument, instead of the present 150 kHz narrowband version, would give the opportunity to measure currents down below the level where warm water can enter the Nordic Seas, and hence provide a reference for a volume transport budget across the North Atlantic. Another important issue is that the new broadband Ocean Surveyor ADCPs are better than the old narrowband in terms of accuracy. It would also simplify maintenance, as it is difficult to find replacement parts for the old instrument.

The thermosalinograph installed on Nuka Arctica does not provide the precision wanted for scientific use. This is probably partly related to some marine growth in the pipes and therefore reduced flow of water through the instrument. There have also been some problems with the operation of the water pump for the pipes leading to the thermosalinograph.

It would be an advantage to not depend on the crew to launch the XBTs, as they do not want to drop the XBTs more often than every third hour. In reality, the drops are not even carried through at that frequency. An automatic release that proved stable also in heavy weather would be great. This should ideally have a two-way communication with land for possible instructions or follow up in real-time. In addition it should be connected to a computer and get input from the navigation to determine launches.

There should be an internet connection with the ship while in port in Aalborg so that one could access the onboard computers from anywhere and transfer the data to land without the need of someone to physically enter the ship. Any software upgrades or setup modifications would also be much easier and cheaper to implement. In addition, a tighter follow-up on the system and the data would be possible, which is necessary to ensure the success of the research project in the future.

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