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Finnish studies of physical Arctic oceanography

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Abstract

Arctic oceanographic work at the Finnish Institute of Marine Research (FIMR) over the last 20 years started with studying the dense overflow of waters crossing the Greenland-Scotland Ridge at Denmark Strait that take part in the thermohaline circulation. The research was subsequently extended also to the waters carried by the East Greenland Current (EGC) forming the core for the overflow. EGC brings cold and low salinity water out of the Arctic Ocean through Fram Strait, where the water masses and exchanges are studied. Warm and saline Atlantic water enters the Arctic Ocean through Fram Strait and over the Barents Sea, and its interaction with sea ice north of Svalbard contributes to the formation of the Arctic Ocean halocline. The processes involved in the halocline formation are studied as well as the Atlantic water circulation and its importance for heat distribution in the Arctic Ocean. During the International Polar Year (IPY) FIMR took part in several international cruises and programmes inside the Arctic Ocean and this work is now continued at the Finnish Meteorological Institute. The main focus presently lies in the interpretation of the hydrographical observations made on the IPY cruises.

Key words: Water masses, geostrophy, heat exchanges, Arctic Ocean, Fram Strait, Denmark Strait

1. Introduction

The interest to study the Arctic Ocean lies partly in the human curiosity towards the cold unknown. The conservation of the northern nature and way of life as well as the exploitation of the natural resources of the Arctic Ocean are further motives for exploring the processes in the area. The main scientific interests are in understanding the role of the Arctic Ocean in the general ocean circulation, the water mass transformations taking place in the Arctic and how the Arctic Ocean affects and is affected by the climate.

In this paper an overview is given of the research made in Finland in the field of physical oceanography of the Arctic Mediterranean Sea. The Baltic Sea, where most of the Finnish oceanographic research has been performed due to its proximity and its importance for the shipping and recreation, is not included here. Oceanographic research in the Arctic involves expensive expeditions to remote locations in harsh conditions, and because of limited resources the work must be conducted in close co-operation with international partners. Here only such expeditions where Finnish researchers have participated are mentioned. The studies presented are based on analyses and interpretation of collected observational data.

During the International Geophysical Year (IGY) of 1957–1958 Finland participated in research work in the Barents Sea in an international expedition with the research vessel Aranda (II). This was the first time a Finnish research vessel was operating outside of the Baltic Sea (*Hela*, 1959), (Table 1). Twenty years later, in 1980, Finnish scientists participated in the Ymer expedition around Svalbard and in Fram Strait where their studies were concentrated on the sea ice and its salinity, thickness and ridge concentration and transformations (*Leppäranta and Palosuo*, 1987).

Table 1. Expeditions of Finnish RV Aranda in the Arctic and sub-Arctic Seas.

Vessel	**Year**	**Area**	**Programme**
Aranda II	1957	Barents Sea	IGY
Aranda III	1989	North Atlantic	Test cruise
Aranda III	1990	Denmark Strait	Nordic WOCE
Aranda III	1993	Denmark Strait	Nordic WOCE
Aranda III	1997	Denmark Strait	VEINS
Aranda III	2002	Fram Strait	FRAMZY
Aranda III	2003	Fram Strait	ACSYS-ABSIS

The on-going studies of physical oceanography of the Arctic Ocean began at the Finnish Institute of Marine Research (FIMR) in the early 1990s within the Nordic WOCE (World Ocean Circulation Experiment) programme (*Mälkki*, 2001), where the focus was on the exchanges of mass, heat and freshwater across the Greenland-Scotland Ridge. Thereafter the work continued in the EC VEINS (Variability of Exchanges In the Northern Seas) programme. In particular the water properties and entrainment into the overflow crossing the 620m deep sill in Denmark Strait were examined (Fig. 1). The dense overflow waters contribute to the North Atlantic Deep Water and thus take part in the global thermohaline circulation. The thermohaline circulation, bringing warm saline water to the north and transporting cold, deep water to the south, ventilates and renews the deep waters of the oceans and is an important factor for the climate of northern and northeastern Europe (*Dickson et al.*, 2008).

The origins of the Denmark Strait overflow water cannot be determined by only examining the waters south of and in the strait, but it is also necessary to study the source waters in the north. The overflow is formed from the denser waters in the Nordic Seas (i.e., the Greenland, Iceland and Norwegian Seas) and the Arctic Ocean, carried southward by the East Greenland Current (EGC) (Fig. 2). The densest waters, however, are unable to cross being located too deep (*Swift et al.*, 1980; *Mauritzen*, 1996a, b; *Rudels et al.*, 1999; *Rudels et al.*, 2002). The EGC, bringing cold and dense overflow water as well as low-salinity water and ice from the Arctic Ocean through Fram Strait, was studied from observations made on the RV Polarstern in 1998 and IB Oden in 2002.

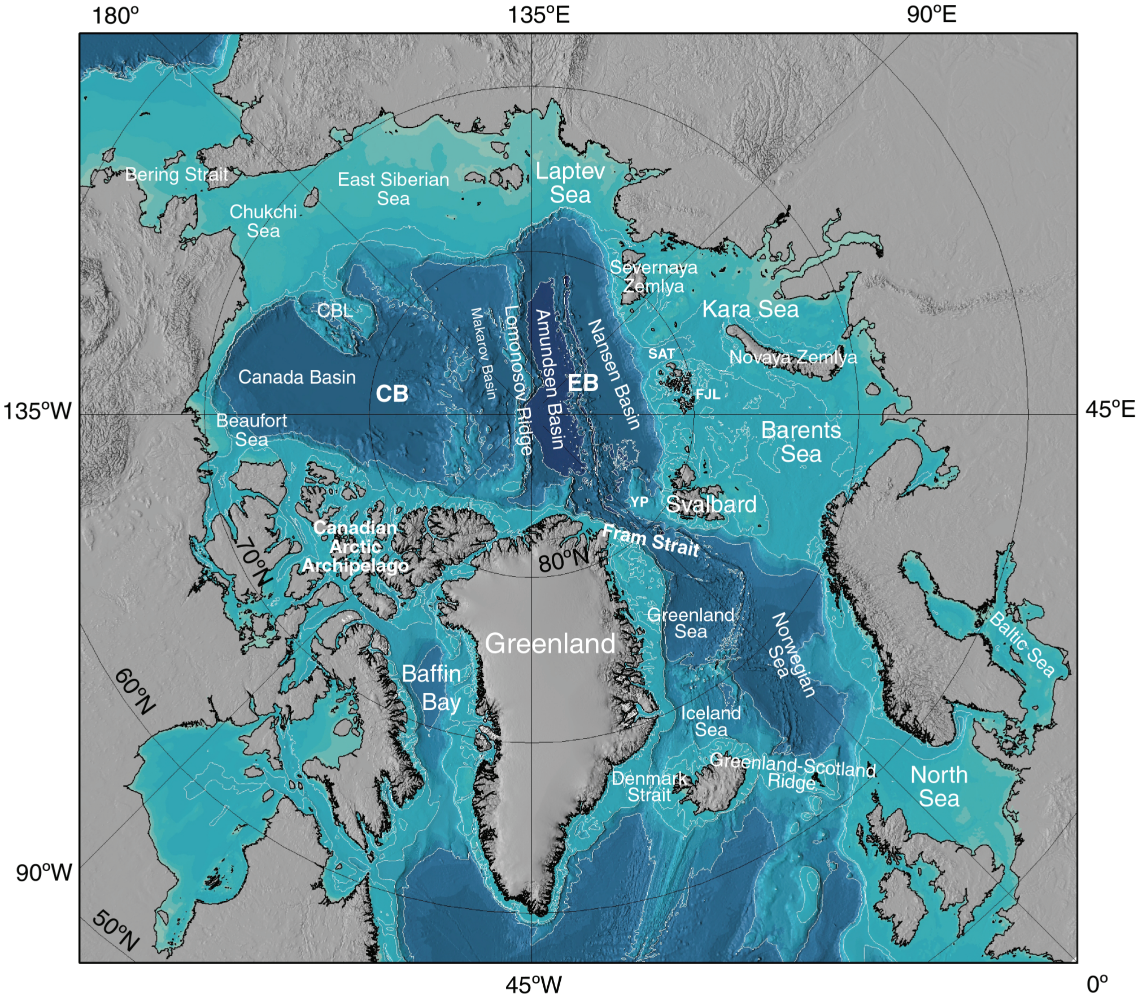

Fig. 1. The Arctic Ocean bathymetry. CB = Canadian Basin, CBL = Chukchi Borderland, EB = Eurasian Basin, FJL = Franz Josef Land, YP = Yermak Plateau, SAT = St. Anna Trough. Adapted from Encyclopedia of Ocean Sciences, 2nd ed., 2008.

Within the VEINS and later ASOF (Arctic-Subarctic Ocean Fluxes) programmes the research of FIMR gradually shifted towards Fram Strait. The water masses and the exchanges in Fram Strait were examined using hydrographic data from 1980 to 2005. During 2002 and 2003 also the FIMR research vessel RV Aranda (III) was taking part in field experiments in Fram Strait (Table 1). The main focus was on the drift of the sea ice and the interactions between air and ice, but also hydrographical observations were made (*Johansson et al.*, 2005). During VEINS and ASOF it was found that the processes inside the Arctic Ocean influence the water mass formation, and the distribution of temperature and salinity within the Arctic Ocean needs to be studied to understand the long-term variability in the observations. Such research was conducted in the HOTRAX (Healy-Oden TRans-Arctic eXpedition) with IB Oden in 2005 and with several expeditions to the Arctic Ocean during the International Polar Year (IPY).

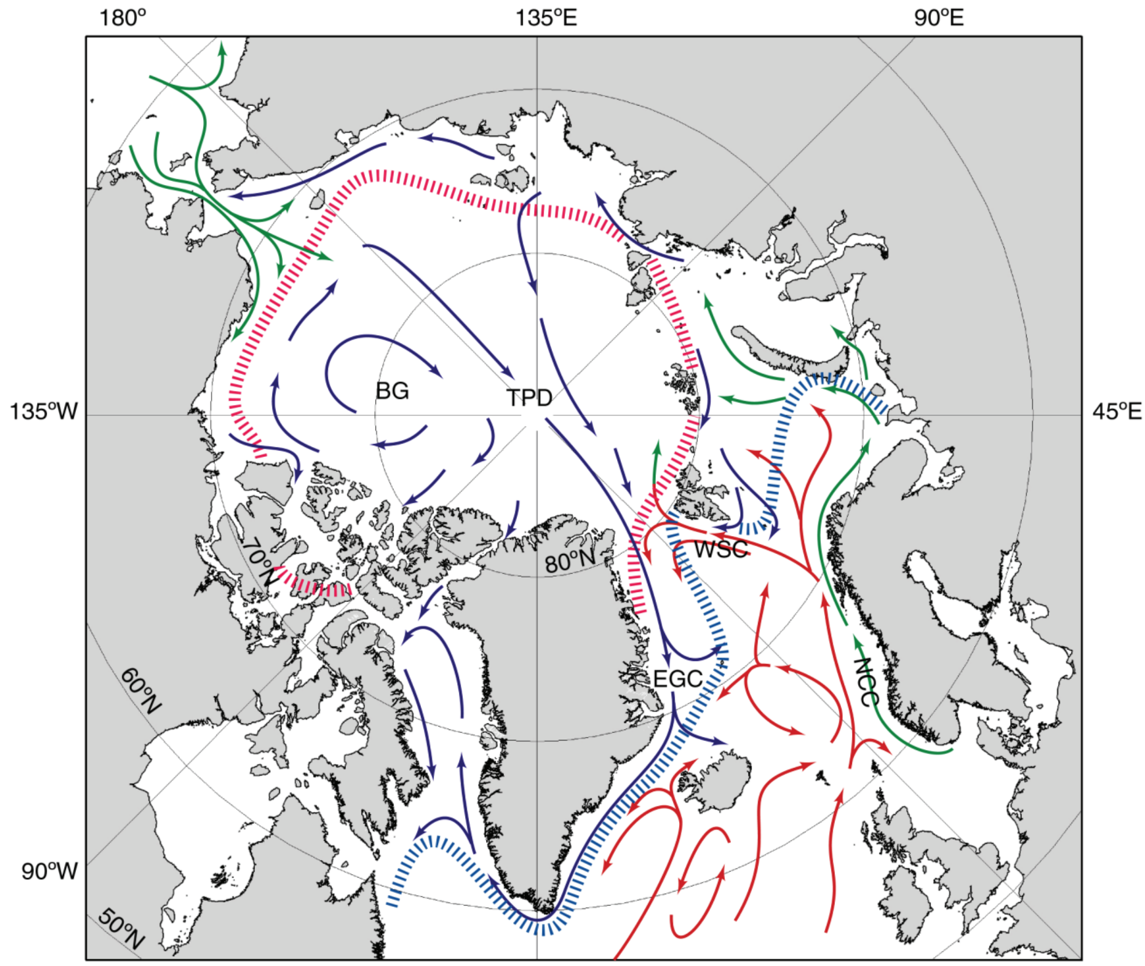

Fig. 2. Upper layer circulation in the Arctic Ocean with the average summer (pink) and winter (blue) ice limits. Warm Atlantic currents are shown with red arrows, cold Arctic currents with blue and less saline or transformed currents with green. BG = Beaufort Gyre, EGC = East Greenland Current, NCC = Norwegian Coastal Current, TPD = Transpolar Drift, WSC = West Spitsbergen Current. Adapted from Encyclopedia of Ocean Sciences, 2nd ed., 2008.

As FIMR was closed down at the beginning of 2009 the research groups studying physical oceanography were moved to the Finnish Meteorological Institute (FMI), where a unit of marine research was formed and now continues the Arctic physical oceanography work in Finland. The ultimate aim of the research remains the same, to gain understanding on the role of the Arctic Ocean in the global circulation, how it affects and how it would be affected in a changing climate.

In this paper transport estimates for Denmark Strait overflow are presented in Section 2 as well as the exchanges of different water masses, heat and freshwater in Fram Strait. In Section 3 the circulation, mainly of Atlantic water, in the Arctic Ocean and the water mass transformations are discussed. In Section 4 activities involving Finnish physical oceanographers during IPY are described and some preliminary results are shown.

2. *Exchanges*

2.1 *Denmark Strait*

The work that started at FIMR in Denmark Strait during the Nordic WOCE was continued in the VEINS programme 1997–2000. A cruise was made with RV Aranda (III) in 1997 to Denmark Strait where hydrographic measurements were made to study the overflow waters crossing the Greenland-Scotland Ridge.

2.1.1 *Entrainment*

Rudels et al. (1999) observed a low salinity lid comprising the upper part of the dense overflow (Fig. 3) from the hydrographical data south of the Denmark Strait. The

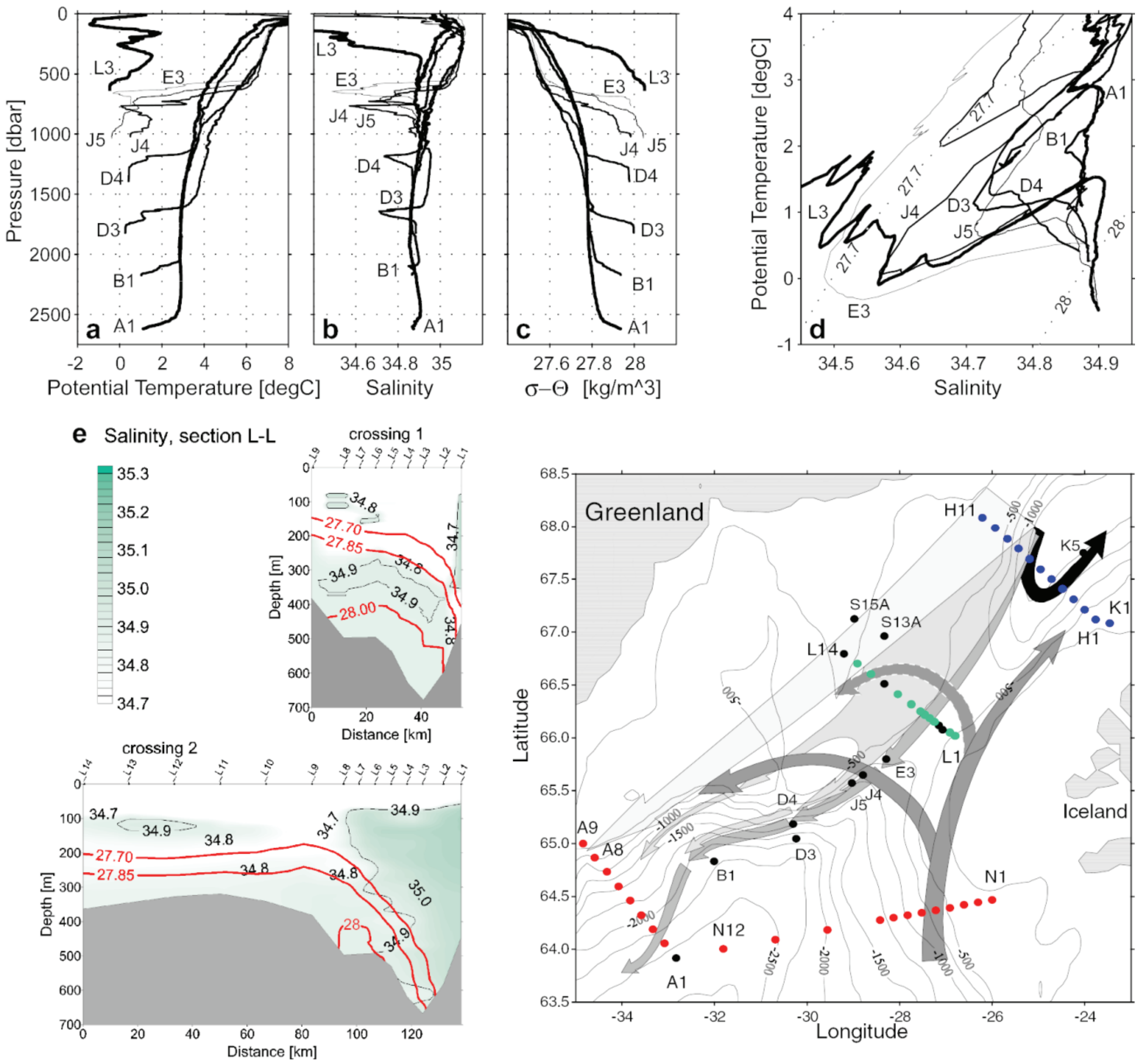

Fig. 3. A "low salinity lid" capping the Denmark Strait overflow water. A layer with a salinity minimum in the density range σ_θ = 27.70 – 27.85 was observed during an Aranda cruise in 1997, and could be traced along the descent of the Denmark Strait overflow plume. The lid is evident in the vertical profiles of potential temperature, salinity and potential density on the different cross sections. From *Dickson et a*l. 2008.

lid indicates that the overflow is stratified and the lid could be followed from just south of the 620 m deep Denmark Strait sill downstream along the continental slope to depths of more than 2000 m. This suggests that ambient waters are not easily entrained into the overflow plume. There still is uncertainty of how this lid can survive the descent and how it is compatible with the strong entrainment often associated with the overflow (*Dickson and Brown*, 1994; *Dickson et al.*, 2008). It has been suggested i.e. that instead of entrainment the changes observed downstream of the sill are due to internal mixing of the initially stratified plume during the descent (*Rudels et al.*, 1999) or that the entrainment could be patchy enough in space and time to allow these features to survive in places (*Dickson et al.*, 2008).

2.1.2 Observations and transport estimates based on them

An array of moored current meters was deployed at Angmassalik south of the strait in 1997 and has been maintained ever since, and hydrographic sections have been taken yearly in connection with the mooring replacement. The amount of overflow water flowing southward through Denmark Strait is estimated to 3 Sv by *Hansen and Østerhus* (2000) and 4 Sv (1 Sv = 10^6 m^3/s) from direct observations (*Dickson et al.*, 2008) and a total of 6 Sv flows across the Greenland-Scotland Ridge (*Hansen and Østerhus*, 2000).

FIMR continued to study the Denmark Strait overflow waters during the EU funded ASOF programme, 2003–2005. Estimates of the overflow were made based on geostrophic calculations using the method of *Jacobsen and Jensen* (1926) to account for the sloping bottom. An average transport of 3.6 Sv was obtained for the southward volume transport (*Dickson et al.*, 2008). The origins of the overflow waters were studied from the hydrographic sections south of the Denmark Strait by computing percentages of the water masses whose combinations could create the observed temperature and salinity properties (*Dickson et al.*, 2008). The water masses contributing to the overflow are the intermediate and Atlantic waters from the Nordic Seas and the Arctic Ocean, both the Atlantic water recirculating in Fram Strait and the part that loops in the Arctic Ocean as well as the Greenland and Iceland Seas intermediate waters and the upper Polar Deep Water (uPDW) from the Arctic Ocean (*Rudels et al.*, 2002). The water masses carried southward by the EGC were studied in detail from hydrographic data obtained from the Arctic Ocean – 02 cruise with IB Oden with sections crossing the EGC from Fram Strait to Denmark Strait by *Rudels et al*. (2005).

2.2 Fram Strait

During ASOF focus was shifted towards Fram Strait where the deep exchanges between the Arctic Ocean and the rest of the oceans take place. There a substantial amount of freshwater leaves and warm and salty Atlantic water (AW) enters the Arctic Ocean. The transports of different water masses were estimated based on a geostrophic method where constraints were set on the deep part of the flow assuming a steady net southward flow of more saline Arctic Ocean deep waters for the period of observations, between 1980 and 2005, and using the method of *Jacobsen and Jensen* (1926) for the sloping bottom (*Rudels et al*., 2008). The net transport was estimated to 2.5 Sv out of the Arctic Ocean.

2.2.1 Time variability and budget considerations

The geostrophic method does not take into account the barotropic flow strongly present in the strait, especially on the Svalbard side, and *Rudels et al*. (2008) combined the geostrophic result with budget considerations for the Arctic Ocean. The mean transport through Bering Strait is estimated to 0.8 Sv with large seasonal variations (*Coachman and Aagaard*, 1988; *Woodgate and Aagaard* 2005). The volume of Atlantic Water that enters the Arctic Ocean across the Barents Sea opening has been estimated to 1.5 Sv during EU funded VEINS and ASOF projects (*ASOF-N Final Report*, 2006) and this value was used in the budget considerations, a later estimate by *Skagseth et al*. (2008) is 1.8 Sv. Also Norwegian Coastal Current brings low-saline water to the Arctic Ocean, about 0.7 Sv (*Aagaard and Carmack*, 1989; *Blindheim*, 1989). The Arctic Ocean receives 0.15–0.2 Sv freshwater from precipitation and runoff (*Serreze et al*., 2006). The estimates for volume transport out of the Arctic through the Canadian Arctic Archipelago vary between 1 and 2 Sv, 1.7 Sv being most often used (e.g. *Melling*, 2000; *Prinsenberg and Hamilton*, 2005). *Rudels et al*. (2008) used the value 1.44 Sv from *Dickson et al*. (2007) and obtained a net transport estimate out of the Arctic through Fram Strait of 1.7 Sv. The transport out of the Arctic Ocean through Fram Strait has been estimated to 2.0 Sv from direct observations, which consist of an array of current meters maintained in the strait continuously since 1997 (*Schauer et al*., 2008).

2.2.2 Double sections

The Fram Strait estimates are compared with transports computed from geostrophy by applying conservation constraints on a closed box formed of CTD sections north of Fram Strait, at about 81–82.5°N (80-83°N) and in the strait, at 79°N, and by Greenland and Svalbard slopes to the west and east (Fig. 4). The transports obtained across 79°N are 2.7 / 2.3 Sv, the first value for the whole width of the section and the latter for the area of 6°W to 9°E, which was used in the *Rudels et al*. (2008) estimates, with 2.1 / 1.8 Sv in 1984 (as compared with the previous geostrophy derived value of 1.4 Sv, not corrected with budget considerations), 4.1 Sv in 1997 (4.0 Sv) and 1.8 / 1.1 Sv in 2004 (1.9 Sv). (Fig. 5).

The transports of heat and freshwater between the Arctic Ocean and the Nordic Seas were also computed (Fig. 5). The heat transport at 79°N is of the same order as that derived from direct current meter moorings, i.e. 26–50 TW by *Schauer et al*. (2008), but smaller in the north, which would imply heat loss between the sections. Fresh water transport southward is larger on the southern section which could be due to sea ice melting between the sections. Both these processes are expected.

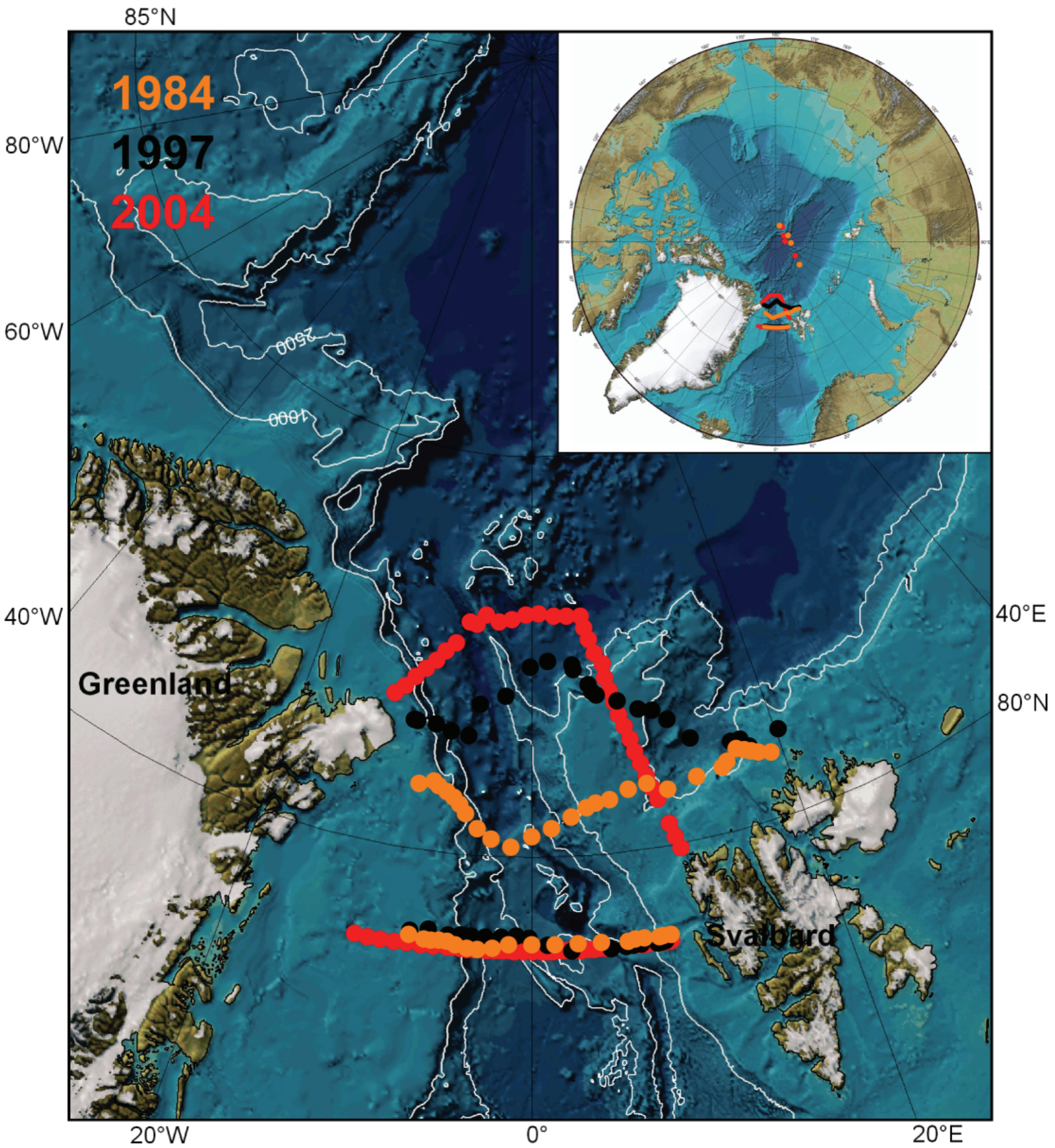

Fig. 4. Locations of the CTD double sections used for geostrophic transport estimates.

Rabe et al. (2009) concluded based on hydrographic and mooring observations that in some years a considerable part of the net southward freshwater transport in Fram Strait, about 80 mSv in liquid form, takes place on the shelf rather than on the continental slope, and a modeling study by *Gerdes et al*. (2008) suggests that about half of the liquid freshwater transport occurs on the East Greenland Shelf. The part of the section studied by *Rudels et al*. (2008) is from 6°W to 9°E and they estimated that an additional 25 mSv of freshwater and a maximum of 1 Sv in southward volume flow occurred on the shelf. They got an average net transport of freshwater of 40 mSv through Fram Strait. Adding these numbers would give a freshwater flux of 65 mSv, well comparable with the number presented by *Dickson et al*. (2007), 65–95 mSv. The sea ice export is estimated as 80 mSv by *Dickson et al*. (2007).

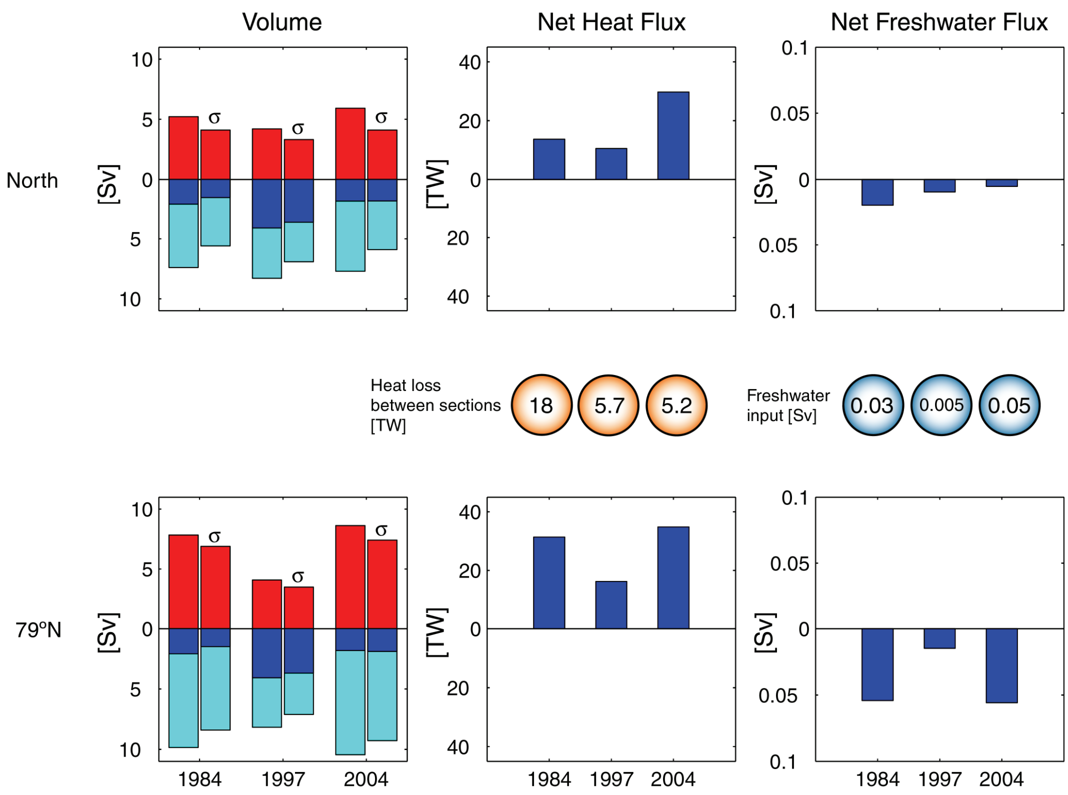

Fig. 5. Transports of volume (medium grey northward, light grey southward, dark grey net) at Fram Strait and north of it for the whole water column of the double sections and for the upper part (σθ < 28.06, marked with σ) and the net heat and freshwater fluxes for the upper part of the sections.

2.2.3 Intermediate water

The net transport in Fram Strait was found by *Rudels et al*. (2008) to be southward in all water masses with little net southward transport seen in the upper waters. The largest net southward transports occur in the ranges of the dense Atlantic and intermediate waters, suggesting transport from the Arctic Ocean of the denser parts of the Barents Sea inflow.

The northward transport of Arctic Intermediate Water (AIW) is little known. The inflow of AIW to the Arctic Ocean has to be taken into account when estimating the production of intermediate water in the Arctic Ocean, the upper Polar Deep Water. The intermediate waters leaving the Arctic Ocean directly contribute to the overflow and to the global thermohaline circulation. A transient tracer, sulphur hexafluoride (SF_6), released in the Greenland Sea in 1996 in a mixing experiment described by *Watson et al*. (1999), can be used as a marker for AIW to separate between AIW and uPDW. About 70% of the intermediate water volume on the eastern section (1) taken north of Svalbard on the Oden 2002 cruise (*Marnela et al*., 2008) showed traces of excess SF_6, indicating that AIW from the Greenland Sea enters the Arctic Ocean. From geostrophy it was estimated that 0.8 Sv of intermediate water passes the section, which suggested that 0.5 Sv AIW is entering the Arctic Ocean. The AIW transport was also estimated from Lowered Acoustic Doppler Current Profiler measurements, which indicated a larger transport of 2.8 Sv. (*Marnela et al*., 2008)

3. *Processes in the interior of the Arctic Ocean*

About 2–4 Sv of warm and saline Atlantic water enter the Arctic Ocean through Fram Strait, and slightly less across the Barents Sea, based on models and observations (*Rudels*, 1987; *Blindheim*, 1989; *Holland et al*., 1996; *Ingvaldsen et al*., 2004; *Maslowski et al*., 2004; *Schauer et al*., 2008; *Skagseth et al*., 2008). The Fram Strait branch follows the continental slope north of Svalbard and circulates in an anti-clockwise way. The Barents Sea branch becomes cooled and freshened in the Barents Sea and enters the Arctic Ocean at St. Anna Trough (*Rudels et al*., 1994; *Karcher et al*., 2002).

The transformations of the Atlantic water and intermediate waters of the Arctic Ocean occur mainly through isopycnal mixing between the two inflow branches as they join north of the Kara Sea and the Severnaya Zemlya and by the interaction with dense shelf/slope plumes caused by freezing and brine-rejection (*Rudels et al*., 2000; *Rudels*, 2001; *Rudels et al*., this issue). Both branches take part in the formation of the Arctic Ocean lower halocline that is formed as the outflow of low salinity shelf water overruns the winter mixed layer in the Nansen Basin (*Rudels et al*., 1996; *Rudels et al*., 2004). The mixing of the Fram Strait and Barents Sea branches has been studied and is presented in more detail by Rudels et al. (this issue). Part of the AW recirculates in the Nansen and Amundsen Basins, especially along the Lomonosov Ridge, while a part continues further into the Canadian Basin along the continental slope (*Rudels*, 2001).

It is still unknown how much of the heat carried by AW is actually released in the Arctic because of the strong stratification and the halocline that lie on top of the Atlantic layer preventing the heat to be released directly to the sea surface (see e.g. *Rudels et al*., 2008).

The processes inside the Arctic Ocean have been studied from Oden 2005 HOTRAX data. A pathway of deep water from the Makarov Basin (MB) to the Amundsen Basin (AB) through an intra basin in the Lomonosov Ridge was discovered. This is likely the most important passage for deep water from the MB to the AB (*Björk et al*., 2007). By contrast none of the expected deep water flow from the AB to the MB (*Jones et al*., 1995) was observed on the HOTRAX expedition.

4. *Activities during the International Polar Year (IPY) 2007-2009*

During the IPY FIMR studied the water masses and the circulation in the Arctic Ocean in an Academy of Finland funded project “Heat and freshwater distribution in the Arctic Ocean” and in the EU funded programme DAMOCLES (Developing Arctic Modelling and Observing Capabilities for Long-term Environmental Studies). The water mass distributions and the circulation as well as the processes and mixing mechanisms that determine the water mass properties in the Arctic Ocean and the Nordic Seas were studied. FMI is one of the original partners in DAMOCLES and boundary layer meteorology in the Arctic as well as part of the sea ice research have been conducted at FMI already before the unit of marine research was formed at FMI.

FIMR participated in a LOMROG (Lomonosov Ridge off Greenland) expedition in 2007 with IB Oden where the path of the MB deep water that in 2005 was discovered to cross the central Lomonosov Ridge was further examined, and in the SPACE (Synoptic Pan-Arctic Climate and Environment study) expedition on RV Polarstern where especially the mixing, circulation and transformation of the Barents Sea and Fram Strait branches of AW in the Nansen, Amundsen and Makarov Basins were studied. One further finding is that beyond the Nansen Basin, the Barents Sea inflow rather than the Fram Strait inflow appears to contribute most of the water to the Atlantic layer in the Arctic Ocean (*Rudels et al.*, this issue).

FIMR had planned to continue the study of the Fram Strait inflow in the ice-free area called Whalers' Bay north of Svalbard and around Yermak Plateau, where the Arctic Intermediate Water (AIW) and upper Polar Deep Water (uPDW) had been investigated from Oden 2002 data. However, these plans were compromised by lack of funding for the RV Aranda cruise in 2008 and by engine problems that cancelled the RV Maria S. Merian cruise leg in the area in 2007.

Instead FIMR participated in the Chinare 2008 cruise with MV XueLong as part of the DAMOCLES project but also within the Academy of Finland funded Finnish IPY activity. FIMR joined the standard CTD (conductivity, temperature, depth) observational work and also provided backup CTD equipment. Together with the Chinese researchers FMI is now taking part in the analysis of the data, and in the interpretation of the temperature and salinity structures in the context of the Arctic Ocean circulation, mixing processes and changes in water mass properties (Fig. 6). Due to the tight schedule only 6 deep stations were obtained inside the Arctic Ocean that can

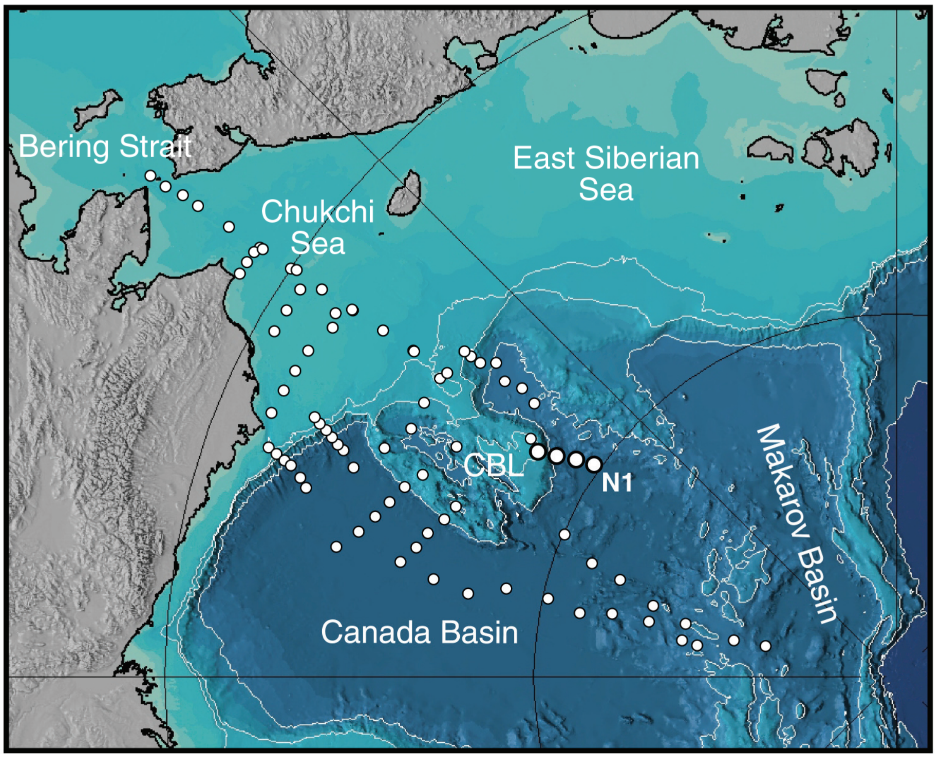

Fig. 6. CTD station locations on the Chinare 2008 cruise.

be used for studying the deep waters. The focus of FMI therefore will mainly be on the halocline, on AW properties as well as on the freshwater storage. These studies of water masses, including the Atlantic water, their transformation and circulation at the Chukchi Borderland and in the Canadian Basin are made in co-operation with Chinese colleagues. FIMR also conducted sea ice and atmospheric boundary layer research on the cruise and this data will be combined with the data obtained from the previous Chinare 2003 cruise (*Cheng et al.*, 2008).

In Figure 7 on the left the temperature and salinity characteristics are shown for section N on the western side of the Chukchi Borderland. Station N1 is the outermost station on section N and the temperature minimum at the salinity around 34 indicates the presence of lower halocline water originating in the Nansen Basin.

In Figure 7 on the right the temperature and salinity characteristics for the deep and intermediate waters for the same section are shown. The strongest interleaving in the intermediate water ranges was found in section N and the lower salinity in the intermediate water range on the western side of the Chukchi Borderland (CBL), note especially station N1 (bold), where the colder and fresher intermediate layer indicates a stronger influence of Barents Sea water at the western side. The data shown are preliminary and the work is in progress.

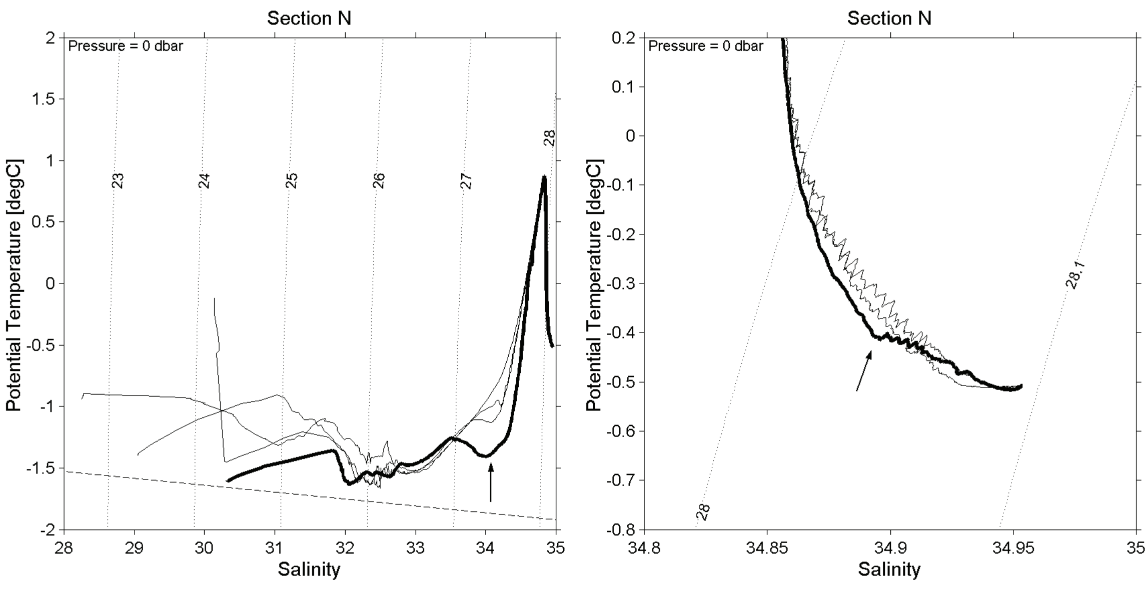

Fig. 7. θ-S diagrams of the Chinare 2008 cruise section N located on the western side of Chukchi Borderland. On the left the temperature minimum around salinity 34 indicating the presence of lower halocline water originating from the Nansen Basin at station N1 (bold line) is pointed out with an arrow. On the right an arrow points at the colder and fresher intermediate waters of station N1 indicating the presence of Barents Sea water.

5. *Concluding remarks*

The work done during the IPY by the Finnish physical oceanographers in the Arctic Ocean will be continued as international co-operation. The research done in Finland on the Arctic seas is quite marginal in spite of their impact on our climate and the North Atlantic also plays an important role in renewing the bottom/deep waters of the Baltic Sea. In general the field of oceanography, and not just physical, is surprisingly small in Finland considering how much coastline the country has with the Baltic Sea.

Acknowledgments

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References

Aagaard, K., and E.C. Carmack, 1989. The role of sea ice and other fresh water in the arctic circulation, *J. Geophys. Res*., **94**, 14485–14498.

ASOF-N Final Report, 2006. Bremerhaven, 112 pp.

Björk, G., M. Jakobsson, B. Rudels, J.H. Swift, L. Anderson, D.A. Darby, J. Backman, B. Coakley, P. Winsor, L. Polyak and M. Edwards, 2007. Bathymetry and deep-water exchange across the central Lomonosov Ridge at 88–89˚N, *Deep Sea Res. I*, **54**, 8, 1197–1208, doi:10.1016/j.dsr.2007.05.010.

Blindheim, J., 1989. Cascading of Barents Sea bottom water into the Norwegian Sea, *Rapports et Procès-Verbaux des Réunions du Conseil International pour l'Exploration de la Mer,* **188**, 49–58.

Coachman, L.K. and K. Aagaard, 1988. Transports through Bering Strait: Annual and interannual variability, *J. Geophys. Res.*, **93**, 15535–15539.

Cheng, B., Z. Zhang, T. Vihma, M. Johansson, L. Bian, Z. Li and H. Wu, 2008. Model experiments on snow and ice thermodynamics in the Arctic Ocean with CHINARE2003 data, *J. Geophys. Res.,* **113**, C09020, doi:10.1029/2007JC004654.

Dickson, R.R. and J. Brown, 1994. The production of North Atlantic Deep Water: Sources, rates and pathways, *J. Geophys. Res.*, **99**, 12319–12341.

Dickson R.R., B. Rudels, S. Dye, M. Karcher, J. Meincke and I. Yashayaev, 2007. Current estimates of freshwater flux through Arctic & Subarctic seas, *Prog. in Oceanogr.*, **73**, 210–230, doi:10.1016/j.pocean.2006.12.003.

Dickson, B., S. Dye, S. Jónsson, A. Köhl, A. Macrander, M. Marnela, J. Meincke, S. Olsen, B. Rudels, H. Valdimarsson and G. Voet, 2008. The overflow flux west of Iceland: Variability, origins and forcing. In: B. Dickson, J. Meincke & P. Rhines (Eds.), *Arctic-Subarctic Ocean Fluxes: Defining the role of the Northern Seas in Climate*, Springer Verlag. 443–474.

Gerdes R., M. Karcher, C. Köberle and K. Fieg, 2008. Simulating the long term variability of liquid freshwater export from the Arctic Ocean. In: B. Dickson, J. Meincke & P. Rhines (Eds.), *Arctic-Subarctic Ocean Fluxes: Defining the role of the Northern Seas in Climate*, Springer Verlag. 405–425

Hansen, B. and S. Østerhus, 2000. North Atlantic – Nordic Seas exchanges, *Progr. in Oceanogr.*, **45**, 109–208.

Hela, I., 1959. Suomen osallistuminen merentutkimusalus Arandalla kansainvälisen geofysiikan vuoden 1957–58 tutkimuksiin, *Societas Scientiarum Fennica*. Årsbok/vuosikirja **35 B** (4), 19 pp.

Holland, D.M., L.A. Mysak and J.M. Oberhuber, 1996. An investigation of the general circulation of the Arctic Ocean using an isopycnal model, *Tellus*, Ser: A, **48**, 138–157.

Ingvaldsen, R.B., L. Asplin and H. Loeng, 2004. The seasonal cycle in the Atlantic transport to the Barents Sea during 1997–2001, *Continental Shelf Research*, **24**, 1015–1032, doi:10.1016/j.csr.2004.02.011.

Jacobsen, J.P. and A.J.C. Jensen, 1926. Examination of hydrographic measurements from research vessels Explorer and Dana during the summer of 1924, *Conseil Permanent International pour l'Exploration de la Mer, Rapports et Procès-Verbaux*, **39**, 31–84.

Johansson, M. M., J. Launiainen, G. Müller and B. Brümmer, 2005. Fram Strait studies (FRAMZY 2002 and ACSYS-ABSIS 2003) ice drifter data evaluation for sea ice kinematics and dynamics studies – technical report, *Meri – Report Series of the Finnish Institute of Marine Research*, **54**, 3–40.

Jones, E.P., B. Rudels and L.G. Anderson, 1995. Deep Waters of the Arctic Ocean: Origins and Circulation, *Deep-Sea Res*., **42**, 737–760.

Karcher, M. and J. M. Oberhuber, 2002. Pathways and modification of the upper and intermediate waters of the Arctic Ocean, *J. Geophys. Res*., **107***,* No C6, doi:10.1029/2000JC000530.

Leppäranta, M. and E. Palosuo, 1987. Isarna kring Ymer. In: G. Hoppe, S. Björn-Rasmussen & M. Wiberg Roland (Eds.), *Expeditionen Ymer-80 – en slutrapport*, Tryckindustri AB Solna. 30–35.

Marnela, M., B. Rudels, K.A. Olsson, L.G. Anderson, E. Jeansson, D.J. Torres, M.J. Messias, J.H. Swift and A.J. Watson, 2008. Transports of Nordic Seas water masses and excess SF6 through Fram Strait to the Arctic Ocean, *Prog. in Oceanogr*., **78**, 1–11.

Maslowski, W., D. Marble, W. Walczowski, U. Schauer, J. L. Clement and A. Semtner, 2004. On climatological mass, heat, and salt transport through the Barents Sea and Fram Strait from pan-Arctic coupled ice-ocean model simulation, *J. Geophys. Res*., **109**, C03032, doi:10.1029/2001JC001039.

Mauritzen, C., 1996a. Production of dense overflow waters feeding the North Atlantic across the Greenland-Scotland Ridge. Part 1: Evidence for a revised circulation scheme, *Deep-Sea Res*., I, **43**, 769–806.

Mauritzen, C., 1996b. Production of dense overflow waters feeding the North Atlantic across the Greenland-Scotland Ridge. Part 2: An inverse model, *Deep-Sea Res*., I, **43**, 807–835.

Melling, H., 2000. Exchanges of freshwater through the shallow straits of the North American Arctic. In: Lewis, E.L, E.P. Jones, P. Lemke, T.D. Prowse, P. Wadhams (Eds.), *The freshwater budget of the Arctic Ocean*, Kluwer Academic, Dordrecht, 479–502.

Mälkki, P., 2001. Oceanography in Finland 1918–2000, *Geophysica* **37**(1–2), 225–259.

Prinsenberg, S.J. and J. Hamilton, 2005. Monitoring the volume, freshwater and heat fluxes passing through Lancaster Sound in the Canadian Arctic Archipelago, *Atmosphere-Ocean*, **43**, 1–22.

Rabe, B., U. Schauer, A. Mackensen, M. Karcher, E. Hansen and A. Beszczynska-Möller, 2009. Freshwater components and transports in the Fram Strait – recent observations and changes since the late 1990s, *Ocean Sci*., **5**, 219–233.

Rudels, B., 1987. On the mass balance of the Polar Ocean, with special emphasis on the Fram Strait, *Norsk Polarinstitutt Skrifter*, **188**, 53 pp.

Rudels, B., E.P. Jones, L.G. Anderson and G. Kattner, 1994. On the intermediate depth waters of the Arctic Ocean. In: Johannessen, O.M., Muench, R.D., Overland, J.E. (Eds.), The Polar Oceans and Their Role in Shaping the Global Environment, *Geophysical Monograph Series*, vol. **84**. AGU, Washington DC. 33–46.

Rudels, B., L.G. Anderson and E.P. Jones, 1996. Formation and evolution of the surface mixed layer and the halocline of the Arctic Ocean, *J. Geophys. Res*., **101**, 8807–8821.

Rudels, B., P. Eriksson, H. Grönvall, R. Hietala and J. Launiainen, 1999. Hydrographic observations in Denmark Strait in fall 1997, and their implications for the entrainment into the overflow plume, *Geophys. Res. Lett*., **26**(9), 1325–1328, doi:10.1029/1999GL900212.

Rudels, B., R. Meyer, E. Fahrbach, V.V. Ivanov, S. Østerhus, D. Quadfasel, U. Schauer, V. Tverberg, R.A. Woodgate, 2000. Water mass distribution in Fram Strait and over the Yermak Plateau in summer 1997, *Ann. Geophys*., **18**, 687–705.

Rudels, B., 2001. Ocean Current: Arctic Basin circulation. In: Steele J., S. Thorpe, K. Turekian (Eds.), *Encyclopedia of Ocean Sciences*, Academic Press, London, pp 177–187.

Rudels, B., E. Fahrbach, J. Meincke, G. Budéus, P. Eriksson, 2002. The East Greenland Current and its contribution to the Denmark Strait overflow, *ICES Journal of Marine Science* **59** (6), 1133–1154.

Rudels, B., E.P. Jones, U. Schauer and P. Eriksson, 2004. Atlantic sources of the Arctic Ocean surface and halocline waters, *Polar Res*., **23**, 181–208.

Rudels, B., G. Björk, J. Nilsson, P. Winsor, I. Lake and C. Nohr, 2005. The interactions between waters from the Arctic Ocean and the Nordic Seas north of Fram Strait and along the East Greenland Current: results from the Arctic Ocean-02 Oden expedition, *J. Marine Systems*, **55**, 1–30, doi:10.1016/j.jmarsys.2004.06.008.

Rudels, B., M. Marnela and P. Eriksson, 2008. Constraints on Estimating Mass, Heat and Freshwater Transports in the Arctic Ocean: An Exercise. In: B. Dickson, J. Meincke & P. Rhines (Eds.) *Arctic-Subarctic Ocean Fluxes: Defining the role of the Northern Seas in Climate*, Springer Verlag. 315–341.

Rudels, B., N. Kuzmina, U. Schauer, T. Stipa and V. Zhurbas, 2009. Double-diffusive convection and interleaving in the Arctic Ocean – Distribution and importance, *Geophysica*, this issue.

Schauer, U., A. Beszczynska-Möller, W. Walczowski, E. Fahrbach, J. Piechura and E. Hansen, 2008. Variation of measured heat flow through the Fram Strait between 1997 and 2006. In: B. Dickson, J. Meincke & P. Rhines (Eds.), *Arctic-Subarctic Ocean Fluxes: Defining the role of the Northern Seas in Climate*, Springer Verlag. 65–85.

Serreze, M.C., A. Barrett, A.J. Slater, R.A. Woodgate, K. Aagaard, R. Lammers, M. Steele, R. Moritz, M. Meredith and C. Lee, 2006. The large-scale freshwater cycle of the Arctic, *J. Geophys. Res.*, **111**, C11010, doi:10.1029/2005JC003424.

Skagseth, Ø., T. Furevik, R. Ingvaldsen, H. Loeng, K.A. Mork, K.A. Orvik and V. Ozhigin, 2008. Volume and heat transports to the Arctic Ocean via the Norwegian and Barents Seas. In: B. Dickson, J. Meincke & P. Rhines (Eds.), *Arctic-Subarctic Ocean Fluxes: Defining the role of the Northern Seas in Climate*, Springer Verlag. 45–64.

Swift J.H., K. Aagaard and S.-A. Malmberg, 1980. The contribution of the Denmark Strait overflow to the deep North Atlantic, *Deep-Sea Res.*, *27*, 29–42.

Watson, A.J., M.-J. Messias, E. Fogelqvist, K.A. Van Scoy, T. Johannessen, K.I.C. Oliver, D.P. Stevens, F. Rey, T. Tanhua, K.A. Olsson, F. Carse, K. Simonsen, J.R. Ledwell, E. Jensen, D.J. Cooper, J.A. Kruepke and E. Guilyardi, 1999. Mixing and convection in the Greenland Sea from a tracer-release experiment, *Nature,* **401**, 902–904.

Woodgate, R.A., K. Aagaard, 2005. Revising the Bering Strait freshwater flux into the Arctic Ocean, *Geophys. Res. Lett.,* **32**, L02602, doi:1029/2004GL021747.