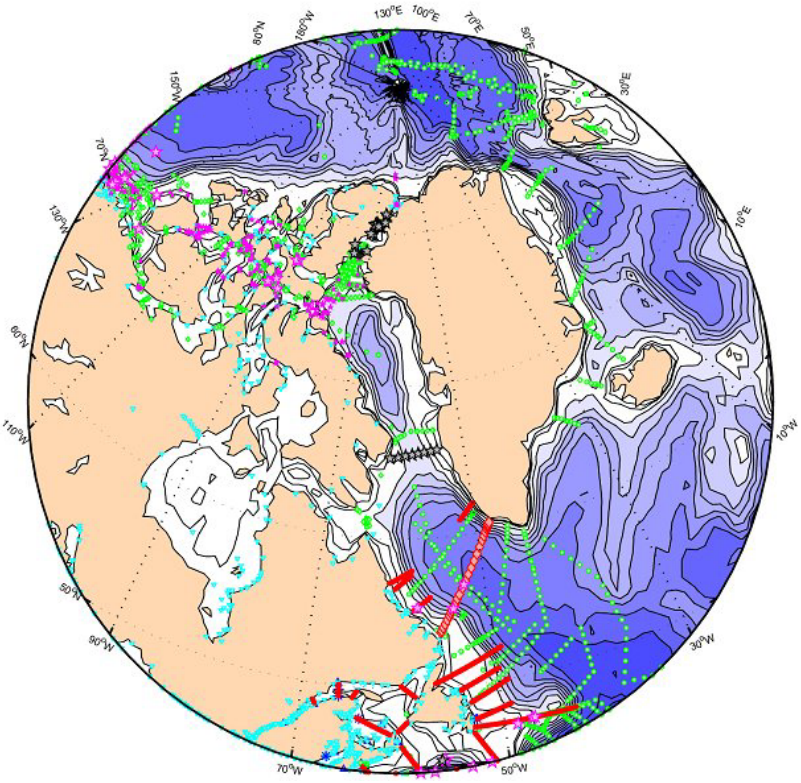
CANADIAN ARCHIPELAGO THROUGHFLOW STUDY/ASOF-WEST MEETING: INSTITUTE OF OCEAN SCIENCES SIDNEY, B.C., CANADA 19-20 JUNE 2003



ASOF-WEST and some of the related observational sites aimed at sustained observations of Arctic-Atlantic ocean by North American investigators. Red are regular sections on shallow shelves and crossing the Labrador Sea; green points are hydrographic stations occupied by Canada in the past decade; these are likely to be continued via ship and autonomous glider; black stars are planned and past mooring and hydrography sites in Davis and Nares Straits. These include Seaglider sections. Purple are Canadian Archipelago mooring measurements, past and (large stars) present. Blue are the Canadian water-level gauging network. Future ship-borne hydrography/chemical tracer/biology sections are not yet well-planned. Not shown are work in Bering Strait and the Beaufort shelf region, hydrographic programs and moorings on the Canadian continental slope. Figure by I. Yashayaev.

Notes by Peter Rhines, 11 July 2003

CANADIAN ARCHIPELAGO (CAA) THROUGHFLOW STUDY (CATS)/ASOF MEETING, IOS BC, CANADA, 19-20 JUNE 2003

This meeting involved primarily ASOF (Arctic SubArctic Ocean Flux program) activities in the Arctic and subArctic west of Greenland. It was concerned both with imminent deployments west of Greenland and broader issues of climate dynamics of the Arctic/subArctic system. It was organized by Kelly Falkner (OSU) and hosted by Eddy Carmack (IOS).

Throughout the 'Arctic change debate' we experience competing causes: both global warming and pattern changes in wintertime winds are warming the Arctic and reducing ice cover; both increased hydrologic cycle and stronger wind-blown surface layers are freshening the Atlantic Ocean. A principal goal of ASOF is to build sustained observations which can see through these uncertain balances.

This meeting was exciting in many ways. Major components of the ASOF-West arrays are headed north for deployment. At this early stage we are discovering surprising logistical and scientific connections, for example between oceanography and nearby Greenland ice sheet observations. Below we summarize the presentations and briefly the following discussion. A few general impressions stand out:

- A great deal of planning and preparation is focusing on the deployments of summer 2003, with generally successful use of icebreaker resources, both US and Canadian.
- The differing strategies (moorings, drifters, gliders, ship-borne water-mass hydrography, chemical tracers, satellites) of measuring exchange between Arctic and subpolar Atlantic and Pacific need to be brought together, looking forward to the creation of sustainable long-term monitoring.
- There is as yet no coordinated plan for hydrography/tracers observations in CATS/ASOF, even though it is a key component of many projects.
- Understanding freshwater transit and retention in the Arctic Basin and its boundary current is crucial to a successful CATS/ASOF.
- Addressing delivery of low-salinity waters to the head of the global meridional overturning circulation in the Labrador and Greenland Seas is an objective that should steer observations.
- Quantifying transports of solid and liquid freshwater on shallow yet broad continental shelves is particularly difficult yet important.

- Atmospheric winds with fine horizontal scales are channeled by the rugged topography of CAA and Greenland, and need to be observed. Hemispheric-scale atmospheric dynamics, expressed in the Atlantic/Arctic storm track and NAO, are crucial components of ASOF science.
- Satellite remote sensing products, including scatterometer and SAR winds, radiometric (cloud penetrating) sea-surface temperatures, and ice motion need to be accessible and archived as the program develops.
- The several nations involved in ASOF-West programs, the Arctic Basin programs to the north and CLIVAR related observations to the south, need to press for commitment to sustained time-series which will reveal global change patterns and their local impacts. In some cases this suggests new relationships, for example with Greenlandic and Danish science laboratories.

In the following summaries, in order of presentation, the speaker's name is italicized.

Peter Rhines (UW) described the scope of ASOF-West, and some underlying scientific issues: particularly, polar amplification of global warming; the overarching influence of the Icelandic Low and Atlantic/Arctic storm track on the Arctic/subArctic system; meridional heat- and freshwater transports and their vital oceanic components, and, quantifying the transports through straits and over sills. Analysis of Davis Strait transports of volume, freshwater and heat are displayed on the potential temperature/salinity plane, allowing one to look at individual elements of the system rather than focusing only on net Sverdrups of transport. The transport/θ/S diagrams have as their two first-spatial-moments freshwater and heat-transport diagrams, and the choice of reference salinity and potential temperature, respectively, is graphically explored. There followed a discussion of the atmospheric forcing environment set up by the Icelandic Low, the deep penetration of that Low into the Arctic in high-NAO/AO years and the energetic interaction of storms cycling about the low in the Arctic basin. An animation of 1993 storms can be grabbed from www.ocean.washington.edu/research/gfd/gfd.html. Cyclonic systems, and the overall transport of heat- and freshwater into the Arctic, is highly dependent on the circulating ocean and its heat-supply in ice-free regions.

The programs that are either in place or in transit to the Arctic include the NSF OPP funded CATS study of Nares Strait by *Kelly Falkner* (OSU), Agnew, Jones, Melling, Muenchow, Carmack, McLaughlin, Samelson, Smith, Weaver and Wong. Goals include monitoring water masses and fluxes from the Arctic, including ice, nutrients and chemical tracers. Also proxy records will be developed and dynamics diagnosed. The issue of local vs. remote forcing of passage flow is in mind. The US icebreaker Healy is the platform for

deploying their 26 mooring array that will be in place until 2007. It is a complex logistical effort involving ships and aircraft, and coordination of US, Greenlandic and Canadian jurisdictions, including involvement of native communities. Kelly identified some short- and long-term gaps in the program: met observations in the Strait, lack of an ice-ocean-atmosphere model dedicated to the region, and need for upstream ocean chemical tracer observations.

The flux observing Canadian programs in the Cardigan Strait/Hellgate (Melling) and Barrow Strait (Prinsenberg) have been in place since 1998. Prinsenberg's arrays this year involve the first recovery of the Icycler (vertical profiling ctd), and augmented adcp/Seacat moorings in Barrow Strait, with the goal of monitoring water masses, transports and ice movement. 3-year time series show, in Barrow Strait, strong interannual variability on top of expected late summer pulse of freshwater transport. Meanwhile in Cardigan Strait/Hell Gate flow is remarkably steady: hydraulic control? The freshwater transport is dominated by liquid freshwater, only 2 to 3% as ice. Tide gauges have been installed to develop the use of long-channel pressure difference driven throughflows, and geostrophic cross-channel observation of surface transport. Logistics are also challenging, both in accessing the region and servicing moorings, and in dealing with the nearby, time-varying magnetic pole. Watson compasses referenced to nearby land station magnetometers are used by Prinsenberg, and torsionally rigid moorings referenced by tidal velocity directions, or by local geography are used by Melling. Neither of these key efforts has long-term funding beyond roughly 2004.

Mike Steele of Polar Sciences, UW described his ASOF project (with Smethie (LDEO), Schlossser (LDEO) and Ron Kwok (JPL)) involving aircraft ctd line from Alert to the North Pole. Ice trajectories in the transpolar drift depend on the state of the Arctic/North Atlantic Oscillation, and with them the efflux of significant fresh water. Rigor's analysis suggests that under positive NAO index years (as in the early 1990s) transit speeds for ice are typically double those in years with negative NAO index. The 'switchyard' has the potential to shift the Arctic boundary currents and outflows relative to the many outlets.

Steele also described the varieties of Bering Strait water seen in summer, and their dependence on the relative strength of Beaufort gyre and the cyclonic winds invading from the Atlantic.

In Davis Strait, *Craig Lee* (UW, with Moritz, Gobat, Petrie (BIO), Drinkwater (BIO)) described their multi-year program to establish moorings in 2004 while developing an ice-capable Seaglider for dense hydrographic coverage of this wide strait. The broad, shallow, iceberg scoured west Greenland continental shelf poses a particular challenge, since neither moorings nor Seaglider do well such regions. Retrospective analysis of

Ross' (BIO) 3 year observations in Davis Strait by Cuny illustrates both the value and shortcoming of fixed moorings, where normally one misses the upper 150m of the water column due to iceberg transits. Various light-weight extensions of the intermediate moorings to cover the upper 150m are being considered.
The Seaglider modifications underway include passive acoustics for navigation among a mesh of low-frequency RAFOS sound sources, and an altimeter for sensing the ice and ocean-bottom.

In all cases flux monitoring of straits is an evolving science. We have some very large arrays in place elsewhere (Fram Strait, more than 14 moorings). Developing a long-term plan of sustainable measurements, using smaller arrays, is important. Currently there are no plans to monitor Hudson Strait.

Konrad Steffen of CIRES, Boulder described observations of the Greenland ice-sheet: radar penetrates to great depth (~ 2 km, or 50Kyrs), allowing the profiling of glacial tongues floating out to sea. Increasing surface melting and thinning at the margins has been observed in the 1990s, and melt-water can penetrate to bedrock and lubricate the glacier's movement, accelerating its flow seasonally. The Greenland climate network is on the Web, and is a model for CATS/ASOF real time monitoring in future. PARCA, the Program for Arctic Regional Climate Assessment, provides an organizational structure for the Greenland ice sheet monitoring program, with its great diversity of observational techniques.

Steffen has an array of portable surface meteorological stations deployed in Greenland, and expansion of this network could greatly improve ASOF. Because of time constraints, however, this initiative will not be pursued until next year.

Steffen described the use of RADARSAT SAR data to look at very fine-scale winds (~100m) in fjords. This relates to QuikSCAT's roughly 25 km resolution winds, also only in ice-free waters. Both can provide important resources for ASOF. RADARSAT overflight data has been organized for the summer 2003 Healy cruise.

Humfrey Melling of IOS described the entire CAA region, and our state of understanding of its transports. The need is both instrumental, to measure fluxes of volume, freshwater, chemical tracers, nutrients (Baffin Bay's nutrient source is likely the Arctic inflow), and also to understand what drives and regulates fluxes. With typical sill depths of 120m only the surface waters pass through yet deep basins lie below, and by mixing make the transition of Arctic waters to subpolar Atlantic waters complex. Fresh water transport estimates range from 1230 km^3 yr^{-1} (Aagaard+Carmack 1989) to 3100 (Loder et al 1998) to 7100 (Ingram and Prinsenberg 1998). Melling's discussion of the

'spectrum' of FW flux provides more detailed relationship with water masses. The transport plots as a function of θ and S, by Cuny and Rhines make the connection between the spectrum of water masses and the overall transport. The possible importance of land-fast ice to the freshwater budget was noted. Wind channels formed by high terrain are likely important to transport variations. 6 years of experience in Hell Gate/Cardigan Strait suggest 1/3 Sverdrup net transport. The adcp, moored θ/S and ice draft mooring measurements for the Nares Strait array are concentrated at the 350m X 38 km wide Cape Jefferson Section, 80.5N, with shallow water pressure recorders widely dispersed.

Chris Garrett and *Helen Johnson* of SEOS, Univ. of Victoria described some of the basic dynamical ideas being applied to flow through straits, including Rossby-radius scaling of channel widths, mixing and recirculations. The passage of Pacific Water through the Archipelago and Fram Strait belies the notion that buoyancy driven boundary currents will flow dominantly through the first strait they encounter (in this case, Amundsen Gulf, then M'Clure Strait/Parry Channel). Indeed, Melling's estimates show in late winter (April-June) only 50 milliSv of freshwater passing through Parry Channel compared with 450 milliSv moving through Barrow Strait, fed from the north (the annual average freshwater flux partition is not yet known). Papers from a meeting at Villefranche-sur-Mer in 2001 can be found by searching 'Villefranche straits' on the Web.

Many dynamical ideas need to explored in models and observations: relating sea-surface elevation derived pressure differences to throughflow (both along- and across channel pressure gradients); topographic drag at the seafloor and ice canopy; transformation of the potential-temperature/salinity diagram from Arctic to Atlantic through mixing and injection of heat and freshwater; Lagrangian aspects of mixing in channels.

Atmospheric forcing is of vital concern. Thin layers of low salinity are 'slippery', since mixing is inhibited at their base. Wind driven transport of these layers, in straits and on shallow continental shelves, is very significant and the relevant winds are ducted by topography and poorly represented by synoptic scale weather center data.

Tom Agnew of Environment Canada, Downsview, showed a remarkable animation of sea ice movement over the Arctic and CAA region, from AMSR data. This graphically showed the opening of ice-bridge polynyas in Barrow Strait and Smith Sound, and generally the rapid response of ice to passing storms (including dramatic lead openings). This data is available through National Snow and Ice Data Center and Environment Canada, although high resolution RADARSAT data is more voluminous and has to be organized in advance. In 2002 the CAA ice was above normal, yet Nares Strait was nearly ice free and the summer ice-cover in the Arctic basin was at a record low. A history, 1987-2003 of the Nares drainage event has been developed, using AVHRR, AMSR and

RADARSAT imagery when available. This kind of imagery is a tremendous resource for CATS/ASOF and yet manpower is needed to make full application of it.

Helga Schaffrin of Courant Institute, NYU, described the dynamics of ice bridges and the cycle observed in Nares Strait. Helen is pursuing this topic for her doctoral thesis working with Tabak, Holland and Buehler. The goal is to make a mathematical model for prediction of the annual cycle of ice arches, calibrating the constitutive laws for compressed ice with observations.

Roger Samelson of OSU described a mesoscale meteorological model being developed to provide wind stress information for Nares Strait and the broader CAA region. Steep mountain slopes and stable stratification make channeling of winds very strong (and on the larger scale, define the mean winter winds, NW-SE, passing through the Labrador Sea). Neither the 90-km NCEP winds nor the 12-km ETA model winds are adequate. Roger summarized various efforts: the polar MM5 model of Bromwich at Ohio State, DMI HIRLAM model in Denmark (Leif Laursen) and GEM/REM (24 km) in Canada. Nested grids are used, reaching several km resolution for Kennedy-Robeson channels. In conjunction with a network of portable satellite-communicating met stations, this will be important to CATS/ASOF. Interaction of the mesoscale winds with the larger synoptic scales and Icelandic Low will be of great interest. Katabatic winds from Greenland and other high relief are known to be significant.

Eddy Carmack, our IOS host, talked on how fresh water moves, giving a large scale discussion of processes involved in the river/coastal domain and in the CAA, including numerous examples of the complex vertical structure resulting as river plumes are submerged downstream. Eddy emphasizes the size and complexity of the CAA, with very deep basins, providing reservoir effects, divided by very shallow sills. A program to instrument Canadian icebreakers with XCTD probes, joint with JAMSTEC support, will be continued in 2003. This is providing a longitudinal section up the 'spine' of the Labrador Sea/Davis Strait/Baffin Bay system into the CAA.

Bill Crawford of IOS spoke on the use of satellite altimetry to monitor Bering Strait throughflow. With a 10-day repeat cycle, there are dense tracks near the turning point of the Topex/Poseidon orbit. Tidal aliasing is a problem and also the O(100 cm) sea-surface elevations due to winds both of which hinder the use of Topex/Poseidon altimetry on continental shelves. The 10 year altimetry record is providing a useful measure of decadal variability.

Fiona McLaughlin of IOS described hydrography and freshwater storage as seen in the SHEBA experiment. The relative shoaling thermocline during positive phases of the AO/NAO (e.g. 1993) is evident in vertical profiles. Bering Strait Winter Water was traceable at the base of the Pacific Water, as a temperature minimum and nutrient maximum. Its 3 dominant pathways (Herald Canyon, vicinity of Hanna Shoals, Barrow Canyon) were described. In work with Eddy Carmak, CAA 'sub-basin' circulations were also portrayed as having 3 distinct components, buoyancy boundary current (young), mid-depth flow of intermediate age and deep sub-basin circulations (old), using particularly data from Viscount Melville Sound.

Peter Jones of BIO Canada talked on Nares Strait water, and the use of nitrate-phosphate offset to identify Pacific Water. This dramatic use of basic nutrients is beginning to show water-mass volumes and transports of great value to CATS/ASOF (particularly in combination with other tracers indicative of river sources of freshwater). Surprisingly large concentrations of Pacific Water are seen by the method in Davis Strait, Labrador Current, Hudsons Bay, Fram Strait and deep Baffin Bay. The issue of biological modification of the N:P diagram was discussed. Combining the work with mooring/hydrography based transports will be important.

Julie Lobb (IOS/UVic) described her doctoral thesis work on the ventilation of Baffin Bay, discussing frontal structures and the general evolution of water masses on the θ-S diagram. Sections crossing Baffin Bay and along the west Greenland shelf were broken into a 3-layer water-mass model, showing evolution from Atlantic to CAA waters as end-points.

Koji Shimada of JAMSTEC, Japan spoke on Barrow Canyon and Pacific Water spreading in the Canada Basin. In the thin-ice cover region sensitivity to climate change may involve the Pacific Water source. Indication of warming and thinning of ice during 1996-2002 was shown, coinciding with the negative or slightly positive AO/NAO index. Circulation of Atlantic Water across the Chukchi Borderlands is also sensitive to the AO/NAO through the strength of the Beaufort high. Polynya formation affects modification of the water-mass. Ship-based analyses combine with mooring and Bering Strait throughflow to provide upstream conditions for the CAA.

Andreas Muenchow of Univ. of Delaware, described analysis of Davis Strait transports using the Ross data set from 1987-90. These observations are a model for monitoring of straits, and illustrate both the success and difficulty of the method.

Mary O'Brien with MacDonald and Torres described a part of the Nares project involving reconstruction of climate from bivalve shells, spanning back several decades.

Mya truncate lives 30 to 50 years and may yield stable isotopes (δ18O, $\delta^{13}C$) and Ba, Cd, Sr ratios with respect to calcium, dated by growth bands.

Mellissa Zweng (Univ. Of Delaware) described her doctoral thesis work focusing on an historical analysis of Baffin Bay, 1916-99, to see how it fits in with the subpolar salinity decline seen elsewhere. Apparent warming occurs as a trend between 1940 and 1990, in central Baffin Bay and the West Greenland Current (0.2C/decade, 400-2500m depth), with some sign of correlation of NAO index and central waters (roughly 800-1000m depth). Apparent freshening occurs in the northwestern sounds and the boundary current along Baffin Island at 150-200m depth. Meanwhile the northward moving west Greenland Current is warming (600-1200m) and becoming more saline (600-800m).

Though not present physically, *John Smith's* (BIO) work on recent ^{129}I and ^{137}Cs tracer was described; it provides a remarkable tracer for conversion of warm Atlantic Waters into dense Atlantic overflows, and for tracing Atlantic water circulation in the Arctic Basin. AMS analysis allows small water samples. The Sellafield and La Hague reprocessing plants in UK and France, respectively are the sources. Cesium input peaked in early 1980s, while Iodine input rose greatly after 1995 (their ratio making a good clock). The 'front' of Iodine has been observed moving into the abyssal circulation, passing through the Labrador Sea. Transit times from the Norwegian Coastal Current to various sites in the Arctic Basin give strong, independent measures of the circulation in the late 1990s. Transit times from Europe to Greenland and Labrador Seas are 5 to 8 years. Ventilation ages are 2-3 years for Denmark Strait Overflow Water in the Labrador Sea, with a dilution factor of 2 (1:1 mixture with Iceland-Scotland Overflow Water),

DISCUSSION

The discussion brought up several important problems; among these:

- the need for meteorological observations at the fine scale of passages and straits, and the opportunity to use the technology put in place on Greenland by Steffen.
- the need to make full use of satellite observations. Discussion of access to RADARSAT and other SAR and scatterometer products followed. MODIS and AMSR and ENVSAT are apparently available for free, and the US Coast Guard purchases low resolution RADARSAT data for its missions and agrees to scientific access of it. Both ice motion and winds are possible; Konrad Steffen has done a 2-year compilation from RADARSAT in Nares Strait. Altimetry and scatterometer winds over open water are valuable.
- the need for repeat hydrography along carefully defined lines. Problems of tidal

aliasing are already clear (making lowered ADCP/hydrography sections inaccurate) and in the Labrador Sea there is a 10 to 30 day oscillation affecting the boundary currents, and aliasing section data.

- data management, exchange and archiving systems need to be defined.

Many kinds of high latitude data do not have a single archival destination. The role of individual labs and their web-sites will be important. Getting and saving satellite imagery and fine-scale meteorological records is a particular challenge.

- as mentioned at the beginning, shallow continental shelves carry essential components of the Arctic freshwater outflow, and yet are difficult to observe and model. Global climate models do not even have continental shelves!
- dynamical numerical modelling of the CAA is in its infancy, and will only be of value in the presence of high quality observations. The hydraulic, turbulent, highly stratified flows are not amenable to numerical models that also cover the entire region. The models must develop a strong connection with fine-scale meterological models, and the simplest possible indices of Arctic-subArctic exhange found.
- global climate models need to improve representation of the Arctic rim and Arctic Basin: air, sea and ice. This can only happen if lines of communication between ASOF, SEARCH and CLIVAR and between modelers and observational programs are strengthened.

We want to thank Kelly and Eddy for producing a fine meeting, with a memorable evening at Bouchart Gardens. And, of course, US (NSF/NOAA/ONR), Canadian, and Japanese funding agencies for their support of the research.

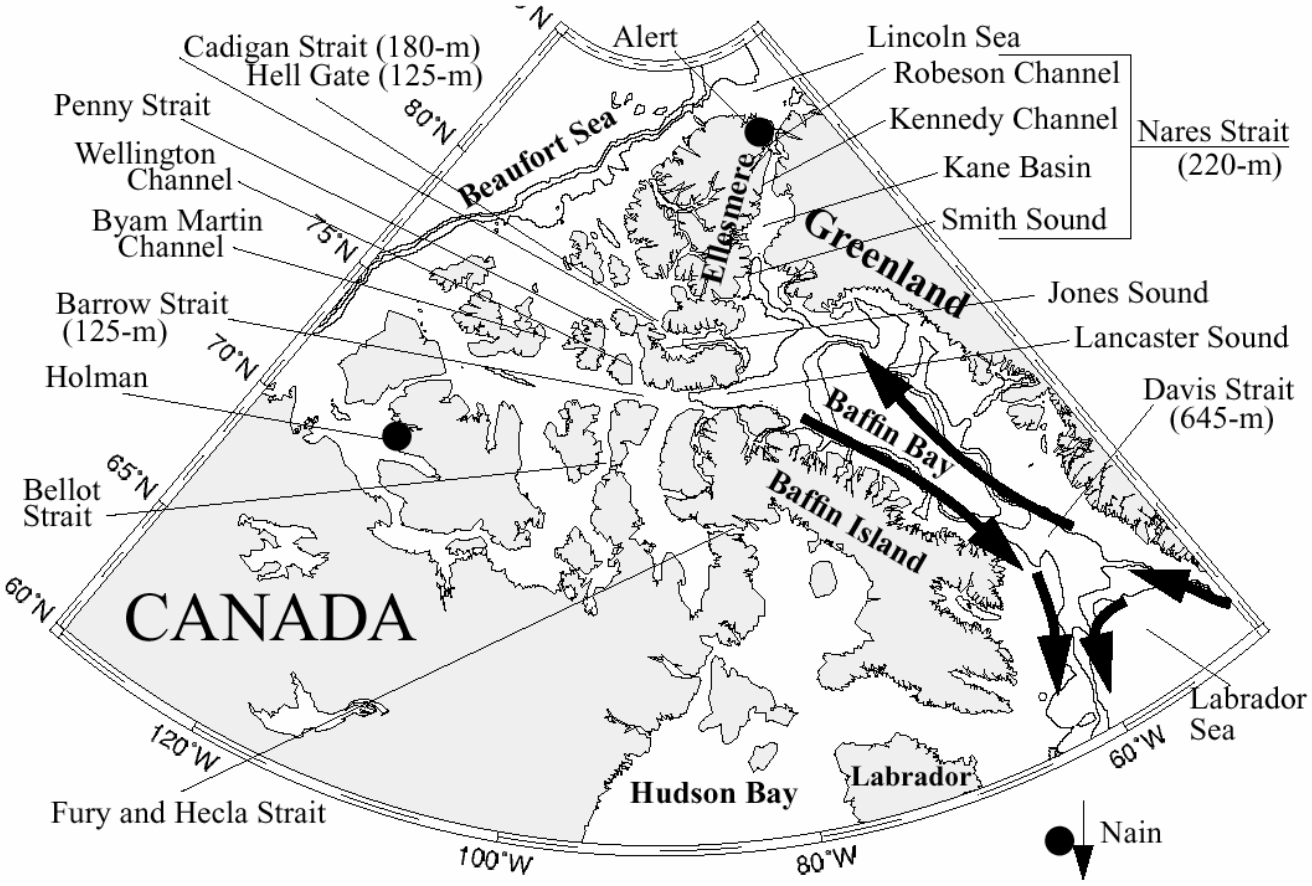
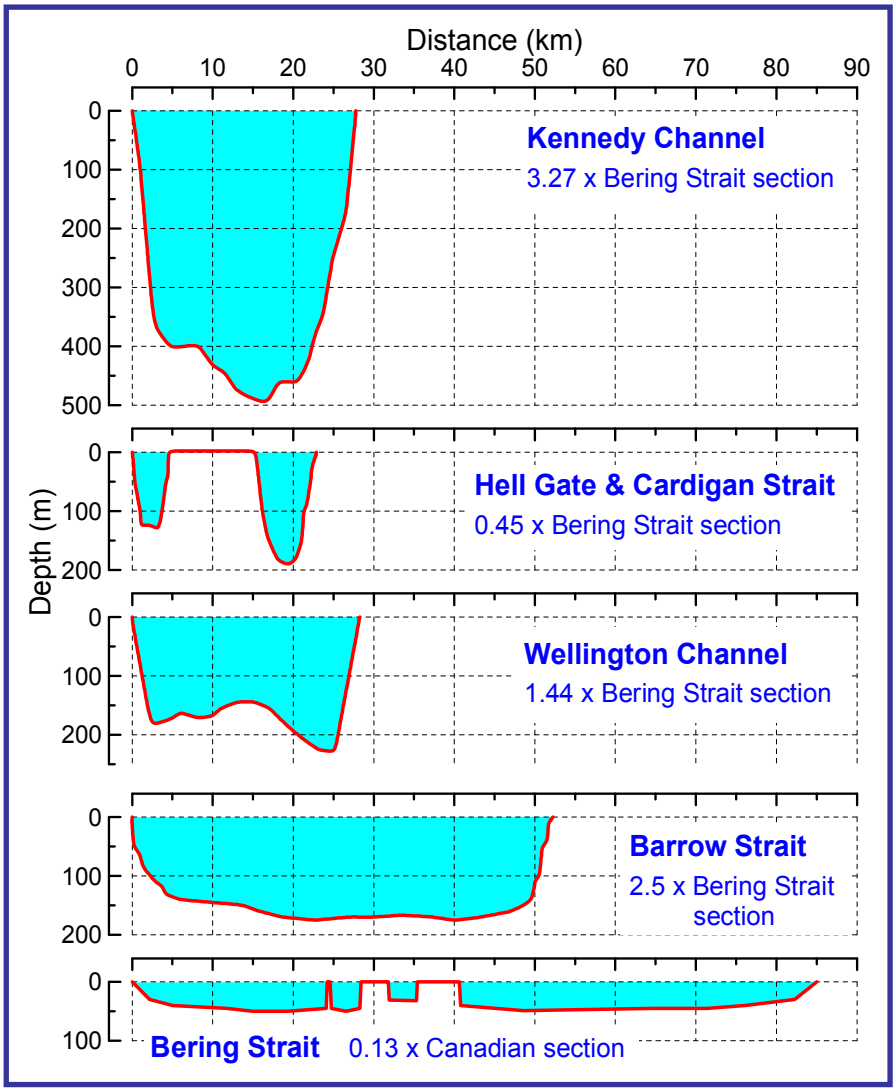


FIGURE 1. Map illustrating the complex topography of the islands and passages of the Canadian Archipelago. Contours are 500-m, 1000-m, and 1500-m isobaths. Glacial action has formed channels and deepened sections to form basins as deep as 600-m separated by a series of shallow sills whose depths in meters is indicated adjacent to their name. Note that Bellot (1.9 km wide, <24-m deep) and Fury and Hecla (16-km wide, 94-m deep) are too small to allow significant throughflow. Arrows off Greenland indicate the (warm) West Greenland Current while the arrows off Baffin Island indicate the (cold) Baffin Current. Filled circles indicate Canadian GOOS collocated tide gauges. Nain, Labrador is located to the south-east off this map.

Humfrey Melling



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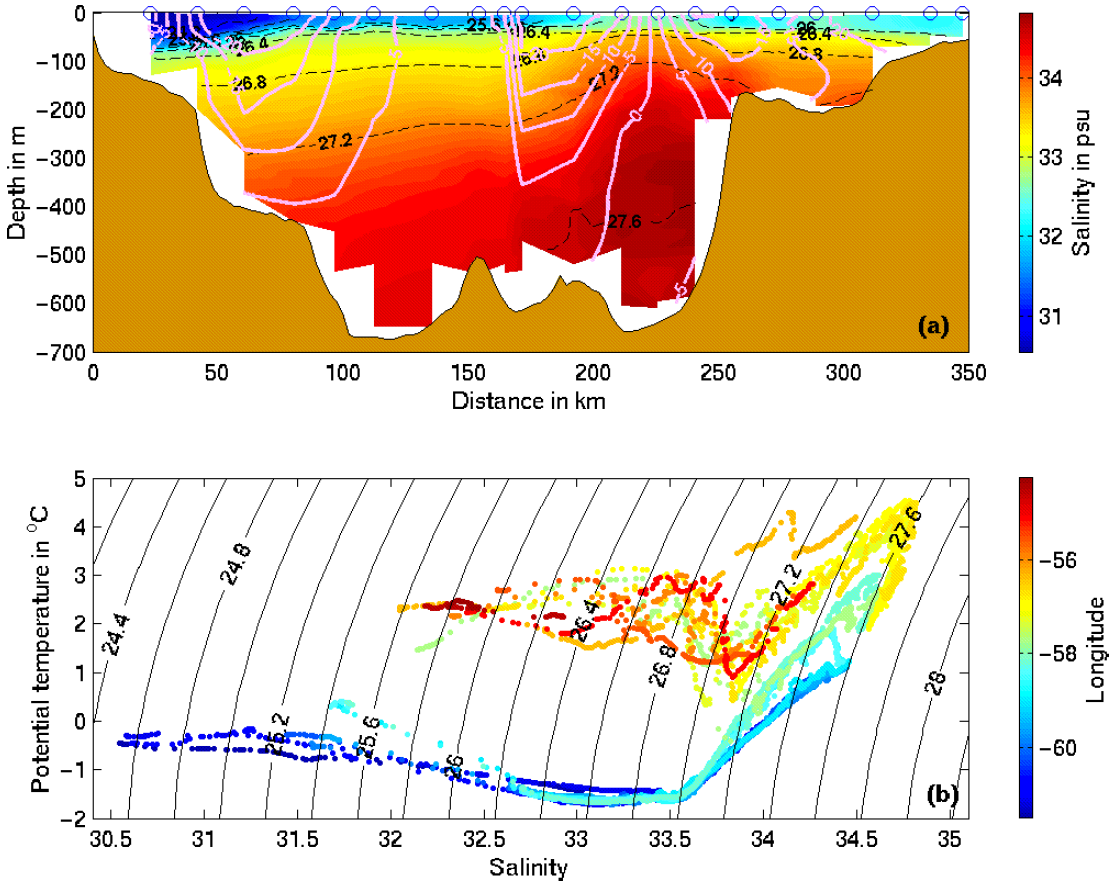

Davis Strait, Sept. 1987 (note difference in km scale compared with other passages)
C.Ross data analyzed by *Jerome Cuny, UW*

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