

Baffin Island and West Greenland Current Systems in Northern Baffin Bay: Synoptic Observations and Climatological Context

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ABSTRACT

Temperature, salinity, and velocity distributions in northern Baffin Bay are presented from a highly resolved summer 2003 survey. The data reveal interactions between fresh and cold Arctic and salty and warm Atlantic waters. Geostrophic currents estimated from hydrography are compared to directly measured ocean currents above 600 m depth. A cyclonic circulation pattern emerges that consists of a barotropic branch over the continental slope off Greenland and a baroclinic branch over deeper waters off Canada. Acoustic Doppler current profiler observations suggest that the West Greenland Current System near 75 N latitude advected about 4.2 ± 0.27 Sv ($Sv = 10^{-6} m^3 s^{-1}$) towards the north-west at this time. The most prominent features were a surface intensified coastal current advecting 0.5 Sv and a bottom intensified slope current advecting about 2.5 Sv in the same direction. Most of this north-westward circulation turned southward in the Baffin Island Current System near 72 N latitude. The Baffin system was transporting up to 5.4 ± 0.24 Sv to the south-east at the time. The imbalance of north- and south-going fluxes reflects empirical uncertainty that arises from unknown inflows via Jones and Lancaster Sounds, temporal variations at weekly time scales, and perturbations introduced by eddies. Eddies with 10 km horizontal and 400 m vertical scales were common and recirculated up to 1 Sv. Our observations represent climatological normal conditions when the North-Atlantic Oscillation index (NAO) is close to zero. During NAO-positive years the baroclinic circulation in Baffin Bay becomes more intense than 2003 with stronger southward flow of fresher Arctic waters along Baffin Island and

stronger northward inflow of saltier Atlantic waters along Greenland. During negative NAO this cyclonic circulation weakens.

1. Introduction

Baffin Bay is a semi-enclosed, seasonally ice-covered basin between northern Canada and Greenland. It connects to the North-Atlantic Ocean in the south via Davis Strait and to the Arctic Ocean in the north via passages of the Canadian Archipelago. Fig. 1 shows the tracks of two location beacons placed in September of 2008 and 2010 on ice islands that calved from Petermann Glacier, Greenland 4 weeks prior (Johnson et al. 2011). Within 6 months each of these ice islands made its way from this Greenland glacier at 81N latitude to the southern terminus of Baffin Island while swiftly transiting along the shelf break off Baffin Island. Enhanced delivery of fresher and colder waters from the Arctic along the shelves and slopes of Baffin Island and Labrador contributes to vertical stratification as far south as the Gulf of Maine and the Mid-Atlantic Bight where interannual ecosystem variability appears to correlate with upstream conditions (Greene et al. 2008). Here we investigate the dynamics of flows in which such quasi-Lagrangian motions are embedded using data that we obtained during a highly resolved sectional survey of northern Baffin Bay in July and August of 2003. Our data provide a snapshot of spatial variability that resolves the relevant baroclinic scale of motion, namely the internal Rossby radius of deformation. This first meso-scale survey of velocity and density fields shows intense baroclinic eddies and jets seaward of steeply sloping bottom topography off northern Baffin Island and Greenland that have not been reported previously.

In April 1912 the RMS Titanic was sunk by an iceberg off Newfoundland near 42N latitude. Most likely, this iceberg originated from Greenland or northern Canada along a path similar to that shown in Fig. 1. The dramatic loss of life in 1912 led to the formation

of the International Ice Patrol that was charged with monitoring and predicting the location of ice and icebergs as they enter the busy sea lanes of the North Atlantic Ocean. Starting 55 with the 1928 Marion expedition, the US Coast Guard conducted pioneering studies of the waters between Canada and Greenland that established the generally southward discharge of ice, icebergs, and buoyant surface waters from Baffin Bay via Davis Strait into the North Atlantic. Early hydrographic observations such as those taken during the Marion (Smith 1931) and Gothaab (Kiilerich 1939) expeditions in 1928 mapped water temperature and 60 salinity of Baffin Bay, Davis Strait, and the Labrador Sea. These data were used to estimate geostrophic velocity shear and circulation from which to predict iceberg motions (Smith 1931). The most recent expedition of the US Coast Guard to northern Baffin Bay in 2003 made direct velocity measurements along several sections from a vessel-mounted acoustic Doppler Current Profiler (ADCP). These data allow evaluation of geostrophically estimated 65 currents and, more importantly, they demonstrate mesoscale spatial variability that impacts shelf-basin exchange. Any predictive tool to guide anticipated future economic activity related to shipping, resource development, and tourism off northern Greenland and Canada will need to include ocean dynamics at these scales.

Two main circulation features emerge from limited past hydrographic, modeling, and 70 mooring studies of Baffin Bay. A cold and buoyant near-surface Baffin Island Current advects Arctic ice, waters, and properties southward towards Davis Strait (LeBlond 1980; Fissel et al. 1982; Tang et al. 2004) and a warm and salty subsurface West Greenland Current advects Atlantic water northward towards Cape York in northern Baffin Bay (Bourke et al. 1989; Muench 1971). A summary and synthesis of mostly Canadian mooring and hydrographic 75 efforts in Baffin Bay from 1978 through 1989 is given by Tang et al. (2004) while Cuny et al.

(2005) provides a similar synthesis for Davis Strait. The net volume flux out of Davis Strait is given as 2.6 ± 1.0 Sv by Cuny et al. (2005) who use current meter mooring records below 150-m and geostrophically estimated velocity shear above this depth. Measurements from a year-long 2004/05 deployment resulted in 2.3 ± 0.7 Sv which includes directly measured currents both in the upper 100-m of the water column and on the shelves (Curry et al. 2011). Using only hydrographic observations, Muench (1971) estimate the net transport across a section of northern Baffin Bay to vary between 1.5-2.7 Sv which agrees with the Davis Strait estimate. Ingram et al. (2002) reviews earlier work in northern Baffin Bay in relation to the North Water polyna (Dumont et al. 2009) and references Addison (1987) who distinguishes Baffin Island Current volume flux contributions to consist of 0.3 Sv from Nares Strait, 0.3 Sv from Jones Sound, 1.1 Sv from Lancaster Sound, and 0.5 Sv from a recirculating West Greenland Current to give a total southward transport of 2.3 Sv. These values represent snapshots based on the untested assumption that the flow is geostrophic relative to an arbitrary reference velocity.

These early measurements provide a first description of the larger basin-wide circulation features and ice drift climatology, however, they do not always resolve dynamically relevant vertical and horizontal scales of motions. Hence it is unclear that the estimated volume fluxes associated with the cyclonic circulation are adequately resolved at both (small) spatial and (long) temporal scales. For example, hydrographic observations from which to estimate geostrophic shear do not resolve seasonal cycles. These cycles vary substantially across Davis Strait and Baffin Bay in both amplitude and phase (Zweng and Münchow 2006) on account of different time histories of forcing of the West Greenland and Baffin Island Currents, respectively. Furthermore, the assumption of geostrophic balance is rarely tested.

While our present study cannot address seasonal cycles of the salinity, temperature, and density for lack of sufficient data, we do test the assumption of geostrophy and investigate the spatial scales of velocity, salinity, and density fields in northern Baffin Bay both off Baffin Island that are dominated by the Arctic outflow and off Greenland that are dominated by the Atlantic inflow. Our synoptic observations from the 2003 summer surveys reveal that the cyclonic circulation exhibits substantial spatial variability that we attribute to instabilities and eddies. We find that the Baffin Island Current is well constrained by the geostrophic thermal wind relation, but that the West Greenland Current is not. Furthermore, both currents are better described as current systems that contain multiple velocity cores and eddies that can be traced to water properties found in the surface-intensified Baffin Island Current or the bottom-intensified West Greenland Current over the continental slope off Greenland near 75N latitude. After introducing our data sources and discussing 2003 temperature, salinity, and velocity observations, we provide context to demonstrate that our 2003 survey represents climatologically normal conditions with regard to the hydrography and the North-Atlantic Oscillation (NAO) index.

2. Study Area and Data

Baffin Bay is linked to the Atlantic Ocean across a 640 m deep sill in Davis Strait and to the Arctic Ocean via Lancaster Sound, Jones Sound, and Nares Strait with sill depths of about 125, 190, and 220 m, respectively (Melling et al. 2008). Fig. 1 shows locations. These channels and straits vary in minimal width from 320 km (Davis Strait), 80 km (Lancaster Sound), to 25 km (Nares Strait). They thus are generally wider than the local internal

deformation radius that is about 10 km (Münchow et al. 2006). Hence even the narrowest channel can accommodate opposing baroclinic flows on each side (LeBlond 1980). Baffin Bay contains wide and gently sloping shelf areas off Greenland in the east and narrower, more steeply sloping shelves off Baffin Island in the west. All shelves are ruptured by deep troughs and canyons that connect the continental slope and basin to the ice caps via fjords in mountainous terrain. 125

We primarily use data from the 2003 expedition of the USCGC Healy to northern Baffin Bay and Nares Strait. This ship is equipped with a 75 kHz phased array ADCP that provides continuous profiles of instantaneous horizontal velocity along the ship track from about 20 m below the sea surface to about 300-600 m depth. For absolute positioning we use the ships's military grade p-code differential GPS as well as an AshTech GPS that also provides accurate heading, pitch, and roll information. For details on calibration, performance, and processing, we refer to Münchow et al. (2006) and Münchow et al. (2007) where the system, novel data processing, and results from Nares Strait north of 78N are discussed. Here we simply note that data are obtained in 15 m vertical bins every 2 minutes. These data are further averaged in space along the track into roughly 2-km horizontal bins for display as sections. Tidal currents are removed using predictions from the barotropic model of Padman and Erofeeva (2004) at the location and at the time of our measurements. Detided currents are extrapolated to the surface by fitting detided subsurface velocity profiles to an Ekman layer profile as described and evaluated by Münchow et al. (2007). Assuming a random standard error of 1 cm/s for vertically averaged currents due to uncertainties in the reference velocity (from bottom-tracking or GPS), detiding, and surface extrapolation, we find 95% confidence limits for volume transport across sections of about ± 0.25 Sv. 130
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All hydrographic data were taken with a SeaBird 911Plus sensor package mounted on a 24 bottle rosette system with dual temperature and conductivity sensors that were factory calibrated 3 months prior to their use in Baffin Bay. An Autosal by Guildline was used throughout the expedition to compare bottle salinities with those derived from the SeaBird 911Plus package to ensure integrity of the CTD data collection. The 2003 data are processed identically to those described in Münchow et al. (2007) and salinities are accurate within ± 0.001 (PSS78).

We collected 30 CTD casts in northern Baffin Bay between July 26 and August 3 of 2003. Thirteen stations are on a line emanating southward from Cape York, Greenland at 76N along longitude 67W to the center of Baffin Bay. Six stations are distributed across Smith Sound near 78N latitude. A third section emanating from northern Baffin Island consists of 11 stations and connects almost perpendicular to the Cape York section at the center of Baffin Bay near 73N. Our focus is on properties above 600-m that roughly coincides with the sill depth of Davis Strait. All temperatures are presented as potential temperatures.

In order to place our 2003 data into a larger spatial and temporal context, we also use temperature, salinity, and density data collected from 1916 through 2003 in Baffin Bay as it has been assembled by the U.S. National Oceanographic Data Center and the Canadian Bedford Institute of Oceanography (NODC/BIO data). Zweng and Münchow (2006) describe these data, their distribution in space and time, and report on a distinct warming trend in central Baffin Bay below Davis Strait sill depths and a small, but significant freshening trend of surface shelf waters from Nares Strait to Labrador.

We use the NAO index derived from normalized winter sea level pressure differences (December through March) between Lisbon, Portugal and Reykjavik, Iceland as a proxy for

atmospheric variability over the northern hemisphere (Hurrell and Deser 2009).

sectionSpatial Context Baffin Bay We start our discussion of the hydrographic climatol-
ogy of northern Baffin Bay with Fig. 2 which shows the potential temperature on a constant
density surface ($\sigma_t = 27.4 \text{ kg m}^{-3}$) derived from the NODC/BIO data as well as our own 170
2003 data. The vertical location of this density surface varies from about 50-m in eastern
Davis Strait to more than 350 m depth along Baffin Island. The distribution of potential
temperature in Fig. 2 reveals the warm (and thus salty) waters off Greenland exceeding
 1°C as compared with the cold (and thus less salty) waters off Ellesmere and Devon Is-
lands in the north-west with temperatures below 0°C . These are the signatures of the West 175
Greenland and Baffin Island Currents that together comprise the cyclonic circulation. The
shallow occurrence of the $27.4 \sigma_t$ feature in the center of Baffin Bay near 66°W longitude and
 72°N latitude is consistent with this cyclonic circulation. Note also the patchy temperature
distribution north of 72°N where the colder, fresher northern waters meet the warmer, saltier
southern waters. This area of transition and transformation is the focus of this study. To 180
the north of 76°N lies the North Water polynya, a prominent open water and thin ice region
to the south of Smith Sound whose waters are described for a period from April through
July of 1998 by Bacle et al. (2002).

3. The West Greenland Current Regime

The data from the Cape York and Smith Sound sections portray the principal water 185
masses with southern and northern signatures, respectively. All CTD casts exhibit pro-
nounced subsurface temperature maxima at salinities larger than 33.9 psu (Fig. 3) that are

indicative of waters from the North Atlantic Ocean. Following Bacle et al. (2002), we distinguish between such water entering our study area from the north via Nares Strait, which has subsurface temperatures no higher than $-0.4\text{ }^{\circ}\text{C}$ and water entering our study area from the south, wherein the subsurface maximum temperature is $+2.0\text{ }^{\circ}\text{C}$ (Fig. 3). The distinction becomes particularly clear if we depict temperature along the $\sigma_t = 27.4\text{ kg m}^{-3}$ isopycnal which we highlight in Fig. 3 for comparison with the historical data shown for this isopycnal in Fig. 2.

The southern waters with $2.0\text{ }^{\circ}\text{C}$ near 34.5 psu are often associated with the West Greenland Current. However, we find these waters in at least 2 flavors with a slightly fresher (and warmer) branch located on the continental shelf inshore of the 500 m isobath and a saltier (and cooler) branch seaward of this isobath. The exception is a single cast of intermediate temperature and salinity that represents an anomaly seaward of the 2000 m isobath. Both the spatial distribution of salinity and temperature as well as underway ADCP velocity along this section suggest that this is an anti-cyclonic eddy of West Greenland shelf waters in deep Baffin Bay. Such eddies have not previously been reported in Baffin Bay.

Fig. 4 shows the density, salinity, and temperature along a north-south line that is oriented perpendicular to bathymetric contours. The shelf off Cape York slopes steeply from 50 m to 400 m within 30 km off the coast, flattens for about 40 km to plunge below 2000 m about 100 km from the coast. Surface waters are below $-1.5\text{ }^{\circ}\text{C}$ or within about $0.3\text{ }^{\circ}\text{C}$ of the freezing point. Bourke et al. (1989) refer to this water as the Baffin Bay Arctic Water to consist of a mixture of waters strongly impacted by the annual summer melting and winter freezing cycle, as well as local runoff from Greenland. Below this layer which extends to about 200 m depth, we find water of about $1.2\text{ }^{\circ}\text{C}$ at salinities of about 34.4 psu; Bourke

et al. (1989) called this Atlantic Intermediate Water. Within these waters, however, we find two distinct cores with temperatures exceeding 2°C and 1.6°C shoreward and seaward of the 600 m isobath, respectively. Between these cores there is a cooler fresher water with properties between those seaward and landward of the 600 m isobath (see Fig. 3). Note that the isopycnals are largely flat near the 350 m depth where this feature is most pronounced, 215 i.e., the large lateral temperature and salinity gradients compensate such that the lateral density gradient is small.

If lateral density gradients are small in a geostrophic flow, then we expect vertical gradients of horizontal velocity to be small also. Figs. 5 and 6 display snapshots of the West Greenland Current system, derived via ship-based ADCP survey, both as a section and a 220 vertical average. This current system comprises 1) a surface intensified westward coastal current, 2) a sluggish flow on the shelf, 3) an intense, narrow westward jet over the continental slope that spills onto the shelf near the shelf break, 4) an anti-cyclonic eddy, and 5) a sluggish circulation over the deep Baffin Bay (details to follow). The net transport of this current system above 600 m depth combines to about 4.2 ± 0.27 Sv with more than 2 Sv 225 carried by a less than 40 km wide slope current that we will refer to as the West Greenland Slope Current.

a. Coastal Current

Although our survey of northern Baffin Bay was not designed to resolve baroclinic flows within 10 km of the coast, both the along-shore velocity (Fig. 5) and three casts within 230 25 km off Cape York, Greenland (Fig. 4) reveal a wedge of warm, buoyant surface waters

with salinities less than 33.4 psu and density anomalies less than 27.0 kg m^{-3} . Adjacent to the coast, this buoyant wedge extends to 100 m depth but shoals within 30 km to less than 20 m depth. Relatively large westward flows (reaching 0.2 m s^{-1}) are estimated by extrapolating measured flows below 25 m depth with an Ekman layer profile (Münchow et al. 2007). Similarly large flows (0.17 m s^{-1}) are estimated from Margule’s equation that assume geostrophic flow relative to negligible flow below a sloping frontal boundary, e.g., $v = i \times f/g \times \Delta\rho/\rho$ where f is the local Coriolis parameter ($1.41 \times 10^{-4} \text{ s}^{-1}$), g is the constant of gravity (9.81 ms^{-2}), ρ is the density of the dynamically active upper layer (1026 kg m^{-3}), $\Delta\rho$ is the density difference across the density interface (1 kg m^{-3}) which has a slope of i (80 m over 30 km). Geostrophic coastal currents driven by local buoyancy fluxes are common at both mid-latitudes (Münchow and Garvine 1993; Pimenta et al. 2008) and off Greenland (Bacon et al. 2002; Sutherland and Pickart 2008). While the impact of such coastal currents on basin scale volume flux may be small, about 0.5 Sv here, their potential contribution to freshwater flux is large as the swift surface flow may carry low salinity waters far from their origins as coastally trapped flows (Sutherland et al. 2009).

b. Shelf Flow

The flow seaward of the coastal current varies little with depth and is always less than 0.1 m s^{-1} . The depth-averaged flow is always westward and reaches a local minimum about midway across the shelf at km-260 (Fig. 6). The integrated volume flux from the shelf to this location carries about 0.5 Sv. The waters are somewhat warmer than waters on the same isopycnal over the deep basin offshore. The shelf break jet that we discuss next, spills

onto the shelf near the bottom. Largest subtidal velocities exceeding 0.1 m s^{-1} occur near the 400 m deep bottom close to the shelf break.

c. West Greenland Slope Current

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We find a pronounced westward flow over the continental slope where the water depth plunges from 600 m at the shelf break to 2000 m within 30 km. The largest vertically-averaged velocity occurs at the 600 m isobath reaching 0.2 ms^{-1} (Fig. 6). This flow is about 40 km wide at the surface, but it becomes more intense below 200 m depth where it exceeds 0.2 ms^{-1} to at least 500 m depth (Fig. 5). The shoreward edge of this velocity core coincides with the subsurface temperature maximum at 350 m depth near the 500 m isobath (Fig. 4). In the seaward direction the current extends to the 1500 m isobath. The current is thus contained entirely over the slope and does not extend to the foot of the continental slope where the bottom changes its slope from 0.05 to 0.002. We will refer to this current as the West Greenland Slope Current to distinguish it from the weaker westward flows on the shelf. The slope current carries a volume of about 2.0 Sv westward over the top 500 m (Fig. 6).

Horizontal density gradients associated with the West Greenland Slope Current are small, because higher temperature and higher salinity relative to ambient waters compensate each other with regard to density. Thus while conventional hydrographic measurements may trace the origin of waters off western Greenland, they cannot reveal the geostrophic circulation, because the West Greenland Slope Current contains a large barotropic component.

The relative vorticity ξ of a geostrophic flow is much smaller than the planetary vorticity f (Gill 1982). We estimate ξ for the vertically averaged flow (Fig. 6) as $\xi \approx \Delta u / \Delta y \approx 0.1f$

where $f = 1.4 \times 10^{-4} \text{ s}^{-1}$ and $\Delta u = 0.15 \text{ m s}^{-1}$ is the along-slope velocity difference over an across-slope distance $\Delta y = 12 \text{ km}$. Since nonlinear inertial effects are scaled by $\xi/f \approx 0.1$,
we discern that they are small relative to Coriolis effects and that the barotropic flow is in geostrophic balance to first order during our expedition.

d. Anti-Cyclonic Eddy

Seaward of the West Greenland Slope Current near km-170 both a single CTD cast and the velocity measurements approaching and leaving this location from south to north reveal
anomalous water properties and ocean currents. Ocean currents change from 0.15 m s^{-1}
westward to 0.15 m s^{-1} eastward over a distance of less than 20 km just seaward of the
continental slope (Figs. 4, 5, and 6). Water within this feature is cooler and fresher than
that below 200 m and above 500 m depth. This signature extends to about 800 m depth,
however, the temperature effect vanishes below 500 m depth and the lower than ambient
salinity leads to a horizontal density minimum (Fig. 7). The locally depressed isopycnals
suggest a clock-wise geostrophic circulation relative to no flow at greater depths which is
consistent with the observed flow shown in Fig. 5. We thus interpret our observations to
represent an anti-cyclonic eddy.

The almost axisymmetric velocity distribution with a linear shear of 0.3 m s^{-1} over
10 km suggests an eddy core with radius $r_m \approx 5 \text{ km}$ in solid-body rotation that can be
modeled as a Rankine vortex (Timmermans et al. 2008). The Rankine vortex emerges as a
particular simple solution in steady fluids where nonlinear advective and pressure gradient
forces contribute to the dynamics. For a Rankine vortex the azimuthal velocity increases from

zero at the center of the vortex to a maximum V_g at r_m (0.15 ms^{-1}) and then decreases with 295
the inverse distance from the eddy center, e.g., $v(r) = V_g r / r_m$ for $r \leq r_m$ and $v(r) = V_g r_m / r$
for $r > r_m$. Fig. 6 shows the analytical solution demonstrating that it fits the observed
velocity distribution well both for the 10-km wide eddy core and at least another 10 km to
either side. The Rankine vortex as a uniform potential vorticity distribution $\Pi = 2V_g / r_m$
for $r \leq r_m$ and zero potential vorticity for $r > r_m$. An estimate of the Rossby number 300
 $Ro = \Pi / f \approx 0.4$ indicates a nonlinear flow. It recirculates a volume flux of at least 0.5 Sv
within its core of uniform potential vorticity.

e. Deep Basin Circulation

The largest subsurface isopycnal slopes and implied geostrophic velocity occur over the
deep basin where the $27.0 \sigma_\theta$ surface slopes from 80 m at km-40 to about 150 m at km-5 305
(Fig. 4) which coincides with the location of a surface intensified eastward flow. We believe
that these isolated baroclinic flow features are related to processes off Baffin Island that we
discuss next. Sloping isopycnals extend to about 1000 m depth. Below this depth we find
uniformly stratified waters to about 1800 m as potential temperature decreases from $+0.8^\circ\text{C}$
at 1000 m depth to -0.4°C at 1800 m depth (Fig. 7). This stratified deep layer includes 310
deep salinity minimum at 34.485 psu at 1400 m depth with values larger than 34.52 psu
above towards the West Greenland slope and values below 34.49 below 1800 m depth where
the uniform waters are termed Baffin Bay Bottom Water by Bourke et al. (1989).

4. The Baffin Island Current Regime

a. Water Masses

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Fig. 8 shows potential temperature salinity relationships above 600 m as well as the measurement locations over bottom topography. For salinities at depths below the surface mixed layer and below 33.7 psu, temperatures are almost constant off Baffin Island at -1.6°C . These winter-mixed polar waters are distinct from northern Arctic source waters that enter from Nares Strait where waters at these salinities are at least 0.5°C warmer. As salinities increase towards 34.5 psu, temperature increases towards a maximum of $+1.0^{\circ}\text{C}$ near the $27.4 \sigma_{\theta}$ density surface. Again, these waters are distinct from Nares Strait waters which are almost 2°C cooler. Nevertheless, the warm subsurface waters off Baffin Island are always cooler than those found off western Greenland at similar salinities. We thus identify the West Greenland Current System as the main source of the subsurface waters off Baffin Island which is consistent with the cyclonic circulation in northern Baffin Bay. Waters from Nares Strait are a minor source that modify fresher waters near the surface towards warmer temperatures while saltier waters at depth are modified towards cooler temperatures on density surfaces.

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Fig. 9 presents the same data along a section that extends from the coast of Baffin Island near 72°N latitude towards the center of Baffin Bay (Fig. 1). A cold and relatively fresh layer above 300 m depth separates a seasonally warmed 20 m thin surface mixed layer from the warm and salty West Greenland Current waters. At salinities below 33.8 psu, the coldest waters of -1.6°C are found more than 120 km from the coast as well as near the shelf break 50 km from the coast where, as we will discuss below, velocities are generally small.

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These colder and fresher waters are remnants of winter waters. Comparing the properties of these waters along isopycnals with waters from either the West Greenland shelf or Smith Sound (see Fig. 3), we find those northern waters warmer (and thus saltier) by almost $0.5^{\circ}C$ at a salinity near 33.6. The waters at these salinities in Smith Sound likely contain a larger fraction of Pacific waters that enter the Arctic Ocean via Bering Strait (Woodgate and Aagaard 2005; Münchow et al. 2007). 340

b. Velocity

The most dramatic feature in Fig. 9, however, are undulating isopycnal excursions that exceed 50 m over 40 km. If the associated baroclinic pressure gradients are balanced by the Coriolis force, then we can estimate the geostrophic velocity field that these isopycnals imply. 345
In Fig. 10 we show these geostrophic (thermal wind) velocities that we reference at 500 m depth to observed ADCP velocities. The reference velocities are always smaller than $0.1ms^{-1}$ while the geostrophic surface velocities exceed $0.3ms^{-1}$ in both northward and southward directions as isopycnals slope upward and downwards towards the east, respectively. Opposing flows are particularly strong about 220 km from the coast where a southward jet exceeds 350
 $0.4ms^{-1}$ adjacent to a northward flow of about $0.2ms^{-1}$. We find weak geostrophic flows over both the narrow shelf and steeply sloping continental shelfbreak within 50 km off Baffin Island.

The flow calculated via geostrophy compares favorably to concurrent direct observations of velocity derived via ADCP, shown in Figs. 11 and 12. These direct observations consist of 355
both geostrophic and ageostrophic velocity components. The directly observed flow clearly

reveals the strong vertical component of shear above 300 m depth. The largest lateral velocity gradient occurs near the surface between 200 km and 220 km from the coast, where the value changes from about -45 cm/s to + 25 cm/s in both realizations. Clearly the lateral shear is closely linked to the undulations of density surfaces at this location (Fig. 9). Scaling this velocity difference of $\delta U \approx 0.7 \text{ m s}^{-1}$ over $L=20$ km by the Coriolis parameter $f=1.38 \text{ s}^{-1}$, we find a first rough estimate of the Rossby number $R = \delta U / (f L) \approx 0.25$ which indicates that nonlinear inertial effects may contribute to the dynamics and stability characteristics of the observed currents.

Integrating the vertically averaged alongshore velocity along the section, we show with Fig. 12 how the volume transport perpendicular to our section reaches 4 ± 0.24 Sv. Over the shelf and shelfbreak to 800 m bottom depth within 50 km of Baffin Island, volume transports are below 0.2 Sv. Seaward of the 800 m isobath, two much larger current structures emerge. The first represents a broad and sluggish flow less than 10 cm/s from about 50 km to 130 km offshore. This flow carries about 1.6 Sv, but a 30 km wide counter-current or eddy structure reduces the net transport to less than 0.8 Sv over the top 500 m of the water column. Most of the volume transport across the Baffin Island section is contained within a southward jet about 160 km from shore near the 2000 m isobath. It alone carries almost 3.5 Sv over its 60 km width from 160 km to 220 km from the coast. The same flow emerges via geostrophy from the hydrographic observations (Figs. 10 and 9). The along-shore velocity within this 60 km wide jet is vertically sheared, so that lateral shear more or less vanishes at 500 m depth, that is, the velocity observed by ADCP at 500 m contributes little to the geostrophic currents that contain both vertical and lateral shear above 300 m. This gives confidence that directly observed ADCP surface currents are consistent with independently estimated

5. Climatological Context 1916-2003

The temporal context of our detailed 2003 observations is demonstrated via the North-Atlantic Oscillation (NAO) which represents the dominant mode of atmospheric variability in the northern hemisphere (Hurrell and Deser 2009). A more deeply depressed Icelandic Low than normal constitutes the positive NAO phase. Smith (1931) used the NAO in a regression to predict the number of icebergs emanating from Baffin Bay to impact shipping south of Newfoundland. He discovered that years of positive NAO correspond to higher iceberg counts off Newfoundland. Zweng and Münchow (2006) demonstrate that subsurface temperature fluctuations in Baffin Bay correlate significantly with the NAO reflecting Baffin Bay's connection to the climate regime of the North-Atlantic. Fig. 13 shows the NAO index from 1910 through 2004 with non-dimensional amplitudes with a range of ± 5 . We form conditional averages of hydrographic properties for years with NAO amplitudes larger than +0.5 and smaller than -0.5. Positive values are associated with more intense storms at higher latitudes causing drier and colder winter conditions over Greenland and northern Canada while negative values are associated with both weaker and more southerly storm tracks (Hurrell and Deser 2009). The NAO value for 2003 is +0.2, close to the average conditions and our observations from that year can be considered climatologically normal.

It is instructive to examine how the implied geostrophic circulation in Baffin Bay differs between positive and negative NAO states. We average the climatological data into a section across Baffin Bay created by binning observations according to water depth. By doing so, we

assume that hydrographic properties are uniform along isobaths from 67N to 76N latitude. Depth on the Greenland side have been separately binned from those on the Canadian side separated at the thalweg - the locus of points at having the greatest depth for each latitude (see Fig. 1).

Fig. 14 shows the results of this conditional averaging in time (separately for high and 405 low NAO years) and space (separately east and west of the thalweg by bathymetry) for a vertical bin that extends from 200 m to 400 m below the surface. This layer likely contains elements of both the Baffin Island and the West Greenland Currents in Baffin Bay. During the positive NAO phase this layer is both fresher and cooler off Canada in the west and saltier and warmer off Greenland in the east relative to the NAO negative phase. This indicates 410 a stronger (weaker) than normal cyclonic circulation during the NAO positive (negative) phases consistent with the earlier findings of Smith (1931) that more (less) icebergs occur off Newfoundland during years with a positive NAO anomaly.

The density gradients across Baffin Bay increases from west to east in all years, indicative of a net baroclinic outflow from the Arctic into the North-Atlantic Ocean relative to zero 415 flow below. Nevertheless, there are smaller baroclinic features confined to the continental slope (1500-2000 m isobaths) that demarcates the shelf from the deep basin off Baffin Island. Specifically during negative NAO years, the density anomaly σ_t varies by only 0.03 kg m^{-3} ($27.32\text{-}27.35 \text{ kg m}^{-3}$), but during positive NAO years σ_t varies across the shelf break by more than 0.09 kg m^{-3} ($27.28\text{-}27.35 \text{ kg m}^{-3}$). We speculate that the waters above the 1500-2000 420 m isobath at 200-400 m depth are part of the climatological Baffin Island Current. This interpretation is consistent with the 2008 and 2010 paths of the Petermann ice island shown in Fig. 1.

The density increase towards Baffin Island shoreward of the 1500-m isobath. If the lateral density gradients are geostrophically balanced relative to a deeper level without flow, then this gradient implies a possible northward counter-current in shallow water that has escaped notice to date. However, the inference of circulation from geostrophic tendencies can be problematic. There are implicit assumptions and historical composites may have intrinsic temporal and spatial biases. It is wise to work with short-term synoptic surveys, as presented above, wherein both hydrography and velocity have been observed.

6. Discussion and Conclusions

Analyses of hydrographic data in Baffin Bay during the 1916-2003 period indicate that the NAO index modulates the baroclinic pressure distribution inside Baffin Bay (Fig. 14), creating a stronger geostrophic cyclonic circulation during the NAO-positive years such as 1919, 1973, 1984, and 1990 than it is during the NAO-negative years such as 1916, 1936, 1969, and 1996 (Fig. 13). Surface waters off Baffin Island are fresher and colder during NAO-positive years while those off Greenland are saltier and warmer. This finding is consistent with larger fluxes of Arctic waters into Baffin Bay from the north and larger fluxes of Atlantic waters into Baffin Bay from the south. Zweng and Münchow (2006) demonstrate that the warming of subsurface waters in Baffin Bay correlates significantly with the NAO which emphasizes the connection of the regional oceanography with remote atmospheric forcing over the North-Atlantic at interannual time scales. We consider our 2003 observations to represent a climatological mean rather than an extreme state, because the NAO index was close to zero in both 2002 and 2003.

During our summer 2003 survey of northern Baffin Bay we find a delicate spatial ar- 445
rangements of water masses and ocean currents within about 600 m of the surface. The
waters off western Greenland are strongly impacted by relatively warm and salty waters
originating from the North-Atlantic entering via Davis Strait (Cuny et al. 2005; Tang et al.
2004) while those off Baffin Island are strongly impacted by relatively cold and fresh waters
originating from the Arctic Ocean (Münchow and Melling 2008; Prinsenber and Hamilton 450
2005). Waters are strongly stratified in the vertical both off West Greenland in the east
and off Baffin Island in the west, however, the lateral density gradients over the slope off
Greenland are small relative to those found off Baffin Island. Geostrophically estimated
flows off West Greenland based on hydrographic observations alone will not provide velocity
or volume flux estimates on account of a weak baroclinic, but strong barotropic circulation. 455
We thus conclude that direct velocity measurements are needed to describe the slope current
off western Greenland.

Note, however, that weak baroclinic circulation does not imply weak flows as the total flow
also contains a barotropic component. Specifically, we find a 20 km wide, largely barotropic
flow centered over the 600 m isobath west of Greenland. This flow, which we call the West 460
Greenland Slope Current, carried volume at a rate of about 2 Sv ($10\text{ m}^6\text{ s}^{-1}$) towards the
north-west during our survey. It contains the warmest waters found in northern Baffin Bay
with potential temperatures exceeding $2\text{ }^\circ\text{C}$ at 400 m below the surface in 600 m deep water.
This slope current is distinct from the flows both seaward over the deep basin and landward
over the the continental shelf. The shelf flow off Greenland is frequently considered part of 465
a West Greenland Current in waters south of Davis Strait in the Labrador Sea (Myers et al.
2009; Fratantoni and Pickart 2007). North of Davis Strait, a greater width of shelf and fewer

observations have prevented a clear hydrographic description.

In contrast to conditions off West Greenland, geostrophically estimated flows off Baffin Island replicate well the directly measured ocean current and flux (Figs. 10 and 11) as 470 barotropic contributions are much smaller than off Greenland. Both velocity observations and geostrophic diagnostics reveal the main circulation features over the sloping topography off Baffin Island, namely (1) a slow broad southward flow within about 150 km of the coast and (2) an intense, surface intensified cyclonic feature with southward velocities exceeding 0.4 m s^{-1} within 15 km of a weaker, but northward surface velocity core reaching 0.2 m s^{-1} . 475 The broad sluggish inshore flow carries about 1 Sv while the 50 km wide offshore feature carries another 4.4 Sv of volume southward. The latter is centered near the 2000 m isobath about 180 km from the coast of Baffin Island. It coincides with isopycnals that slope by about 100 m over 20 km almost uniformly from 450 m to 50 m depth. Comparing the direct velocity observations with those estimated from hydrography via the geostrophic thermal 480 wind relation, we conclude that that the vertical shear measured by the vessel-mounted ADCP off Baffin Island is largely geostrophic and baroclinic.

Our two sections across the shelf, slope, and basin off Greenland and Baffin Island intersect near 73 N latitude at the thalweg over the deep Baffin Bay basin (Fig. 1). These sections define a volume that is open to Nares Strait and Jones Sound in the north-east and 485 Lancaster Sound in the north-west. The net flow into our study area from Nares Strait in the summer of 2003 is about 1.0 ± 0.1 Sv in the absence of winds Münchow et al. (2007). The West Greenland current systems adds 4.2 ± 0.27 Sv inflow from the south-east for a combined flux of 5.2 ± 0.37 Sv. While we have no synoptic observations to estimate contributions from Jones and Lancaster Sounds, it is clear that the combined inflows are not balanced by the 490

outflow of 4.0 ± 0.24 Sv off Baffin Island. We suspect that eddies contribute substantially to the volume flux estimated from quasi-synoptic transect lines and potentially introduce biases of up to 1 Sv.

Seaward of the West Greenland Slope Current we identify anomalous waters that extend from the surface to about 800 m depth within an anti-cyclonic circulation feature that is well modeled as a Rankine vortex with a diameter of about 10 km (Fig. 6). The small 10-km scale of this eddy corresponds to the internal (baroclinic) Rossby radius of deformation which is the dominant spatial scale for a stratified fluid in geostrophic balance (Gill 1982), however, it also corresponds to the width of the continental slope and the width of the barotropic West Greenland Slope Current. The anti-cyclonic eddy extends across the entire halocline with a thickness exceeding 400 m near a topography slope where most of the kinetic energy is contained within the largely barotropic West Greenland Slope Current. It recirculates a volume flux of about 0.8 ± 0.2 Sv.

A single CTD cast from the core of the vortex distinctly separates temperature-salinity correlation curves from a grouping representative of West Greenland shelf waters off Cape York and a grouping representative of Baffin Bay basin waters with salinities above 33.5 psu (Figs. 3 and 8). Specifically, above salinities of 33.5 psu, the entire salinity-temperature correlation falls between the shelf and basin cluster of CTD profiles. Water temperatures within the vortex are about 0.2 °C warmer than than slope and basin waters and 0.4 °C cooler than shelf waters on the same isopycnals. The northward flow of Atlantic waters via Davis Strait is the source of the waters over the slope (Tang et al. 2004). This inflow is seasonally modulated in both its velocity magnitude (Cuny et al. 2005), its subsurface temperature maximum (Zweng and Münchow 2006), and its heat transport into Baffin Bay. Davis Strait

is about 800 km to the south. Assuming a swift flow over the slope of 0.2 m s^{-1} , a water parcel would arrive at our study region about 45 days later. We thus speculate that the eddy represents hydrographic conditions of the West Greenland Slope Current at least 2 months prior. 515

A definite explanation for the origin of this anticyclonic circulation feature requires more comprehensive observations and numerical modeling. Katsman et al. (2004) and Spall et al. (2008) discuss eddy dynamics related to slope and boundary currents in numerical models to explain observations off south-west Greenland and north-west Alaska, respectively. Both these studies identify baroclinic instability as the main eddy formation process, however, our limited observations indicate that most of the kinetic energy over the slope off West Greenland is barotropic. The scale of the vortex is of the same order of magnitude as both the width of the slope and the internal deformation radius. Hence we are presently unsure which instability process generated the anti-cyclonic eddy seaward of the West Greenland Slope Current. We do note, however, that the barotropic circulation over the continental slope off West Greenland resembles the West Spitsbergen Current in the Greenland Sea (Walczowski et al. 2005) which is postulated to become barotropically unstable (Teigen et al. 2010). 520 530

The Arctic outflows from Nares Strait and Lancaster Sound transform into the Baffin Island Current with substantial contributions from the West Greenland Current system. It is unclear, however, how a barotropic circulation over the steeply sloping shelf break off West Greenland transforms into a baroclinic circulation largely detached from the bottom over much deeper water off Baffin Island. Within about 150 km off Baffin Island the circulation is sluggish during our observations in July 2003, however, we find largest currents as a 535

single surface intensified, 50-km wide baroclinic jet about 180 km from the coast. Vertical currents shears predicted from geostrophy agree well with vertical shears measured from vessel-mounted ADCP surveys. Counter-currents or eddies appear in the velocity section (Fig. 11) that correspond to sloping and undulating isopycnals in apparent geostrophic balance. Lateral current shears suggest Rossby numbers of up to 0.25 or a weakly nonlinear flow off Baffin Island. 540

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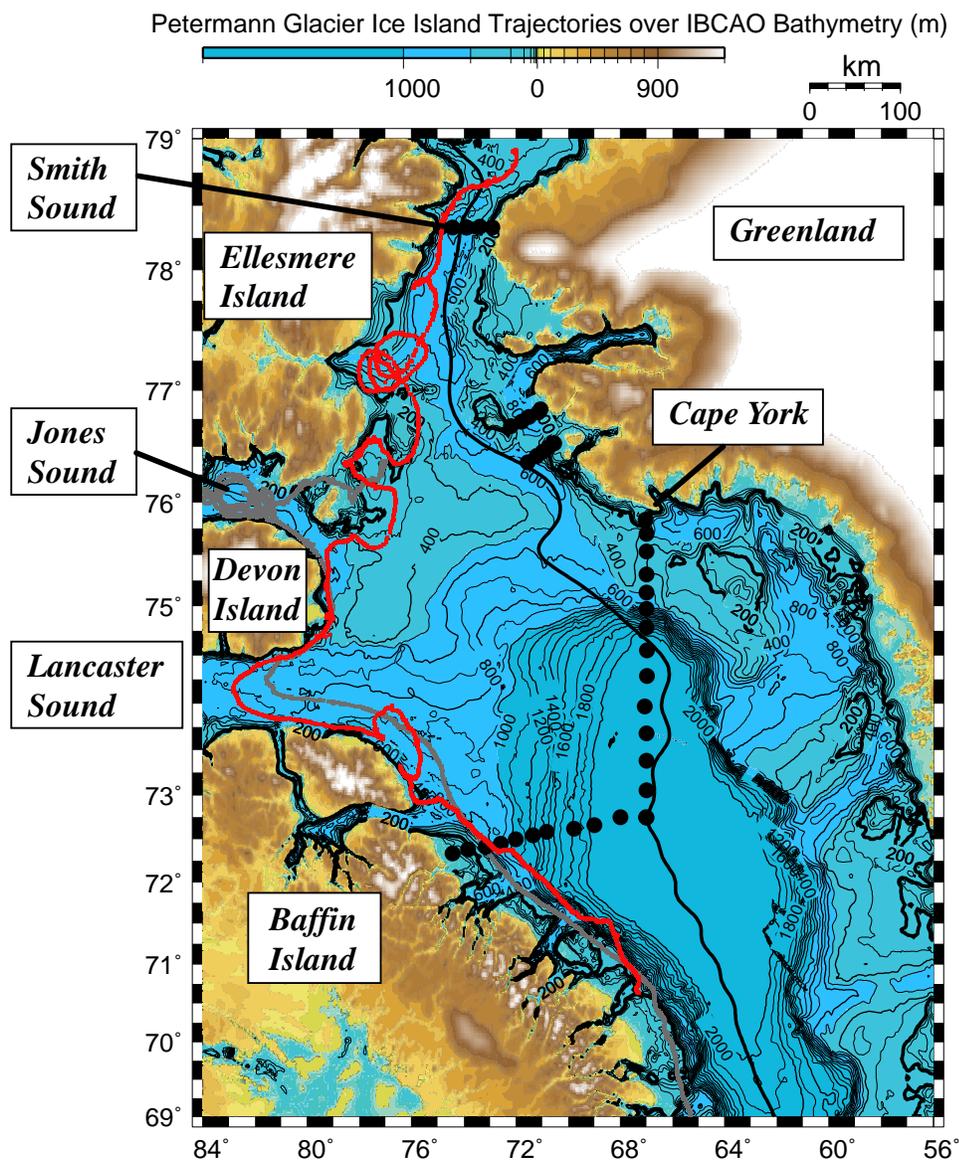


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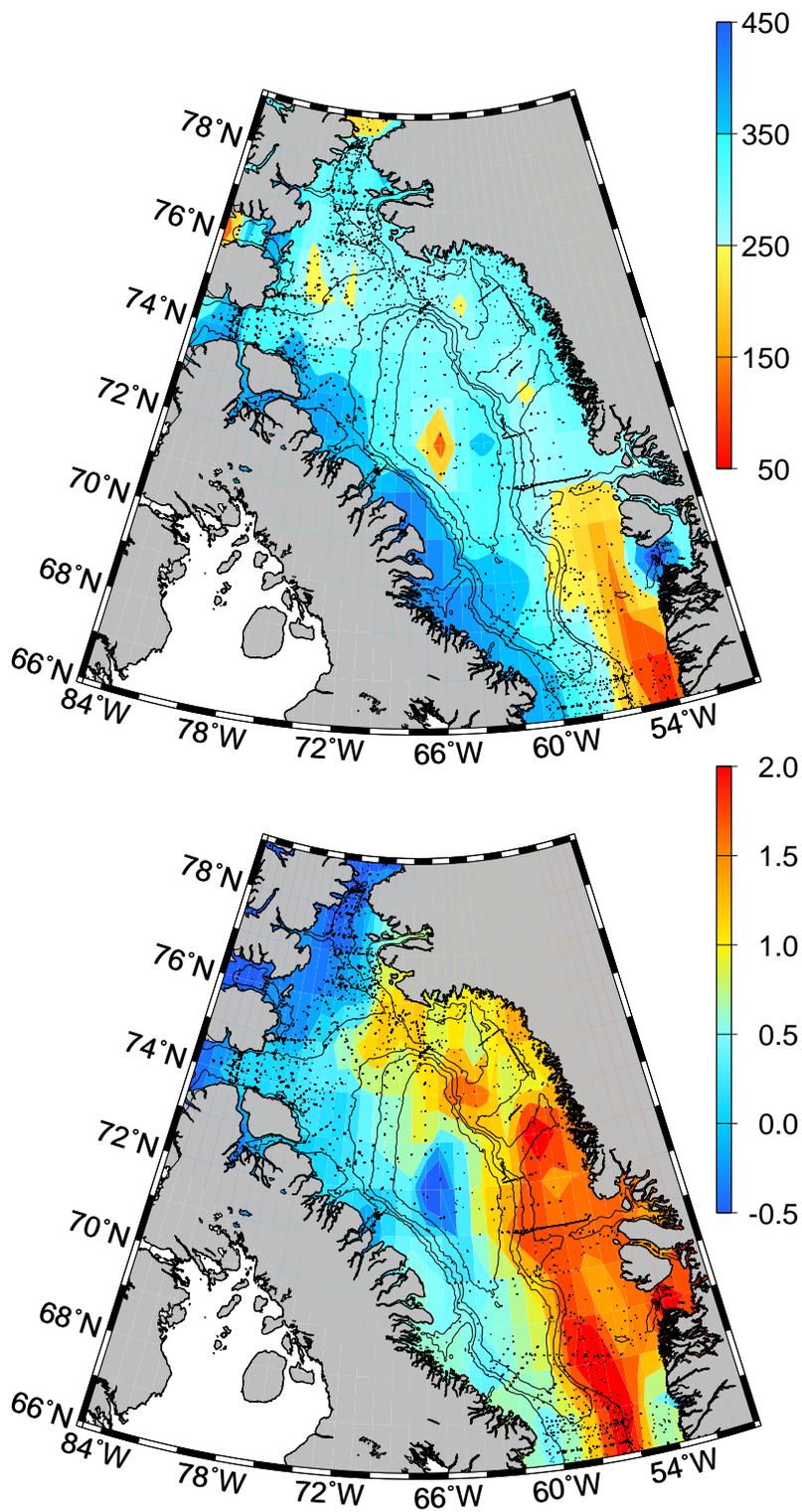


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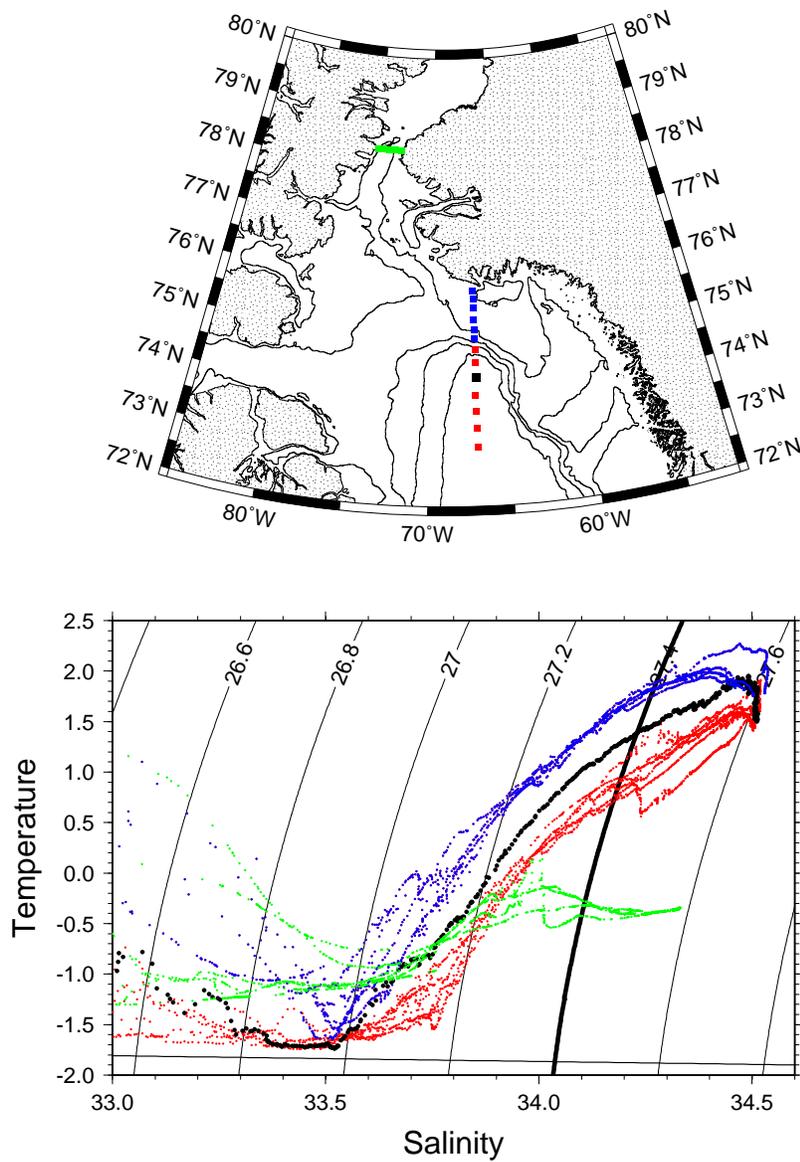


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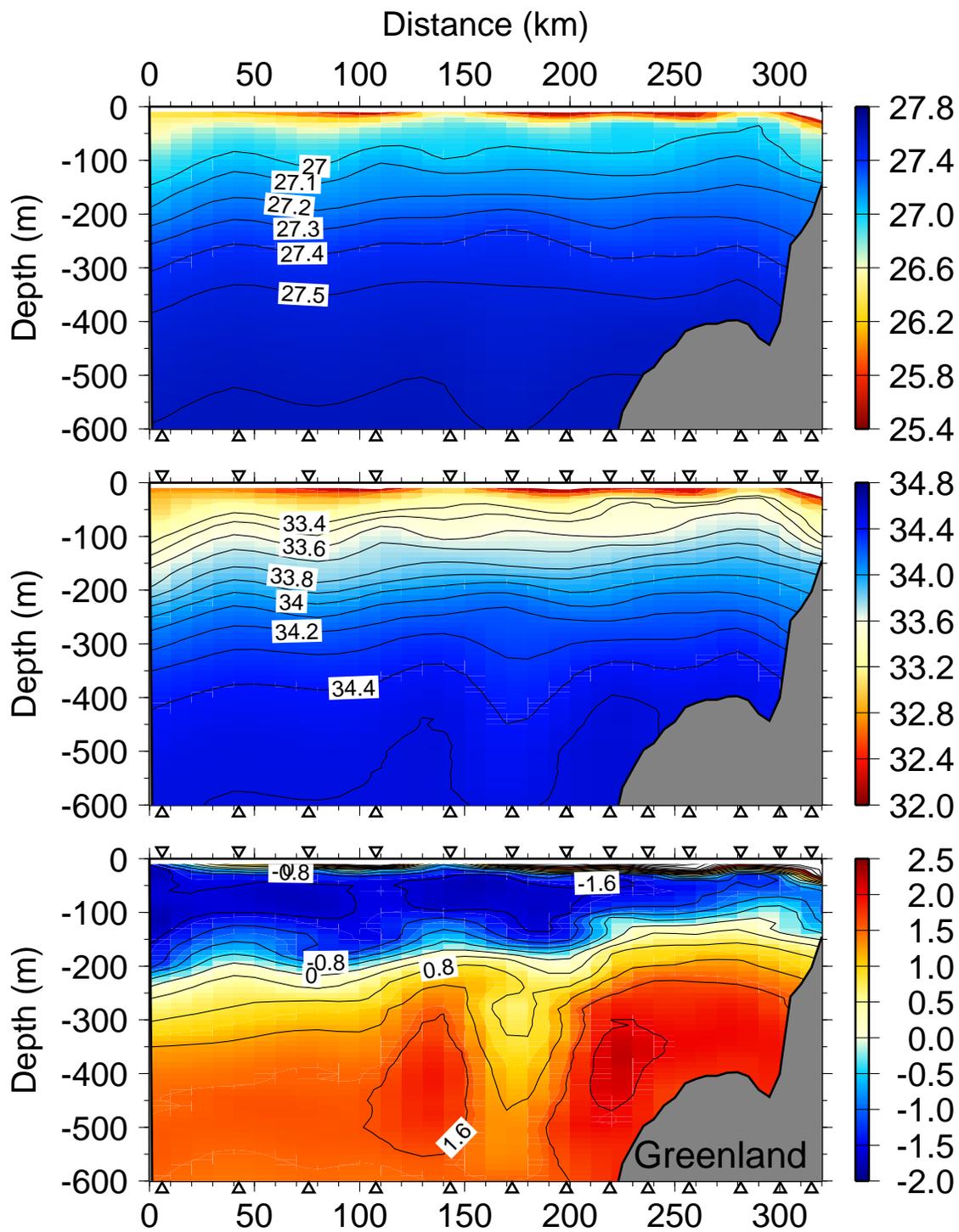


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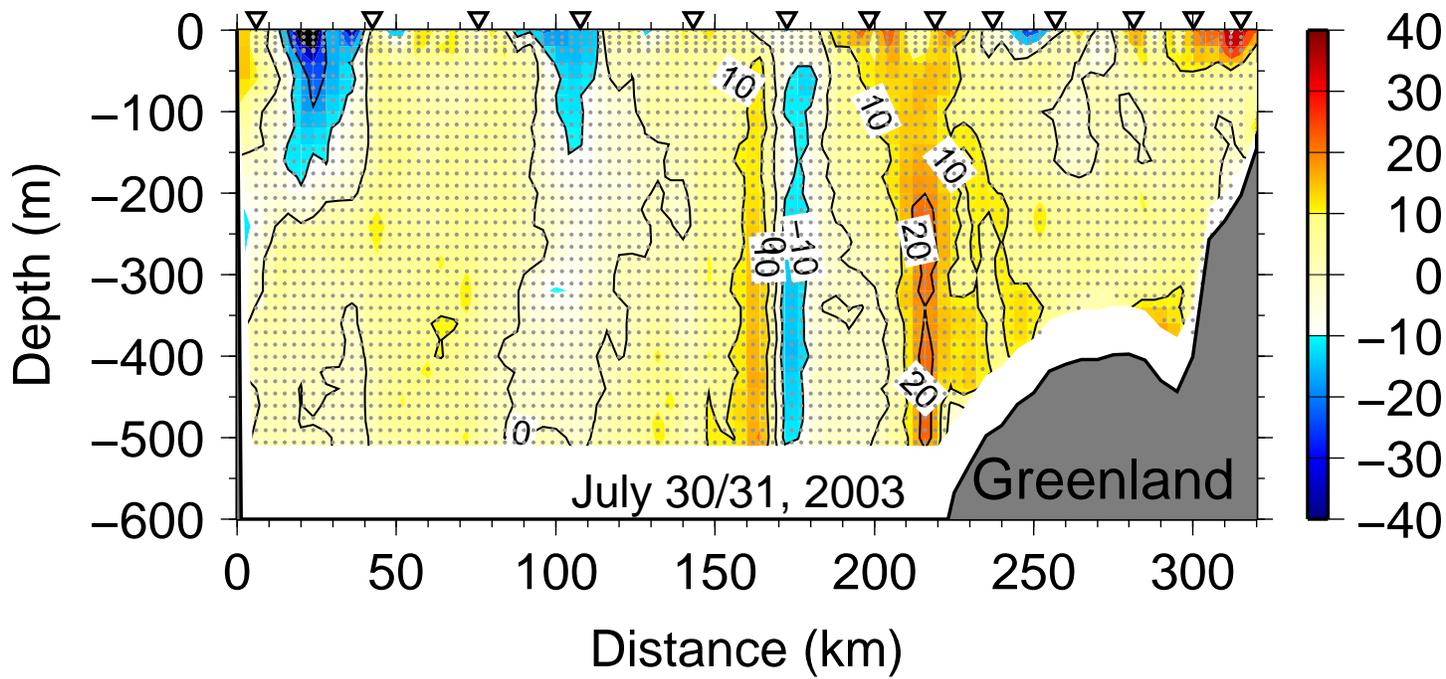


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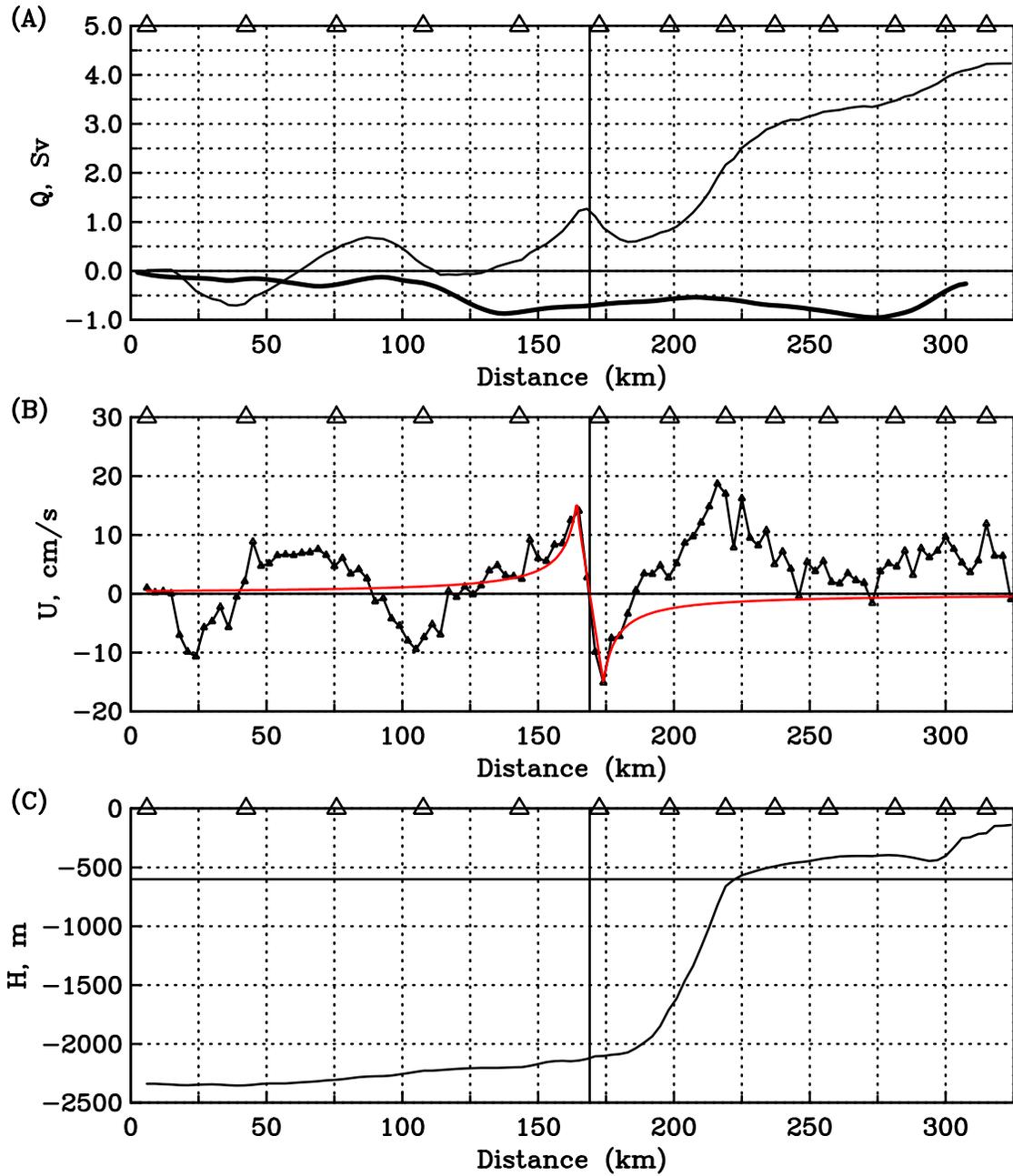


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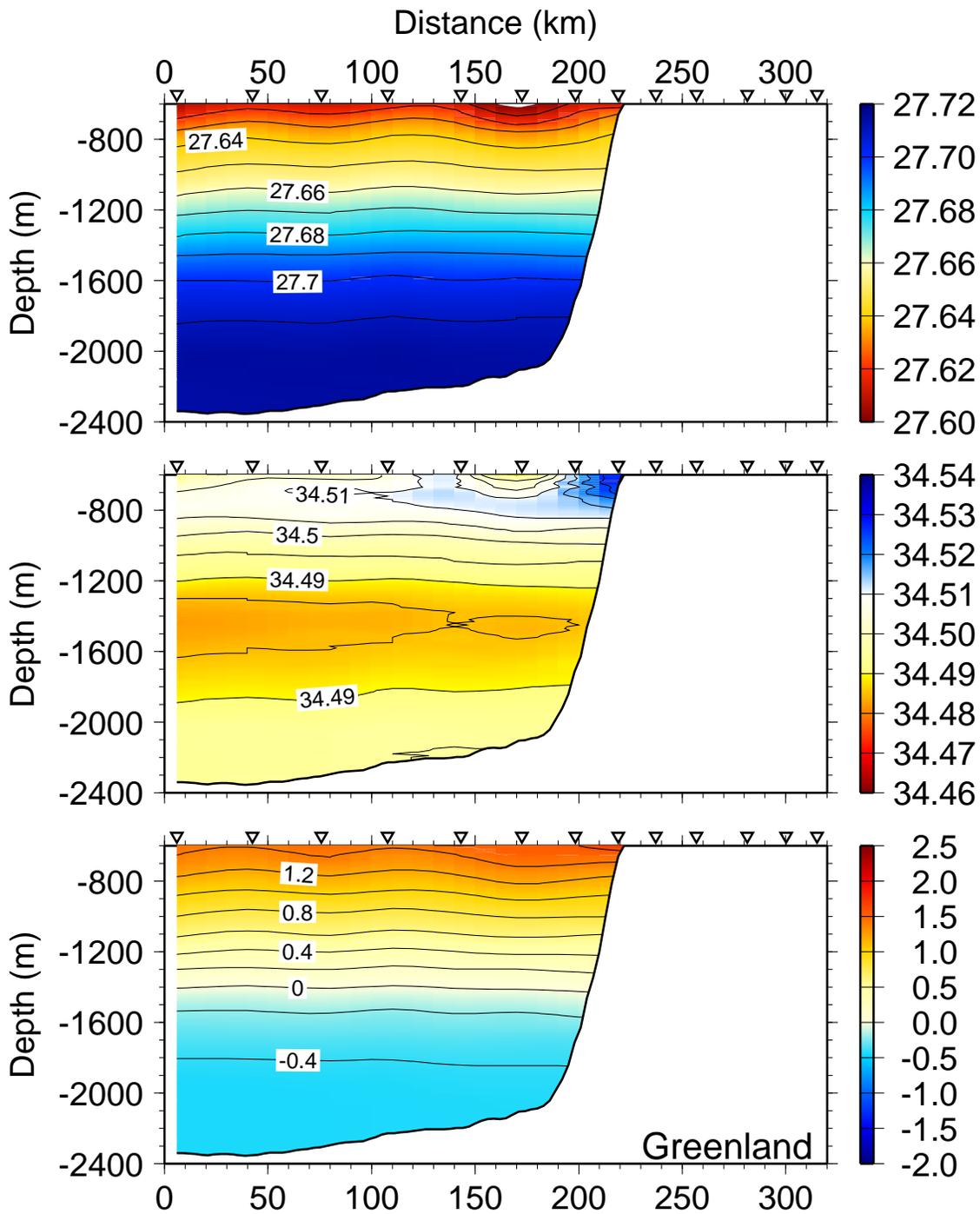


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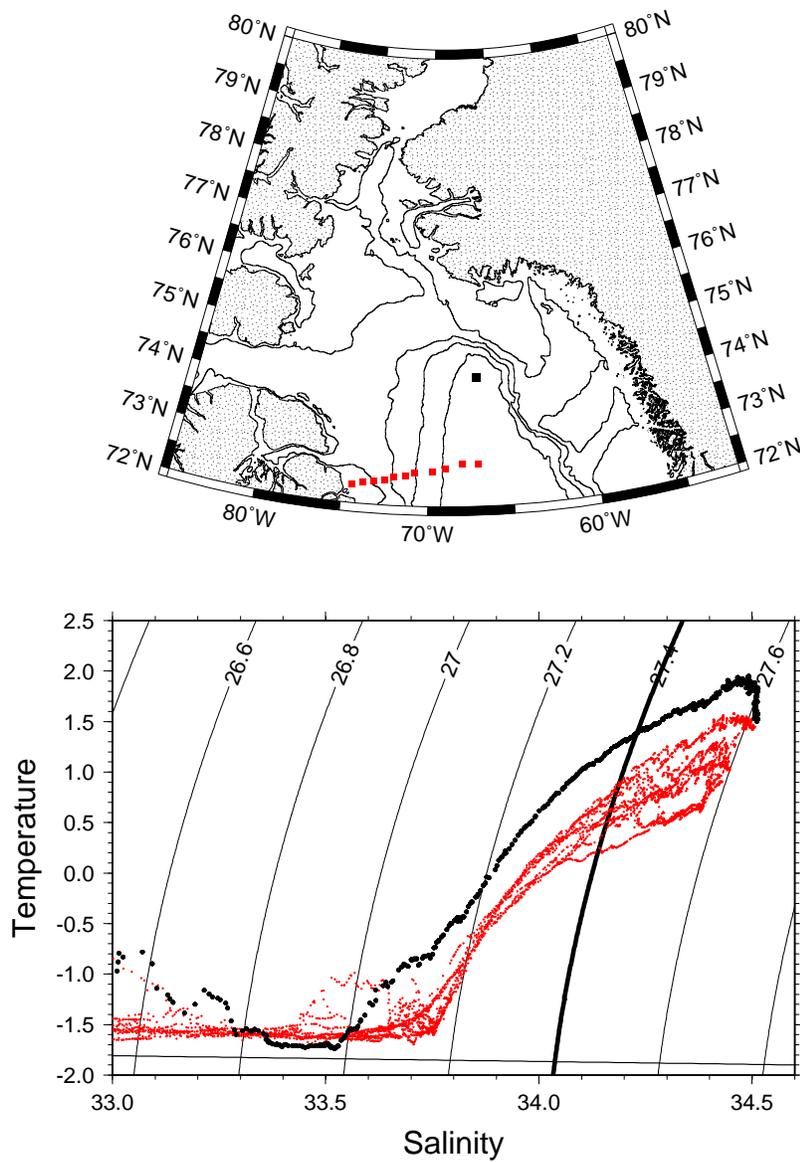


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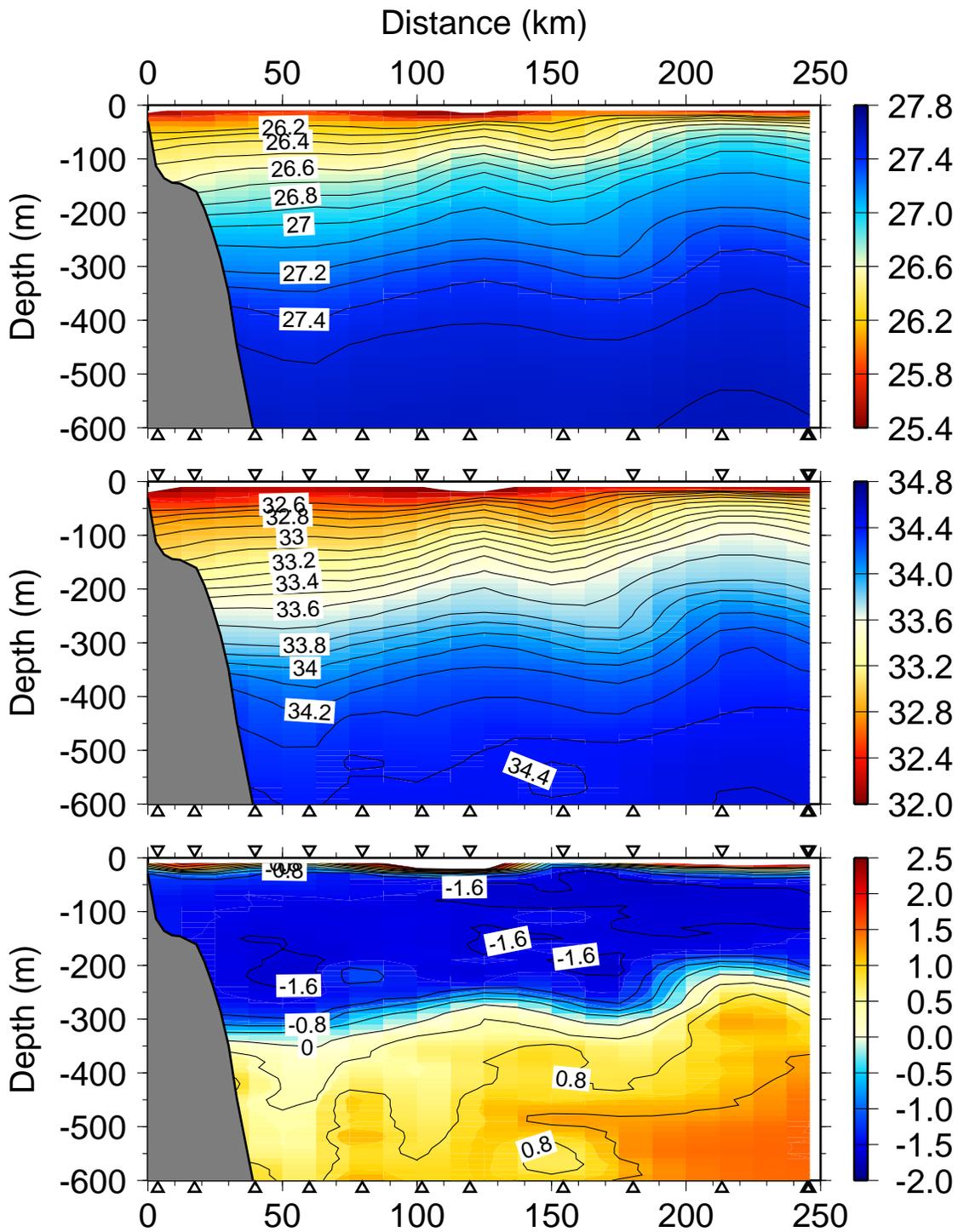


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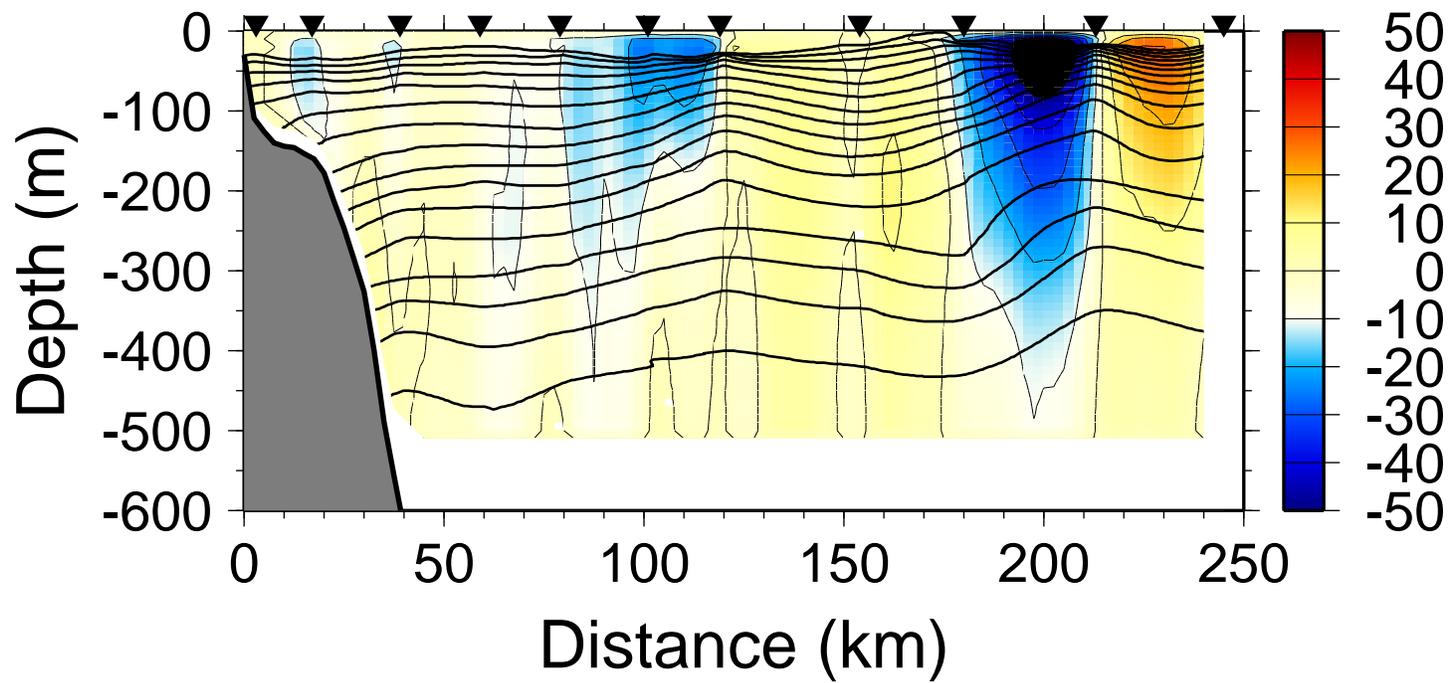


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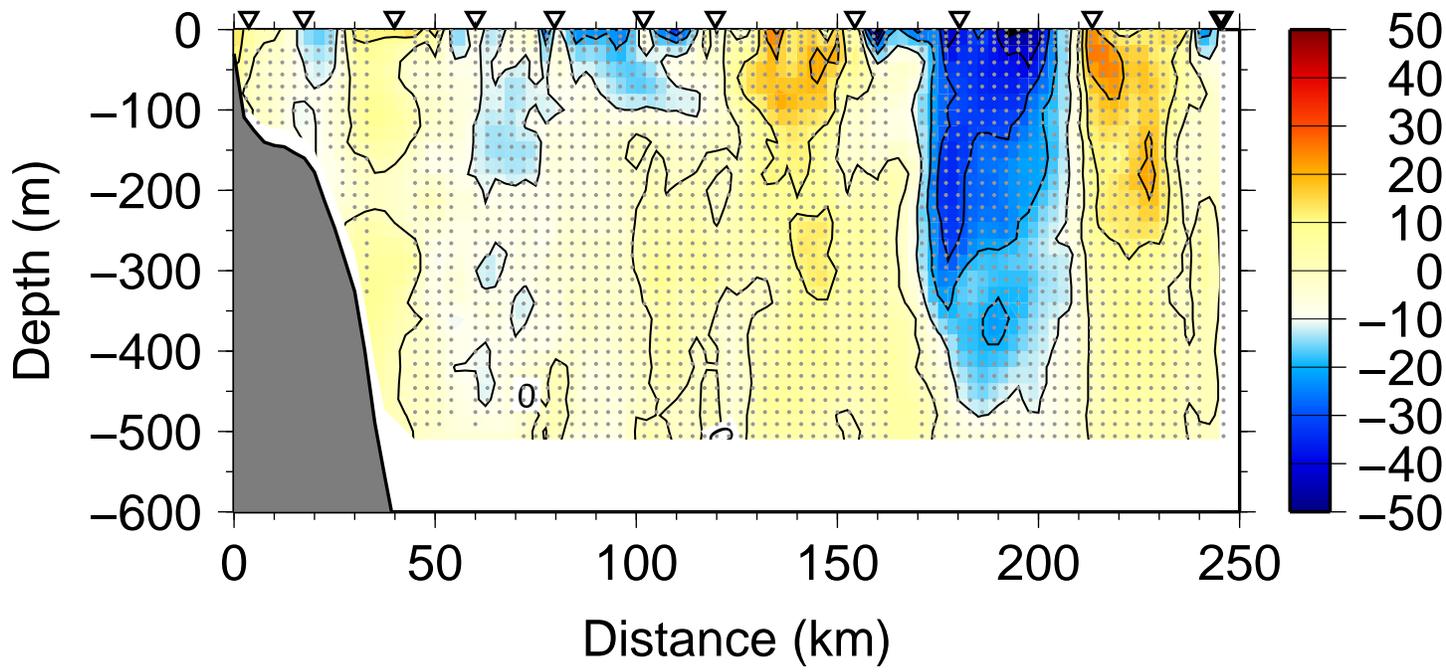


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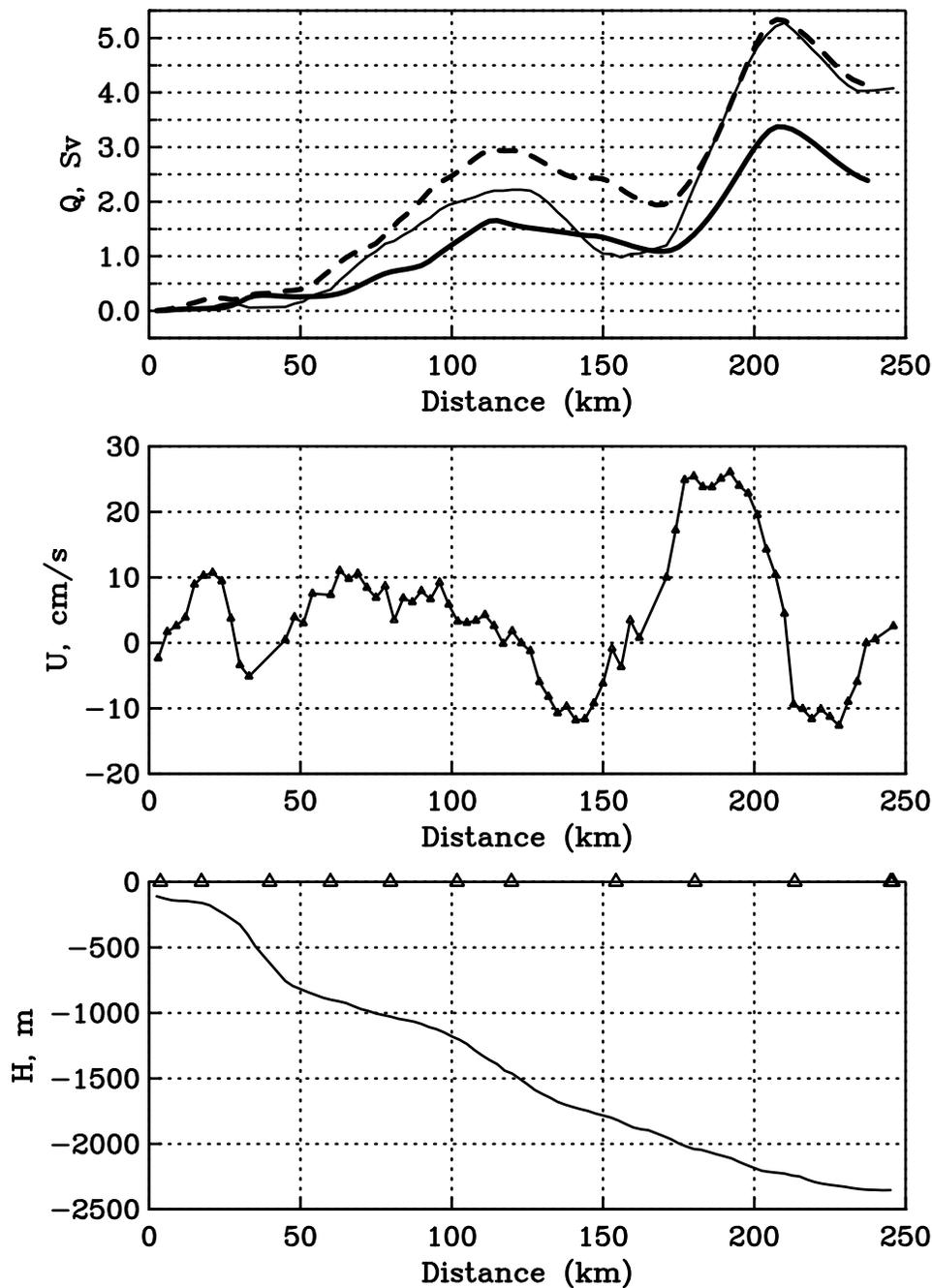


FIG. 12. Averaged properties for Baffin Island section July 26/27, 2003: (a) cumulative volume flux over top 500 m from ADCP (thin line) and hydrography with geostrophy (thick line) representing total and baroclinic flux with dashed line representing geostrophic flux relative to observed ADCP bottom currents (Fig. 10); (b) vertically averaged along-shore velocity component, and (c) bottom topography. Symbol indicate CTD station location, e.g., Fig. 9.

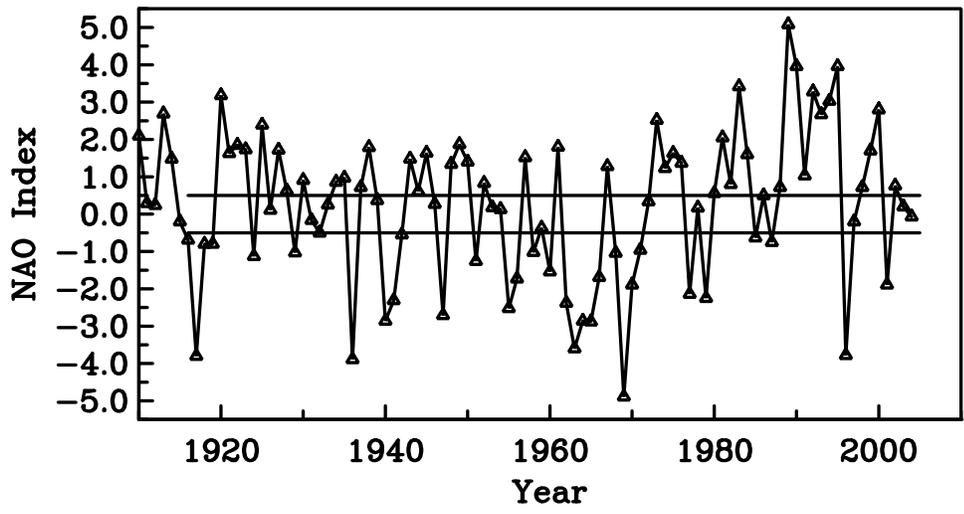


FIG. 13. Time series of the North-Atlantic Oscillation index from 1910 through 2004. Horizontal lines at ± 0.5 separate larger positive and larger negative NAO years that we use in the NAO conditional averaging in Fig. 14.

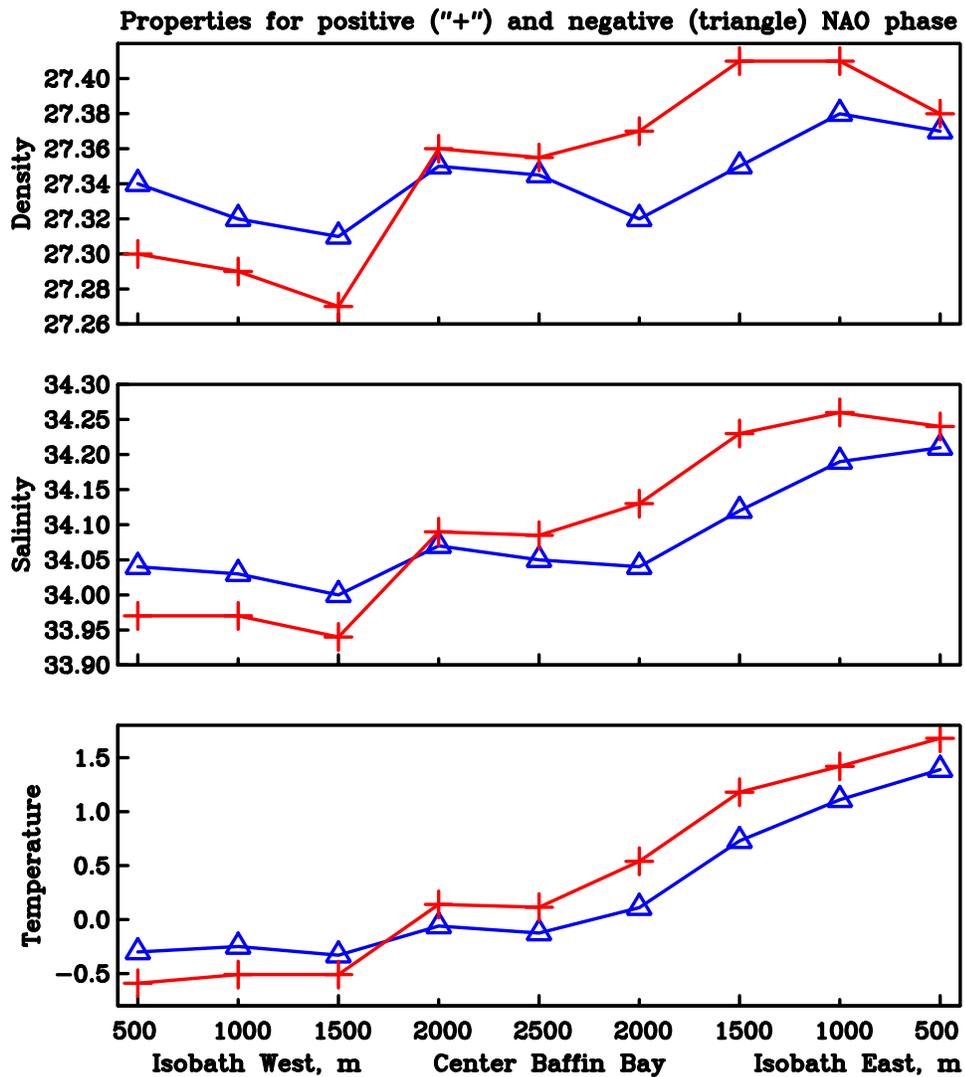


FIG. 14. Water properties across Baffin Bay averaged conditionally for positive and negative NAO phase by bottom depths west (off Canada) and east (off Greenland) of the thalweg shown in Fig. 1. A positive NAO is associated with fresher and cooler waters off Canada and saltier and warmer waters off Greenland relative to a negative NAO.