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Oceanographic Investigations off West Greenland 2009

By

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Abstract

The regional hydrography in summer 2009 is presented and discussed based on data from standard sections along the west coast of Greenland and data retrieved during trawl surveys. In addition, data from five Southwest Greenland fjords are presented.

In winter 2008/2009, the North Atlantic Oscillation (NAO) index was positive describing anomalous westerlies over the North Atlantic Ocean. Often this results in colder conditions over the West Greenland region, but the air temperature was higher than normal – especially over the Baffin Bay. The extension of multi-year-ice ("Storis") was about normal.

The general settings in the region have traditionally been presented with offset in the hydrography observed over the Fylla Bank. Here, time series of mid-June temperatures on top of Fylla Bank show above average conditions in 2009 with noticeable high salinities. In general, the surface and subsurface temperatures and salinities were higher than normal suggesting lower presence of Polar Water than normal.

The presence of Irminger Water in the West Greenland waters was above normal in 2009. Pure Irminger Water (waters of Atlantic origin) could be traced north to the Sisimiut section with the exception of the Fylla Bank section where only modified Irminger Waters were found. This suggests that the pure Irminger Water seen north of Fylla Bank has passed Fylla Bank earlier - for example as a result of a decreasing strength of the Irminger Water inflow during spring/summer compared to wintertime. Nevertheless, the mean (400–600 m) salinity and temperature west of Fylla Bank (st.4) was both above normal. For the same depth interval at Maniitsoq (st.5) and Sisimiut (st.5), the salinities were the highest observed yet with highest and 5^{th} highest temperature respectively. In the Disko Bay off Ilulissat (st.3), the bottom temperature and salinity was the highest observed – however only observed since 1980.

Introduction to the west Greenland oceanography

This report describe the hydrographic conditions in West Greenland Waters in 2009 from Cape Desolation in the southeastern Labrador Sea northward to Upernavik in the Western Baffin Bay (Figure 1). After describing data and methods, the atmospheric conditions are described, then the oceanographic conditions and finally fjord observations are presented.

The ocean currents around Greenland are part of the cyclonic sub-polar gyre circulation of the North Atlantic and the Arctic region. The bottom topography plays an important role for guiding the circulation and for the distributing the water masses. Consequently, the strongest currents are found over the continental slope.

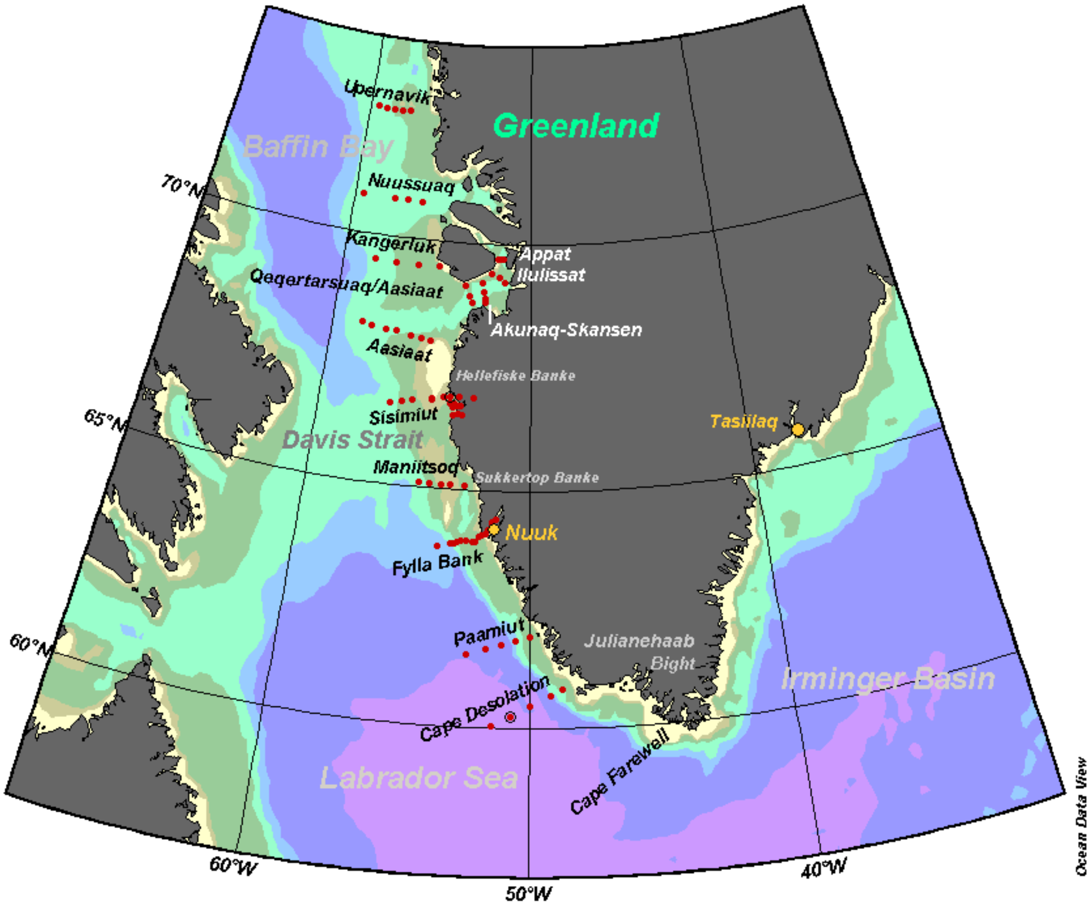

Figure 1. Position of the oceanographic sections off West Greenland where measurements were preformed in 2009. The fjord sections at Sisimiut and Godthaabsfjorden are shown in Figure 4 and Figure 5. Contours shown for water depths in colours. Map produced using Ocean Data View (Schlitzer, 2007).

The surface circulation off West Greenland is dominated by the north going West Greenland Current. It is primarily composed of cold low-saline Polar Water (PW) of the Arctic region and the temperate saline Irminger Water (IW) of the Atlantic Ocean. At intermediate depths Labrador Sea Water is found, and at the bottom overflow water from the Nordic Seas are found. Only the surface circulation will be handled in this report.

The watermass characteristics in the West Greenland Current are formed in the western Irminger Basin where the East Greenland Current and the Irminger Current meets and flowing southward side by side. As they round Cape Farewell the IW subducts the PW (Figure 2b) forming the West Greenland Current (WGC). These water masses gradually mix along West Greenland, but IW can be traced all along the coast up to the northern parts of Baffin Bay (Buch, 1990). At Cape Farewell IW is found as a 500–800 m thick layer over the continental slope with a core at about 200–300 m depth. The depth of the core gradually decreases from east to west as seen in Figure 2b, whereas the depth gradually increases from south to north to below 400 m in the northern Davis Strait and Baffin Bay.

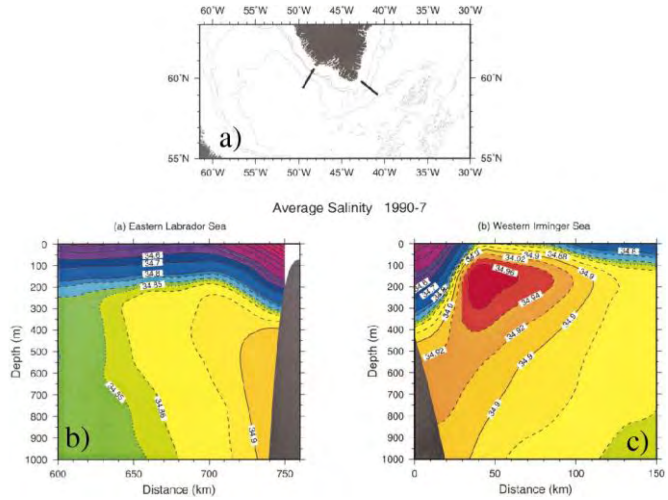

Figure 2. Mean upper-layer salinity sections for the period 1990–1997. a) Location of the two sections. Isobaths shown: 1000, 2000 and 3000 m. b) Eastern Labrador Basin. c) Western Irminger Basin. From Pickart et al. (2002).

Over the fishing banks off West Greenland a mixture of IW and PW dominates, as sketched in Figure 3. PW is continuously diluted by freshwater run-off from the numerous fjord systems. As the WGC reaches the latitude of Fylla Bank it branches. The main component turns westward and joins the Labrador Current on the Canadian side, while the other component continues northward through Davis Strait.

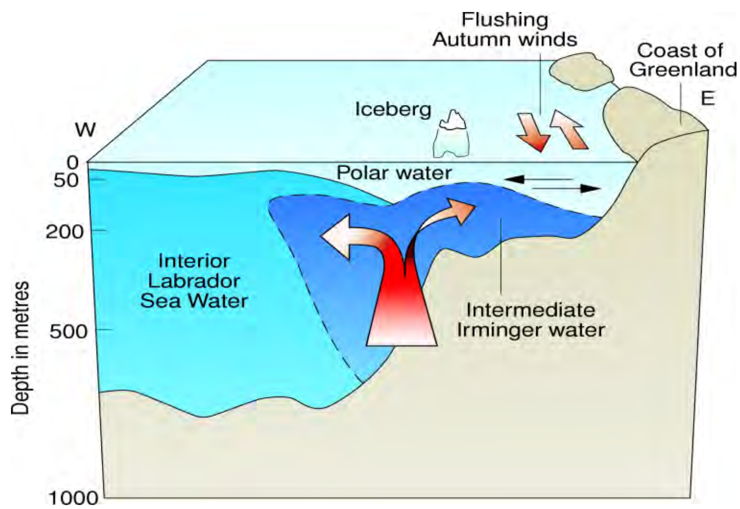

Figure 3. Sketch of the water masses off West Greenland in the Davis Strait region. From Valeur et al. (1997).

The tidal signal is significant. At West Greenland the strongest tidal signal is located close to Nuuk at 64°N. The tides are primarily semidiurnal with large difference between neap and spring (1.5 m versus 4.6 m at Nuuk, Buch, 2002). The interaction between the complicated topography and the strong tidal currents gives rise to a residual anticyclonic circulation around the banks in the Davis Strait area (Ribergaard et al., 2004).

Sea-ice is important in Greenlandic Waters. The West Greenland area is mainly dominated by 2 types of sea-ice. "Storis" is multi year ice transported from the Arctic Ocean through Fram Strait by the East Greenland Current to Cape Farewell, where it continues northward by the West Greenland Current. "Vestice" is first-year ice formed in the Baffin Bay, Davis Strait, and western part of the Labrador Sea during winter.

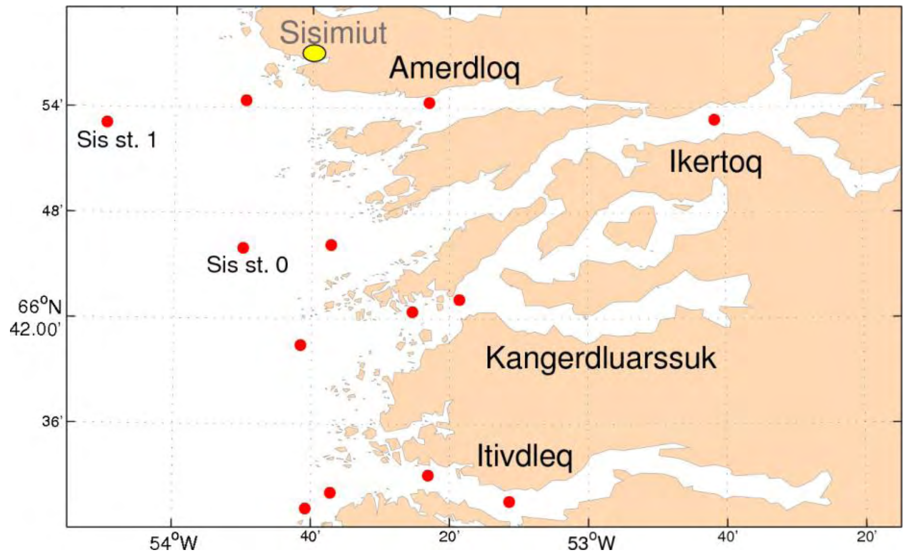

Figure 4. Position of the oceanographic stations around Sisimiut where measurements were preformed in 2009. See Figure 1 for position of all sections measured in 2009.

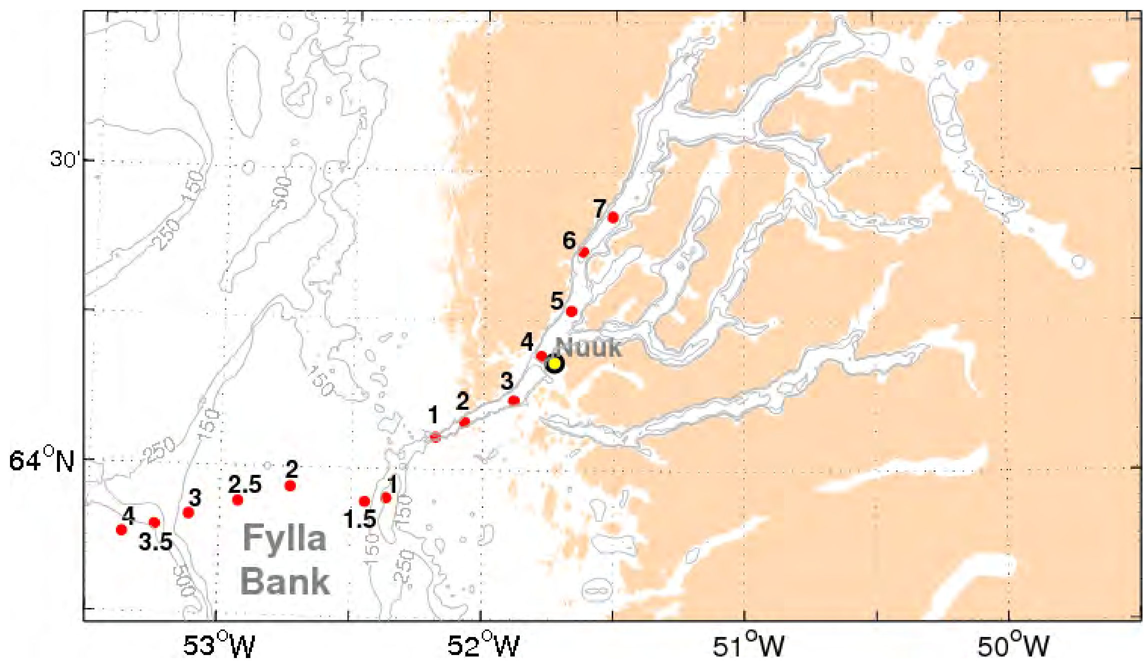

Figure 5. Position of the oceanographic stations in Godthaab Fjord and Fylla Bank. In 2009 measurements were only preformed over Fylla Bank and st. 1–7 in the "main arm" of the Godthaab Fjord. The numbers refeer to standard station numbers as shown in Figure 40. See Figure 1 for position of all sections measured in 2009.

1. Measurements

The 2009 cruise was carried out according to the agreement between the Greenland Institute of Natural Resources (GINR) and Danish Meteorological Institute (DMI) during the period June 10–16, 2009 onboard the Danish naval ship "I/K TULIGAQ"**.** Observations were carried out on the following standard stations (Figure 1):

Offshore Labrador Sea/Davis Strait:

- Cape Desolation St. 1–5
- Paamiut (Frederikshaab) St. 1–5
- Fylla Bank St. 1–5
- Maniitsoq (Sukkertoppen) St. 1–5
- Sisimiut (Holsteinsborg) St. 1–5 and St. 0

Fjords around Sisimiut (Figure 4):

- Amerdloq St. 2, 4
- Ikertoq St. 1, 4
- Kangerdluarssuk St. 1–3
- Itivdleq St. 1–4

Godthaab Fjord (Figure 5):

- Godthaab Fjord St. 1–7

Additional stations on the Fylla Bank section:

- Fylla Bank St. 1.5, 2.5, 3.5

On each station the vertical distributions of temperature and salinity was measured from surface to bottom, except on stations with depths greater than 900 m, where approximately 900 m was the maximum depth of observation. At Godthaab Fjord station 2–7 additional parameters were measured (Oxygen, Florescence, Irradiance).

Unfortunately, due to the weather conditions in combination with limited time allocated, the Cape Farewell section was totally skipped. In addition, the Godthaab Fjord measurements were cancelled midway due to ship-logistic reasons. Sea ice was absent on the stations taken but were likely to be meet at the inner Cape Farewell station (Figure 6).

During the period June 20 – July 18, 2009 the Greenland Institute of Natural Resources carried out trawl survey from Sisimiut to the Disko Bay area and further North onboard "R/V PAAMIUT". During this survey CTD measurements were carried out on the following standard stations (Figure 1):

Offshore Davis Strait/Baffin Bay:

- Sisimiut (Holsteinsborg) St. 1-5
- Aasiaat (Egedesminde) St. 1–7
- Kangerluk (Disko fjord) St. 1–4
- Nuussuaq St. 2–5
- Upernavik St. 1–5

Disko Bay:

- Qeqertarsuaq–Aasiaat (Godhavn–Egedesminde) St. 1, 3−4
- Skansen–Akunaq St. 1–4
- Ilulissat (Skansen–Jakobshavn) St. 1–3
- Appat (Arveprinsens Ejlande) St. 1–3

2. Data handling

Measurements of the vertical distribution of temperature and salinity were carried out using a SEABIRD SBE 9-01 CTD except for the Godthaab Fjord st.2−7, where a SEABIRD SBE 19plus was used. On the Paamiut cruise a new SEABIRD SBE 25plus was used. All sensors were newly calibrated in 2009 except for SBE 19plus which were calibrated in 2008.

For the purpose of calibration of the salinity measurements of the CTD, water samples were taken at great depth on stations with depths greater than 500 m or below sill depth in fjords. The water samples were after the cruise analysed on a Guildline Portosal 8410 salinometer.

The CTD data were analysed using SBE Data Processing version 5.37d software provided by SEABIRD (www.seabird.com). Onboard the SBE 9-01 data was uploaded using term17 in SEASOFT version 4.249 (for DOS) provided by SEABIRD. For uploading SBE 19plus and SBE 25plus data, the SEABIRD program Seasave (for windows) was used.

All quality-controlled data are stored at the Danish Meteorological Institute from where copies have been sent to ICES. Data are also stored at Greenland Institute of Natural Resources who are the owner of the data.

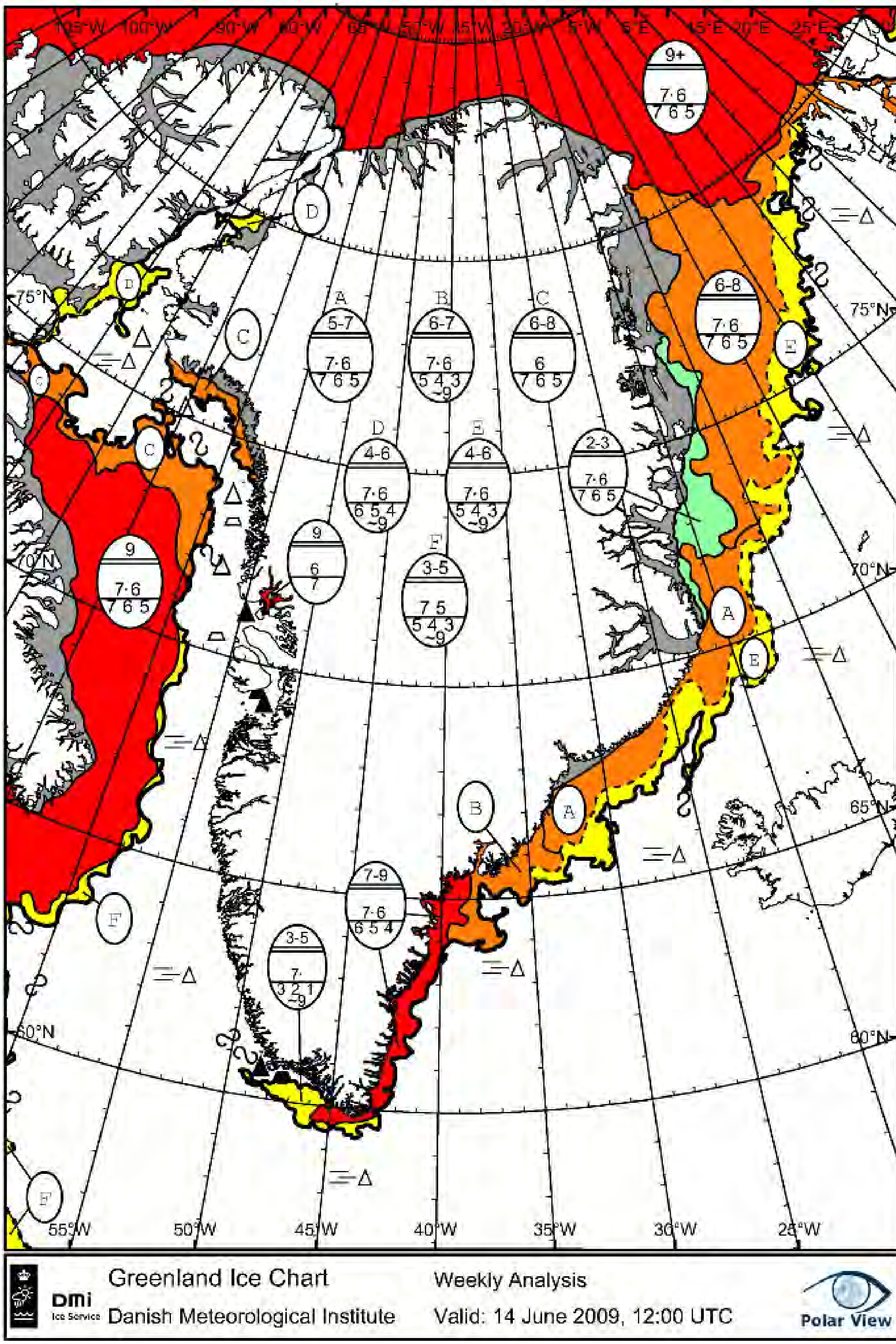

Figure 6. Distribution of sea ice in Greenland Waters valid for 14. June 2009.

3. Atmospheric conditions in 2009

The North Atlantic marine climate is to some extend controlled by the so-called North Atlantic Oscillation (NAO), which is a measure of the strength of the westerlies driven by the pressure difference between the Azores High and the Iceland Low pressure cells. We use wintertime (December–March) sea level pressure (SLP) difference between Ponta Delgada, Azores, and Reykjavik, Iceland, and subtract the mean SLP difference for the period 1961–1990 to construct the NAO anomaly. The winter NAO index during winter 2008/09 was positive[1] (Figure 2). The Icelandic Low was during the winter months (December–Marts) centred over the northern Irminger Basin (Figure 8), which is close to normal position but the pressure anomaly was slightly lower than nomal over the Labrador Sea (Figure 9). Whereas the strength of the Icelandic low were about normal, the Azores High was strengthen and tilted towards northeast (Figure 9) resulting in an increased pressure difference over the North Atlantic sector compared to normal conditions.

The pressure difference has the effect that the westerlies over the North Atlantic Ocean was to some extent strengthened with anomalous[2] winds towards northeast across the North Atlantic Ocean but south of Greenland (Figure 11).

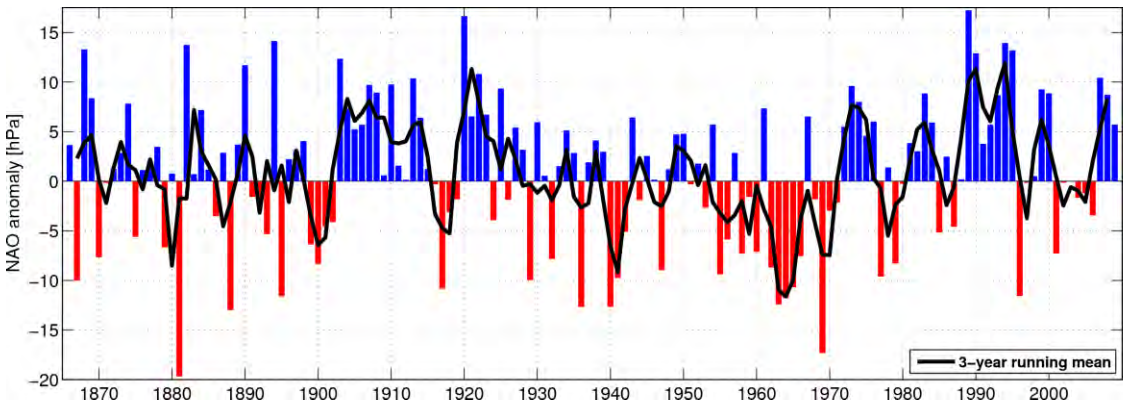

Figure 7. Time series of winter (December–March) index of the NAO from 1865/1866–2008/2009. The heavy solid line represents the NAO index smoothed with a 3-year running mean filter to remove fluctuations with periods less than 3 years. In the figure the winter 1865/1866 is labelled 1866 etc.. The mean and standard deviation is 0.9 ± 7.3 hPa. Data updated, as described in Buch et al. (2004), from http://ww.cru.uea.ac.uk/cru/data/nao.htm.

West Greenland lies within the area which normally experiences cold conditions when the NAO index is positive. This does not seem to be the case for 2009. During winter 2008/09, the mean temperature was above normal for most of the eastern North Atlantic region including the waters surrounding Greenland. Remarkable positive anomalies were found over the Baffin Bay and Davis Strait with anomalies above 4°C (Figure 12). The mean air temperature in Nuuk was about one degree above average during winter 2008/09 (DJFM, Figure 13). Similar anomalies are seem on an annual basis for 2009 over the North Atlantic region (Figure 14) and the Nuuk[3] annual air temperature was about one degree above normal (Figure 15).

Sea surface temperatures in West Greenland often follow those of the air temperatures, major exceptions are years with great salinity anomalies i.e. years with extraordinary presence of Polar Water. In 2009 the mean temperature (2.44ºC) and salinity (33.80) on top of Fylla Bank in the middle of June was above normal conditions – especially the salinity was high (Figure 16 and Table 1), suggesting lower than normal presence of Polar Water.

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1 The NAO index using December − February was also positive.

2 Anomaly defined as the difference from normal conditions relative to the period 1968–1996.

3 Nuuk temperature for October 2007 and November 2008 was taken from the Nuuk airport synop station 04254 due to failure on the instrument on synop station 04250 (Nuuk) for more than half of the months.

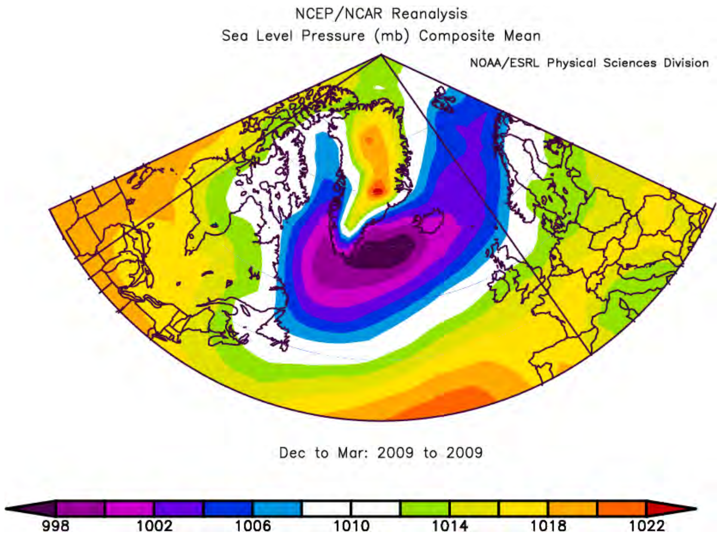

Figure 8. Winter (DJFM) sea level pressure for 2008/09 in the North Atlantic region. NCEP/NCAR re-analysis (from http://www.esrl.noaa.gov/psd/).

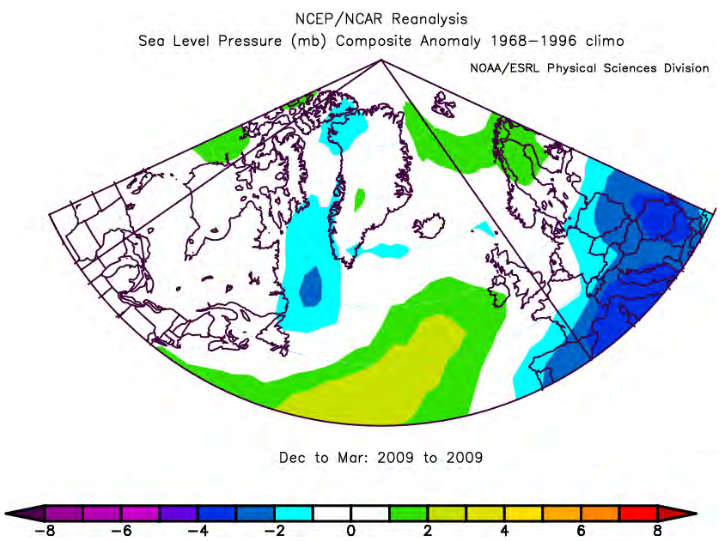

Figure 9. Winter (DJFM) sea level pressure anomaly for 2008/09 in the North Atlantic region. NCEP/NCAR re-analysis (from http://www.esrl.noaa.gov/psd/).

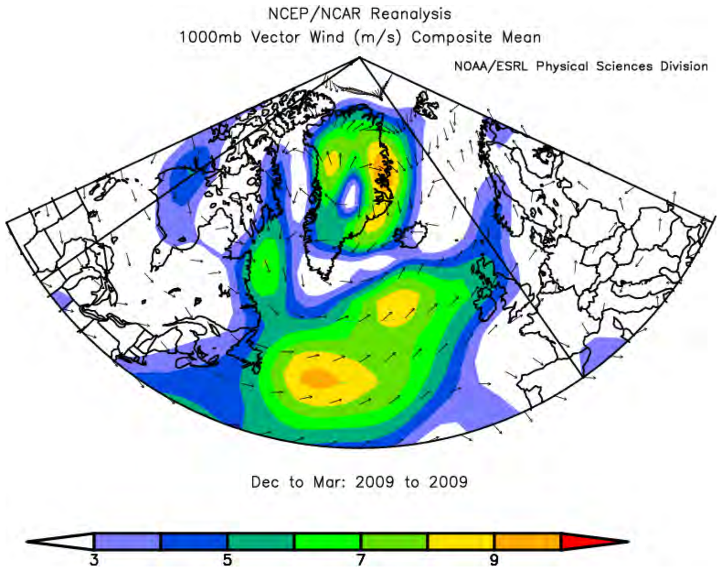

Figure 10. Winter (DJFM) wind for 2008/09 in the North Atlantic region. NCEP/NCAR re-analysis (from http://www.esrl.noaa.gov/psd/).

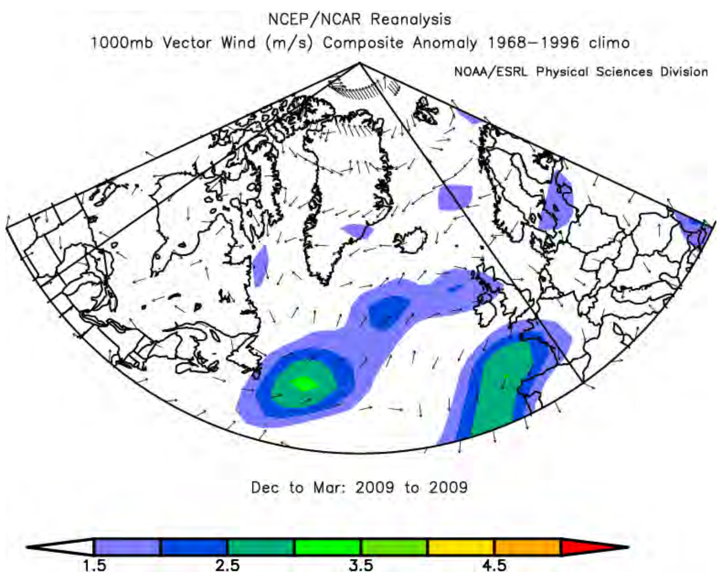

Figure 11. Winter (DJFM) wind anomaly for 2008/09 in the North Atlantic region. NCEP/NCAR re-analysis (from http://www.esrl.noaa.gov/psd/).

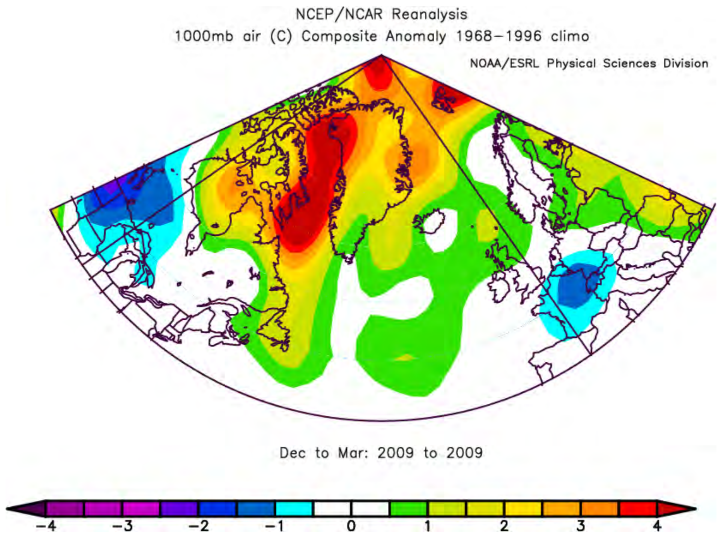

Figure 12. Winter (DJFM) mean air temperature anomaly for 2008/09 in the North Atlantic region. NCEP/NCAR re-analysis (from http://www.esrl.noaa.gov/psd/).

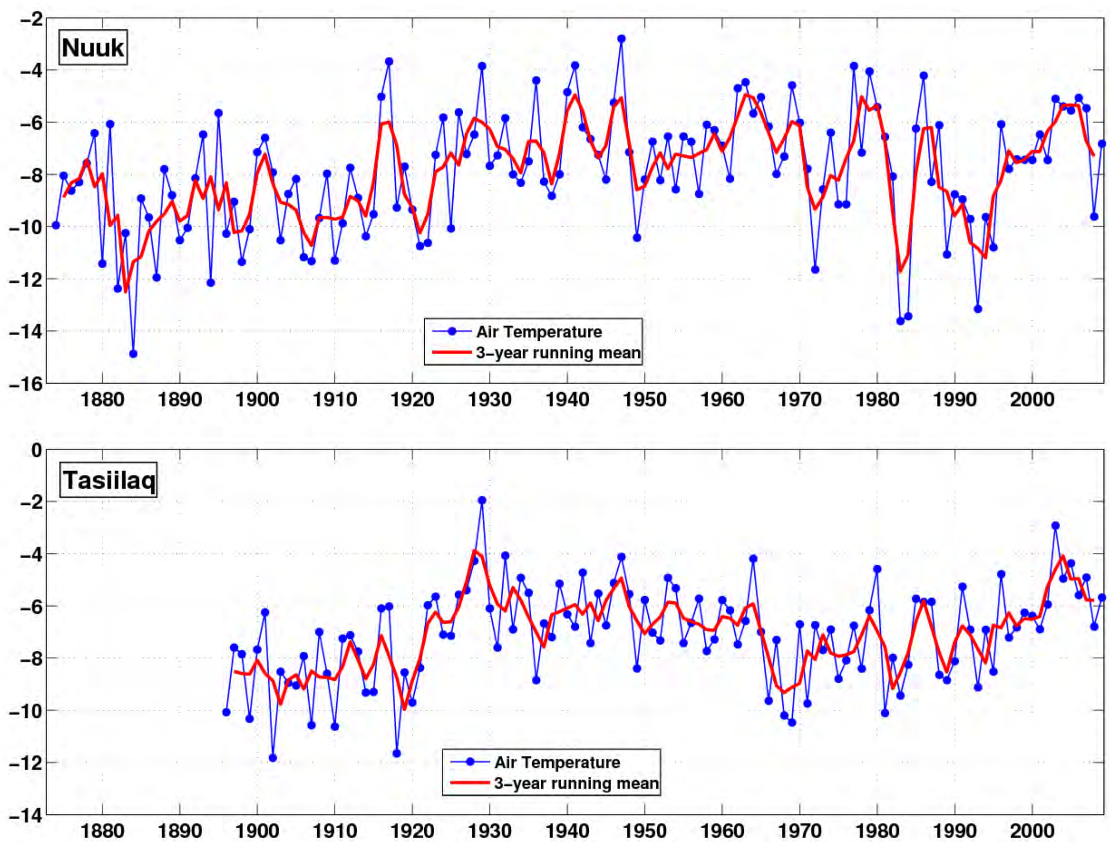

Figure 13. Winter (DJFM) mean air temperature observed at Nuuk and Tasiilaq for the period 1874–2009. The mean and standard deviation is -7.9 ± 2.3 °C for Nuuk and -7.1 ± 1.8 °C for Tasiilaq.

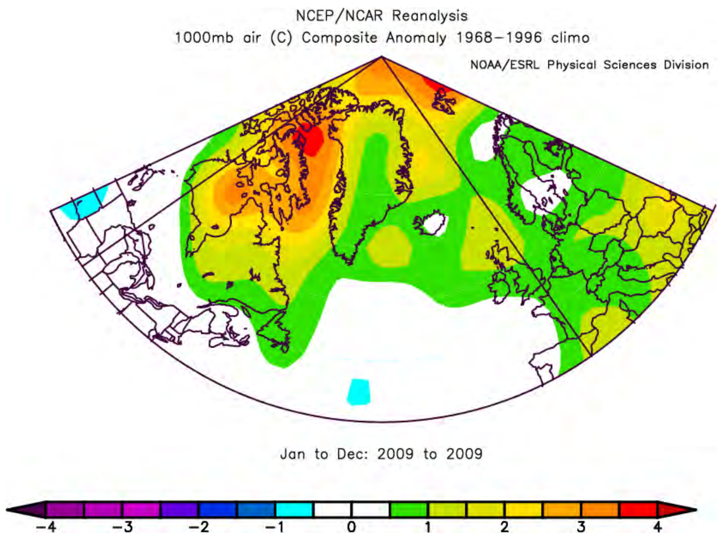

Figure 14. Anomalies of the annual mean air temperature for 2009 in the North Atlantic region. NCEP/NCAR re-analysis (from http://www.esrl.noaa.gov/psd/).

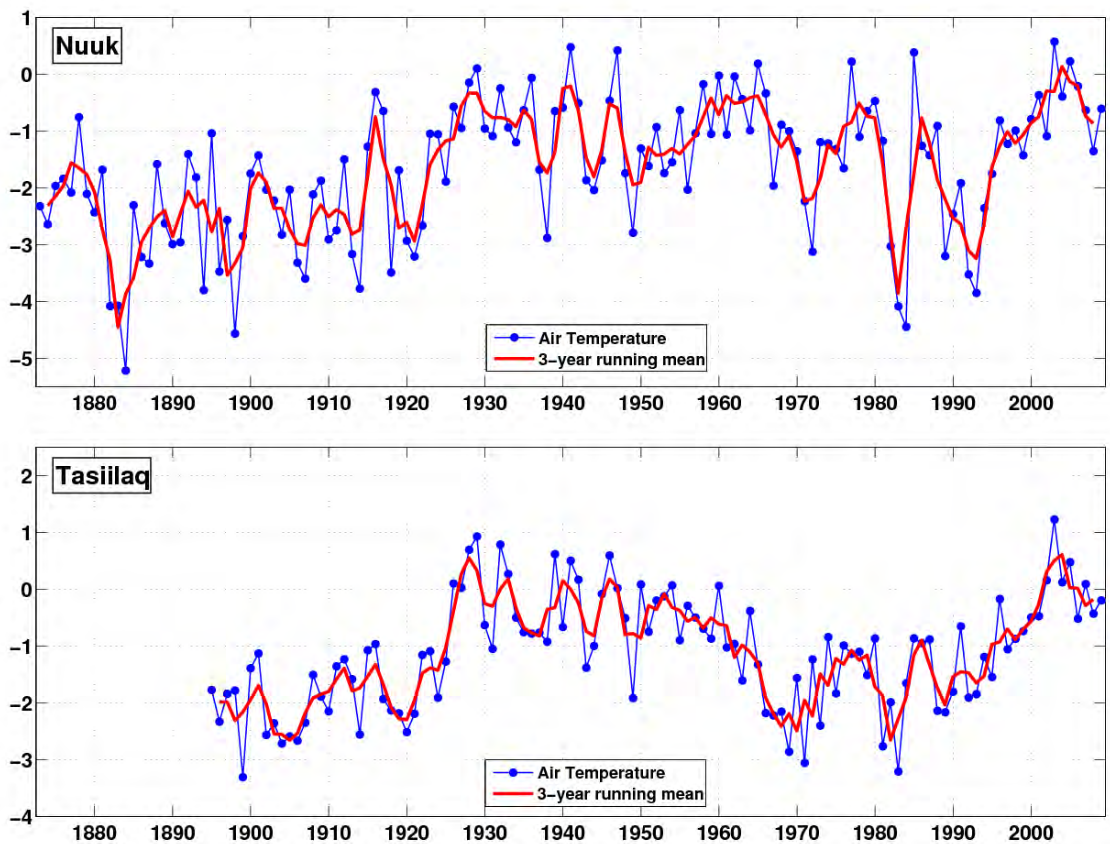

Figure 15. Annual mean air temperature observed at Nuuk and Tasiilaq for the period 1873–2009. The mean and standard deviation is -1.67 ± 1.20 °C for Nuuk and -1.13 ± 0.99 °C for Tasiilaq. Nuuk temperature for October 2007 and November 2008 was taken from the Nuuk airport synop station 04254 due to a failure on the instrument (Nuuk synop 04250) for more than half of the respective months.

Table 1. Statistics for potential temperature and salinity Fylla Bank st. 2. The timeseries are corrected for annual variations in order to get the temperature in mid-June. Smed data are not included for the statistics.

Fylla Bank St. 2	Temperature [°C] Mean ± std	Salinity Mean ± std	2009 Tpot	2009 S
0–40 m	1.79 ± 0.75°C	33.41 ± 0.26	2.44°C	33.80

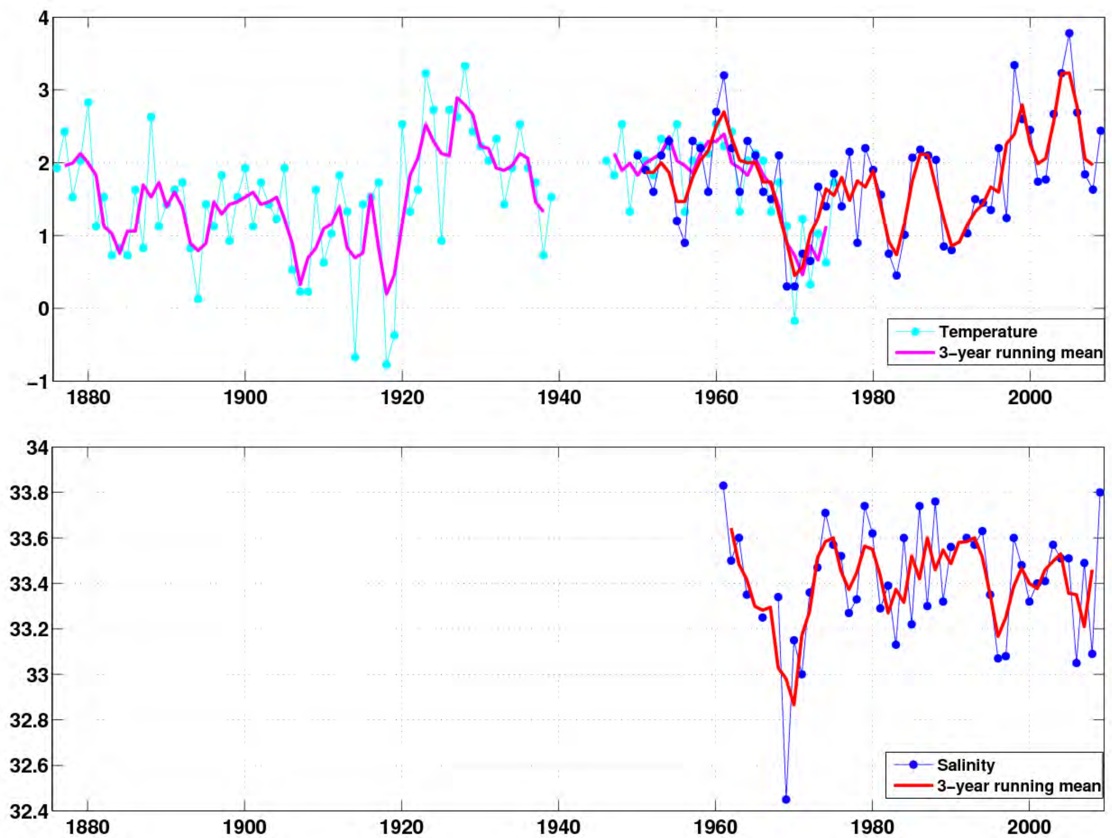

Figure 16. Timeseries of mean temperature (top) and mean salinity (bottom) on top of Fylla Bank (0–40 m) in the middle of June for the period 1950–2009. The red curve is the 3 year running mean value. Statistics is shown in Table 1. The timeseries for temperature (top, magenta/purple) is extended back to 1876 using Smed-data for area A1 (Smed, 1978). See Ribergaard et al. (2008) for details.

4. Oceanographic conditions off West Greenland in 2009

The surface temperatures and salinities observed during the 2009 cruise are shown in Figure 17. The cold and low salinity conditions observed close to the coast off Southwest Greenland reflect the Polar Water carried to the area by the East Greenland Current. This year the salinities were generally higher than normal except on the southern sections, where multi-year-ice ("Storis") was presence during the cruise (Figure 6) but not on stations. Water of Atlantic origin ($T>3^oC$; $S>34.5$) is normally found at the surface at the three outermost stations on the Cape Desolation sections (Figure 26), but this year the salinities were lower suggesting recent modification by Polar Waters.

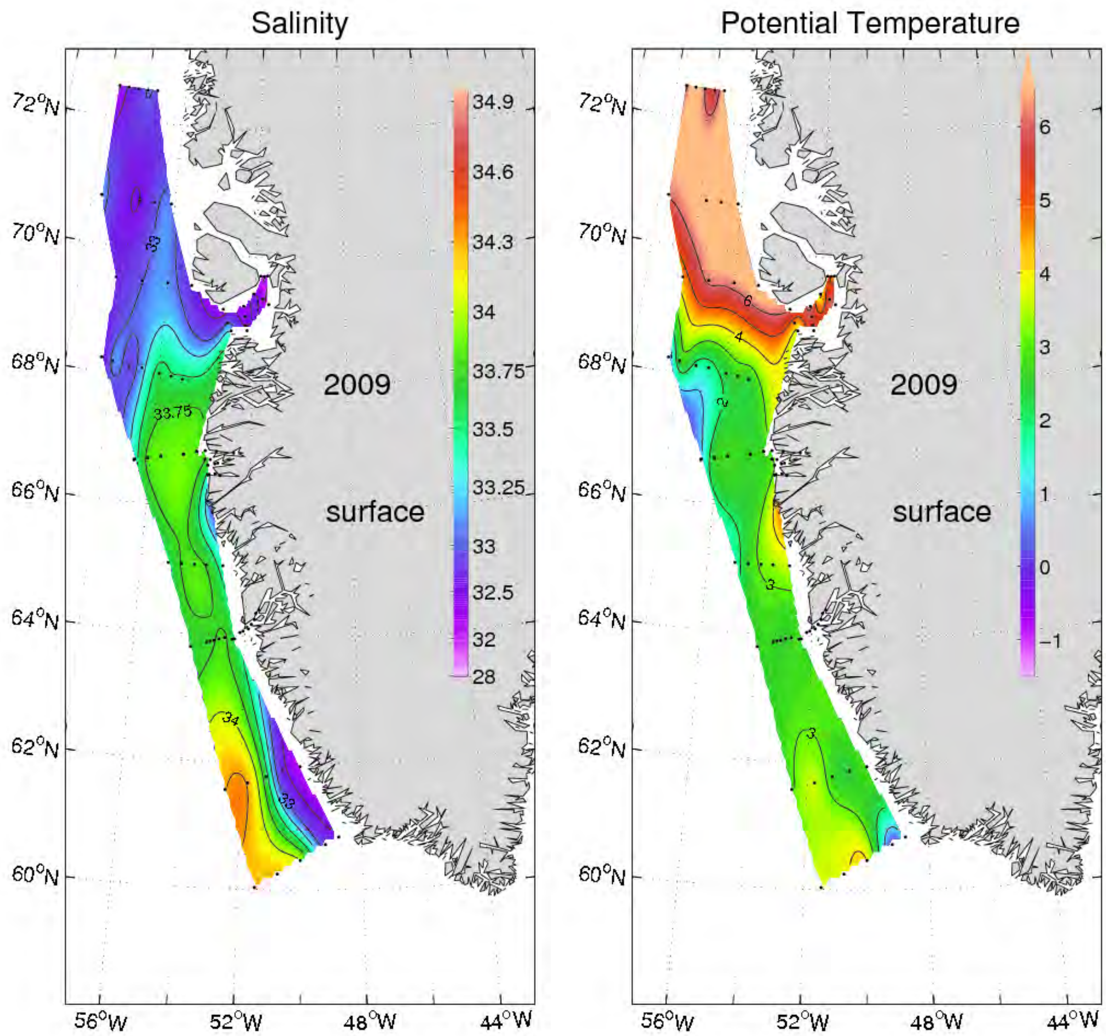

Figure 17. Salinity (left) and temperature (right) observed in 2009 at the surface (max. 4 meter depth). The data are all from June (south of Sisimiut) and June/July (north of Sisimiut).

In the Baffin Bay the highest salinities reflect the core of the West Greenland Current, which is slightly modified by Atlantic Water. In the Disko Bay the low surface salinities, generally below 33, originate from the large outlet glaciers but also from melting of sea-ice during summer forming a 20–30 m thin surface layer. A thin low-saline surface layer is also observed in the Baffin Bay outside Disko Bay properly formed by melting of sea-ice. Due to solar heating these thin surface layers are relatively warm. The strong halocline acts as an effective isolator and thereby the subsurface waters remain considerable colder (Figure 18). The coldest waters <0°C observed in the subsurface of the Baffin Bay (Figure 18) is likely the remains of past winters convection, where formation of sea-ice rejects enough salt to overcome the shallow surface halocline.

A vertical section of salinity, temperature and density over the shelf break from Cape Farewell to Sisimiut is shown in Figure 24 and over the shelf in Figure 25. The vertical distribution of temperature, salinity and density at sections along the West Greenland coastline is shown in Figure 26 − Figure 35 and within the Disko Bay in Figure 36 – Figure 39.

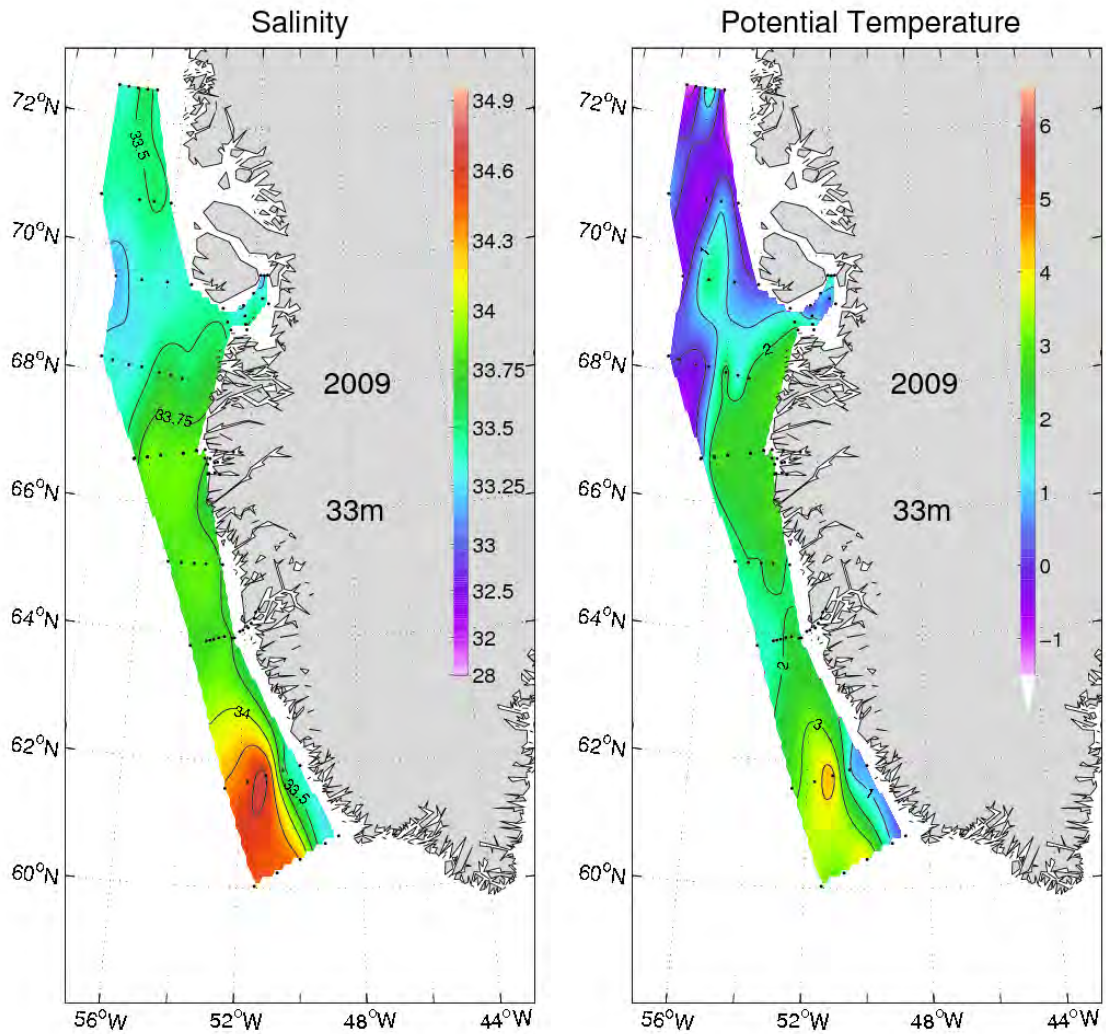

Figure 18. As Figure 17, but for 33 m depth.

At intermediate depths pure Irminger Water ($T \geq 4.5^{o}C$; $S \geq 34.95$) was traced north to the Sisimiut section with the exception of Fylla Bank section. Modified Irminger Water ($T \geq 3.5^{o}C$; $34.88 \leq S < 34.95$) was observed all the way north to Sisimiut section. The northward extension of Irminger Water may indicate intensified inflow of water of Atlantic origin to the West Greenland area.

The average salinity and temperature at 400–600 m depth west of Fylla Bank (st. 4), which is where the core of the Irminger Water normally is found, is shown in Figure 19 (red curves). The temperature of this layer was 4.40°C which is above normal and the average salinity of 34.92 was high (Table 2). Despite the high average salinity, the maximum were below 34.95. Temperatures and salinities above normal may indicate, that the presence of Irminger Water was higher than normal.

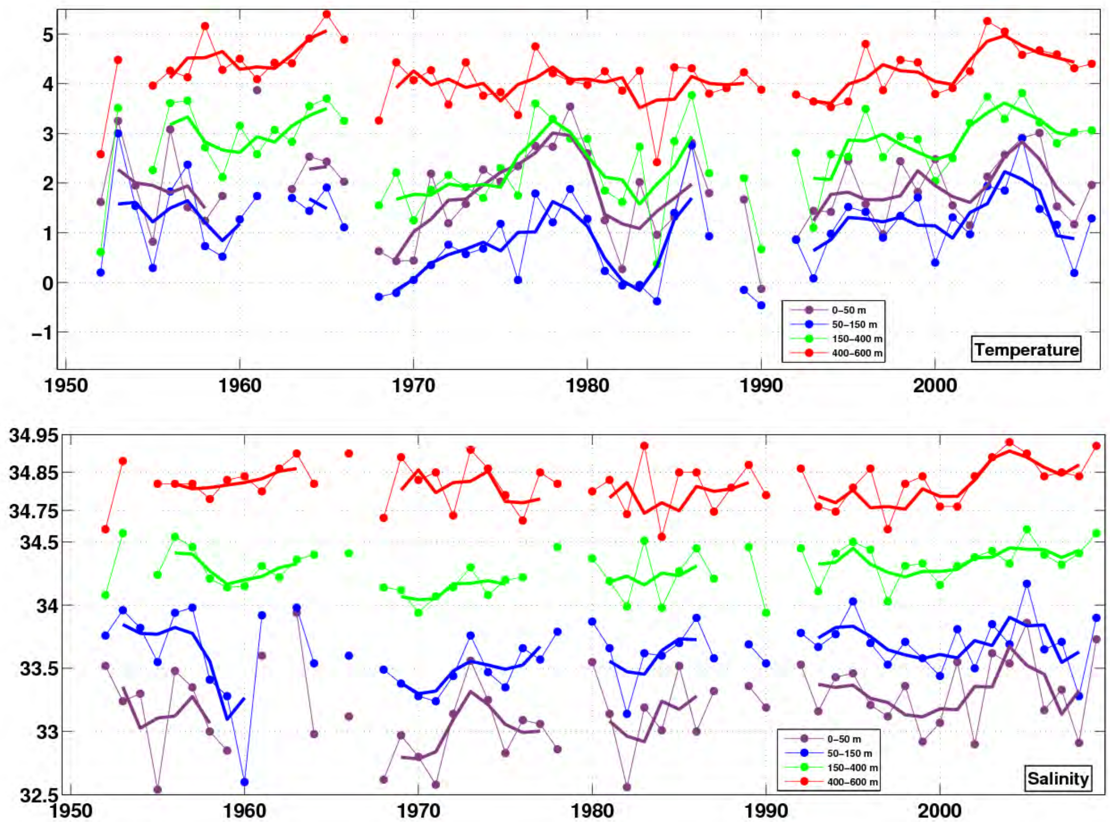

Figure 19. Timeseries of mean June-July temperature (top) and salinity (bottom) for the period 1950–2009 averaged in four different depth intervals west of Fylla Bank (st.4) over the continental slope. Thick curves are the 3 year running mean values. Note the change in scales at 34.75 for salinity. Statistics are shown in Table 2.

Table 2. Statistics for potential temperature and salinity at Fylla Bank st. 4. and values for 2009.

Fylla Bank	Temperature [°C]	Salinity	2009	
St.4	Mean ± std	Mean ± std	Tpot	S
0–50 m	1.85 ± 0.85°C	33.20 ± 0.33	1.96°C	33.73
50–150 m	1.03 ± 0.84°C	33.63 ± 0.27	1.29°C	33.90
150–400 m	2.58 ± 0.85°C	34.29 ± 0.17	3.06°C	34.57
400–600 m	4.18 ± 0.57°C	34.81 ± 0.08	4.40°C	34.92

Similar timeseries west of the banks further north at Maniitsoq st.5 (Figure 21, Table 3) and Sisimiut st.5 (Figure 22, Table 4) confirms, that the Irminger Water component of the West Greenland Current still brings considerable amount of heat and salt to the area. Temperatures and salinities measured in 400–600 m was high at both Sisimiut and Maniitsoq. Indeed the salinities were the highest observed yet on these stations. However, contrary the Fylla Bank st.4 (Figure 19), Maniitsoq st.5 and Sisimiut st.5 are only regular measured since 1970, while the former “warm period” in the 1950s–1960s is only sporadically measured. Consequently the statistical means are less certain. Similar, record high bottom temperature and salinity are seen within the Disko Bay just outsite Ilulissat (”Jakobshavn”) at station Skansen-Ilulissat st.3. However, the timeseries are quite short compared to the three above mentioned timeseries.

The bottom salinities and temperatures in 400–600 m at Maniitsoq st.5 and Sisimiut st.5 was higher than observed further south at Fylla Bank st.4. This was also the case in 2007 (Ribergaard et al., 2008) and 2008 (Ribergaard, 2009). As the warm and saline water can only enter from south, the bottom waters at Sisimiut, Maniitsoq and Ilulissat are likely arrived during spring/winter followed by a decreasing presence of the Irminger Water inflow during spring/summer.

North of Paamiut, the core of the Polar Water is found in the depth interval 50–150 meter over the continental shelf. In 2009 the salinity was high and the temperature above normal (Table 2 – Table 4) suggesting lower than normal presence of Polar Water. The relative low surface temperatures, but high salinities, at Maniitsoq and Sisimiut, might reflect recent retreat/melting of west-ice in the area. Whereby solar heating has only been possible for a short time period.

Further south multi-year-ice "Storis" was present off the southeast coast of Greenland extending north of the Julianehaab Bight (Figure 6).

At the Aasiaat (Egedesminde) section and further north to the Upernavik section a distinct Polar Water core was absent. Instead a colder layer was found with temperatures below 1°C (below -1°C at its core) with its center at about 75 m depth. This layer was most likely formed during winter by convection. Brine rejection increases the low surface (0–50 m) salinities, so it can overcome the strong upper halocline which is created during summer by melting of sea-ice and run-off of fresh water from land. The top of this layer can be seen in Figure 18. Below the cold subsurface layer, a relative warm (> 3°C) watermass was found below 150–200 m. This water is the extension of the Irminger Water component of the West Greenland Current.

West of Fylla Bank (st.4, Figure 19), the temperature and salinity was above normal throughout the water column down to 600 m. Generally, the same conditions is seen further to the northwest, off the "Sukkertopbanke" and "Store Hellefiskebanke" (Figure 21 and Figure 22), where high salinities and temperatures was observed throughout the water column except for colder surface conditions but still more saline than average. This suggest higher than normal presence of both Irminger Water and lower than normal presence of Polar Water.

Noticeably, since the early 2000s, the mean salinity and temperature of the Irminger Water at 400–600 m depth west of Fylla Bank (Figure 16) "Sukkertopbanke" (Figure 21) and "Store Hellefiskebanke" (Figure 22) has increased which may indicate increased strength of the Irminger Current as suggested by Ribergaard (2004). Similar findings was reported by Myers et al. (2007, 2009) and Stein (2005) which they linked to the North Atlantic subpolar gyre circulation (Hátún et al., 2005). Not surprisingly, similar increase in salinity and temperature are observed in the Atlantic Water in the eastern North Atlantic and the Nordic Seas (Holliday et al., 2008), suggesting that the recent changes in the Irminger Water property is an outcome of changes in the circulation in the North Atlantic subpolar gyre circulation.

For a more comprehensive study of the hydrographic conditions off West Greenland, the reader is refereed to the work done by Myers et al. (2009, 2007). Here calculations of volume, heat and fresh water transport for the 6 southern sections are given for the time period up to 2008.

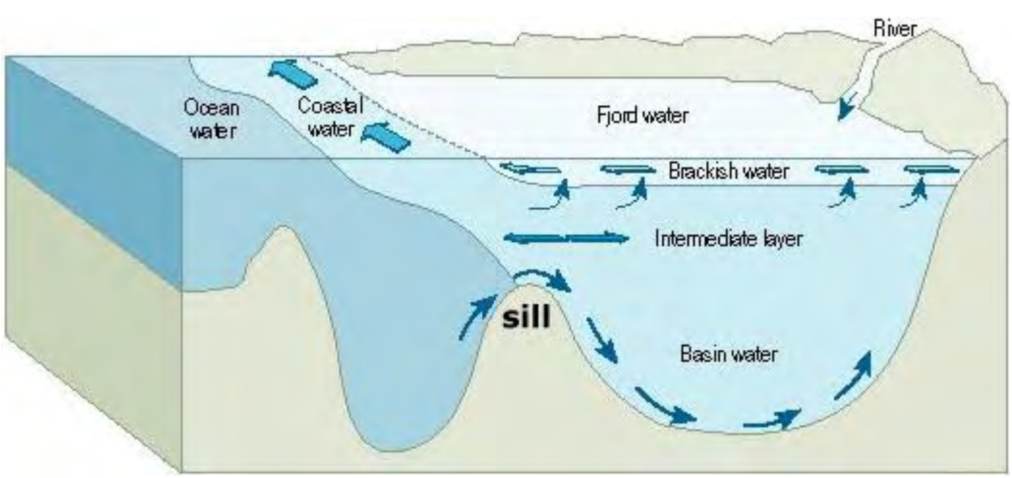

Figure 20. Sketch of the circulation in a fjord (modified from AMAP Assessment Report: Arctic Pollution Issues, Figure 3.20, http://www.amap.no/maps-gra/show.cfm?figureId=58).

West Greenland fjords 2009

The hydrography in fjords is to a large extent determined by the land runoff of fresh water in the surface and at the inflow near the bottom at the mouth of the fjord (see Figure 20). Often fjords have a sill at the opening to the open ocean and it is the depth of this sill that determinate which watermasses are allowed to enter near the bottom. Above sill depth water can freely flow either in or out of the fjord. At the surface the current are often directed out of the fjord caused by the runoff of fresh water, which on average cause a slight increase in the sea level towards the head of the fjord. Thereby a pressure gradient is established and surface water will flow out of the fjord. This surface water will entrain water from below and to compensate for this entrainment, inflow is taking place at the bottom as sketched in Figure 20. Besides, West Greenland fjords experience a large tidal signal which cause extensive vertical mixing and significant horizontal ventilation which by far dominate the fluxes of freshwater to the fjords over shorter timescales. Additional, local wind conditions can also have a major impact on the water exchanges in some fjords by setting up horizontal pressure gradients along the fjord which again affects the interface (Straneo et al, 2010)

Most fjords in West Greenland are sill fjords i.e. resulting in strong limitations of the exchange of water between the deeper parts of the fjord and the open ocean. Mainly three different watermasses can be found in the West Greenlandic fjords:

- Relative warm and saline waters of Atlantic origin (mixed Irminger Water).
- Cold and relative fresh water of polar origin (mixed Polar Water).
- Fresh surface water from land, either as melting of the Greenland Ice Sheet or from precipitation (surface water).

The flux of fresh surface water from land is highly variable on a seasonal scale. When exported out of the fjords, this brackish water is mixed with the surrounding surface waters, which is Polar Water. Mixing continues along the coast, and the watermass stays close to the coast. In the following this water is named Coastal Polar Water.

Godthaabsfjorden

Part of Godthaabsfjorden (Nuuk fjord) was measured in June 2009. The fjord system has a sill depth of about 200 m close to Godthaabsfjord station GF1. Another major sill exists northwest of Nuuk town just offshore station GF4. Between these two sills the water depth is about 400 m forming a narrow channel. Here the tidal current are exceptional strong resulting in high turbulent mixing.

The main fjord system consists of three “arms”. Within these arms, several of “sub-sills” exists, as a result of the movement of the glacier back in time. The northwestern arm (“main arm”) is the deepest of more than 600 m with a sub-sill just offshore station GF6 of 350 m. The southestern arm is also deep in the outermost part, but the bottom raise to about 350 m in its innermost part, which efficient reject the deepest water to enter the inner part though that arm. The middle arm is shallower especially at its inner part and no deep waters are allowed to pass.

The inner part of the fjord ends in a floating glacier and some side brach glaciers which supply the surface layers with a significant amount of fresh water and ice growlers. This fresh water supply set up a horizontal pressure gradient along the fjord which is a main driver of the general fjord circulation.

The deep sills (200m/250m) permit “warmer” water masses to enter the fjord. In 2009 the bottom water in the middle of the main arm (GF7, Figure 5) was below 1.2°C and has salinities of about 33.65−33.67 - coldest but most saline towards the bottom. This water is partly a mixture of Atlantic origin water (Irminger Water) and Polar Water that enter the fjord from outside through the Fylla Bank Channel.

The bottom water at station GF7 was considerable colder and less saline compared to observations in 2008 (Ribergaard, 2009).

Fjords south of Sisimiut

Hydrographic data were obtained from four fjords around Sisimiut in 2009 (Figure 41–Figure 44). They represent two very different types of fjords: two with deep sills (Amerdloq, Ikertoq), one with shallow sills (Kangerdluarssuk). Itivdleq fjord has an intermediate sill depth. None of the fjords are directly connected to the Greenland ice sheet, as can be seen directly on a topographic map, and so the fresh water supply added are limited to runoff from land.

Between 2008 and 2009 the bottom waters of all fjords has been renewed.

I the two fjords with the deepest sills, Ikertoq (Figure 41) and Ikertoq (Figure 42), relative warm (>3°C) and saline (>34.3) waters have entered with Ikertoq slightly warmer and saline compared to Amerdloq. Relative warm and saline waters did also enter the fjord with intermediate sill depth, Itivdleq (Figure 44), with temperature >2°C and salinity >34.0. The bottom waters in all three fjords do have an imprint of Irminger Waters revealed by its relative high temperatures and salinities. It enters the fjords as a bottom layer at about sill depth. The density of this bottom water is higher than the Coastal Polar Water above, even at the freezing point of the Coastal Polar Water. Thereby winter convection to the bottom is prevented unless driven by brine rejection during sea-ice formation. Above sill depth the temperature is coldest just above the interface between the diluted Irminger Water and the Coastal Polar Water. This cold water could be a result of winter convection of Coastal Polar Water, or it is just the core of the Polar Water.

The bottom waters in the fjord with the shallow sill, Kangerdluarssuk (Figure 43), do have another characteristic. The salinity has increased compared to the former years to almost 33.6, which, however, are much lower than in the other three fjords. Similar, the temperature has increased to about 0.6°C, which is much lower than in the other fjords. This waters is likely formed locally during winter by convection of Coastal Polar Water and do not necessary enter the fjord at sill depth. The water above sill depth is also Coastal Polar Water.

In the very top of all fjords a thin surface layer are formed caused by runoff from land. This shallow layer is warmed by solar radiation.

Figure 45 − Figure 48 shows the temporal evolution in the properties in all four fjords. All fjords have become warmer and more saline in the bottom layer indicating higher than normal renewal of the bottom waters. For the three fjords with the deepest sills, this is likely linked to the high presence of Irminger Water during winter 2008/09 and for Kangerdluarssuk fjord by the relative low presence of Polar Waters.

Conclusions

Atmospheric and oceanographic conditions off West Greenland during the summer 2009 were characterised by:

- Positive NAO index resulting in strengthen westerlies over the North Atlantic.
- Winter air temperatures over Greenland waters was warmer than normal – especially over the Baffin Bay / Davis Strait with temperature anomalies above 4°C. Similar findings on an annual basis.
- Winter air temperatures over most of the North Atlantic sector outside Greenland was only 0−1°C warmer than normal.
- About normal concentration of multi-year-ice ("Storis").
- Mean annual and mean winter air temperature in Nuuk was one degree above normal.
- Water temperature on top of Fylla Bank was above average in June and the salinity was high.
- Below normal presence of Polar Water and above normal presence of Irminger Water indicated by:
  - Higher than normal salinities in the surface over the shelf and shelfbreak and generally higher than normal surface and subsurface temperatures.
  - Water temperature and salinity on top of Fylla Bank was above average in June
  - Pure Irminger Water was observed north to the Sisimiut section – except on the Fylla Bank section.
  - West of Fyllas Bank (st.4) the mean temperature and salinity in 400–600 m depth was above average.
  - West of "Sukkertop Banke" and "Store Hellefiskebanke", the observed temperatures were among the highest observed in 400–600 m depth and the salinities the highest observed. However the time series are not as complete as the Fylla Bank st.4.
  - Record high bottom temperature and salinity observed within the Disko Bay off Ilulissat.

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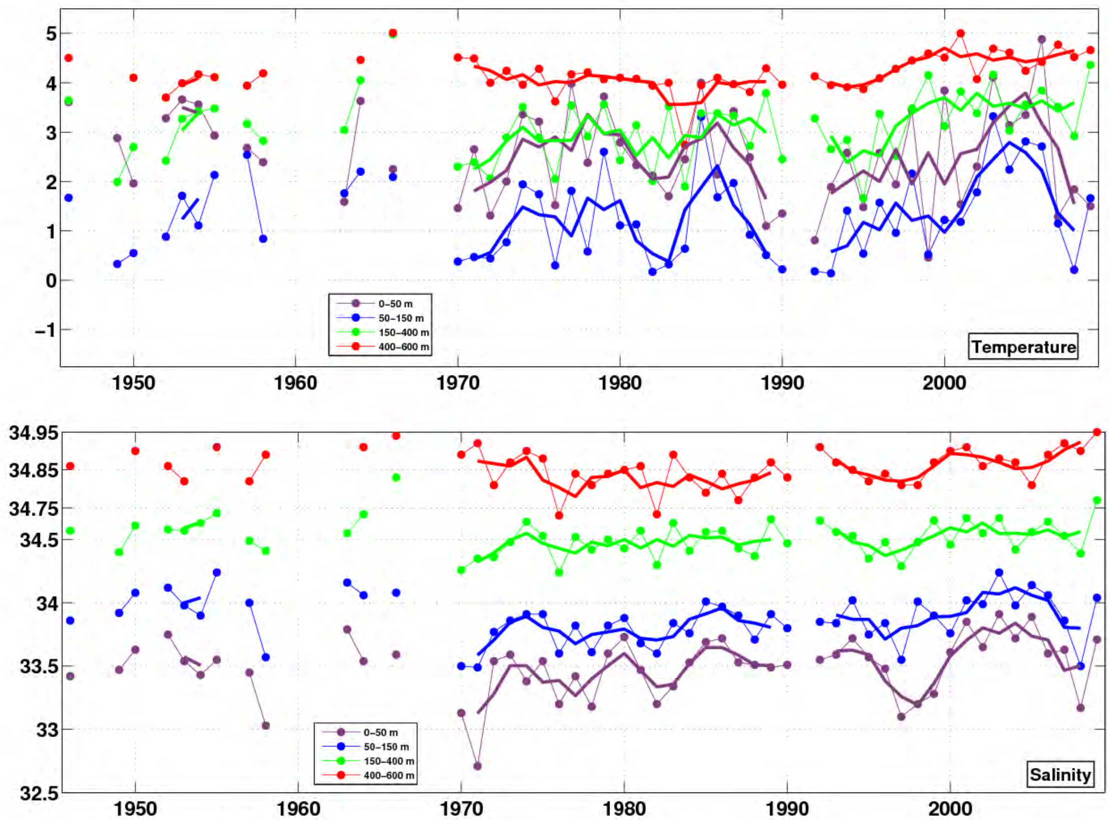

Figure 21. Timeseries of mean temperature (top) and mean salinity (bottom) for the period 1946–2009 in four different depth intervals west of "Sukkertop Banke" (Maniitsoq, st.5) over the continental slope. The thick curves are the 3 year running mean values. Note the change in scales at 34.75 for salinity. Statistics is shown in Table 3.

Table 3. Statistics for potential temperature and salinity at Maniitsoq (Sukkertoppen) st. 5. and values for 2009.

Maniitsoq St.5	Temperature [°C]	Salinity	2009	
	Mean ± std	Mean ± std	Tpot	S
0–50 m	2.53 ± 0.98°C	33.50 ± 0.23	1.50°C	33.71
50–150 m	1.31 ± 0.87°C	33.88 ± 0.19	1.66°C	34.04
150–400 m	3.11 ± 0.69°C	34.52 ± 0.13	4.36°C	34.77
400–600 m	4.19 ± 0.38°C	34.86 ± 0.05	4.66°C	34.95

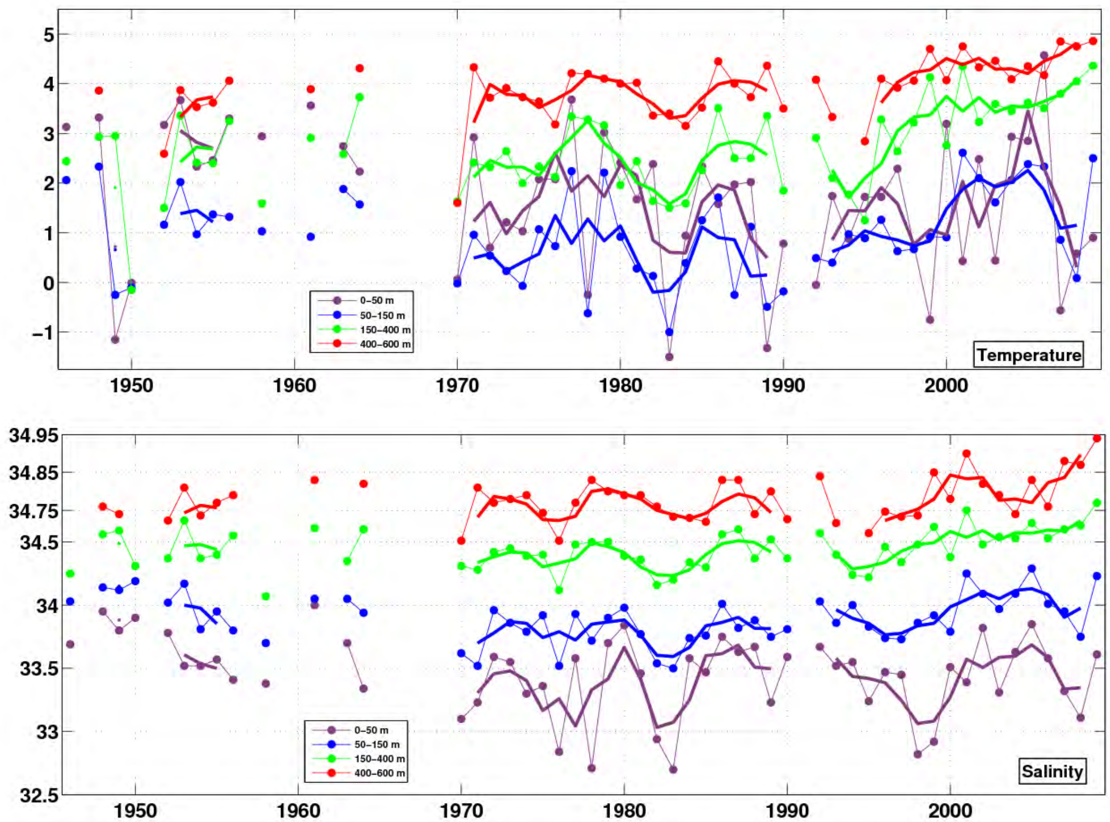

Figure 22. Timeseries of mean temperature (top) and mean salinity (bottom) for the period 1946–2009 in four different depth intervals west of "Store Hellefiskebanke" (Sisimiut, st.5) over the continental slope. The thick curves are the 3 year running mean values. Note the change in scales at 34.75 for salinity. Statistics is shown in Table 4.

Table 4. Statistics for potential temperature and salinity at Sisimiut (Holsteinsborg) st. 5. and values for 2009.

Sisimiut St.5	Temperature [°C]	Salinity	2009	
	Mean ± std	Mean ± std	Tpot	S
0–50 m	1.68 ± 1.43°C	33.46 ± 0.31	0.90°C	33.61
50–150 m	0.98 ± 0.90°C	33.90 ± 0.19	2.50°C	34.23
150–400 m	2.70 ± 0.89°C	34.44 ± 0.16	4.36°C	34.77
400–600 m	3.90 ± 0.61°C	34.76 ± 0.09	4.86°C	34.94

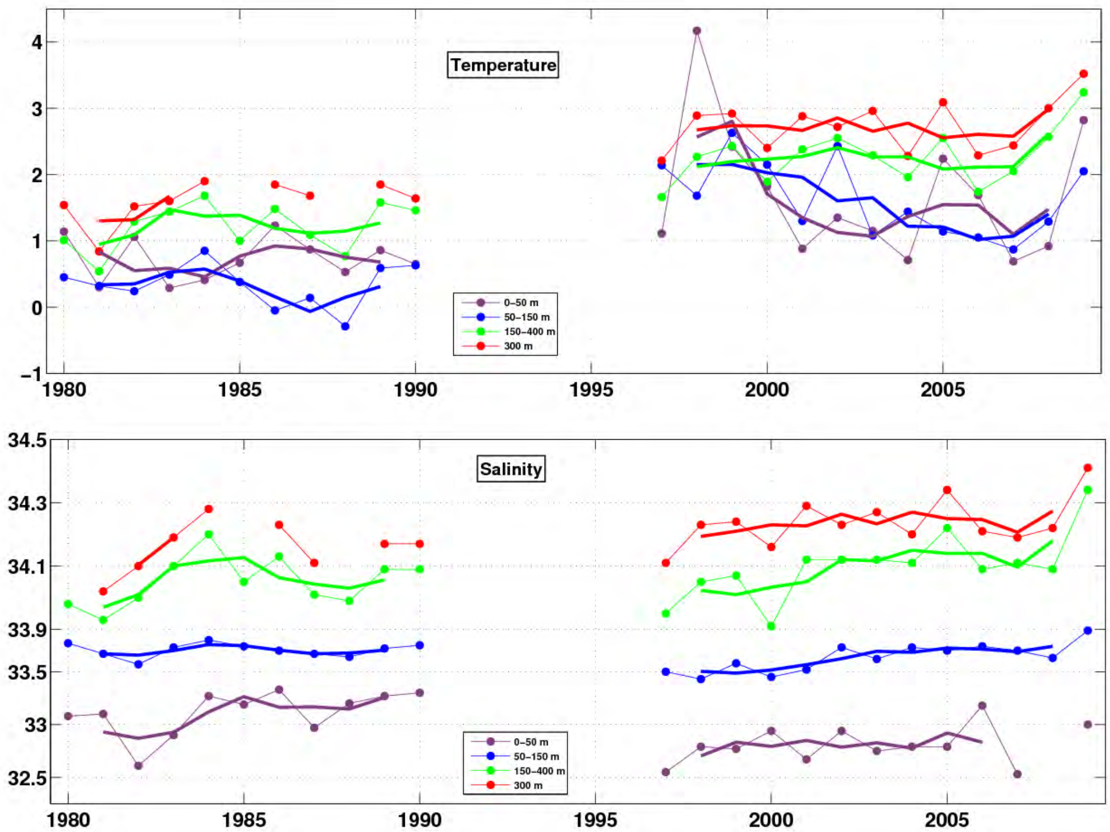

Figure 23. Timeseries of mean temperature (top) and mean salinity (bottom) for the period 1980–2009 in four different depth intervals west of “Jakobshavn-Skansen” (Ilulissat-Skansen) st.3 in the Disko Bay close to Jakobshavn Isbræ. The thick curves are the 3 year running mean values. Note the change in scales at 33.9 for salinity. Statistics is shown in Table 4.

Table 5. Statistics for potential temperature and salinity at Ilulissat-Skansen (Jakobshavn-Skansen) st. 3. and values for 2009.

Ilulissat	Temperature [°C]	Salinity	2009	
St.3	Mean ± std	Mean ± std	Tpot	S
0–50 m	1.32 ± 0.95°C	32.98 ± 0.27	2.82°C	33.00
50–150 m	1.04 ± 0.79°C	33.67 ± 0.11	2.05°C	33.89
150–400 m	1.77 ± 0.66°C	34.08 ± 0.09	3.24°C	34.34
300 m	2.25 ± 0.66°C	34.21 ± 0.08	3.52°C	34.41

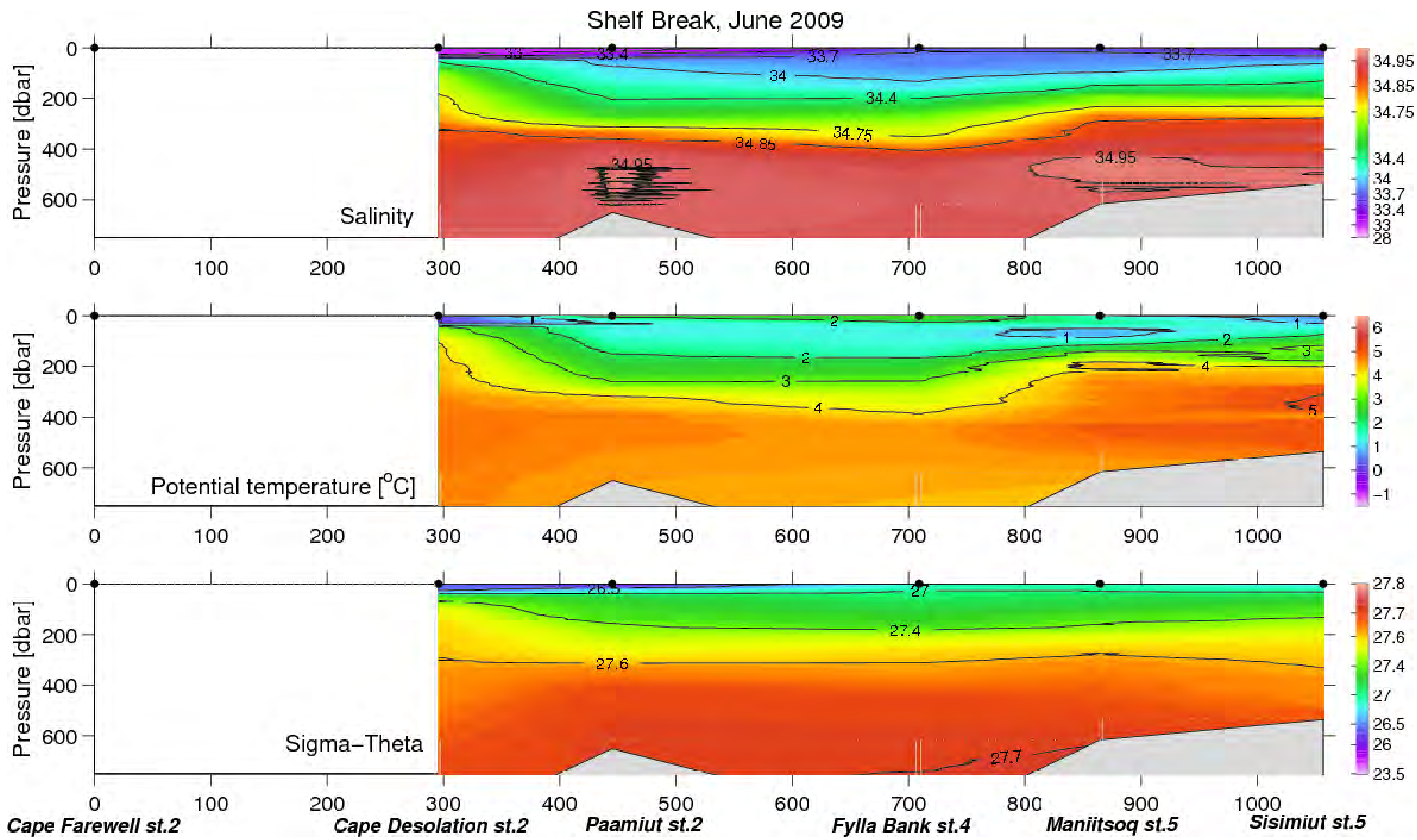

Figure 24. Vertical distribution of temperature, salinity and density over the continental shelf break from Cape Desolation to Sisimiut, June 11–16, 2009.

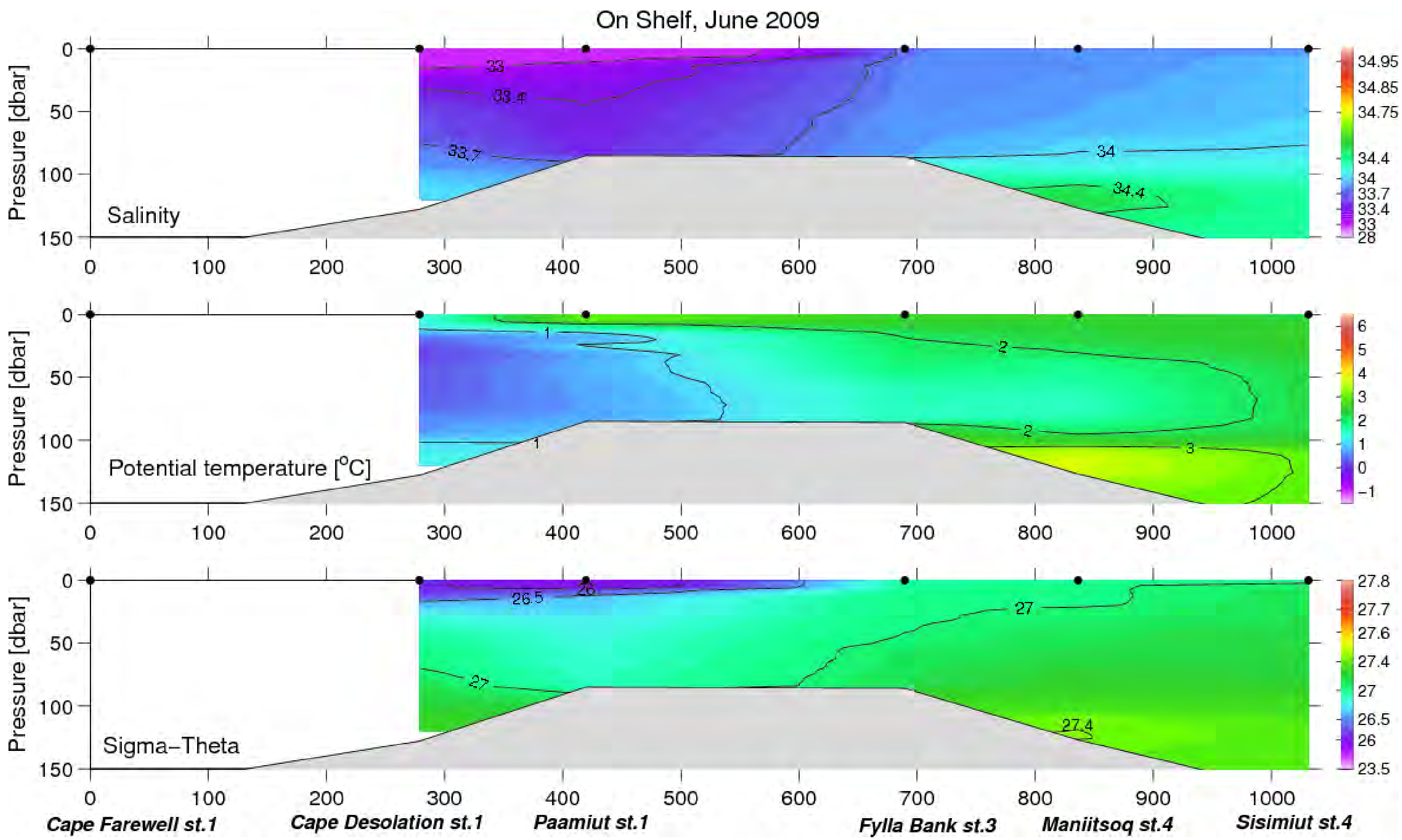

Figure 25. Vertical distribution of temperature, salinity and density over the shelf banks from Cape Desolation to Sisimiut, June 11–16, 2009.

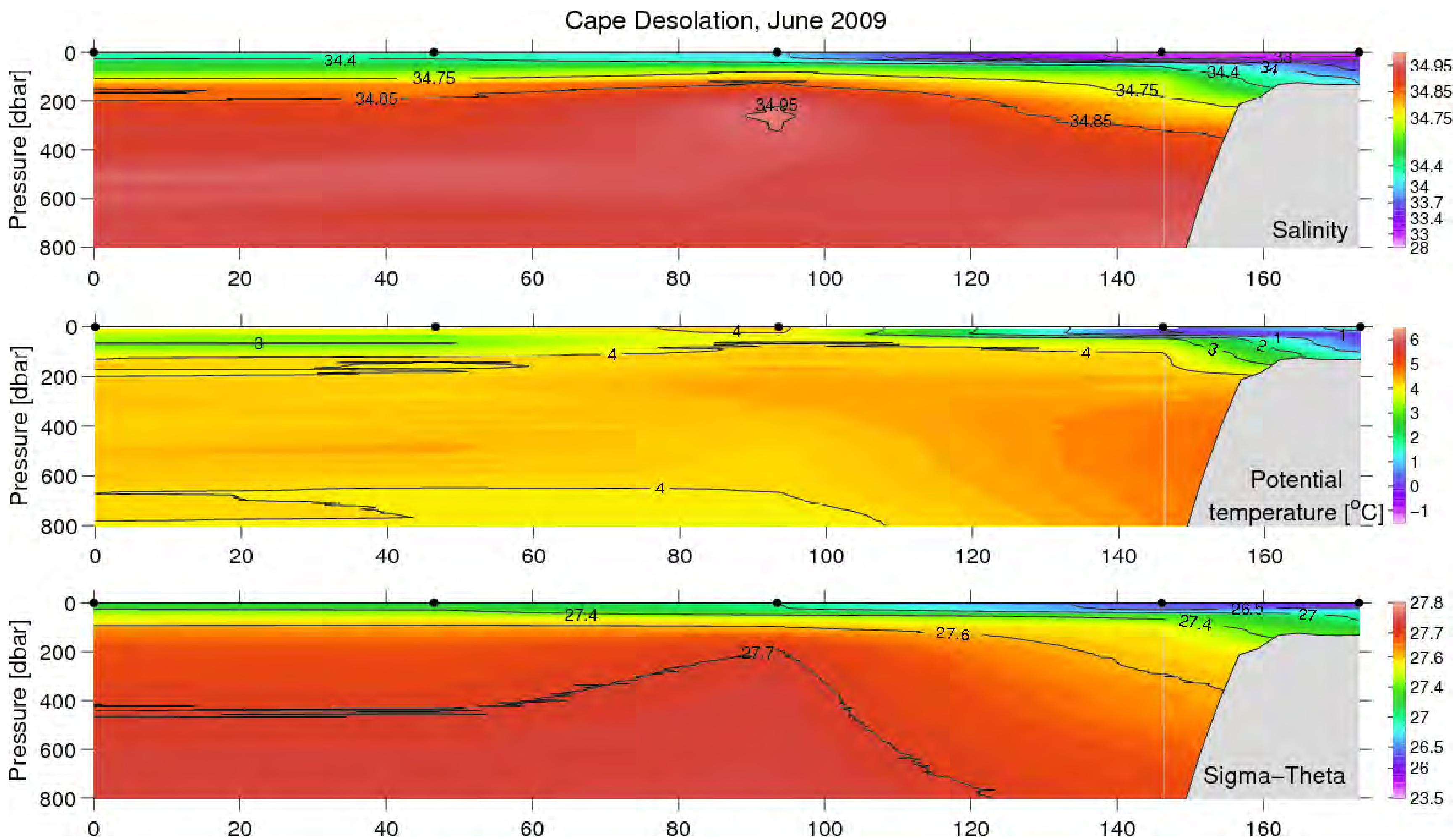

Figure 26. Vertical distribution of temperature, salinity and density at the Cape Desolation section, June 16, 2009

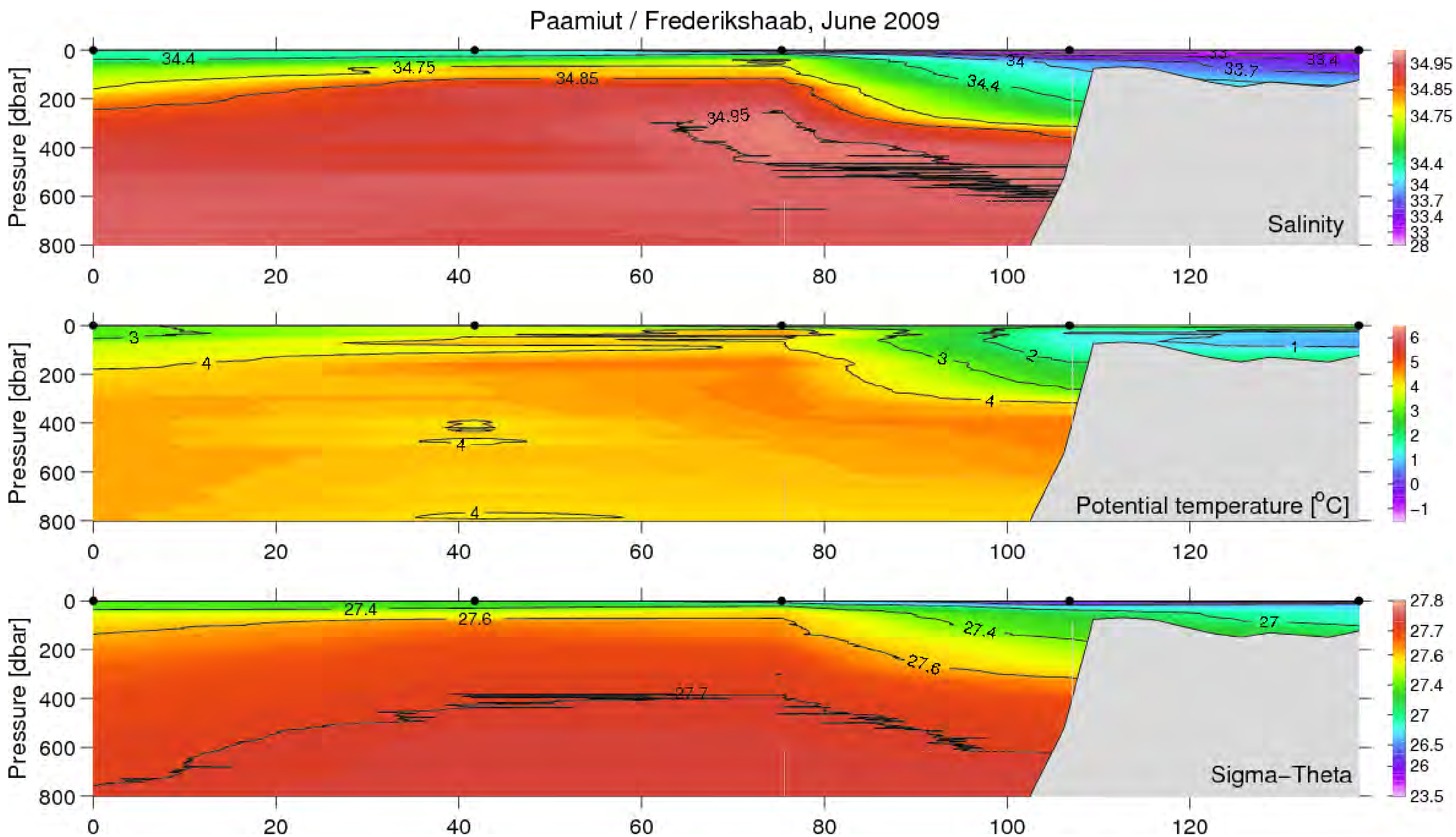

Figure 27. Vertical distribution of temperature, salinity and density at the Paamiut (Frederikshaab) section, June 15–16, 2009.

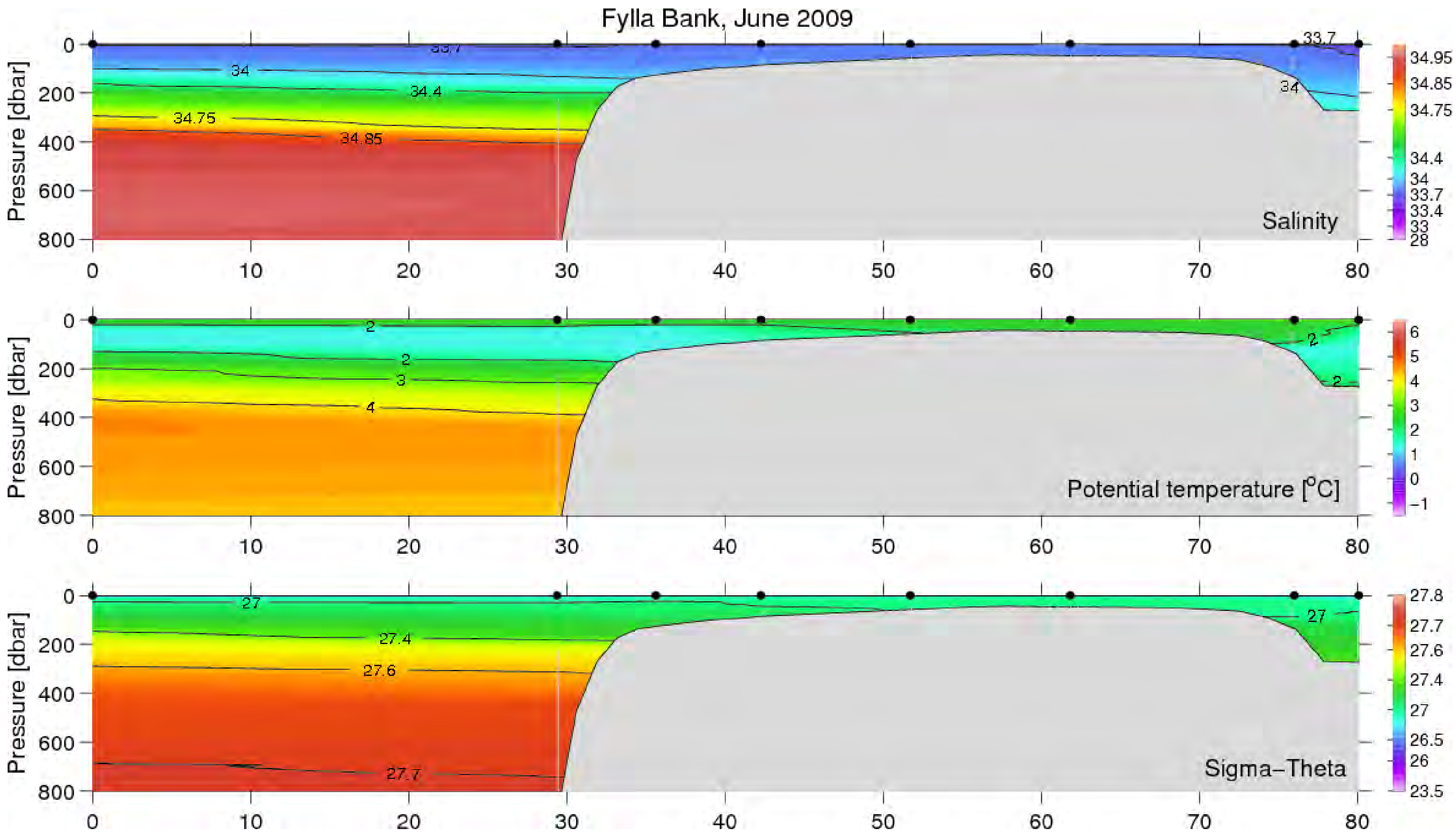

Figure 28. Vertical distribution of temperature, salinity and density at the Fylla Bank section, June 13, 2009. Three intermediate stations were taken too.

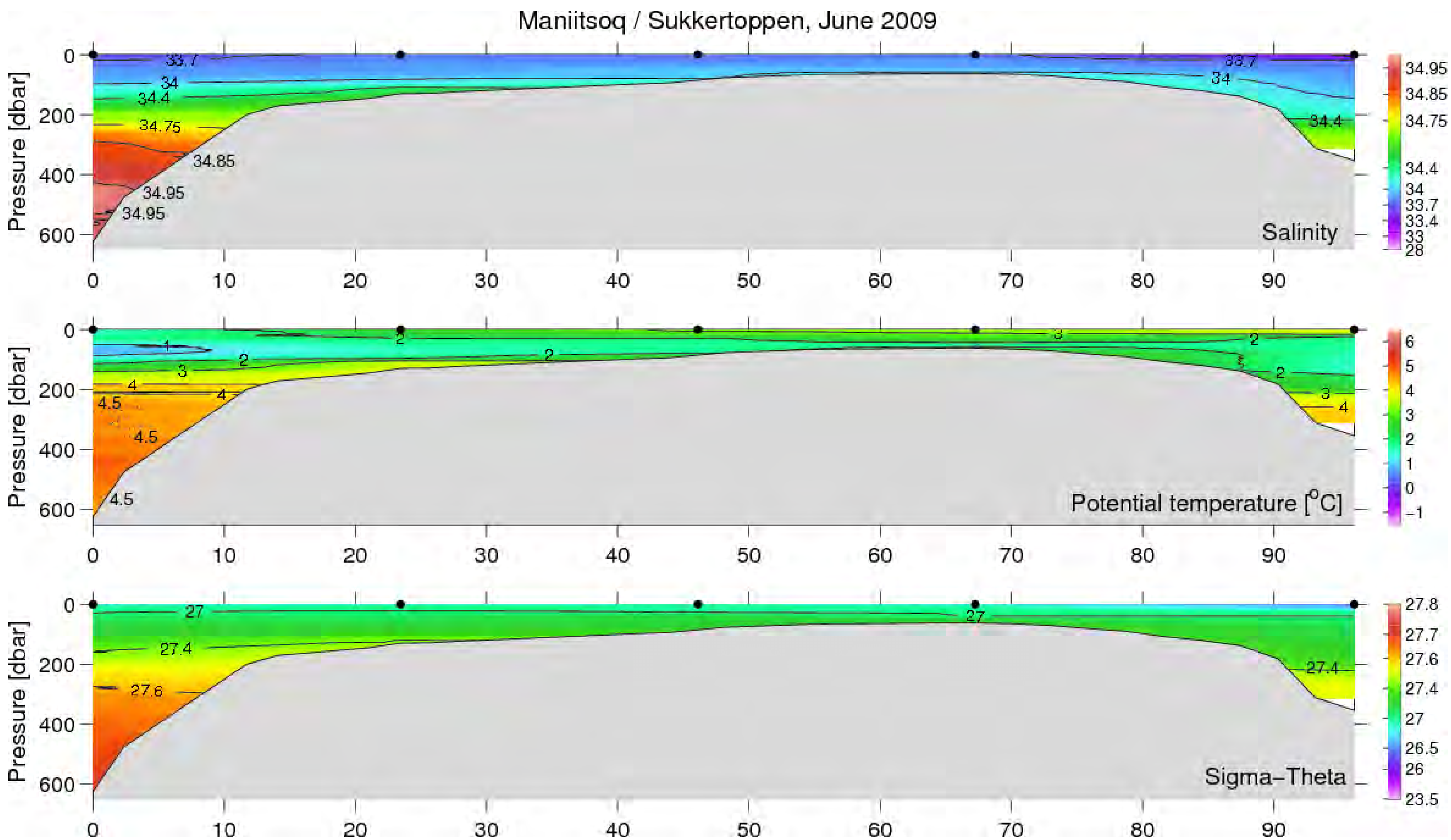

Figure 29. Vertical distribution of temperature, salinity and density at the Maniitsoq (Sukkertoppen) section, June 12, 2009.

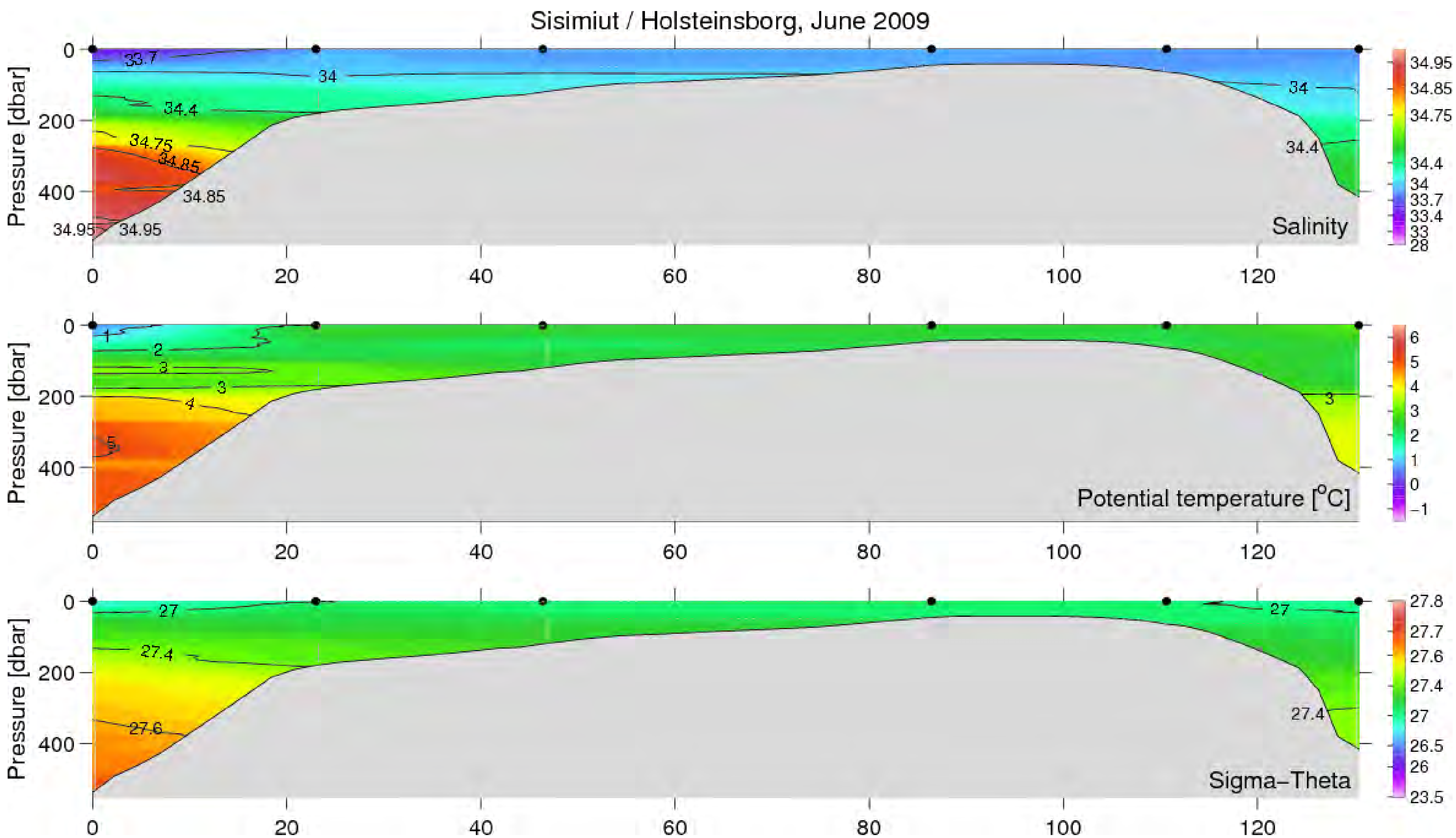

Figure 30. Vertical distribution of temperature, salinity and density at the Sisimiut (Holsteinsborg) section, June 11, 2009. Sisimiut st. 0 right.

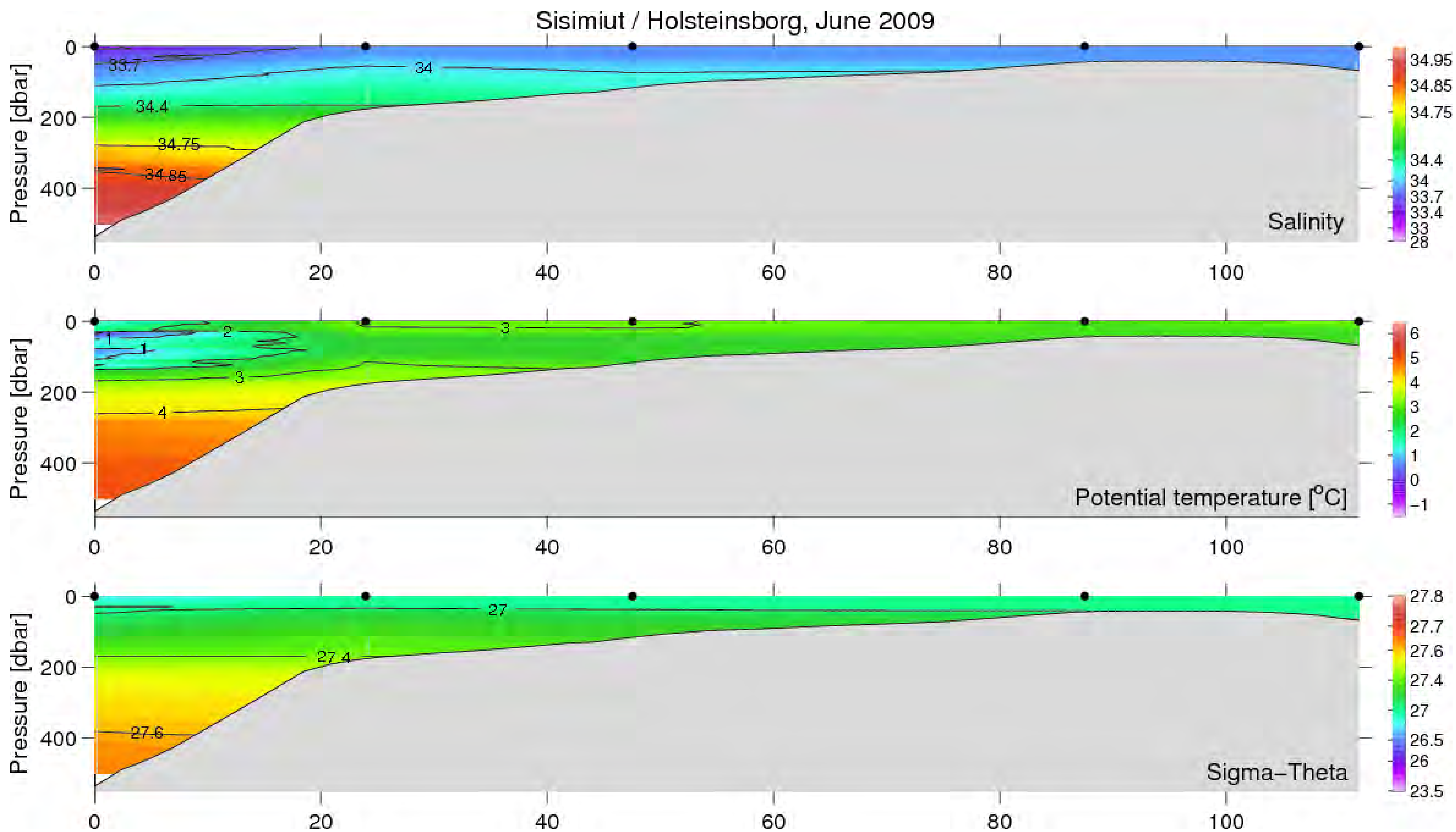

Figure 31. Vertical distribution of temperature, salinity and density at the Sisimiut (Holsteinsborg) section, June 20–21, 2009.

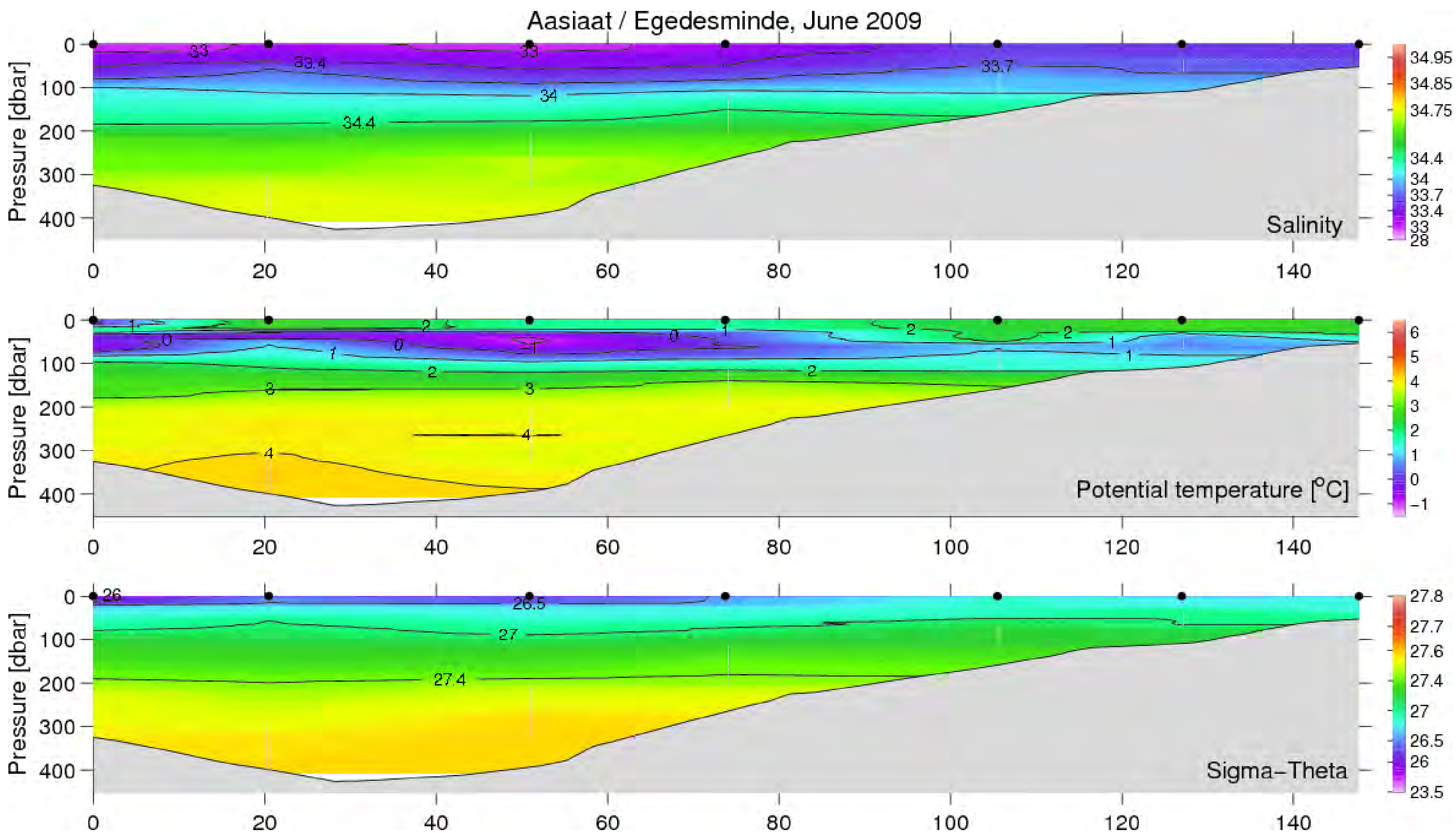

Figure 32. Vertical distribution of temperature, salinity and density at the Aasiaat (Egedesminde) section, June 25–26, 2009.

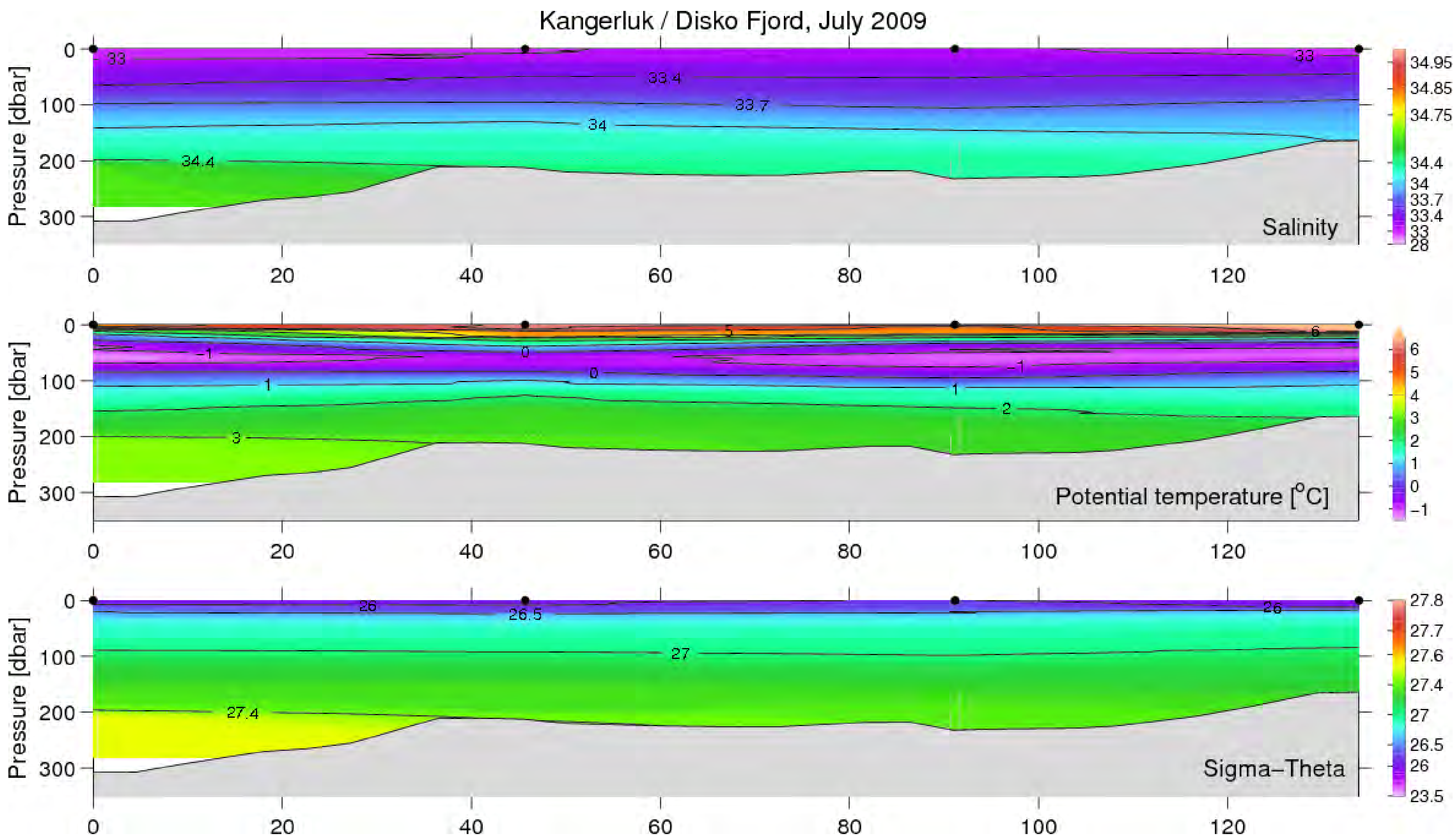

Figure 33. Vertical distribution of temperature, salinity and density at the Kangerluk (Disko Fjord) section, July 17–18, 2009.

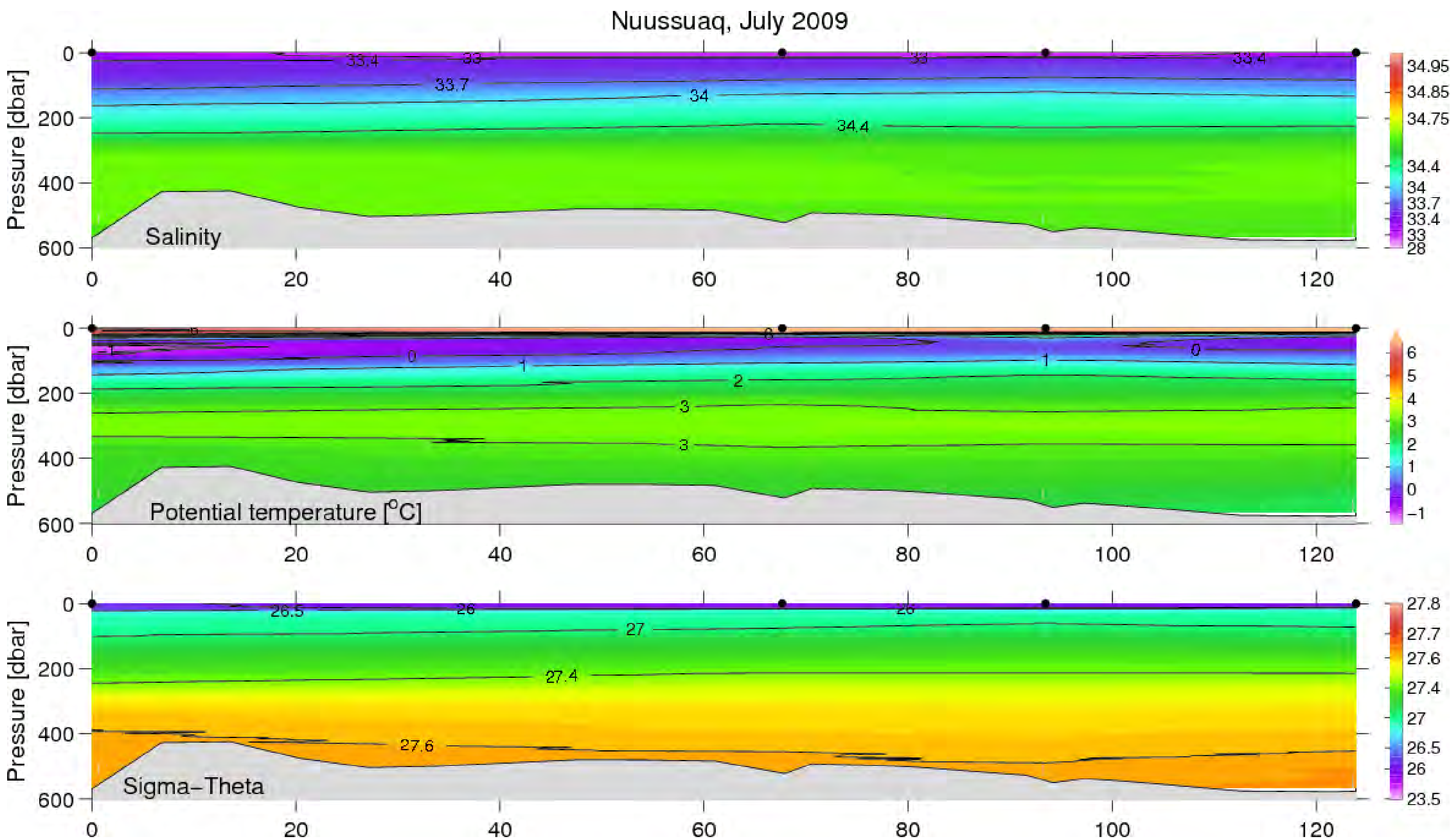

Figure 34. Vertical distribution of temperature, salinity and density at the Nuussuaq section, July 15–16, 2009.

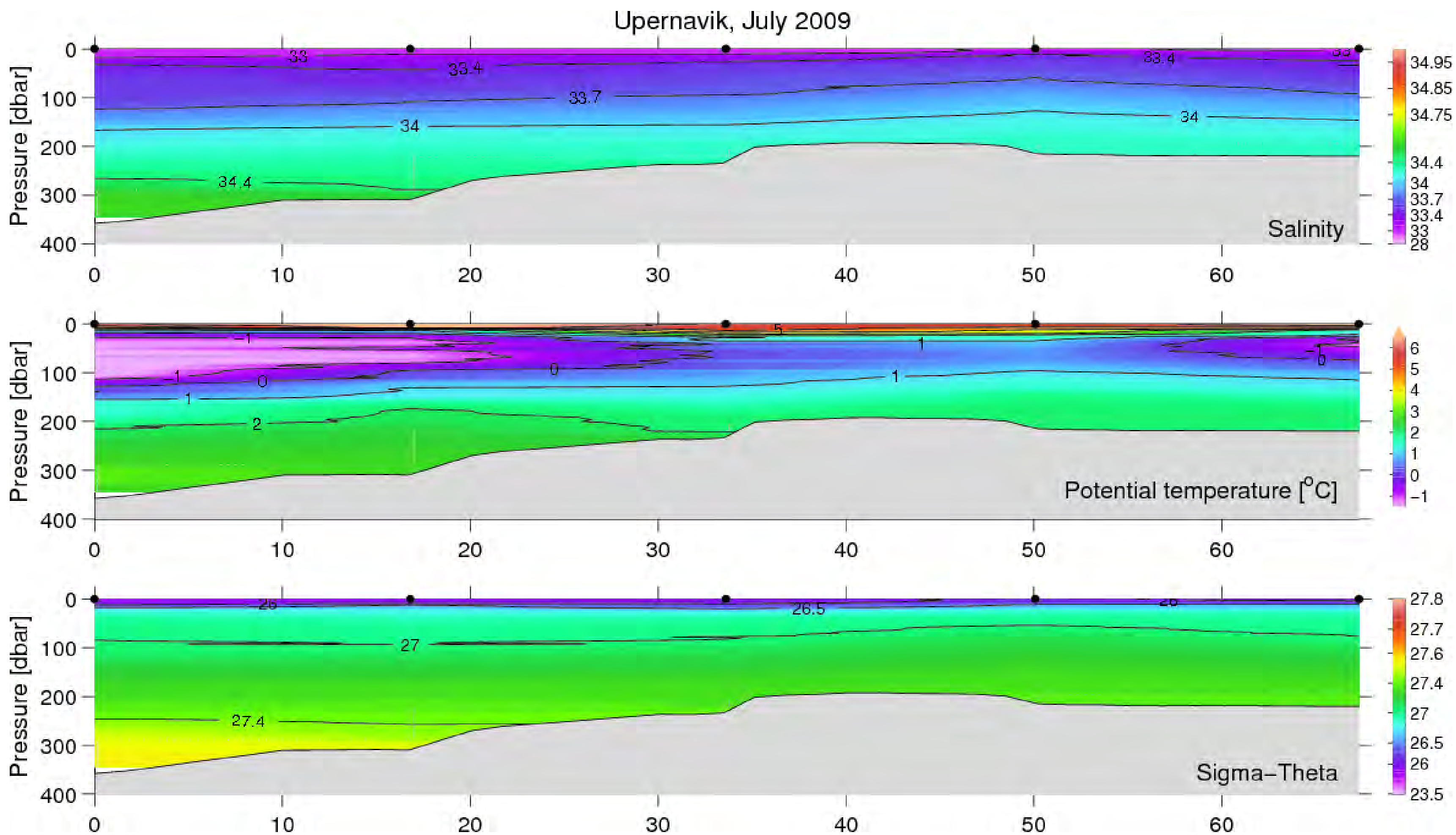

Figure 35. Vertical distribution of temperature, salinity and density at the Upernavik section, July 13, 2009.

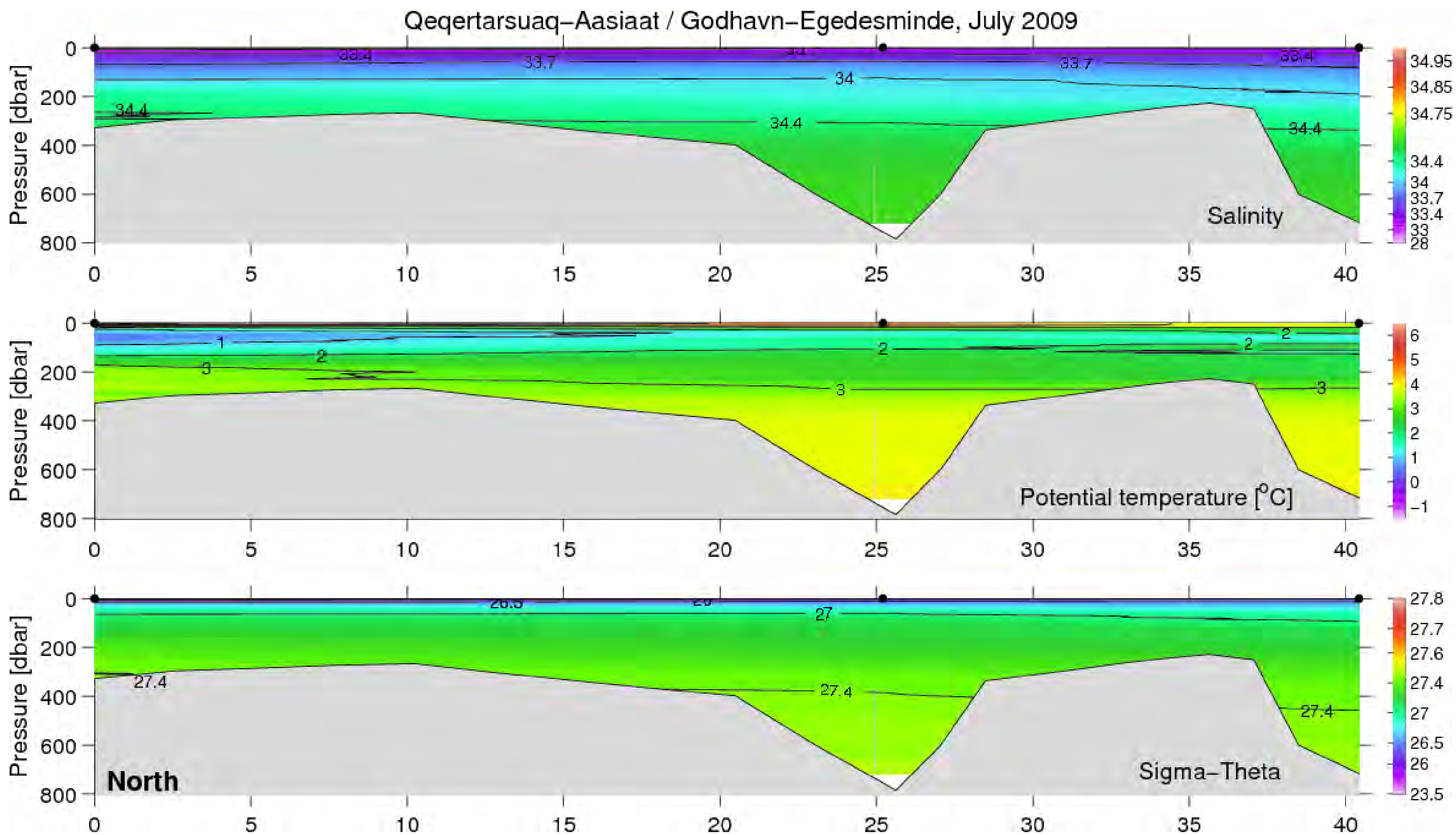

Figure 36. Vertical distribution of temperature, salinity and density at the Aasiaat–Qeqertarsuaq (Egedesminde–Godhavn) section, July 1–2, 2009.

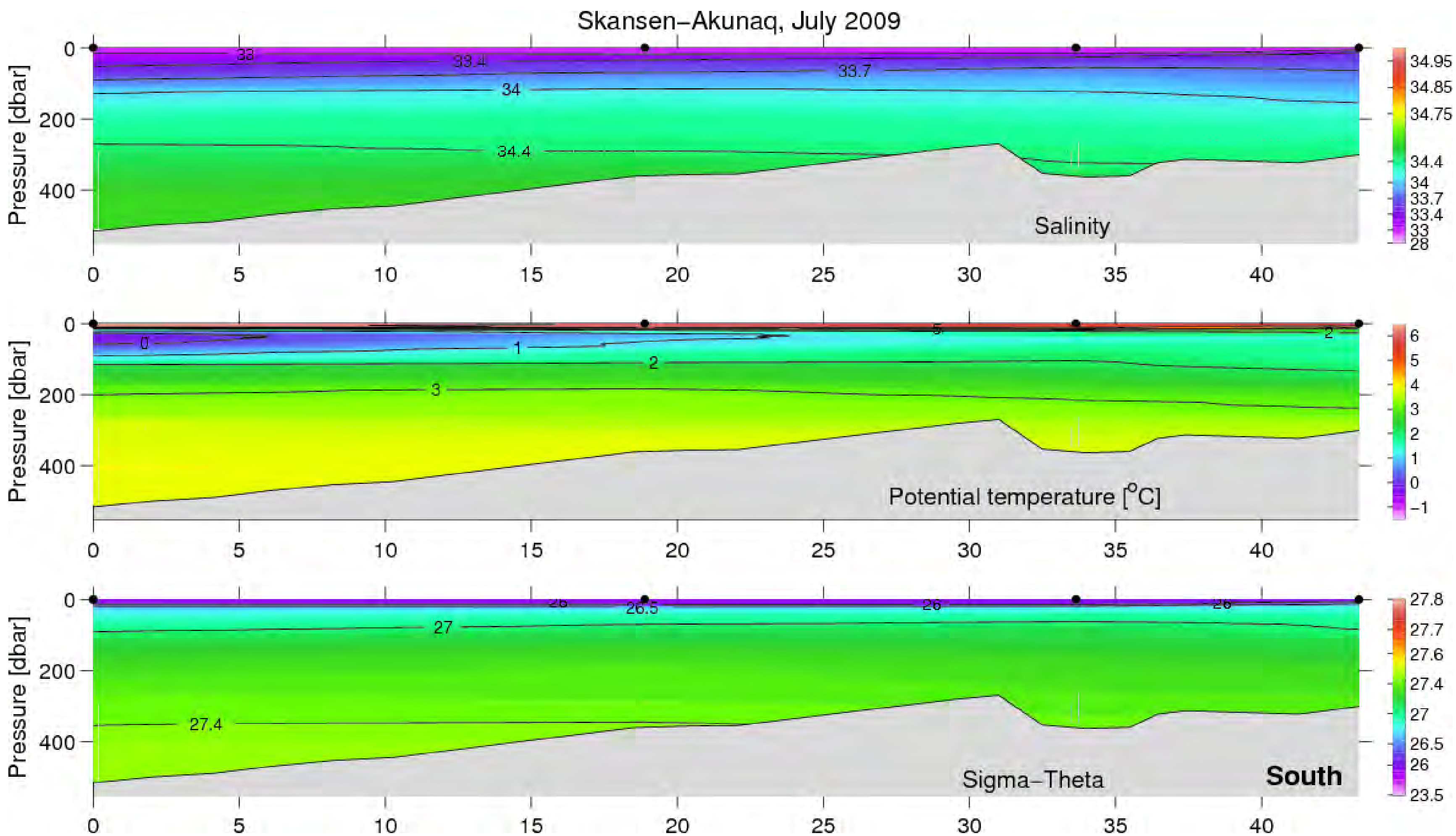

Figure 37. Vertical distribution of temperature, salinity and density at the Skansen–Akunaq section, July 2, 2009.

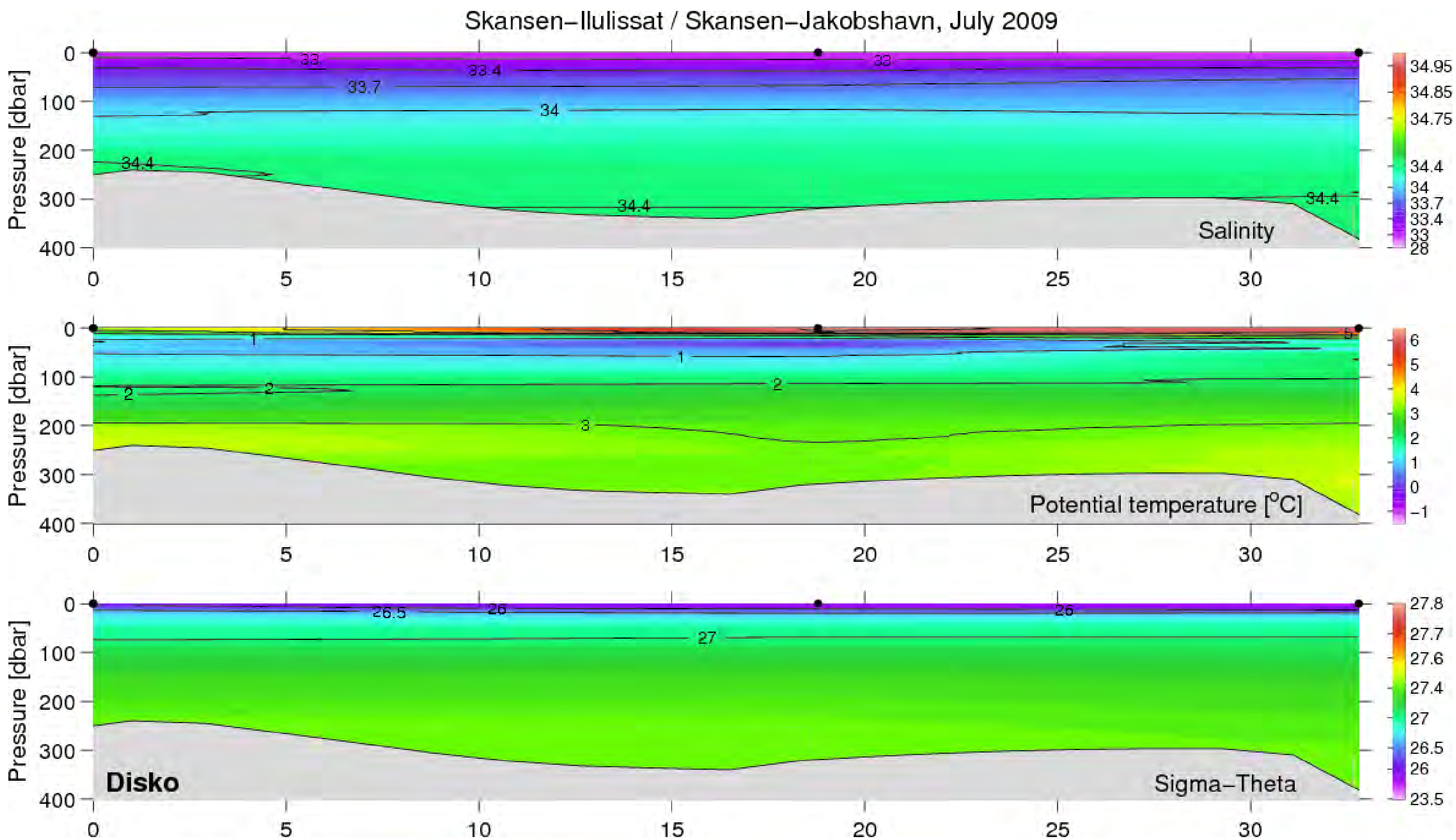

Figure 38. Vertical distribution of temperature, salinity and density at the Skansen–Ilulissat (Skansen–Jakobshavn) section, July 3, 2009.

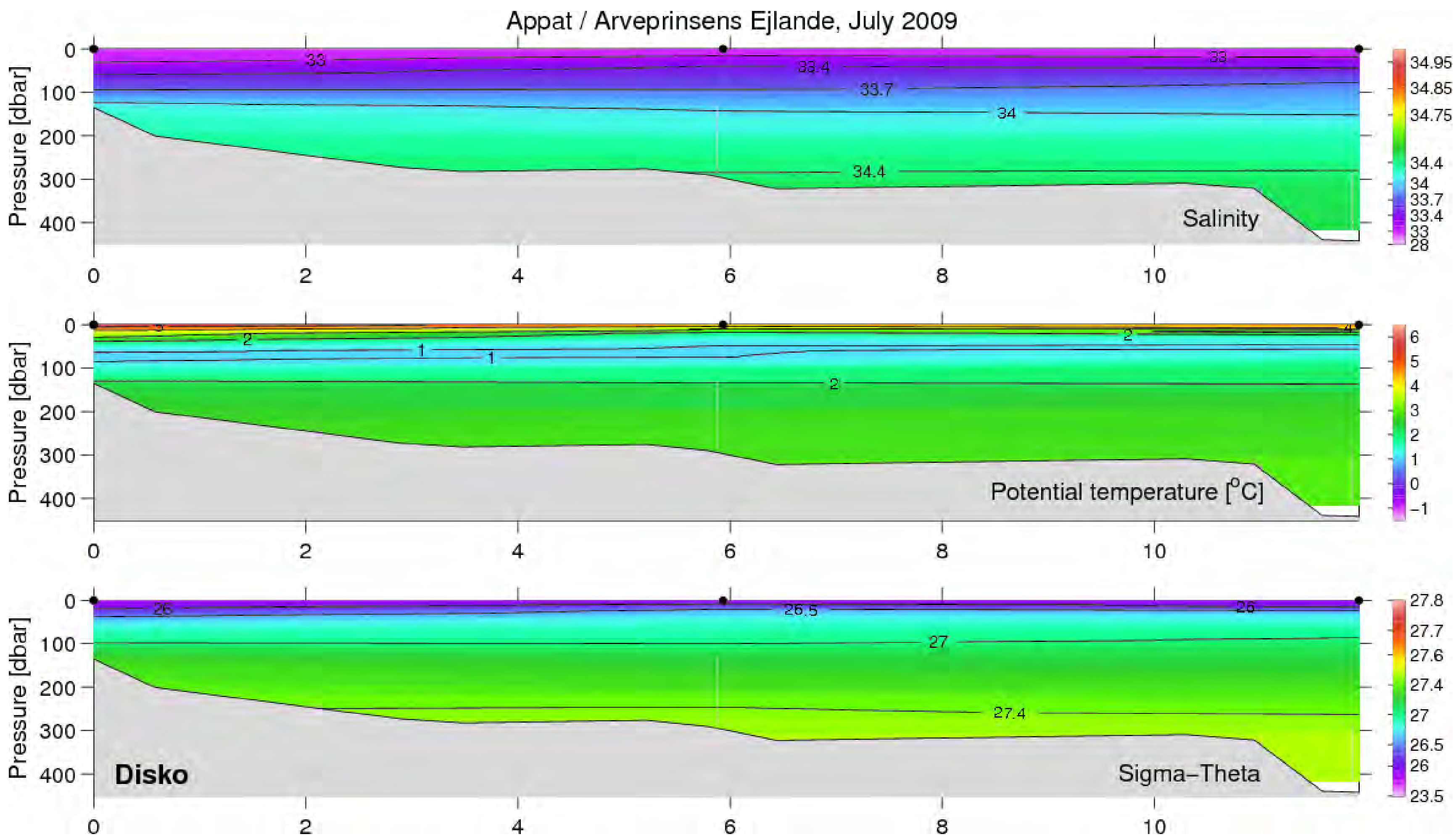

Figure 39. Vertical distribution of temperature, salinity and density at the Appat (Arveprinsens Ejlande) section, July 8–9, 2009.

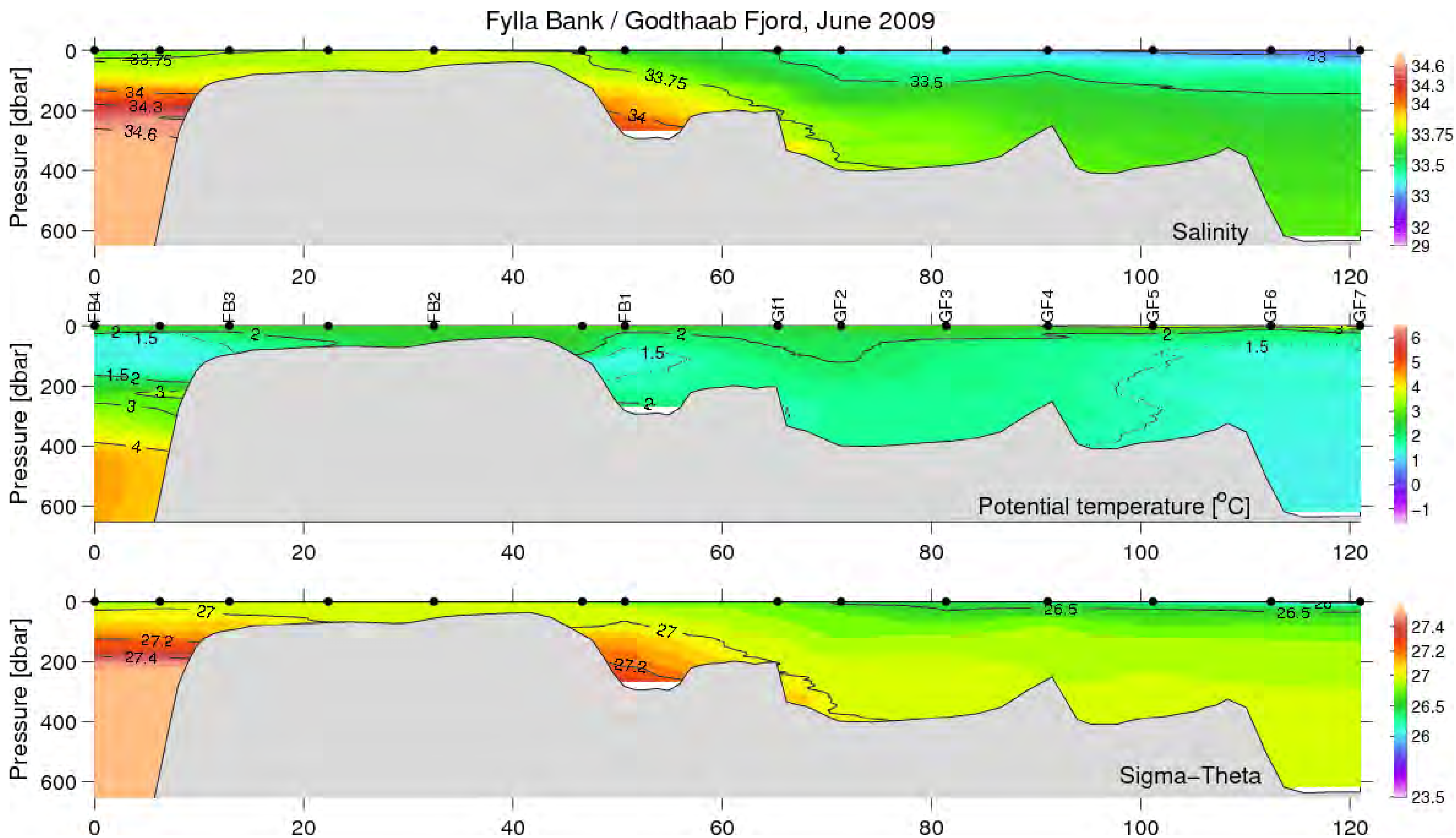

Figure 40. Vertical distribution of temperature, salinity and density at the Godthaab fjord section, June 13–14, 2009. Fylla Bank section left (as in Figure 28).

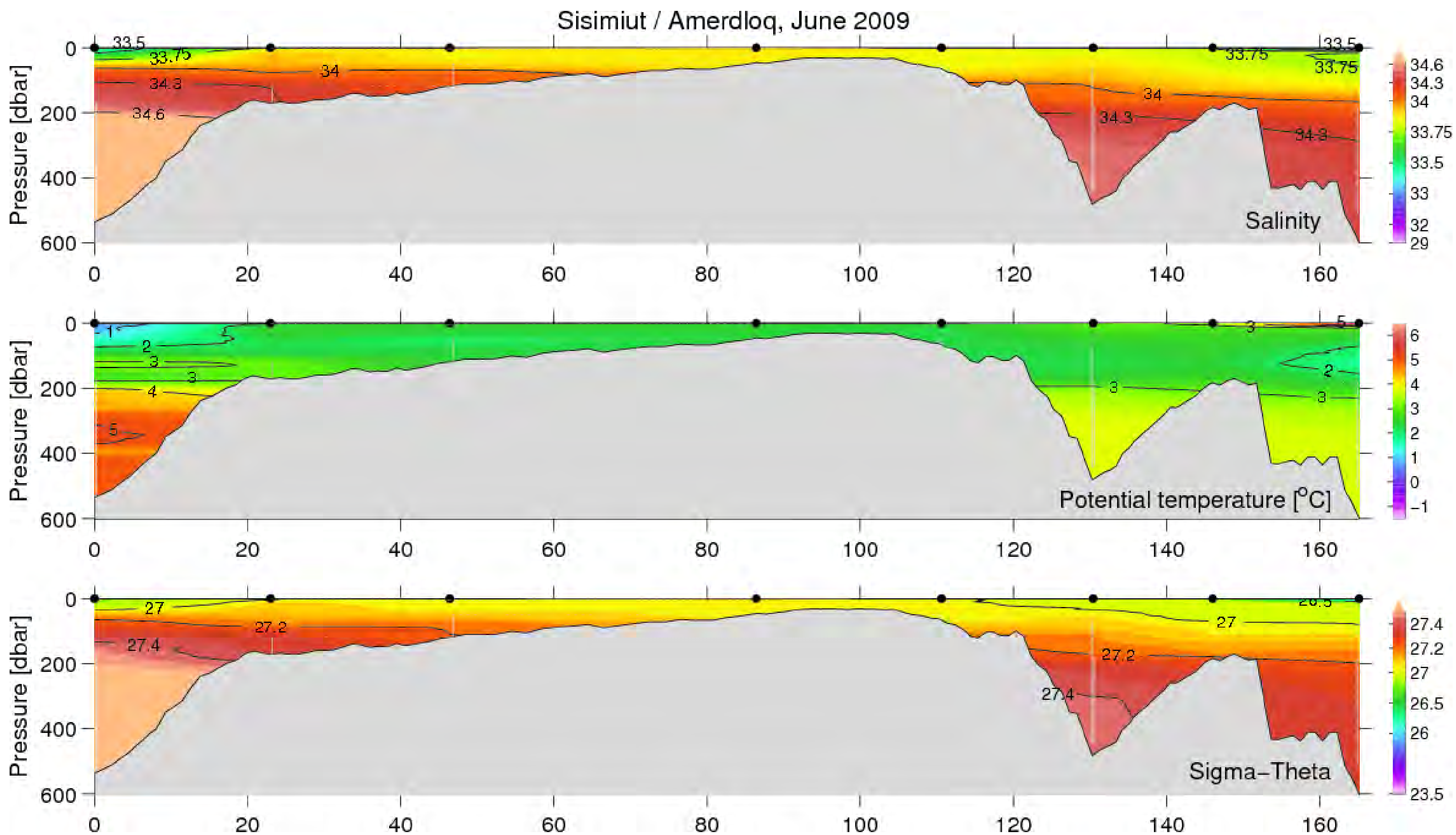

Figure 41. Vertical distribution of temperature, salinity and density at the Amerdloq fjord, June 11, 2009. Sisimiut section left (identical to Figure 30).

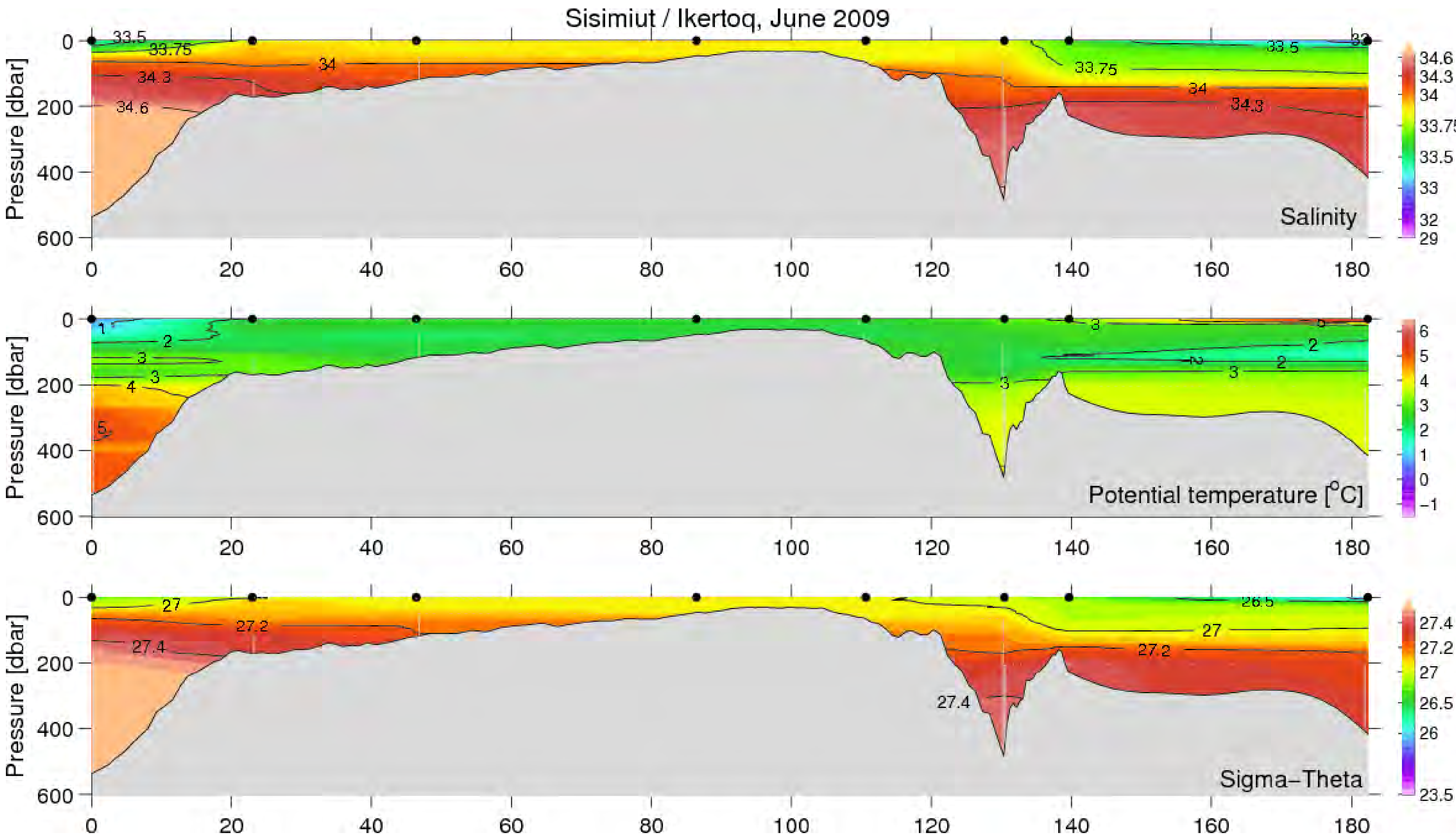

Figure 42**.** Vertical distribution of temperature, salinity and density at the Ikertoq fjord, June 11, 2009. Sisimiut section left (identical to Figure 30).

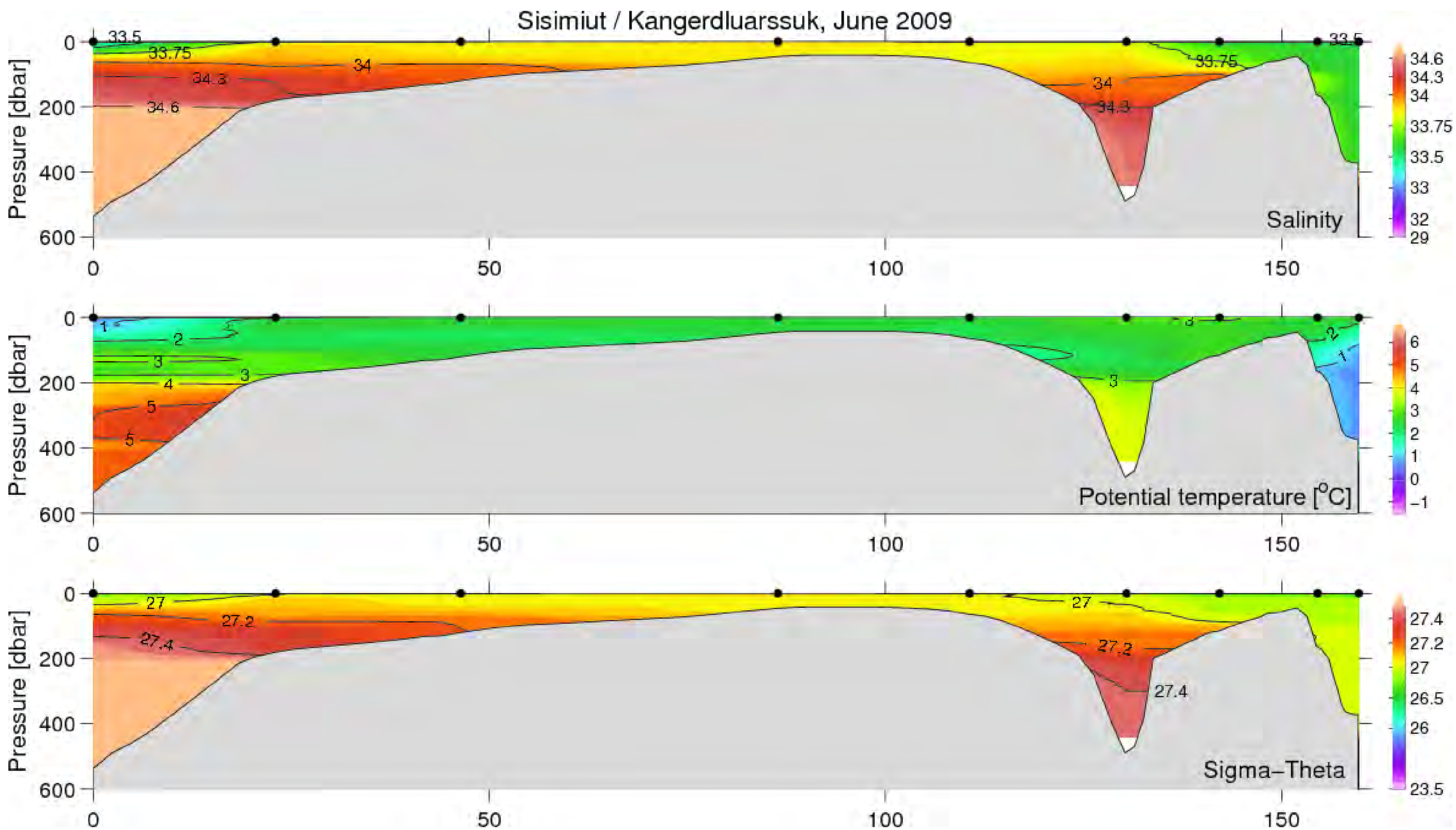

Figure 43**.** Vertical distribution of temperature, salinity and density at the Kangerdluarssuk fjord, June 11–12, 2009. Sisimiut section left (identical to Figure 30)

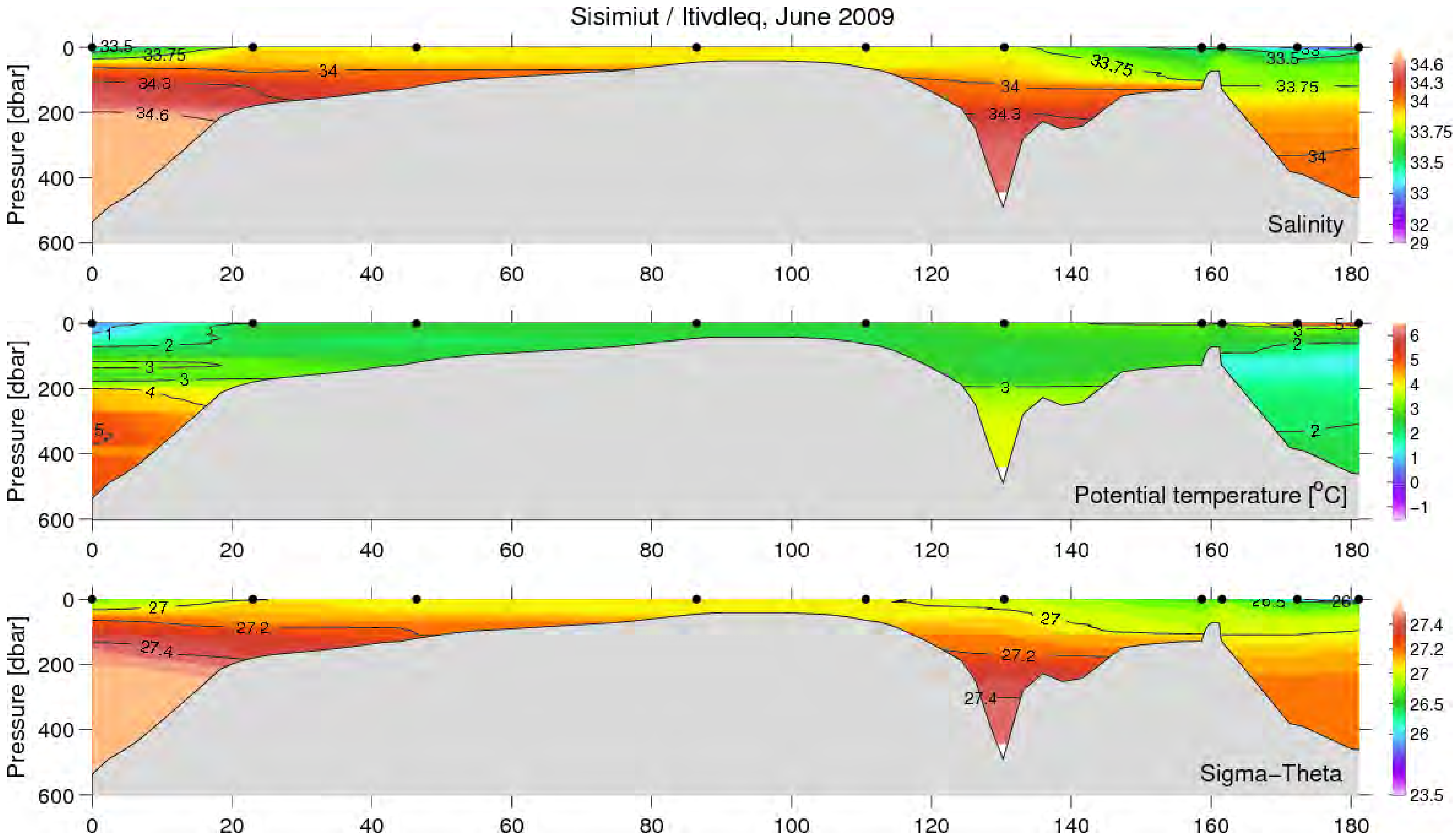

Figure 44**.** Vertical distribution of temperature, salinity and density at the Itivdleq fjord, June 11–12, 2009. Sisimiut section left (identical to Figure 30).

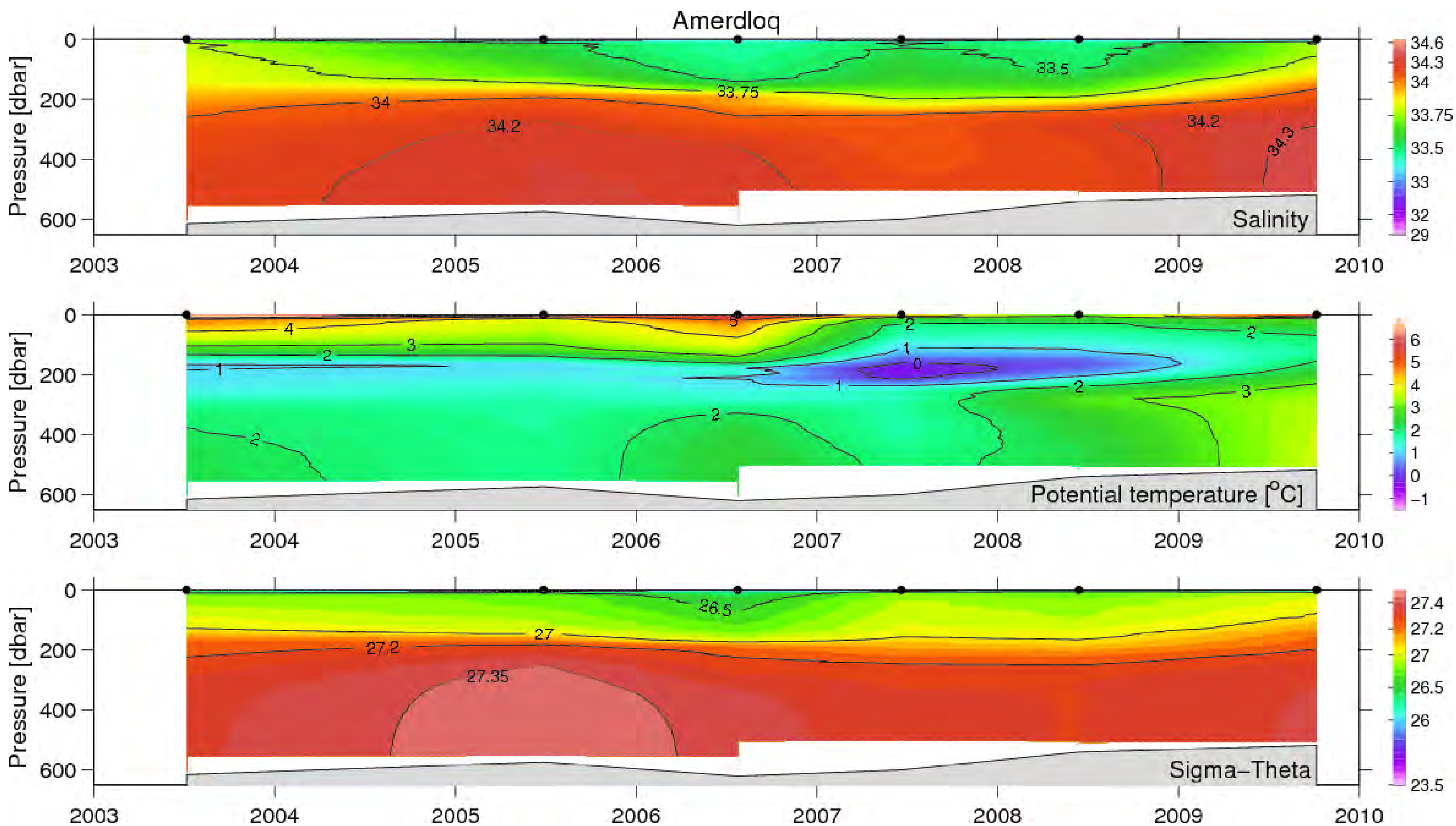

Figure 45. Hovmöller diagram of vertical distribution of temperature, salinity and density at the Amerdloq fjord st.4, late June/July 2003, 2005–2009.

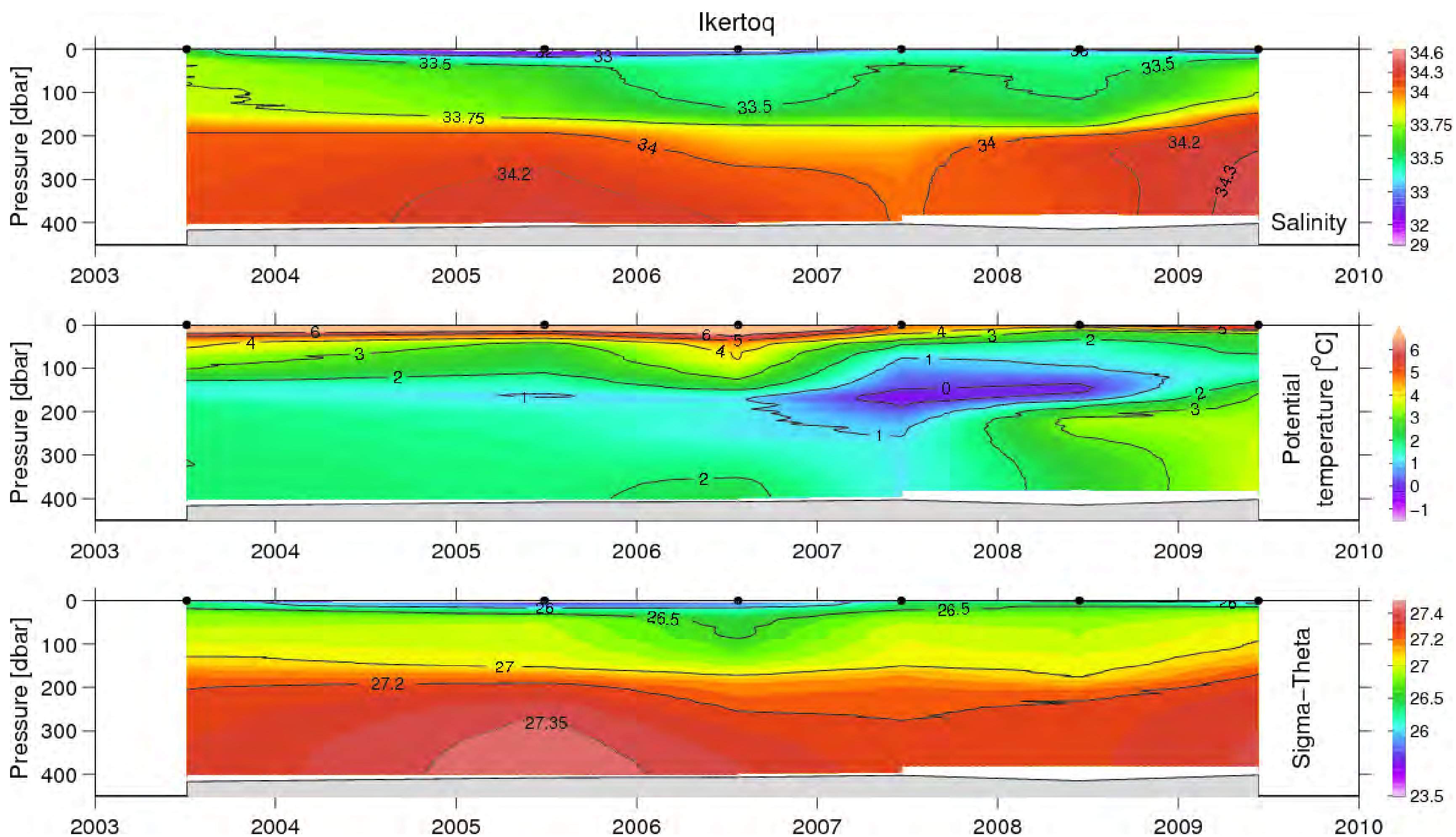

Figure 46. Hovmöller diagram of vertical distribution of temperature, salinity and density at the Ikertoq fjord st.4, late June/July 2003, 2005–2009.

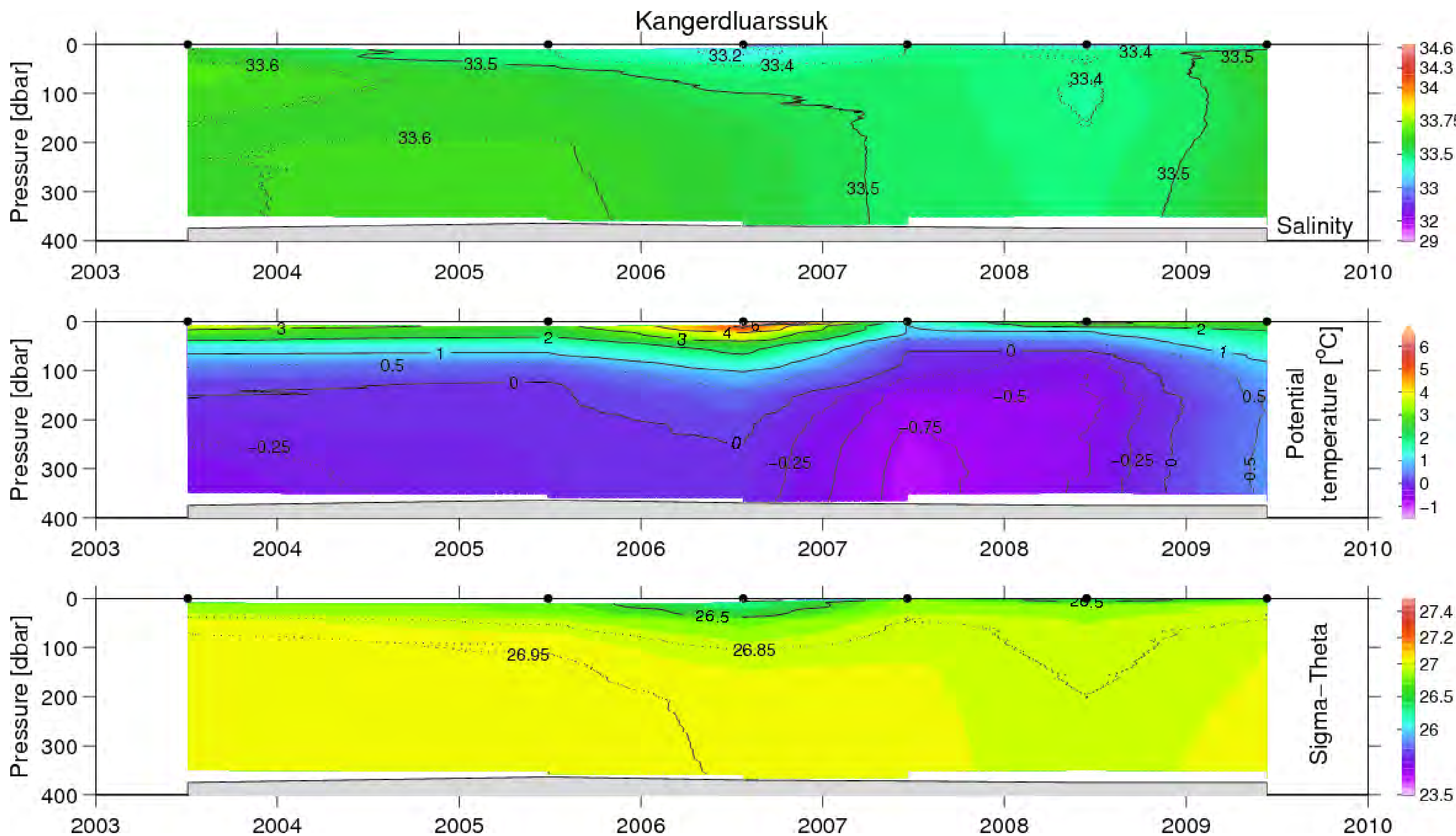

Figure 47. Hovmöller diagram of vertical distribution of temperature, salinity and density at the Kangerdluarssuk fjord st.3, late June/July 2003, 2005–2009.

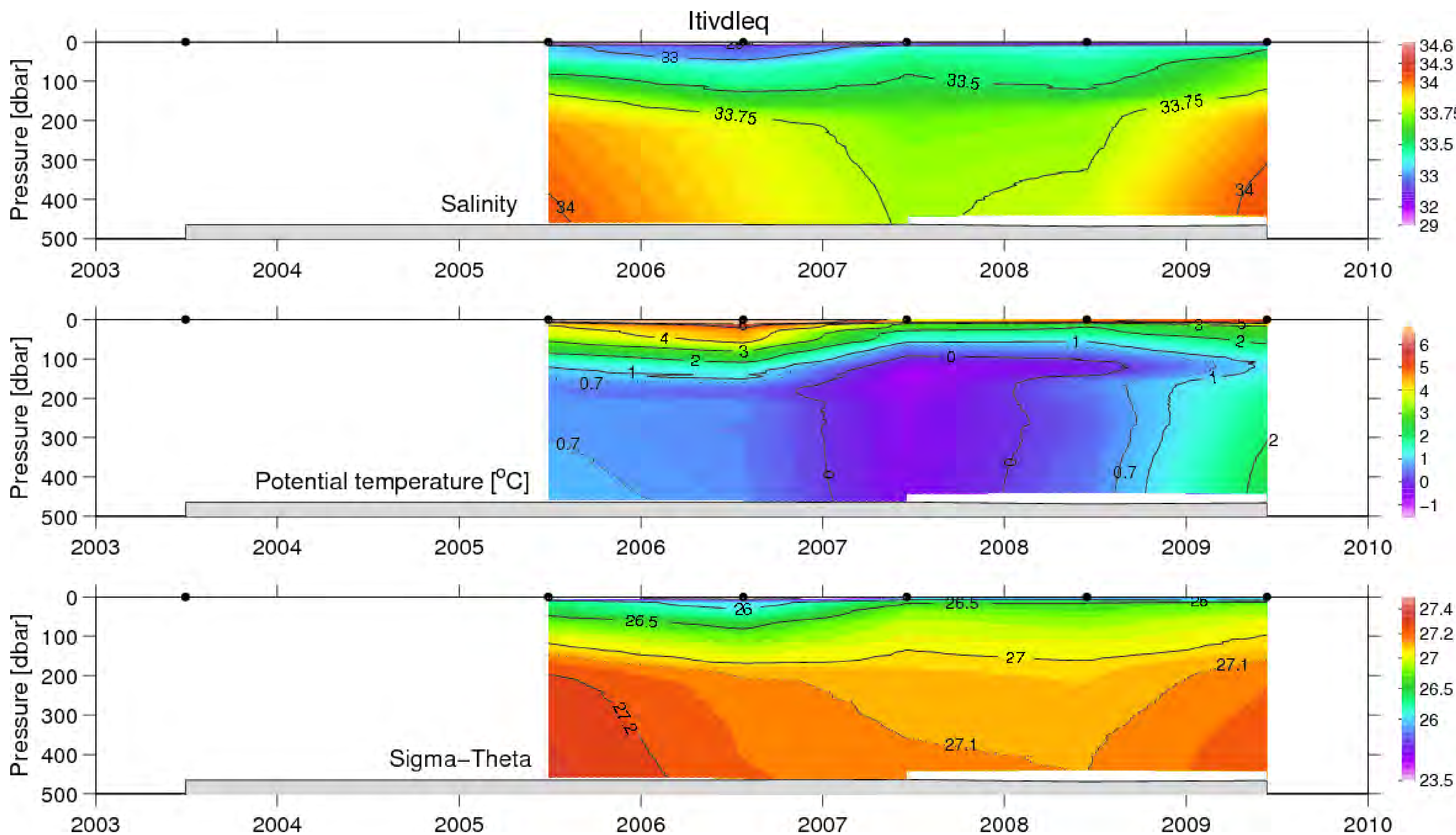

Figure 48. Hovmöller diagram of vertical distribution of temperature, salinity and density at the Itivdleq fjord st.4, late June/July 2005–2009.