Oceanographic Investigations off West Greenland 2007

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Abstract

The regional hydrography in summer 2007 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 four Southwest Greenland fjords are presented.

In 2007, the winter North Atlantic Oscillation (NAO) index was positive describing anomalous strong westerlies over the North Atlantic Ocean.

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 and salinities on top of Fylla Bank show only slightly above average conditions indicating a normalization relative to the recent extreme warming.

The presence of Irminger Water in the West Greenland waters were above normal in 2007. Pure Irminger Water was observed at the sections off Cape Farewell and Cape Desolation, and Modified Irminger Water could be traced north to the Maniitsoq section. The Irminger water (water of Atlantic origin) was warmer than normal, but their salinities were just above normal. The mean (400–600 m) salinity west of Fylla Bank (st.4) was only slightly above normal while the temperature was 0.4°C above normal. However, mean temperatures and salinities for the same depth interval for Maniitsoq and Sisimiut were among the highest observed consistent with the large scale settings in the Subpolar North Atlantic (Holliday et al. 2008).

As for the Irminger Water, the presence of Polar Water are also slightly above normal in 2007. The extension of multi-year-ice (“Storis”) encountered during the survey was about normal. West of Fylla Bank a clear cold Polar Water core was observed, which had about normal temperature and salinity, but further north west of “Sukkertop Banke” and “Store Hellefiskebanke” the surface temperatures was colder than normal.

1. Introduction to the west Greenland oceanography

This report describe the hydrographic conditions in West Greenland Waters in 2007 from Cape Farewell 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.

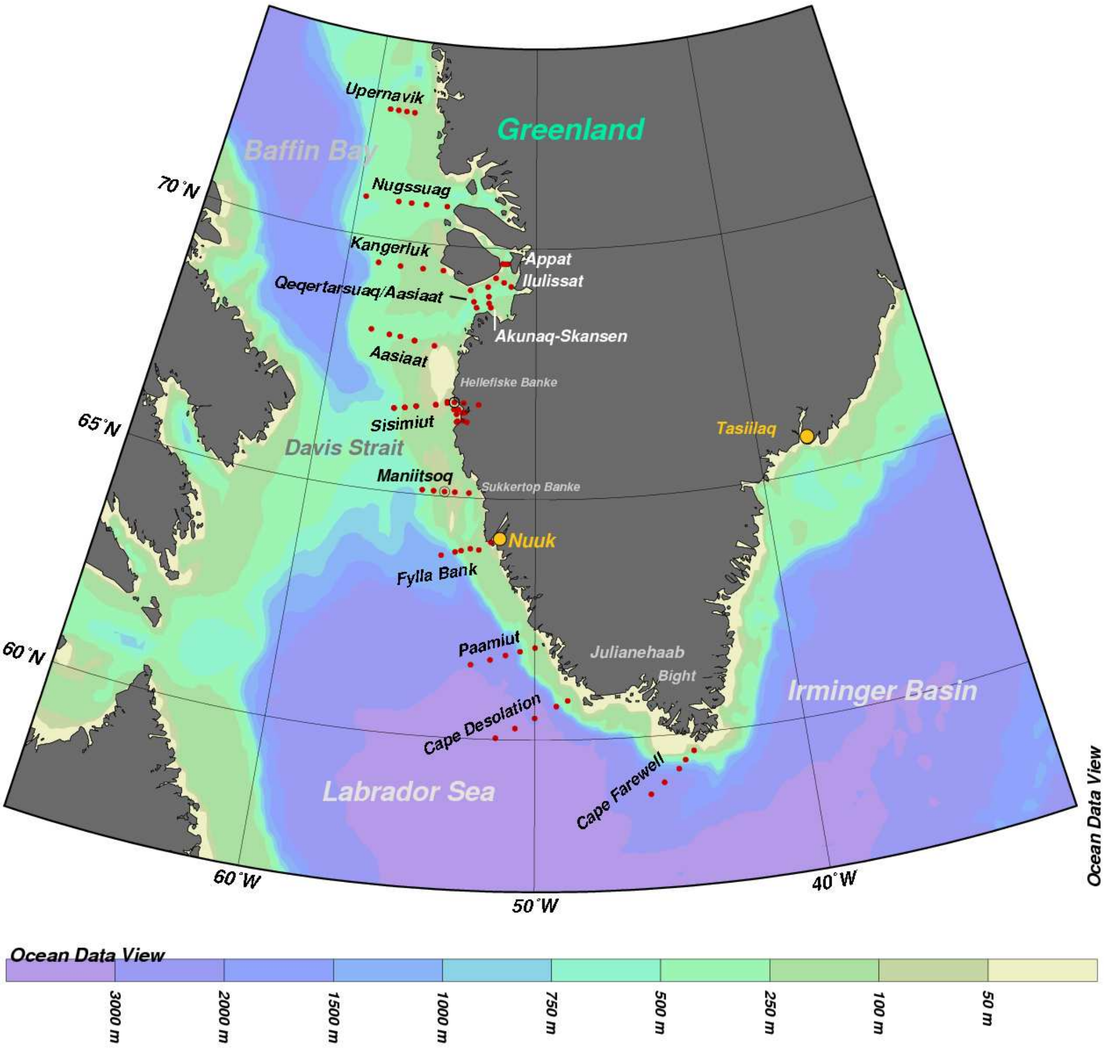


Figure 1. Position of the oceanographic sections off West Greenland where measurements were preformed in 2007. The fjord sections at Sisimiut, but part of the sections was measured in 2007 (see Figure 4). Contours shown for water depths in colours. Map produced using Ocean Data View (Schlitzer, 2007).

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.

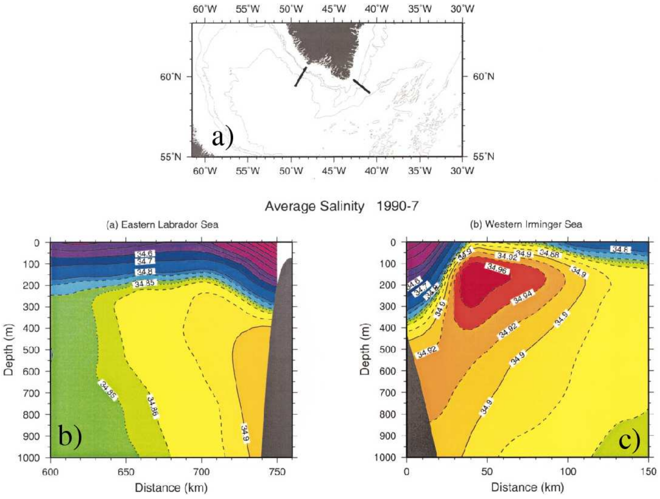


Figure 2. Mean upper-layer salinity sections for the period 1990–1997. a) Location of the two sections. Isobaths shown: 1000, 2000 and 3000 m. b) Eastern Labrador Basin. c) Western Irminger Basin. From Pickart et al. (2002).

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.

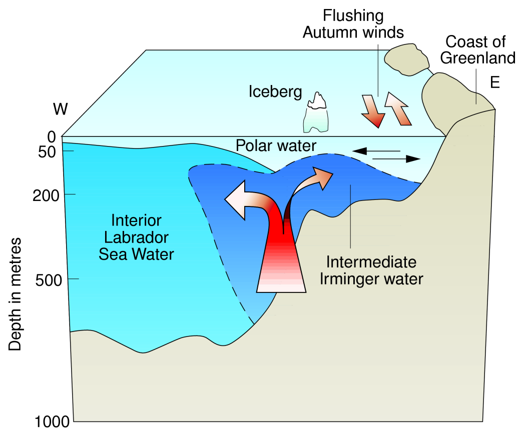


Figure 3. Sketch of the water masses off West Greenland in the Davis Strait region. From Valeur et al. (1997).

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.

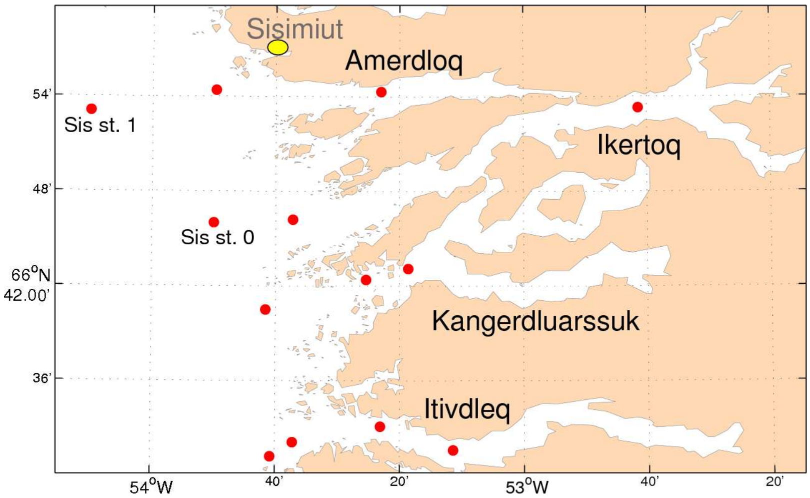


Figure 4. Position of the oceanographic stations around Sisimiut where measurements were preformed in 2007. See Figure 1 for position of all sections measured in 2007.

2. Measurements

The 2007 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 09–20, 2007 onboard the Danish naval ship “AGDLEK”**.** Observations were carried out on the following standard stations (Figure 1):

Offshore Labrador Sea/Davis Strait:

- Cape Farewell St. 1–5
- Cape Desolation St. 1–5
- Paamiut St. 1–5
- Fylla Bank St. 1–5
- Maniitsoq St. 1–5
- Sisimiut 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

Additional, Nuuk fjord st.3 (“hovedstationen”) was measured.

On each station the vertical distributions of temperature and salinity was measured from surface to bottom, except on stations with depths greater than 750 m, where approximately 750 m was the maximum depth of observation.

Multi-year-ice (”Storis”) was presence on the innermost stations to the south and “Vestice” (first-year ice) was meet on the outermost station on the Sisimiut section (Figure 5). Nevertheless, all planned stations was occupied, expect Cape Farewell st.1, which was taken off position, but as close as one third of a kilometer.

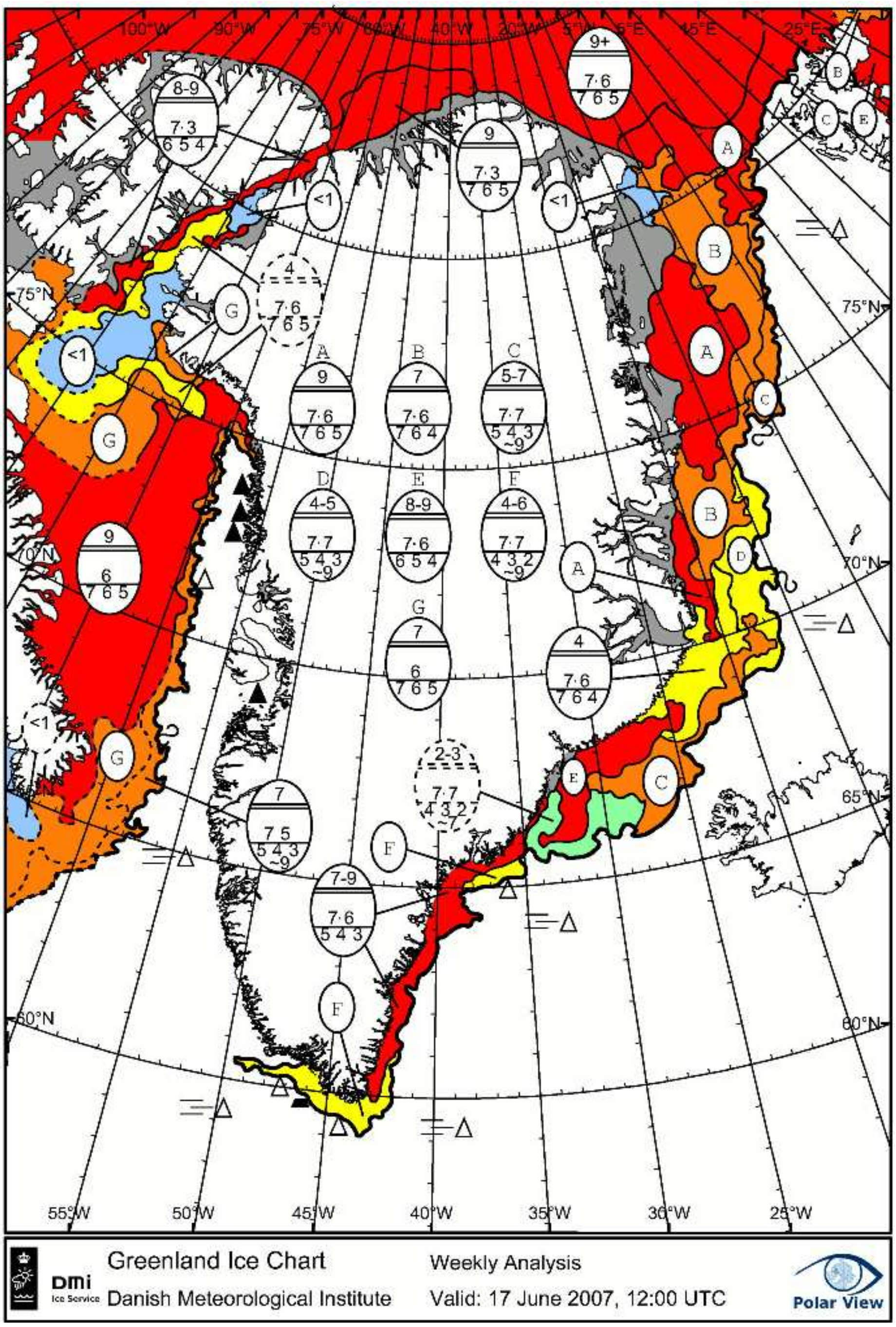


Figure 5. Distribution of sea ice in Greenland Waters valid for 17. June 2007.

During the period July 4–23, 2007 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 St. 1-5
- Aasiaat (Egedesminde) St. 1–6
- Kangerluk (Disko fjord) St. 1–4
- Nugssuag St. 1–5
- Upernavik St. 1–5

Disko Bay:

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

3. Data handling

Measurements of the vertical distribution of temperature and salinity were carried out using a SEABIRD SBE 9-01 CTD. 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 data was uploaded using term17 in SEASOFT version 4.249 (for DOS) also provided by SEABIRD.

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

4. Timeseries

4.1. Top of Fylla Bank (st.2)

The classic West Greenland timeseries of temperature and salinity on top of Fylla Bank (st.2, 0−40m) in the middle of June are extended using a surface temperature climatology initiated by Ryder (1917) from 1875, and maintained by Smed (1978) until 1975. The time series are shown in Figure 15 and statistics in Table 1. Smed used data available within a large square region southwest of Greenland (area A1: 50−60°W, 60−70°N) to estimate monthly means. An earlier study by Buch and Hansen (1988) presented these timeseries together, but they used 5-year running mean for the two series, and did not attempt to merge them.

Despite the averaging method used by Smed covering a much larger area than the single point Fylla Bank st.2., the overlapping period (1950−1975) shows, that the Smed data from June seem to be representative for Fylla Bank st. 2 (0−40 m) temperature. The correlation coefficient is significant with r=0.70 for the de-trended overlapping period. The Fylla Bank st.2 climatology is offset by +1.3277°C relative to mean of Smed's series for the overlapping period. The series are merged by adding this offset to the full Smed's series. The "real" offset was not found in the old literature. However, the value of this value is not that important, as the Smed data is now “calibrated” towards the Fylla Bank st. 2 time series.

The temperature generally increase during spring. To compensate for difference in between years, the Fylla Bank st.2 temperatures measured in July are subtracted 1°C, which is approximately the mean difference in all temperatures in June and July. A linear regression on the data gives a slope of 0.032±0.014°C/day corresponding to roughly 1.0±0.4°C/month (Figure 6), but the data are quite scattered. We could have used this information to correct using the exact day of year, but we choose to stick to the simpler solution which have been used historically. We note, that the monthly slope is similar in amplitude as the standard division, but about a factor of 3 lower than the total temperature range for the time series. The salinity generally decreases marginally from June to July. The slope of a linear regression is -0.014±0.006 day^{-1} corresponding to about -0.4±0.2 per month (Figure 7). This is of the same order as the standard division (Table 1), but more than 3 times lower than the total salinity range of the time series. The latter stems from the Great Salinity Anomaly in the late 1960s. We choose not to correct the salinity.

Due to the temperature correction, the timeserie are valid for mid-June.

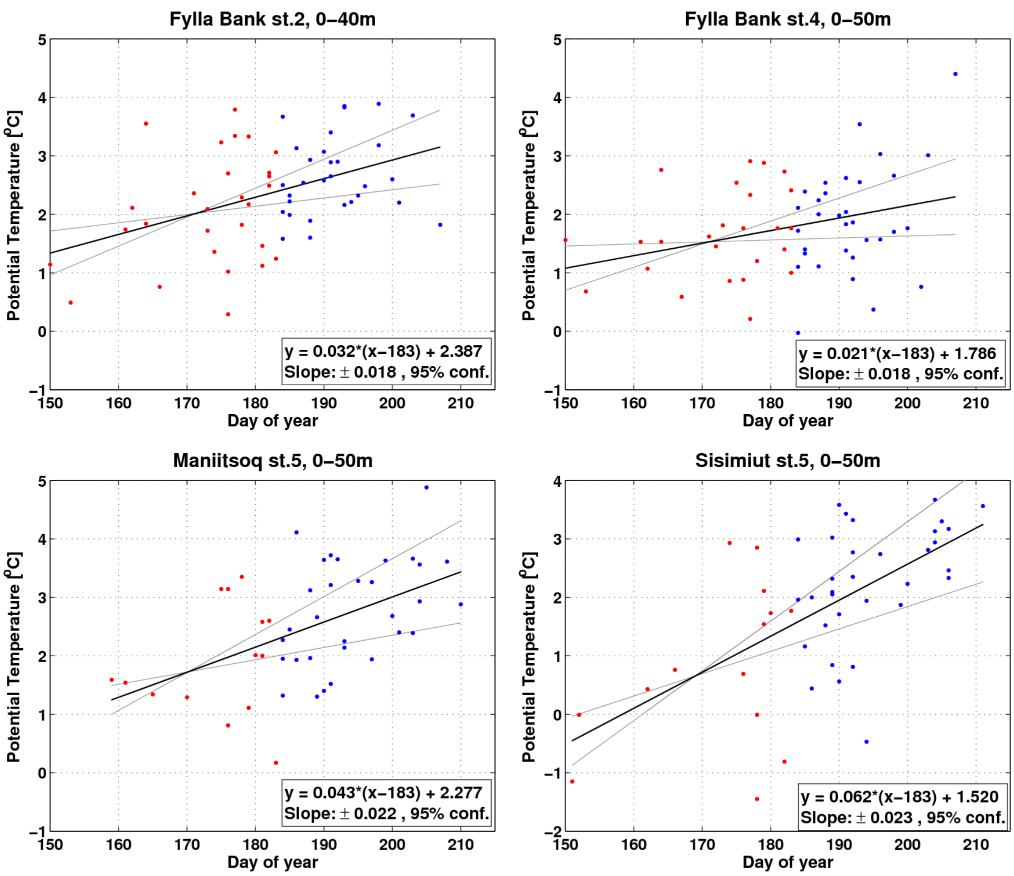


Figure 6. Scatterplot of surface mixed layer temperature as a function of “day of year”. Black line: Linear regression line. Grey lines: 95% confidence interval for slope. Red/blue points: before/after day 183.

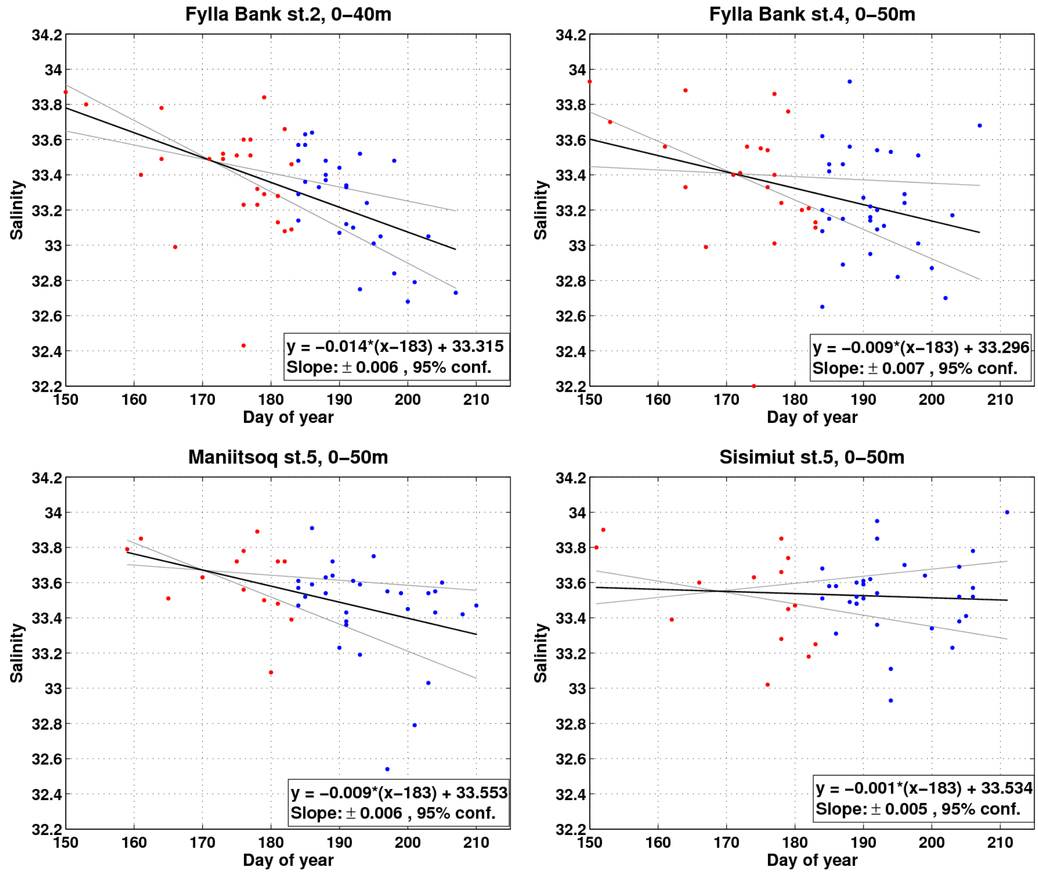


Figure 7. Scatterplot of surface mixed layer salinity as a function of "day of year". Black line: Linear regression line. Grey lines: 95% confidence interval for slope. Red/blue points: before/after day 183.

4.2. Timeseries west of fishing banks: Fylla Bank, Maniitsoq and Sisimiut sections

Timeseries are presented of June-July temperature and salinity averaged in 4 different depth intervals west of Fylla Bank (Fylla bank st.4), "Sukkertoppen Banke" (Maniitsoq st.5) and "Store Hellefiskebanke" (Sisimiut st.5). The timeseries are shown in Figure 18, Figure 20 and Figure 21 and the corresponding statistics summarized in Table 2, Table 3 and Table 4. The stations used are all on the continental slope, where currents are expected to be intense and watermasses at depth showing minimal dilution.

The depth intervals represent different characteristica of the water column: surface mixed layer (0–50 m), the core of the Polar Water (50–150 m), the core of the Irminger Water (400–600 m). In contrast, waters in the interval 150–400 m do not represent any specific watermass but encompass the interface between the Polar Water and the Irminger Water. Consequently, variability in this layer can be related to both interface changes and to changes in the properties of the pure watermasses and this time-series is mainly shown for completeness.

The time-series are updated from Buch (2002) using quality checked data from the ICES database. In Buch (2002) Maniitsoq st.5 and Sisimiut st.5 covered the years 1970–2000 and Fylla Bank from early 1950s to 2000. Data are preferable as close as possible to mid-June, but are taken from late May to July. A regression analysis has been done, but only at the surface mixed layer (0–50 m) significant slopes are found for temperature and salinity (Figure 6 and Figure 7). However, we choose not to correct any of the data with regards to time of the year.

For Fylla Bank st.4 (0−50m) the data are very scattered with a slope is about 0.6±0.5°C/month for temperature and -0.27±0.21 month^{-1} for salinity. These monthly slopes are lower than the standard divisions (Table 2) and much lower than the bounds of the data.

For Maniitsoq st.5 (0−50m) the slopes are 1.3±0.7°C/month and -0.3±0.2 month^{-1} for temperature and salinity. The monthly temperature slope is slightly higher than the standard deviation (Table 3), whereas the monthly salinity slope is lower and more scattered (uncertain). For Sisimiut st.5 (0−50 m) the slopes are 1.8±0.7°C/month for temperature and 0.0±0.2 month^{-1} for salinity. The monthly temperature slope is slightly higher than the standard deviation (Table 4), whereas (almost) no trend is found for salinity.

We choose not to correct the surface temperatures (0−50 m) on these stations, though you could argue to do so – especially for Maniitsoq and Sisimiut. Therefore, conclusions drawn form the surface should be taken with caution.

However, below 50 m we did not find any significant slopes and those found were well below the standard deviation. Thereby we can rule out, that changes in between years are due to the timing of observation on these timeseries.

5. Atmospheric conditions in 2007

The North Atlantic marine climate is to some extend controlled by the so-called North Atlantic Oscillation (NAO), which is 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 2006/2007 was positive[1] (Figure 2) and among the 10% highest observed in the past 143 years. The Icelandic Low was during the winter months (December–Marts) centred south of Greenland over the Irminger Sea and Labrador Sea south of Greenland (Figure 9), which correspond to a slightly displacement towards the Labrador Sea (Figure 10). Both the Icelandic Low and the Azores High was strengthen (Figure 10) resulting in an increased pressure difference over the North Atlantic sector than normal.

The pressure difference has the effect that the westerlies over the North Atlantic Ocean south of the Nova Scotia/Great Britain line was strengthened with anomalous[2] winds towards west (Figure 12). Over the East Greenland shelf, especially between Jan Mayen and Greenland, the mean wind direction was towards south (Figure 11). South of Iceland the wind anomaly was slightly deflected towards Greenland. Over the Labrador/Davis Strait area, the wind anomaly was normal, i.e. not strengthened/intensified winds from Canada onto the ocean, due to the displacement of the Icelandic low towards the Labrador Sea. Instead, the increased land-to-sea wind anomalies were displaced southward from Nova Scotia.

[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.

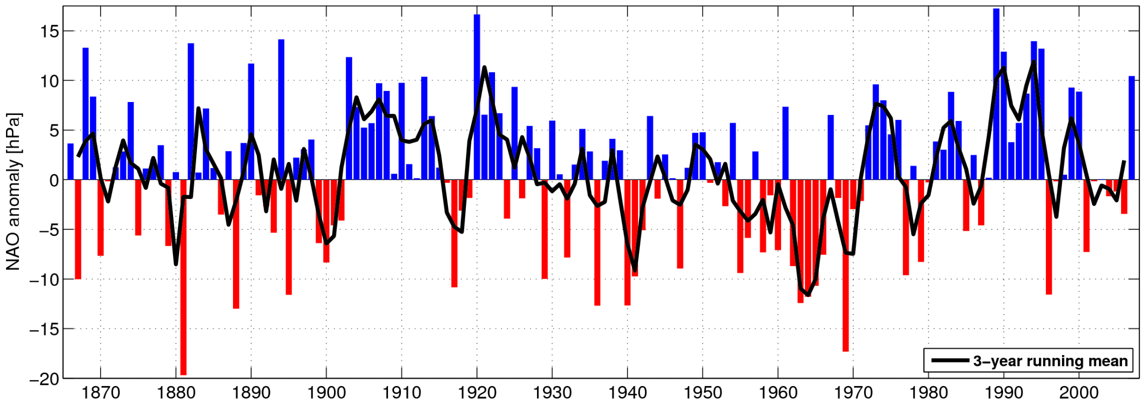


Figure 8. Time series of winter (December–March) index of the NAO from 1865/1866–2006/2007. The heavy solid line represents the NAO index smoothed with a 3-year running mean filter to remove fluctuations with periods less than 3 years. In the figure the winter 1865/1866 is labelled 1866 etc.. The mean and standard deviation is 0.8 ± 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. However, as can be seen from Figure 13 the annual mean air temperature for 2007 in Nuuk[3] was -0.62°C which is about 1°C above average, despite of a positive NAO index. The explanation is likely due to the displacement of the Icelandic Low towards Labrador Sea combined with general higher temperatures in the North Atlantic during the last years (Holiday et al., 2008). The mean annual air temperature for 2007 was above normal for almost the entire North Atlantic region with anomalies above 1°C West of Greenland and even above 2°C over the Davis Strait region (Figure 14).

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. However, in 2007 the mean temperature (1.84ºC) and salinity (33.49) on top of Fylla Bank in the middle of June was close to normal conditions (Figure 15 and Table 1), despite air temperatures in Nuuk and Tasiilaq are way above normal (Figure 13).

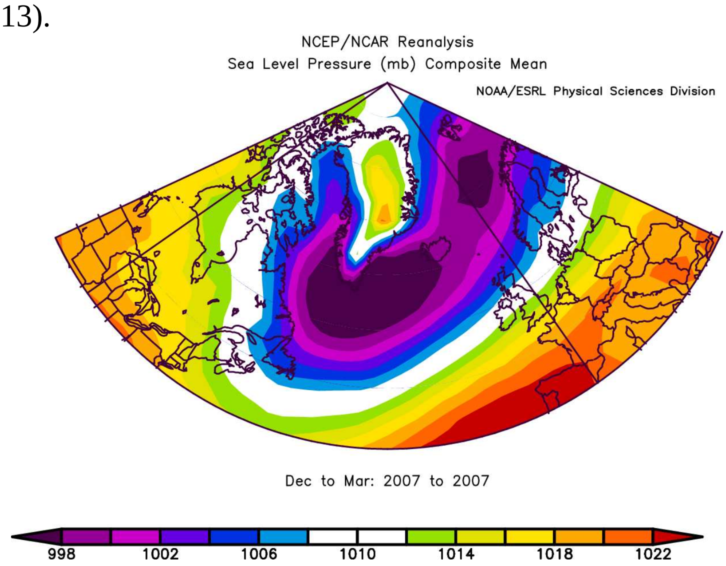


Figure 9. Winter (DJFM) sea level pressure for 2006/2007 in the North Atlantic region. NCEP/NCAR re-analysis (from http://www.cdc.noaa.gov).

[3] Nuuk temperature for October was taken from the Nuuk airport synop station 04254 due to failure on the instrument on synop station 04250 (Nuuk)..

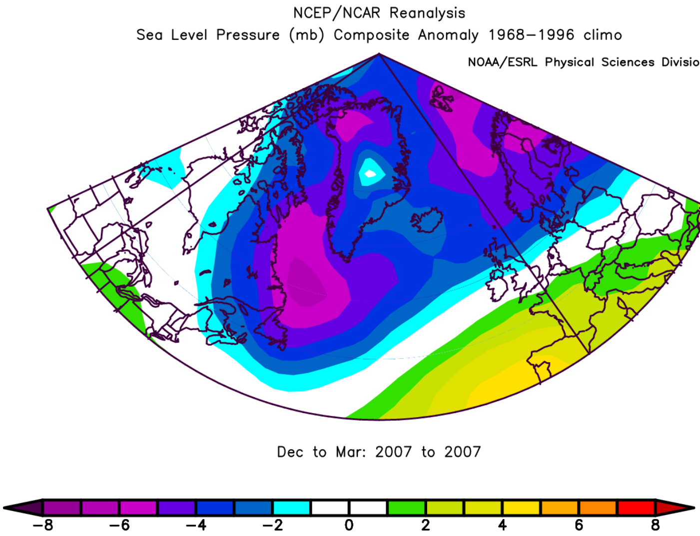


Figure 10. Winter (DJFM) sea level pressure anomaly for 2006/2007 in the North Atlantic region. NCEP/NCAR re-analysis (from http://www.cdc.noaa.gov).

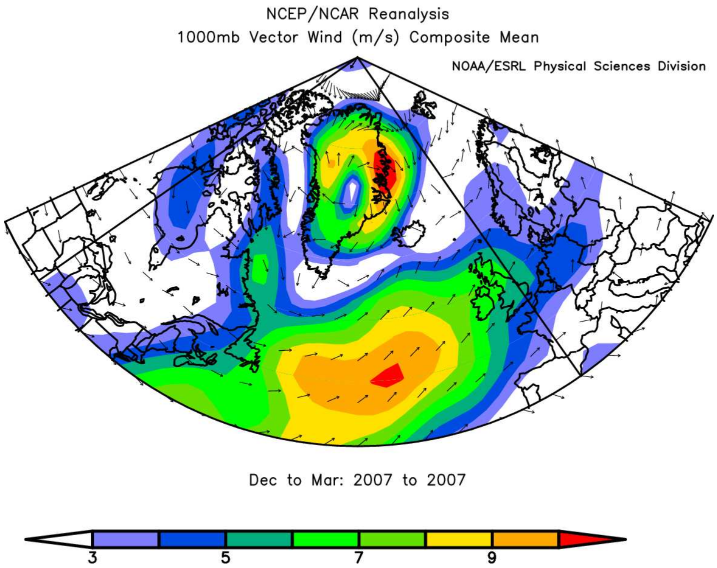


Figure 11. Winter (DJFM) wind for 2006/2007 in the North Atlantic region. NCEP/NCAR re-analysis (from http://www.cdc.noaa.gov).

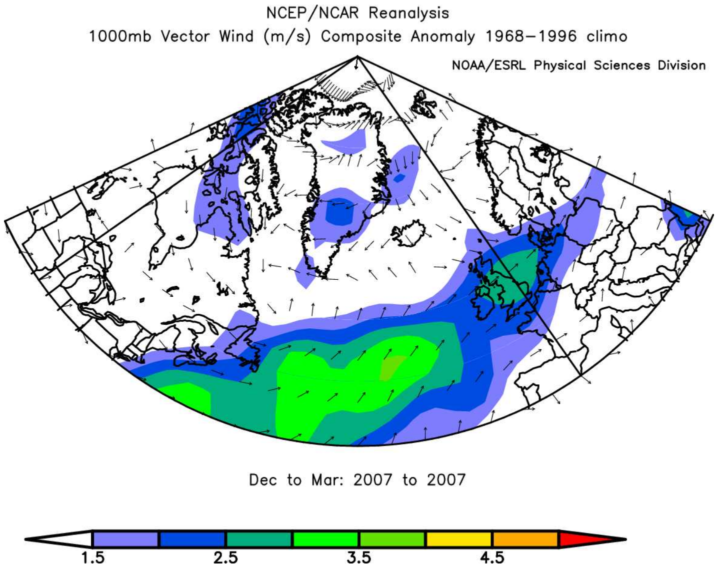


Figure 12. Winter (DJFM) wind anomaly for 2006/2007 in the North Atlantic region. NCEP/NCAR re-analysis (from http://www.cdc.noaa.gov).

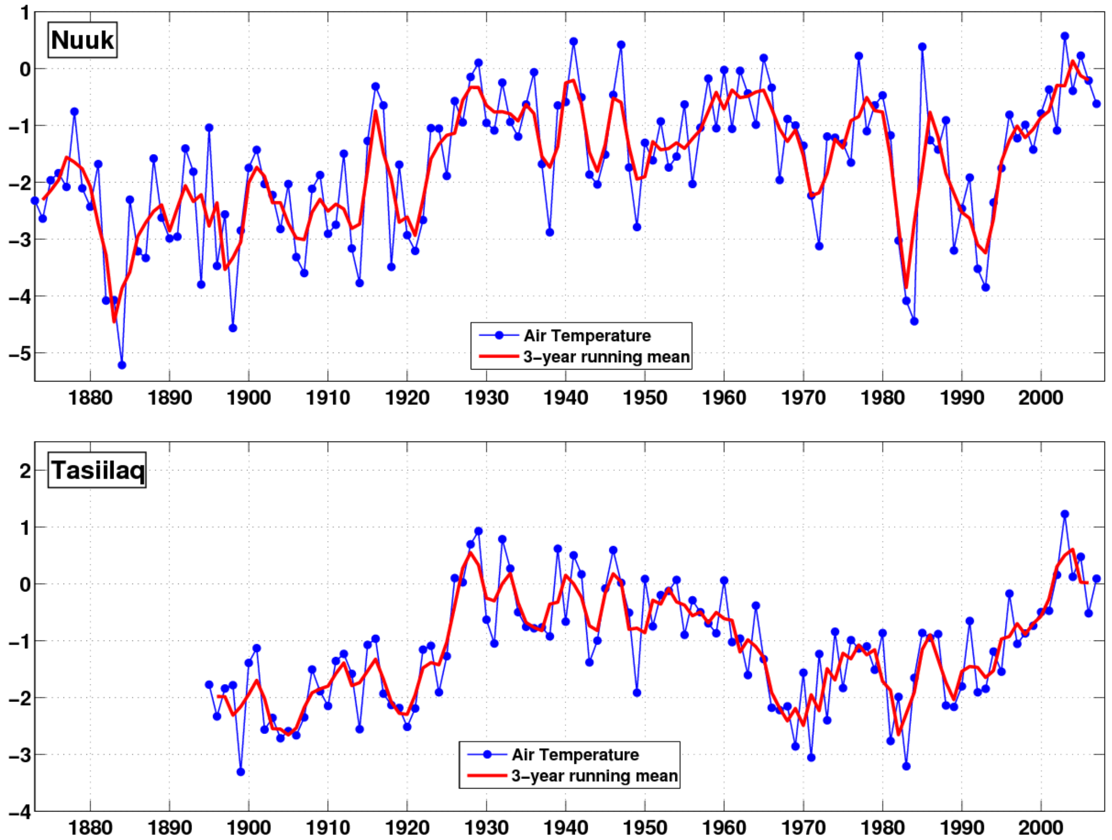


Figure 13. Annual mean air temperature observed at Nuuk and Tasiilaq for the period 1873–2007. The mean and standard deviation is -1.68 ± 1.21 °C for Nuuk and -1.14 ± 0.99 °C for Tasiilaq. Nuuk temperature for October 2007 was taken from the Nuuk airport synop station 04254 due to a failure on the instrument (synop 04250).

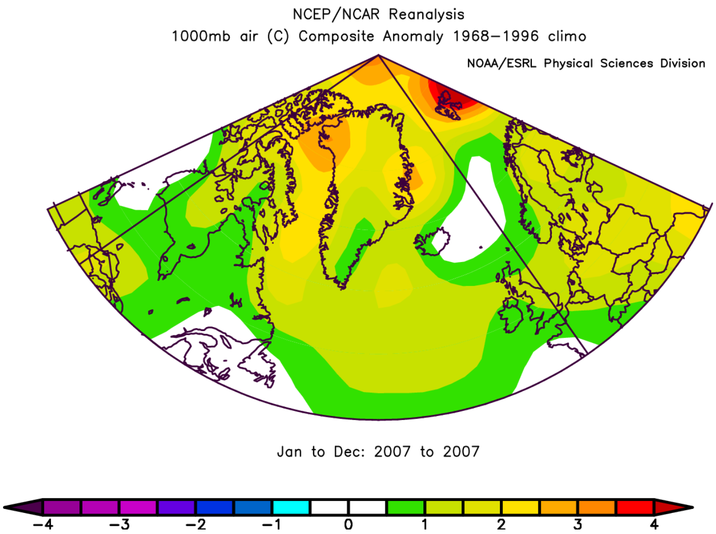
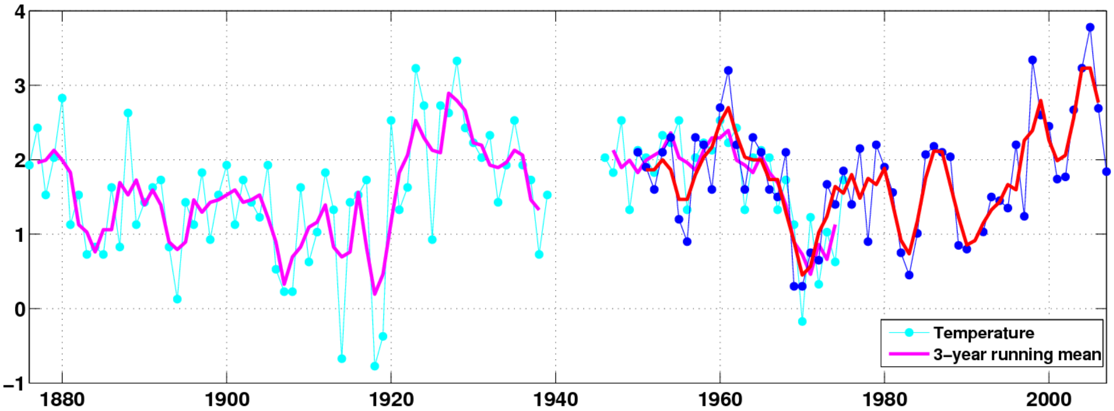


Figure 14. Anomalies of the mean air temperature for 2007 in the North Atlantic region. NCEP/NCAR re-analysis (from http://www.cdc.noaa.gov).

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 not included for the statistics.

Fylla Bank St. 2	Temperature [°C] Mean ± std	Salinity Mean ± std	2007 Tpot	2007 S
0–40 m	1.78 ± 0.76°C	33.41 ± 0.25	1.84°C	33.49



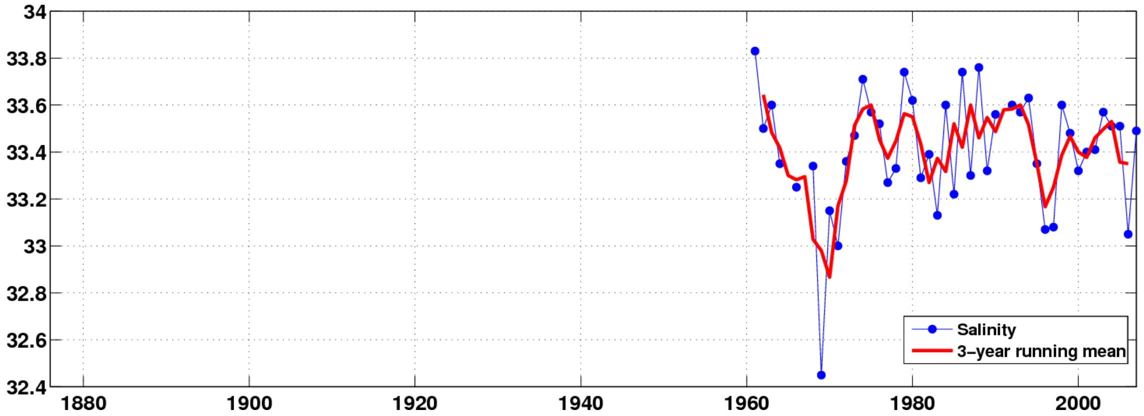


Figure 15. Timeseries of mean temperature (top) and mean salinity (bottom) on top of Fylla Bank (0–40 m) in the middle of June for the period 1950–2007. The red curve is the 3 year running mean value. Statistics is shown in Table 1. The timeseries for temperature (top, magenta/purple) is extended back to 1875 using Smed-data for area A1 (see chapter 4.1. for details).

6. Oceanographic conditions off West Greenland in 2007

The surface temperatures and salinities observed during the 2007 cruise are shown in Figure 16. The cold and low salinity conditions observed close to the coast off Southwest Greenland reflect the inflow of Polar Water carried to the area by the East Greenland Current. Water of Atlantic origin (T>3^{o}C; S>34.5) is normally found at the surface at the three outermost stations on the Cape Farewell and Cape Desolation sections (Figure 24 and Figure 25). This year this water was found just below a thin surface layer (compare Figure 16 and Figure 17), but not as pronounced as last year (Ribergaard, 2007). The relative low salinities are caused by a thin layer of Polar Water that was spread out towards the interior of the Labrador Sea and heavily mixed from below by waters of Atlantic origin. This thin layer was heated by solar insolation and possibly also from below by the warmer waters of Atlantic origin.

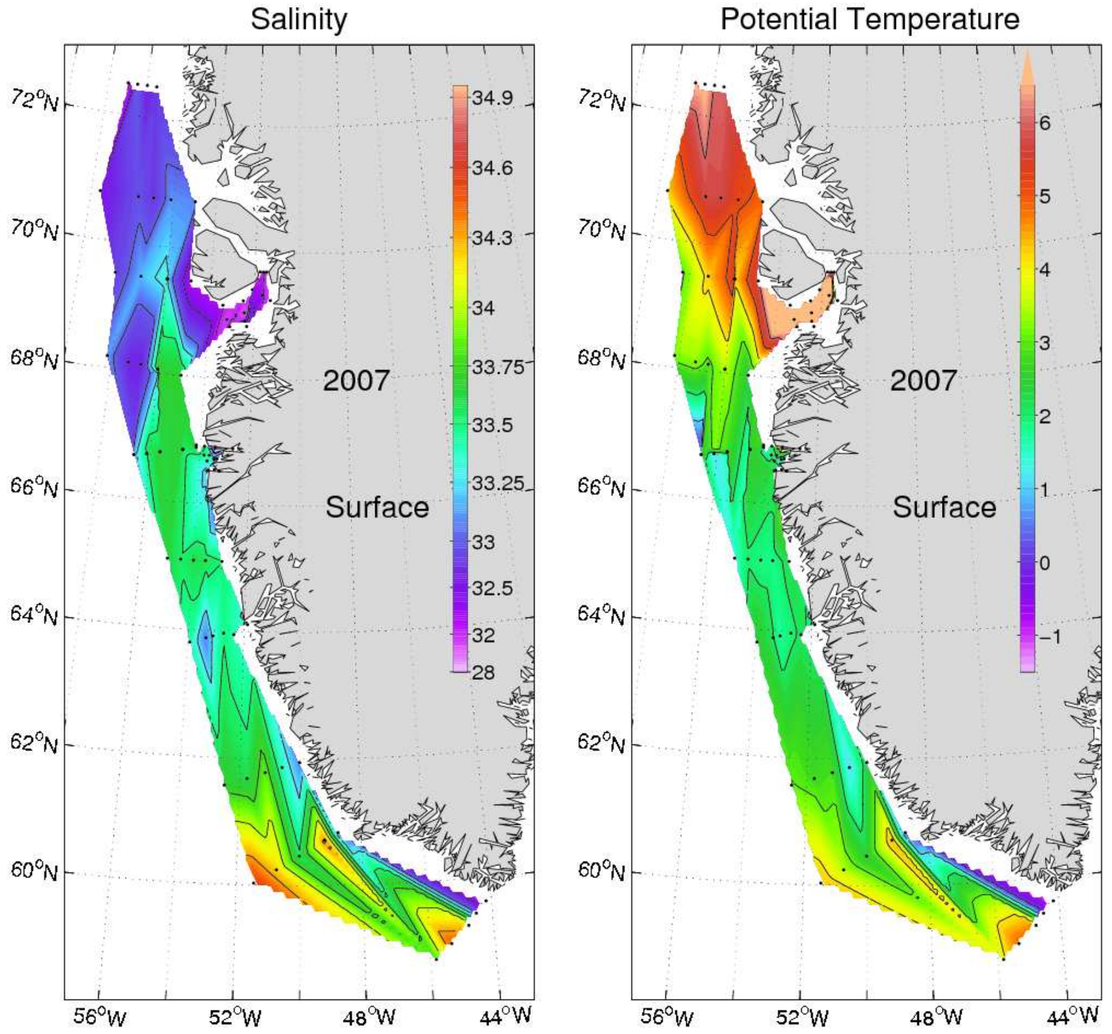


Figure 16. Salinity (left) and temperature (right) observed in 2007 at the surface (mostly 2–6 m). The data are all from June (south of Sisimiut) and July (north of Sisimiut).

In the Baffin Bay the low surface salinities, generally below 33, originate from the large outlet glaciers but also from melting of sea-ice during summer. Salinities of about 33.5–34 reflect the core of the West Greenland Current, which is slightly modified by Atlantic Water. The warm surface waters in and around the Disko Bay was caused by solar heating of the 20–30 m thin low-saline surface layer. Therefore it is not seen at 34 m, but only at the surface. The cold waters <0°C observed offshore in the subsurface of the Baffin Bay (Figure 17) is the top of the layer of previous winter convected waters. Above (Figure 16), a thin low-saline surface layer is found formed by melting of sea-ice. This layer is heated due to solar radiation.

A vertical section of salinity, temperature and density over the shelf break from Cape Farewell to Sisimiut is shown in Figure 22 and over the shelf in Figure 23. The vertical distribution of temperature, salinity and density at sections along the West Greenland coastline is shown in Figure 24 – Figure 34 and within the Disko Bay in Figure 35 – Figure 38.

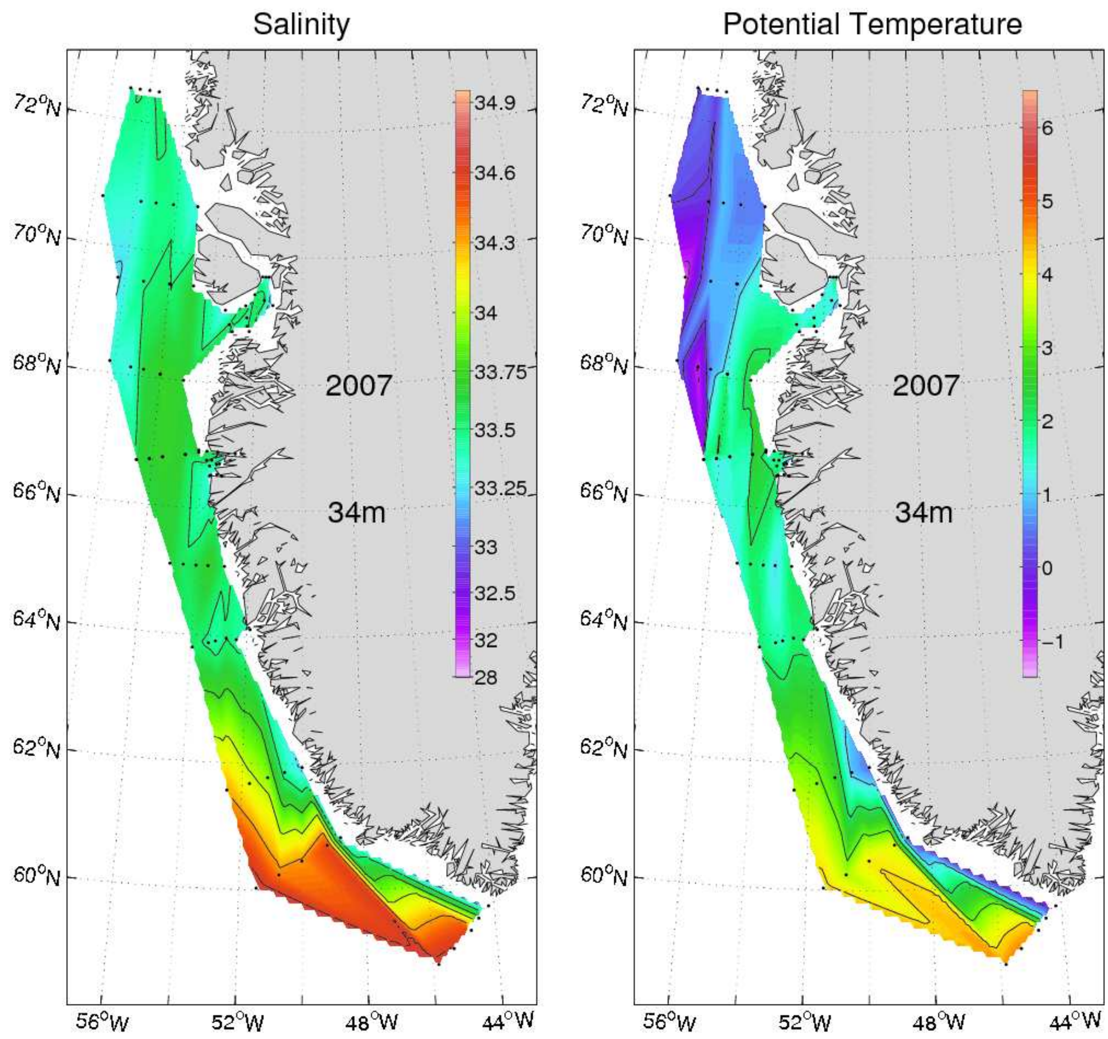


Figure 17. As Figure 16, but for 34 m depth.

At intermediate depths pure Irminger Water (T ~ 4.5^{o}C; S > 34.95) was traced north to the Paamiut section. Modified Irminger Water (T > 3.5^{o}C ; 34.88 < S < 34.95) was observed all the way north to Maniitsoq section. The northward extension of Irminger Water may indicate intensified inflow of water of Atlantic origin to the West Greenland area. The temperature of the Irminger Water was in general higher than in normal conditions. As the Irminger Water is not in direct contact with the atmosphere in West Greenland waters, local heat gain is not a likely explanation, instead elevated temperatures may be linked to the recent maximum of heat in the North Atlantic currents feeding the Irminger current (Holliday et al 2008) in addition to warmer air temperatures than normal over the North Atlantic (Figure 14).

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 18 (red curves). The temperature of this layer was 4.59°C which is about 0.4°C higher than normal whereas the average salinity of 34.85 was just above normal by 0.04 (Table 2). Temperatures and salinities above normal may indicate, that the inflow of Irminger Water was stronger than normal.

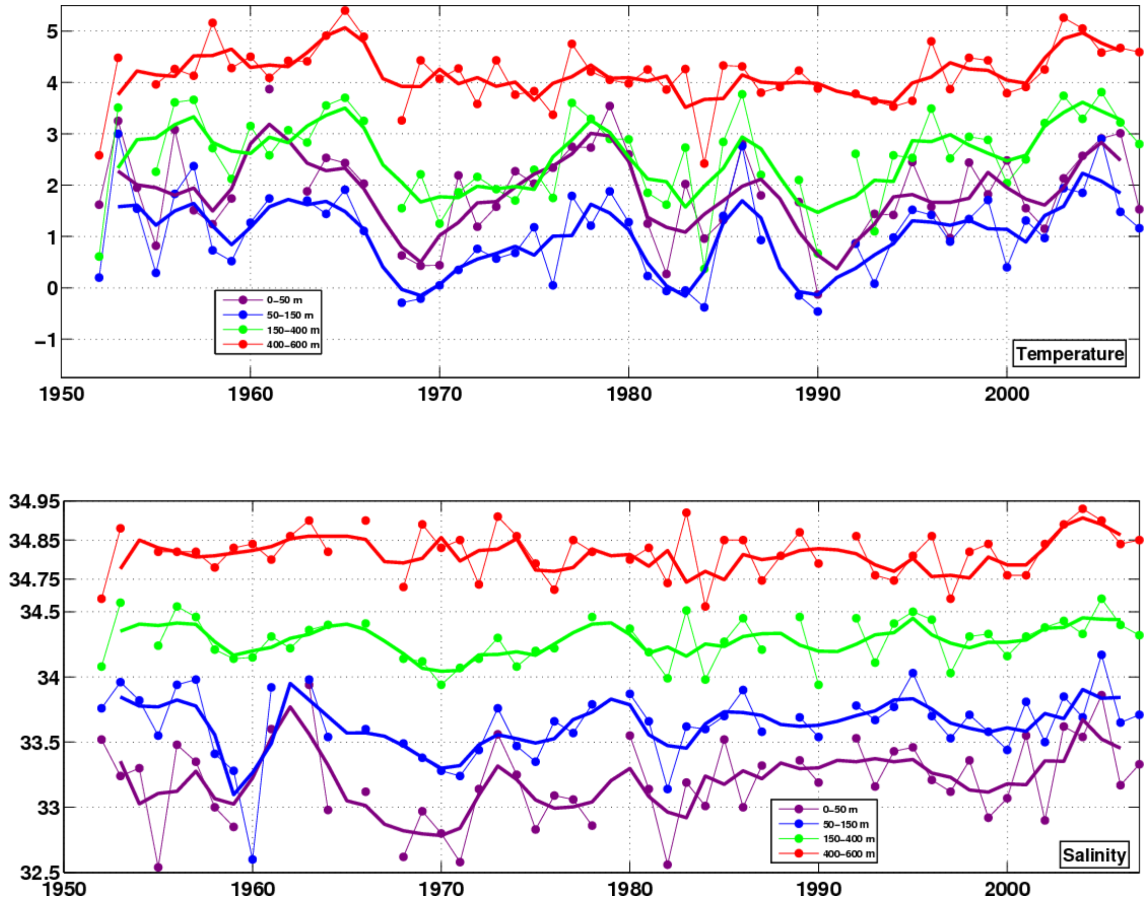


Figure 18. Timeseries of mean June-July temperature (top) and salinity (bottom) for the period 1950–2007 averaged in four different depth intervals west of Fylla Bank (st.4) over the continental slope. Thick curves are the 3 year running mean values. Note the change in scales at 34.75 for salinity. Statistics are shown in Table 2.

Table 2. Statistics for potential temperature and salinity at Fylla Bank st. 4. and values for 2007.

Fylla Bank St.4	Temperature [°C] Mean ± std	Salinity Mean ± std	2007 Tpot	2007 S
0–50 m	1.86 ± 0.87°C	33.20 ± 0.32	1.53°C	33.33
50–150 m	1.04 ± 0.85°C	33.63 ± 0.26	1.16°C	33.71
150–400 m	2.57 ± 0.86°C	34.28 ± 0.17	2.80°C	34.32
400–600 m	4.17 ± 0.57°C	34.81 ± 0.08	4.59°C	34.85

Similar timeseries west of the banks for further north at Maniitsoq st.5 (Figure 20) and Sisimiut st.5 (Figure 21) confirm, that the Irminger Water component of the West Greenland Current still brings heat and salt to the area. The temperature measured in 400–600 m was record high at Sisimiut and the third highest at Maniitsoq, while the salinity was the second highest observed on both timeseries. However, contrary the Fylla Bank st.4 (Figure 18), 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.

In the early 2000s the air temperatures has increased considerable (Figure 13). In 2007 the air temperature in Nuuk was still very high, but lower than the past few years. Similar, Tasiilaq air temperature was still above normal and comparable with the warm period from the mid-1920s to the mid-1960s. The high air-temperature at Nuuk could be a result of a general positive air-temperature anomaly over the Davis Strait (Figure 14).

In general, the surface salinity over the shelf seems to be close to normal and the multi-year-ice "Storis" was present off the southeast coast of Greenland and in the Julianehaab Bight in normal concentrations (Figure 5).

In 2007, a well defined core of Polar Water, revealed by its low temperature, was observed west of Fylla Bank at 50–100 m depth. It was much more pronounced than in 2003–2005 (Ribergaard and Buch, 2004; Ribergaard and Buch, 2005; Ribergaard, 2006) but less pronounced than in 2006 (Ribergaard, 2007). The Polar Water core was also remarkably well defined on the Maniitsoq section and also seen at the Sisimiut section indicating above normal inflow and presence of Polar Water.

At the outermost station (st.5) of Sisimiut, very low salinities were observed in the surface due to melting of the sea-ice, which was present at station, and the temperature of the top 100 m was below 0°C. This water is most likely Polar Water transported southward by the Baffin Current, as indicated by the slope of the isopycnals.

From the Aasiaat section in the south to the Upernavik section in the north, a distinct Polar Water core was absent. Instead a colder layer was found with temperatures below 1°C (below -1°C at Nugssuaq and Upernavik) in the center at depth at about 75 m. 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 haline upper stratification 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 17. Below the cold subsurface layer, a relative warm (> 2–3°C) watermass was found with a core around 400–500 m. This water is the extension of the Irminger Water component of the West Greenland Current.

West of Fylla Bank (st.4, Figure 18), the salinity was about normal in the upper 400 m and slightly above normal below 400 m (Table 2). However, the surface temperature (0–50 m) was slightly below normal, while the temperature in the core of the Polar Water in 50–150 m was about normal. Below 150 m, and especially below 400 m, the temperature was higher than normal. Generally, the same conditions is seen further to the northwest, off the "Sukkertop banke" and "Store Hellefiskebanke" (Figure 20 and Figure 21), but surface temperatures was lower than normal in the upper 150 m. On these northern stations, lower surface temperatures in the surface mixed layer (0–50 m) could be explained by the presence or nearby presence of west-ice.

Surface temperatures below normal despite of anomalous positive air temperatures over the Davis Strait (Figure 14) and about normal temperatures in the core of the Polar Water indicates normal to above normal inflow of Polar Water. The presence of both multi-year-ice and west-ice (Figure 5) likely also has the effect, that the surface temperatures remain lower than normal.

Noticeably, since the mid-1990s, the temperature west of and on top of Fylla bank seems to be relative warm without sudden particular cold periods as has happen in the late 1960s, the early 1980s and the early 1990s (Figure 15 and Figure 18). Likewise, since the early 2000s, the mean salinity at 400–600 m depth west has increased which may indicate increased strength of the Irminger Current as suggested by Ribergaard (2004). Similar record high property values are observed further northwest of "Sukkertop banke" and "Store Hellefiskebanke", with the two exceptions, that relative cold surface waters is also observed in the late 1990s and the increase in temperature are more gradually during the late 1990s and remains high in the 2000s below 150m (Figure 20 and Figure 21). Using more advanced analytical methods,, Myers et al. (2007) also reported increased strength of the Irminger Water component on the Cape Farewell, Cape Desolation and Paamiut sections, which is likely linked to the North Atlantic subpolar gyre circulation (Hátún et al., 2005). This warming of the subpolar gyre was also observed by Stein (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.

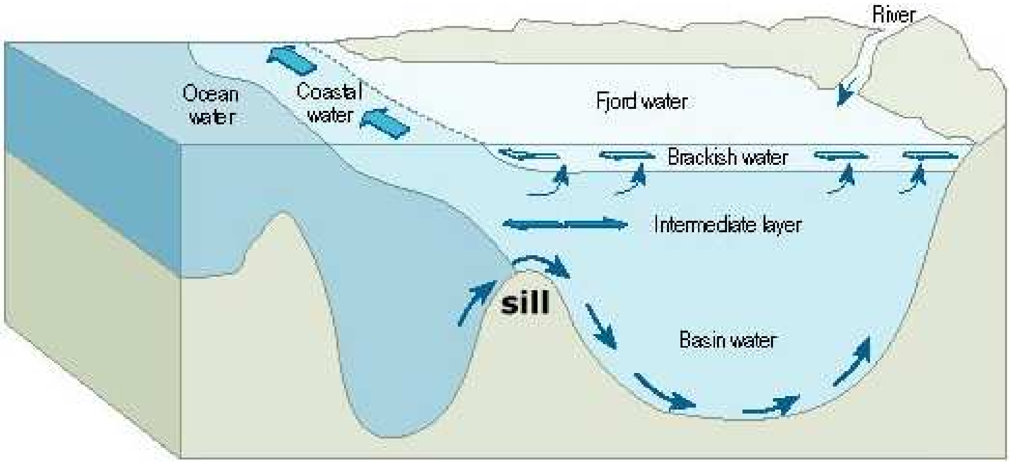


Figure 19. Sketch of the circulation in a fjord (modified from http://www.amap.no/maps-gra/show.cfm?figureId=58).

West Greenland fjords 2007

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 19). 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 19. 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.

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 from the fjords, this brackish water is mixed with the surrounding surface waters, which is Polar Water. Mixing continues along the coast, and the watermass keeps close to the coast. In the following it is named Coastal Polar Water.

6.1. Fjords south of Sisimiut

Hydrographic data were obtained from four fjords around Sisimiut in 2007 (Figure 39–Figure 42). 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, and somewhat confusing, this categorizes it as a fjord with a shallow sill, which however occasionally show properties resembling a fjord with a deep 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.

In the deep sill fjords, Amerdloq and Ikertoq fjord (Figure 39 and Figure 40), the sill depth is about 150–180 m. These sill depths allow relative warm and saline waters of Atlantic origin to enter the fjords close to the bottom. 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. The bottom water up to about sill depth remains saline and “warm” (1-3°C). Above sill depth the salinities are almost homogenous whereas 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. Close to the surface a thin warm layer was found caused by the sun heating of runoff water from land.

Kangerdluarssuk fjord (Figure 41) can be considered as a fjord with shallow sill. Kangerdluarssuk fjord has a sill depth of about 50 m. The whole bottom layer below sill depth is filled with Coastal Polar Water and the salinity is very homogeneous. During winter the Coastal Polar Water are cooled and undergoes convection. As the water inside the fjord have homogenous salinities the whole water column are gradually cooled by winter convection and the water become totally homogenous (neutral stability). Therefore cold temperatures are measured below sill depth. The bottom temperature is below 0°C and the bottom salinity is around 33.6. The low salinity at depth indicates that the winter cooled water is actually Coastal Polar Water. At the surface relative warm water is found caused by the solar radiation during spring and summer. In the top a thin warm solar heated fresh water cap was found caused by runoff from land.

Itivdleq fjord (Figure 42) has a sill depth about 70 m, largely prohibit warm and saline water of Atlantic origin to enter the fjord. However, occasionally, the deep water is influenced by water from outside the fjord, which is denser and more saline than the water found in the fjord above sill depths. The bottom salinities are around 33.75 and temperatures below 0°C. Increasing salinity with depth below sill depth indicates, that winter convection to the bottom has not taken place in the last few years. However, the density of the bottom water is only marginally higher than the calculated density of the Coastal Polar Water found just above sill at its freezing point. This indicate, that the total heat loss during winter 2007 was just not enough to create deep convection. In the top near the mouth of the fjord, a thin warm solar heated fresh water cap is found caused by runoff from land.

Figure 43 and Figure 44 displays the temporal evolution in the properties in the Amerdloq/Ikertoq fjords. Between 2003 and 2005 (no measurements in 2004) the bottom water has become slightly more saline (and denser) indicating increased influence of mixed Irminger Water. This is in agreement with the findings by Ribergaard and Buch (2005) showing record high salinities in 2004 west of Fylla Bank in 400–600m and with Ribergaard (2006) showing lower, but still high, salinities in 2005. From 2005 to 2006 the salinity (and density) decreased slightly, which is to be expected, as the sub-surface salinities in 2006 west of Fylla Bank was lower than in 2005 (Figure 18) indicating that no inflow to the bottom has taken place. In 2007 the salinity continued to decrease and a cold water tongue is seen close to the sill depth. This is most likely the remaining water from previous winter convection, as the cold waters are not seen outside the fjord (Figure 39 and Figure 40). The decrease in salinity and density are due to mixing within the fjords. In both fjords, the upper ocean (around 150m) salinities decreased from 2005 to 2006 indicating an increased influence of Polar Water.

Bottom temperatures in the Kangerdluarssuk fjord has become colder and slightly less saline than previous years 2003, 2005 and 2006 (Figure 45). This is likely due to a combination of colder atmospheric winter temperatures in 2006/7 than previous years resulting in a larger surface heat flux. The slightly decrease in bottom salinity could be due to increased influence of Polar Water in 2006 (Ribergaard, 2007) compared to 2003–2005, leaving lightly fresher waters in the surface, which undergoes convection during winter.

Itivdleq fjord was only observed in 2005, 2006 and 2007 (Figure 46). Both the bottom and surface salinity has become less saline and the density has decreased throughout the water-column and the temperature of the water below sill-depth has become colder. This is a sign of increased influence of Polar Water and colder winters as for the Kangerluarssuk fjord.

Conclusions

Atmospheric and oceanographic conditions off West Greenland during the summer 2007 were characterised by:

- Positive NAO index.
- Displacement of the center of the Icelandic Low towards the Labrador Sea.
- The strength of the westerlies over the North Atlantic has decreased, caused by weakened Icelandic low and the Azores high. But only south of the Nova Scotia/Great Britain line.
- The wind conditions over the southern part of Greenland was about normal.
- Increased strength of winds towards south over the East Greenland shelf centred at about Jan Mayen.
- Anomalies warm air over most of the North Atlantic sector by about 1–2°C.
- Air temperature in Nuuk was about 1°C higher than normal.
- Water temperature and salinity on top of Fylla Bank was about average in June.
- Slightly above normal presence of Polar Water and above normal presence of Irminger Water indicated by:
  - Normal concentration of multi-year-ice (“Storis”).
  - Generally cold surface waters on the northern sections and over the shelf.
  - Well defined cold Polar Water core was observed west of Fylla Bank.
  - About normal temperature on top of Fylla Bank, despite of higher air temperatures over the Davis Strait area than normal.
  - Pure Irminger Water was observed north to the Paamiut section and Modified Irminger Water could be traced up to the Sisimiut section.
  - The Atlantic Water component was warmer and more saline than normal indicating above normal strength of the Irminger Current but other explanations cannot be ruled out.
  - West of Fyllas Bank (st.4) the mean temperature in 400–600 m depth was approximately 0.4°C above average and the salinity was above normal as well.
  - West of “Sukkertop Banke” and “Store Hellefiskebanke”, the observed temperatures and salinities were among the highest observed in 400–600 m depth. However the time series are not as complete as the Fylla Bank st.4.

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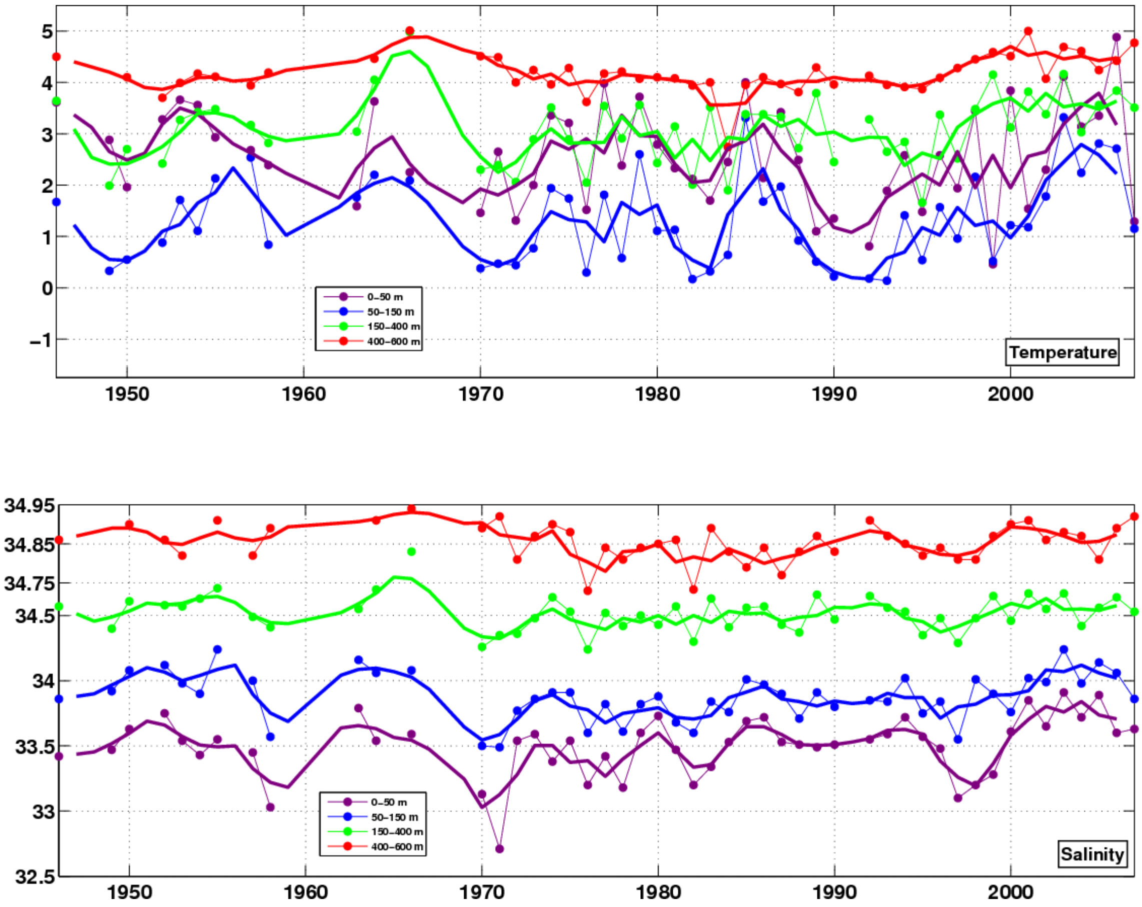
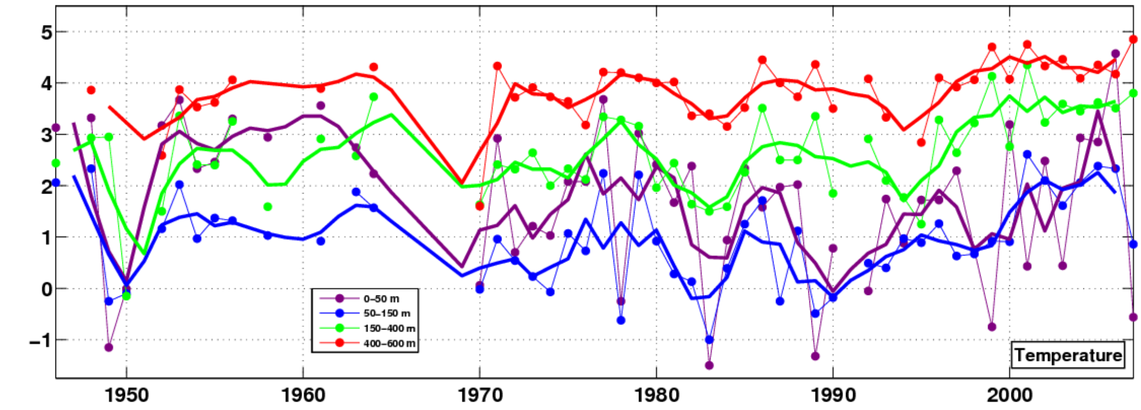


Figure 20. Timeseries of mean temperature (top) and mean salinity (bottom) for the period 1946–2007 in four different depth intervals west of "Sukkertop Banke" (Maniitsoq, st.5) over the continental slope. The thick curves are the 3 year running mean values. Note the change in scales at 34.75 for salinity. Statistics is shown in Table 3.

Table 3. Statistics for potential temperature and salinity at Maniitsoq (Sukkertoppen) st. 5. and values for 2007.

Mamiitsoq St.5	Temperature [°C] Mean ± std	Salinity Mean ± std	2007 Tpot	2007 S
0–50 m	2.58 ± 0.98°C	33.51 ± 0.24	1.29°C	33.63
50–150 m	1.35 ± 0.89°C	33.89 ± 0.20	1.15°C	33.86
150–400 m	3.10 ± 0.68°C	34.52 ± 0.13	3.51°C	34.53
400–600 m	4.18 ± 0.37°C	34.85 ± 0.05	4.77°C	34.92



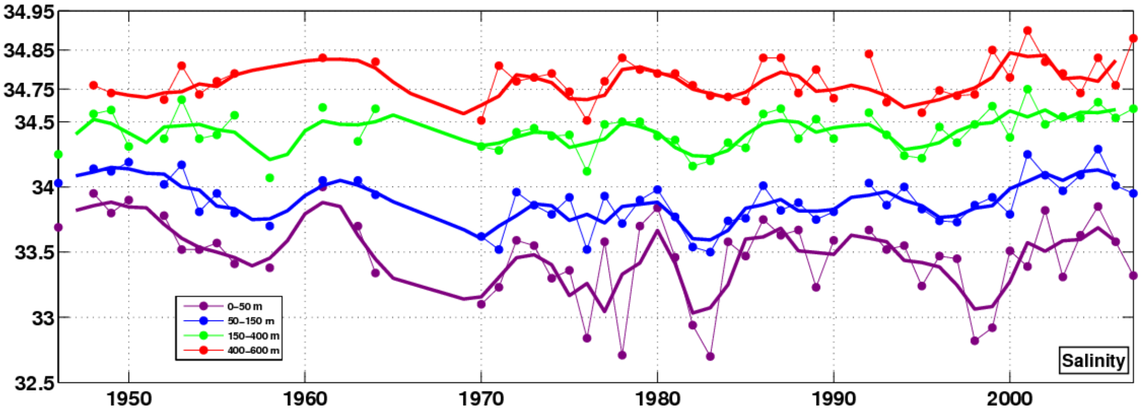


Figure 21. Timeseries of mean temperature (top) and mean salinity (bottom) for the period 1946–2007 in four different depth intervals west of "Store Hellefiskebanke" (Sisimiut, st.5) over the continental slope. The thick curves are the 3 year running mean values. Note the change in scales at 34.75 for salinity. Statistics is shown in Table 4.

Table 4. Statistics for potential temperature and salinity at Sisimiut (Holsteinsborg) st. 5. and values for 2007.

Sisimiut	Temperature [°C]	Salinity	2007	
St.5	Mean ± std	Mean ± std	Tpot	S
0–50 m	1.72 ± 1.45°C	33.47 ± 0.31	-0.56°C	33.32
50–150 m	0.97 ± 0.89°C	33.89 ± 0.19	0.86°C	33.95
150–400 m	2.64 ± 0.85°C	34.43 ± 0.15	3.80°C	34.60
400–600 m	3.86 ± 0.59°C	34.75 ± 0.08	4.85°C	34.88

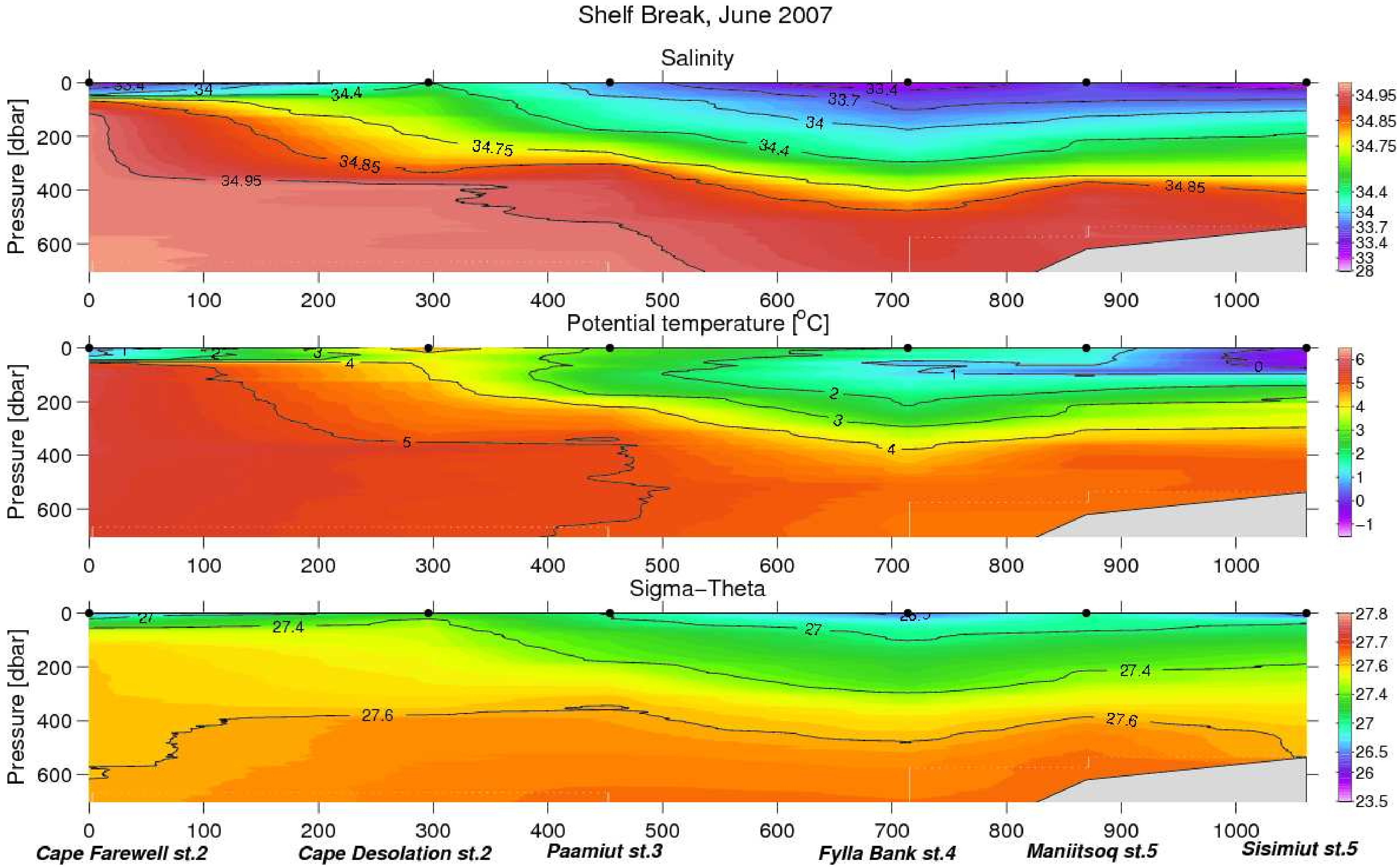


Figure 22. Vertical distribution of temperature, salinity and density over the continental shelf break from Cape Farewell to Sisimiut, June 9–20, 2007.

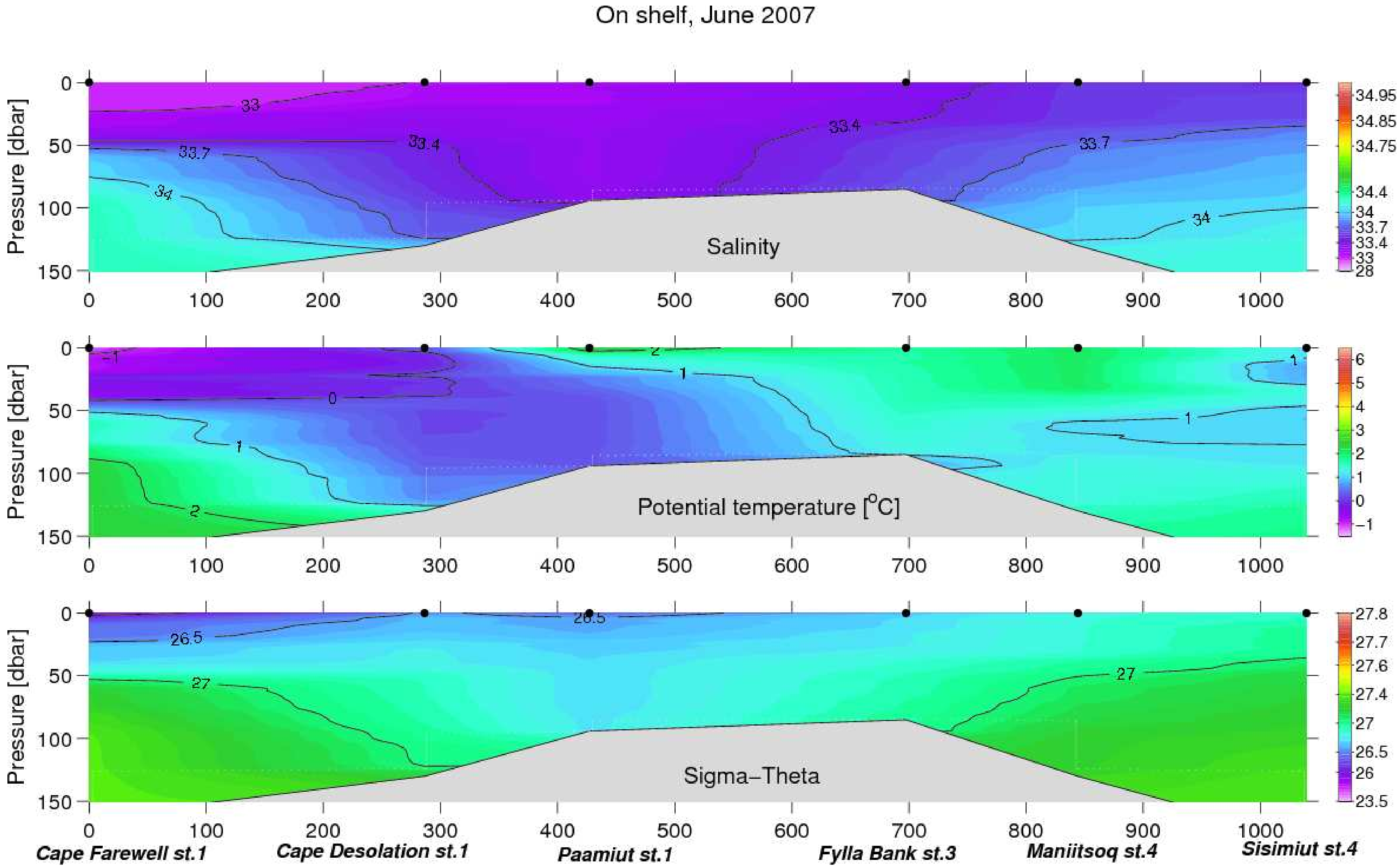


Figure 23. Vertical distribution of temperature, salinity and density over the shelf banks from Cape Farewell to Sisimiut, July 10–19, 2007.

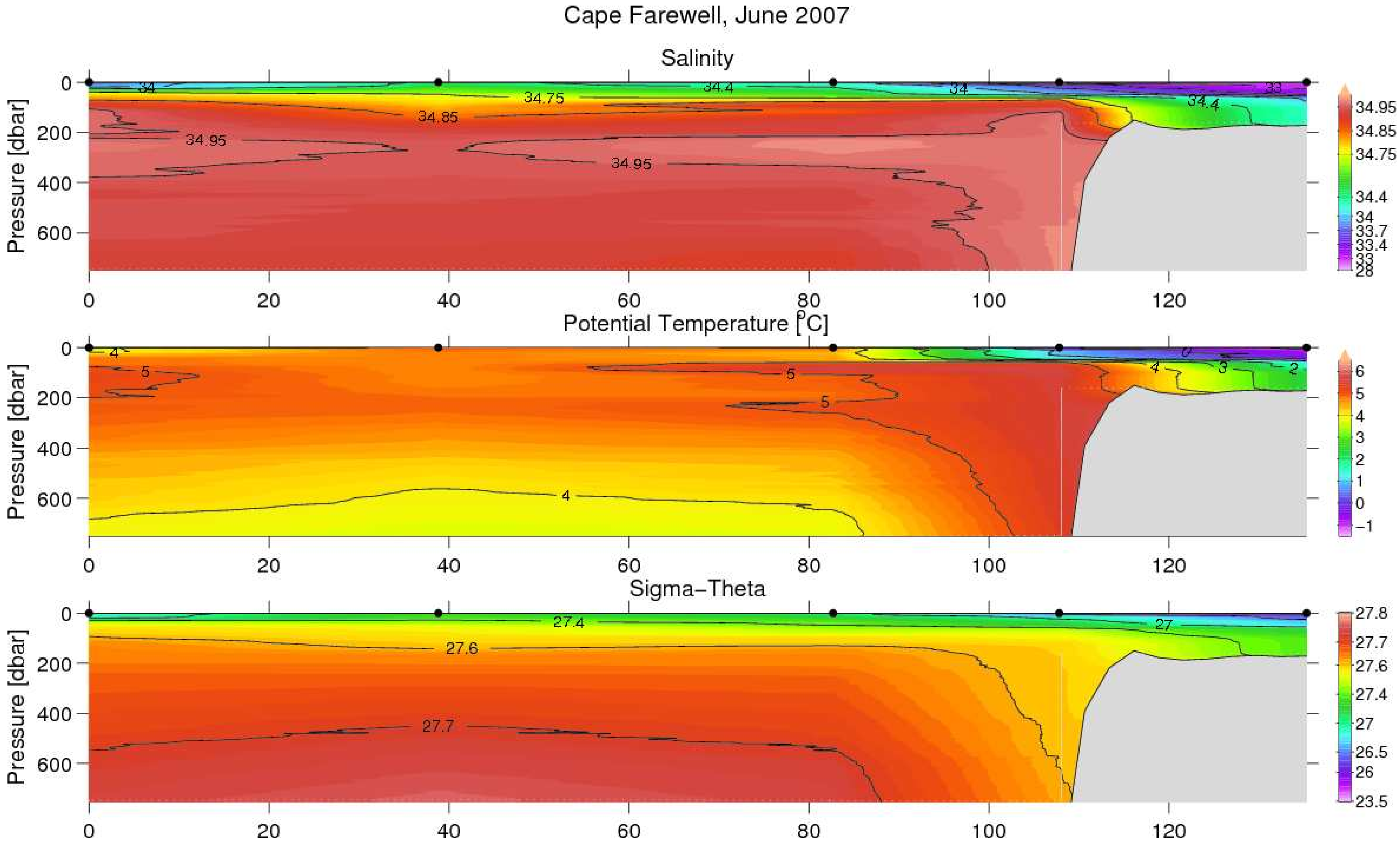


Figure 24. Vertical distribution of temperature, salinity and density at the Cape Farewell section, June 9–10, 2007.

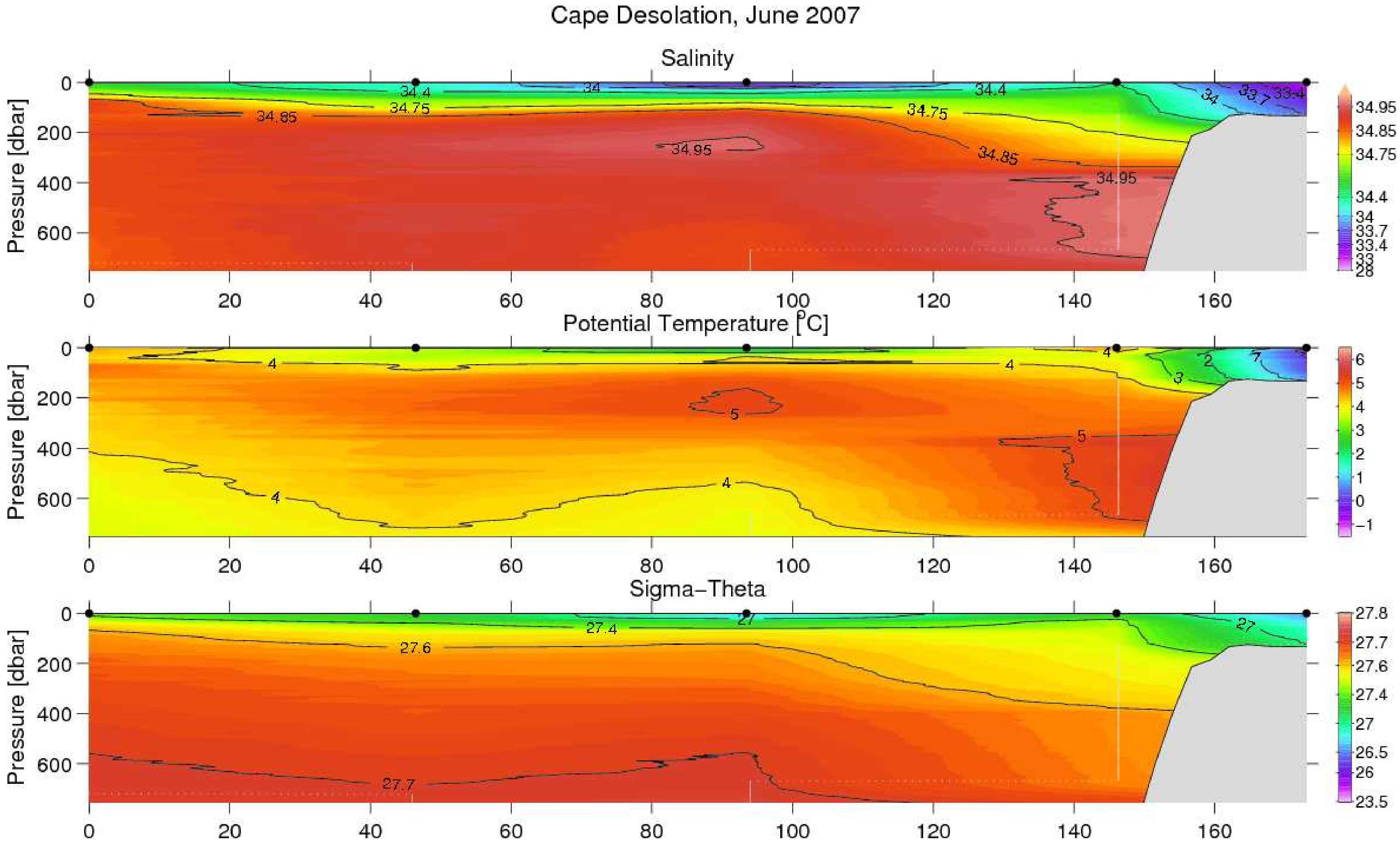


Figure 25. Vertical distribution of temperature, salinity and density at the Cape Desolation section, June 10–11, 2007.

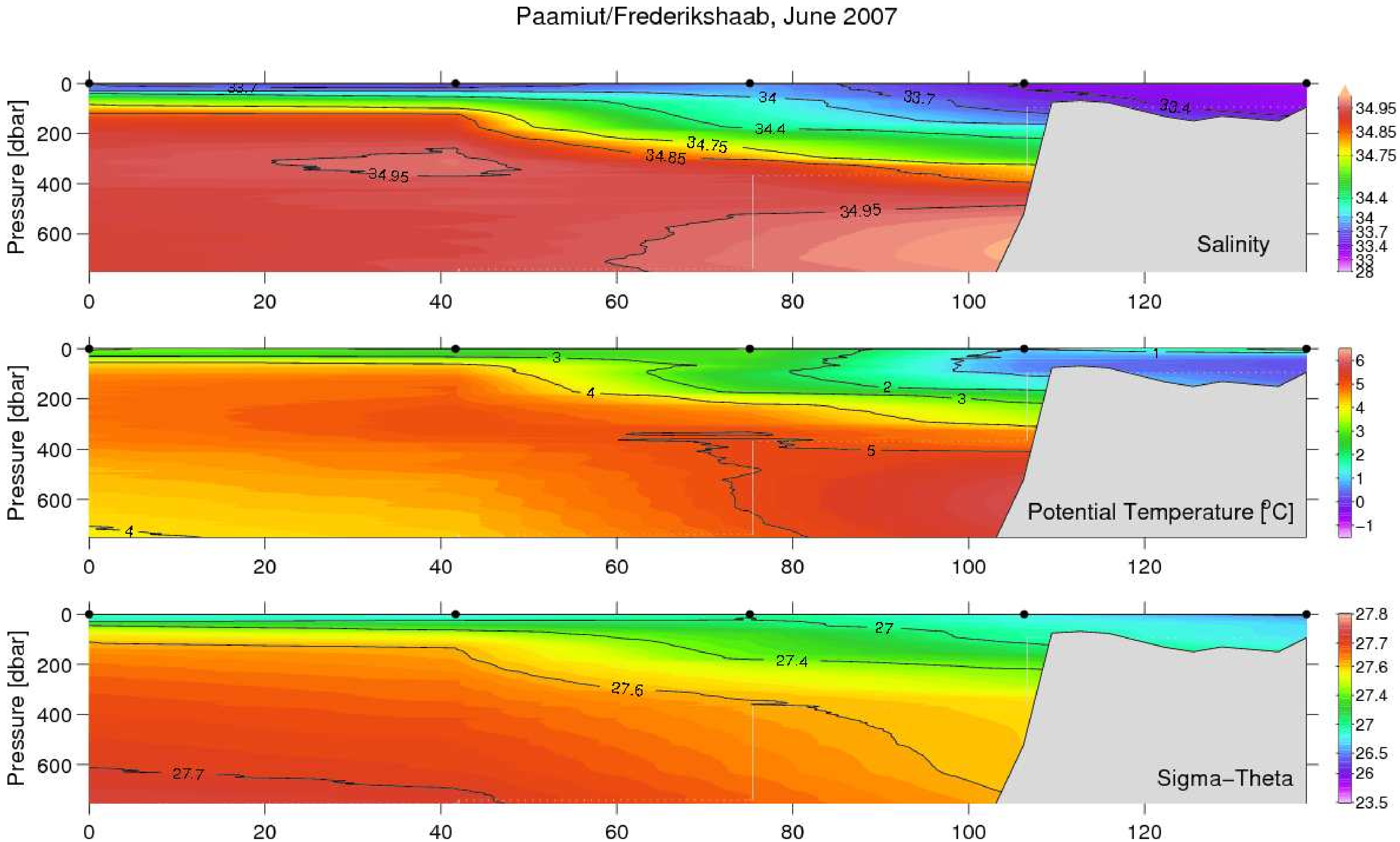


Figure 26. Vertical distribution of temperature, salinity and density at the Paamiut (Frederikshaab) section, June 12, 2007.

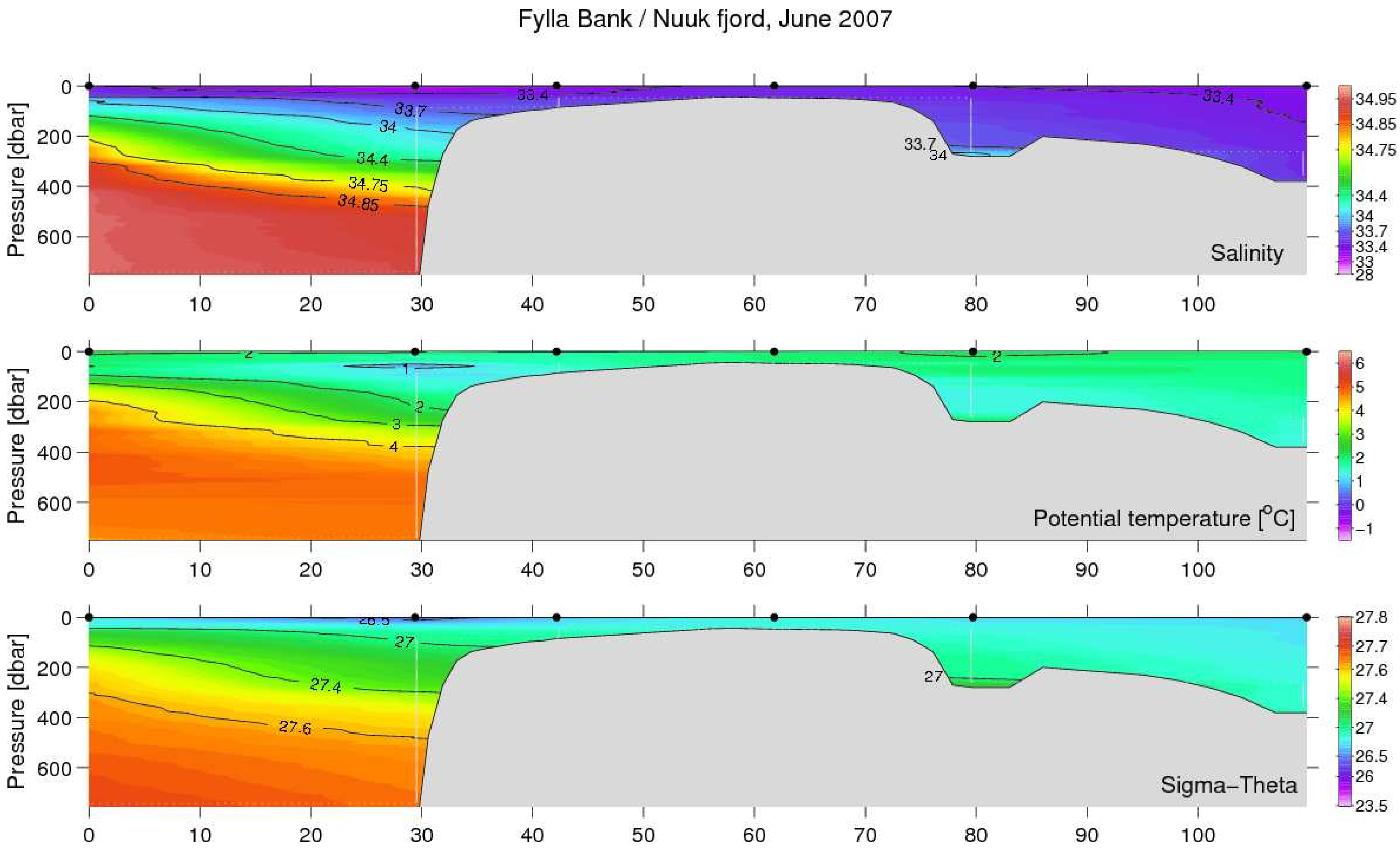


Figure 27. Vertical distribution of temperature, salinity and density at the Fylla Bank section, June 12–13, 2007. The section is extended by Godthaab (Nuuk) fjord st. 3 (“hovedstationen”) on right side of the plot.

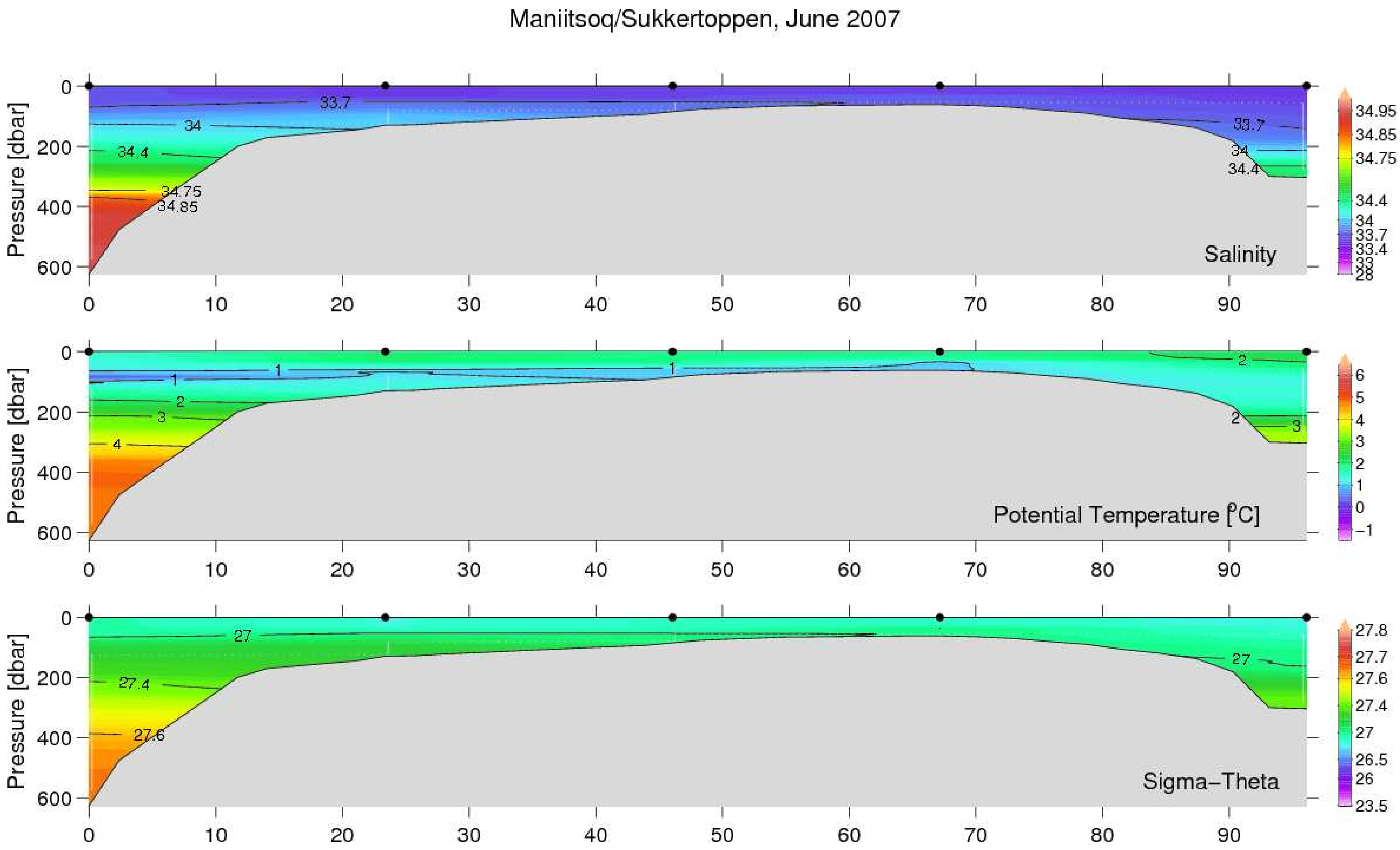


Figure 28. Vertical distribution of temperature, salinity and density at the Maniitsoq (Sukkertoppen) section, June 17–18, 2007.

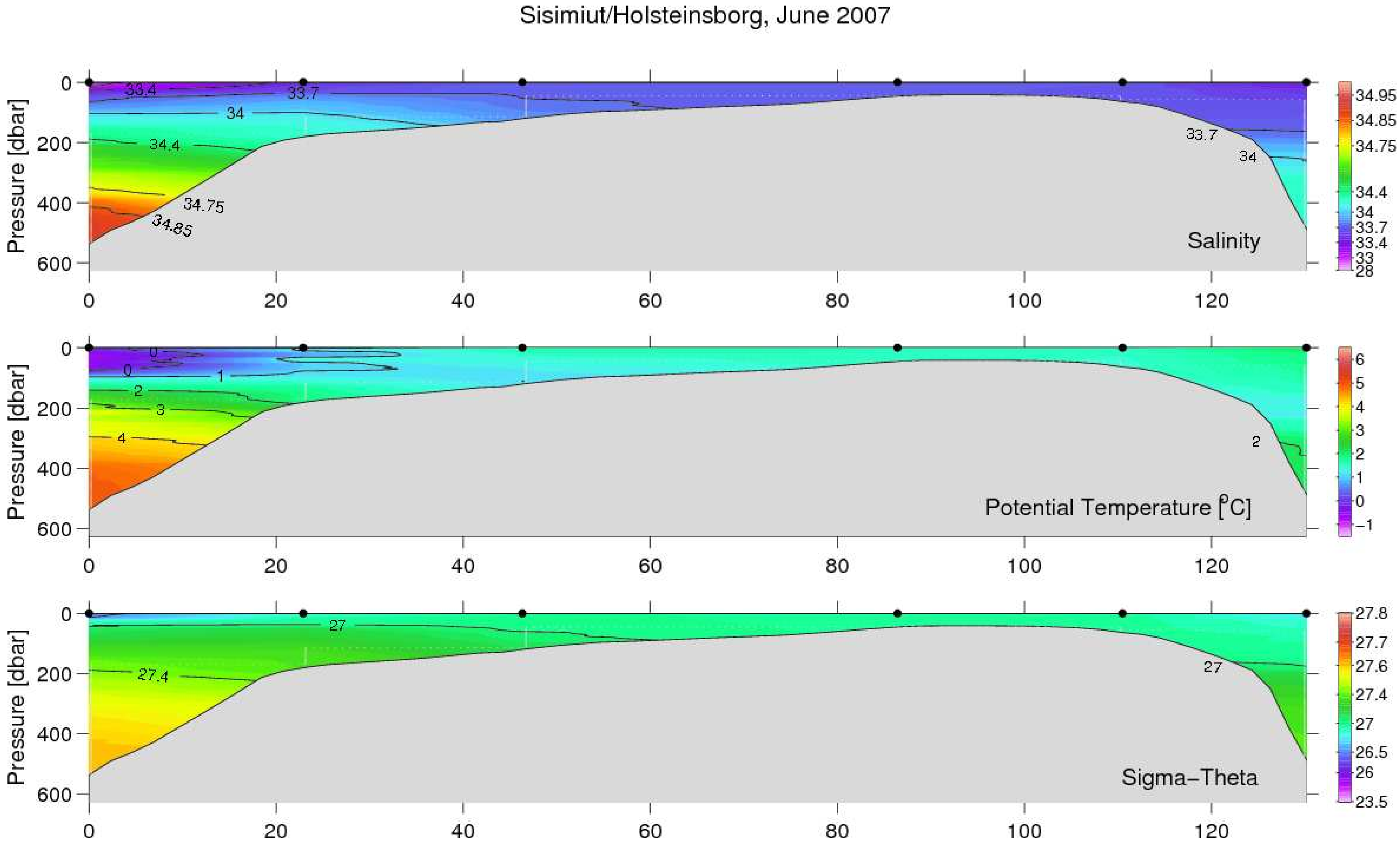


Figure 29. Vertical distribution of temperature, salinity and density at the Sisimiut (Holsteinsborg) section, June 19–20, 2007. Sisimiut st. 0 right.

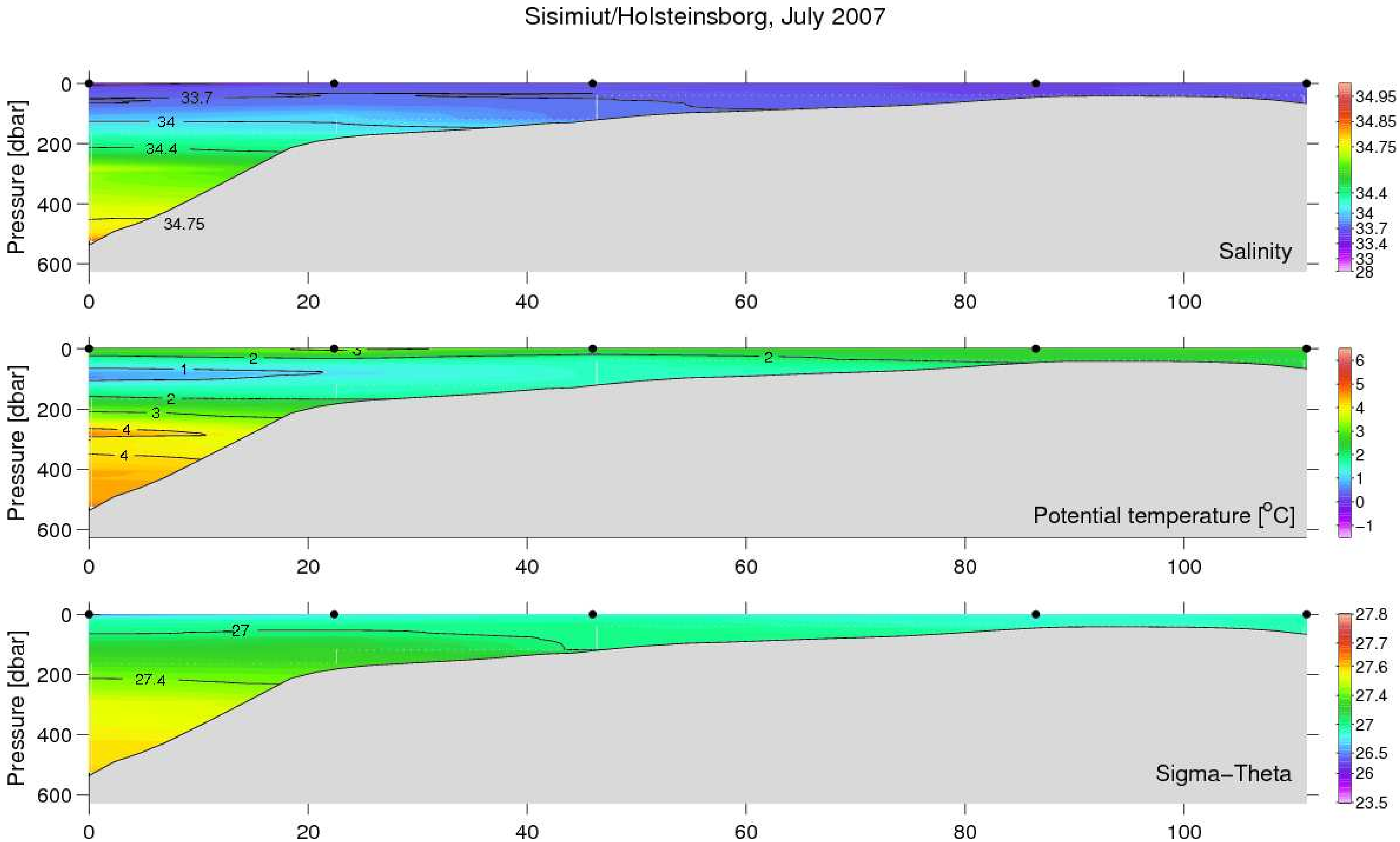


Figure 30. Vertical distribution of temperature, salinity and density at the Sisimiut (Holsteinsborg) section, July 4–5, 2007.

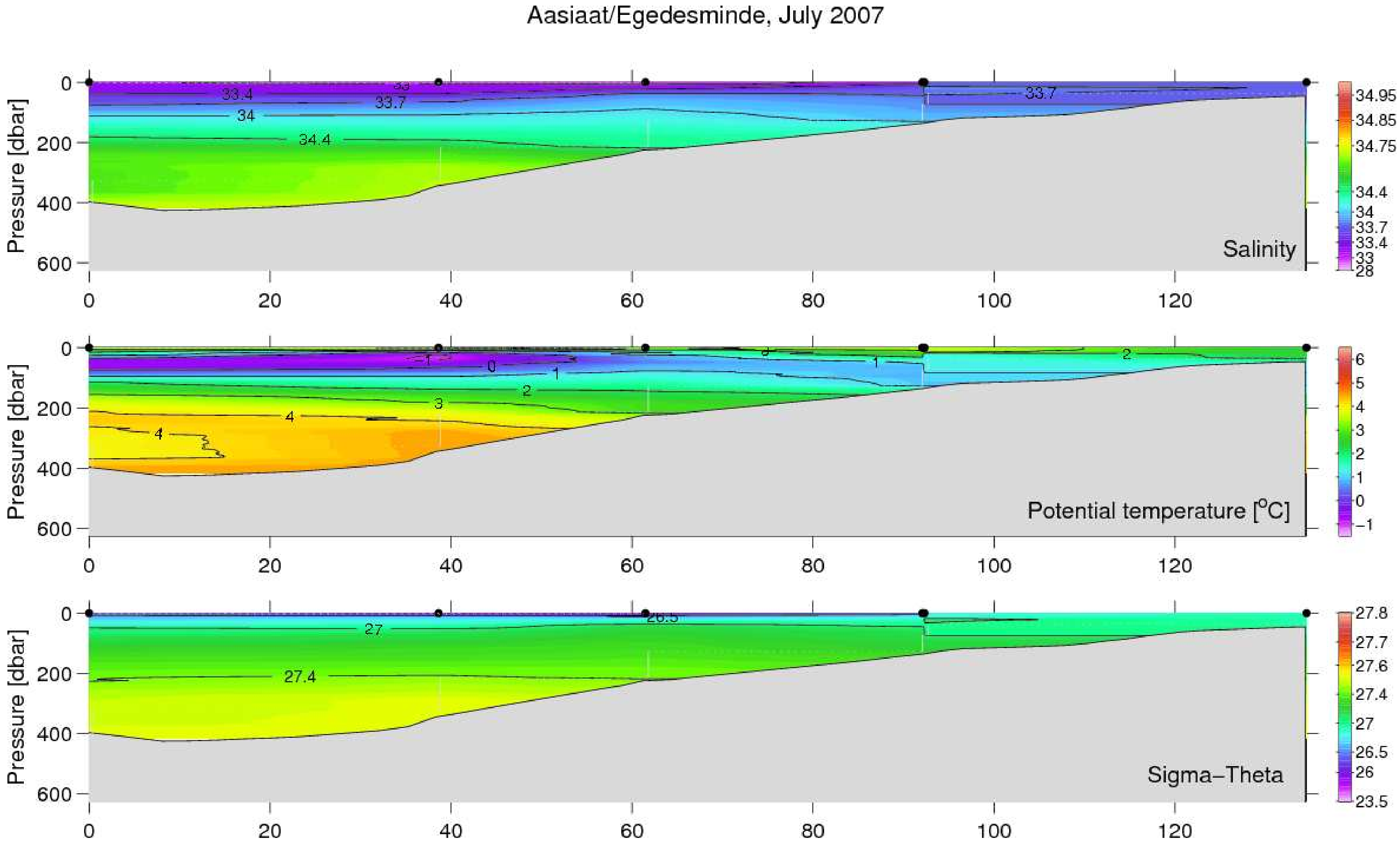


Figure 31. Vertical distribution of temperature, salinity and density at the Aasiaat (Egedesminde) section, July 7–8, 2007.

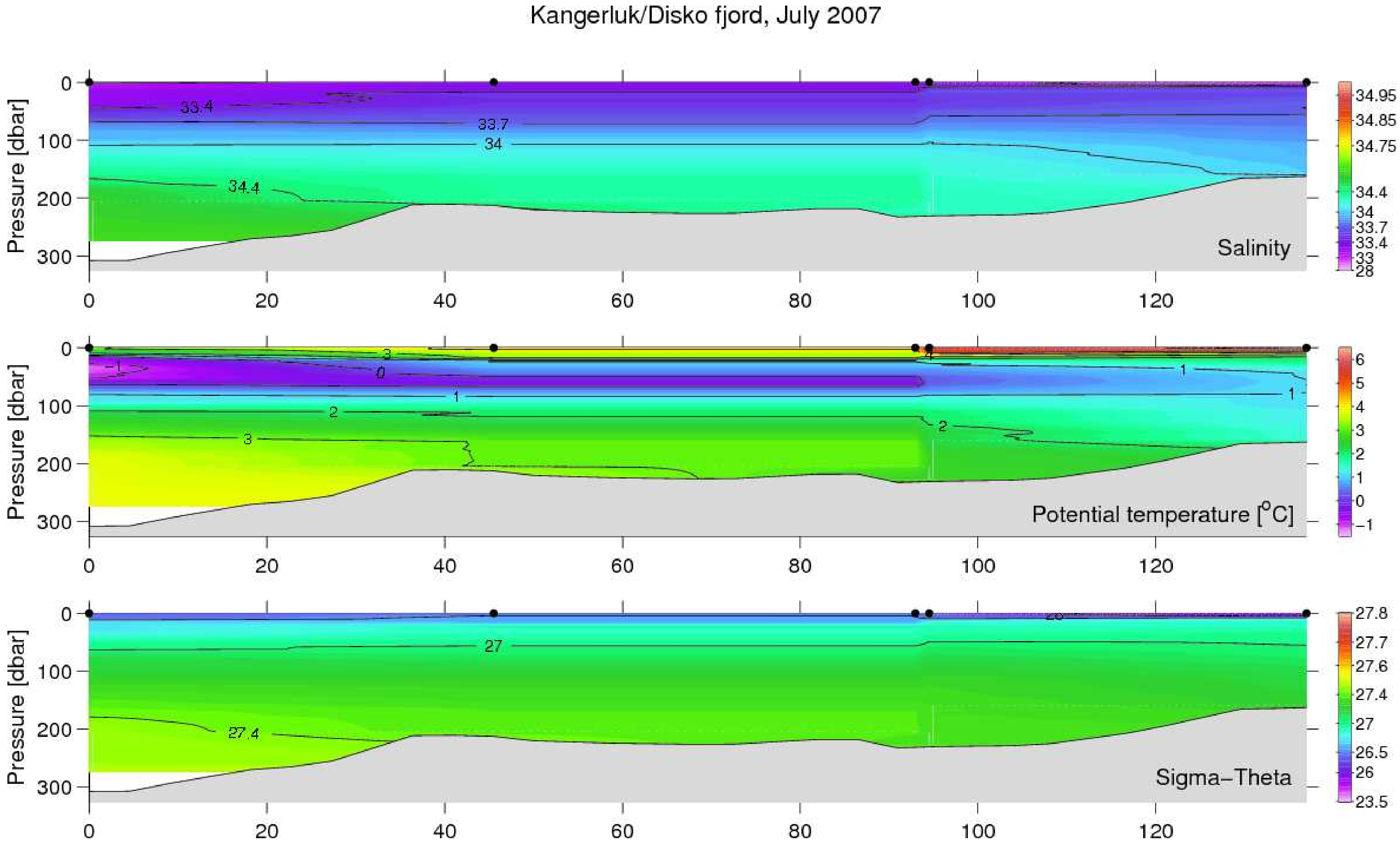


Figure 32. Vertical distribution of temperature, salinity and density at the Kangerluk (Disko Fjord) section, July 10–11, 2007.

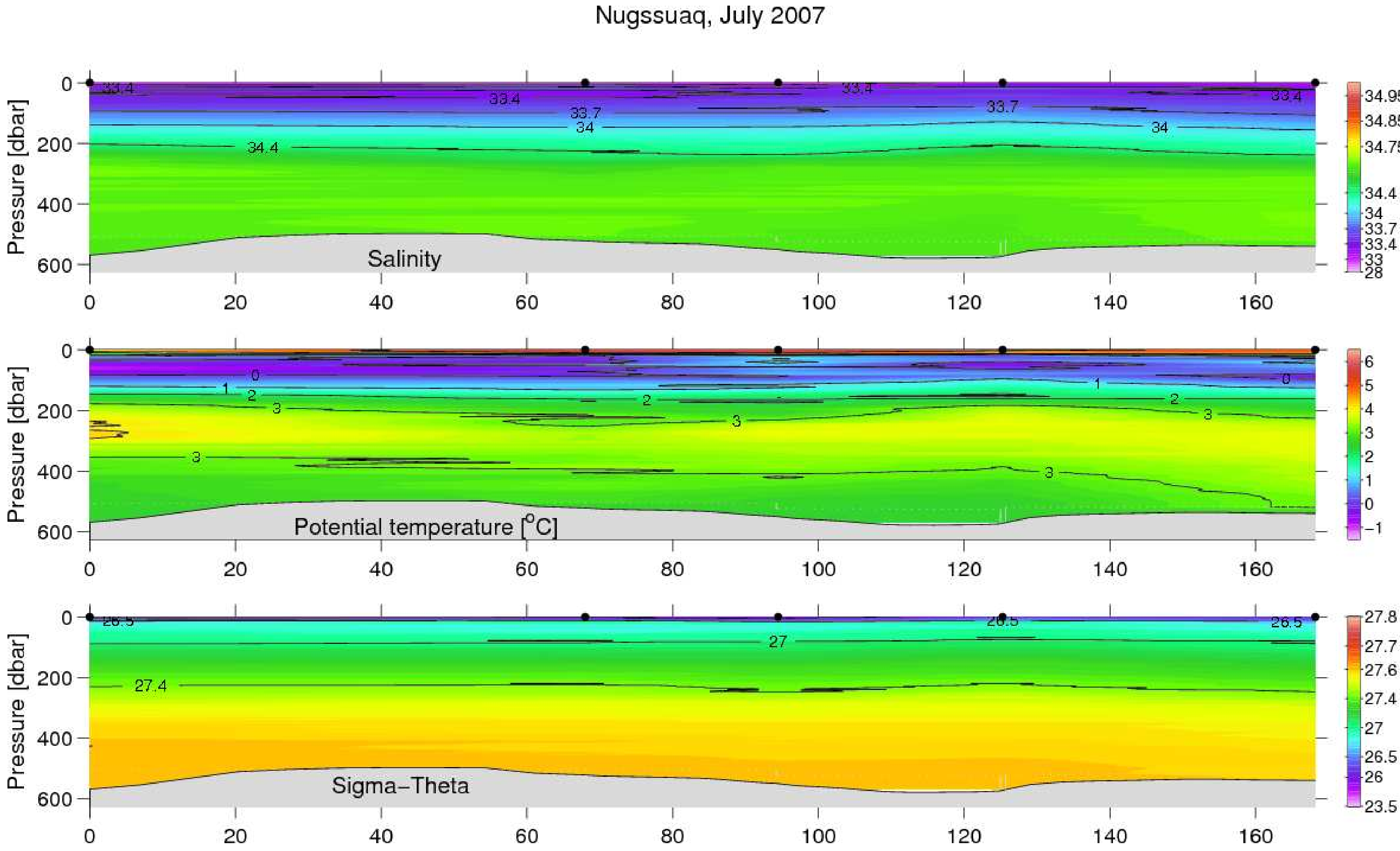


Figure 33. Vertical distribution of temperature, salinity and density at the Nugssuaq section, July 21–22, 2007.

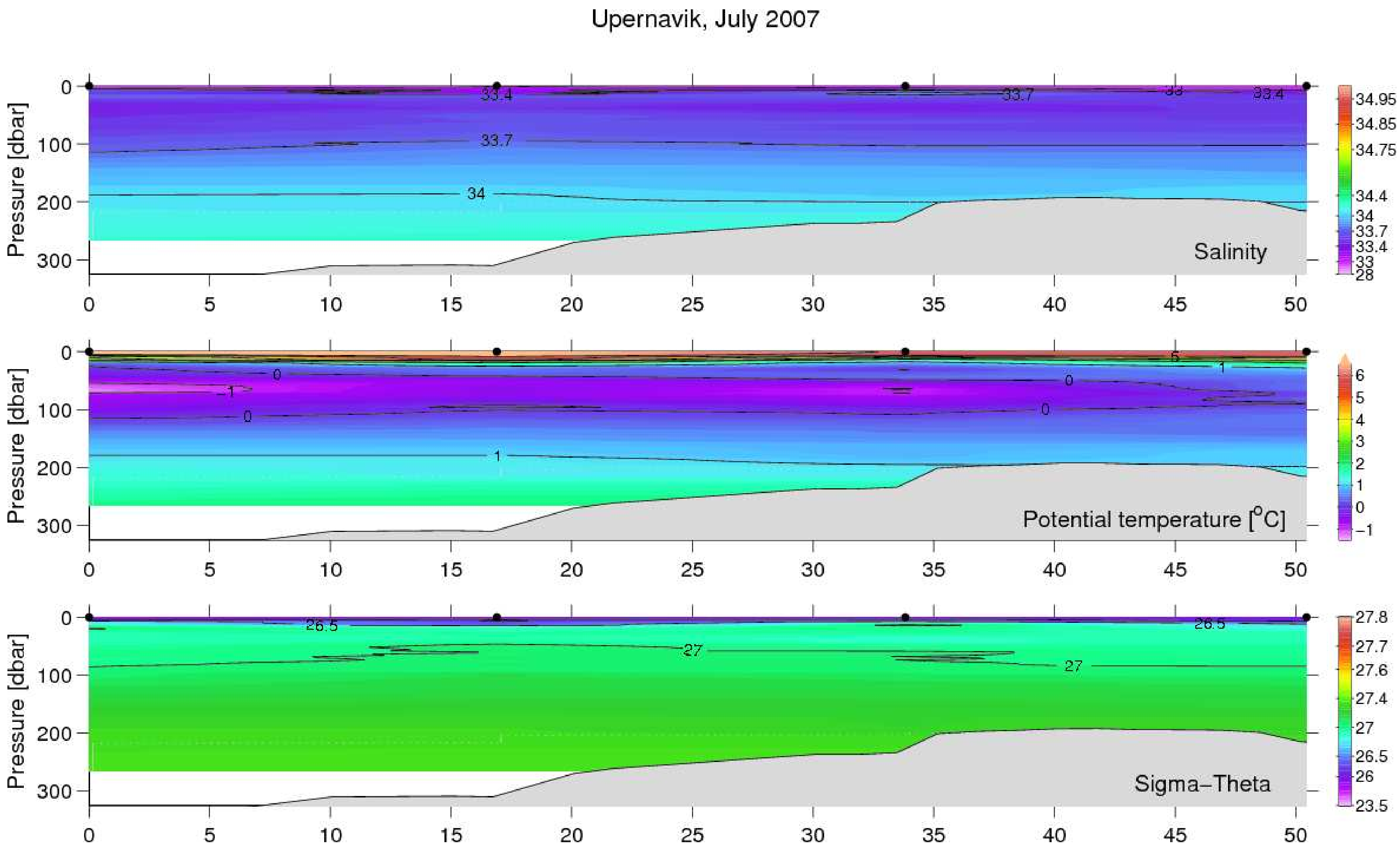


Figure 34. Vertical distribution of temperature, salinity and density at the Upernavik section, July 22–23, 2007.

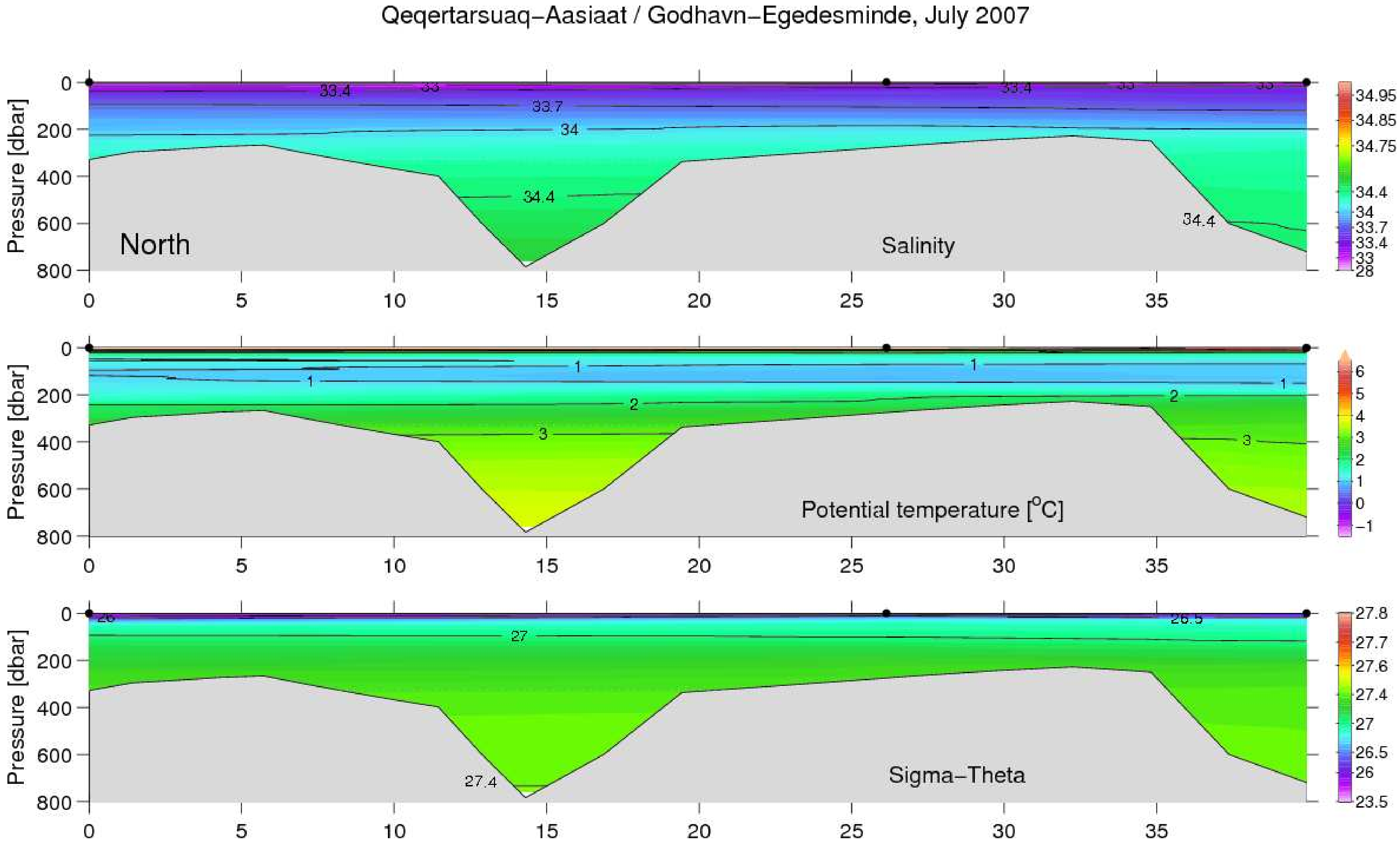


Figure 35. Vertical distribution of temperature, salinity and density at the Aasiaat–Qeqertarsuaq (Egedesminde–Godhavn) section, July 13–14, 2007.

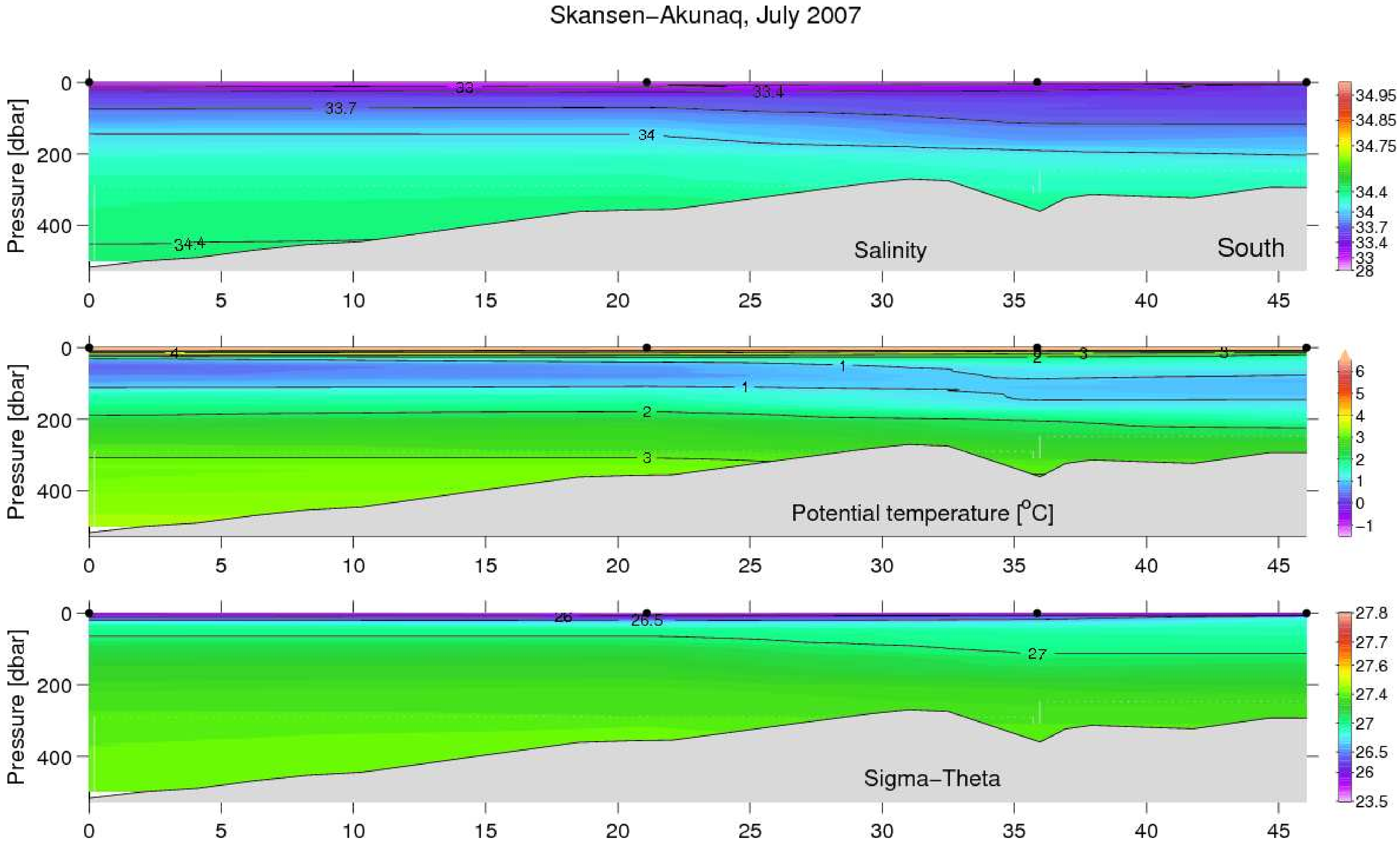


Figure 36. Vertical distribution of temperature, salinity and density at the Skansen–Akunaq section, July 14, 2007.

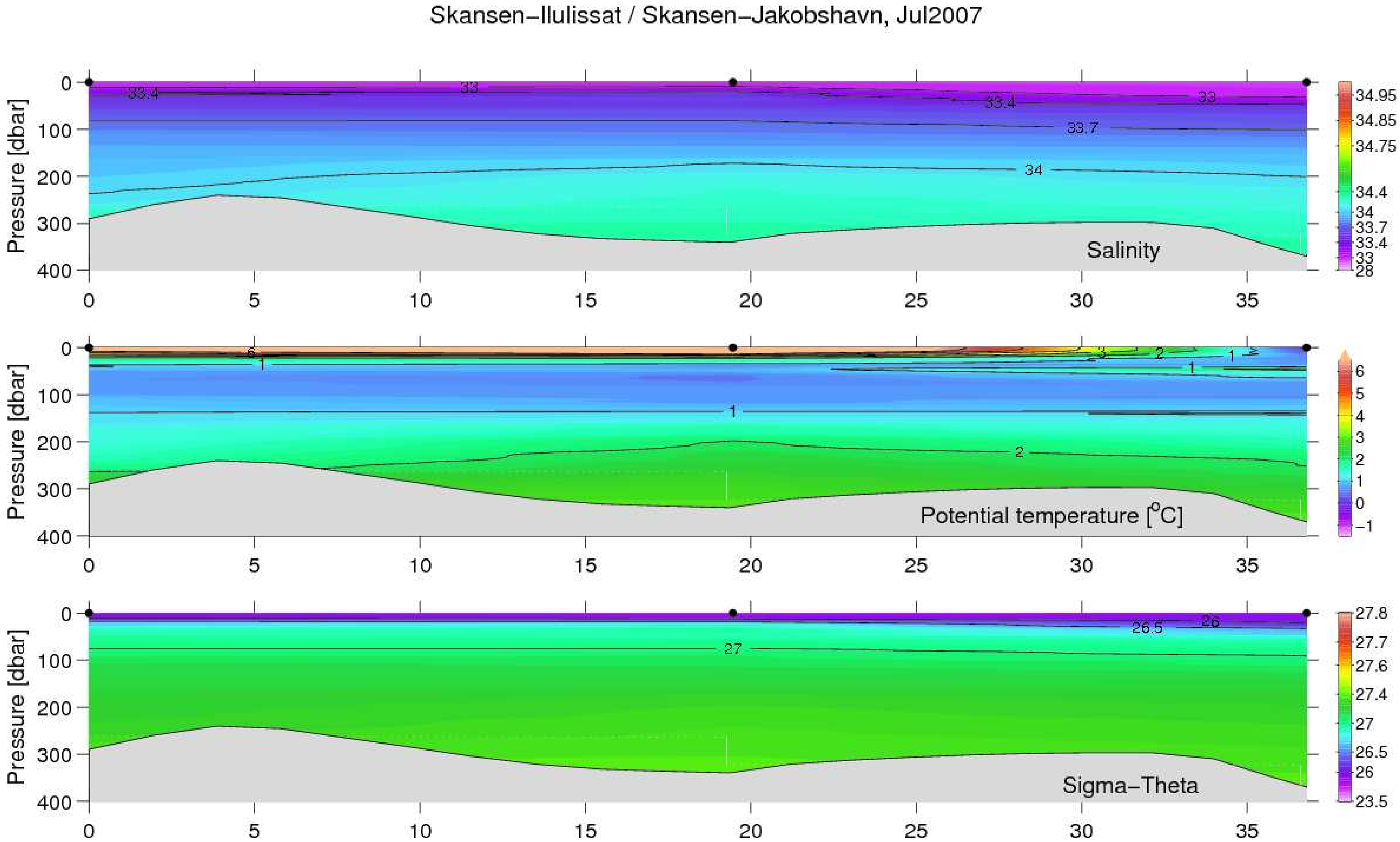


Figure 37. Vertical distribution of temperature, salinity and density at the Skansen–Ilulissat (Skansen–Jakobshavn) section, July 15, 2007.

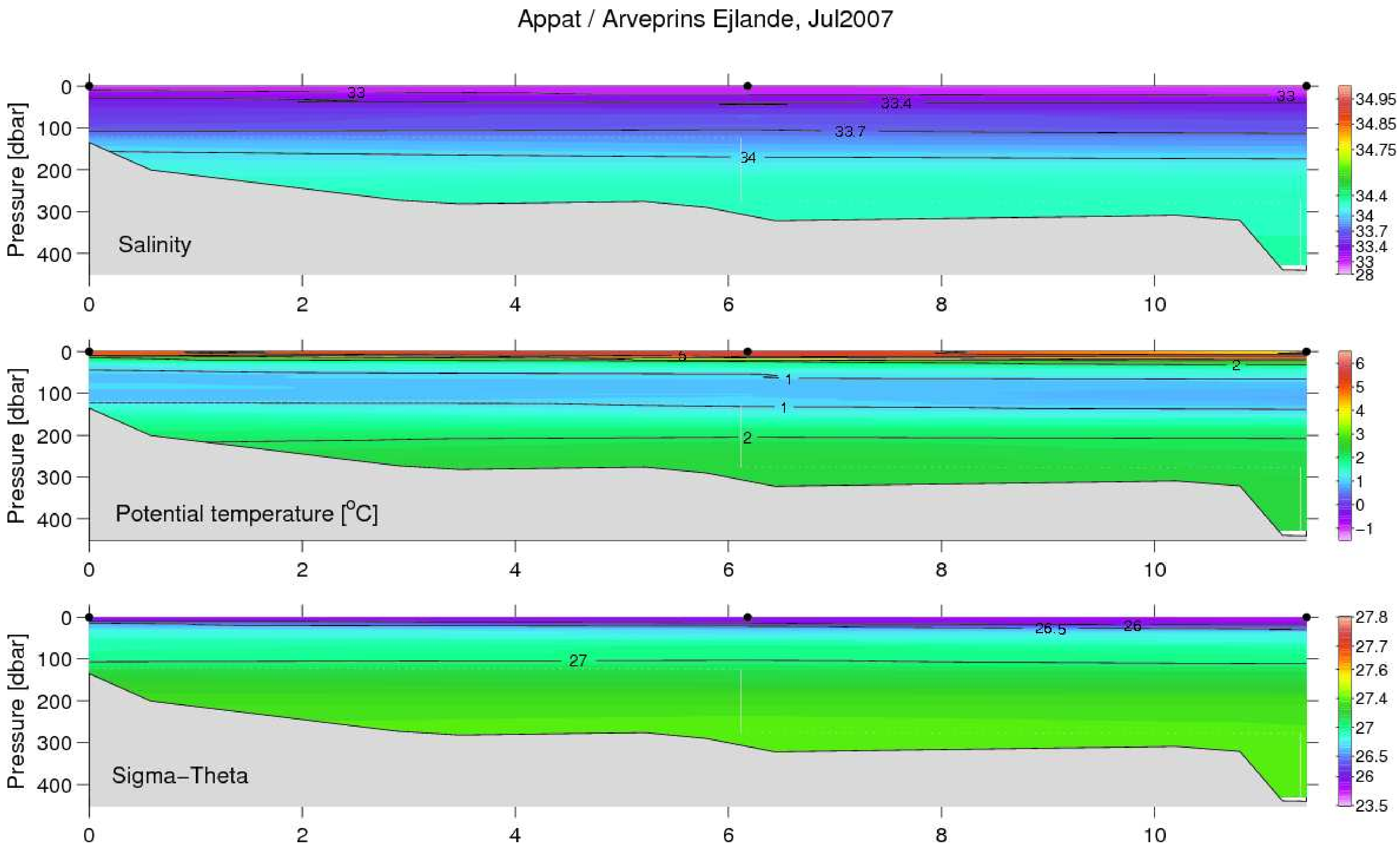


Figure 38. Vertical distribution of temperature, salinity and density at the Appat (Arveprins Ejlande) section, July 18, 2007.

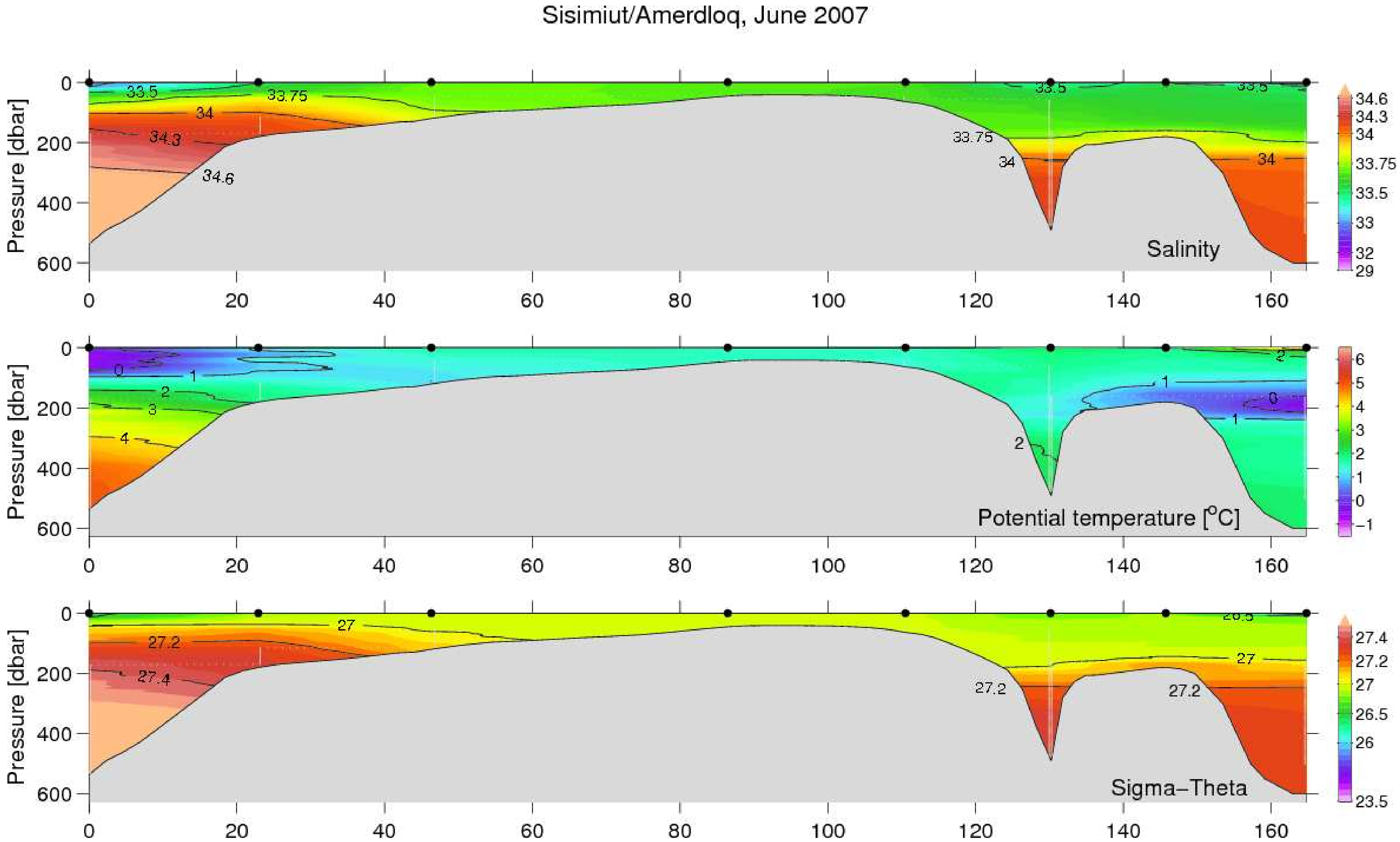


Figure 39. Vertical distribution of temperature, salinity and density at the Amerdloq fjord, June 19–20, 2007. Sisimiut section left (identical to Figure 27).

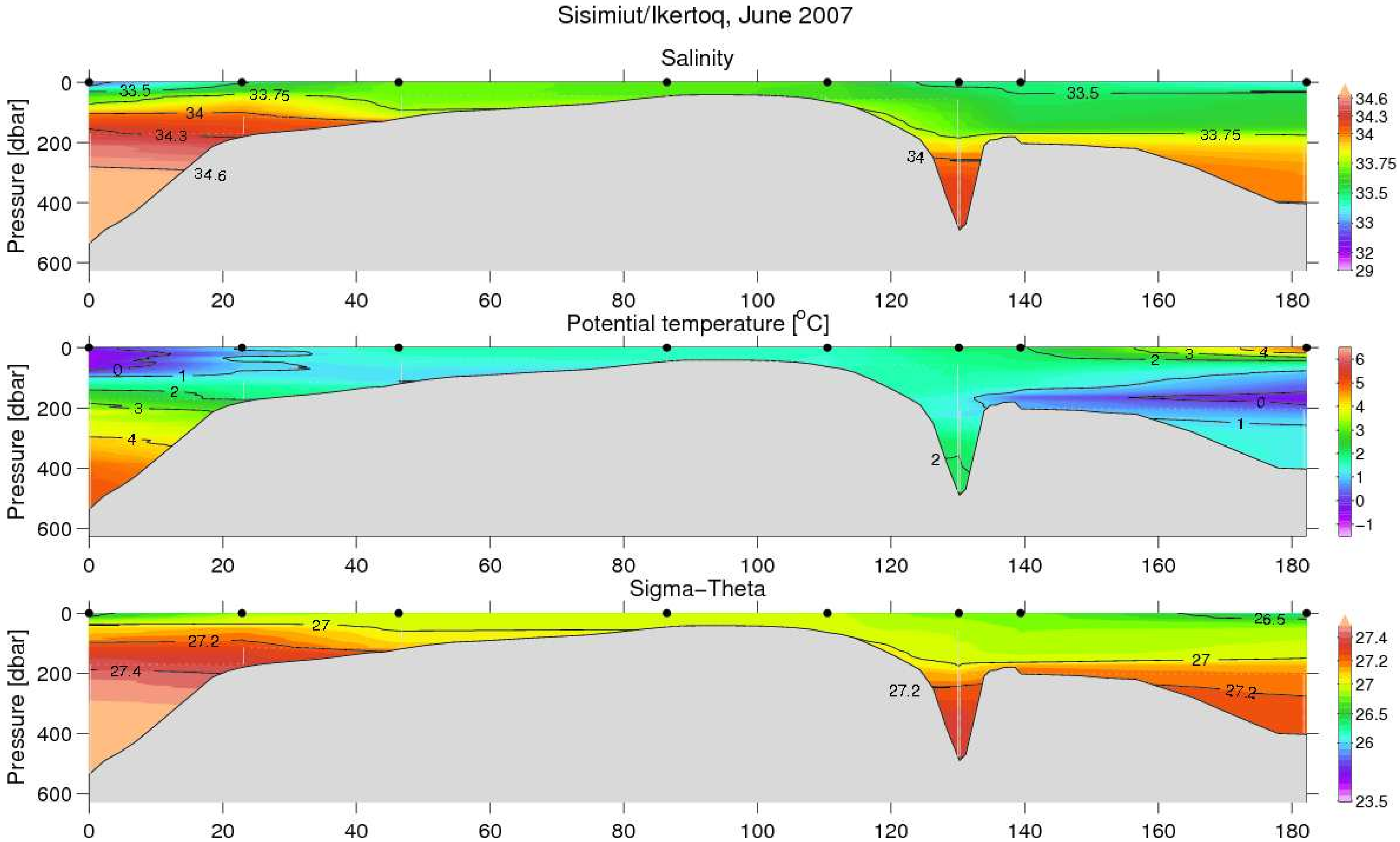


Figure 40**.** Vertical distribution of temperature, salinity and density at the Ikertoq fjord, June 20, 2007. Sisimiut section left (identical to Figure 27).

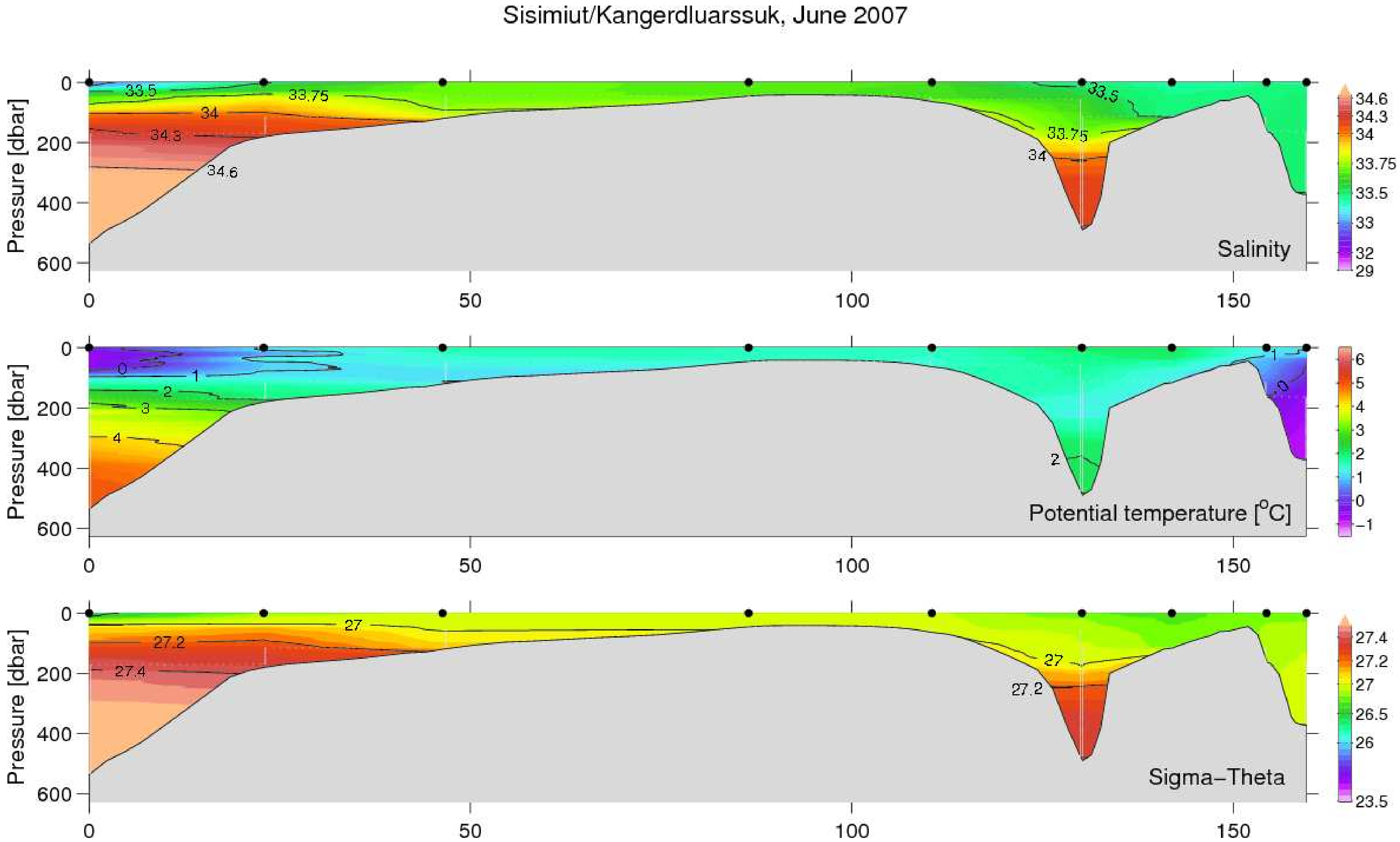


Figure 41. Vertical distribution of temperature, salinity and density at the Kangerdluarssuk fjord, June 20, 2007. Sisimiut section left (identical to

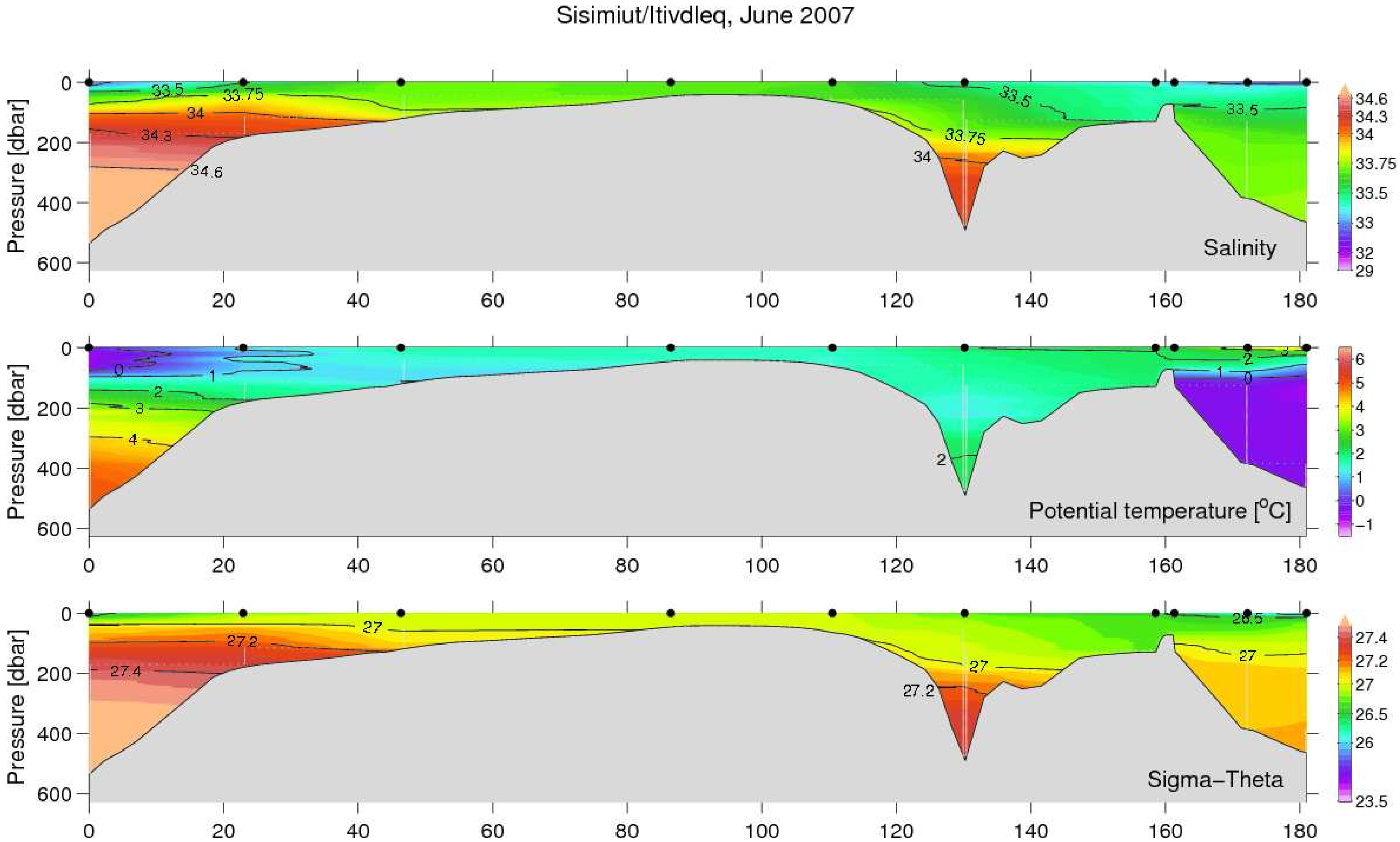


Figure 42**.** Vertical distribution of temperature, salinity and density at the Itivdleq fjord, June 21, 2007. Sisimiut section left (identical to Figure 27).

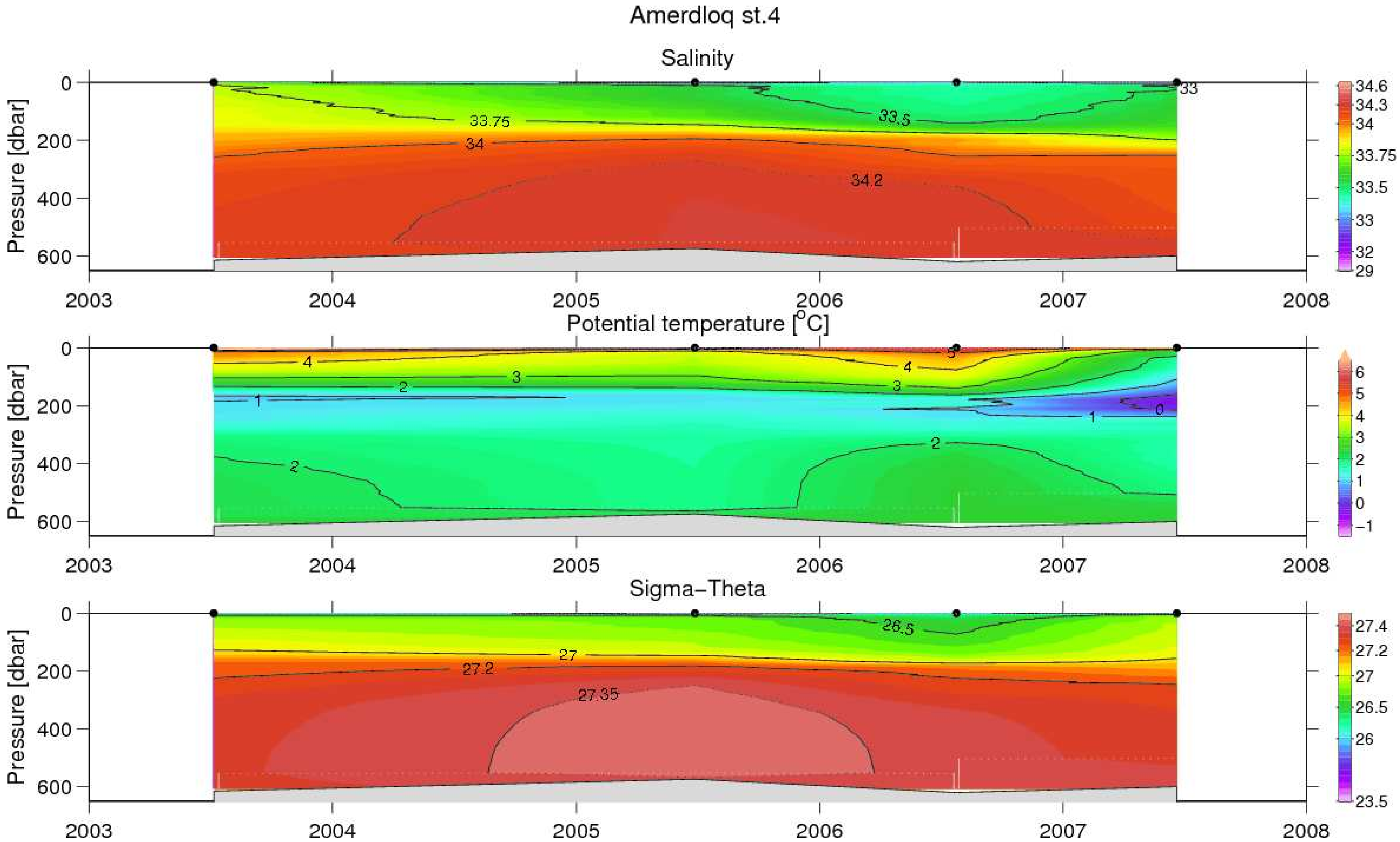


Figure 43. Hovmöller diagram of vertical distribution of temperature, salinity and density at the Amerdloq fjord st.4, late June/July 2003, 2005–2007.

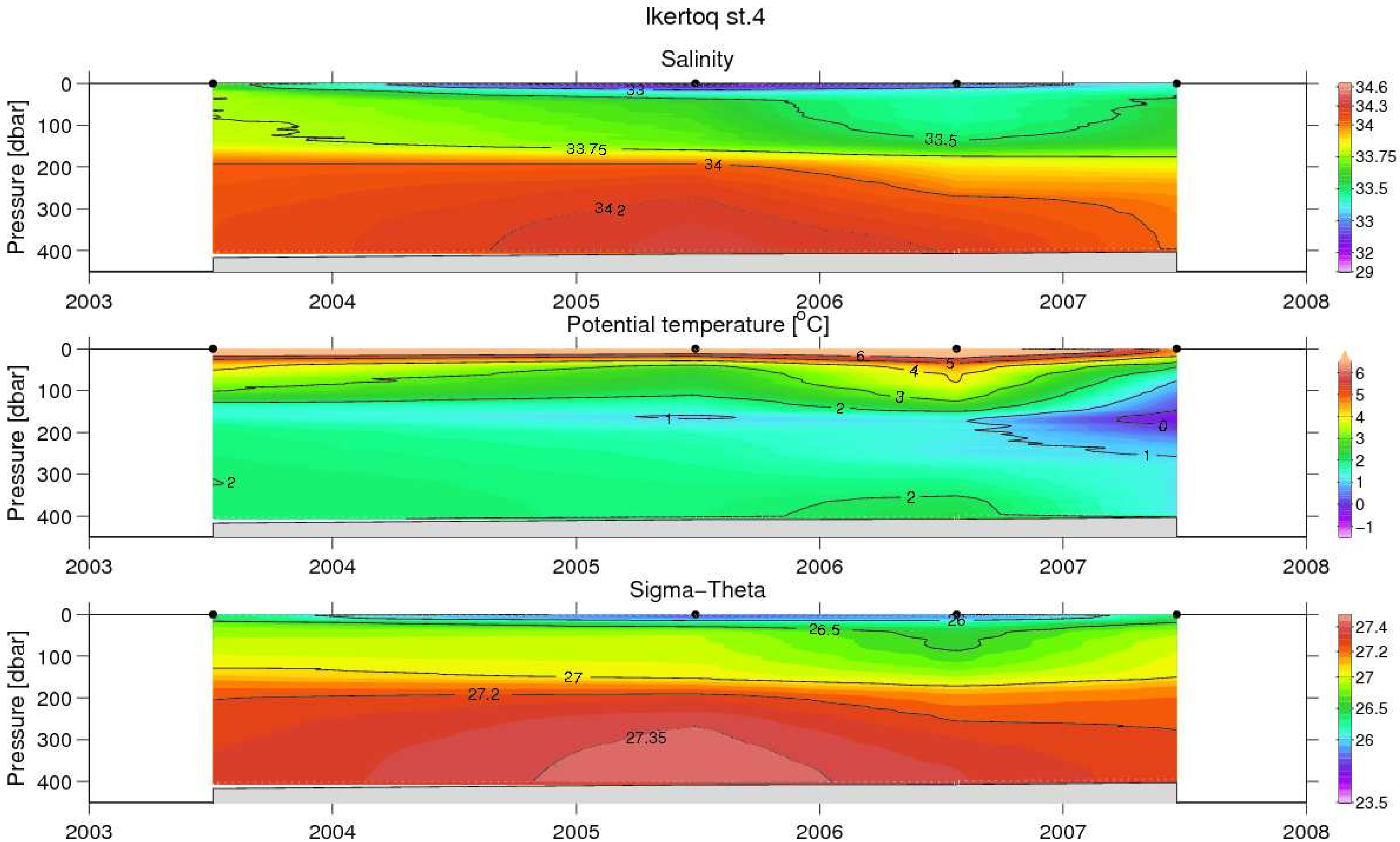


Figure 44**.** Hovmöller diagram of vertical distribution of temperature, salinity and density at the Ikertoq fjord st.4, late June/July 2003, 2005–2007.

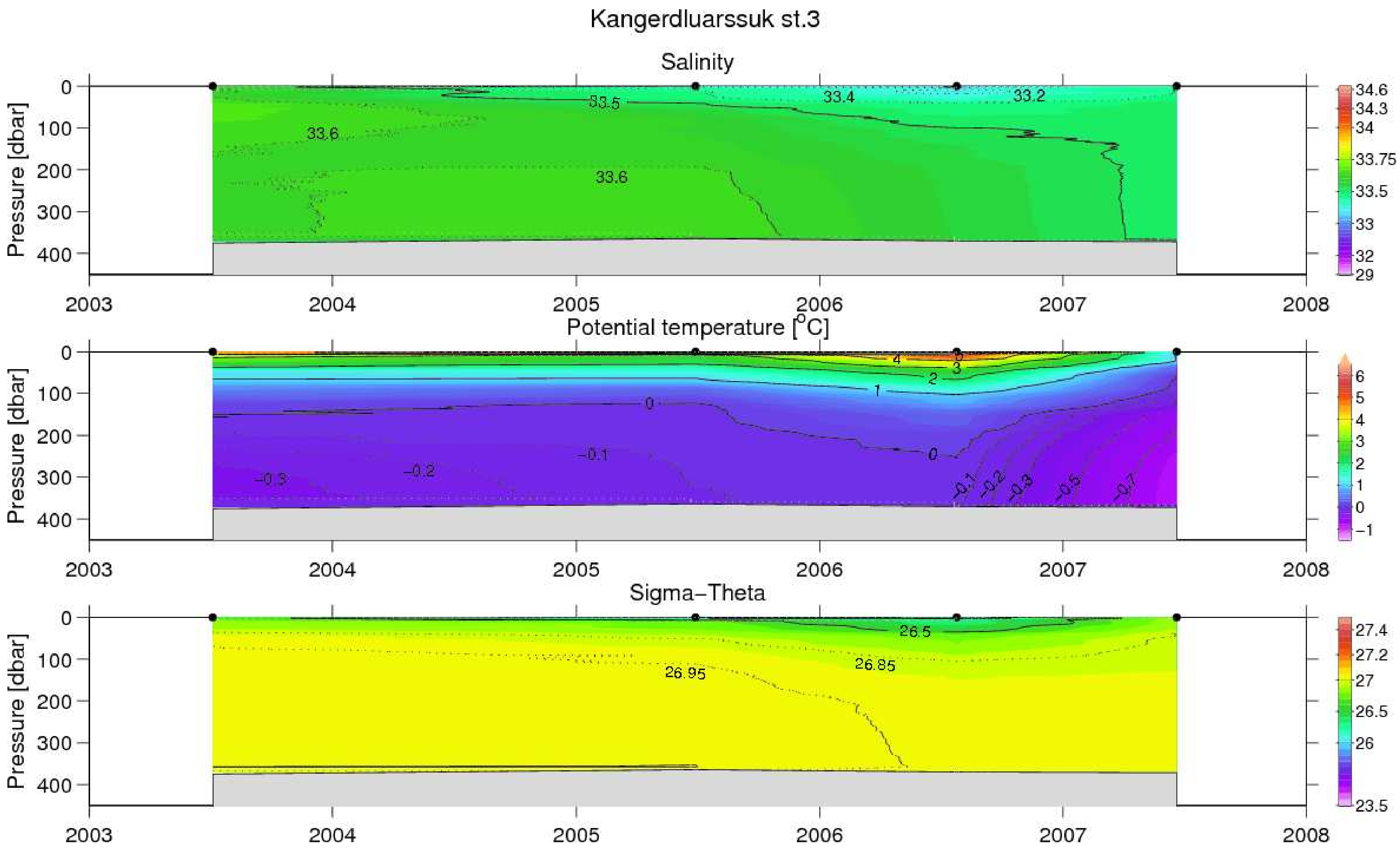


Figure 45. Hovmöller diagram of vertical distribution of temperature, salinity and density at the Kangerdluarssuk fjord st.3, late June/July 2003, 2005–2007.

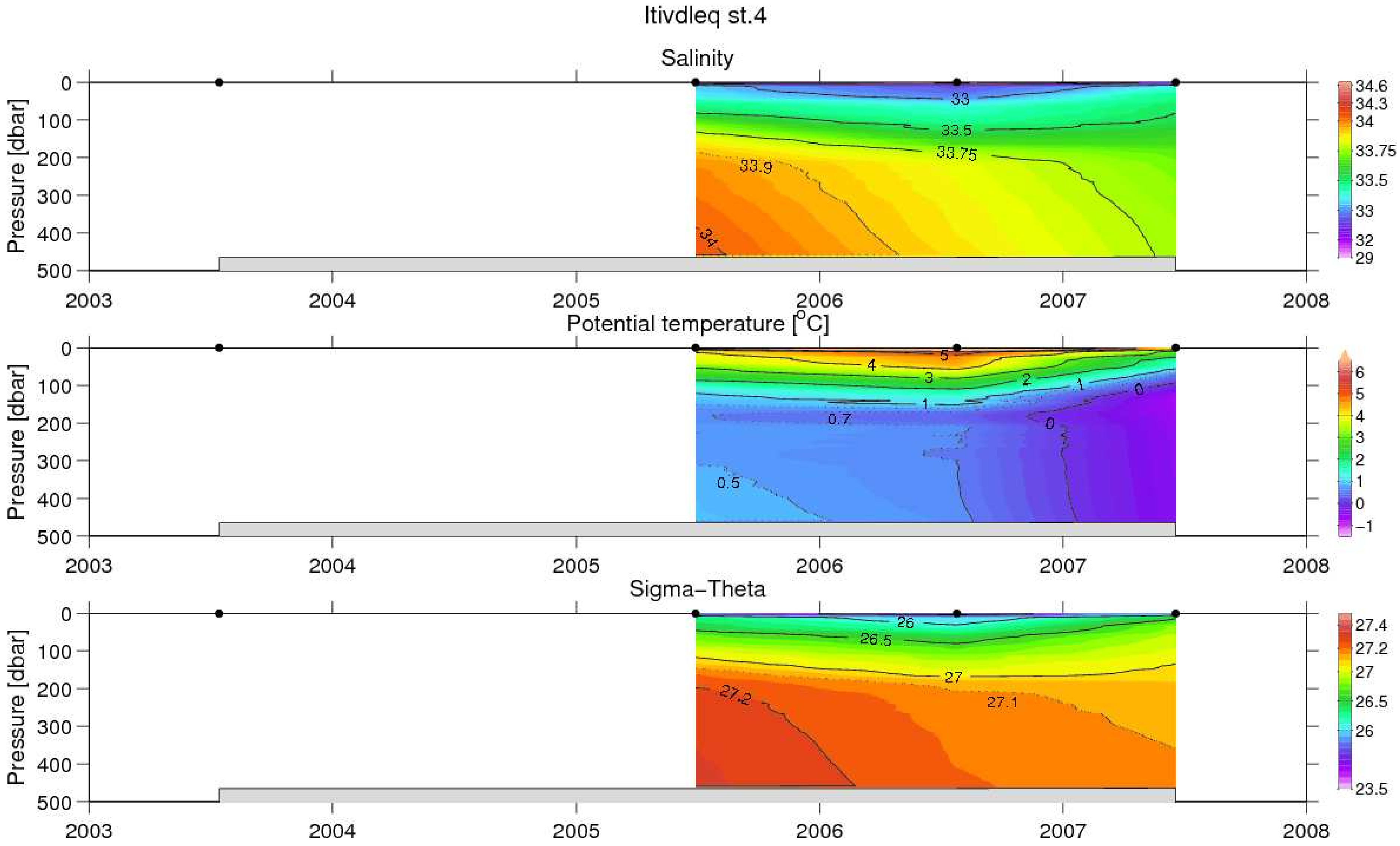


Figure 46. Hovmöller diagram of vertical distribution of temperature, salinity and density at the Itivdleq fjord st.4, late June/July 2005–2007.