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Oceanographic Investigations off West Greenland 2011

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Abstract

The regional hydrography in summer 2011 is presented and discussed based on data from standard sections along the west coast of Greenland and data retrieved during trawl surveys.

In winter 2010/11, the North Atlantic Oscillation (NAO) index was negative describing weakening westerlies over the North Atlantic Ocean. Often this results in warmer conditions over the West Greenland region which was also the case for this winter. The air temperature was higher than normal during winter – especially over the Davis Strait.

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 temperatures 0.4°C above average conditions in 2011 and the salinity was 0.2 above average.

The presence of Irminger Water in the West Greenland waters was high in 2011. Pure Irminger Water (waters of Atlantic origin) could be traced north to the Maniitsoq section and modified Irminger Water further north to the Sisimiut section. The mean (400–600 m) temperature and salinity was high over the Southwest Greenland Shelf Break. After one single year of decrease (Ribergaard, 2011) the bottom temperature and salinity off Ilulissat (st.3) in the Disko Bay has increased again to high values above values before mid-1990.

Introduction to the west Greenland oceanography

This report describe the hydrographic conditions in West Greenland Waters in 2011 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 and then the oceanographic conditions.

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.

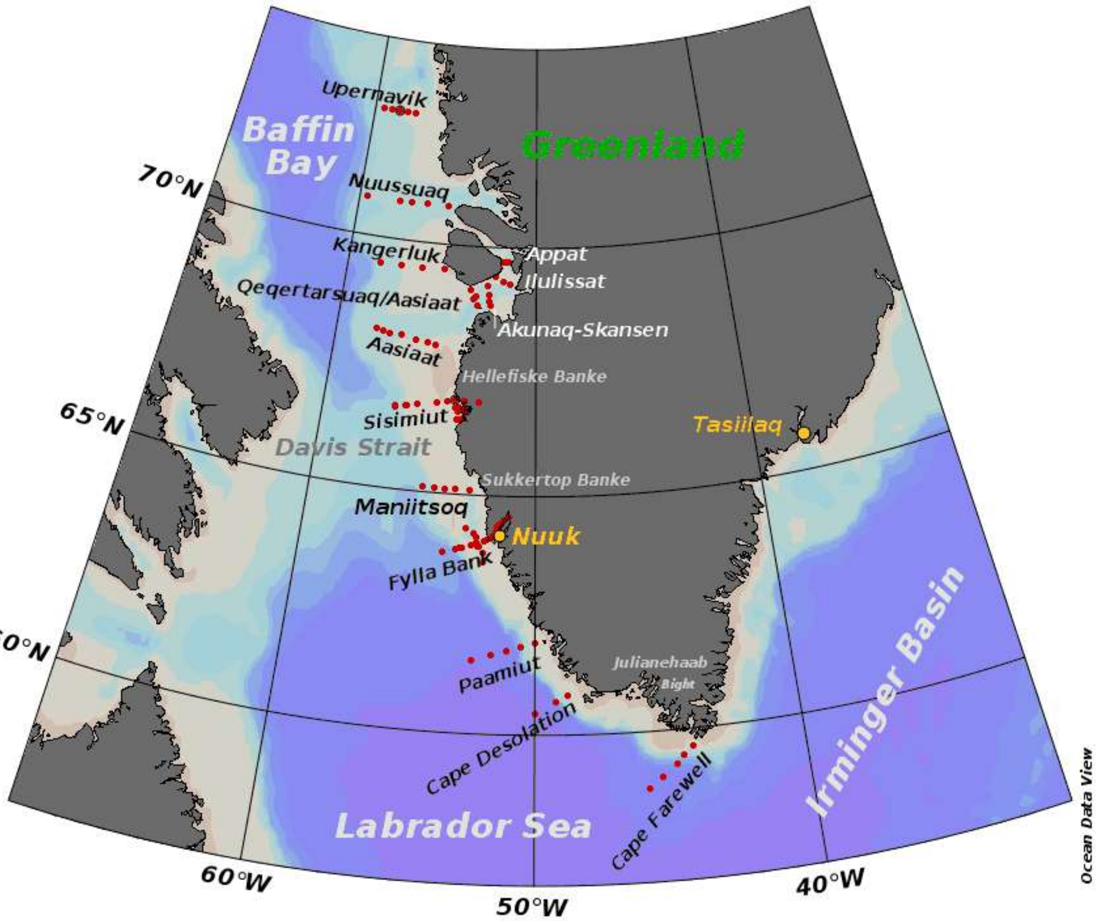

Figure 1. Position of the oceanographic sections off West Greenland where measurements were preformed in 2011. Map produced using Ocean Data View (Schlitzer, 2007).

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 near the bottom. Only the circulation in the upper ~900m will be handled in this report.

The water mass 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.

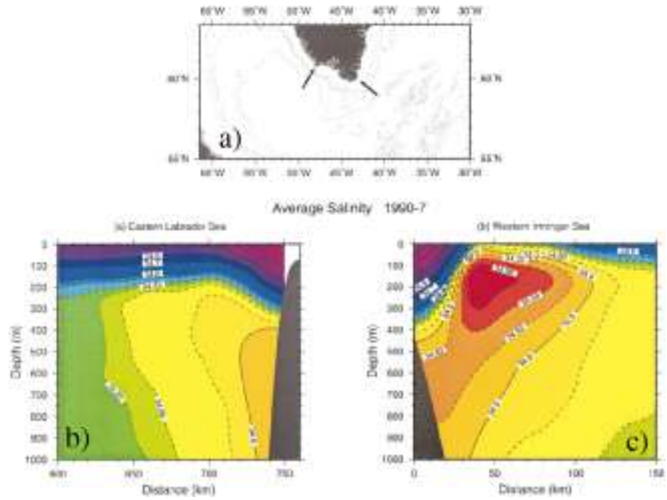

Figure 2. Mean upper-layer salinity sections for the period 1990–1997. Top: Location of the two sections. Isobaths shown: 1000, 2000 and 3000 m. Lower left: Eastern Labrador Basin. Lower right: Western Irminger Basin. From Pickart et al. (2002).

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.

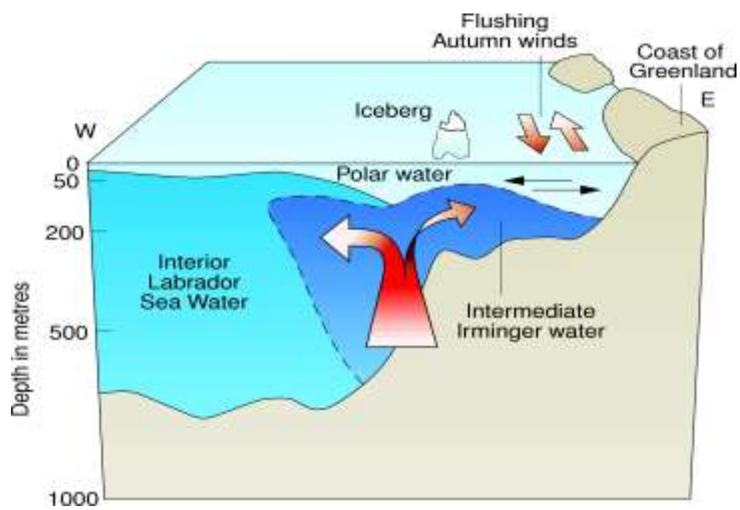

Figure 3. Sketch of the water masses off West Greenland in the Davis Strait region. From Valeur et al. (1997).

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.

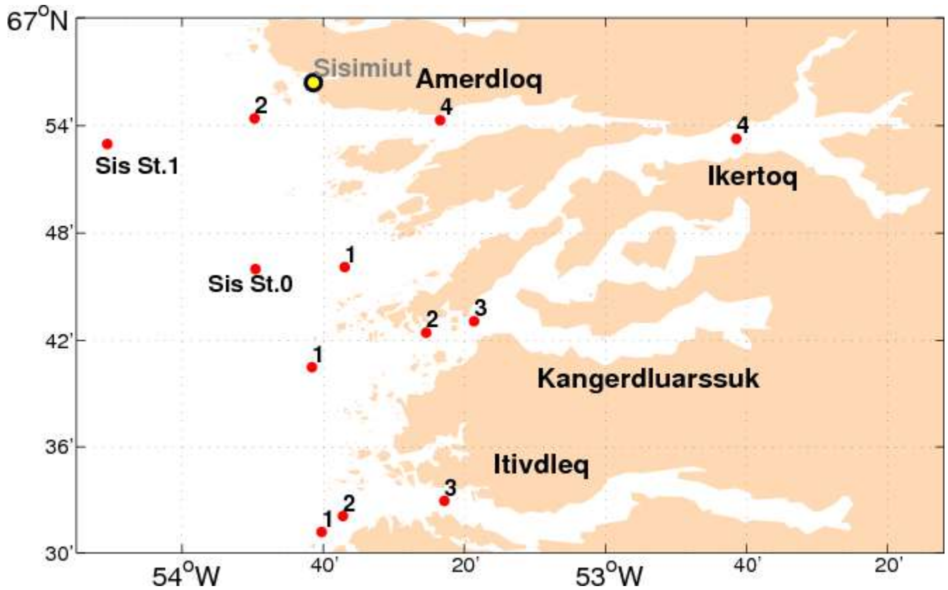

Figure 4. Position of the oceanographic stations around Sisimiut where measurements were preformed in 2011. See Figure 1 for position of all sections measured in 2011.

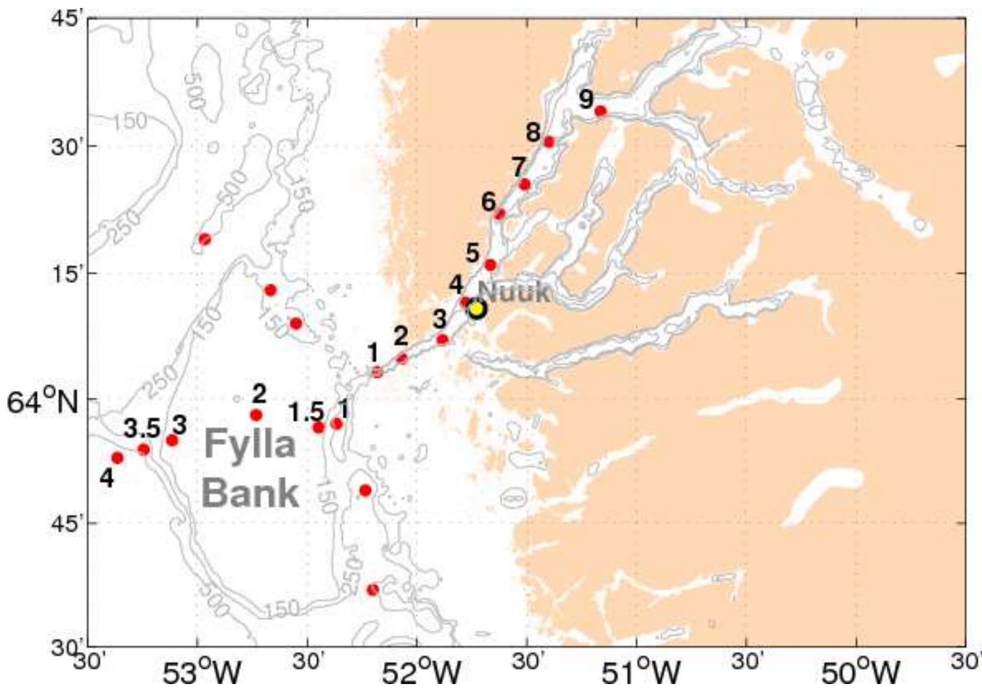

Figure 5. Position of the oceanographic stations in Godthaabfjorden and Fylla Bank. In 2011 measurements were only preformed over Fylla Bank and st. 1–9 in the "main arm" of the Godthaabfjorden. The numbers reefer to standard station numbers as shown in Figure 43. Moreover some additional stations were taken in the channels east of the Fylla Bank. See Figure 1 for position of all sections measured in 2011.

1. Measurements

The 2011 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 28 – July 13, 2011 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 Farewell St. 1–5
- Cape Desolation St. 1–3
- Paamiut (Frederikshaab) St. 1–5
- Fylla Bank St. 1–5
- Maniitsoq (Sukkertoppen) St. 1–5
- Sisimiut (Holsteinsborg) St. 1–5

Additional stations on the Fylla Bank section:

- Fylla Bank St. 1.5, 3.5

Additional stations on the Fylla Bank section:

- Sukkertop dyb: 3 extra stations
- Godthaab dyb: 2 extra stations

Additional stations inside Greenlandic fjords:

- Godthaabfjorden St. 1–9
- Amerdloq St. 2, 4
- Ikertoq St. 1, 4
- Kangerdlussuaq St. 1–3
- Itivdleq St. 1–3

Some of the observations done will directly support ongoing projects within the Greenland Climate Research Centre (GCRC).

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.

Sea-ice was only present at the southern sections which did not have affect on the ability to conduct the stations but delayed the time to reach their positions (Figure 6). Unfortunately, due to the weather conditions in combination with limited time allocated, the Cape Desolation station 4 and 5 was skipped. In addition, station 4 in Itivdleq fjord south of Sisimiut was not measured due to technical reasons.

During the period June 15 – July 10, 2011 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. 1–6, St. 6 (approximate) repeated after 22 days
- Kangerluk (Disko fjord) St. 1–4
- Nuussuaq St. 1–5
- Upernavik St. 1–5

Disko Bay:

- Qeqertarsuaq–Aasiaat (Godhavn–Egedesminde) St. 1−4
- 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 19plus CTD and replaced by a Seabird SBE 9-01 CTD during the cruise due to failure on the instrument. The instruments were lowered with a descent rate of approximately 45 m/min but slower in the upper ~100m. On the Paamiut cruise a Seabird SBE 25plus was used. All sensors were newly calibrated in 2011.

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. 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 25plus and 19plus data, the Seabird program Seasave Ver. 1.59 (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.

2.1. Calibration and accuracy

For the purpose of calibration of the salinity measurements obtained by the CTD, water samples were taken at great depth on stations with depths greater than 500 m in water masses which are to be expected to be relative stable in time due to a week stratification. A Niskin water sampler was mounted on the wire just above the CTD and it was closed close to the bottom using a drop messenger with an expected fall speed above 100 m/min. Due to the nature of the setup we do not know exactly at which time the drop messenger force the water sampler to close and additional the water sample is taken a few meters above the water intake of the CTD. However, the samples are taken in water masses which is to be expected to be very stable/weakly stratified with a CTD fluctuation of about ±0.002, which is similar to the precession of the conductivity sensor. The salinity measurement used is taken as the mean CTD value centred around the expected time of water sampler closure.

For the “DMI” cruise water samples was taken on 9 stations with two replicates on each from the same Niskin water sampler.

Bottle salinities were measured using an Autosal Guildline 8410 portable lab salinometer with a nominal precision of 0.003 in salinity. IAPSO standard seawater references were used purchased from OSIL (www.oscil.co.uk): Batch: P153, K15=0.99979, Practical Salinity 34.992 and to be used by 8th March 2014. The Autosal salinometer was placed in stable temperature environment of ~21.5°C and left to warm up 24 hours prior to standardization, zero calibration and analysis. Bath temperature was set to ~1½ degrees above ambient temperature, 23 °C. The bottle samples were analyzed in one series half a year after the bottle samples were taken. Three flushes followed by three readings were performed for each bottle and the mean error between CTD salinity and bottle salinities could be estimated with at precision of 0.002.

To our surprise, the replicates did not reproduce each other and are useless. Expect for the last "sample pair" the values measured from the first bottle taken in-situ was higher than the second. A possible explanation could be, that the water sampler did leak at the top cap. This will lead to a stratification within the sampler results, as the water sampler slowly entrain small quantities of less saline waters on accenting. As we tab water for salinity bottles at the bottom of the Niskin water sampler, the highest salinities is obtained on the first water tapped. Based on the former years use/calibration of the SBE9-01, the offset is usually on the forth digit after comma, with observations higher than CTD readings.

For the “R/V PAAMIUT” cruise water samples was taken on 12 stations with two replicates on each from the same Niskin water sampler. However 6 bottles was broken and 18 bottles remains. Bottle salinities were measured using an Autosal Guildline 8410 portable lab salinometer with a nominal precision of 0.003 in salinity. The mean offset between CTD and bottle data was 0.0063 +/- 0.0120 (CTD highest). The standard deviation was high, but no obvious outliers were found. Expect of two bottle samples the salinities was fairly similar, which prevent us to determine a possible slope as a function of salinity. It was decided not to correct the salinity.

For SBE 9-01, the nominal temperature sensor accuracy is +/- 0.001°C with an instrument resolution of about 0.0001°C. The real accuracy is likely better than the nominal temperature accuracy judging the weak drift of the sensor between calibrations. Nominal sensor (pressure) accuracy is 0.015% of full scale (3400 m) corresponding to about half a meter on maximal depth with a similar annual drift. The accuracy is 0.001% of full scale corresponding to a few centimeters.

For SBE 19plus, the nominal temperature sensor accuracy is +/- 0.005°C with an instrument resolution of about 0.0002°C. The real accuracy is likely better than the nominal temperature accuracy judging the weak drift of the sensor between calibrations. Nominal sensor (pressure) accuracy is 0.02% of full scale (3500 m) corresponding to about 0.7 meter for maximal depth with a similar annual drift. The accuracy is 0.0025% of full scale corresponding to less than 10 centimeters.

For SBE 25, the nominal temperature sensor accuracy is +/- 0.001°C with an instrument resolution of about 0.0003°C. Nominal sensor (pressure) accuracy is 0.1% of full scale (2000 m) corresponding to about 20 meters on maximal depth. The accuracy is 0.015% of full scale corresponding to roughly 30 centimeters.

2.2. Data Processing

The CTD data were analysed using SBE Data Processing version 5.37d software provided by Seabird (www.seabird.com). A chain of standard processing tools was used:

- *Data Conversion*: After calibration, raw data from the CTD (HEX format) are
- converted to engineering units including pressure, in situ temperature and salinity.
- *Filter*: Pressure readings are initially high pass filtered two ways in order to smooth high frequency data and to obtain a uniform descent history of the cast.

Filter: Instrument	Temperature (seconds)	Conductivity/Salinity (seconds)	Pressure (seconds)
SBE 9-01			0.15
SBE 19plus	0.5	0.5	1.0
SBE 25		0.03	0.5

- *Align CTD*: Inherent misalignment time delay in sensor responses and transit time delay in the pumped pluming line are corrected by advancing the measurements relative to pressure. By alignment, measurements refer to same parcel of water and the procedure eliminated artificial spikes in the calculated profiles especially in steep gradients.

Align CTD: Instrument	Temperature relative to pressure (seconds)	Conductivity/Salinity relative to pressure (seconds)	Oxygen relative to pressure (seconds)
SBE 9-01		0.073	
SBE 19plus	0.5		7.0
SBE 25		0.1	7.0

- *Loop Edit*: The tool removes scans with slow descent rate or reversals in pressure. Minimum descent rate is chosen between 0.1 and 0.2 m/s.
- *Derive* and *Bin Average*: A number of derived parameters is included (eg. potential temperature and density) and post processed data is averaged into 1 dbar bins

Some of the CTD profiles taken by the SBE 9-01 showed oscillating behaviour forming spurious peaks. This was also seen during the 2010 cruise (Ribergaard, 2011). At that time it was concluded it might be due to an unstable conductivity sensor, as a change of the pump did not solve the problem. However as the conductivity sensor has been send to Seabird in the meantime, it is obvious not the problem and a total inspection of the instrument is suggested.

However, due to the tight time schedule, the cruise was continued using the instrument, as the profiles looks fairly ok disregarding the peaks and therefore there was hope that the main part of the errors could be corrected/filtered out after the cruise. With this decision more stations were taken, however with a poorer result.

The peaks were after the cruise removed from the raw timeseries before the data processing and calibration describing above was started. Initial, the local peaks were found using a fixed time window for defining a local peak and data around the peaks are marked bad. Then a linear interpolation is done on the timeseries to replace these bad data. The procedure is identical to what has been done for the 2010 data and an example of the procedure can be found in Ribergaard (2011).

The resulting profiles are obvious not as accurate as the rest of the profiles. Data interpolated to 1 dbar in the vertical still makes small oscillation fluctuations with a maximal amplitude of about 0.002–0.003. However if data is not needed in 1 dbar resolution a simple running mean filter will remove the major part of the fluctuations.

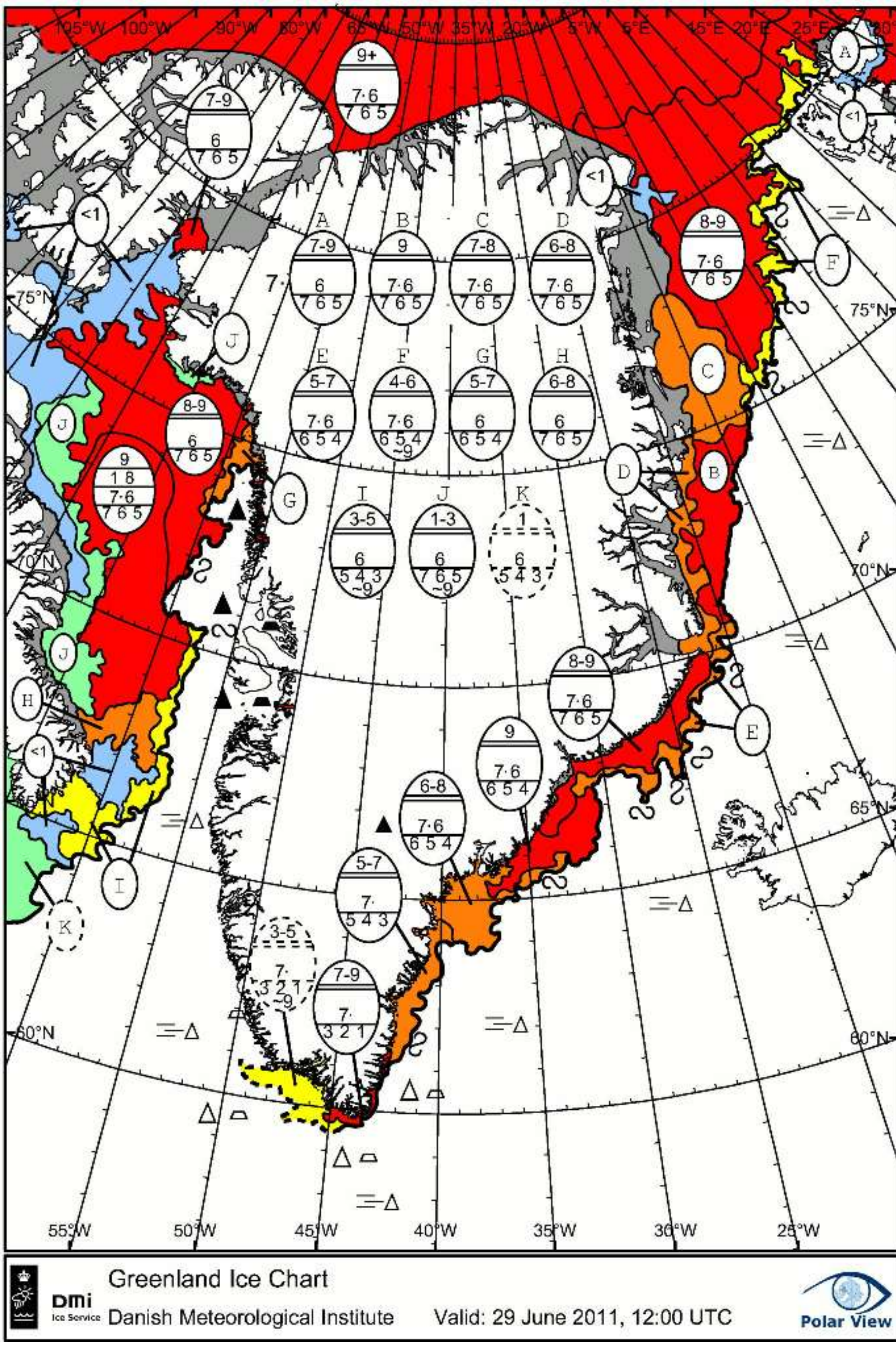

Figure 6. Distribution of sea ice in Greenland Waters valid for 29. June 2011.

3. Atmospheric conditions in 2011

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 2010/11 was negative[1] (Figure 2).

The mean low pressure route during the winter months (December–Marts) was similar to normal from Labrador, across Iceland and further towards Northern Norway (Figure 8a). However, the Icelandic Low and Azores High was both weakened (Figure 8b), resulting in weaker westerlies over the North Atlantic Ocean compared to normal conditions[2] (Figure 9).

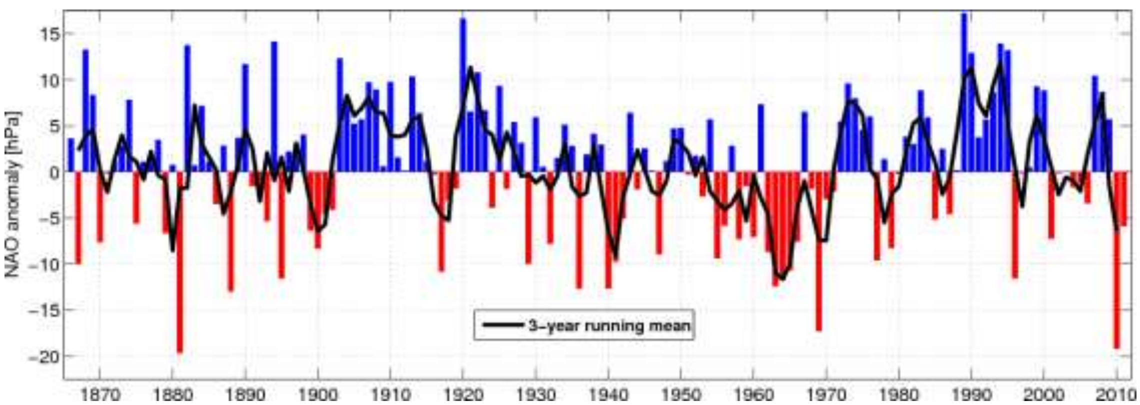

Figure 7. Time series of winter (December–March) index of the NAO from 1865/1866–2010/11. The heavy solid line represents the NAO index smoothed with a 3-year running mean filter to remove fluctuations with periods less than 3 years. In the figure the winter 1865/1866 is labelled 1866 etc.. The mean and standard deviation is 0.71 ± 7.5 hPa. The 2010/11 value is -5.93 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 warm conditions when the NAO index is negative. During winter 2010/11, the mean temperature was above normal over the West Greenland region and cold in northern Europe (Figure 11). In Nuuk the mean winter air temperature (DJFM) was above normal (Figure 12).

However, the annual temperature anomaly for 2011 was slightly negative or zero in the southwest Greenland waters, while the western Labrador Sea and Baffin Bay experienced slightly higher temperatures than normal (Figure 13). In Nuuk, the 2011 air temperatures was above normal in June, July and August, as well as in January, but below normal for the remaining 8 months (Cappelen, 2012) resulting in an annual mean temperature slightly below normal (Figure 14).

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

2 Normal conditions/anomaly defined as the difference from normal conditions relative to the period 1968–1996.

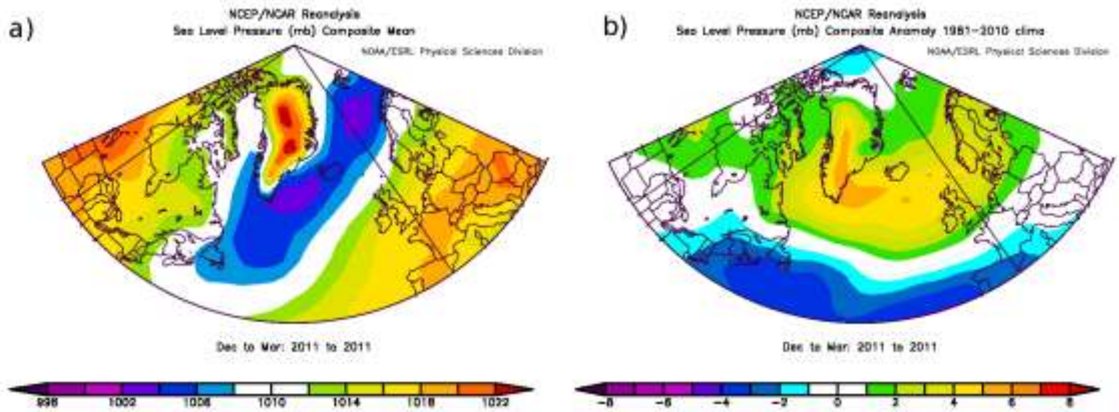

Figure 8. a) Winter (DJFM) sea level pressure for 2010/11 in the North Atlantic region. b) Sea level pressure anomaly. NCEP/NCAR re-analysis (from http://www.esrl.noaa.gov/psd/).

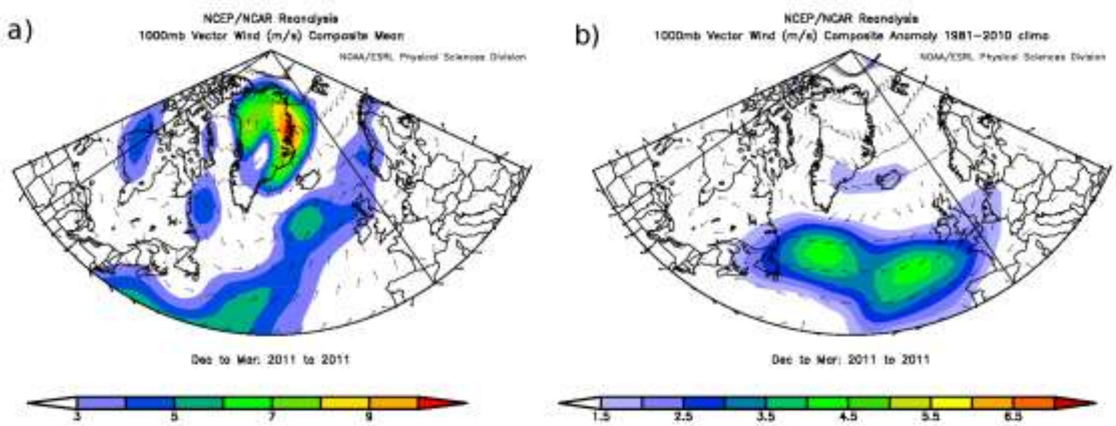

Figure 9. a) Winter (DJFM) wind (left) for 2010/11 in the North Atlantic region. b) Wind anomaly. NCEP/NCAR re-analysis (from http://www.esrl.noaa.gov/psd/).

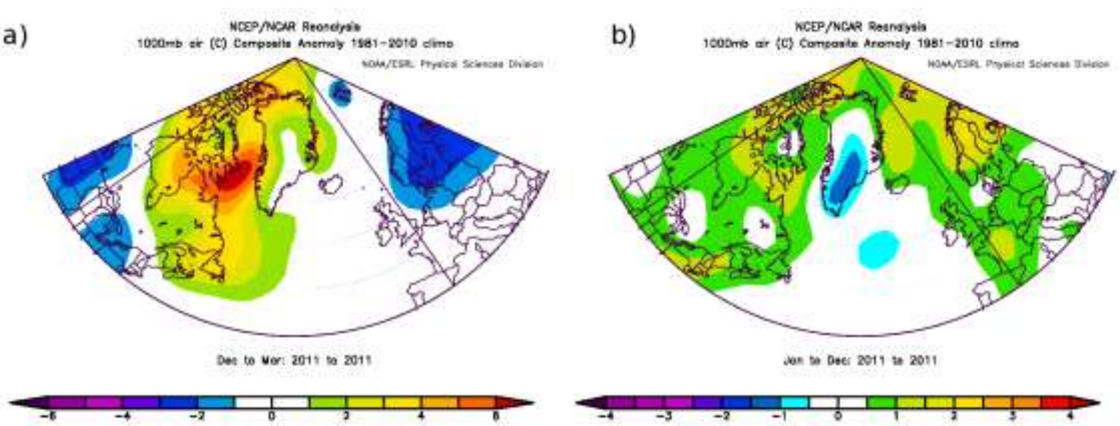

Figure 10. a) Winter (DJFM) mean air temperature anomaly for 2010/11 in the North Atlantic region. b) Annual mean air temperature anomaly for 2011. NCEP/NCAR re-analysis (from http://www.esrl.noaa.gov/psd/).

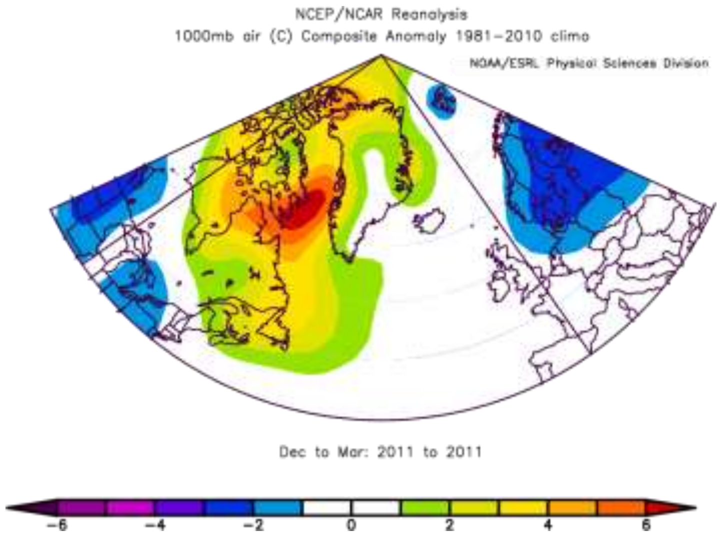

Figure 11. Winter (DJFM) mean air temperature anomaly for 2010/11 in the North Atlantic region. NCEP/NCAR re-analysis (from http://www.esrl.noaa.gov/psd/).

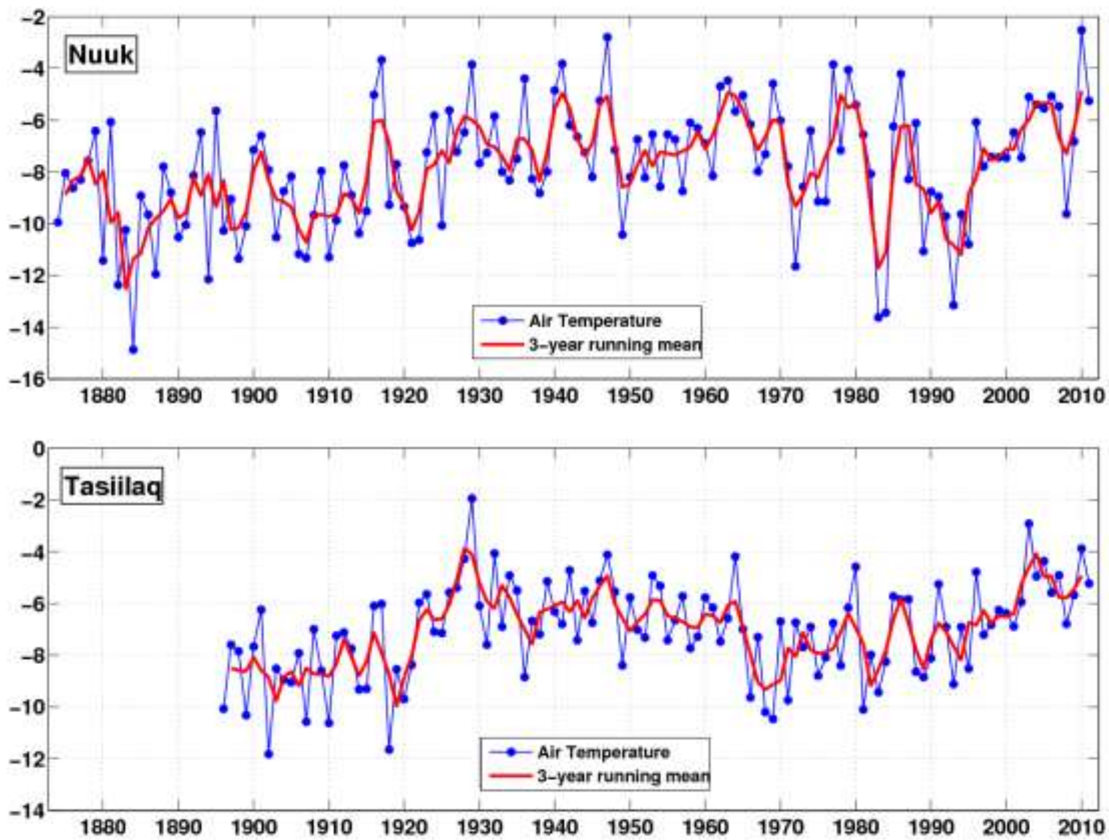

Figure 12. Winter (DJFM) mean air temperature observed at Nuuk and Tasiilaq for the period 1874–2011. The mean and standard deviation for the whole timeseries is -7.9 ± 2.3 °C for Nuuk and -7.0 ± 1.8 °C for Tasiilaq. Values for 2011 are respectively -5.26 °C and -5.24 °C. Nuuk temperature was taken from the Nuuk airport synop station 04254 due to a failure on the instrument (Nuuk synop 04250) for more than 65% of the following months (yyyymm): 200505, 200710, 200712, 200811, 201101.

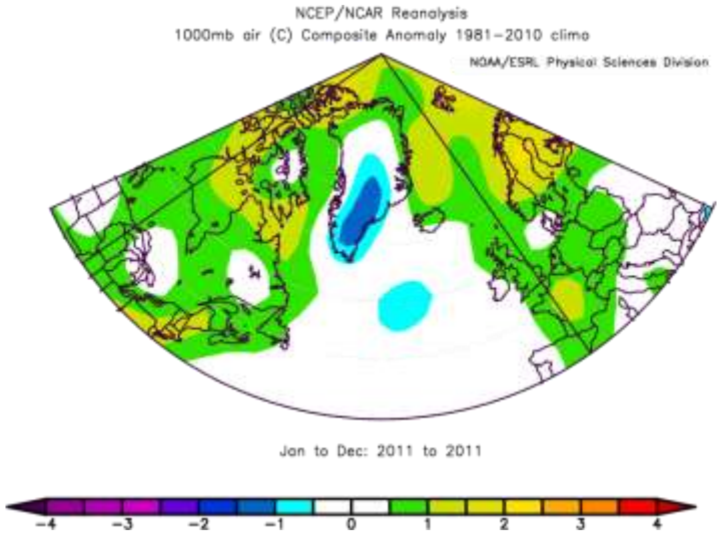

Figure 13. Anomalies of the annual mean air temperature for 2011 in the North Atlantic region. NCEP/NCAR re-analysis (from http://www.esrl.noaa.gov/psd/).

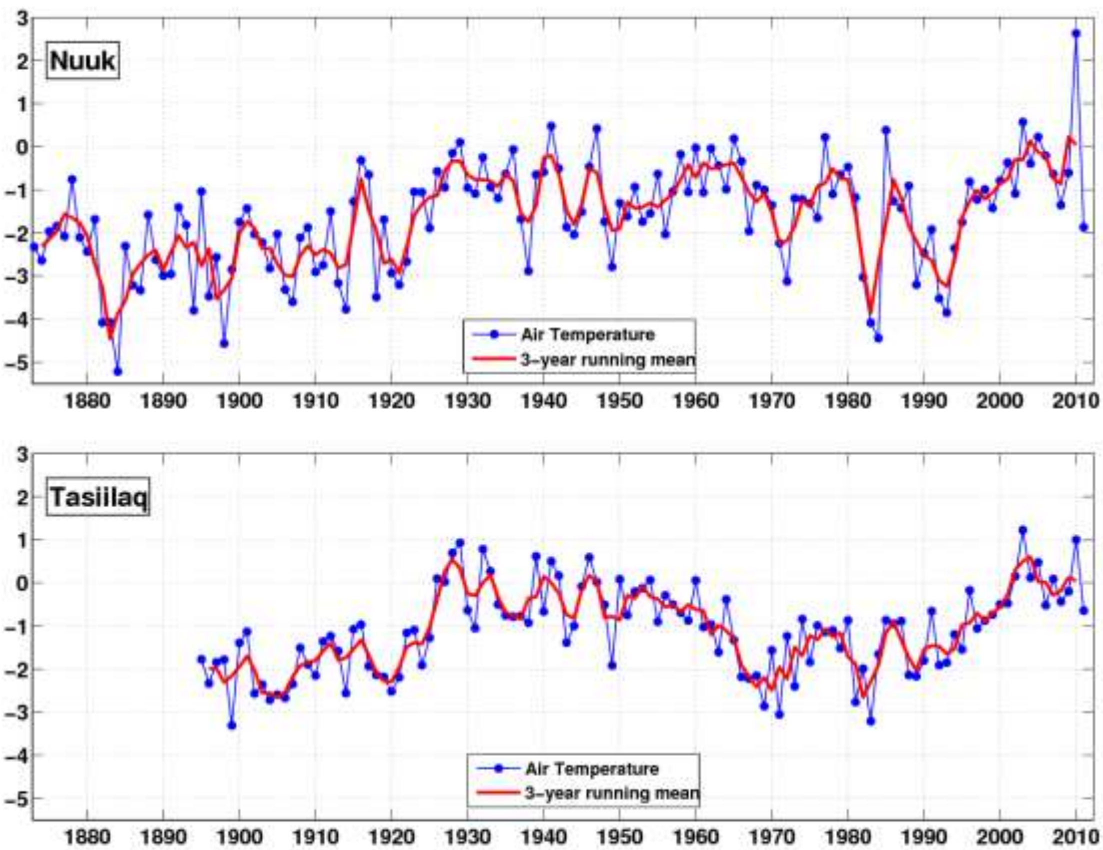

Figure 14. Annual mean air temperature observed at Nuuk and Tasiilaq for the period 1873–2011. The mean and standard deviation is -1.64 ± 1.25 °C for Nuuk and -1.11 ± 1.00 °C for Tasiilaq. Values for 2011 are respectively -1.72 °C and -0.64 °C. Nuuk temperature was taken from the Nuuk airport synop station 04254 due to a failure on the instrument (Nuuk synop 04250) for more than 65% of the following months (yyyymm): 200505, 200710, 200712, 200811, 201101.

4. Oceanographic conditions off West Greenland in 2011

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 2011 the mean temperature (2.25ºC) and salinity (33.61) was above average on top of Fylla Bank in the middle of June.

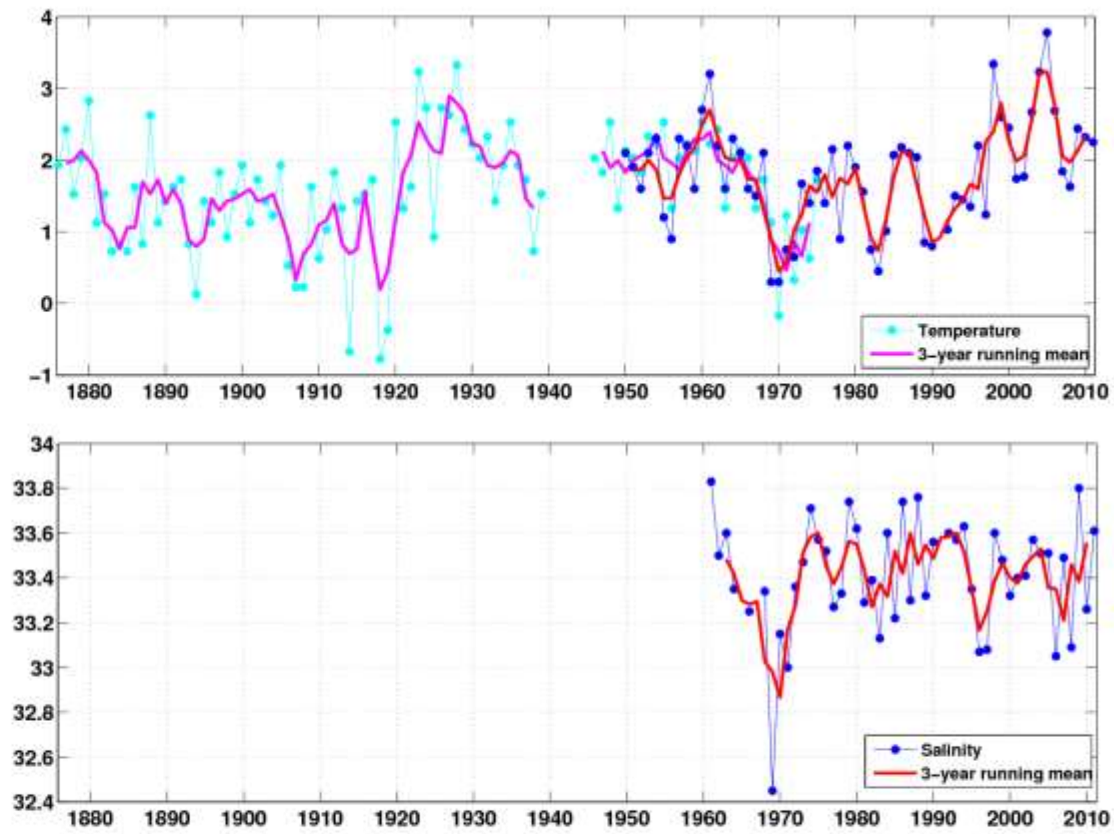

Figure 15. Timeseries of mean temperature (top) and salinity (bottom) on top of Fylla Bank (Station 2, 0–40 m) in the middle of June for the period 1950–2011. The red curve is the 3 year running mean value. Statistics is shown in Table 1. The timeseries for temperature (top, magenta/purple) is extended back to 1876 using Smed-data for area A1 (Smed, 1978). See Ribergaard et al. (2008) for details.

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. Means are calculated on the full timeseries using all years with measurements. Smed data are not included for the statistics.

Fylla Bank	Temperature [°C]	Salinity	2011	
St. 2	Mean ± std	Mean ± std	Tpot	S
0–40 m	1.81 ± 0.74°C	33.41 ± 0.25	2.25°C	33.61

A vertical section of salinity, temperature and density over the shelf from Cape Farewell to Upernavik is shown in Figure 27. Polar Water is found in the upper ~100 m up to Paamiut with salinities mainly below 33.4 and cold (<1°C) sub-surface temperatures. At Fylla Bank the salinities has increased due to mixing but the salinity remains quite low below about 34. From Aasiaat and further north Polar Water originating from the Baffin Current is found in the upper ~100 m revealed by its cold core temperatures below -1 °C.

West of Fylla Bank in the depth interval 50–150 m where the core of Polar Water is found, the salinity and temperature was close to average conditions (Figure 18 and Table 2). Further north at Maniitsoq st.5 (Figure 20, Table 3) and Sisimiut st.5 (Figure 21, Table 4), the salinities and in particular the temperatures was above normal in the same depth interval, likely illustrating Polar Water progressing slowly northward and which haven't reached the latter stations yet.

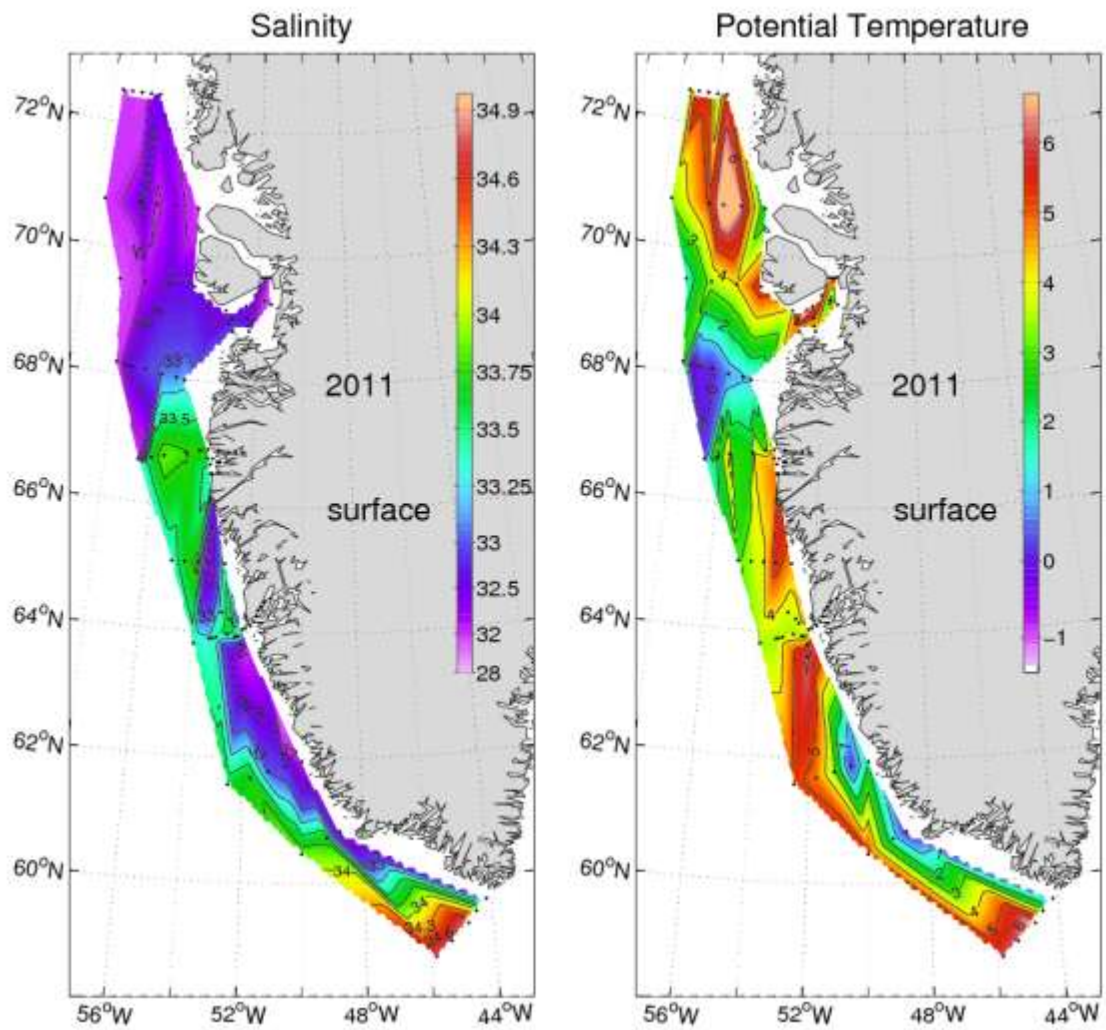

Figure 16. Surface salinity (left) and temperature (right) observed in 2011 taken June 15 – July 13.

The surface temperatures and salinities observed during the 2011 cruise are shown in Figure 16. 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. During the present cruise it can be traced north to Fylla Bank revealed by its low salinity, whereas water of Atlantic origin (T>3°C; S>34.5) is found only on the Cape Farewell section at the surface. However, it was likely found on the Cape Desolation section further offshore station 3, but no measurements was taken in this area in 2011.

In the Baffin Bay the highest salinities reflect the core of the West Greenland Current, which is slightly modified by Atlantic Water. However, in 2011 it was not as easily seem as previous years reflecting newly arrived Polar Water originating from the Baffin Current. In the Disko Bay the lowest surface salinities is due to the runoff from the large outlet glaciers and also partly 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 17). The coldest waters <-1°C observed in the subsurface of the Baffin Bay are likely cold Polar Water from the Baffin Current originating from the Arctic Ocean through the Canadian Archipelago as suggested by Tang et al (2004). The upper part of this water is easily recognized in Figure 17 and in its core in Figure 23. In late June 2011 Baffin Bay Polar Water was also present at south as the outermost station on the Sisimiut section reflected by the cold average temperature in the upper 50m below 0°C (Figure 33). This water mass was not seen two weeks earlier in mid-June (Figure 34) reflecting the temporal dynamic of the front.

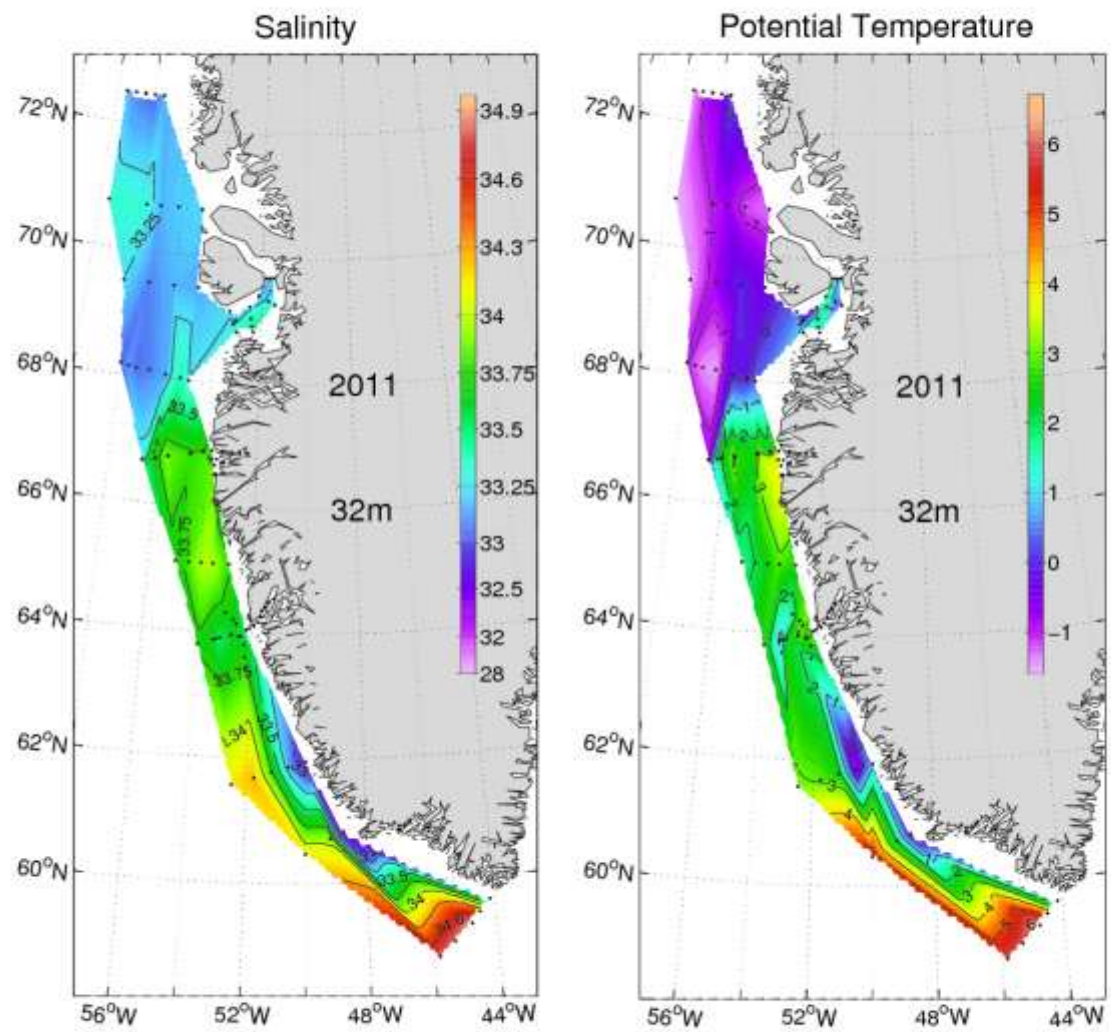

Figure 17. As Figure 16, but for 32 m depth.

At intermediate depths water of Atlantic origin forms a layer with maximum salinity and temperature. Horizontal maps of salinity and temperature at depth of maximal salinity and maximal temperature are shown in Figure 24 and Figure 25. A vertical section of salinity, temperature and density over the shelf break from Cape Farewell to Upernavik is shown in Figure 26. The vertical distribution of temperature, salinity and density at sections along the West Greenland coastline is shown in Figure 28 − Figure 38 and within the Disko Bay in Figure 39 – Figure 42.

Pure Irminger Water ($T \geq 4.5^oC$; $S \geq 34.95$) was traced north to the Maniitsoq section and modified Irminger Water ($T \geq 3.5^oC$; $34.88 \leq S < 34.95$) was observed further north to Sisimiut section. The northward extension of Irminger Water may indicate intensified inflow of water of Atlantic origin to the West Greenland area.

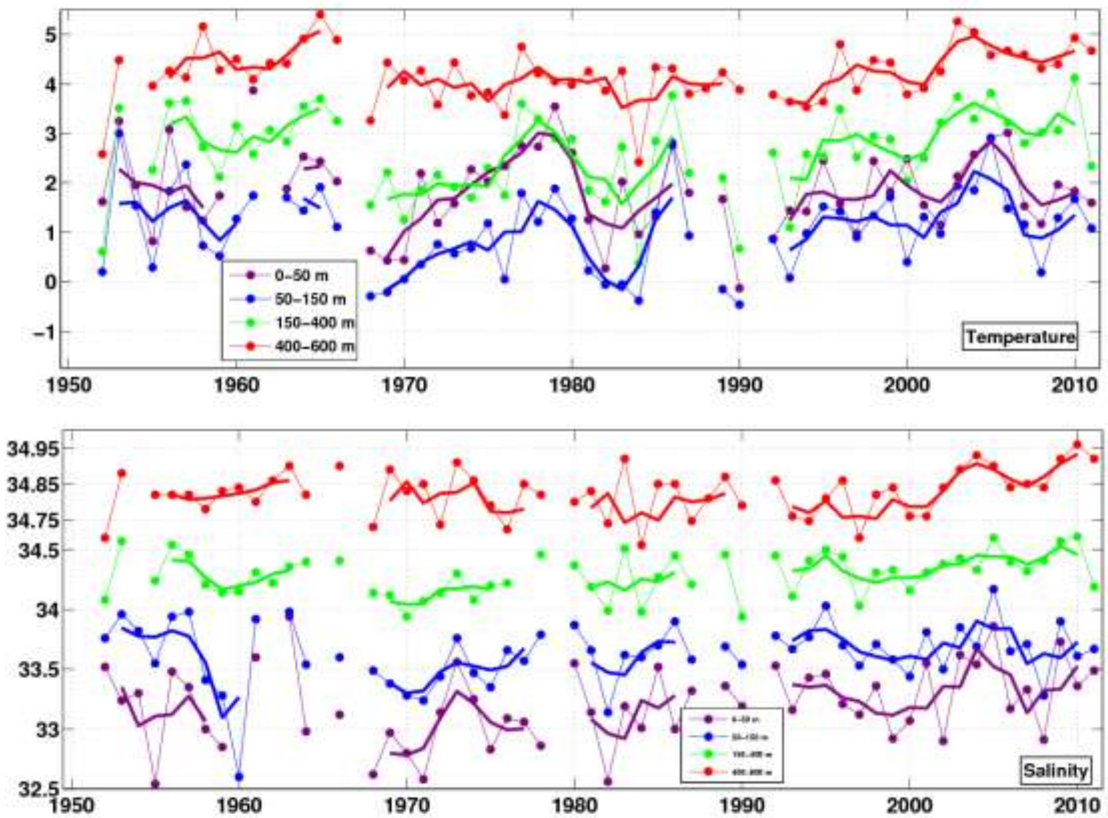

Figure 18. Timeseries of mean June-July temperature (top) and salinity (bottom) for the period 1950–2011 averaged in four different depth intervals west of Fylla Bank (st.4) over the continental slope. Thick curves are the 3 year running mean values. Note the change in scales at 34.75 for salinity. Statistics are shown in Table 2.

Table 2. Statistics for potential temperature and salinity at Fylla Bank st. 4. and values for 2011.

Fylla Bank St.4	Temperature [°C]	Salinity	2011	
	Mean ± std	Mean ± std	Tpot	S
0–50 m	1.85 ± 0.84°C	33.21 ± 0.32	1.60°C	33.49
50–150 m	1.04 ± 0.83°C	33.63 ± 0.26	1.08°C	33.67
150–400 m	2.61 ± 0.86°C	34.29 ± 0.18	2.34°C	34.19
400–600 m	4.20 ± 0.57°C	34.82 ± 0.08	4.67°C	34.92

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 average salinity (34.92) and temperature (4.67°C) of this layer was well above average (Table 2). This indicates, that the presence of Irminger Water in 2011 was still high compared to normal. Similar timeseries west of the banks further north at Maniitsoq st.5 (Figure 20, Table 3) and Sisimiut st.5 (Figure 21, Table 4) confirms, that the Irminger Water component of the West Greenland Current still brings considerable amount of heat and salt to the area in 2011.

The bottom temperature and salinity within the Disko Bay just outside Ilulissat (”Jakobshavn”) at Skansen-Ilulissat st.3 has again increased to values well above average conditions after the surprisingly decrease in 2010 (Ribergaard, 2011). The high values are in line with the high presence of Irminger Water in 2011.

From the Sisimiut 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 in its core) with its center at about 75 m depth which is likely Polar Water from the Baffin Current as described above. Below this cold subsurface layer, a relative warm (> 3°C) water mass was found below 150–200 m. This water is the extension of the Irminger Water component of the West Greenland Current.

The temporal changes in the water mass characteristics over two weeks on the Sisimiut section can be seen by comparing Figure 34 and Figure 33. During these two weeks the presence of Irminger Water has reduced shown by decreased salinity and temperature below ~250m. At the westernmost station Polar Water from the Baffin Bay, reflected by cold average temperature in the upper 50m below 0°C, was only present during the latter survey.

Noticeably, since the early 2000s, the mean salinity and temperature of the Irminger Water at 400–600 m depth west of Fylla Bank (Figure 18.) “Sukkertop Banke” (Figure 20) and “Store Hellefiskebanke” (Figure 21) 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 recommended 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.

West Greenland fjords 2011

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. 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 depth (Straneo et al, 2010)

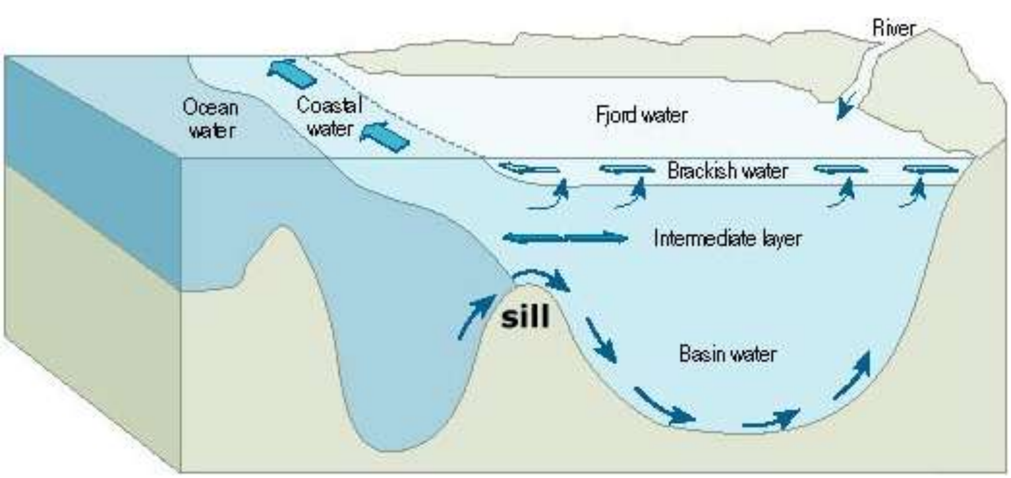

Figure 19. Sketch of the circulation in a fjord (modified from AMAP Assessment Report: Arctic Pollution Issues, Figure 3.20, http://www.amap.no/maps-gra/show.cfm?figureId=58).

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. 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.

Measurements from the fjords taken in 2011 is shown in Figure 43 – Figure 47. For the fjords south of Sisimiut, measurements have been taken several years and Howmüller diagrams are shown in Figure 48 – Figure 51. The Howmüller diagrams reveals relatively high bottom temperatures and salinities in 2011 at the bottom in the fjords with deeper sills allowing relative deep waters to enter consistent with a high Irminger Water presence in Southwest Greenland Waters in 2011. For the shallow sill fjord Kangerluarssuk (Figure 50), the bottom temperature was relative high.

Conclusions

Atmospheric and oceanographic conditions off West Greenland during the summer 2011 were characterised by:

- Negative NAO index resulting in weakening westerlies over the North Atlantic during winter 2010/11.
- Winter air temperature over West Greenland waters was warmer than normal and colder over the northern Europe consistent with negative NAO index. However the annual temperature over Southwest Greenland waters was slightly below normal in 2011, reflecting lower mean temperatures than normal from spring and onwards.
- High presence of Irminger Water and below normal presence of Polar Water indicated by:
    - Pure Irminger Water was observed on all section from Cape Farewell to Maniitsoq and modified Irminger Water at the Sisimiut section.
    - West of Fylla Bank, “Sukkertop Banke” and “Store Hellefiskebanke”, the mean temperature and salinity in 400–600 m depth was high. Similar high values were found off Ilulissat at 300 m depth.
    - Water temperature and salinity on top of Fylla Bank was above average.
    - Low saline water on top of the shelf from Cape Farewell to Paamiut was observed in the upper ~50–100 m. West of Fylla Bank in 50-150 m depth about average salinities and temperatures was observed. Further north the average salinities and temperatures was higher than normal indicating lower than normal presence of Polar Water especially at the northern sections. However the Polar Water could be underway reflected by the higher presence further south.

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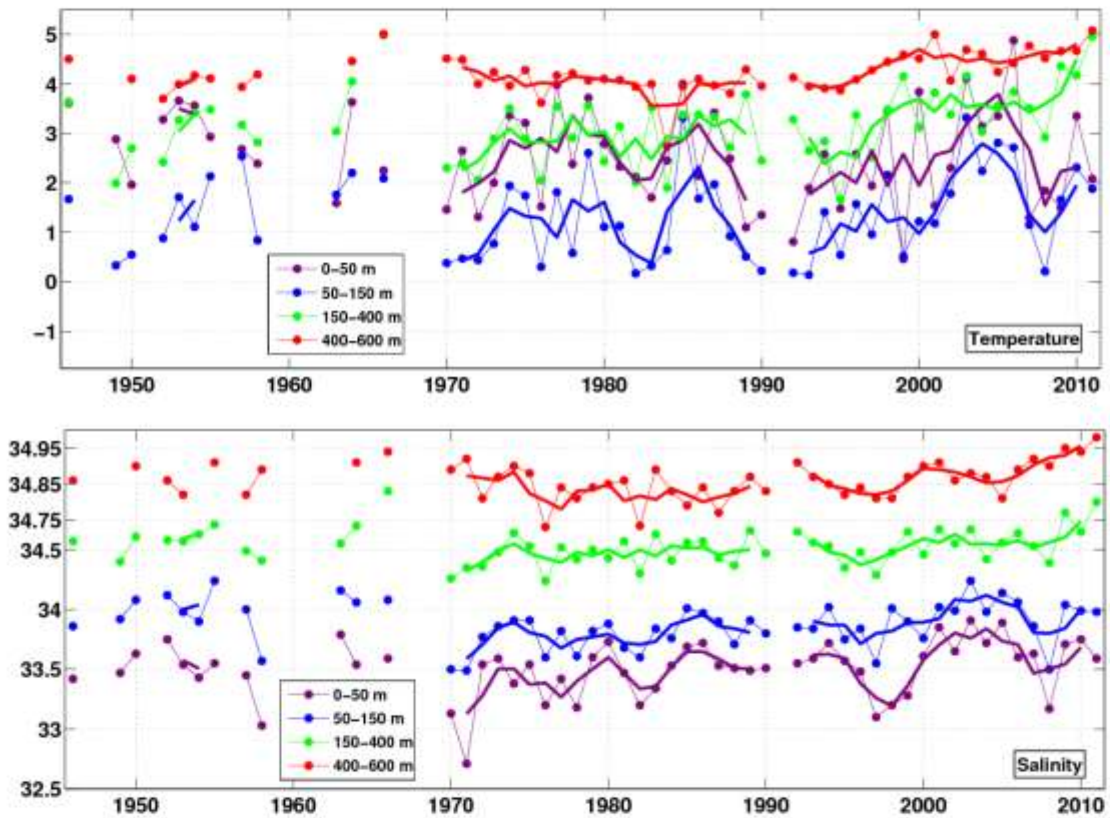

Figure 20. Timeseries of mean temperature (top) and mean salinity (bottom) for the period 1946–2011 in four different depth intervals west of “Sukkertop Banke” (Maniitsoq, st.5) over the continental slope. The thick curves are the 3 year running mean values. Note the change in scales at 34.75 for salinity. Statistics is shown in

Table 3.

Table 3. Statistics for potential temperature and salinity at Maniitsoq (Sukkertoppen) st. 5. and values for 2011.

Maniitsoq St.5	Temperature [°C]	Salinity	2011	
	Mean ± std	Mean ± std	Tpot	S
0–50 m	2.53 ± 0.97°C	33.51 ± 0.23	2.08°C	33.59
50–150 m	1.34 ± 0.86°C	33.88 ± 0.19	1.88°C	33.98
150–400 m	3.17 ± 0.74°C	34.53 ± 0.14	4.96°C	34.80
400–600 m	4.22 ± 0.39°C	34.86 ± 0.06	5.08°C	34.98

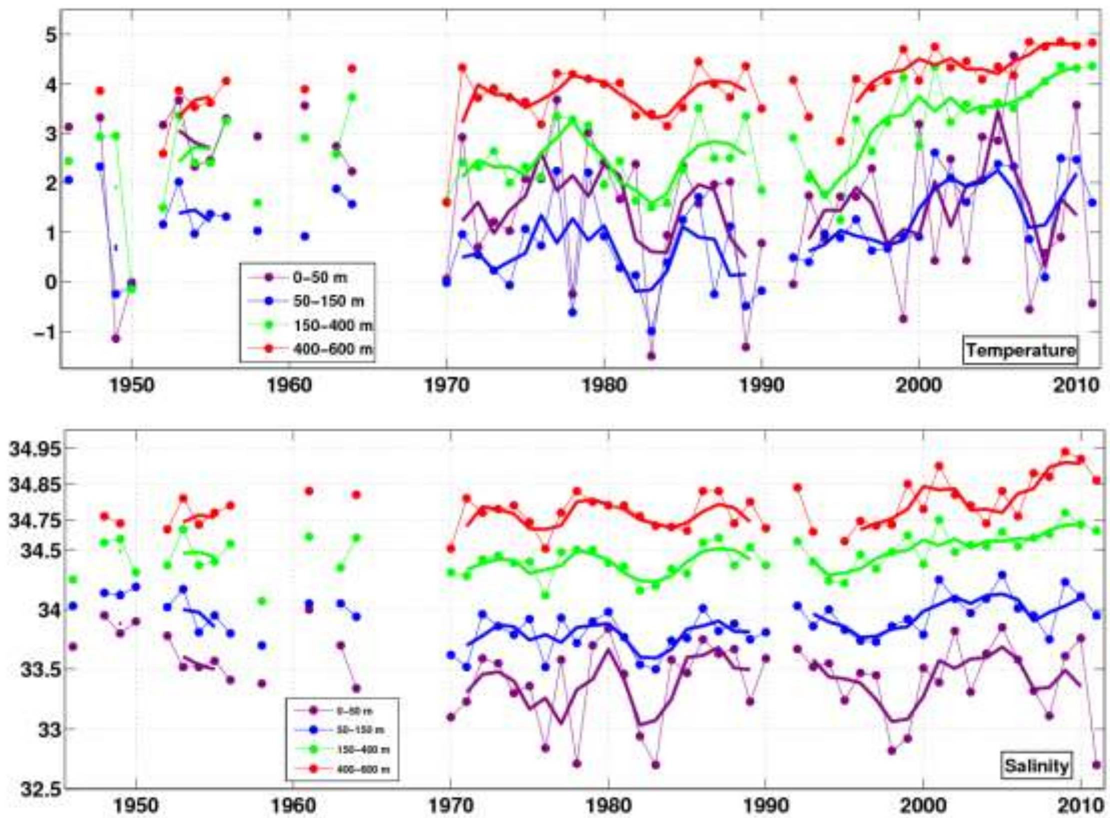

Figure 21. Timeseries of mean temperature (top) and mean salinity (bottom) for the period 1946–2011 in four different depth intervals west of “Store Hellefiskebanke” (Sisimiut, st.5) over the continental slope. The thick curves are the 3 year running mean values. Note the change in scales at 34.75 for salinity. Statistics is shown in Table 4.

Table 4. Statistics for potential temperature and salinity at Sisimiut (Holsteinsborg) st. 5. and values for 2011.

Sisimiut St.5	Temperature [°C]	Salinity	2011	
	Mean ± std	Mean ± std	Tpot	S
0–50 m	1.68 ± 1.46°C	33.46 ± 0.32	-0.44°C	32.70
50–150 m	1.02 ± 0.91°C	33.90 ± 0.19	1.60°C	33.95
150–400 m	2.76 ± 0.93°C	34.45 ± 0.16	4.36°C	34.66
400–600 m	3.94 ± 0.62°C	34.77 ± 0.09	4.83°C	34.86

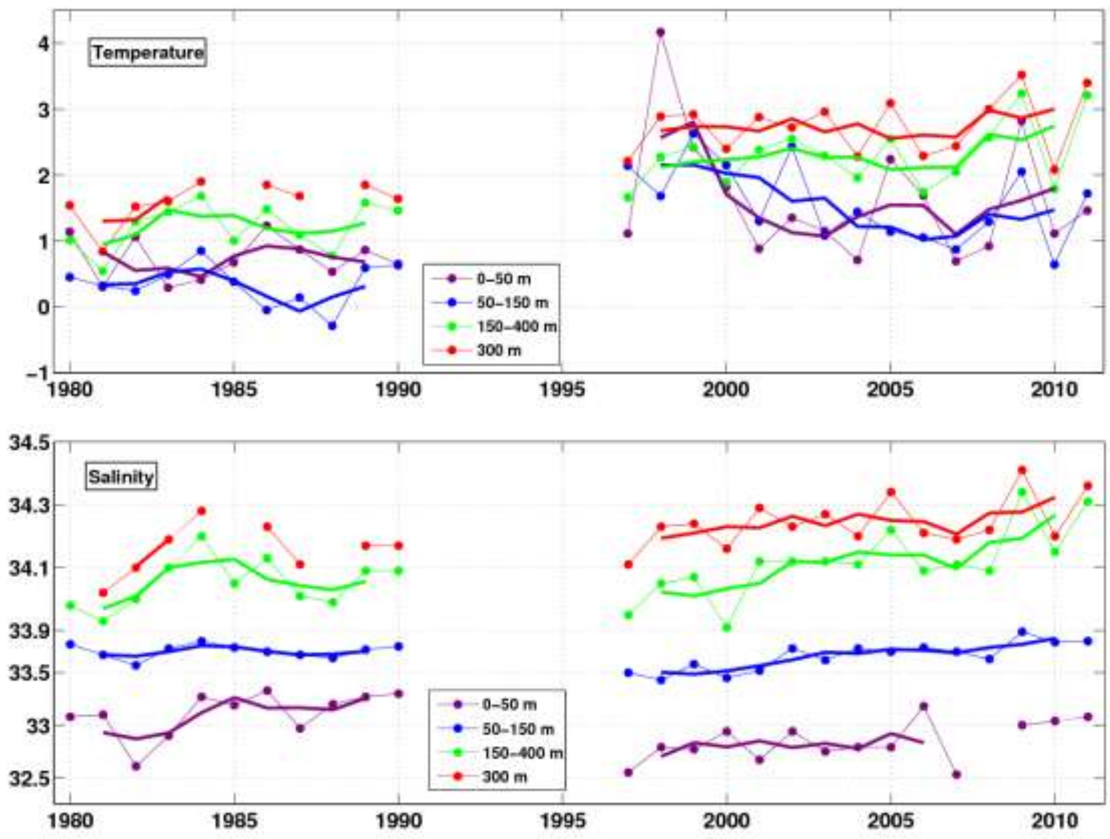

Figure 22. Timeseries of mean temperature (top) and mean salinity (bottom) for the period 1980–2011 in four different depth intervals west of "Jakobshavn-Skansen" (Ilulissat-Skansen) st.3 in the Disko Bay close to Jakobshavn Isbræ. The thick curves are the 3 year running mean values. Note the change 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 2011.

Ilulissat St.3	Temperature [°C] Mean ± std	Salinity Mean ± std	2011 Tpot	2011 S
0–50 m	1.32 ± 0.92°C	32.98 ± 0.26	1.46°C	33.08
50–150 m	1.05 ± 0.78°C	33.68 ± 0.11	1.72°C	33.80
150–400 m	1.82 ± 0.69°C	34.09 ± 0.10	3.21°C	34.31
300 m	2.29 ± 0.68°C	34.22 ± 0.09	3.40°C	34.36

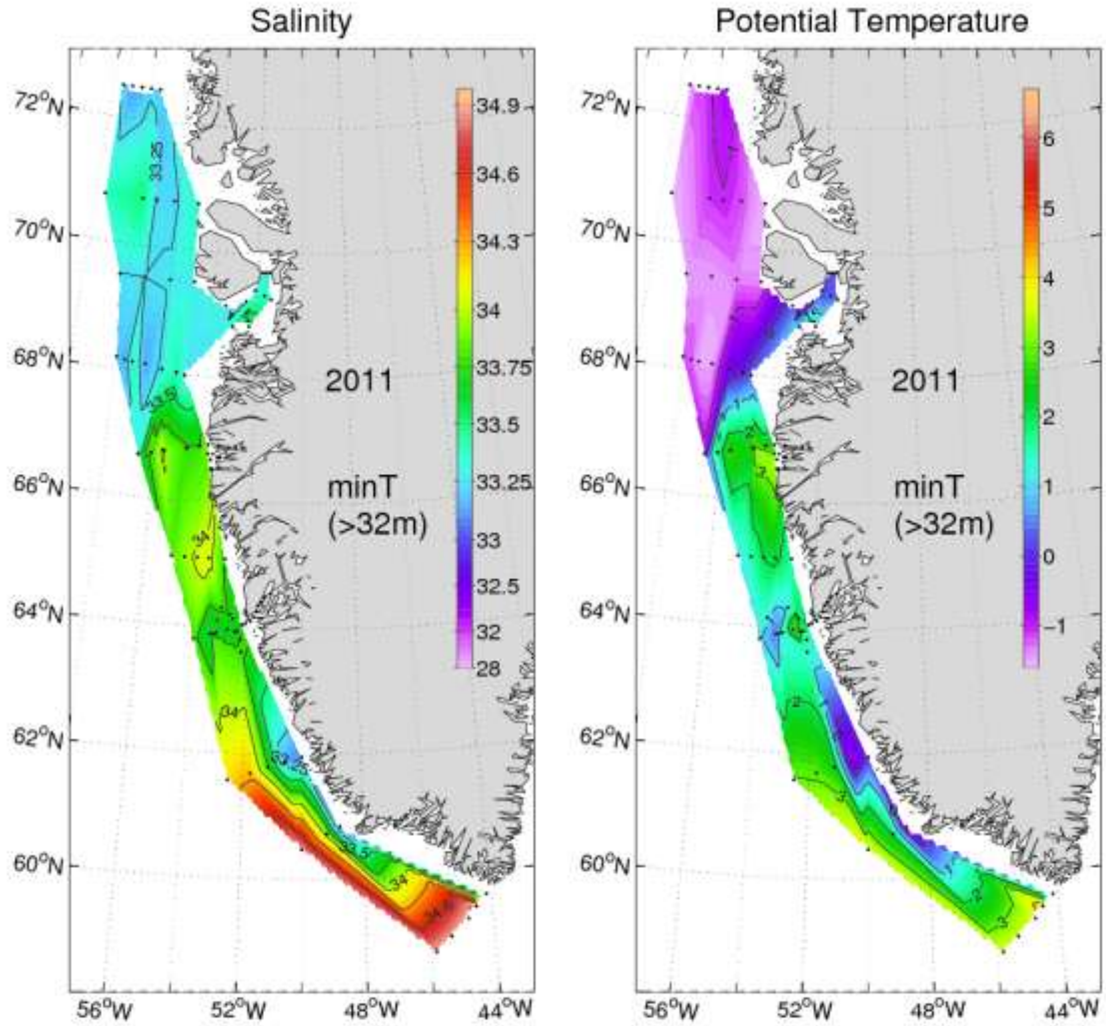

Figure 23. Salinity (left) and temperature (right) observed in 2011 (June 15 – July 13) at the depth of minimum temperature disregarding the upper 32 meters.

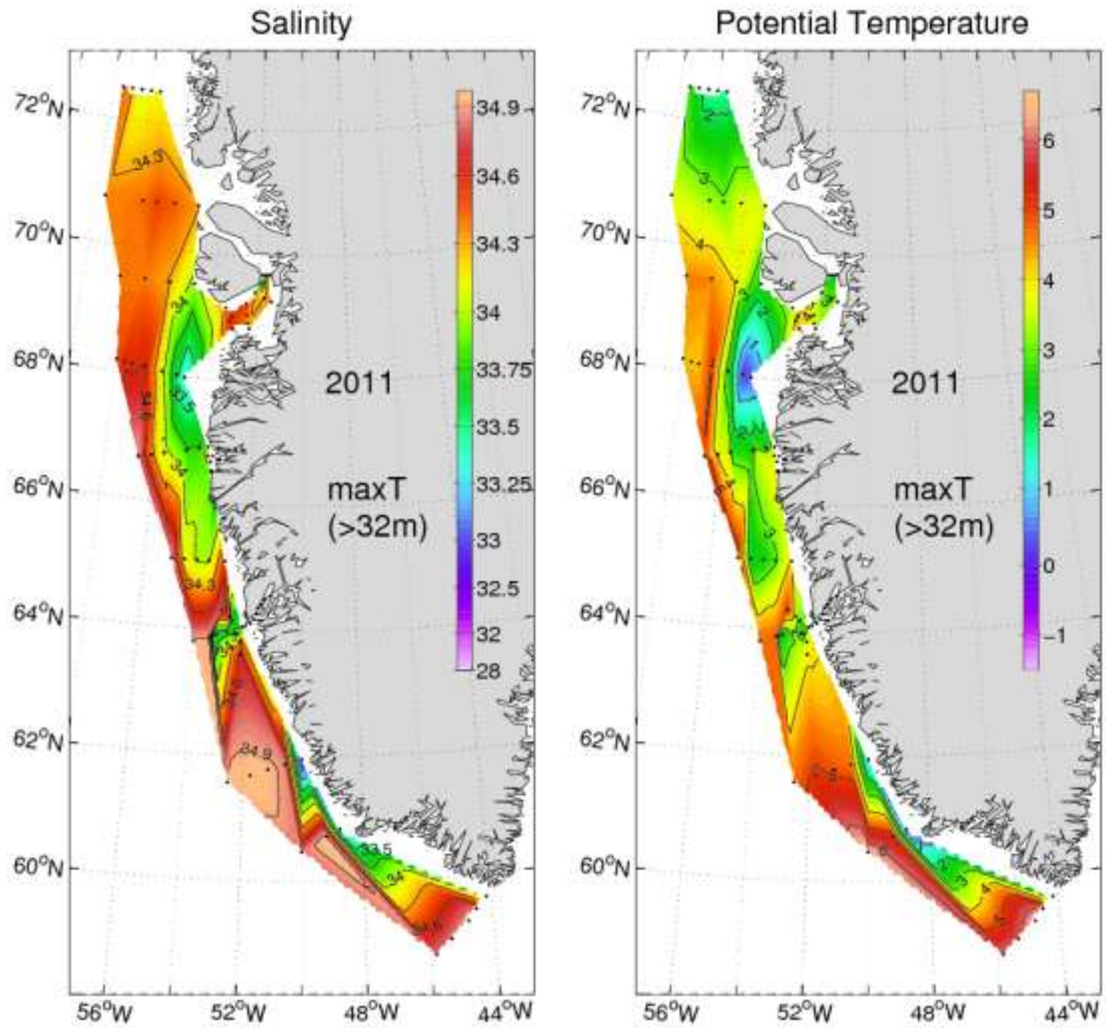

Figure 24. Salinity (left) and temperature (right) observed in 2011 (June 15 – July 13) at the depth of maximum temperature disregarding the upper 32 meters.

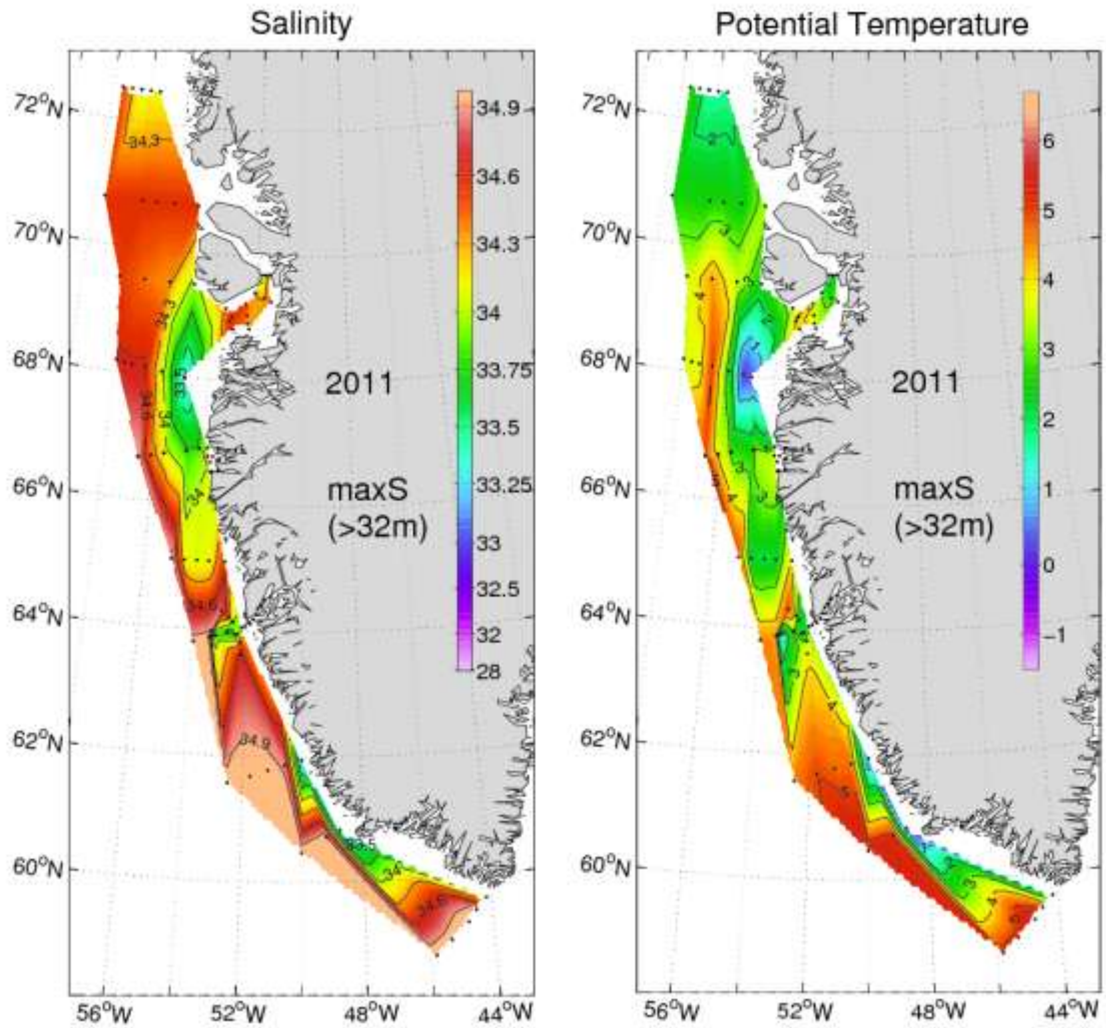

Figure 25. Salinity (left) and temperature (right) observed in 2011 (June 15 – July 13) at the depth of maximum salinity disregarding the upper 32 meters.

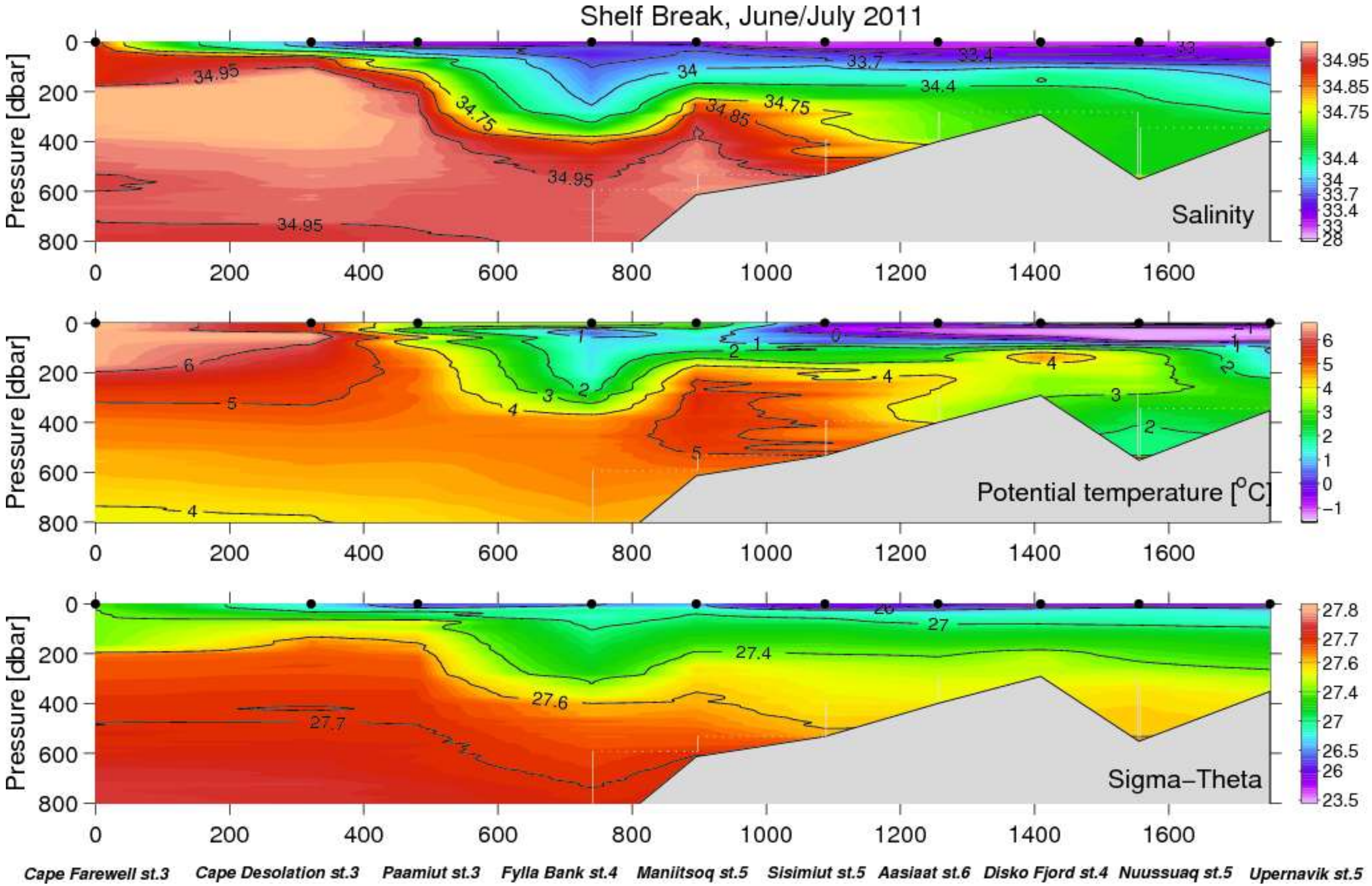

Figure 26. Vertical distribution of temperature, salinity and density over the continental shelf break from Cape Farewell to Upernavik, June 18–July 12, 2011.

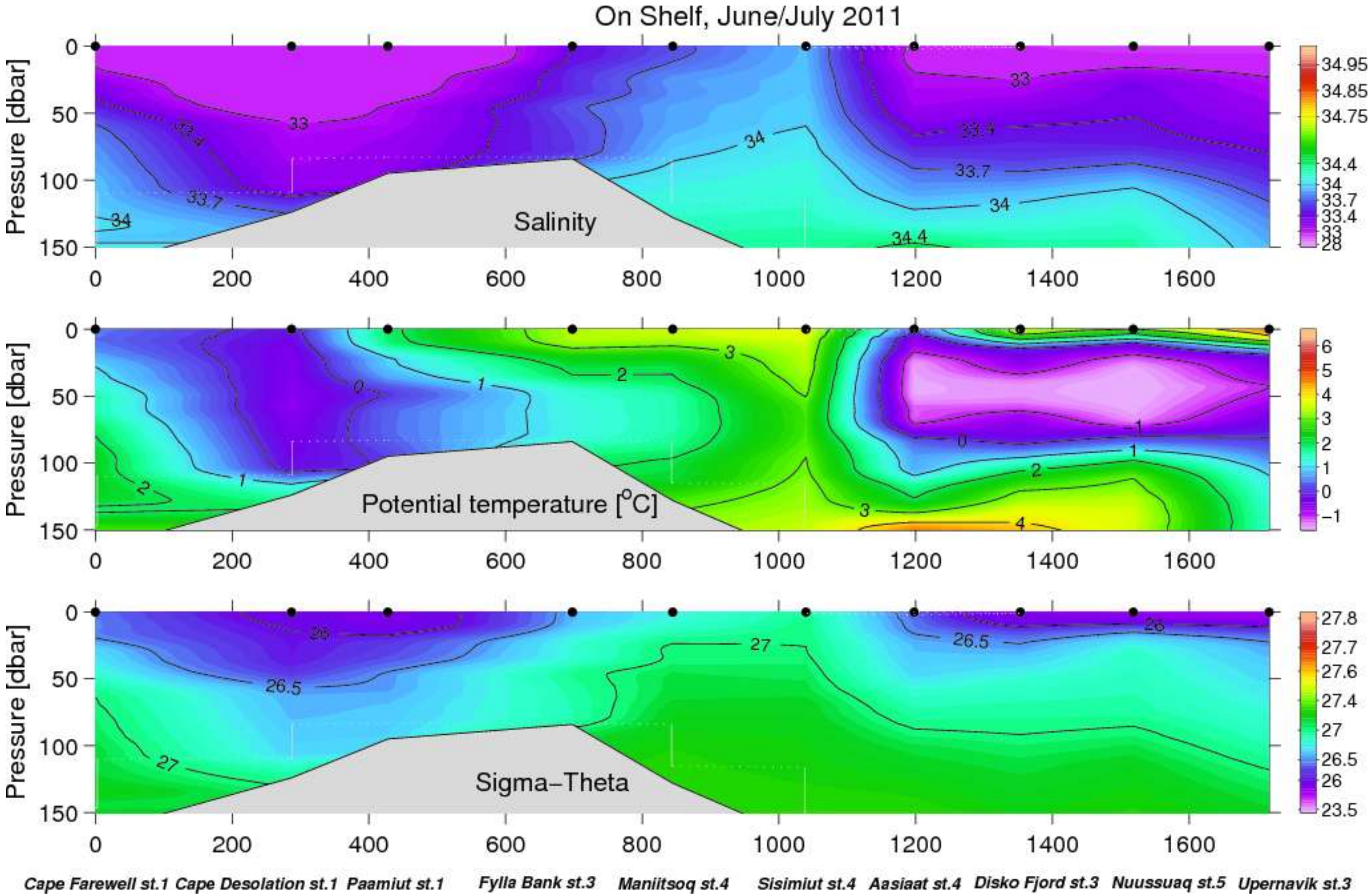

Figure 27. Vertical distribution of temperature, salinity and density over the shelf banks from Cape Farewell to Sisimiut, Cape Farewell to Upernavik, June 18–July 12, 2011.

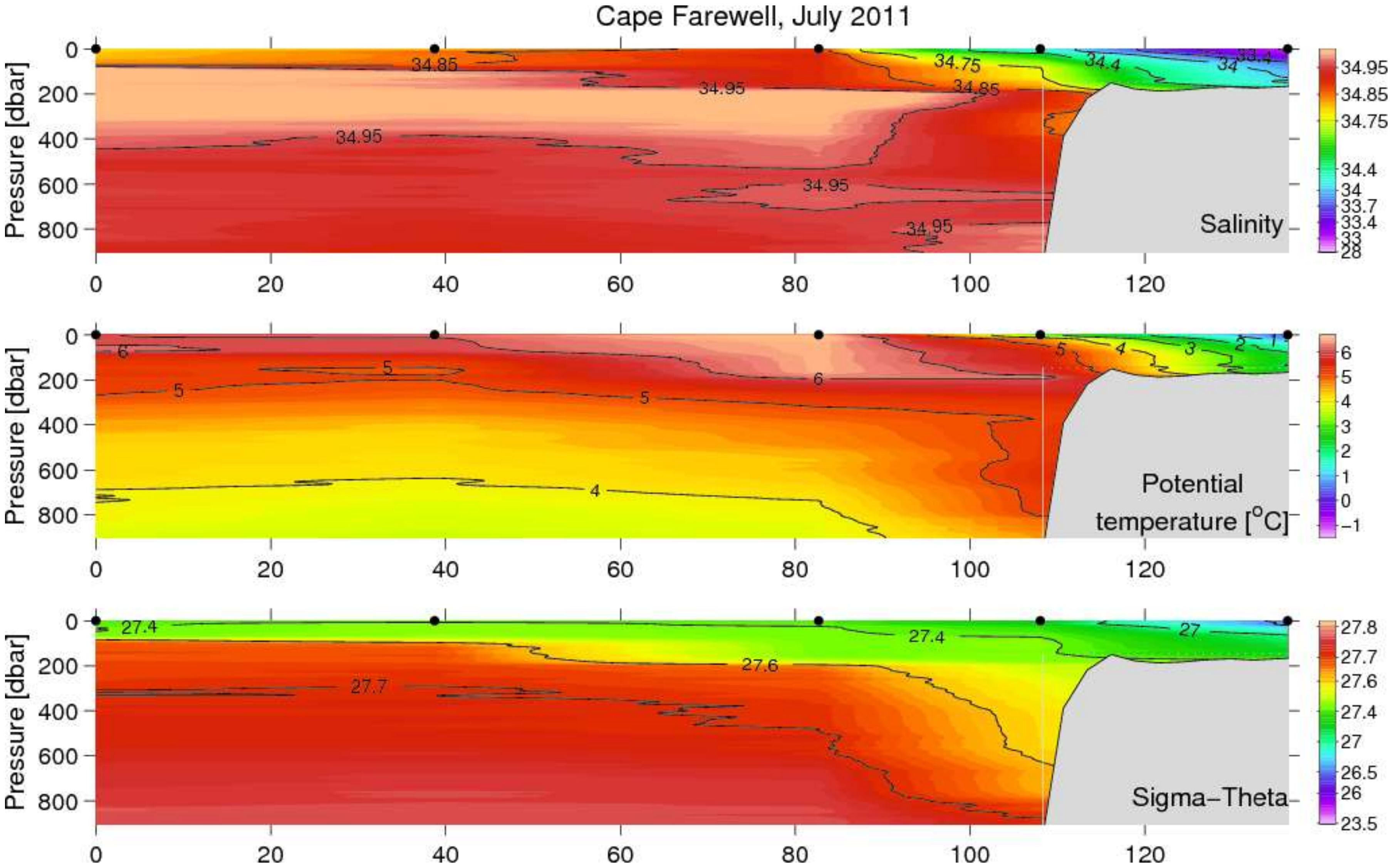

Figure 28. Vertical distribution of temperature, salinity and density at the Cape Farewell section, June 12–13, 2011.

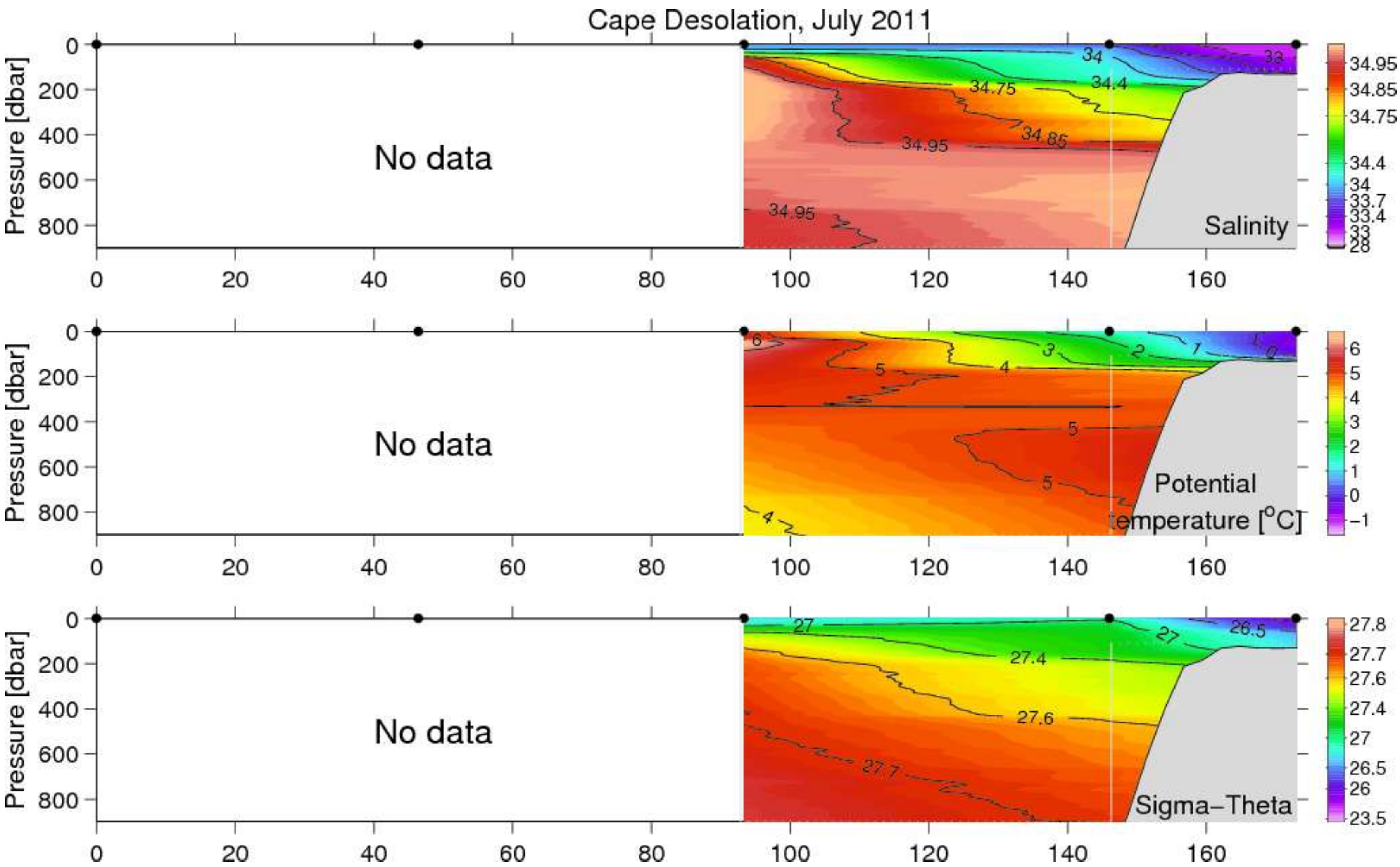

Figure 29. Vertical distribution of temperature, salinity and density at the Cape Desolation section, July 08–09, 2011.

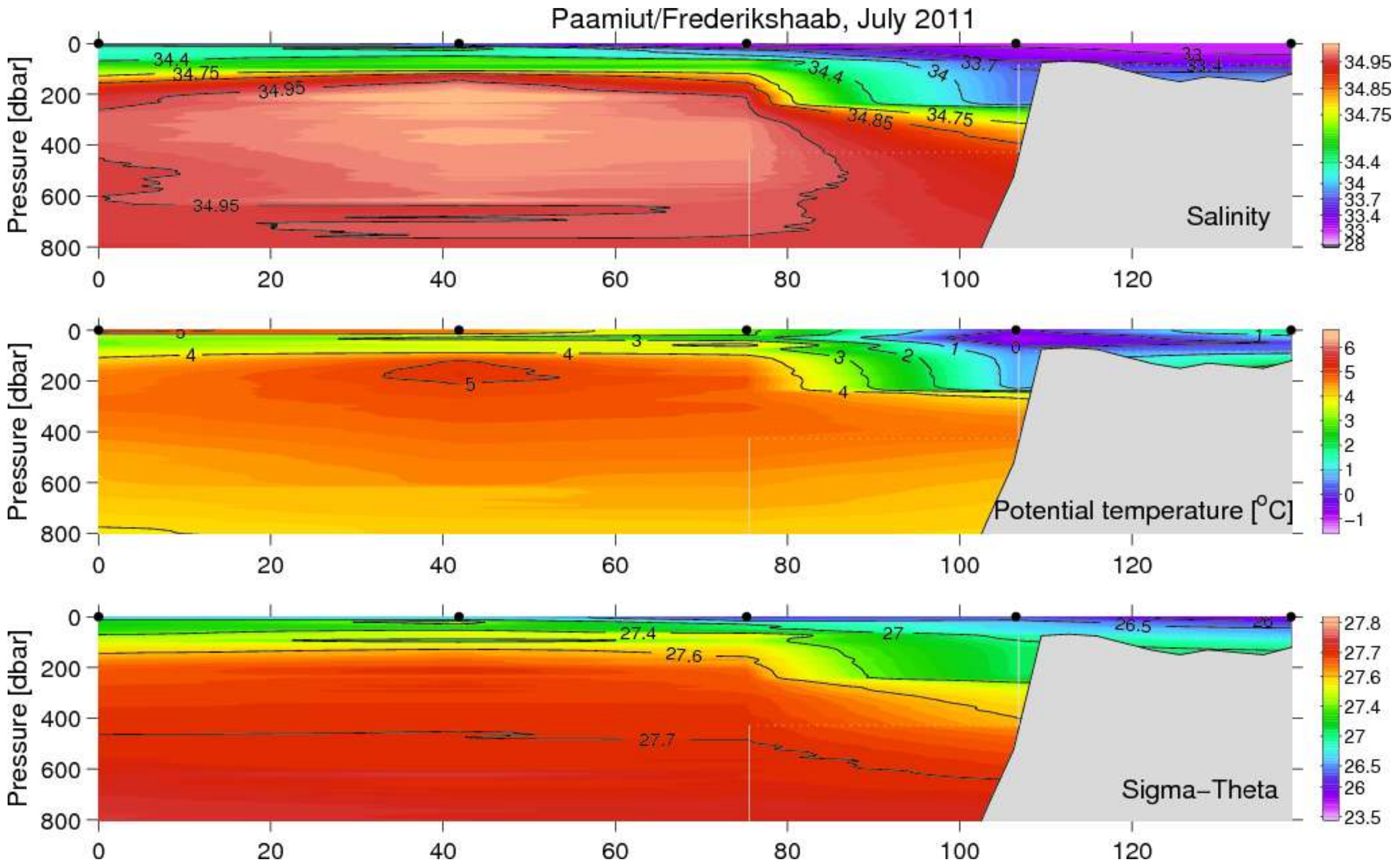

Figure 30. Vertical distribution of temperature, salinity and density at the Paamiut (Frederikshaab) section, July 05, 2011.

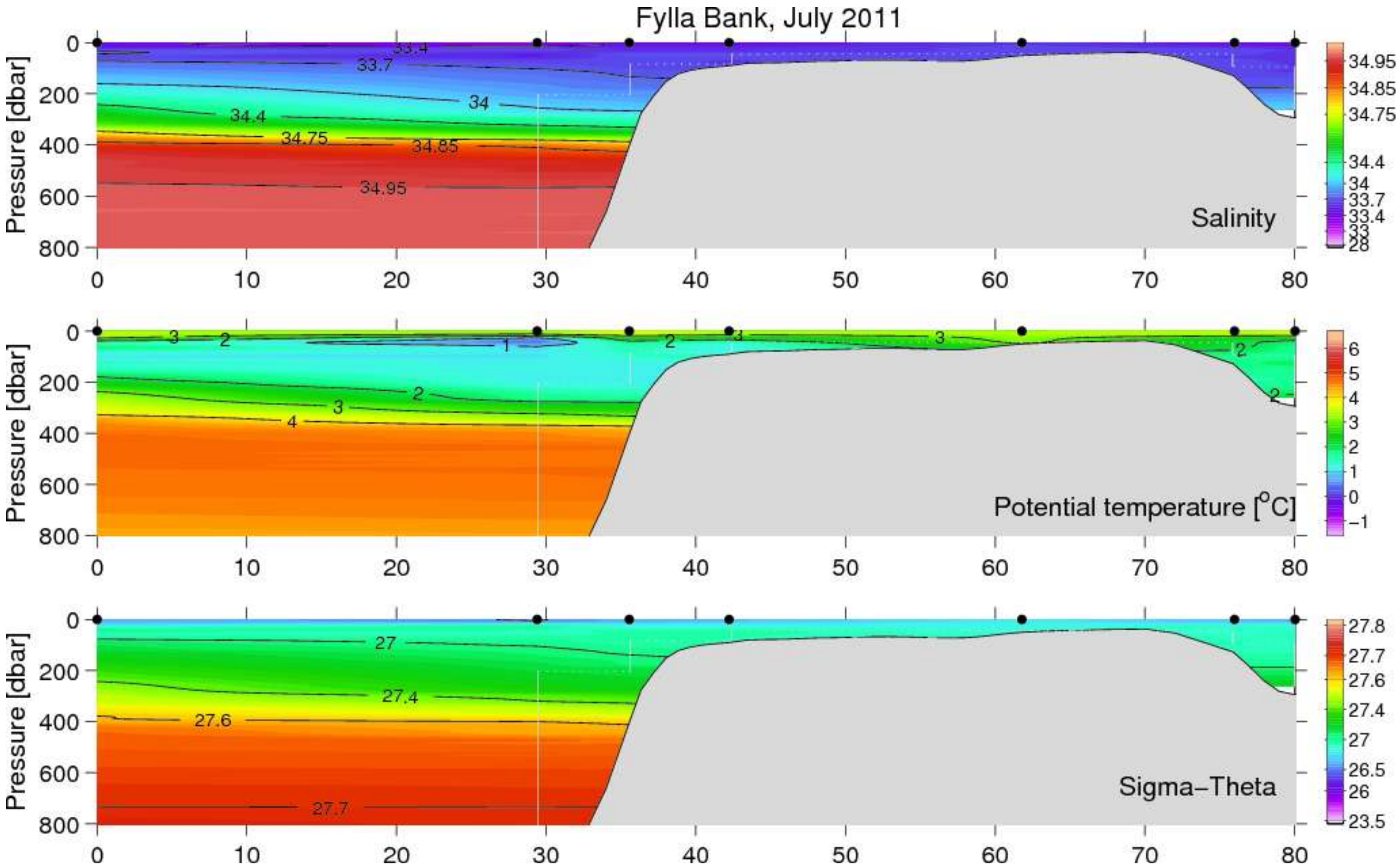

Figure 31. Vertical distribution of temperature, salinity and density at the Fylla Bank section, July 01, 2011. Three intermediate stations were taken too.

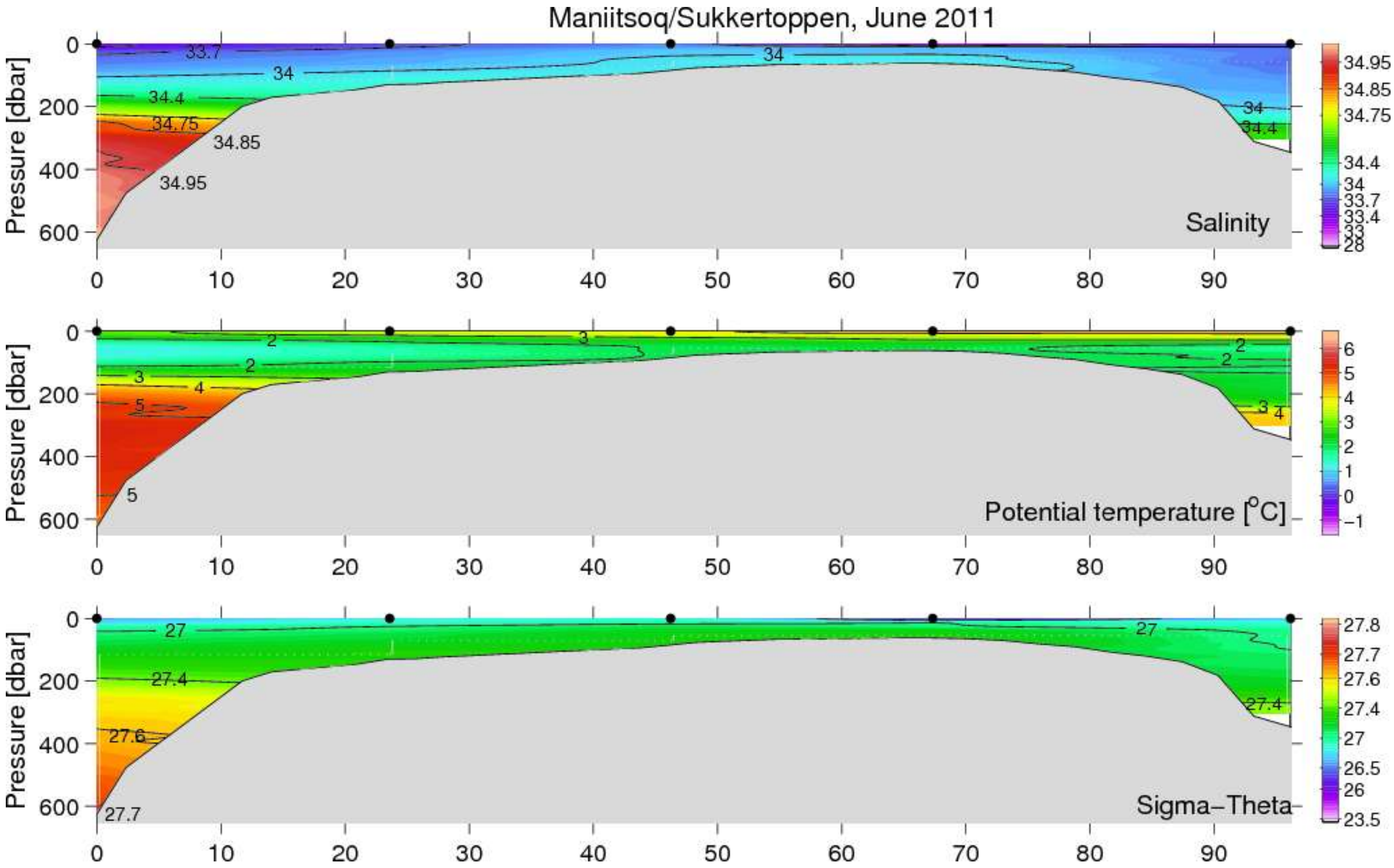

Figure 32. Vertical distribution of temperature, salinity and density at the Maniitsoq (Sukkertoppen) section, June 30, 2011.

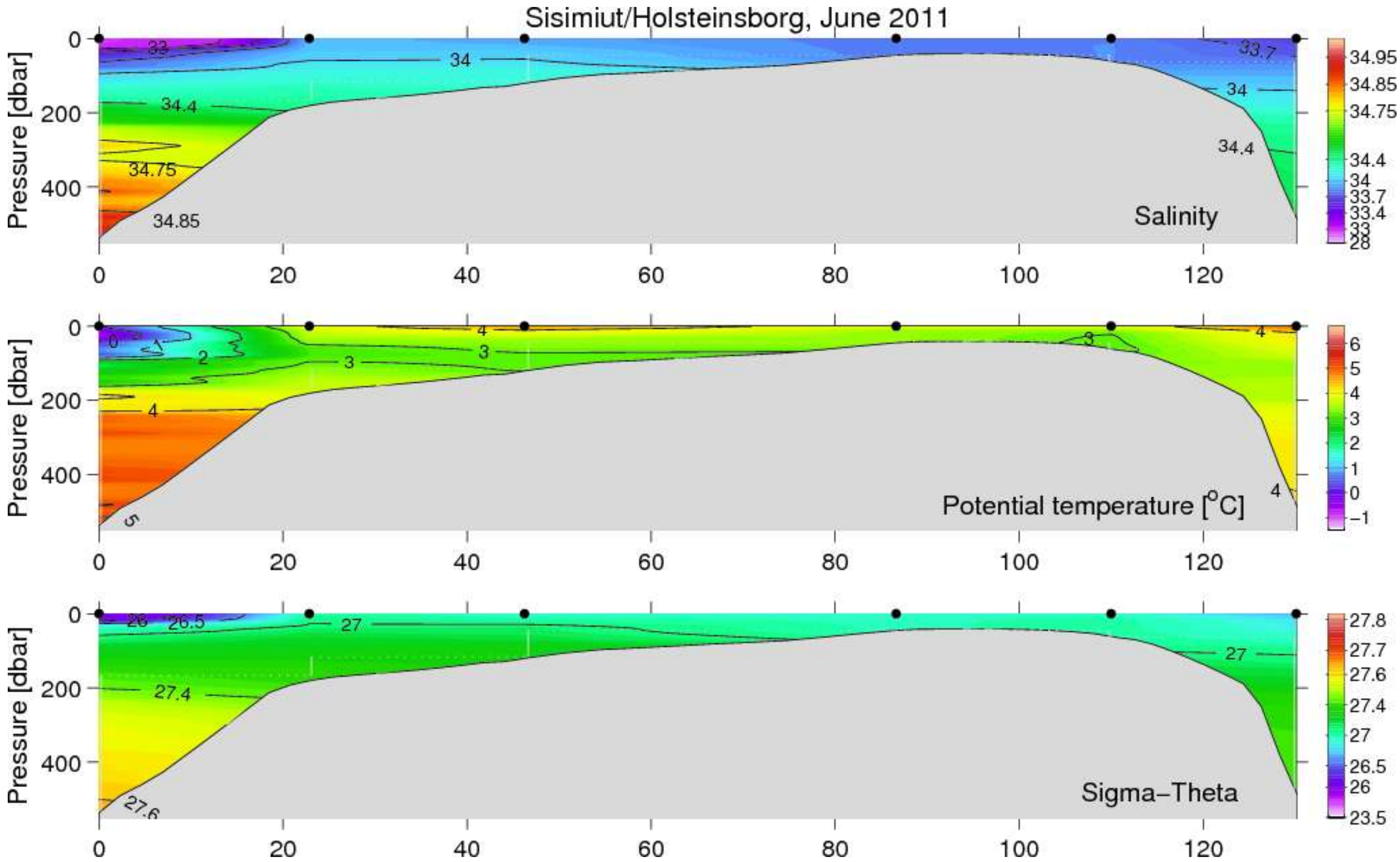

Figure 33. Vertical distribution of temperature, salinity and density at the Sisimiut (Holsteinsborg) section, June 28–29, 2011.

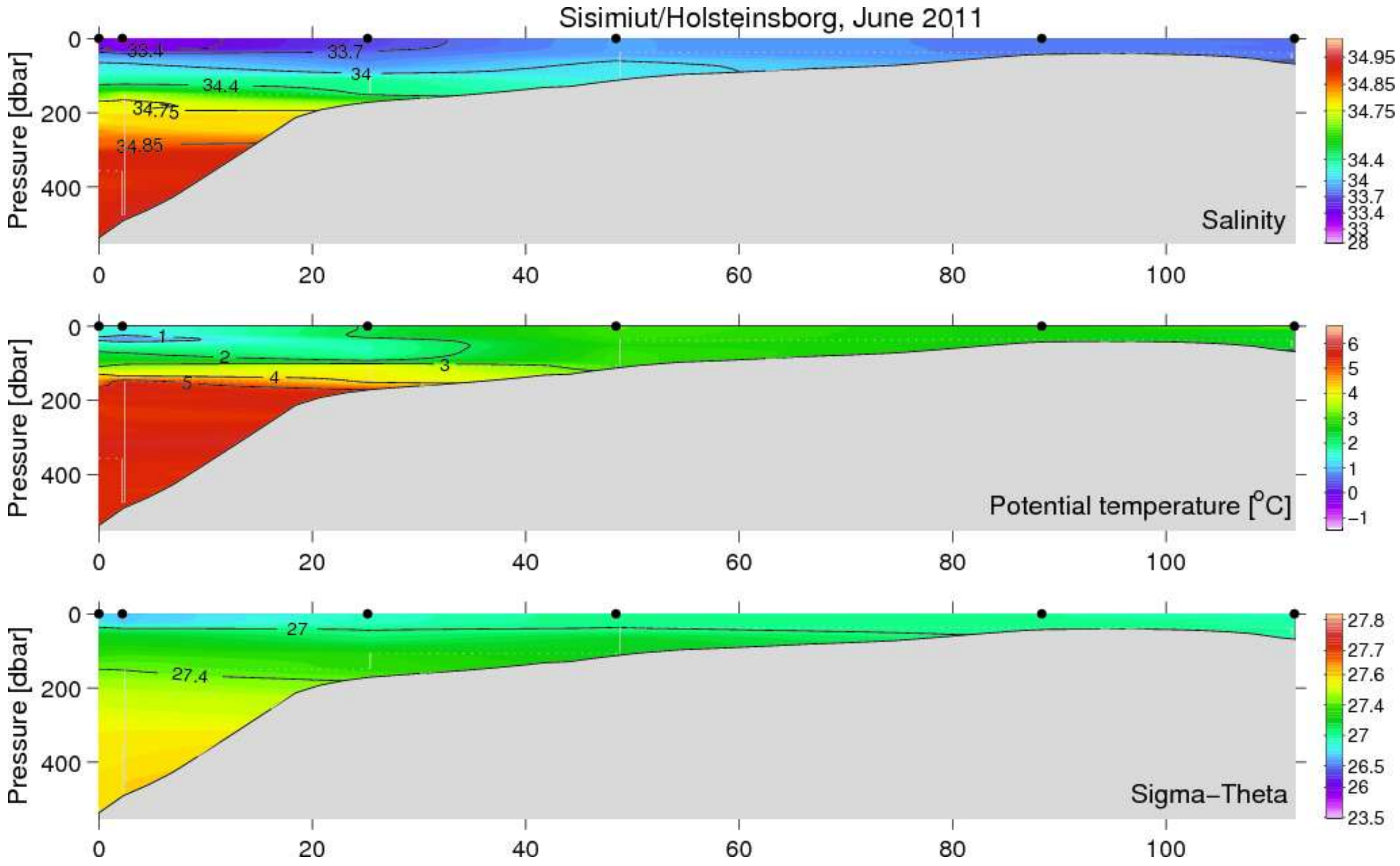

Figure 34. Vertical distribution of temperature, salinity and density at the Sisimiut (Holsteinsborg) section, June 15–16, 2011.

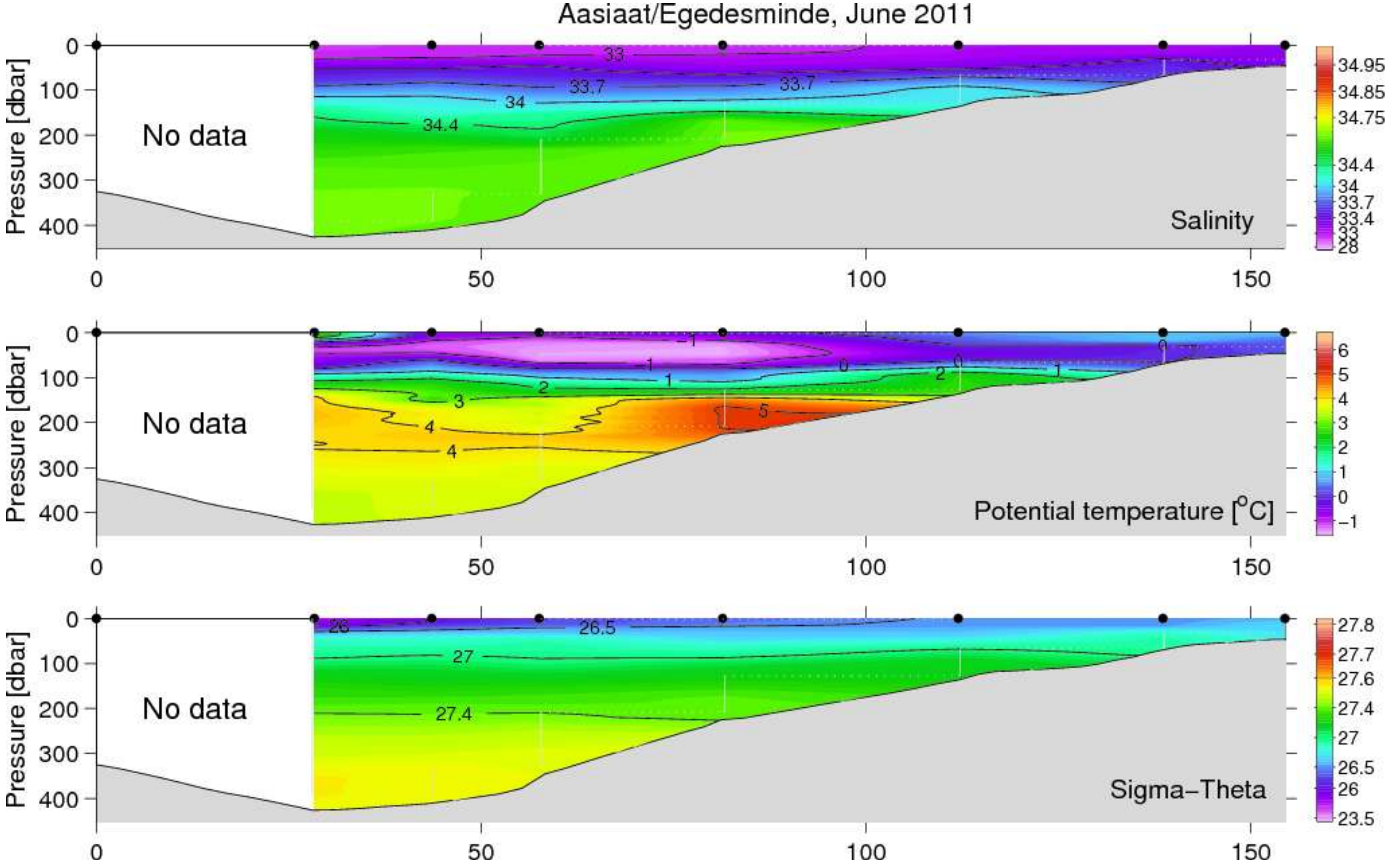

Figure 35. Vertical distribution of temperature, salinity and density at the Aasiaat (Egedesminde) section, June 18–20, 2011.

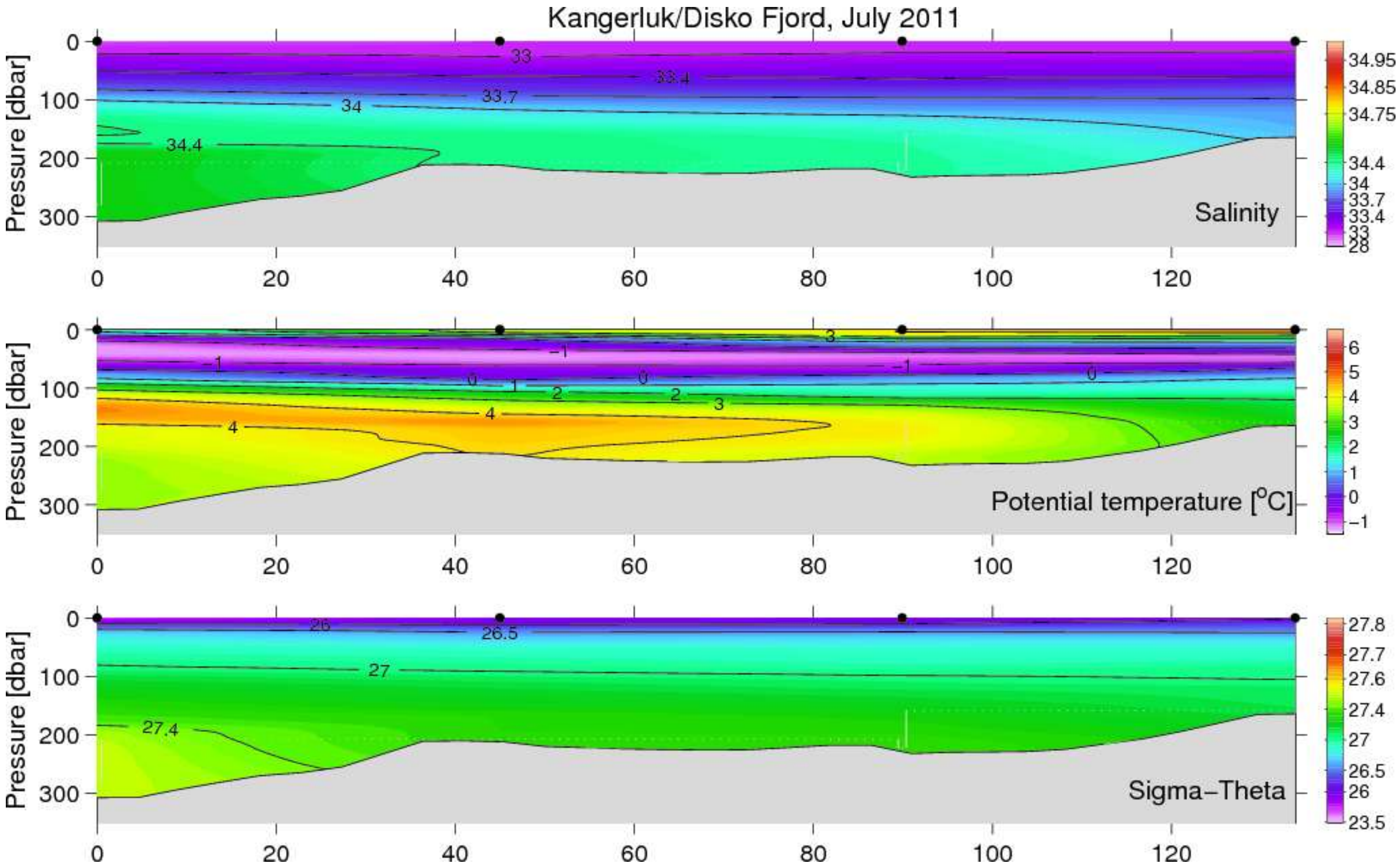

Figure 36. Vertical distribution of temperature, salinity and density at the Kangerluk (Disko Fjord) section, July 01–07, 2011.

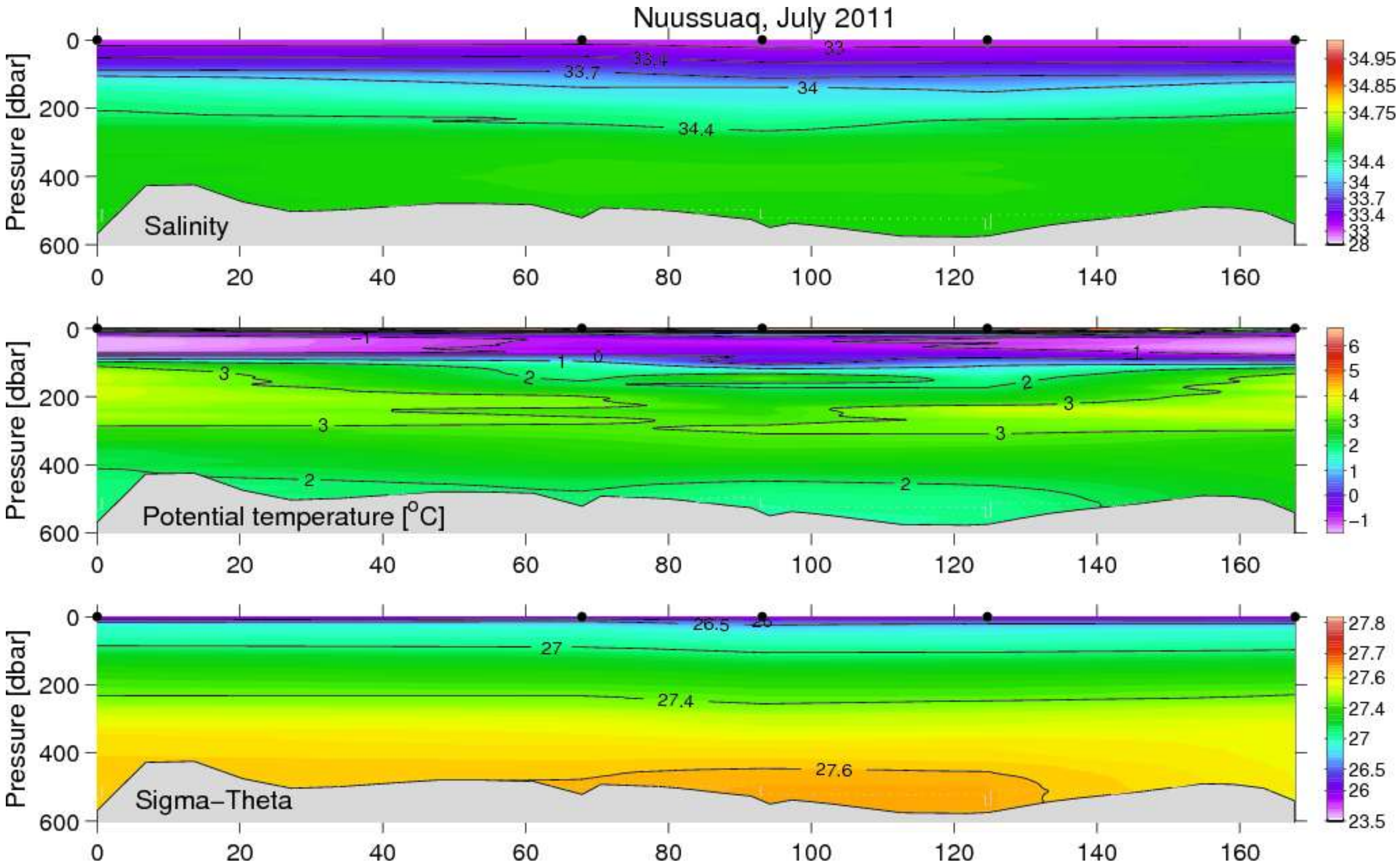

Figure 37. Vertical distribution of temperature, salinity and density at the Nuussuaq section, July 02-07, 2011.

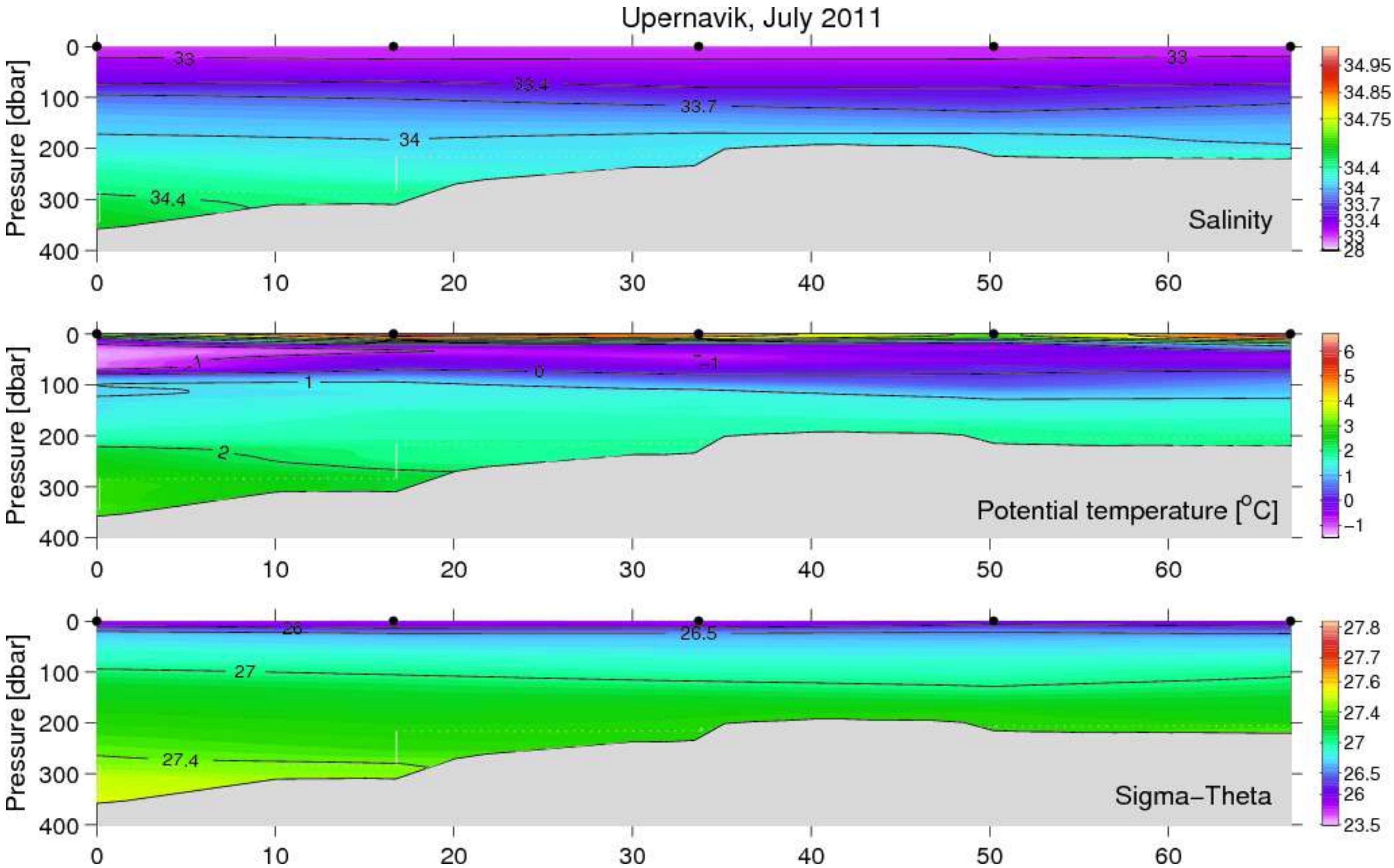

Figure 38. Vertical distribution of temperature, salinity and density at the Upernavik section, July 05, 2011.

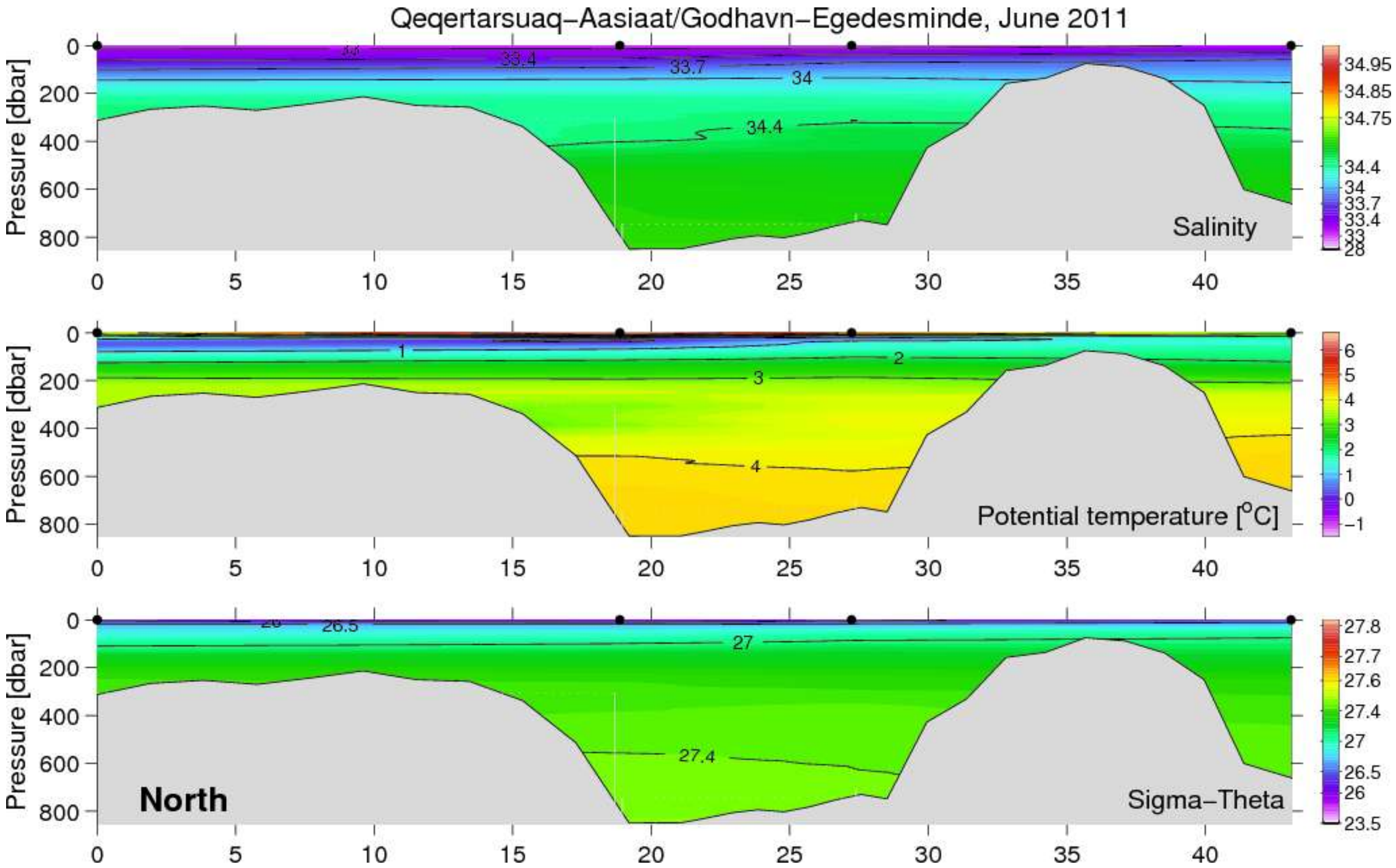

Figure 39. Vertical distribution of temperature, salinity and density at the Aasiaat–Qeqertarsuaq (Egedesminde–Godhavn) section, June 21–22, 2011. Note: The cross section is directed from section 1–4 (see Figure 1). The deep channel (19–28 km) is westward along the deep channel southeast of "Hunde øerne".

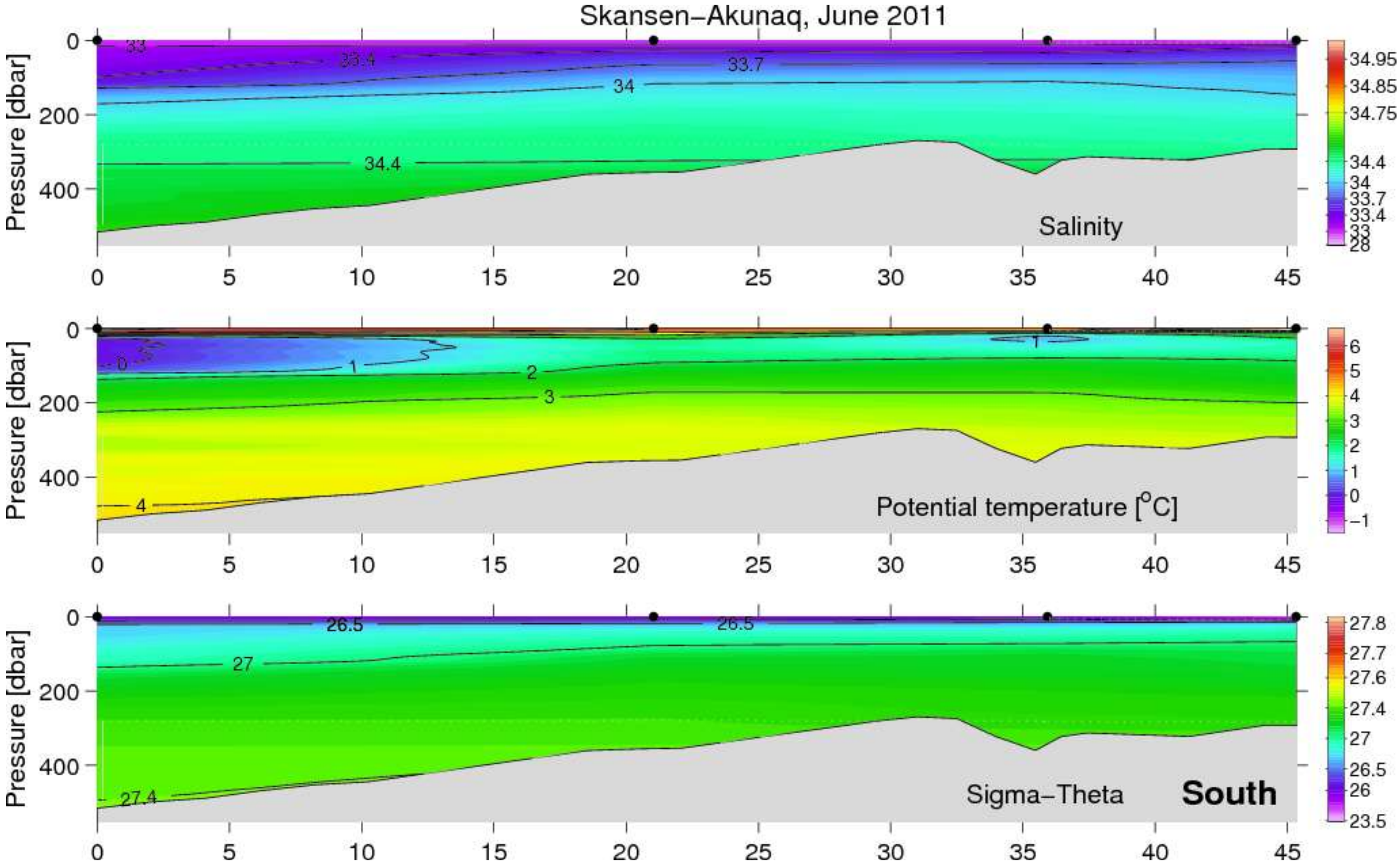

Figure 40. Vertical distribution of temperature, salinity and density at the Skansen–Akunaq section, June 21–24, 2011.

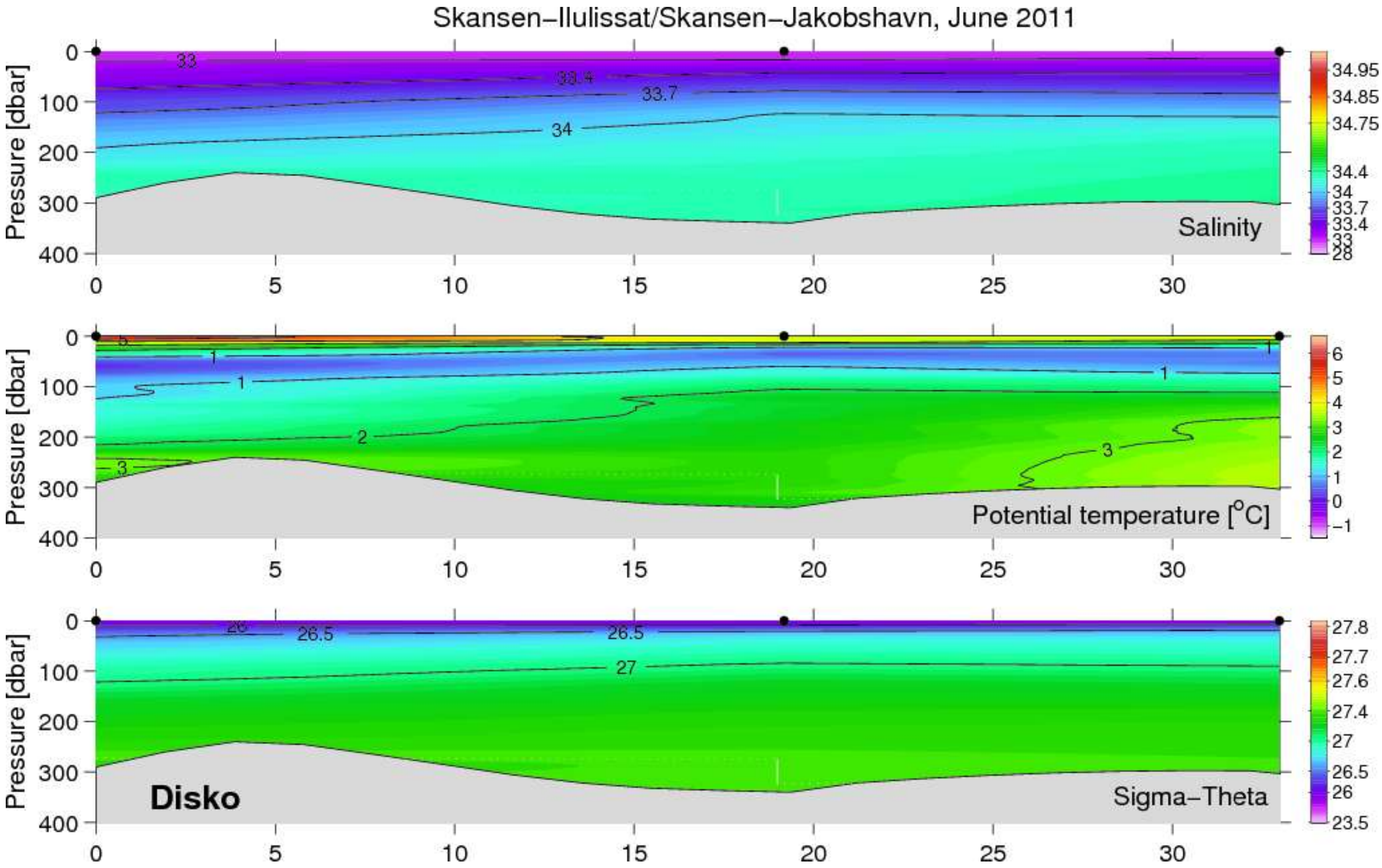

Figure 41. Vertical distribution of temperature, salinity and density at the Skansen–Ilulissat (Skansen–Jakobshavn) section, June 24–25, 2011.

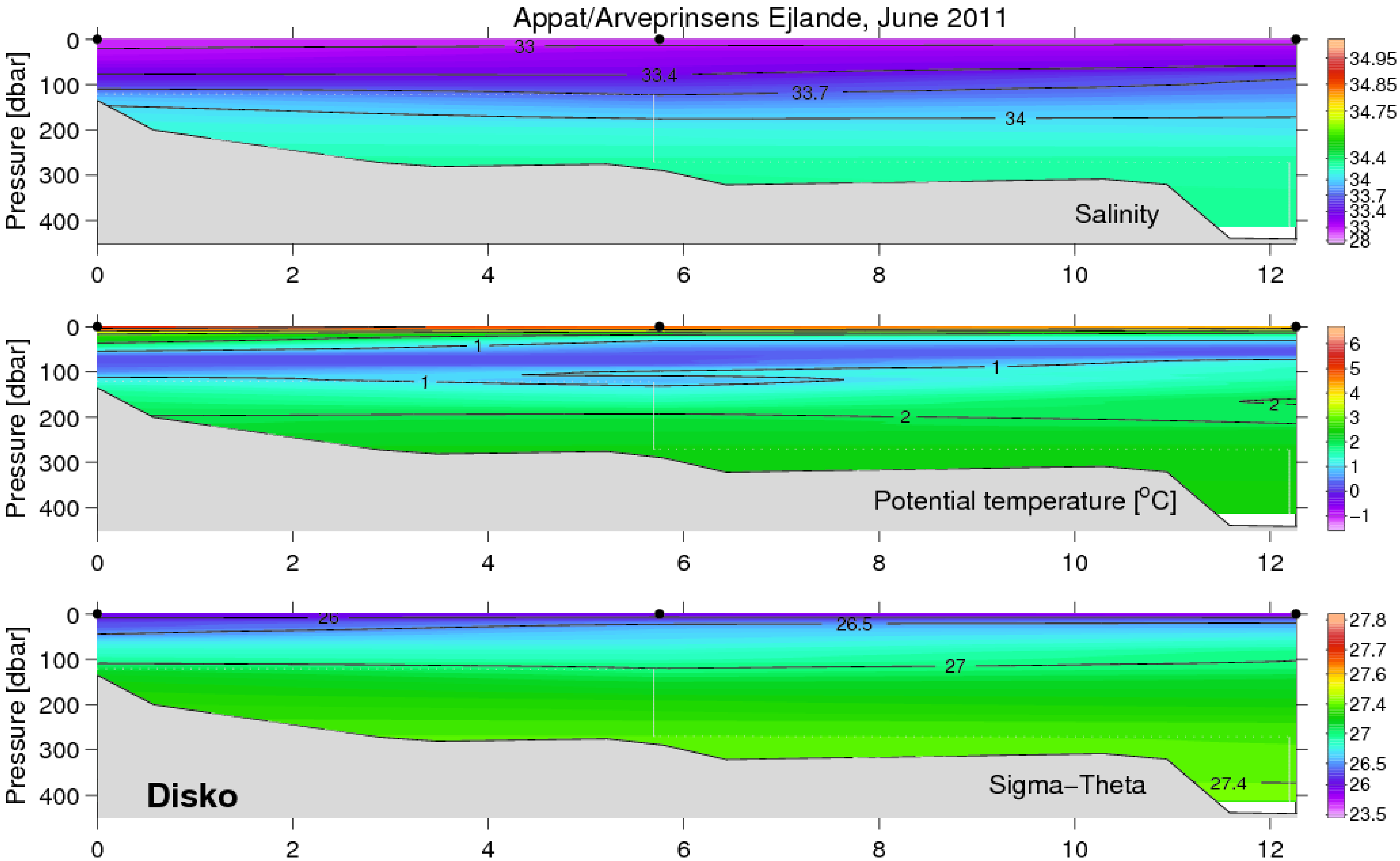

Figure 42. Vertical distribution of temperature, salinity and density at the Appat (Arveprinsens Ejlande) section, June 28–29, 2011.

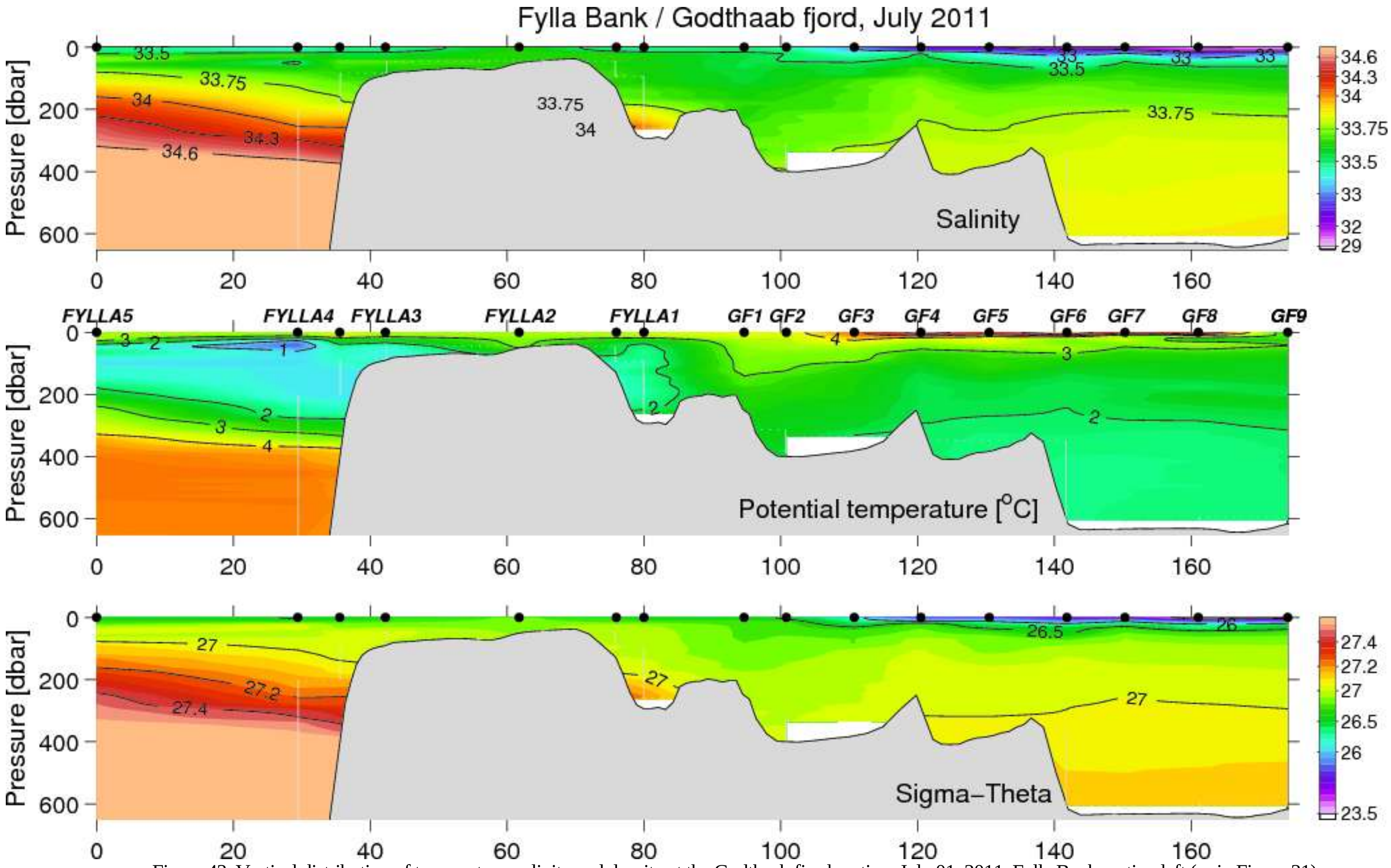

Figure 43**.** Vertical distribution of temperature, salinity and density at the Godthaab fjord section, July 01, 2011. Fylla Bank section left (as in Figure 31).

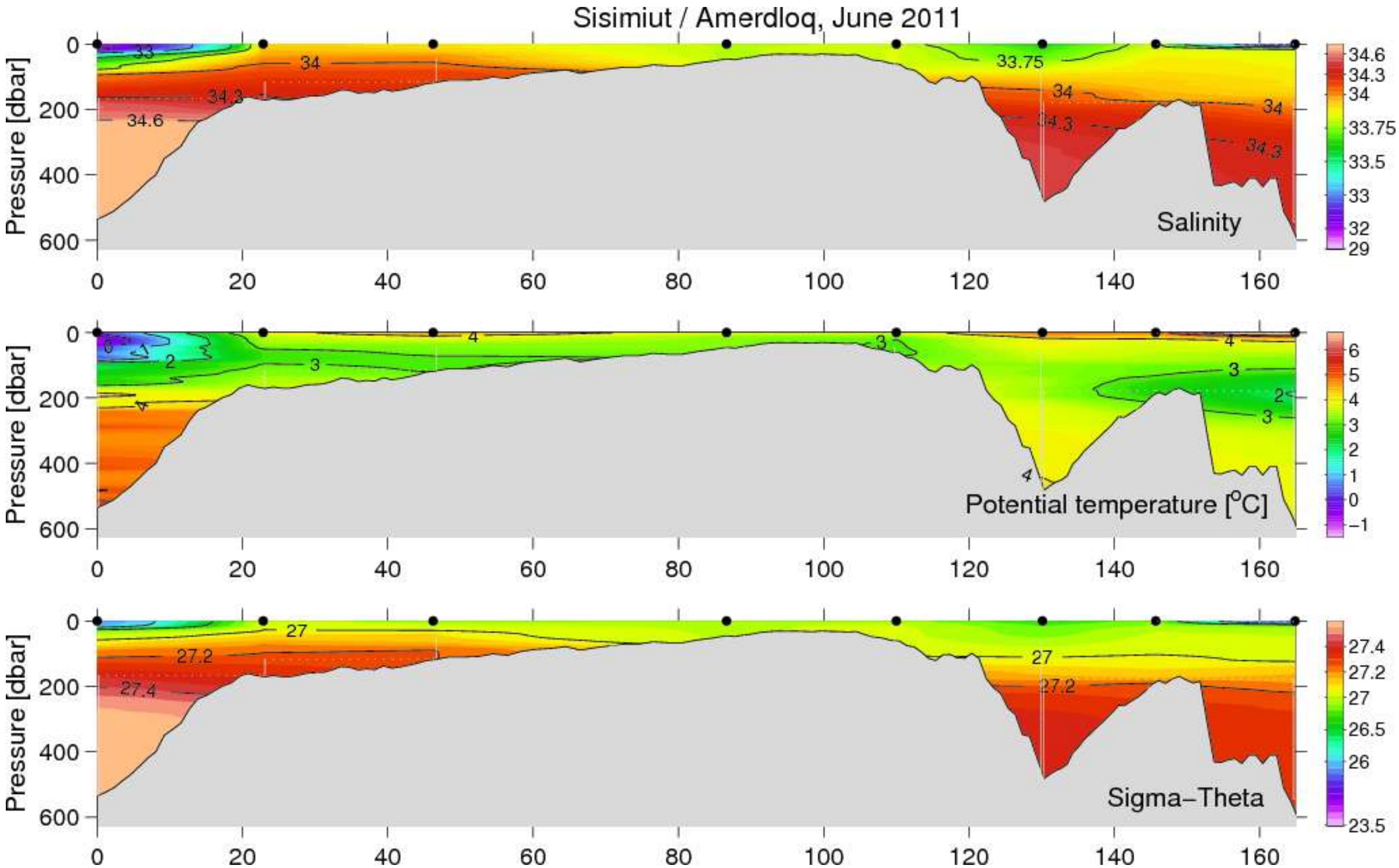

Figure 44. Vertical distribution of temperature, salinity and density at the Amerdloq fjord, June 28–29, 2011. Sisimiut section left.

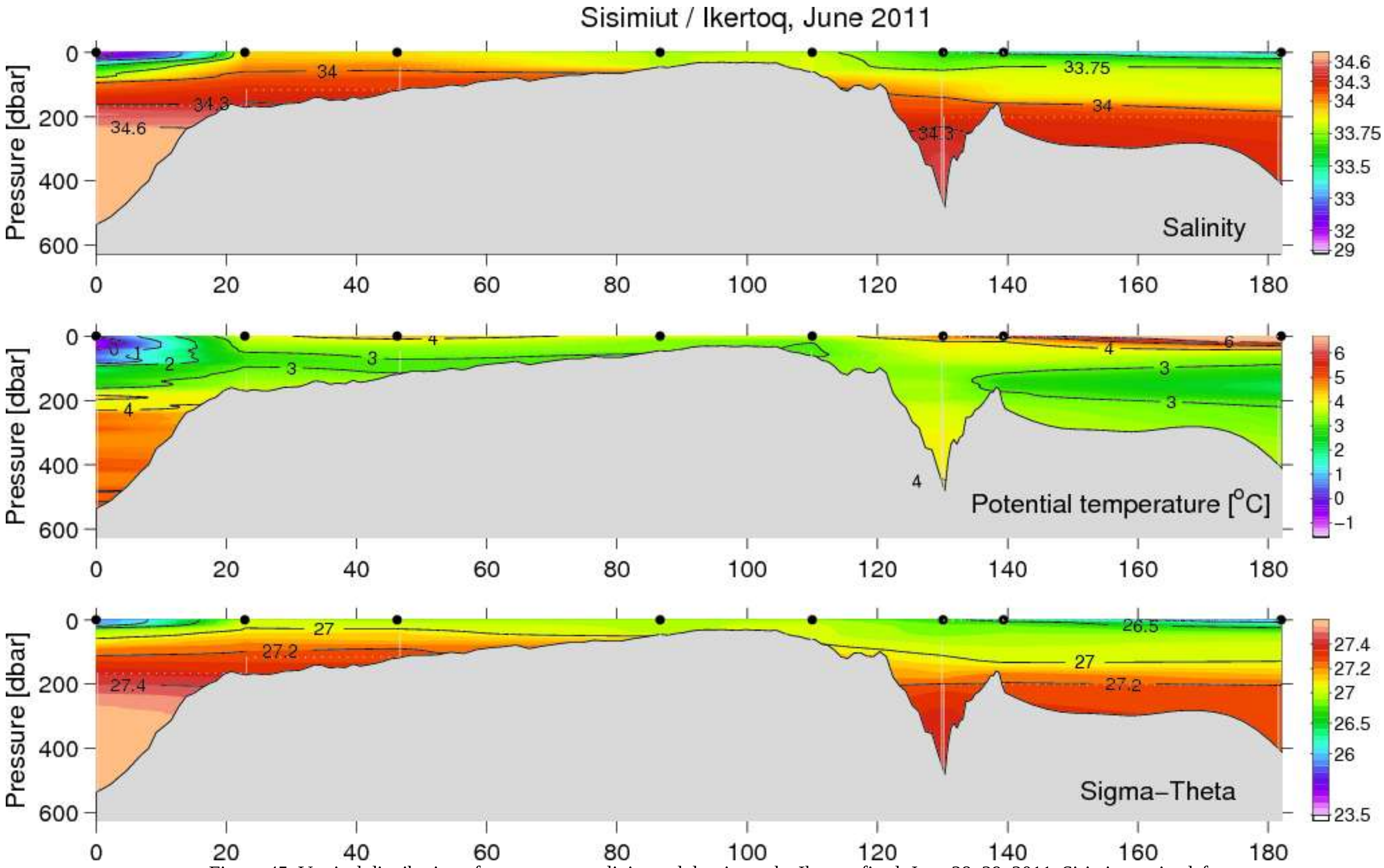

Figure 45**.** Vertical distribution of temperature, salinity and density at the Ikertoq fjord, June 28–29, 2011. Sisimiut section left

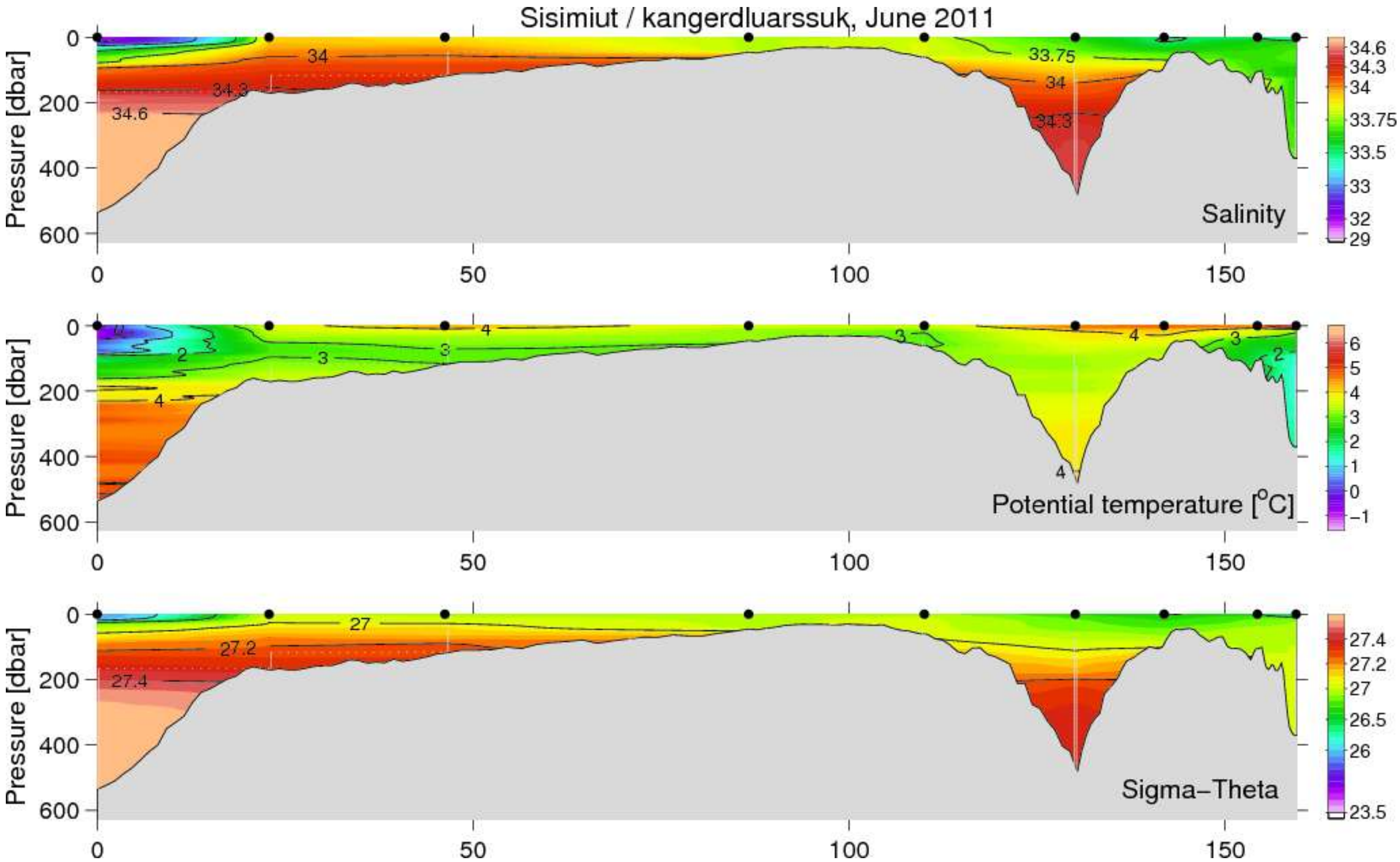

Figure 46**.** Vertical distribution of temperature, salinity and density at the Kangerdluarssuk fjord, June 28–29, 2011. Sisimiut section left.

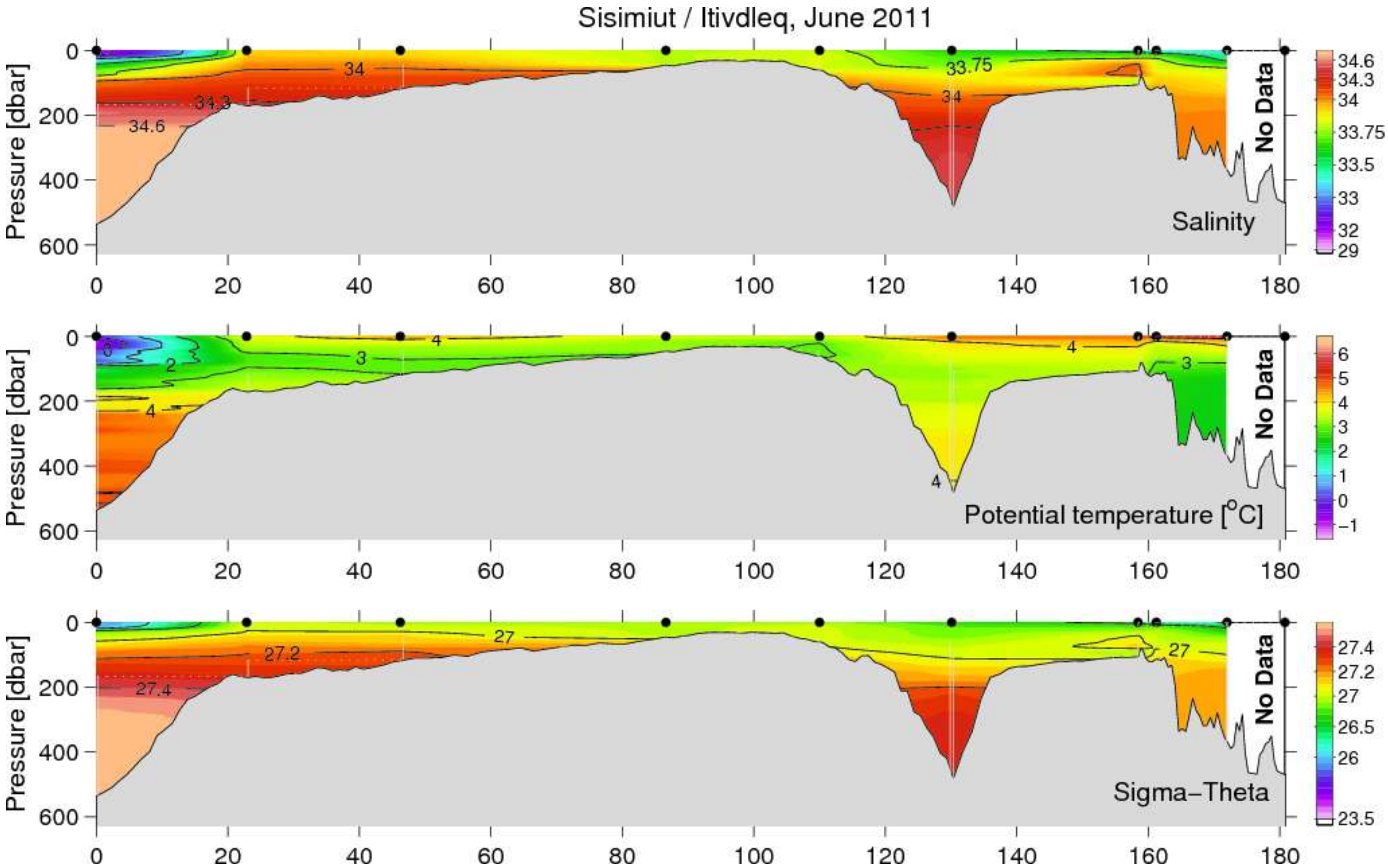

Figure 47. Vertical distribution of temperature, salinity and density at the Itivdleq fjord, June 28–29. 2011. Sisimiut section left.

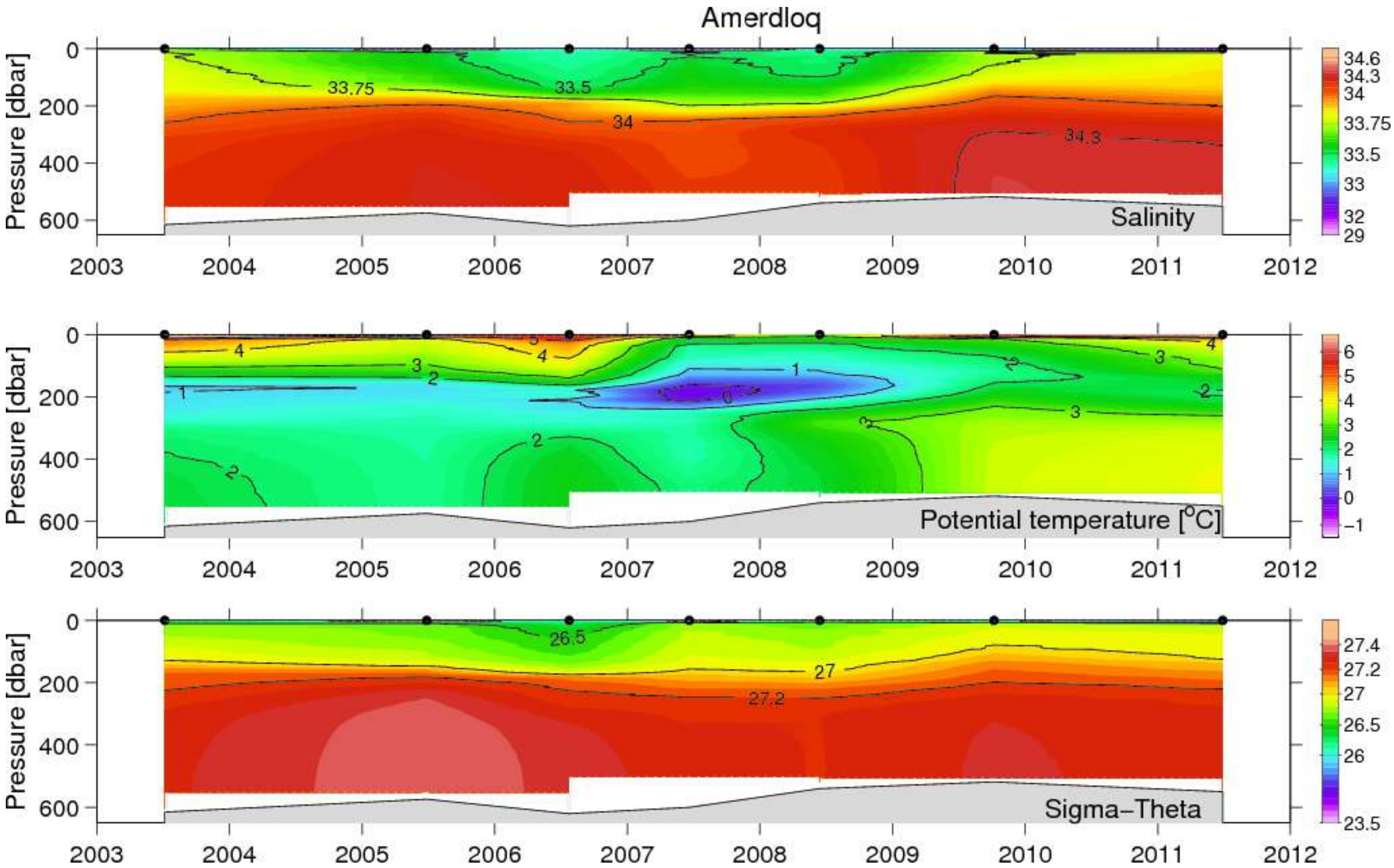

Figure 48**.** Hovmöller diagram of vertical distribution of temperature, salinity and density at the Amerdloq fjord st.4, late June/July 2003, 2005–2009, 2011.

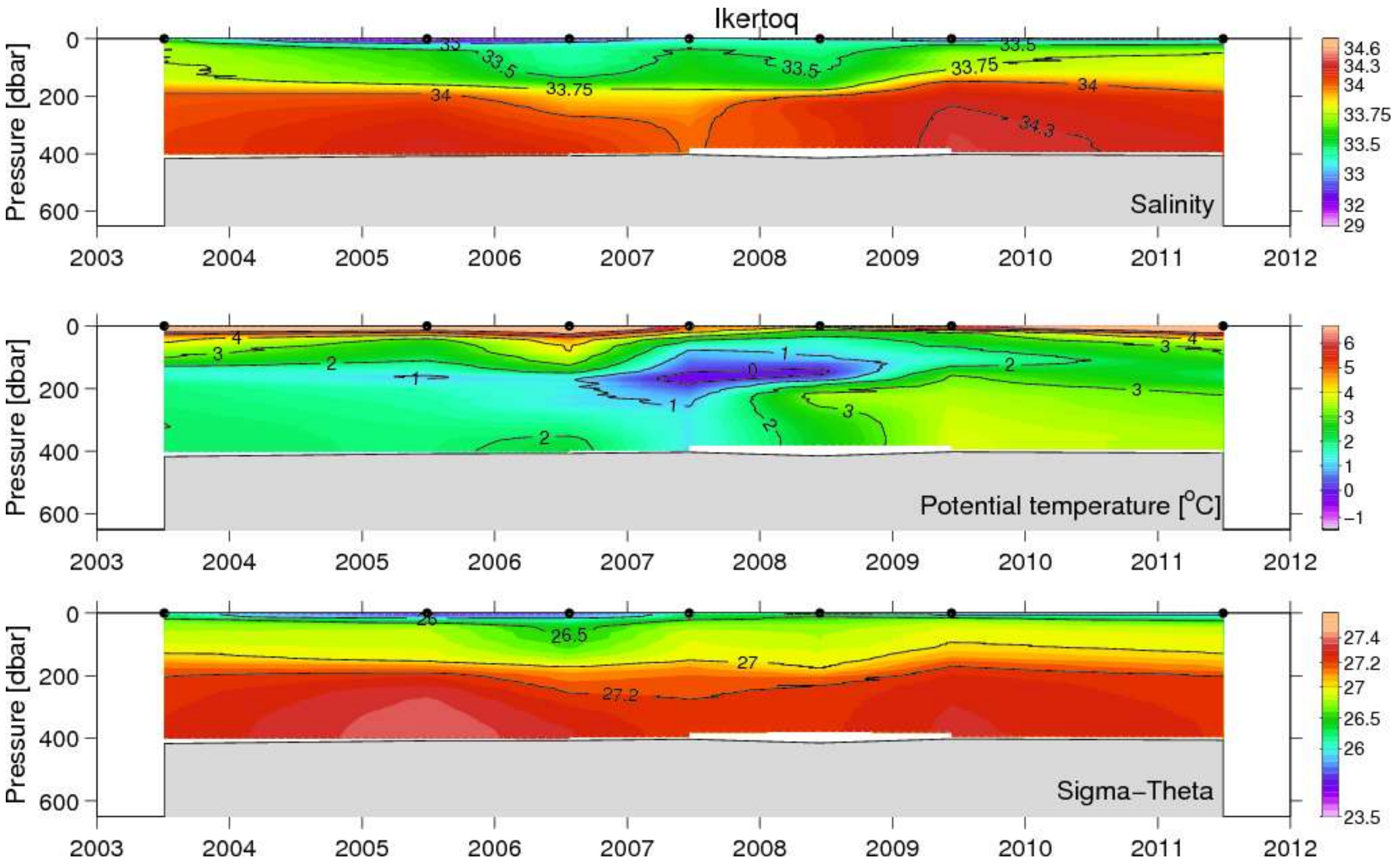

Figure 49. Hovmöller diagram of vertical distribution of temperature, salinity and density at the Ikertoq fjord st.4, late June/July 2003, 2005–2009, 2011.

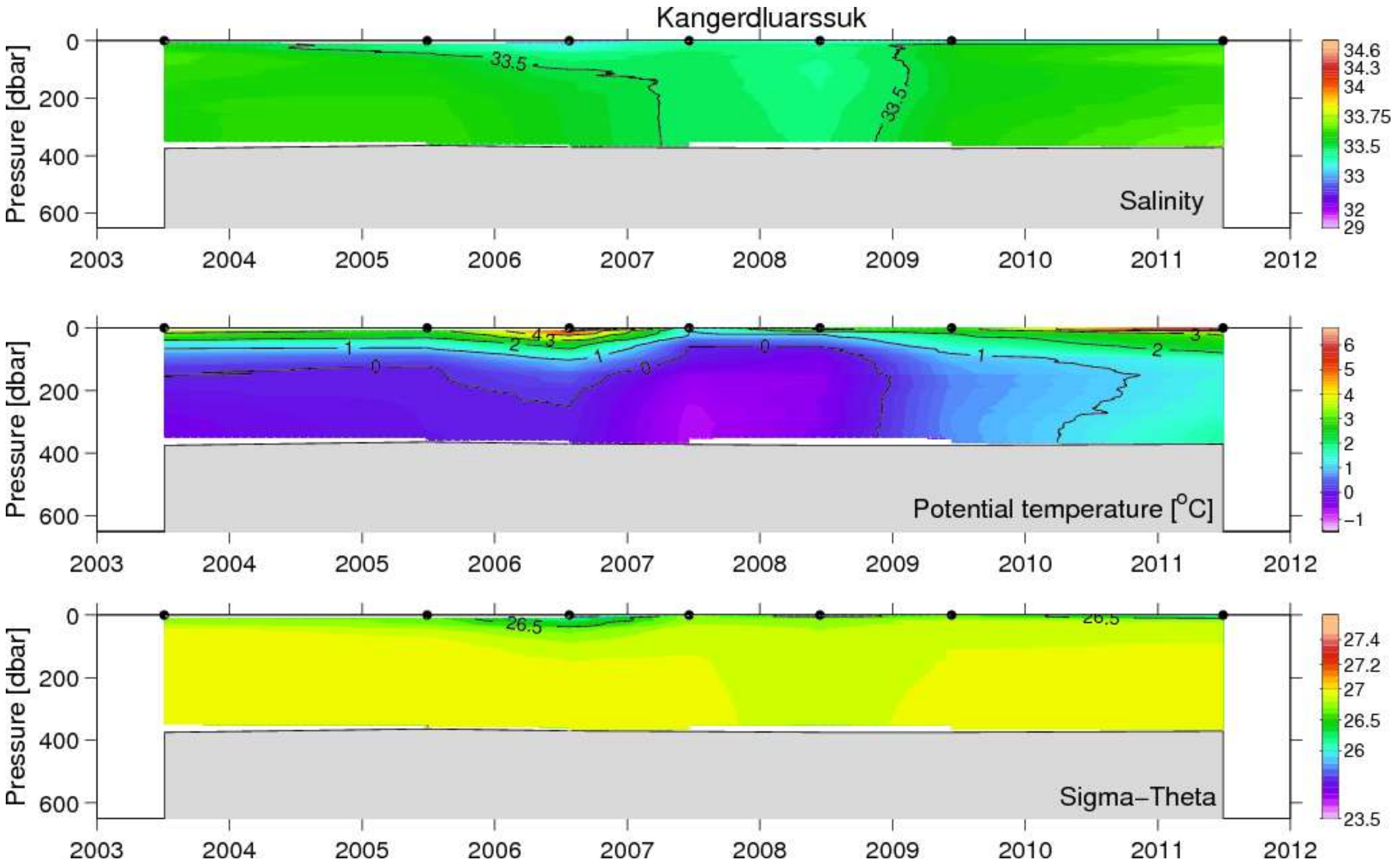

Figure 50**.** Hovmöller diagram of vertical distribution of temperature, salinity and density at the Kangerdluarssuk fjord st.3, late June/July 2003, 2005–2009, 2011.

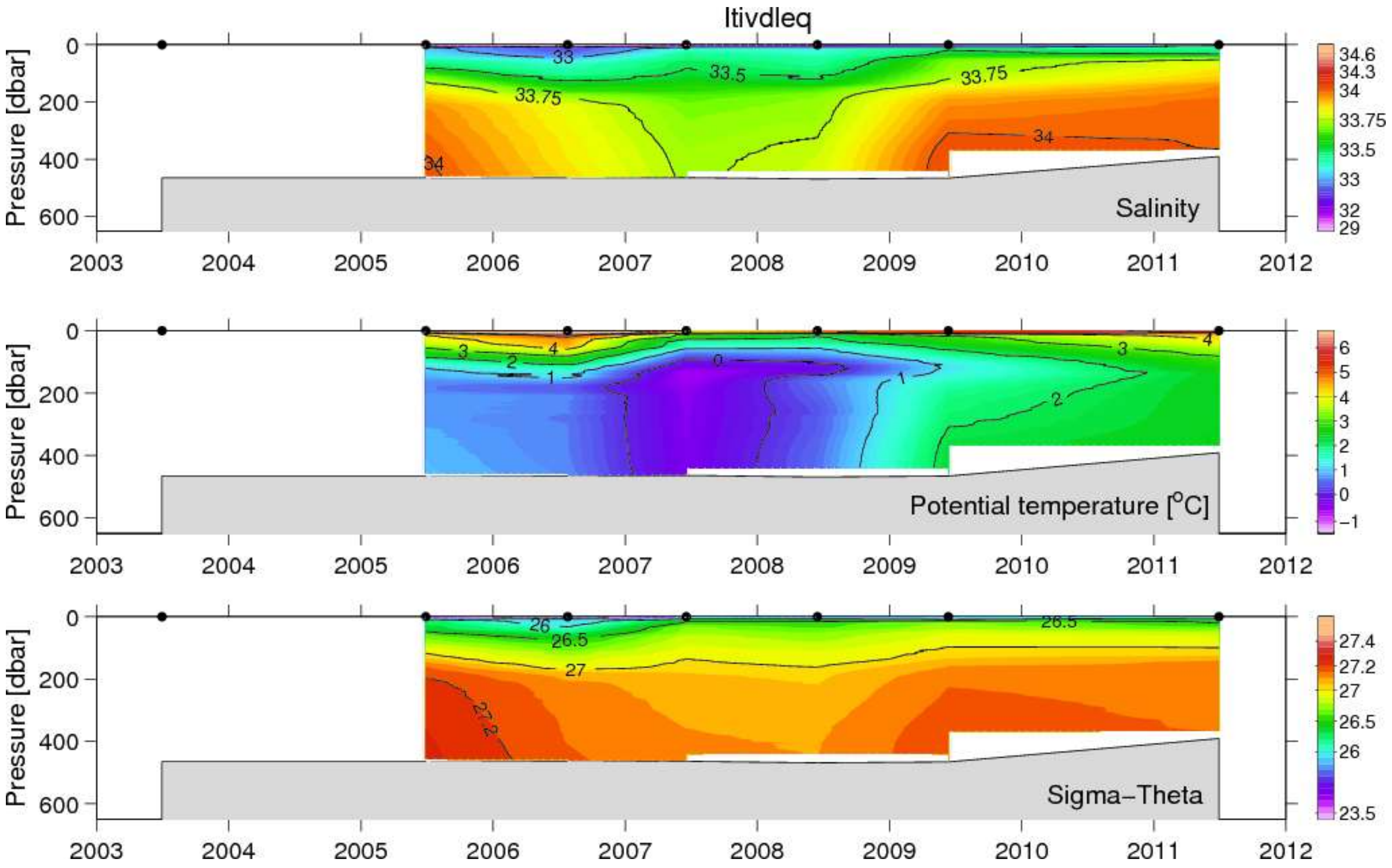

Figure 51. Hovmöller diagram of vertical distribution of temperature, salinity and density at the Itivdleq fjord st.4, late June/July 2005–2009, 2011. Itivdleq St. 3 was used for 2011.