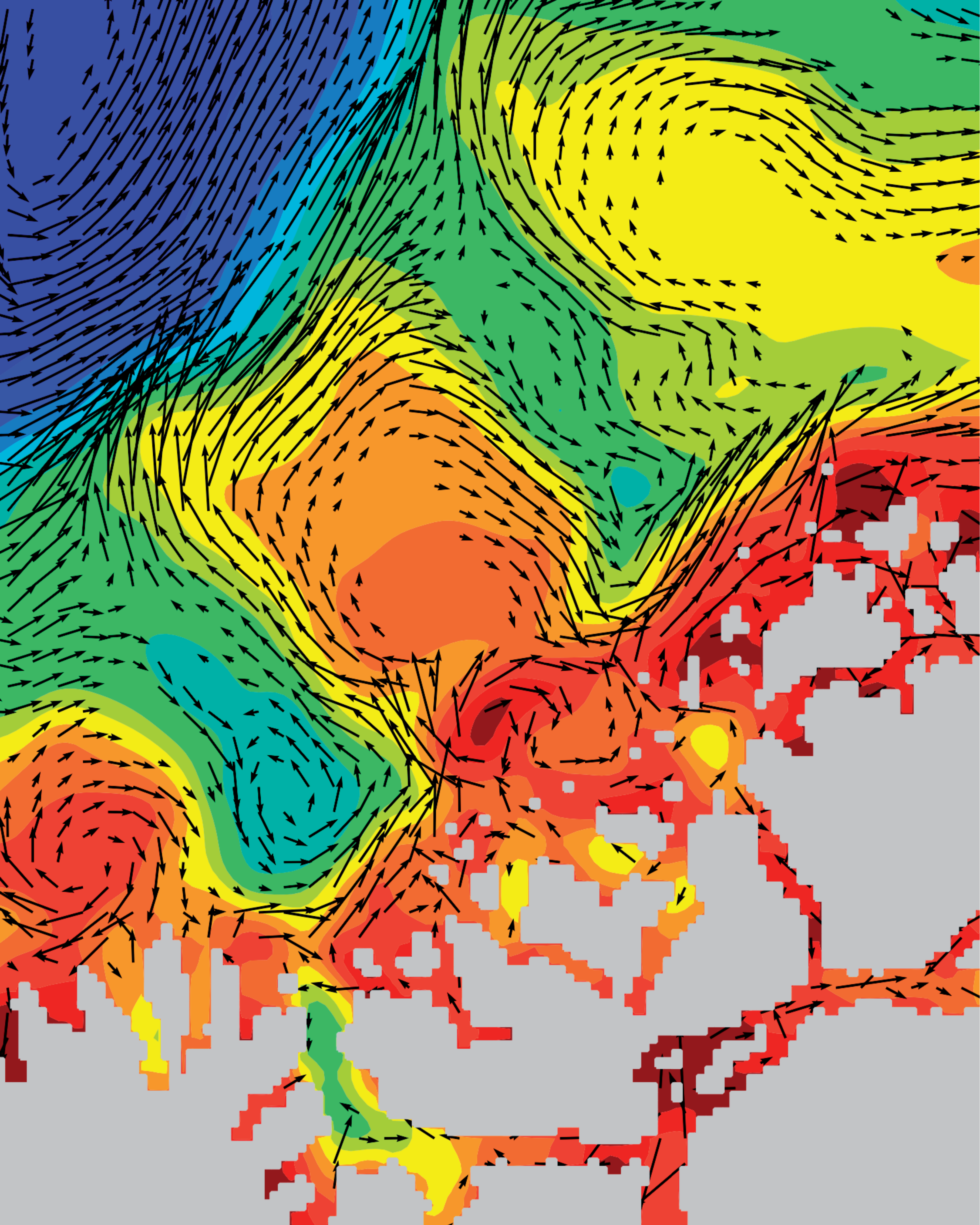

PHYSICAL CONDITIONS OFF THE COAST OF NORTHERN NORWAY

Bjørn Ådlandsvik, Marek Ostrowski and Jofrid Skarðhamar

Processes on the seabed are determined by physical conditions in the ocean. Currents influence sedimentation and thus contribute to forming the seascape. For the benthic fauna, currents are important in that they carry food particles and drifting (pelagic) life stages. The depths where organisms are found are to a large extent determined by the temperature. In this chapter, we look at near bottom physical conditions in general and currents in particular in the area west of Northern Norway.

9.1. WATER MASSES

Along the continental shelf and the slope towards the deep sea off Northern Norway, there are, roughly speaking, three water masses. Close to land, the Coastal Water follows the Coastal Current. This water, which originates in the Baltic Sea and is fed by rivers along the coast, is relatively fresh and varies greatly in temperature from summer to winter. Beyond and beneath we find the Atlantic Water, with its high salinity and relatively stable and high temperatures throughout the year. Underneath the Atlantic Water is the Intermediate Water, which is fresher than the Atlantic Water and significantly colder. The transition between the Atlantic and the Intermediate Waters is called the thermocline. In the deeper parts of the Lofoten Basin in the Norwegian Sea, we also find deep water that is both cold and salty.

9.2. CURRENTS

Marine currents have a number of driving forces. The tidal current is controlled by the gravity of the moon and the sun. Other driving forces are wind and differences in water density. Currents are influenced by bottom topography and the rotation of the earth, which turns currents to the right in the northern hemisphere. As a consequence, currents generally follow the bottom contours with shallow water on the right side. This is called topographic steering. The most important current off Northern Norway is the North Atlantic Current, which is an extension of the Gulf Stream. It carries salty, warm Atlantic Water north and contributes to a mild climate and a rich fauna, considering the latitude.

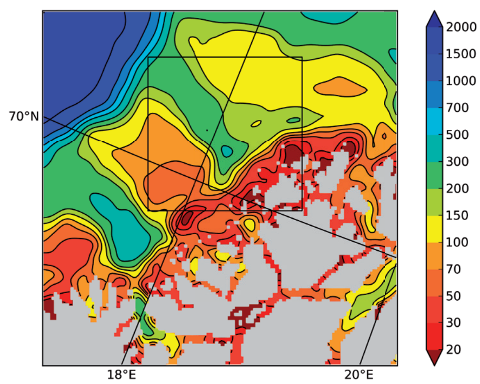

Figure 1. Map of the area with the three banks (from south to north): Sveinsgrunnen, Malangsgrunnen and Nordvestbanken. The rectangular frame marks the depression between Malangsgrunnen and Nordvestbanken.

The strong North Atlantic Current has two branches; one inner, stable branch that follows the continental slope; and a more variable branch in deeper waters further out. Close to Tromsøflaket, the North Atlantic Current splits, with one branch following the continental shelf edge towards Svalbard, and another entering the Barents Sea. Closer to land, the Norwegian Coastal Current follows the coastline northwards and into the Barents Sea.

Currents vary in time and space, which makes it difficult to form a complete picture of the circulation with measurements alone. Current metres are stationary instruments measuring how the currents vary at one specific point. Another way of measuring currents is using drifters that follow the current at a specific depth. A less expensive alternative is mathematical models using basic physical laws to estimate currents based on knowledge of driving forces and topography. Limitations in computing power and insufficient knowledge of driving forces can make current models inaccurate.

9.3. MODELLED BOTTOM CURRENTS

Jon Albretsen at IMR has built and run a relatively fine-scaled model with an 800m resolution covering most of the MAREANO area off Troms. The model is forced by tides, wind and a description at the lateral boundary from a coarser scale model. The modelled area with topography is showed in figure 1. The topography appears relatively smooth compared to the fine-scaled topography measured in MAREANO, because a grid scale of 800m does not show the finer seabed details. The fact that the model does not incorporate these details is one of the sources of error of the model.

The model describes current on a fine time scale but saves only 24 hours mean values, which smooths the results in time and in particular removes the tidal current from the model output. However, it is important to keep the tide in the simulations, as it influences the mixing in the model. Figure 2 shows the modelled average current speed at the seabed. The average is taken from the period January–May 2009. From the figure, we see that the current varies in strength from one place to another. The strongest currents occur in bands following the topography; and the single strongest current runs along the shallower part of the continental slope. This is a steep area shallow enough that the North Atlantic Current reaches all the way down to the seabed. The average current here is up to 30cm/s. Closer to the coast, we see that

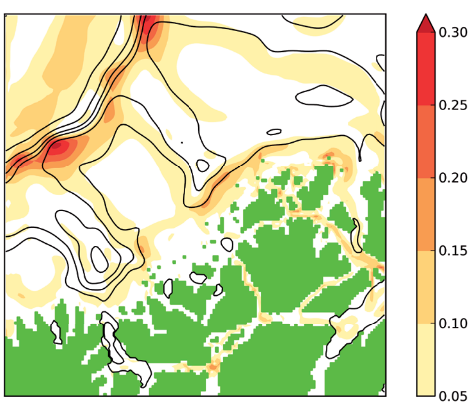

Figure 2. Strength of modelled bottom current in m/s. The black contour lines mark depths of 100, 200, 300, 400, 600 and 1000 metres.

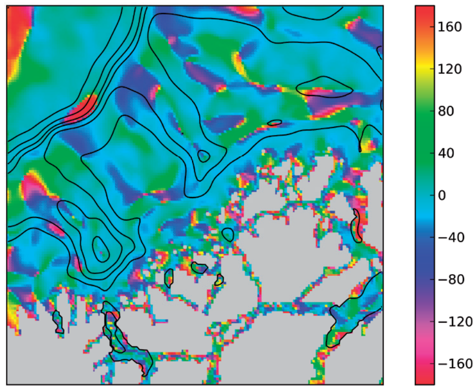

Figure 3. The mean direction of the bottom current relative to the topography.

the average current is weak on the banks and at the bottom of depressions. On the slopes by the edge of the banks, the current is stronger and follows the depressions towards land. Some of this water flows out at the northern end of the depressions, while some follows the coast to the next depression.

Figure 2 shows only the strength of the currents and not the direction. The direction is shown in a separate figure 3 where it is shown as deviation in degrees from the topography. Light blue and green colours, around zero degrees, are currents following the topography with shallow waters to the right. Bright blue

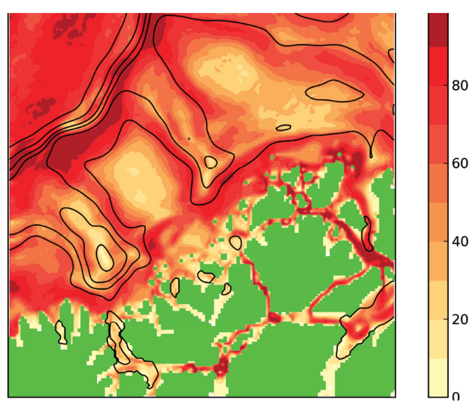

Figure 4. Frequency of 24-hour mean bottom current stronger than 5cm/s.

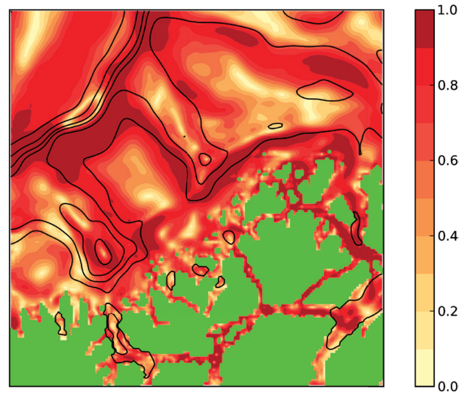

Figure 5. Directional stability of the 24-hour mean bottom current.

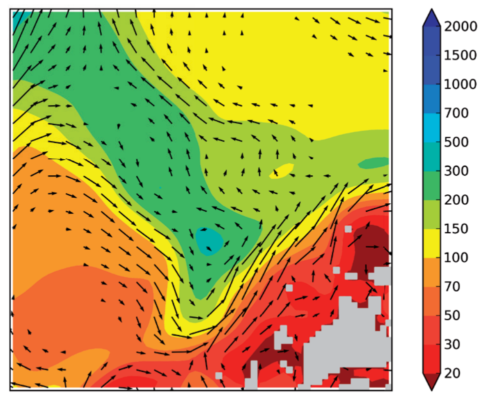

Figure 6. Mean bottom current in the framed area of figure 1. The currents are indicated by arrows (for every third grid cell) while colour indicate depth. Weak currents, less than 2cm/s are not represented. The length of the arrows indicates current strength.

colours to magenta, around minus 90 degrees, are currents crossing the topography towards deeper waters. Plus 90 degrees, bright green and yellow, are currents crossing the topography towards shallower waters. Red colours show currents following the topography in shallow waters in the opposite direction. In general, and particularly in steep areas with accordingly strong currents, the currents follow the topography. One exception is the continental slope in the curve west of Malangsgrunnen. Even though the slope is steep, the current moves in the opposite direction. On the banks and in the deep troughs between the banks where the current is weaker, the topography plays a less important role.

Currents vary both in strength and direction. For sediment resuspension it is interesting to look at the frequency of strong currents. Figure 4 shows the frequency of 24-hour mean currents stronger than 5cm/s. Similar to the mean current, the figure shows bands where the current is strong most of the time. This is particularly evident along the shelf edge. On the banks, the current is weaker and only sporadically reaches speeds of 5cm/s. Note that this is calculated based on 24-hour mean currents without tides; maximum tidal currents may be stronger. The variations in direction can be illustrated by directional stability as shown in figure 5. A value of 1 means that the 24-hour mean current has a constant direction. Lower values give increased variability towards 0, which indicates no preferred direction. Along the shelf edge, around the banks, and close to the coast the direction is very stable and follows the topography. The area with opposite current, at the shelf edge west of Malangsgrunnen, varies in extent and appears as a band of low stability around the core area of a south-going current. On the banks, where the topography is flatter, the direction varies more.

To look more closely at the bottom current, figure 6 focuses on the depression between Malangsgrunnen and Nordvestbanken (framed in figure 1). In this small area, the bottom circulation is illustrated by arrows. The depression is not symmetrical, as a branch reaches north at the Norwest Bank. The current enters close to the coast, along the southern side of the depression, and breaks off towards the north at the bottom of the depression where it splits. The branch that follows the depression outwards is at first weak and wide but intensifies as the slope steepens. The branch heading north along the coast, west of the Northwest Bank, is relatively strong on the steep slope. Closest to the coast, there is an addition to the bottom current, as the Coastal Current fills the whole water column. At depth, two whirlpools form, a small whirlpool over the deepest area closest to the coast and a more elongated whirlpool further out. Both of these rotate anti-clockwise.

9.4. CURRENT MEASUREMENTS

This sub-chapter consists of three parts: The first part looks at how deep the North Atlantic Current flows on the slope off Troms by combining cruise-based oceanographic observations with the detailed topographic mapping from the MAREANO project. The second part uses data from current meters to look at seasonal variations in the same area and how they affect bottom currents. The last part looks at short-term variations in the bottom-near currents with focus on internal tides.

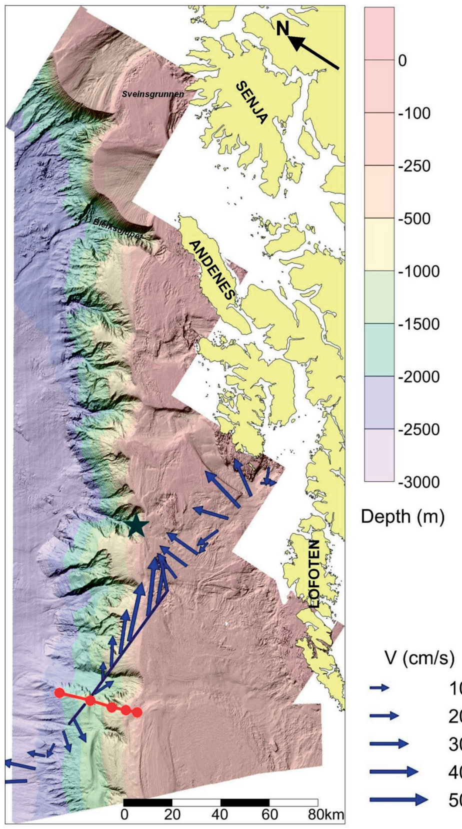

Figure 7. High-resolution bottom topography of the continental shelf and slope from Lofoten to Senja. The positions of the measurements are marked. The current arrows come from MAREANO with G.O. Sars in October 2009. Whole lines indicate transects of current (blue) and hydrography (red). The current meter is marked by a star. The topographic data set has a resolution of 50x50m and comes from MAREANO multi-beam echosounder data. The map is rotated 58° east.

Depth of the North Atlantic Current off Lofoten in October 2009

Figure 7 shows a high-definition bottom map of the shelf off Troms based on multi-beam echo data from MAREANO. Onto this background we have drawn current arrows at 30 metres depth, measured during a cruise with the research vessel, G.O. Sars, in October 2009. The arrows gather and increase in strength close to the shelf edge, indicating the position of the core of the North Atlantic Current flowing northeast in this area. Figure 8a shows a vertical transect across the same current. The core of the North Atlantic Current flows down off the shelf edge. Generally, the current is stronger close to the surface and decreases with depth until it is close to zero at about 520m.

Figure 8b shows the temperature distribution from a hydrographic transect nearby during the same cruise (red line in figure 7). The dominating feature in this figure is the thermocline, characterised by a rapid drop in temperature from 5° C to 1° C from 500m to 650m depth. The water column above the thermocline consists of Atlantic Water, which is relatively warm (T > 5° C) and rich in oxygen. Below the thermocline, the Norwegian Sea has an Intermediate Water mass, which is much colder (T < 1° C) and low on oxygen. Figure 8 shows that the top of the thermocline and the depth with zero current meet on the continental slope. The thermocline thus indicates a shift in the bottom current. In shallower areas, where the bottom is above the thermocline,

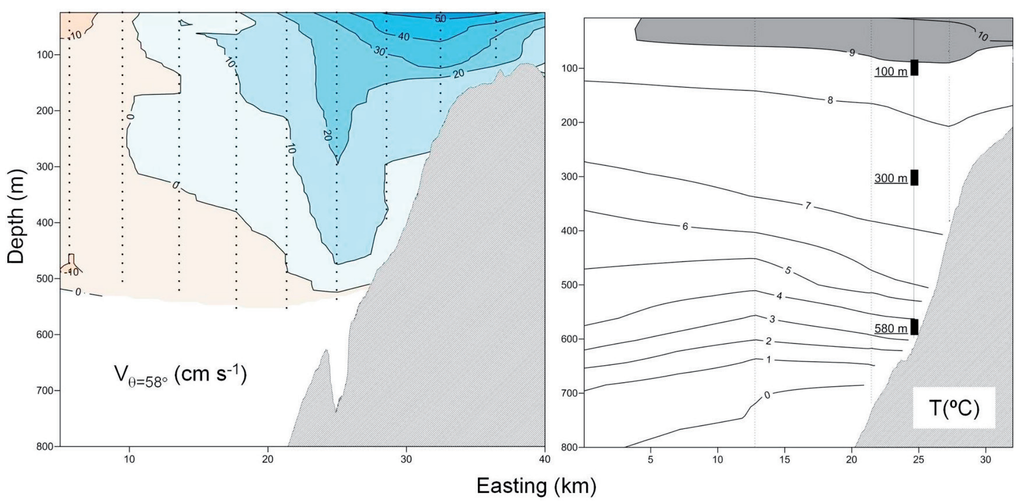

Figure 8. Wertical transects from a cruise with G.O. Sars in October 2009:
(a) Component of the current along the continental slope. Positive values indicate northeasterly currents (into the paper). Deeper currents are below the detection range for the instrument (ADCP, Accoustic Doppler Current Profiler) and have thus been omitted. Horizontal axis shows distance in km gridded topography.
(b) Temperature transect. Stations are marked by vertical dotted lines.
Placement of rig with current metres is marked in black (the rig was not on the transect, see figure 1 for placement).

the bottom current should be connected to the North Atlantic Current, whereas the bottom current in deeper areas will behave more independently. The model shows that there may still be a connection between surface and bottom in deeper areas because the current in the whole water column is determined by topographic features.

Changes in Near-Bottom Currents between June 2007 and October 2008

A current meter mooring was placed in the MAREANO area, the position of which is marked by a star in figure 7. The mooring was equipped with three current metres at 100m, 300m and 580m depth. The deepest was 19m above the seabed and represents near-bottom currents. All three metres registered temperature as well as current strength and direction. The mooring is marked in figure 8b. The two top instruments laid within Atlantic Water and the core of the North Atlantic Current whereas the deepest was situated in the lower part of the thermocline.

Figure 9 shows time series of all three current metres. The series are smoothed with a seven-day moving average to remove short-term variations (such as tides). The colour of the arrows indicates temperature. From September to October 2007, the conditions were similar to the conditions during the MAREANO cruise with G.O. Sars in 2009, with a temperature of 4° C near the bottom and a temperature of 7–8° C higher up in the Atlantic Water. In mid-December, the North Atlantic Current becomes stronger, goes deeper and covers the whole water column down to the bottom. This situation continued until March 2008 after which the circulation close to the bottom returned to thermocline conditions with weak currents and temperatures below 2° C. During this period, only the upper instrument shows the North Atlantic Current as a steady and strong, northerly flow.

Tables 1 and 2 provide a statistical comparison of two 2.5 months periods with a strong winter current and a weaker spring circulation. The periods are marked in figure 9.

During the winter period (table 1, figure 10a), the current followed roughly the same direction at all three current metres and followed the topography in the area (figure 10a). The upper two meters show a high stability in direction, whereas the lower meter shows more variation. During spring, on the other hand, the current properties at 580m are disconnected to what happens at 100m

Depth (m)		Speed (cm/s)	Direction (degrees)	Directional stability	Temperature (°C)
From surface	Above bottom				
100	400	43.5	45.3	0.97	7.7
300	299	22.0	48.2	0.94	7.8
580	19	10.8	50.2	0.52	6.4

Table 1
Statistics for smoothed current from the current meter at latitude 68°51.9´N and longitude 13°15.1´E during the period 10.12.2007–01.03.2008.

Depth (m)		Speed (cm/s)	Direction (degrees)	Directional stability	Temperature (°C)
From surface	Above bottom				
100	400	30.4	43.0	0.90	7.3
300	299	10.1	35.3	0.52	6.7
580	19	5.6	84.3	0.36	2.7

Table 2
Statistics for smoothed current during the period 20.03.2008–06.06.2008.

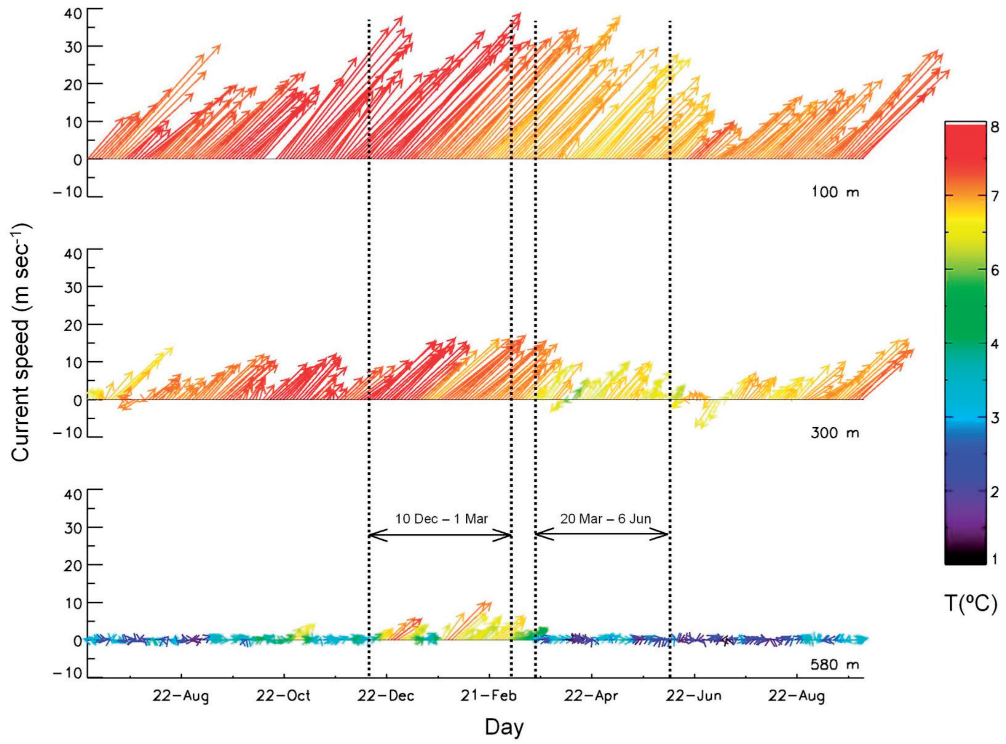

Figure 9. Temperature and current time series from the current meter off Lofoten (latitude 68°51.9´N, longitude 13°15.1´E). The measurement period is June 2007–October 2008. Time series from top to bottom show results from 100m, 300m and 580m. Colour scale shows temperature while current strength is shown along the left axis. The two 2.5 months periods are marked by vertical dotted lines.

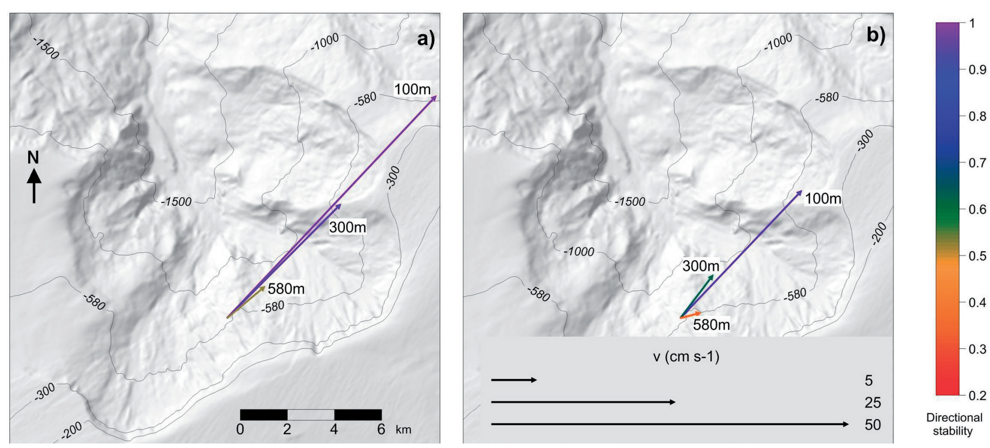

Figure 10. Mean speed, direction and directional stability over two 2.5 months periods: (a) 10.12.2007–01.03.2008, (b) 20.03.2008–06.06. 2008. The map is from the high-resolution topography of MAREANO.

and 300m (table 2, figure 10b). The strength of the current is almost half of what it is in the winter and the direction of the currents at 100m and 580m deviate by more than 40 degrees. The stability in direction near the bottom has declined even more, indicating that short-term variations dominate the circulation during this period.

Short-term fluctuations

In order to study short-term variations more closely, we have selected two 5-day periods, from January where the Atlantic Water reaches the seabed and April when the deepest instrument is below the thermocline. Table 4 and 5 summarise statistics from these series while

Depth (m)		Speed (cm/s)	Direction (degrees)	Directional stability	Temperature (°C)
From surface	Above bottom				
100	500	51.3	47.3	0.97	7.6
300	299	27.8	48.1	0.97	7.7
580	19	17.4	46.7	0.81	7.7

Table 3
Current statistics for the period 26–31 January 2008.

Depth (m)		Speed (cm/s)	Direction (degrees)	Directional stability	Temperature (°C)
From surface	Above bottom				
100	500	30.0	39.2	0.96	7.2
300	299	10.8	42.0	0.81	6.8
580	19	6.1	101.1	0.19	2.6

Table 4
Current statistics for the period 15–20 April 2008.

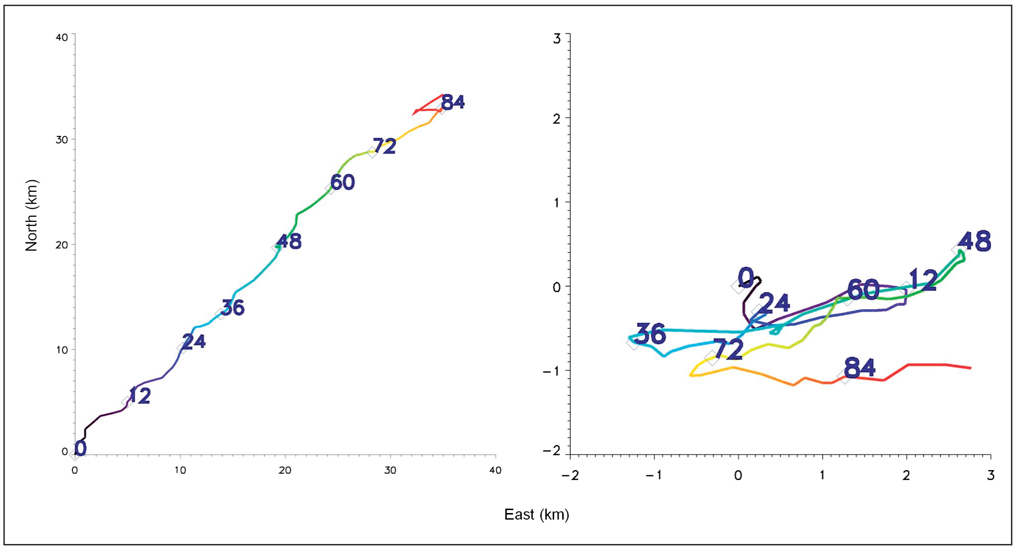

Figure 11. Progressive vector diagrams from the current meter at 580m depth: (a) 26–31 January 2008 and (b) 15–20 April 2008. The horizontal and vertical axes indicate distance in km from starting point. Note that the scales differ. The numbers along the curve specify time from start in hours. The colour scale indicates continuous time.

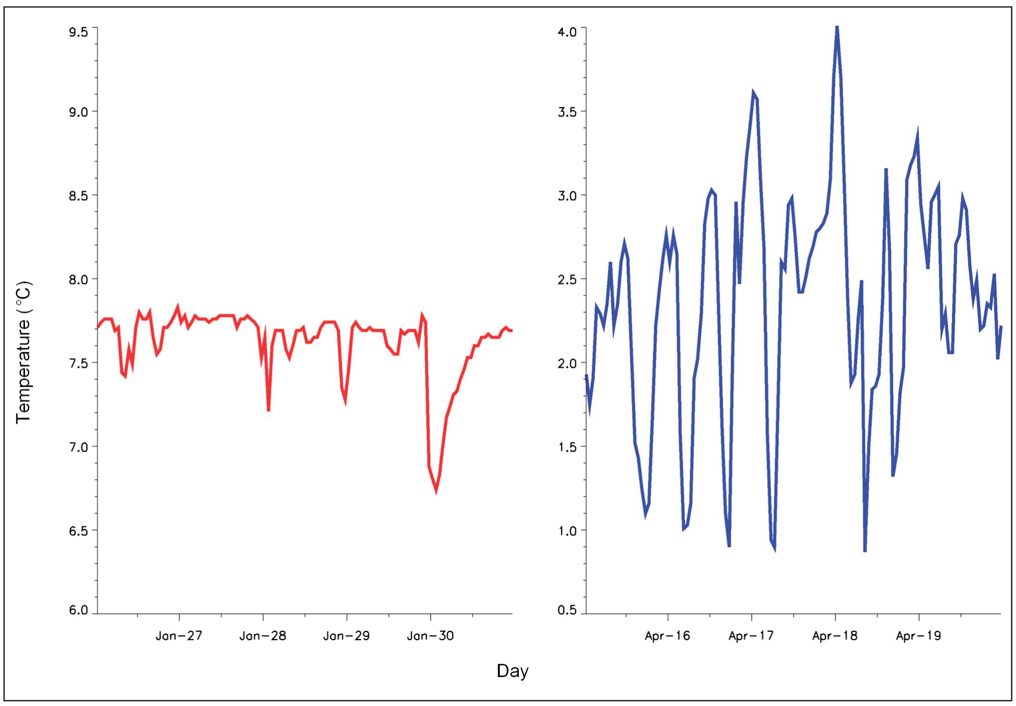

Figure 12. Fluctuations in temperature measured by the instrument at 580m depth: (a) 26–31 January, (b) 15–20 April 2008. Note that the temperature scales are not the same.

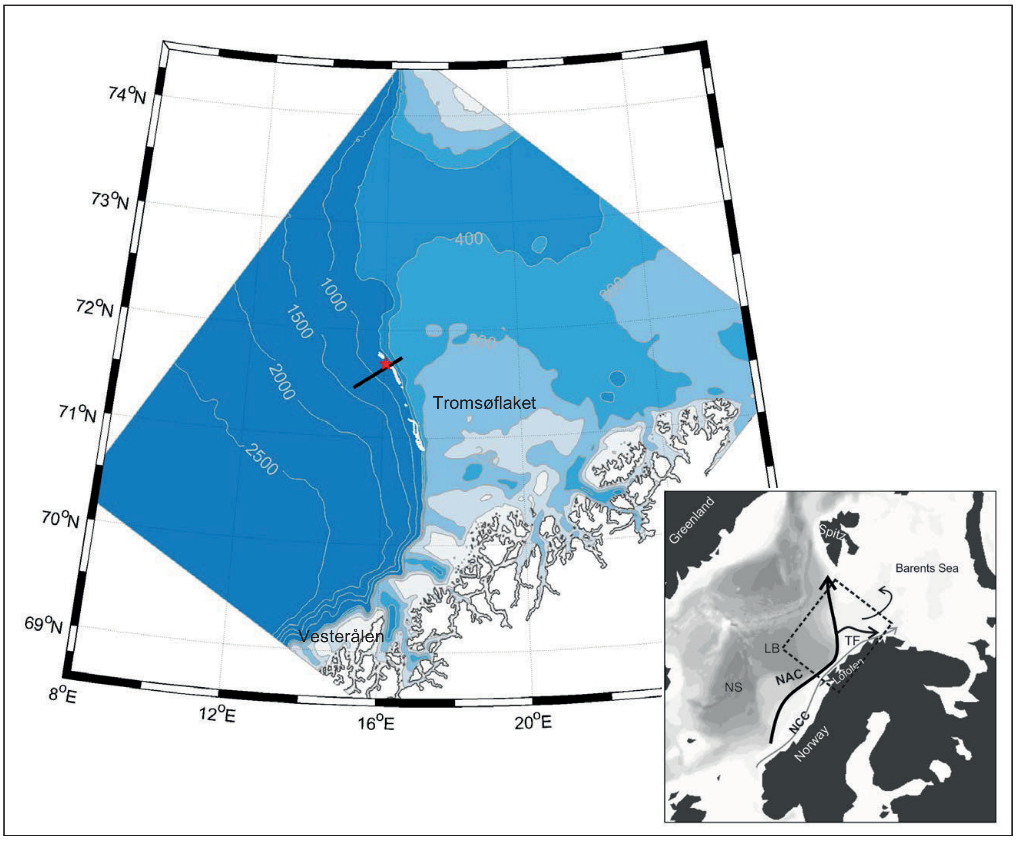

Figure 13. Bathymetric map of the model domain (left), which is marked with a stipled rectangle in the map of the Nordic Seas (right). NAC: North Atlantic Current, NCC: Norwegian Coastal Current, NS: Norwegian Basin, LB: Lofoten Basin, TF: Tromsøflaket, Spitz.: Spitsbergen. The red star indicates the position of the current meter mooring, and the black line shows the CTD transect. Isobaths are drawn for depths 100, 200, 300, 400, 500, 1000, 1500, 2000 and 2500 m. The white contours between 70.5 and 72 °N marks the positions of the sandwave fields described in chapter 3.1 and Bøe *et al.* (2014). The coastline is drawn with black contours. Modified from Skarðhamar *et al.* 2015.

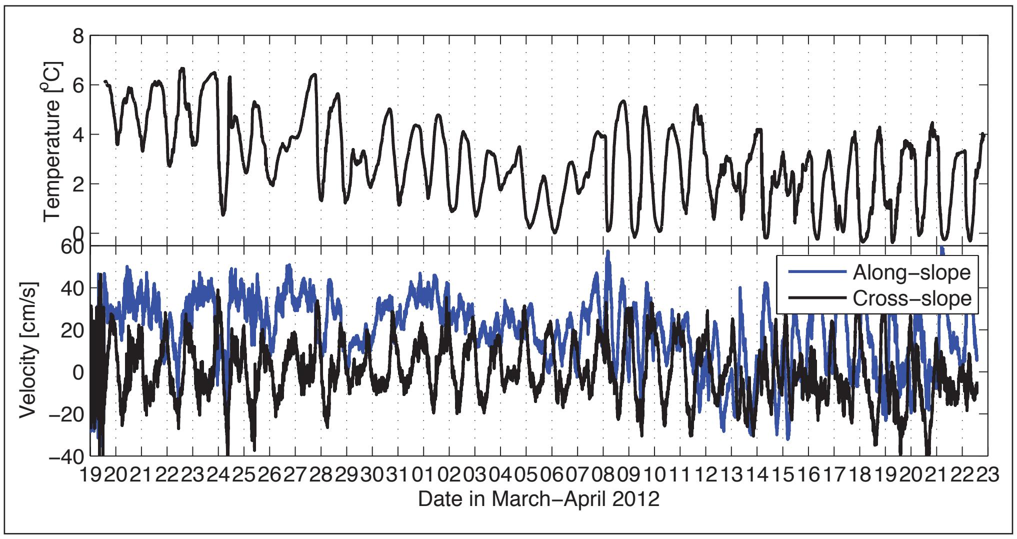

Figure 14. Time series from 19 March to 22 April, 2012 of measured temperature (upper panel) from 20 m above the seabed, from the mooring located on water depth 632 m. Current measurements (lower panel) are from 30 m above bottom, i.e. 602 m depth: along slope (blue) and cross-slope (black) current components. Modified from Skarðhamar *et al.* 2015.

figure 11 shows progressive vector diagrams. (A progressive vector diagram shows how a particle would move with the current if the current measured by the current meter were the same over a larger area).

In the winter period (table 3, figure 11a), a water particle released at 580m depth moves steadily northeast at a speed of 7km per 12 hours. The current shows only weak signs of cyclic behaviour. In spring, under the thermocline (table 4, figure 11b), the situation is different, dominated by strong oscillations and weak mean movement. Figure 12 compares the temperature development at the lower current meter during the same periods. In January (figure 12a), the temperature is relatively unchanged, except from a local minimum towards the end. In April (figure 12b), the temperature shows cyclic fluctuations in periods of about 12 hours and amplitude of 1–2° C. This suggests internal tidal waves in the thermocline. Such waves are often formed by tidal currents over an uneven topography when the water column is layered, which is the case in the continental slope west of Troms.

Topographic waves at the slope west of Tromsøflaket

A mooring equipped with current meters and temperature and salinity sensors, was deployed on ca. 600 m depth at the Tromsøflaket slope in spring 2012 (Figure 13). The measurements revealed large diurnal fluctuations in temperature, salinity and cross-slope current component velocities near the seabed (Figure 14). Numerical modelling of the hydrodynamics in this area show similar oscillations over the slope, and large vertical displacement of the interface between Atlantic Water and Intermediate Water (Figure 15). This variability is interpreted as tidally induced diurnal period topographic waves, moving up and down the slope daily, with amplitudes of about 200 m. The model results show that the magnitudes of the oscillations and the cross-slope currents vary in time, related to the variable strength of the background flow, the Norwegian Atlantic Current. The diurnal topographic waves are confined to the diverging topography west of Tromsøflaket (Figure 16), the same area as large sandwaves fields are identified on the seabed (see chapter 3.1). The diurnal topographic waves can be an effective mechanism for cross-slope exchange between the Norwegian Sea and the Barents Sea shelf, and important for benthic and pelagic biological processes on the shelf and slope.

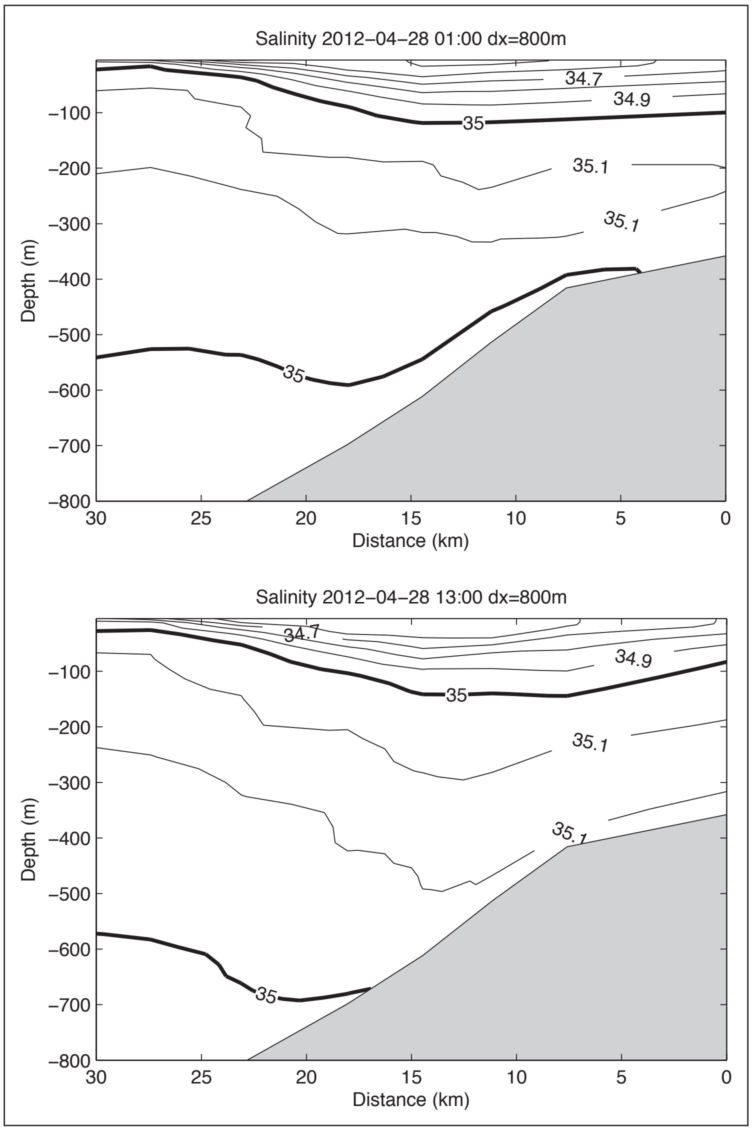

Figure 15. Modeled salinity distribution from the NordKyst800 model setup 28 April, 2012, at 01:00 (upper panel) and 13:00 (lower panel). The section crosses the shelf slope west of Tromsøflaket. See Figure 13 for location of the section. Modified from Skarðhamar *et al*. 2015.

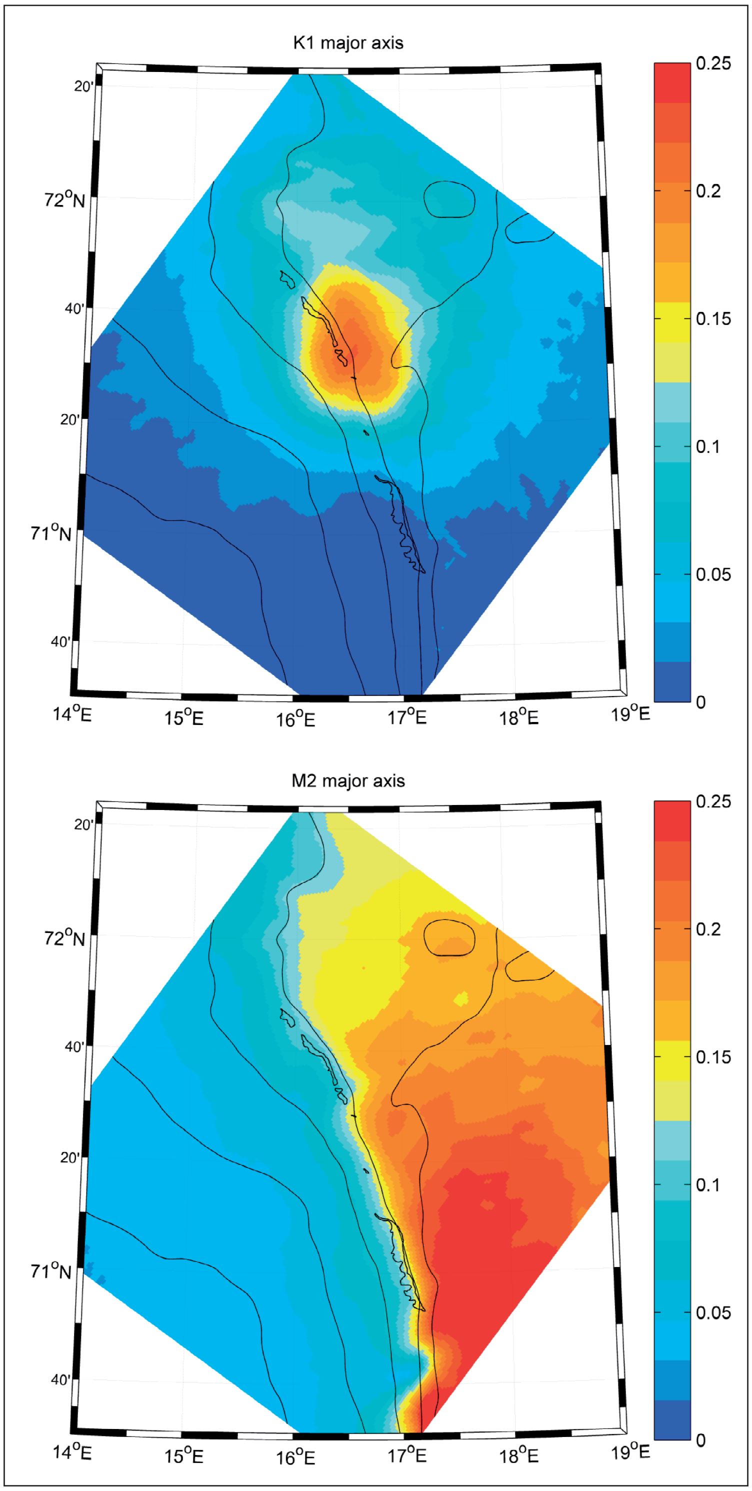

Figure 16. Magnitudes of the major axis of the tidal components K1 and M2, computed with t_tide (Pawlowicz *et al.* 2012) from the modelled barotropic velocities in each model grid cell, April 2012. Depth contours (black lines) are drawn for depths 300, 500, 1000, 1500 and 2000 m. The black closed contours mark the sandwave fields described in chapter 3.1. Modified from Skarðhamar *et al*. 2015.