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Water mass characteristics and sill dynamics in a subpolar cold-water coral reef setting at Stjernsund, northern Norway

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ABSTRACT

The Stjernsund, located in subpolar setting at 70.5°N off northern Norway, hosts a thriving cold-water coral reef community on a morainic sill. Dives with manned submersible JAGO identified the different reef zones and sedimentary facies on top and on the slopes of the sill. Hydrographic investigations indicate different water mass distribution east and west of the sill. Winter Mode Water and Norwegian Coastal Water variability depends on the runoff and freshwater discharge into the fjord. Atlantic Water dynamics are almost entirely tidally driven. High-resolution CTD time series covering a full tidal cycle demonstrate mixing processes occurring east of the sill. Additionally, the different bathymetric distribution of living corals on the western and eastern slope of the sill portrays the dependence on these tidal dynamics. The living corals thrive just below the isopycnal of 27.5 kg m^{-3}, which marks the boundary between Norwegian Coastal Water and Atlantic Water.

1. Introduction

Cold-water coral reefs occur at various sites along the European continental margin, like in the Mediterranean Sea (e.g., Taviani et al., 2005), on carbonate mounds West off Ireland (e.g., Henriet et al., 1998; De Mol et al., 2002; Kenyon et al., 2003; Wheeler et al., 2007), or at shallower depths between 100 and 350 m on the Norwegian shelf (e.g., Mortensen et al., 2001; Freiwald et al., 2004; Fosså et al., 2005). Their occurrence is related to different physical parameters like temperature, salinity, seawater density, dissolved oxygen, and to other environmental parameters such as internal wave activity, nutrient supply, strong currents, which keep sediment input low, etc. (Frederiksen et al., 1992; Rogers, 1999; White, 2007; Dorschel et al., 2007; Dullo et al., 2008).

Along the Norwegian coast, several cold-water coral sites are also known from fjord and sound settings. In these locations, sills play an important role with respect to water mass structure, circulation, sediment transport, and marine life. Fjords are characterized by continuous estuarine circulation patterns (Farmer and Freeland, 1983; Lewis and Thomas, 1986), whereas sounds exhibit a circulation pattern governed by the local wind regime (Klinck et al., 1982; Stigebrandt and Aure, 1989). Tidal forcing and varying seasonal freshwater runoff (snow-melt, ice-melt, rain-storm) have an impact on the current regime (Syvitski et al., 1987). In addition, sounds are characterized by increased through-flow, flushing rate, and reduced residence time of water (Arneborg, 2003).

Our objective during RV POSEIDON cruise P325 was to investigate the facies pattern, geological boundary conditions and characteristics and dynamics of the water masses of the cold-water *Lophelia*-reef structures on Stjernsund-sill, which was first described in the classical comprehensive study by Dons (1932). Since this study, cold-water corals are known to form build-ups or deep-water reefs on the Norwegian margin including spectacular locations such as Oslofjord, Trondheimfjord, Sula Reef, Røst Reef, or Stjernsund (Freiwald et al., 1997, 2002, 2005). However, the controlling factors favouring and maintaining cold-water coral reef growth in subpolar sound-settings have rarely been studied applying swath bathymetry, submersible dives including photo and video surveys, physical oceanography, geology, and biology at one site.

Located at 70.5°N and 22.5°E, the Stjernsund is a 30 km long and up to 3.5 km wide sound connecting the open North Atlantic with the Altafjord (Fig. 1). A deep-seated SW–NE oriented morainic sill with varying depths (203–236 m) splits the more than 400 m deep sound into two troughs. This sill has an asymmetric cross-section with a steep NW slope and a gently inclined SE slope. Living *Lophelia pertusa* dominated reef complexes occur on the NW slope between 235 and 305 m water depths and on the SE slope between 245 and 280 m.

The general surface hydrography in the NE Atlantic and the Norwegian-Greenland Sea is characterized by the northward

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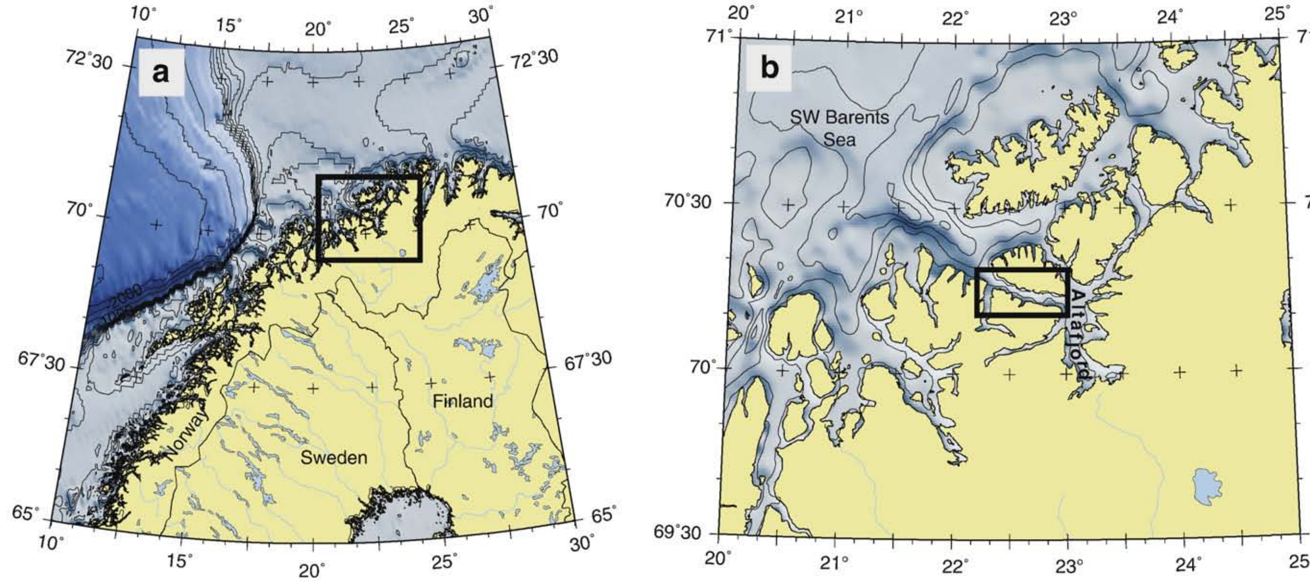

Fig. 1. a) The Finnmark district of northern Norway with b) the study site of Stjernsund (box).

transport of warm subtropical water to high latitudes. Along the Norwegian coast water masses of this surface current regime, the North Atlantic Current (NAC), occur at the relative shallow habitats of living coral reefs (140–380 m; Fosså et al., 2005; Freiwald et al., 2002). The Norwegian Coastal Current (NCC), which originates primarily from the freshwater outflow of the Baltic and the runoff from the mainland flows northwards parallel along the coast and dominates the surface water circulation (Mork, 1981). The main water masses in the study area along the Norwegian coast (Fig. 1b) are of coastal and Atlantic origin. Norwegian Coastal Water (NCW) is part of the NCC with salinities less than 35 psu (Practical Salinity Unit) and stretches like a wedge over the shelf edge merging with Atlantic Water (AW, Skardhamar and Svendsen, 2005). AW is characterized by salinities >35 psu and is present below the low-saline NCW in water depth of >50–250 m. Norwegian Sea Deep Water (NSDW) comprising salinities below 34.95 and potential temperatures less than 0 °C, fills the deep troughs below 800 m water depth west of the study area (l.c., Freiwald et al., 2005). Within the Stjernsund area, the surface water corresponds to NCW with contribution of continental freshwater discharge. The formation of Winter Mode Water (WMW) is a seasonal effect of freshwater discharge, between 100–150 m water depths. It results from the cooling of surface water of the upper few tens of metres during wintertime. NCW comprises the upper 200–250 m while AW is the dominant water mass below.

Due to the maximum ice extent during the last glaciation, several fjords and sounds exhibit a sill structure (moraines) formed by the subsequent retreat of these glaciers. This geomorphological feature separates the sound into troughs and favours the colonization by benthic sessile biota. Furthermore, these bottom thresholds cause flow acceleration, which in turn results in higher nutrient concentrations, a necessary requirement for cold-water coral growth. Advection of water over sills further triggers nutrient and phytoplankton production (Lindahl and Hernroth, 1988) although the advected nutrients represent only a small portion of nutrients over a sill (Aksens et al., 1989). Underwater ridges such as sills affect water turbulence (Huppert, 1980). Processes like internal waves can be generated and add to the complexity of mixing (Murty and Rasmussen, 1980). They can influence nutrient distribution and energy transport. Farmer and Smith (1980), and Xing and Davies (2006) show that narrow sills increase internal mixing on the lee side.

2. Material and methods

2.1. Swath bathymetry

Swath bathymetry was applied to produce the first three-dimensional image of Stjernsund. A 50 kHz Seabeam 1180 swath system with 126 beams with 3 × 3° beam angle was used. The system was installed together with an OCTANS 3000 motion sensor and a sound velocity probe. Sound velocity profiles of the water column were taken from CTD casts. Cruising speed was between 3 and 4 knots. The data were recorded with the *HYDROSTAR ONLINE* software from ELAC-Nautik and edited by *Hydrographic Data Processing/Data Editor*. Digital Terrain Models (DTM) were processed by *Hydrographic Data Processing/Post Processing* and grids of different grid space (3–8 m) were exported as latitude-longitude-depth data in ASCII format. For map visualisation we used *Generic Mapping Tool* (GMT) with WGS84 as reference ellipsoid and Mercator projection. During our field studies, a total of 71 km track lines were recorded. Apart of the 3-D visualisation, the data were used to produce high-resolution maps to identify promising dive sites for video surveys, to locate hydrographic transects for CTD cast and water samples, and to map the extension and geometry of cold-water coral occurrences.

2.2. Submersible dives

"JAGO" is a manned submersible, certified to a maximum operating depth of 400 m. It was designed and built according to the rules for classification and construction of the Germanischer Lloyd. The highly maneuverable vehicle can accommodate two persons, the pilot and a scientist/observer, at atmospheric pressure. The vehicle is equipped with fluxgate compass, Ultra-Short-Base-Line-navigation and tracking system, underwater telephone, sonar, video and photo cameras, oceanographic sensors and a manipulator arm for handling various sampling devices. In total, 30 h were spent underwater on 8 project dives. The *in situ* observations along with video surveys provided the source for the facies mapping of the sill and its slopes.

2.3. Hydrography

A total of thirty-five CTD casts were carried out in the sound (Table 1). CTD profiles were performed West, East, across, and parallel

Table 1
List of CTD-stations in Stjernsund taken during POSEIDON cruise P325.

Station number	Date	Time (UTC)	Depth (m)	Lat. (°N)	Long. (°E)
410	07/25/05	03:15	467	70°14.927′	22°35.496′
410-2	07/25/05	22:47	467	70°14.857′	22°34.977′
418	07/25/05	17:33	420	70°15.507′	22°31.370′
419	07/25/05	18:30	369	70°15.741′	22°30.463′
420	07/25/05	19:09	253	70°16.004′	22°29.108′
421	07/25/05	19:42	210	70°16.096′	22°28.458′
422	07/25/05	20:17	298	70°16.184′	22°28.145′
423	07/25/05	20:55	362	70°16.363′	22°27.066′
424	07/25/05	21:40	388	70°16.646′	22°25.397′
435	07/27/05	16:54	375	70°15.770′	22°30.643′
436	07/27/05	17:41	364	70°16.378′	22°27.244′
437	07/27/05	18:33	374	70°15.731′	22°30.501′
438	07/27/05	19:06	362	70°16.392′	22°27.198′
439	07/27/05	19:53	374	70°15.744′	22°30.489′
440	07/27/05	20:29	362	70°16.409′	22°27.207′
441	07/27/05	21:05	367	70°15.732′	22°30.465′
442	07/27/05	21:42	361	70°16.389′	22°27.231′
443	07/27/05	22:18	371	70°15.740′	22°30.596′
444	07/27/05	22:57	361	70°16.385′	22°27.176′
445	07/27/05	23:42	366	70°15.731′	22°30.486′
446	07/28/05	00:19	360	70°16.370′	22°27.203′
447	07/28/05	01:02	368	70°15.702′	22°30.521′
448	07/28/05	01:45	361	70°16.398′	22°27.193′
449	07/28/05	02:34	370	70°15.714′	22°30.503′
450	07/28/05	03:27	362	70°16.423′	22°27.214′
451	07/28/05	04:03	378	70°15.643′	22°30.811′
452	07/28/05	04:40	359	70°16.365′	22°27.309′
453	07/28/05	05:17	383	70°15.827′	22°30.734′
454	07/28/05	05:53	363	70°16.330′	22°27.158′
475	07/30/05	17:24	211	70°15.555′	22°27.565′
476	07/30/05	17:56	223	70°16.062′	22°27.366′
477	07/30/05	18:29	264	70°16.417′	22°28.966′
478	07/30/05	19:00	210	70°15.726′	22°27.838′
479	07/30/05	19:30	250	70°16.258′	22°28.658′
480	07/30/05	20:16	232	70°15.890′	22°28.238′

to the sill (Fig. 2). The system used was a SeaBird Electronics, model 911 plus type. The underwater unit was built into a rosette housing capable of holding 12 water sample bottles. Pre-cruise laboratory calibrations of the potential temperature, conductivity, oxygen, and pressure sensors were performed, which yielded coefficients for a linear fit. Although no on-board Winkler-titration for oxygen calibration was carried out during the cruise, pre- and post-cruise lab calibration showed no sensor drift. However, the general downcast trend of dissolved oxygen follows previous studies (e.g., WOCE Global Data, World Ocean Database, 2001; Conkright et al., 2002). Therefore, we used oxygen data in a qualitative way to interpret spatial and temporal variation only. Downcast measurements were used for further processing of data applying *SBE Data Processing Version 5.30a* (ftp://ftp.halcyon.com/pub/seabird/out) and *Ocean Data View mp-Version 3.3.2* (http://www.awi-bremerhaven.de/GEO/ODV) for visualisation.

3. Results

The approximately 20-km-long Stjernsund connects the open sea with the Altafjord (Fig. 1b). The mapped portion of the sound is 10 km long, 1.5–2 km wide, and NW–SE oriented. The sound is divided by a SW–NE trending sill of glacial origin (Fig. 2). The sill crest varies between 236 m and 203 m water depth and the adjacent troughs are 410 m (western trough) and 480 m (eastern trough) deep (Fig. 2a). The sill has an asymmetric cross-section with a gently inclined SE slope and a steep NW slope (Fig. 2b). It's geomorphology points to a morainic origin from a former glacier advance through the Altafjord. The glacier load has generated the asymmetric shape of the sill and over-consolidated sediments in the SE trough (Freiwald et al., 1997, 2005).

3.1. Facies pattern

The surface sediments in the NW trough in 407 m depth (Fig. 3) consist of 20 cm-thick sand deposits enriched with pebbles, molluscs, benthic foraminifers, and few coral fragments. The surface is highly bioturbated by polychaetes, echiurids, and ophiuroids. The steep western slope of the Stjernsund sill represents a pattern of different surface sediment types and benthic communities. Winnowed boulders up to 2 m in diameter and boulder fields were encountered from 365 m upslope. Coral rubble is strewn between the boulders, which are colonised with sponges, bryozoans, barnacles, and hydroids. From 337 m upslope, coral rubble forms up to 20 cm thick pavements, which are accentuated by mega-ripples and outwash holes. At depths deeper than 330 m, the ripple crests are oriented perpendicular to the currents but start to bifurcate in shallower slope environments. The rippled character diminishes at depths shallower than 300 m. The rubble facies (Fig. 3) often shows dense colonisation of *Protanthea simplex* and *Tubularia* hydroids. *Paragorgia* colonies occur in both colour types (red and white). Larger colonies (generally >1 m) often collapse as a consequence of vigorous currents. The sandy sediments underneath the coral rubble pavement are inhabited by *Bonellia viridis*, often in great numbers. Isolated *Lophelia* colonies, sometimes up to 1.5 m thick, with spheroid (cauliflower) growth habit were frequently encountered from 309 m depth and shallower. The larger coral rubble fields below 310 m are parautochthonous and derive from living *Lophelia* crops upslope. There, these colonies integrate into larger "reef bodies" covering areas of a few hundreds of square metres. *Lophelia pertusa* occurs in both colour varieties, orange and white, and together with *Mycale* sponges they form a typical widespread biofacies up to 235 m water depth (Fig. 3). Around this bathymetric level, the more monotonous biofacies of *Lophelia* and *Mycale* becomes more diverse and colourful since other non-calcified coelenterates and many more sponges such as *Geodia* take part in the living surface of the reef.

The sill crest from about 238 to 206 m depth trends NE–SW over a distance of ~ 2 km. Large *Lophelia* reefs were observed in this area, measuring about 400 m across and up to 100 m wide. The shape of the individual reefs in each complex shows indications of strong hydrodynamic control. The reefs are oriented parallel to the currents, with a maximum thickness of 2–8 m on average. The top of the sill is barren of living scleractinians. The off-reef/reef transition is very sudden and the living corals grow over the rubble aprons. The reefless gap on the central sill is covered by coral rubble. Coral rubble pavements with features similar to the western slope cover also the more gently inclined eastern slope of the sill more homogenously. Living corals only occur as isolated patches. Winnowed boulders were not observed. At 472 m depth, the sediment is still sand-dominated and very rich in tube-forming polychaetes.

3.2. Hydrography

Stjernsund waters are characterized by four distinct water masses. Surface waters occupy the upper 100 m of the water column. Here, potential temperature ranges from a maximum of 10.0 °C to 5.94 °C. The observed temperature variability is largely caused by local and regional meteorology. Salinity is strongly influenced by freshwater discharge and varies between ~33 and 34.1 psu within the uppermost 20 m. Below 20 m, surface water exhibits a very constant salinity of 34.2 psu (Fig. 4). Density follows a similar pattern as temperature and salinity (Fig. 5). However, oxygen shows a minimum of <5.7 ml/l between 20 and 80 m, thinning out towards the western trough (Fig. 5d).

Winter Mode Water (WMW) between 100 m and 150 m exhibits potential temperatures of 4.56 to 5.93 °C and salinities of 34.04 to 34.50 psu (Fig. 4). This cooler water mass is formed due to seasonal forcing. The temperature minimum results from the winter cooling of the upper few tens of metres until the surface water is colder than the

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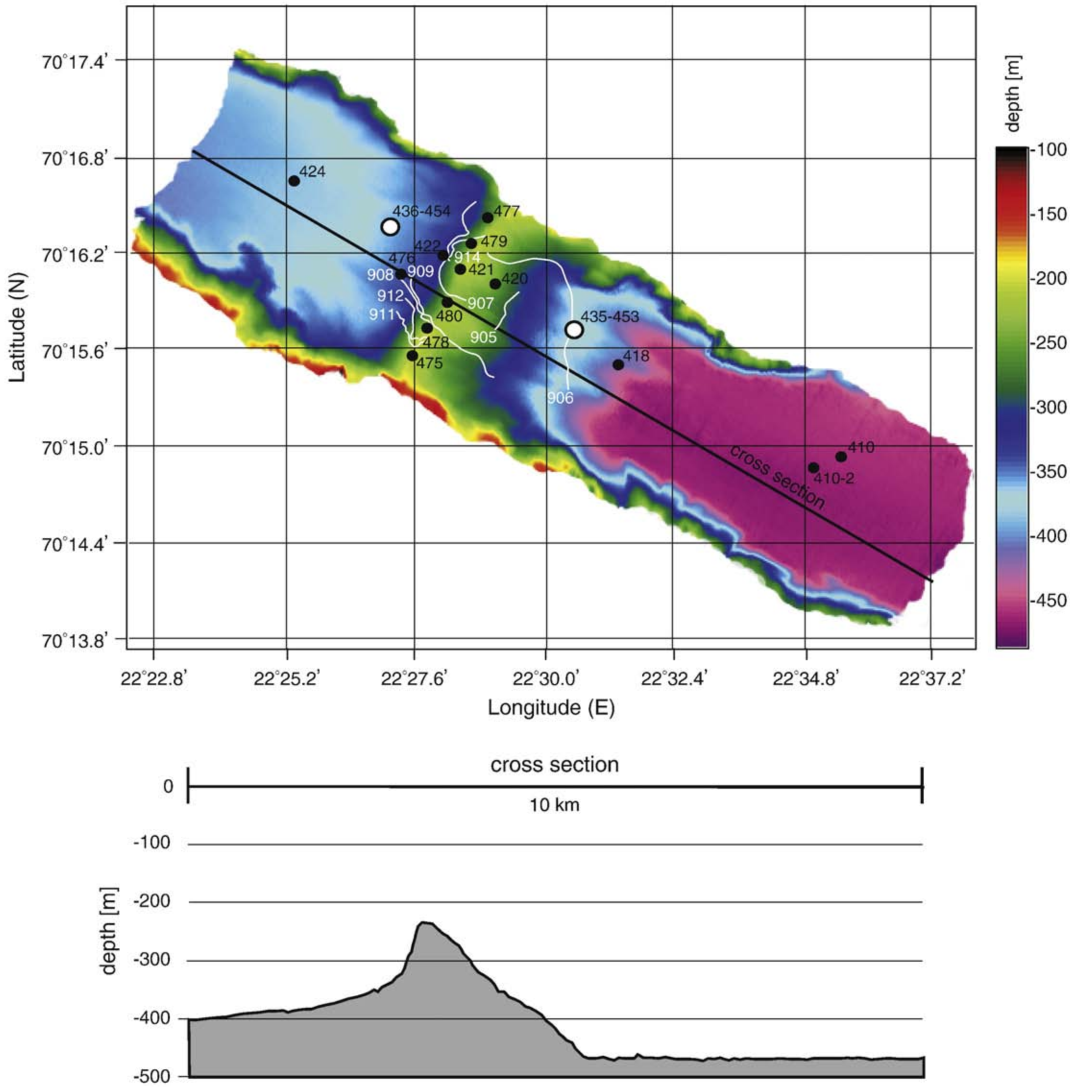

Fig. 2. (a) Swath bathymetry of the Stjernsund and (b) sill cross section (8× vertically exaggerated). Manned submersible dives (white lines) are indicated across the sill, numbers correspond to JAGO dives and mark the start of the track. Black dots mark CTD stations according to their number (Table 1). CTD stations 436–454 (only even numbers) and 435–453 (only uneven numbers) were used for tidal investigations (Fig. 6).

deeper water. Although cooler, it does not sink to the bottom because it is less dense due to its lower salinity. Subsequent warming of the surface waters during spring and summer shifts the WMW into deeper layers of the water column. However, it still rests above the Norwegian Coastal Water (NCW; Fig. 5). This process leads to the observed temporary temperature minimum at 100 m water depth (Syvitski et al., 1987). On both sides of the sill, WMW displays different mean temperatures. In the western trough the mean temperature of WMW is 5.09 ± 0.24 °C, whereas it cools to 4.88 ± 0.25 °C in the eastern trough. The most oxygenated waters characterize WMW. The transect shows that the measured asymmetry of the cool core with temperatures <5 °C is a consistent feature of WMW (Fig. 5a). WMW is characterized by minimal changes of salinity around 34.25 psu (Fig. 5b) and calculated density values (sigma-theta) around 26.85 kg m^{-3} (Fig. 5c). This is in contrast to the adjacent water masses. Dissolved oxygen shows a more complex pattern along the transect (Fig. 5d). Highest dissolved oxygen values mark the western most sections of the transect with a continuous reduction and thinning towards the East. East of the sill the highly oxygenated WMW separates the oxygen minimum of the surface water and the oxygen minimum of the water masses below, in the lee side of the sill.

NCW covers the depth interval between 150 m and 400 m with temperatures of 4.95–6.00 °C and salinities of 34.41–35.00 psu (Figs. 4,5). The sill acts as an obstacle influencing the distribution of NCW west and east of the sill. While NCW reaches from 150 m to about 250 m in the western trough, it is vertically expanded in the eastern trough reaching water depths of >400 m (Fig. 5). Below 150 m NCW occupies the water column and is characterized by a highly asymmetric distribution, which is observed for all four parameters. Temperature shows a continuous undisturbed decrease west of the sill. The dominance of Atlantic Water (AW) is clearly marked by an increase in salinity to values >35 and potential temperatures of 5.9–6.1 °C (Fig. 5a).

The observed differences of water mass characteristics west and east of the sill asked for coherent CTD measurements including a transect across the sill and repeated (jojo) CTD cast. This is illustrated in Fig. 5, indicating the variability of potential temperature, salinity, density (sigma-theta), and dissolved oxygen. The transect covers a time window of four hours (17:33–21:40, 07/25/2005). Additionally, we performed 28 CTD casts; 14 west and 14 east of the sill between 07/25 and 07/30/2005 in order to cover a tidal cycle (Table 1). The time series of the CTD casts shows the permanent presence of the AW west of the sill, while AW flushes over the sill and subducts below NCW only during high tide (Fig. 6).

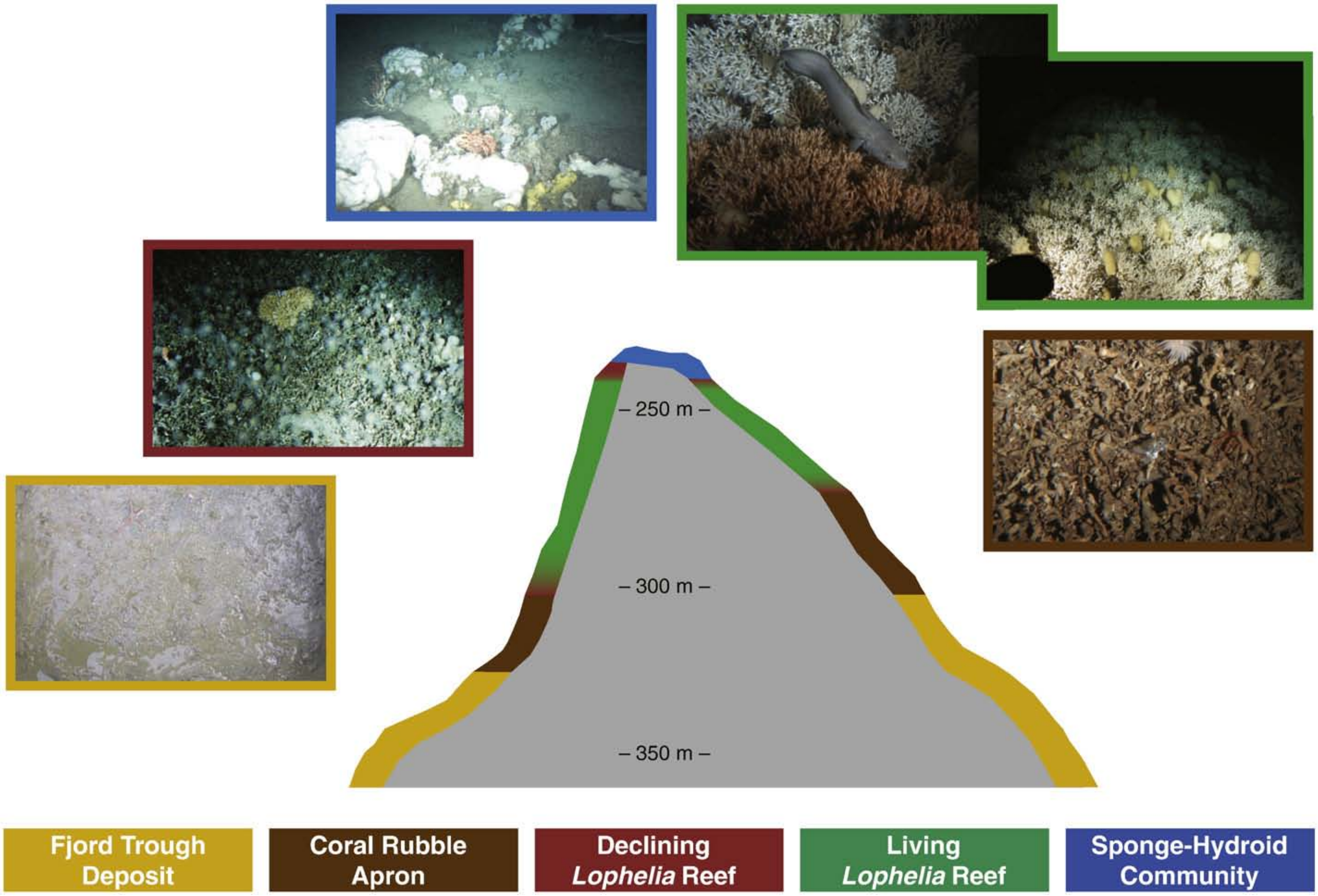

Fig. 3. Sedimentary facies patterns on Stjernsund sill. The colours indicate the bathymetric range of the respective facies.

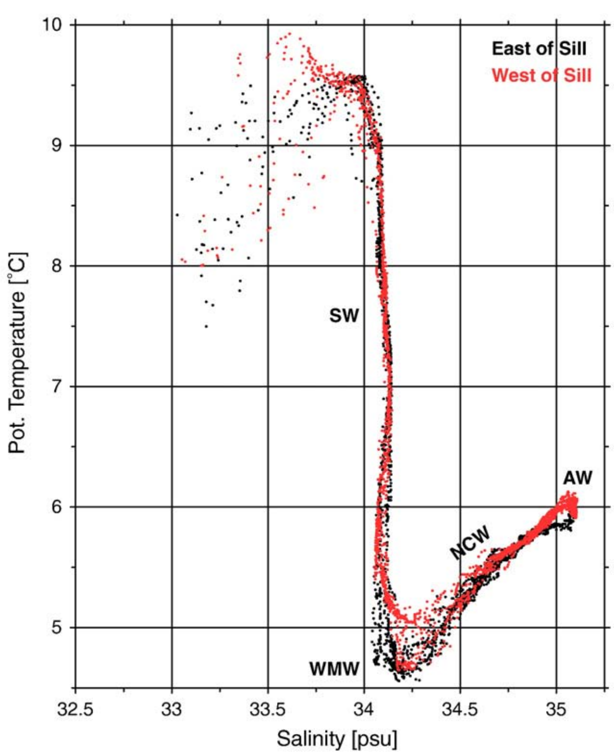

Fig. 4. Potential temperature/salinity plot of water masses West and East of Stjernsund sill. SW = Surface Waters (0–100 m, >6 °C), WMW = Winter Mode Water (100–150 m, <5.5 °C), NCW = Norwegian Coastal Water (150–250 m, S<35), AW = Atlantic Water (>250 m, S>35).

4. Discussion

Cold-water coral reefs have been described in some Norwegian fjords like Malangen, Trondheimsfjord, Børnlafjorden, Sandsfjorden, or Oslofjord (Fosså et al., 2005). As pointed out in the early work of Farmer and Smith (1980) and more recently of Xing and Davies (2006), underwater ridges like sills strongly affect water mass dynamics being important for marine benthic life. The influence of the sill at Stjernsund is well reflected in water mass dynamics, except for the surface waters, which are only modulated by local meteorology and river discharge, varying equally on both sides. WMW exhibits cooler waters east of the sill due to a higher fresh- and melt water runoff into the adjacent fjords. Because of the prevailing local current regime to the East, these cooler waters are trapped, increasing the residence time of the fjord-spilled waters in the East. Moreover, currents from the West hit Stjernsund sill and generate internal waves propagating eastwards. This internal wave formation favours internal mixing on the leeward side of the sill and enhances turnover times of waters above and below the sill depth (Arneborg, 2003) and can be interpreted based on distributions of potential temperature, salinity and density within the NCW (Fig. 5).

Cooler temperatures of WMW East of the sill would suggest better-oxygenated waters due to a higher solubility product of oxygen in cooler water. However, we measured lower values of dissolved oxygen. Additionally to internal wave generation, the depths of troughs and sills influence the environment, e.g. the oxygen consumption (Stigebrandt and Aure, 1989) showing a higher degree of depletion in the NCW in the East. We assume that this process may be initiated through vertical mixing processes in the leeward portion of the sill in connection with internal wave formation. This in turn

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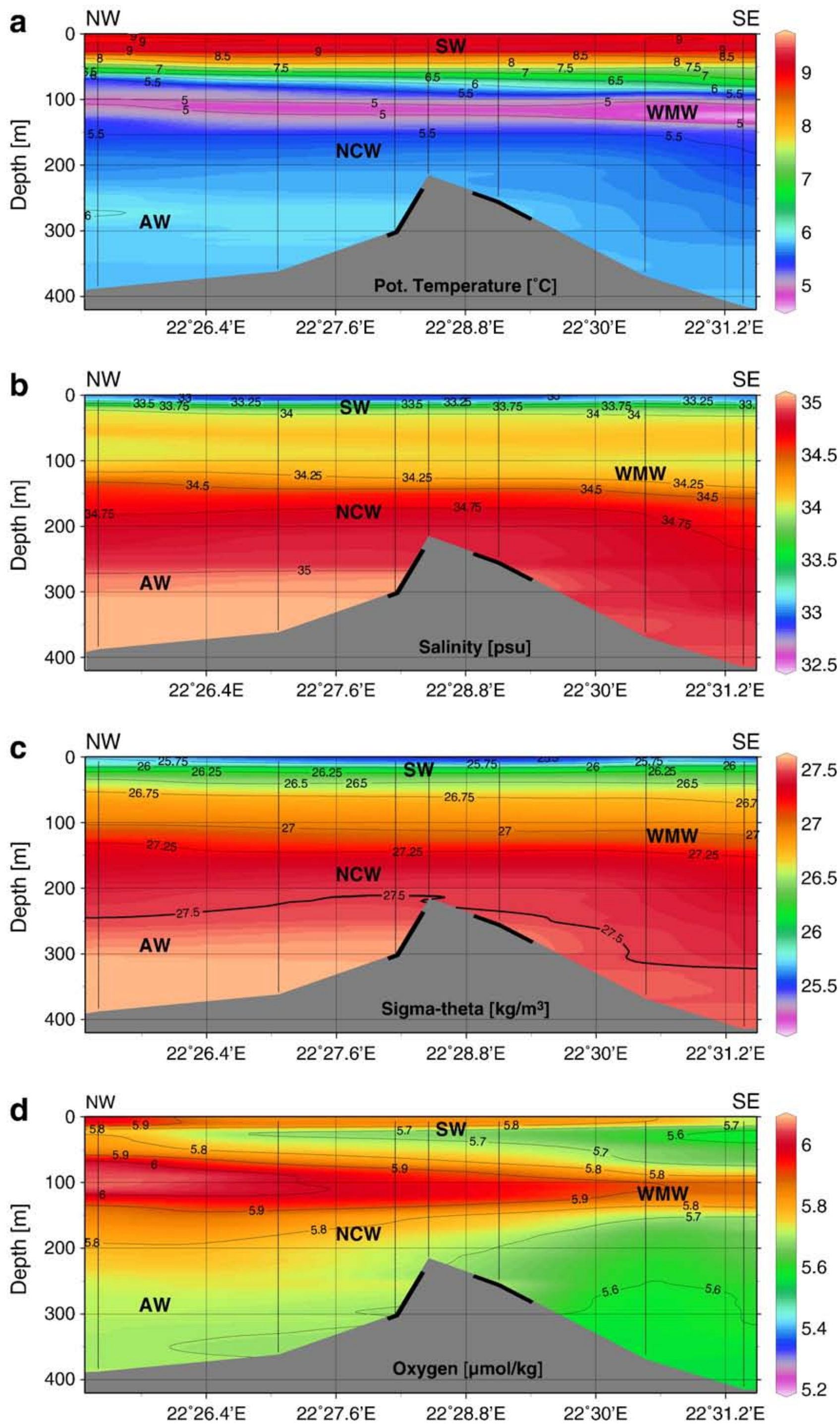

Fig. 5. Profiles of a) potential temperature, b) salinity, c) density (sigma theta), and d) dissolved oxygen across Stjernsund sill. The Coral Reef Complex is indicated with black bars on both flanks of the sill. SW = Surface Waters, WMW = Winter Mode Water, NCW = Norwegian Coastal Water, AW = Atlantic Water.

leads to the formation of an overturning cell in the leeward position, which enhances the residence time of the living biota within the cell and therefore leading to the observed depletion of dissolved oxygen due to ongoing respiration.

A windward–leeward effect of the tidal current is also described by Lavaleye et al. (2009) for another fjord setting with sill. At the southern part of Norway close to the Oslofjord, the protected Tisler reef, a cold-water coral reef on a NW–SE oriented sill connecting the Kosterfjord with the open Skagerrak, is currently used as an observatory for studying long-term variations in hydrography and particle flux. Preliminary results on the quality of particles and nutrients passing the reef indicate differences on the wind- and the leeward side of the reef. Lavaleye et al. (2009) conclude that the reef itself has an impact on the biochemistry of its environments, which can be measured at sites with unidirectional current flow. Therefore, especially sounds with sills and unidirectional currents are unique natural laboratories for evaluating environmental impacts on benthic ecosystems and their influence to the environment themselves.

Variations of hydrographic parameters at Stjernsund sill follow the semi-diurnal tidal cycle. At low tide only NCW enters the eastern

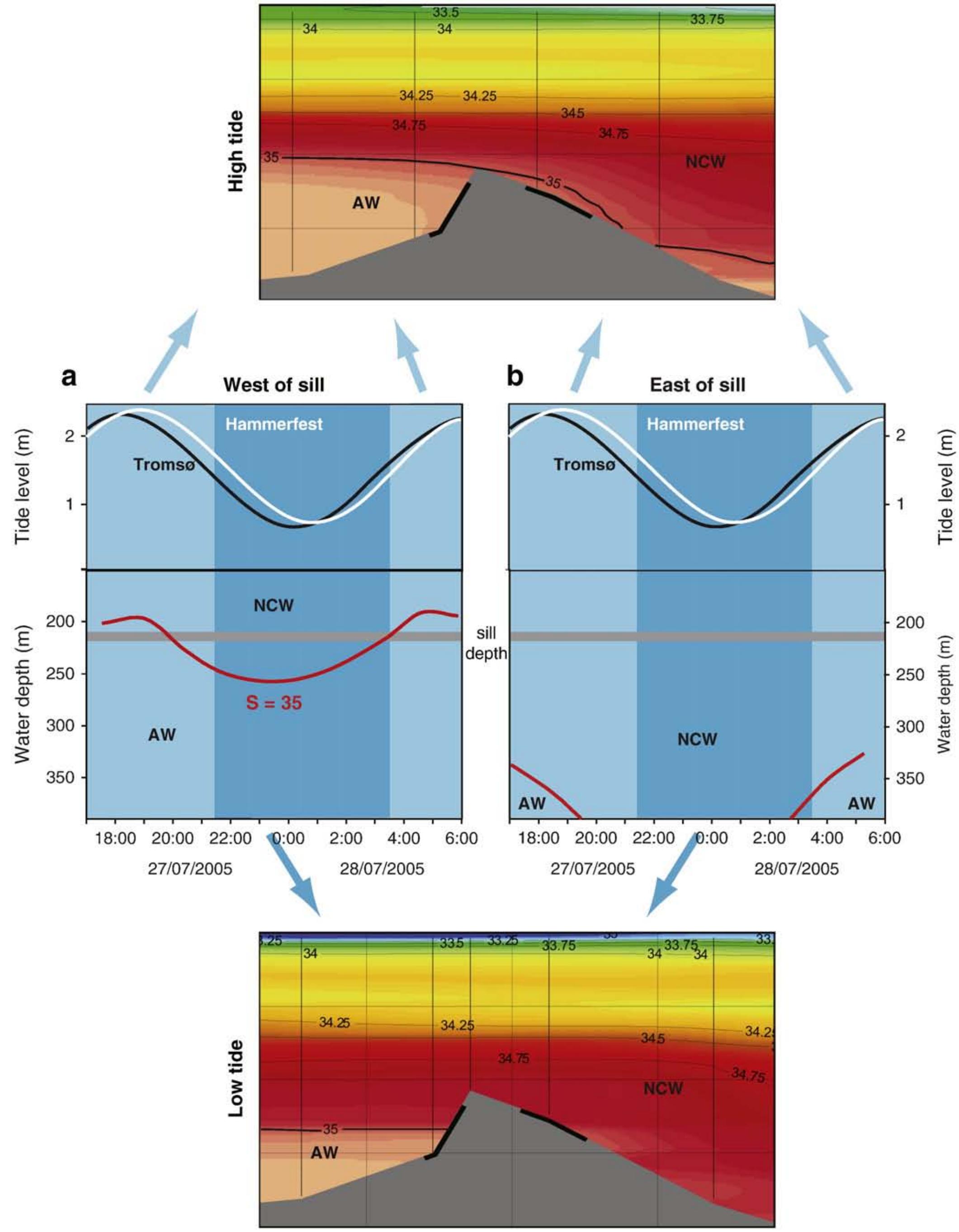

Fig. 6. Tidal dynamics across the Stjernsund sill: the upper graph displays the dynamics during high tide, the lower graph during low tide. High and low tides for Tromsø (69°39′N, 018°58′E) and Hammerfest (70°40′N, 23°41′E) are given for the respective time interval. The bathymetric variability of the boundary between NCW (Norwegian Coastal Water) and AW (Atlantic Water) defined as the 35-salinity-line is illustrated for the (a) western and (b) eastern basins off the sill. The grey bar indicates the maximum depth of the sill. It is clearly evident that AW enters the eastern basin only during high tides.

trough while AW is below sill depth in the western trough. According to Skardhamar and Svendsen (2005), the boundary between NCW and AW is portrayed by the salinity value of 35 psu. Since no tidal data are available for Stjernsund, we show the tidal data for Tromsø and Hammerfest for the investigated time slice. Fig. 6 displays two scenarios of AW dynamics, one for high and one for low tide. Potential temperature and salinity indicate that Atlantic Water (AW) is only present on the eastern side of the sill during tidal high stands at water depths >350 m (Fig. 5) and is absent during tidal low stand (Fig. 6). This result indicates a tidally controlled flow over the sill of Atlantic Water from west to east during tidal high stands.

The slightly asymmetric distribution of living coral reefs is as well controlled by observed sill dynamics. The study of Dullo et al. (2008), focused on the living cold-water coral reefs of the Celtic and Norwegian continental margin, clearly showed that sigma-theta of 27.5 kg m^{-3} is an essential controlling factor for cold-water coral reef formation at least for that part of the Atlantic. Our results also exhibit a striking coherence of the bathymetric depth interval of the 27.5 kg m^{-3} isopycnal with the occurrence of living cold-water coral reefs on the sill of Stjernsund (Fig. 5c). The 27.5 kg m^{-3} isopycnal almost marks the lower boundary of the NCW. The living corals occur within the uppermost levels of AW favoring flourishing reef growth on the western slope. Their existence

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east of the sill is remarkable and obviously controlled by the periodic flushing of AW during high tide. Nevertheless, the flushing is strong enough to maintain coral and reef growth. No living coral reefs have been found above and below the density belt of 27.51–27.63 kg m^{-3}.

5. Conclusions

This study links hydrographic parameters with the occurrence of cold-water coral reefs at Stjernsund sill in subpolar settings of northern Norway. The investigated water masses in Stjernsund comprise surface waters, Winter Mode Water, Norwegian Coastal Water, and Atlantic Water. Their distribution east and west of the sill is asymmetric except for surface waters. The observed differences for Winter Mode Water and Norwegian Coastal Water depend on runoff and freshwater discharge into the fjord and mixing processes east of the sill, Atlantic Water dynamics are almost entirely tidally driven. High-resolution CTD time series covering a full tidal cycle demonstrate the importance of these dynamics. Moreover, the different bathymetric ranges of living corals on the western and eastern slope of the sill portray these tidal dynamics as well. The theory of temperature and salinity *ergo* seawater density controlling occurrences of cold-water coral reefs *sensu* Dullo et al. (2008) is proved to be valid also for the subpolar Norwegian setting. The corals thrive just below the isopycnal of 27.5 kg m^{-3}, which marks the boundary between Norwegian Coastal Water and Atlantic Water.

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References

Aksens, D.L., Aure, J., Kaartvedt, S., Magnesen, T., Richard, J., 1989. Significance of advection for the carrying capacities of fjord populations. Marine Ecological Progress Series 50, 263–274.

Arneborg, L., 2003. Turnover times for the water above sill level in Gullmar Fjord. Continental Shelf Research 24, 443–460.

Conkright, M.E., Locarnini, R.A., Garcia, H.E., O'Brien, T.D., Boyer, T.P., Stephens, C., Antonov, J.I., 2002. World Ocean Atlas 2001: objective analyses, data statistics and figures CD-ROM documentation. National Oceanographic Data Center Internal Report, 17. US Department of Commerce: Silver Spring, MD (USA), p. 17.

De Mol, B., Van Rensbergen, P., Pillen, S., Van Herreweghe, K., Van Rooij, D., McDonnell, A., Huvenne, V., Ivanov, M., Swennen, R., Henriet, J.P., 2002. Large deep-water coral banks in the Porcupine Basin, southwest of Ireland. Marine Geology 188, 193–231.

Dons, C., 1932. Zoologiske Notiser XV. Om Nord-Norges korallsamfund. Det Kongelige Norske Videnskabers Selskab Forhandlingar 5 (4), 13–16.

Dorschel, B., Hebbeln, D., Foubert, A., White, M., Wheeler, A.J., 2007. Hydrodynamics and cold-water coral facies distribution related to recent sedimentary processes at Galway Mound west of Ireland. Marine Geology 244, 184–195.

Dullo, W.-Chr., Flögel, S., Rüggeberg, A., 2008. Cold-water coral growth in relation to the hydrography of the Celtic and Nordic European Continental Margin. Marine Ecological Progress Series 371, 165–176.

Farmer, D.M., Freeland, H.J., 1983. The physical oceanography of fjords. Progress in Oceanography 12, 147–219.

Farmer, D.M., Smith, J.D., 1980. Generation of lee waves over the sill in Knight Inlet. NATO Conference Series: IV In: Freeland, H., Farmer, D.M., Levings, C.D. (Eds.), Fjord oceanography: Marine Sciences, Vol. 4, pp. 259–269.

Fosså, J.H., Lindberg, B., Christensen, O., Lundälv, T., Svellingen, I., Mortensen, P.B., Alvsvåg, J., 2005. Mapping of *Lophelia reefs* in Norway: experiences and survey methods. In: Freiwald, A., Roberts, J.M. (Eds.), Cold-water corals and ecosystems. Springer Verlag, Berlin, Heidelberg, pp. 359–391.

Frederiksen, R., Jensen, A., Westerberg, H., 1992. The distribution of the scleractinian coral *Lophelia pertusa* around the Faroe Islands and the relation to internal tidal mixing. Sarsia 77, 157–171.

Freiwald, A., Henrich, R., Pätzold, J., 1997. Anatomy of a deep-water coral reef mound from Stjernsund, West-Finnmark, northern Norway. Cool-Water Carbonates: In: James, N.P. (Ed.), SEPM, Special Publication, 56, pp. 141–161.

Freiwald, A., Hühnerbach, V., Lindberg, B., Wilson, J.B., Campbell, J., 2002. The Sula Reef complex, Norwegian Shelf. Facies 47, 179–200.

Freiwald, A., Fosså, J.H., Grehan, A., Koslow, T., Roberts, J.M., 2004. Cold-water coral reefs. UNEP-WCMC, Cambridge, p. 84.

Freiwald, A., Dullo, W.-Chr., Shipboard Scientific Party, 2005. RV Poseidon Cruise 325 Bremerhaven–Tromsø: Leg 1: Bremerhaven–Tromsø, 12 July–24 July 2005 Leg 2: Tromsø–Tromsø, 24 July–3 August 2005, p. 65.

Henriet, J.P., De Mol, B., Pillen, S., Vanneste, M., Van Rooij, D., Versteeg, W., Croker, P.F., Shannon, P.M., Unnithan, V., Bouriak, S., Chachkine, P., Porcupine-Belgica Shipboard Party, 1998. Gas hydrate crystals may help build reefs. Nature 391, 648–649.

Huppert, H.E., 1980. Topographic effects in stratified fluids. NATO Conference Series: IV Fjord oceanography: In: Freeland, H. (Ed.), Marine Sciences, Vol. 4.

Kenyon, N.H., Akhmetzhanov, A.M., Wheeler, A.J., van Weering, T.C.E., de Hass, H., Ivanov, M.K., 2003. Giant carbonate mud mounds in the southern Rockall Trough. Marine Geology 195, 5–30.

Klinck, J.M., O'Brien, J.J., Svendsen, H., 1982. A simple model for fjord and coastal circulation interaction. Journal of Physical Oceanography 11, 1612–1626.

Lavaleye, M., Duineveld, G., Lundälv, T., White, M., Guimen, D., Kiriakoulakis, K., Wolff, G.A., 2009. Cold-water corals on the Tisler Reef. Oceanography 22, 54–62.

Lewis, A.G., Thomas, A.C., 1986. Tidal transport of planktonic copepods across the sill of a Britsh Columbia fjord. Journal of Plankton Research 8, 1079–1089.

Lindahl, O., Hernroth, L., 1988. Large-scale and long-term variations in the zooplankton community of the Gullmar fjord, Sweden, in relation to advective processes. Marine Ecological Progress Series 43, 161–171.

Mork, M., 1981. Circulation phenomena and frontal dynamics of the Norwegian Coastal Current. Philosophical Transactions of the Royal Society of London A302, 635–647.

Mortensen, P.B., Hovland, M.T., Fosså, J.H., Furevik, D.M., 2001. Distribution, abundance and size of *Lophelia pertusa* coral-reefs in mid-Norway in relation to seabed characteristics. Journal of the Marine Biological Association of the United Kingdom 81, 581–597.

Murty, T.S., Rasmussen, M.C., 1980. Tidally-forced stratified flow over sills. NATO Conference Series: IV Fjord oceanography: In: Freeland, H. (Ed.), Marine Sciences, Vol. 4, pp. 173–180.

Rogers, A.D., 1999. The biology of *Lophelia pertusa* (Linnaeus 1758) and other deep-water reef forming corals and impact from human activities. International Review of Hydrobiology 84, 315–406.

Skardhamar, J., Svendsen, H., 2005. Circulation and shelf-ocean interaction off North Norway. Continental Shelf Research 25 (12–13), 1541–1560.

Stigebrandt, A., Aure, J., 1989. Vertical mixing in basin waters of fjords. Journal of Physical Oceanography 19, 917–926.

Syvitski, J.P.M., Burrell, D.C., Skei, J.M., 1987. Fjords: processes and products. Springer, Verlag, New York, p. 379.

Taviani, M., Freiwald, A., Zibrowius, H., 2005. Deep coral growth in the Mediterranean Sea: an overview. In: Freiwald, A., Murray, J.M. (Eds.), Cold-water corals and ecosystems. Springer, Berlin Heidelberg New York, pp. 137–156.

Wheeler, A.J., Beyer, A., Freiwald, A., de Haas, H., Huvenne, V.A.I., Kozachenko, M., Olu-Le Roy, K., Opderbecke, J., 2007. Morphology and environment of cold-water coral carbonate mounds on the NW European margin. International Journal of Earth Sciences 96, 37–56.

White, M., 2007. The hydrography of the Porcupine Bank and Sea Bight and associated carbonate mounds. International Journal of Earth Sciences 96, 1–9.

Xing, J., Davies, A.M., 2006. Influence of stratification and topography upon internal wave spectra in the region of sills. Geophysical Research Letters 33, L23606. doi:10.1029/2006GL028092.