Marine Pollution Bulletin 84 (2014) 236–250

Contents lists available at ScienceDirect

Marine Pollution Bulletin

journal homepage: www.elsevier.com/locate/marpolbul

Real time observation system for monitoring environmental impact on marine ecosystems from oil drilling operations

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ARTICLE INFO

Article history:
Available online 4 June 2014

Keywords:
Petroleum industry
Environmental monitoring
Drill wastes
Coral reefs
Lophelia pertusa
Fatty acids

ABSTRACT

Environmental awareness and technological advances has spurred development of new monitoring solutions for the petroleum industry.

This paper presents experience from a monitoring program off Norway. To maintain operation within the limits of the government regulations Statoil tested a new monitoring concept. Multisensory data were cabled to surface buoys and transmitted to land via wireless communication. The system collected information about distribution of the drilling wastes and the welfare of the corals in relation to threshold values.

The project experienced a series of failures, but the backup monitoring provided information to fulfil the requirements of the permit. The experience demonstrated the need for real time monitoring and how such systems enhance understanding of impacts on marine organisms. Also, drilling operations may improve by taking environmental information into account. The paper proposes to standardize and streamline monitoring protocols to maintain comparability during all phases of the operation and between drill sites.

1. Introduction

1.1. Background

Impact of human activity in the marine environment is of increasing concern worldwide (see e.g. Crain et al. (2009)). Oil companies are experiencing increasing attention from governments as well as from Non-Governmental Organisations (NGOs) on risks and the potential disastrous impacts on the environment at various temporal and spatial scales. Catastrophes like the Exxon Valdez oil spill in Alaska and Deepwater Horizon blowout in the Gulf of Mexico receive much attention, with their impacts being both instantaneous and long term (Schmidt, 2012). In contrast, there has been less attention given to the smaller and less voluminous spills and discharges of drilling waste associated with current drilling operations (Neff, 1987), with published work often focusing on oil-based drilling processes (Daan et al., 1994, 1996; Santos et al., 2010) superseded by water-based drilling in European waters today (Neff, 2005;Trannum et al., 2010; Gates and Jones, 2012; Larsson et al., 2013a,b). Further, the methodologies used in impact studies are often based on traditional sampling strategies where data are collected with various sampling platforms and sensors giving substantial temporal gaps. Little emphasis is given on integration of information between time periods of investigation, thus limiting the possibility to separate the impacts from overall natural variation in an area. The Norwegian Environment Agency has prepared a general guidance document on how monitoring of the seabed around drilling sites should be performed (ANON, 2011). However, lack of standardisation of monitoring techniques in accordance with present knowledge and advances in technologies, precludes comparison of the situation before drilling, during drilling, during production and post production. In addition to making identification of impacts from time series difficult, comparison of impacts between regions or drill sites is also made more problematic by not taking advantage of advances in knowledge and technology (Purser and Thomsen, 2012).

Autonomous and cabled observatories are receiving increasing attention in marine science and have been demonstrated as capable platforms for collecting data remotely, and increasing insight into the functioning of remote marine ecosystems (Barnes et al., 2008; Best et al., 2013; Taylor, 2009). Such cabled systems are

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http://dx.doi.org/10.1016/j.marpolbul.2014.05.007
0025-326X/

expected to become an important tool in marine monitoring and management (Aguzzi et al., 2012; Godø et al., 2005; Haugan, 2010; Horne, 2005). The availability of such cabled platforms has catalysed the development of subsea operating instrumentation and sensors, including 'lab on a chip' systems, with *in situ* chemical analysis capability. With increasing frequency, the granting of petrochemical exploration or extraction licenses is accompanied by the requirement that the company carries out new techniques for the investigation or monitoring of the habitats surrounding a drill site. Combining licence requirements for monitoring with technical routine monitoring seems a sensible and efficient way of exploiting the advances in observatory technology for environmental monitoring. Deploying sensor systems for marine environmental monitoring in conjunction with the field's infrastructure should be possible if operational constraints are taken into account. However, during the pre and post production phases cabled infrastructure is lacking at drill sites, and any pre and post baseline studies must be replaced by autonomous instrumentation for the drilling and production periods.

Statoil was given a permit to start production drilling on the Morvin field off Mid Norway in 2009 (Fig. 1), and initiated an associated environmental monitoring program. Here we describe the use of a subsea observatory and network of three moorings tailored for real time monitoring. The Institute of Marine Research (IMR) participated in the EU funded project HERMES (Hotspot Ecosystem Research on the Margins of European Seas (Grehan et al., 2009)) and chaired the supplementary project 'Hermes lander'. This project established a coral reef observatory (Godø et al., 2012b), which was the basis for the observatory technology chosen for the Morvin monitoring program (Tenningen, 2011). Further, a network of three moorings with current and turbidity sensors with real time transfer of key environmental data was established by Metocean Services International PTY LTD. The operational and technological details of this deployment, combined with the data collected during the monitoring program, forms the basis of this paper.

The lack of updated standards and international agreements on how to monitor and assess impact on the physical and biological environment which may be caused by oil and gas drilling activities was underlined by Purser and Thomsen (2012). Their overview of present practice demonstrates the need for systematic and scientifically acceptable approaches, the utilisation of adequate sampling and observation technologies and the design of monitoring strategies most suitable for assessing the risk and impacts of the habitat categories that may potentially be exposed to waste materials such as drill cuttings or drilling muds.

In this paper we follow up the monitoring strategy perspective presented by Purser and Thomsen (2012) and combine it with the basic ideas, the technological challenges and the operational experience acquired during the Morvin environmental monitoring program. We emphasize the uniqueness of the habitat of the Morvin location and the need for basic understanding of its physics and biology in order to tailor a technology solution that meets the requirements of the permit. The operational challenges, failures and successes, and obtained results are given attention (lessons to learn). The overall experience is used to extract factual information about concepts, technology, and operational requirements for next generation of real time monitoring systems, required for responsible drilling activities, and the need for a targeted development program to secure functional systems tailored to the uniqueness of the particular habitats encountered at future drilling locations. Included in these considerations are recent technological advances and experiences. The overarching objective is to stimulate the discussions and interactions among scientists and between science and industry on technology and concept developments that are needed to satisfy the requirements for sustainable management of the marine environment and its resources.

1.2. The area, its biology, regulations and the drilling operation

The Morvin field is located at the western shelf break of the Halten Bank northwest of Trondheim (Fig. 1). The depth is ~360 m and several coral reefs are scattered in the area. The Halten Bank is a traditional fishing ground with the bottom habitat including several deep water *Lophelia pertusa* coral reefs (Mortensen et al., 2001). These habitats are vulnerable to human activities such as trawling (Fosså et al., 2002) and the potential negative impact from

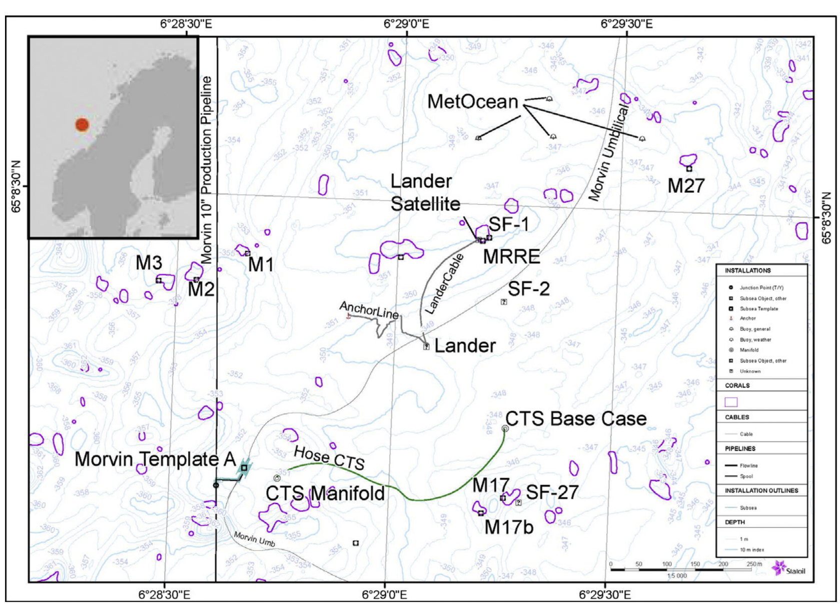

Fig. 1. The location and its topographic features and oil installations including the fixed sampling locations (overview picture given in upper left corner). The three buoy symbols named 'MetOcean' which are located at same latitude mark the position of the three current rigs. The position named 'Lander' show the position of the instrument platform and 'Lander satellite' show the position of the camera at the MRRE coral reef. The positions of the three sediment traps are marked SF-1, SF-2 and SF-27. 'CTS Base Case' marks the discharge point. The various coral reefs are marked with letters and names. Map contributed by Statoil.

drilling by the petroleum industry, as discussed in (Armstrong and van den Hove, 2008; Fosså and Skjoldal, 2010; Purser and Thomsen, 2012).

Requirements from the Norwegian authorities for the development and exploitation of the Morvin field included detailed mapping across and surrounding the drill sites of corals and other vulnerable benthic communities prior to the start of development. A discharge permit was given for drilling of the 36 inches and 26 inches top hole sections for 4 production wells at a sea bed template using water-based drilling muds (Pabortsava et al., 2011). Estimated amount of drill waste from the top sections of each well was 2800 tons. A cutting transport system (CTS) was used to lead the drill waste 500 m away from the well template, to a position, where with respect to the prevailing current, the nearest upstream corals were at 120 m distance, and those downstream at a distance of 300 m (Figs. 1 and 2). Wastes from drilling of deeper sections had to be brought onshore to a waste treatment plant for disposal.

The discharge permit also required that extensive monitoring should be carried out during drilling operations to avoid damaging impacts on the corals as well as supporting the knowledge base on the potential biological effects of drilling waste on corals. The monitoring program should include detailed description of short and long term variability in hydrographical conditions around the discharge site, mapping of the development and distribution of the drill waste plume in the water column, settling pattern of drill waste on the seabed, and visual observations of biological effects on corals close to the discharge site. This requirement was the basis for the Morvin monitoring program, with the results presented here. Additional monitoring of coral reefs more distant from the point of drill waste release was observed by Remote Operated Vehicle (ROV), and the computer modelling of drill waste plumes is presented in Purser (in revision).

The area is, as the rest of the Mid-Norway coast, strongly affected by northerly currents with the Atlantic drift dominating in the western parts and the Norwegian Coastal Current passing along the coast. Water masses mix along shelf break and on the shelf (Sætre, 1999) often due to mesoscale and sub mesoscale physical processes (Godø et al., 2012a; Johannessen et al., 1989). The main topographic and oceanographic features were implemented in a predictive dispersion model, DREAM (Dose-related Risk and Effect Assessment Model) (Reed and Rye, 2011; Rye et al., 2008), with local flow conditions provided by *in situ* current flow meters deployed in the vicinity of drilling. The DREAM model, developed by SINTEF (http://www.sintef.no/home/SINTEF-Materials-and-Chemistry/About-us/Software-development/), uses measured current or, if not available, input from ocean models (e.g. from Norwegian Metrological Institute (www.met.no)), and is commonly used to predict likely drill waste transport during drilling events (Purser and Thomsen, 2012), enabling evaluation of the likely transport pathways of material when accurate current data are available. For drilling in locations such as the Morvin field area, where small reefs are dotted across a region of seafloor, the DREAM model can be used to predict the likely drill waste concentrations and depositions to reach each separate reef (Purser, in revision). When flow condition data for a region is available prior to the commencement of drilling, the model predictions may be used to best decide the release location, i.e. the position of the CTS system. For the current drill campaign, the release location most suitable, based on the DREAM transport predictions, was 500 m from the drilling location (Fig. 1).

Laboratory studies of coral behaviour, welfare and survival after exposure of drill cuttings has indicated *L. pertusa* to be robust and efficient in removing particles after exposure of both drill cuttings and natural sediments (Allers et al., 2013; Larsson and Purser, 2011; Brooke et al., 2009). Exposure to high levels of drill cuttings (23 repeated exposures to 33 mg drill cuttings cm^{-2} over a 45-day period) apparently did not harm their wellbeing (Larsson et al., 2013b). However, burial studies (sediment cover thickness >6.5 mm) showed that totally covering of more than 6.5 mm of drill cuttings may affect the corals and polyp mortality and tissue smothering were observed (Larsson and Purser, 2011). Field studies from *L. pertusa* colonising oil and gas platforms in the North Sea have documented coral mortality in the immediate vicinity of drilling discharges points (Gass and Roberts, 2006). Mortality and decreased growth rates after exposure to drill cuttings have also been reported in several tropical coral species both in laboratory studies and from field observations (Literature review in Nielsen et al., 2010).

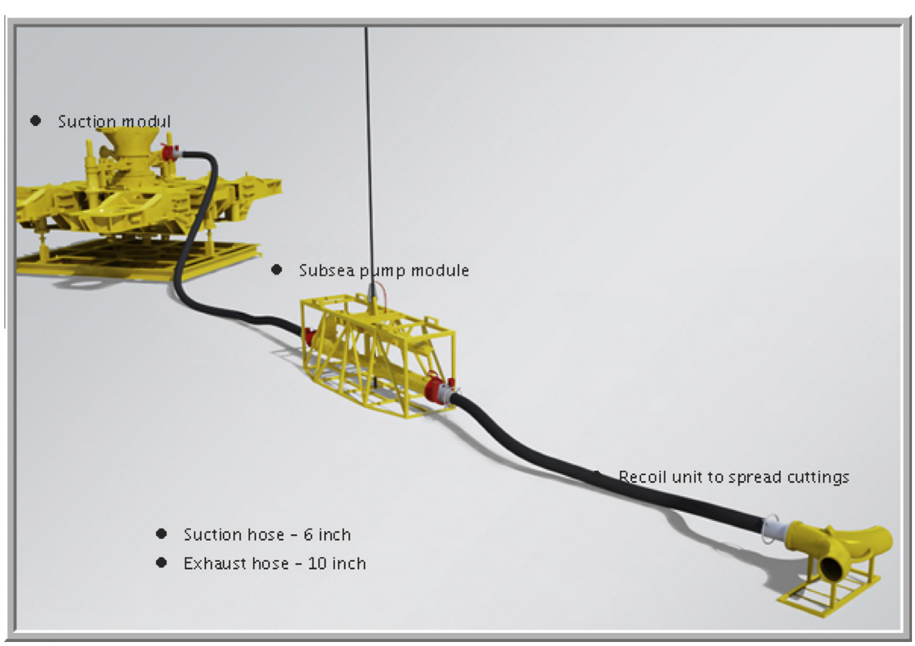

Fig. 2. Illustration of the transportation system of the cuttings to a location away from the drilling site.

It has been suggested that the increased metabolic costs associated with sediment rejection may adversely affect the corals and result in decreased growth rates, and in extreme cases, mortality (Anthony, 2006; Nielsen et al., 2010). In the present paper we therefore investigate if lipid status may be a suitable method for evaluation of sub-lethal effects of exposure to drill cuttings.

2. Material and methods

The granting of the permit for the Morvin drilling operation required that extra monitoring be carried out, with the possibility that the results of the monitoring be fed back into drilling operation; i.e. that certain sediment exposure levels be set as maximum exposure concentrations for *L. pertusa*. In the worst case, should these exposure levels be reached, drilling discharge should be stopped. The permit therefore required the development of a new methodology/technology for monitoring which was not readily available. As shown below, the basic concept accepted for the Morvin drilling included a real time monitoring system (2.1–2.3), a post drilling evaluation system (4–7), and a near real time monitoring system (8) to replace the real time data flow in the event of real time monitoring failure. The basis for the real time monitoring data communication system was a surface buoy that received information from the sensors through a cable and transferred them to land through a link at the drilling platform (Fig. 3). Drilling and sampling periods for the various sampling instruments are indicated in Table 1.

2.1. Camera monitoring

Objectives: To use a camera system close to a coral reef to monitor potential impact of drilling waste sedimentation on the reef.

A standard camera (Nikon G300 12-24 wide angel lens) with time lapse functionality, and flash illumination were placed within a pressure housing (Metas DSC-5210) and mounted on a frame (Fig. 3). This frame was positioned close to a coral reef and pictures taken every 30 min. Additional images were also periodically collected by ROV. The image data are analysed and presented by Buhl-Mortensen et al. (submitted) and will not be dealt with in detail here.

2.2. Active acoustic monitoring

Objectives: (1) Use high frequency acoustics from a stationary platform to observe particles of the cloud of drill cuttings in mid water. (2) Observe marine life in the drilling area.

The acoustic system was made up of two Simrad EK60 split-beam echosounders (38 and 120 kHz) run on batteries. The transducers, both with 7° opening angle, were mounted on a steerable platform (Fig. 3), which enabled a half sphere searching volume around the lander with a maximum radius of about 1000 m for the 38 kHz sounder under good conditions. Due to operational problems only a few sequences of data from the two transducers were available for analysis, nevertheless these were adequate for demonstrating the issues of the objectives.

2.3. Current and turbidity measurements

Objectives: To provide a particle transport model with real time information about currents and collect information about variation in particle densities on a coral reef during drilling. Modelled distribution patterns should be compared with acoustic observations (2) and validated by visual observations under (1).

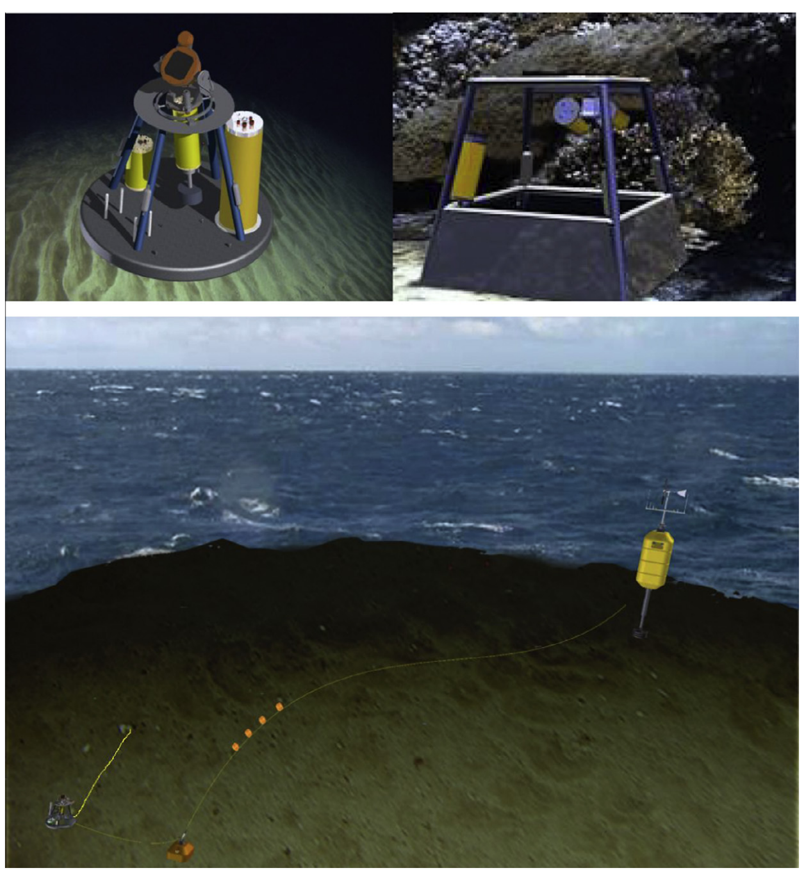

Fig. 3. The design of the sensor platform with satellite camera and a surface communication buoy.

Table 1
Sampling period for the various methods. Stars indicate ponint sampling in time and space. Broken lines indicate routine sampling with temporal gaps.

Sampling time	Before	During				After
		November	December	January	February	March
Drilling operation		↔			↔	
Camera monitoring		↔			↔	
Active acoustic monitoring		↔				
Current and turbidity measurements		↔				
Sediment traps		↔			↔	
ROV core sediment sampling	★					★
ROV biological sampling	★					★
ROV video monitoring (various intervals)		↔ (broken)			↔ (broken)	

An Aanderaa RDCP600 was used for near bottom current measurements. The instrument was mounted on the camera satellite (~150 cm above bottom) close to the MRRE reef (Fig. 1) and recorded current close to bottom, in our case the current measured at 4–6 m range from the sensor was used to assess current at 360 m water depth. A turbidity sensor was mounted on the same unit but produced no data due to a minor water leak (Table 2). Simultaneous current velocities measured from three rigs operated by Metocean Services International PTY LTD. were used to compare spatial variation in currents around the release site (Fig. 1). They employed two Nortek Aquadopps (2 mHz single point measurements) at each mooring to collect data from close to the seafloor (at respectively 353, 342 and 343 m depth) and from within the water column. Only the bottom measurements have been used here for comparison with the RDCP data.

2.4. Sediment traps

Objectives: Record spatial distribution of sedimentation.

Three identical K.U.M. K/MT 234 Sediment traps, each fitted with 21 bottles of 400 ml sampled regularly during the drilling period. The traps collected data during two periods; 09.11.2009–06.12.2009 and 6.2.2010–23.2.2010. Traps were deployed just prior to drilling operations, and retrieved after drilling was completed. Their locations are shown in Fig. 1. The traps had custom made electronics and programming devices constructed by IMR. During each deployment, each trap was programmed to shift the sample bottle every 36 h, to provide a maximum 31.5 day sampling period. The three traps were positioned along the expected current axis, one upstream and two downstream of the discharge point.

2.5. ROV core sediment sampling

Objectives: Use core sediment samples taken with ROV prior and after drilling to study deposition depths and volumes of deposited drill cuttings material on the seabed.

Push core samples were collected prior to and after drilling. The samples were collected at the locations indicated by the map in Fig. 4 in a line along the measured prevailing current direction (N–NW direction) and with a shorter line in a more easterly direction.

Samples for analysis of pollutants were taken with conventional techniques and also analysed with standard laboratory methods. Three samples were collected at each of the core sampling locations shown in Table 3 and Fig. 4. At location D-POS, very close to the discharge point, only one sample was obtained. The sediment core samples were collected by ROVs operated by the vessels *Acergy Petrel* 2nd–6th (May 2009 prior to drilling operations), and *Edda Fauna* 17th–21st (March 2010 after the drilling operations were completed).

2.5.1. Total organic carbon (TOC)

Sediment samples were analysed for weight percentages (wt.%) of total organic carbon (TOC). Aliquots (~200 mg) of the samples were treated with 10% (volume) hydrochloric acid (HCl) at 60 °C to remove carbonate, and then washed with distilled water to remove HCl. We emphasize that the possible loss of organic material by acid leaching is not taken into account. The samples were dried overnight (50 °C) and then analysed using a LECO CS244 analyser.

2.5.2. Total hydrocarbon (THC)

The sediment samples were air dried in open air at room temperature until complete dryness. The samples were then ground in a

Table 2
The various components of the monitoring program and the associated experience.

Approach	Sensors	Technical issues
Real time monitoring		Communication buoy lost. Replaced by periodic data download
	– Active acoustic	Buoy loss caused battery capacity loss.
	– RDCP near bottom current	Only sporadic data
	– CTD	Working but water penetration
	– Turbidity	No data du the water penetration
	– ADCP water column (three separate rigs)	No data du the water penetration
		Communication malfunction. Data Available at intervals through manual download
ROV-based monitoring		Operated regularly due to the communication failure
	– Core samples (pre-post drilling)	OK
	– Video and still pictures (ad hoc real time)	Platform disturbance – infrequent update
	– Visual mapping of sediment plume (ad hoc real time)	Subjective evaluation
Sedimentation	– Sediment traps (three traps)	Improper rotation – uncertainty of sampling periods

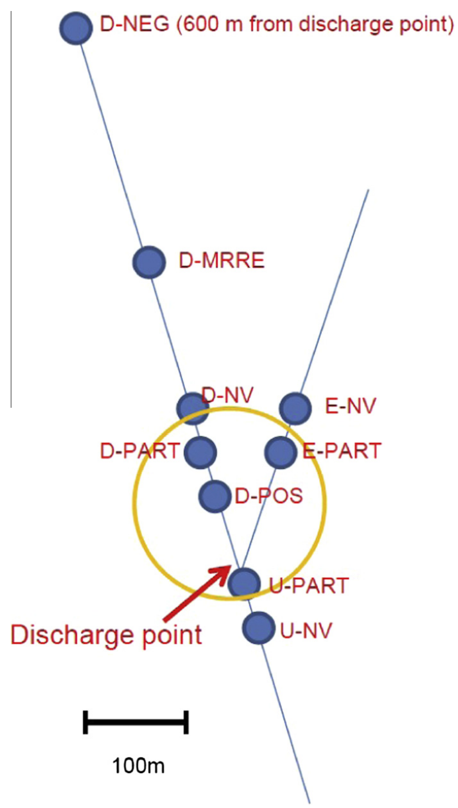

Fig. 4. The core sampling program carried out by ROV. The coding follows the naming in the Statoil operation plan: D-NEG: downstream negative ~600 m from disturbance. D-MRRE: 6 m south of the MRRE coral reef. D-NV: downstream no visible disturbance, 135 m from pipe approximately 10 m from the edge of the visible cuttings. D-PART: downstream partial disturbance 100 m from pipe in partial disturbance zone. D-POS: downstream positive sample – within full disturbance. U-NV: upstream, no visible disturbance 40 m upstream of pipe. U-PART: upstream, partial disturbance 25 m upstream of pipe. E-PART: east, partial disturbance 75 m from pipe. E-NV: east, no visible disturbance 110 m from pipe. See also Table 3.

Table 3
Sampling locations for sediments in distance from discharge point (see Fig. 4).

Location	Degree (°)	Distance (m)	Comments
RC 8	350	100	Before drilling
RC 9	350	200	Before drilling
D-NEG	350	600	Downstream negative
D-MRRE	350	135	6 m South of the MRRE coral reef
D-NV	350	135	Downstream no visible disturbance
D-PART	350	100	Downstream partial disturbance
D-POS	350	0	Downstream high disturbance
U-NV	170	40	Uptream no visible disturbance
U-PART	170	25	Upstream partial disturbance
E-PART	10	75	Partial disturbance
E-NV	10	110	No visible disturbance

mortar and a sample of known size (~10 g) mixed with diatomaceous earth and extracted by ASE (Accelerated Solvent Extractor, Dionex ASE300) using hexane:dichloromethane (1:1) as solvent, removal of sulphur by active copper, clean-up on silica Bond-Elute column and analysed by gas chromatography with flame ionization detector (GC–FID). All results are reported as mg/kg dry sediment and quantification limit was 1.0 mg/kg dry weight.

2.5.3. Metal analysis

Acidified aqueous sample solutions were obtained by dissolving 1 g of freeze-dried sediment in 7 N HNO_3 in an autoclave at 120 °C for 1 h (Norwegian Standard NS 4770). The cadmium (Cd) analysis was done on a Perkin–Elmer SIMA 6000 atomic absorption spectrometer equipped with a graphite furnace (GFAAS). The mercury (Hg) analysis was done with a Cold-Vapour Atomic Absorption Spectrometer (CVAAS) instrument CETAC M-6000A Hg Analyzer. Most of the reported elements were analysed using Inductively Coupled Plasma Atomic Emission Spectrometry (ICP-AES) type Perkin Elmer Optima 4300 Dual View. All results are reported as mg/kg dry sediment.

2.6. ROV biological sampling

Objectives: To use ROV to collect samples of corals close to the platform and from reference areas (not exposed to drill cuttings).

To study possible impact on corals of drill cuttings, biological samples from exposed and unexposed coral were collected at the end of the drilling period using ROV. Samples were collected from two locations; MRRE and NEG, 300 m and 600 m from the discharges point, respectively (Fig. 4). Following collection, the corals were quickly packed in aluminium foil and frozen on dry ice. The samples were maintained on dry ice (−70 °C) for shipping to the laboratory in Bergen, where the samples were stored within a −80 °C freezer until analysis. Two to three colonies from each location were analysed, with 6 polyps sampled from each coral colony.

The lipids were extracted by a modified Folch method with chloroform/methanol (2:1, v/v.) (Meier et al., 2006) and the lipid classes were separated by high-performance thin-layer chromatography (HPTLC) into six fractions (Olsen and Henderson, 1989):

- Polar lipids (PL, a mixture of all the membrane phospholipids).
- Cholesterol.
- Free fatty acids (FFA).
- Triacylglycerol (TAG, storage lipid).
- Unknown fraction (probably monoalkyldiacyl glycerol, MADAG).
- Wax esters (WE, storage lipid).

Fatty acids profiles from each lipid classes and fatty alcohols (from wax esters) were analysed by gas chromatography (GC–FID) as described by (Meier et al., 2006). All method details and methods validation are described in Supporting information.

From this analysis the following were determined:

- Total lipid amount (% of ash-free dry mass).
- Lipid classes distribution (% of fatty acids in each lipid classes relative to total amount of fatty acids).
- Fatty acids profile from total lipid and all lipid classes.
- Fatty alcohols profile of the wax ester.

Detailed discussion of the fatty acids profile is outside the scope of this paper and only results of total lipid and lipid class distributions are presented in the results. All tables of the fatty acids/fatty alcohol profiles together with a more extensive discussion of the lipid data are given in Supporting information.

2.7. ROV video monitoring

Objectives: In case autonomous instrumentation above failed (1–3 above), ROV video surveys could replace or compensate the data from these instruments.

A video survey of the coral reefs was carried out regularly during the drilling phase and after drilling was completed. This is reported by (Purser, in revision) and will not be dealt with in detail here. Further, during these inspections a visual survey of the geographic distribution of the sediment cloud was carried out and reported by Statoil (Rune Weltzien, pers. Comm.). This survey was based on a subjective evaluation of water turbidity.

3. Results and discussion

3.1. Operational experience

The basis for this project was to establish an acceptable environmental monitoring program in accordance with authorities' requirements in order to protect a vulnerable habitat. The components of the monitoring program, the sensors used and the involved operational experience are summarized in Table 2. Although the technology worked under controlled conditions in the laboratory and quayside, in the operational situation and under rough weather conditions, operations are often more problematic, and there are commonly last minute adjustments', modifications and infrastructure reinforcements required which are not necessarily easy to predict in advance. In this monitoring study, it is demonstrated that much of the equipment that was developed and tailored for this particular task had serious limitations. The monitoring program suffered from a high number of technical and operational problems and failures that could have invalidated the whole monitoring program. These will be dealt with in detail below. The planned backup solutions supplied by vessels equipped with ROVs enabled a basic monitoring program to be completed, which secured the satisfactory fulfilment of the most important monitoring requirement. In brief, this study underlines the fact that methodological and technological development and testing of new monitoring approaches can be carried out within the context of a live operational drilling event, but such novel approaches should never be initiated without tried and tested backup monitoring plans also being in place. Further, time constraints, as are often present in such drilling situations, may prevent the appropriate functionality testing of new equipment prior to deployment.

The platforms and instrumentation used for the Morvin monitoring program was initiated and established for fulfilling authority requirements, as determined by an industry-science partnership. Such an approach further supported Statoil's long term goal of developing real time monitoring approaches for their offshore operational activities (Hepsø et al., 2012). The focus of the monitoring program was to avoid negative impact on key locations and vulnerable organisms, in this case corals. A classical impact analysis requires key observations to be taken at habitats at risk and at reference locations not exposed to drill cuttings material. Due to technological and time constraints (which limited the instrument availability), this could not be done in this case, further illustrating the experimental nature of this program.

The advantage of real time monitoring is that it allows for the possibility to use the gathered data directly in predictive dispersal models, thus ensuring that governmental requirements on exposure concentrations are either met or alternatively, supporting e.g. relocation of the release site so that acceptable exposure concentrations are maintained. In principle we should be able to predict the distribution of drill cuttings over the coral reefs if ocean current measurements are available along with information on the position of release, time of release, volume and composition of drill cuttings released and/or a plume descriptor, e.g. as may be indicated via acoustic samplers. Reliable models may reduce the need for direct sampling substantially, but such accurate predictive models require high quality and regular incoming key environmental and discharge data.

3.2. Communication and real-time monitoring

The basis for the data communication system was the surface buoy that received information from the sensors and transferred them to land. During a severe storm with wave heights of 6–11 m in the beginning of the drilling period the buoy connection was lost. A weak link in the buoy tether designed to avoid the possibility that the buoy be pressed under water (with fatal consequences for the onboard instrumentation) released the buoy from the anchor, with the communication and power cable then rupturing. This cut off the communication channel, and the broken power cable caused an electric shortcut and the loss of half the battery power bank. An ad hoc solution was established that allowed download of data at intervals; a communication cable with a water proof end plug was picked up at depth by an ROV and transferred to the surface vessel where data could be downloaded manually and transferred to IMR for analysis. Several other technical difficulties were reported by Statoil (see Table 4) demonstrating the need for time and resources for pre operational tests when new technology and concepts are to be deployed.

The communication system was designed and produced without any prior operation and testing. Operation of surface structures such as buoys under rough conditions is demanding and requires reconsideration. First, operation of exposed solutions of the type employed here could be made more robust by separating power supply for communication and sensor data transfer. A broken communication cable could easily be replaced. The safest solution would be if the drilling platform could provide power and communication directly to the monitoring instrument platform(s) directly via a subsea junction box. During pre and post drilling monitoring periods the same instrumentation could be operated with power bank and data storage units, as real time monitoring is not needed to gather the background environmental data from a region.

3.3. Current and sedimentation

Current measurements are crucial for understanding distribution and transport pathways of particles. As the drill cuttings were released close to seafloor we were primarily interested in the measurements from the near bottom region, as given by the high frequency acoustic Doppler current meter (RDCP). The measurements showed a prevailing northwesterly flow direction with

Table 4
Summary of the technical difficulties reported by the oil company.

Incident	Cause	Measures
Sea current data from RDCP not online	Water penetration in cable	New cable from the manufacturer of RDCP
No communication with camera	Errors in power supply	New type of relay base
Camera stopped taking photos	Error in the internal battery in the camera	Battery removed
Cable from the bottom to the surface buoy broke	Attrition/not best cable available	More powerful cable and other fastening
Fibre break in cable	Handling on deck	Better protection of fibre provided by cable supplier
Sonar stopped	Conflict with RDCP data transmission	The cause is not so far solved by supplier
Water penetration into the battery container	Too much grease on the O-rings	New O-rings and a new type of grease
Damage by taking on board	Lander hooked in the side of the ship	Future designs more robustimprove communication between the deck and crane

maximum speeds of ~35 cm^{-1} (Fig. 5). The mud cloud thus kept clear of the MRRE reef for most of the drilling period, but for short periods the current turned more easterly and the mud cloud could cover the reef as demonstrated in Fig. 6. Such events were also observed by the time lapse camera (Fig. 7, Supplementary Video).

The acoustic current meters (Aquadopp) operating from three rigs north of the drilling location (Fig. 1), were supposed to send detailed current information at regular intervals to give robust measurements of spatial variability in the prevailing currents. Also, this automatic data transfer failed and the data had to be downloaded manually by visiting the rigs at regular time intervals. As these measurements inform about the spatial variability of the current in the area, the bottom sensor data are here compared to the RDCP measurements (Fig. 5). In general all sensors gave similar data on current velocity and flow direction. The RDCPs tended to measure lower speeds than the Aquadopp for part of the time series. This indicates that spatially resolved measurement might be needed to correctly model distribution of drill cuttings.

The sediment volumes collected by the two downstream sediment traps was generally much greater than by the upstream trap and contained high barium concentrations, indicating the influence of drilling mud and cuttings on settling particulate compositions (Tenningen, 2011). The sediment trap upstream of the discharge point contained barium levels that were an order of magnitude lower than at the other sediment trap sites, although concentrations of Ba at this location were still considerably above the local background levels, so some minor contamination at that location is possible. The sediment trap results are not given more attention here due to failure in the rotational functioning of all the traps, precluded a more detailed discussion of sedimentation at the trap locations.

3.4. Sediment analysis

Due to limited amounts of sample material collected, grain size characteristics were not determined from the sediment cores collected at Morvin. The 2009 regional monitoring program for the Halten Bank describes the sediments as silty or fine sand (Akvaplan-niva Report No. 4664-03, 2010). Visual inspection of the sediment cores from Morvin were in accordance with this

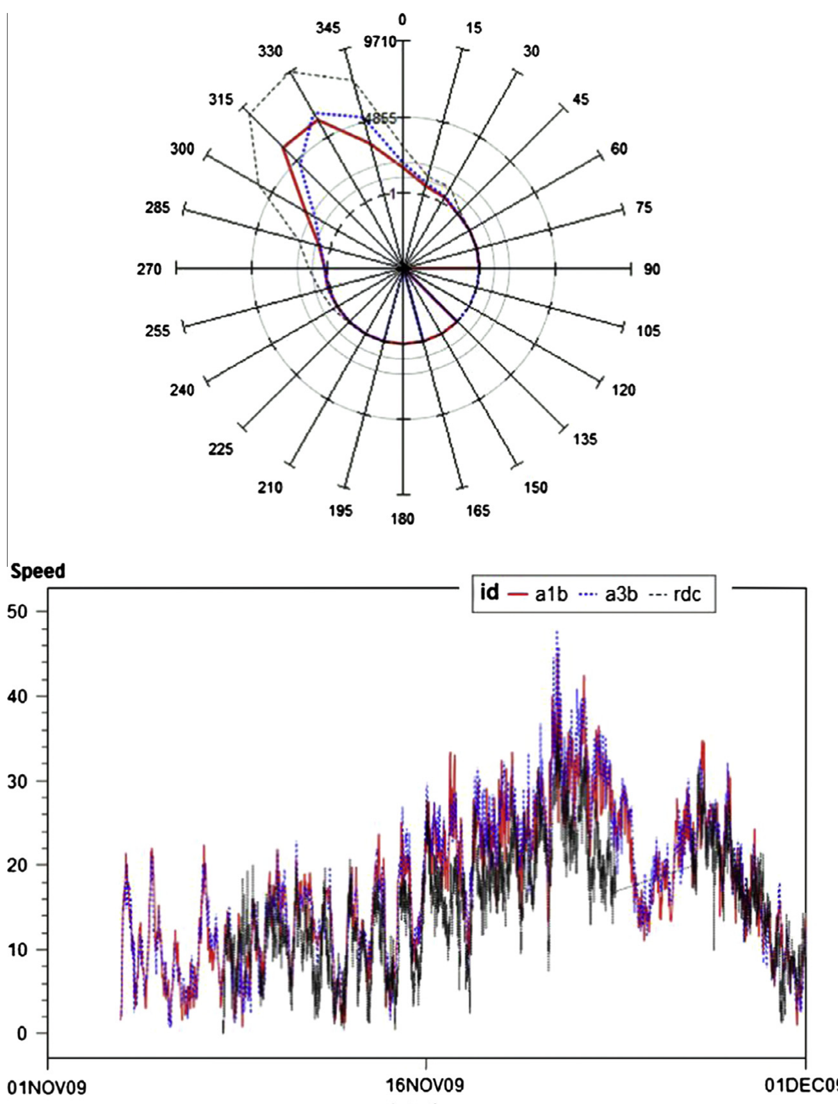

Fig. 5. Current speed (cm^{-1}) and direction as observed by the RDCP and the two of the moored Aquadopp point measurements. Upper panel shows prevailing direction of speed recorded as number of observation in various directions. ID identifies the moorings (a1b and a3b compared to the RDCP (rdc). Lower panel shows the current speed variation of the same instruments (break in time series of the RDCP is due to maintenance).

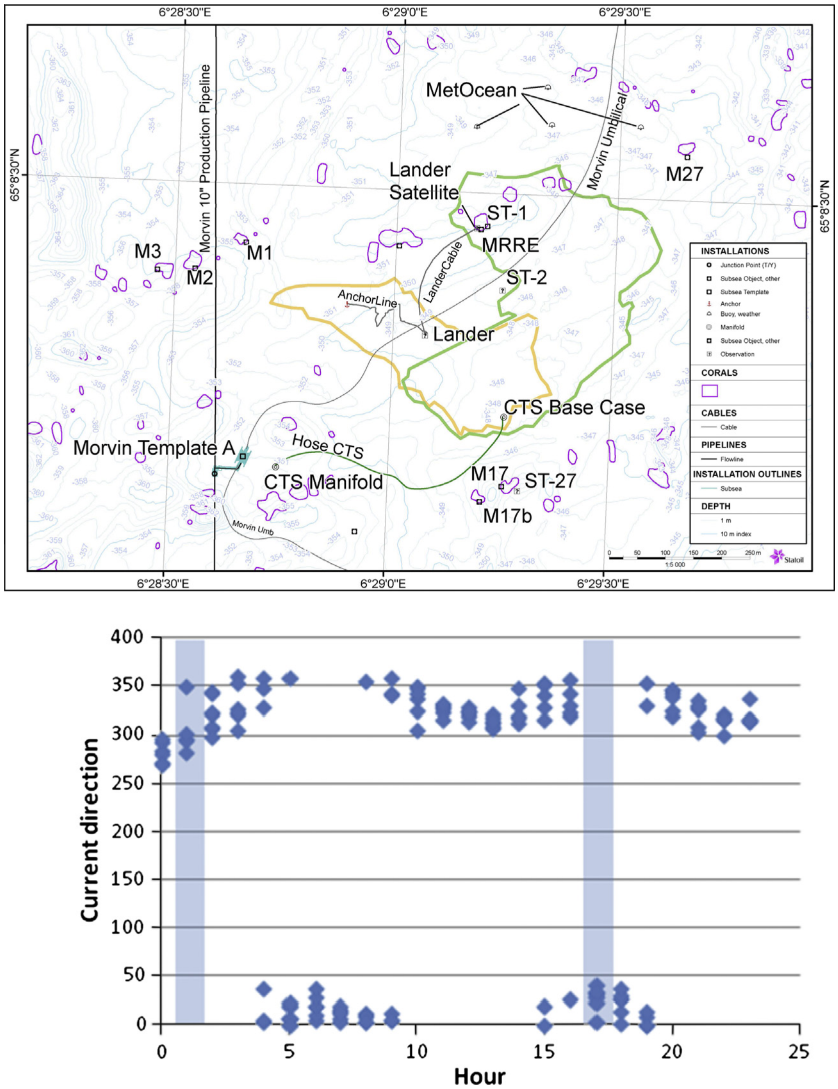

Fig. 6. Two examples of the distribution of the mud cloud as visually mapped by ROV on November 30, 2009 at 01:25 AM (orange line) and 17:30 PM (green line) (upper panel with courtesy R. Welzin, Statoil). Lower panel shows current direction during that day and the difference between the two sampling periods (indicated in hatched columns).

description. TOC levels were relatively low with small differences between positions most exposed to drilling waste compared with the situation prior to drilling (Table 5). These results were expected since only water-based mud were permitted the drilling operations.

Generally the levels of Total HydroCarbons (THC) as indicator for oil contamination in the sediment cores from Morvin were low (Table 5) and similar to the 15 regional stations collected 2009 at Haltenbanken which showed THC concentrations in the range 1.8–4.1 mg/kg dry weight (Akvaplan-niva Report No. 4664-03, 2010). However, the results show that the sediment core in position D-POS, which is very close to the release point, contains elevated levels of THC (178.1 mg/kg dry weight). This is significantly higher (factor >20) than for the rest of the samples (Table 5) and may indicate a low concentration of oil from the reservoir rocks, which had migrated into overlying strata as a result of natural processes. Such variations in oil content within overlying strata have been reported previously on the Norwegian Margin (Pabortsava et al., 2011).

In the regional study the range of background concentration for barium (Ba) were 83–287 mg/kg dry weight, cadmium (Cd) 0.048–0.11 mg/kg dry weight, copper (Cu) 6.5–12.2 mg/kg dry weight, chromium (Cr) 16.4–34.6 mg/kg dry weight, lead 13.9–20.9 mg/kg dry weight, mercury (Hg) 0.023–0.237 mg/kg dry weight, zinc (Zn) 40.7–90.0 mg/kg dry weight. (Akvaplan-niva Report No. 4664-03, 2010).

Assuming background concentrations for Ba at Morvin is below 300 mg/kg dry weight, 6 of 9 positions showed elevated levels of Ba (Table 6). The highest concentrations were found at the positions close to discharge point. The analysis for Ba was found to be a useful tracer for observation of the spread of drilling mud at Morvin, with a decreasing concentration gradient correlating with increasing distance from discharge point (Table 6). For the other elements only weak indications of elevated concentrations were found at locations in close proximity to the discharge point.

3.5. Lipids analysis

Lipid analyses of the cold water corals, *L. pertusa*, were designed to identify potential reduction of the energy stores of coral in the vicinity of the platform compared with corals from a references area nearby. The hypothesis being that changes in the lipid amount and fatty acids composition can occur either as a result of reduced

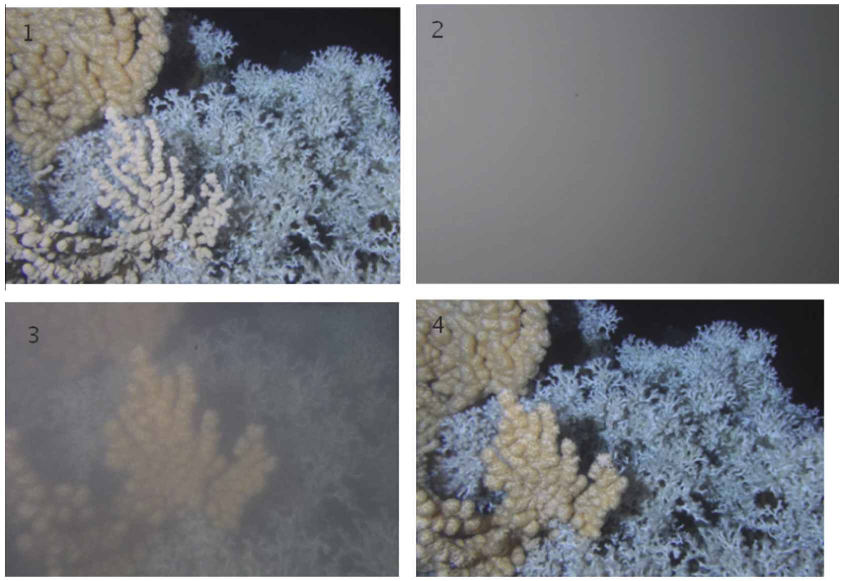

Fig. 7. Photo sequence at the monitored coral reef before, during and after an episode of particle exposure (turbid water). The sequence representing a 3 h interval. Apparently the polyps are active during the whole period.

Table 5
Weight % of total organic carbon (TOC) and total hydrocarbons (THC) (mg/kg dry weight) in sediment samples.

Location	TOC (%)		THC (mg/kg dw.)	
	Mean	St.dev.	Mean	St.dev.
RC 8	0.33	0.01	4.0	0.9
RC 9	0.35	0.01	3.3	0.05
D-NEG	0.37	0.02	5.3	2.0
D-MRRE	0.35	0.02	3.0	0.8
D-NV	0.38	0.01	3.4	0.5
D-PART	0.36	0.04	4.3	1.5
D-POS	0.31		178	
U-NV	0.40	0.02	3.7	0.5
U-PART	0.43	0.06	8.7	4.3
E-PART	0.36	0.01	6.9	0.7
E-NV	0.34	0.02	3.9	0.1

feeding or of the increased metabolic cost required for sediment removal.

There were no difference in the lipid content from the exposed corals (MRRE C1 and C2) and the reference samples (NEG C1 and C2) (Table 7). One sample (NEG C3) had significantly lower lipid levels. This coral sample was in bad visual condition and heavily covered with black sediment, and with a low percentage of soft tissue in the coral.

The lipids of the corals can be divided into neutral lipids (WE, TAG, MADAG) that function as a source of metabolic energy and polar lipids (PL) which are essential components of cellular membranes (Imbs, 2013).

The *L. pertusa* lipids were clearly dominated by storage lipids, approximately 50% of the FAs were found in the WE fraction and around 30% in the TAG. Hence the energy storage lipid contributed to more than 80% of the total amount of FA. At MRRE C2 there were significantly higher levels of WE and lower levels of TAG compared to the other samples sites (see test Table 7). MRRE C1 had relatively lower levels of polar lipid (PL). There is a lack of published data for lipid class analysis of coral and we can therefore not tell if this is a significantly different distribution when compared to a natural variation. However, since all corals from both areas had high levels of storage lipids (WE and TAG) there is no support for the hypothesis that exposed coral had eaten less food than coral from the control area.

Recent laboratories studies on growth and lipid composition in *L. pertusa* after long starvation durations (6 month) (Larsson et al., 2013a) or long-term exposure to drill cuttings (3 months) (Larsson et al., 2013b) have been carried out. These studies indicated that the lipid composition (ratio between neutral storage lipids and polar structural lipids) in the corals are very persistent to starvation and particle stress and do not show any decline in the lipid energy storage even after long periods of starvation. This may

Table 6
Concentrations of trace elements in sediment samples (mg/kg dry sediment).

Location	Ba		Cd		Cr		Cu		Hg		Pb		Zn	
	Mean	Sd.	Mean	Sd.	Mean	Sd.	Mean	Sd.	Mean	Sd.	Mean	Sd.	Mean	Sd.
RC 8	86	11	0.06	0.01	15.3	0.65	3.4	0.20	0.13	0.00	10.0	0.42	30.4	1.59
RC 9	132	33	0.07	0.00	17.0	0.15	3.8	0.11	0.14	0.00	11.0	0.47	33.1	0.84
D-NEG	274	33	0.06	0.02	16.3	0.93	3.9	0.35	0.16	0.02	12.2	1.44	33.3	1.62
D-MRRE	196	21	0.06	0.02	16.0	0.35	3.6	0.11	0.23	0.01	10.7	1.07	32.0	1.22
D-NV	1210	147	0.05	0.00	15.1	0.72	3.5	0.30	0.14	0.01	10.1	0.78	30.2	1.27
D-PART	6250	3230	0.07	0.02	19.3	1.00	6.7	2.17	0.27	0.07	12.9	0.97	37.3	2.05
D-POS	8060		0.07		32.7		39.7		0.58		36.8		47.4	
U-NV	193	16	0.07	0.01	17.9	0.21	4.3	0.49	0.15	0.01	11.7	0.99	35.5	1.22
U-PART	1933	1251	0.08	0.01	25.5	3.17	8.1	2.11	0.17	0.00	11.8	0.40	45.9	5.49
E-PART	1670	131	0.07	0.02	21.5	1.78	5.8	0.50	0.16	0.01	10.9	0.20	38.4	1.99
E-NV	353	191	0.06	0.01	22.2	3.70	6.0	1.34	0.14	0.01	11.4	0.67	40.3	4.97

Table 7
Amount of lipid (% of ash free dry weight) and lipid classes composition (% of FA in each lipid class relative to total FA) for reference samples (NEG) and exposed samples (MRRE). WE = wax esters, TAG = triacylglycerol, PL = phospholipids, Unknown (likely to be monoalkyldiacyl glycerol), FFA = frie fatty acids. Different letters = significant difference between sampling sites (ANOVA, $p < 0.05$).

		Lipid classes composition (FA% of totally FA)				
	Lipid (%)	WE	TAG	PL	Unknown	FFA
NEG C1	17.6 ± 3.2^{a}	52.8 ± 0.7^{b}	30.7 ± 1.1^{a}	9.4 ± 1.6^{a}	5.8 ± 0.2^{a}	1.3 ± 1.5^{b}
NEG C2	14.8 ± 3.8^{a}	52.5 ± 2.2^{b}	31.1 ± 2.6^{a}	8.9 ± 2.6^{a}	5.6 ± 0.7^{a}	1.9 ± 0.3^{ab}
NEG C3	5.9 ± 2.5^{b}	51.5 ± 1.7^{b}	32.4 ± 1.3^{a}	5.1 ± 1.8^{ab}	7.1 ± 0.6^{a}	3.9 ± 0.6^{a}
MRRE C1	16.5 ± 2.5^{a}	57.1 ± 4.9^{b}	31.5 ± 4.6^{a}	3.5 ± 1.1^{b}	6.3 ± 0.9^{a}	1.6 ± 0.4^{ab}
MRRE C2	13.8 ± 4.1^{ab}	63.5 ± 3.8^{a}	20.9 ± 1.5^{b}	9.7 ± 5.8^{a}	4.3 ± 0.6^{b}	1.7 ± 0.2^{ab}

The difference between lipid% and lipid classes composition were tested by Analysis of Variance (ANOVA) with Tukey (HSD) post hoc tests. All statistical analyses were carried out using XLSTAT software (Addinsoft, U.S.).

indicate that lipid analysis not is a suitable method to study sublethal effects after exposure to drill cuttings.

Fatty acids profiles in the storage lipids can, on the other hand, give information on what the corals have been eating, and may give information about changes in food sources during and after a drill operation (Dodds et al., 2009). The corals from MRRE C2 had higher levels of saturated FA (SFA) and lower levels of mono unsaturated FA (MUFA) in neutral lipids (WE, TAG, MADAG) compared with the others corals (details given in Supporting information). This may suggest a lower input of food particles related to copepods (*Calanus finmarchicus*) at the site, but there were no differences between MRRE C1 and the control (NEG), so it is not possible to draw any conclusion from this analysis.

ROVs provide a focused and controlled opportunity to sample at deep waters, and are efficient platforms from which to collect corals and other benthic organism for studying effects of drilling disturbance associated to petroleum activities (Hughes et al., 2010; Jones et al., 2012; Purser and Thomsen, 2012). We still lack appropriate tools that can identify direct "cause-and-effect" between drill cuttings exposure and effects on welfare of cold water corals (Nielsen et al., 2010; Purser and Thomsen, 2012). A number of molecular methods have been established to study sub-lethal effects on the cellular levels for tropical corals. It is likely that at least some of these methods in the future can be adapted to provide more knowledge on the homeostatic responses to different stressors in deep water corals such as *L. pertusa* (Downs et al., 2012; Rotchell and Ostrander, 2011). However, suitable assays have yet to be developed and validated in laboratory studies before we can recommend using biological sampling of corals in the context of surveillance of environmental impact from drilling operations.

3.6. Applicability of active acoustics in observation of particles and biomass

The idea behind the acoustic observation system was twofold: First we wanted to observe the distribution of drill cuttings particles in the neighbourhood of the release to better estimate sedimentation based on modelling. Secondly, the system was designed to observe marine organisms, and we wanted to see if marine organisms were affected by the particle cloud. Fig. 8 shows a 38 kHz echogram demonstrating how the system detects single organisms and follows them over several successive pings. The split beam tracking facility (Handegard et al., 2005) allows detailed mapping of swimming activity of individuals, which can be compared to potential impact variables such as the distribution of drill cuttings and noise. Not even the highest frequency could detect the mud cloud that was visually mapped by the ROV (Fig. 5). Sand particle released from surface can easily be detected by acoustics (Solberg, 2008). In our case the particles found in the water column were re-suspended material as the cuttings were released on the seafloor by the CTS. These re-suspended particles are commonly small, in the range of a few microns (Pabortsava et al., 2011) so that only frequencies in the MHz range could have detected them. When the communication buoy was lost during the storm a short-cut in one of the battery packages heavily reduced the capacity of the whole system. As detection of pelagic marine organisms was not part of the required monitoring program, the echosounder was turned off to save power.

3.7. Optical methods for monitoring vulnerable habitats

For this particular monitoring program the focus was the well-being of the coral organisms. The initial idea was to take pictures with the time lapse camera regularly and transfer the information. With the communication failure the strategy was changed. The pictures could only be downloaded at intervals coincident with ROV surveys and could thus support the near synoptic monitoring of the coral reefs.

The time lapse camera recordings successfully demonstrated the power of high resolution camera deployments in monitoring behaviour of coral polyps and associated organisms (Buhl-Mortensen et al., submitted). The camera recorded on 30 min basis and showed that the coral reef was unaffected most of the time, but could occasionally be flushed by turbid waters from the drilling operation. This gave useful data to study possible impact on corals. Image analyses revealed no significant behavioural differences between corals that were exposed to drill cuttings and unexposed corals. Detailed analyses of the time series from the exposed coral reef revealed that changes in current direction and speed were the main reasons for changes in coral polyp behaviour. The authors underline that no long term impact can be evaluated based on these few data. The use of time lapse camera in monitoring impact on vulnerable habitats seems thus a powerful tool, but such analysis should be carried out with quantitative information on sedimentation. The sediment traps, if working properly, would have given such information, but the resolution would not have matched the resolution of the time lapse camera. There is an urgent need for a real time sedimentation sensor that supports quantitative analysis in combination with time lapse data.

The ROV video survey was an integral part of the near real time monitoring system. The video analysis of a number of the small reefs in the vicinity of drilling over time is presented in (Purser, in revision). The paper compares coral reefs under varying drill cuttings exposure concentrations and concludes that no immediate or long term (one year after drilling) effect could be observed on either *L. pertusa* scleractinian corals, or the associate *Paragorgia arborea* gorgonian coral or *Acesta excavata* bivalve species.

The Norwegian authorities require gathering of knowledge and a better understanding of the possible risks posed by drilling discharges on biological organisms, in this case on corals. As long as this knowledge base is low, the precautionary principle to drilling

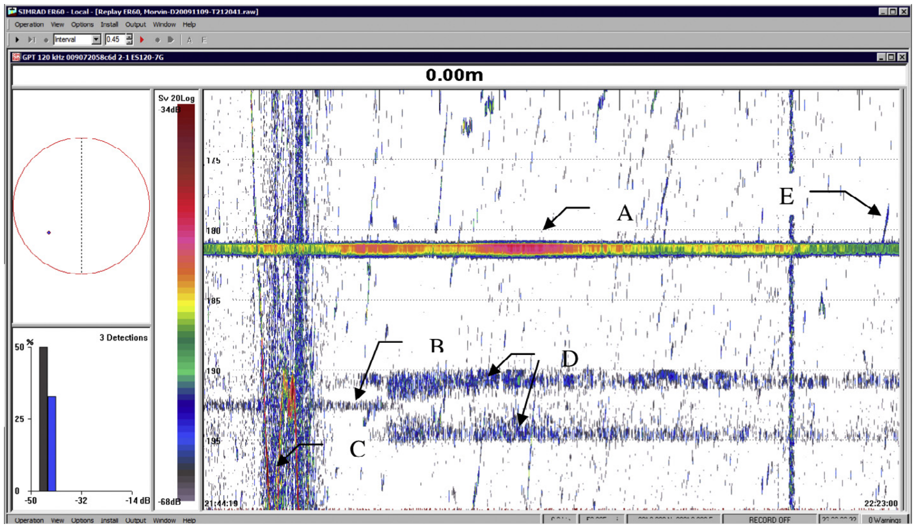

Fig. 8. Echogram of the 120 kHz echosounder poiting towards the recoil unit of the CTS (see Fig. 2). (A) Recoil unit at 150 m. (B) Recoil unit at 200 m. (C) Noise from ROV covering the whole echogram and ROV appearing as red well defined line. (D) Suspended material appearing on both sides of the recoil unit. Mark that there are no signal from resuspended materials associated to the cutting, which was easily visible to and tracked by the ROV (Fig. 6). Top left hand panel demonstrate single echo identified by the split beam system and lower panel gives the size distribution of such detections. Targets like E were identified by the ROV to be saithe (*Pollachius virens*).

operations should apply. This requires that drilling should cease or the point of cuttings release be relocated (see Fig. 2) if observations exceed certain thresholds, e.g. sedimentation depth exceeding 2 mm at the coral reefs. To support such knowledge and to allow management actions in real time, or close to real time, continuous data access is required. For this monitoring program, technology was prepared for real time monitoring of camera, echosounders, current and turbidity sensor data. The sensors were connected to a surface communication buoy through a fibre-optic cable and data transferred to land through a wireless connection (Fig. 3). The system was designed to give key information about the distribution of the drill cuttings through acoustic monitoring and status of possible impact on the coral reef most likely to be exposed to the drill cuttings through the time lapse camera. Current data would further inform on sediment distribution through a particle drift model. Data from some key sensors are for various reasons (physical, operational or analytical) not available for real time analysis due to limitations in present sensor technology. Such monitoring for post drilling analysis included in this study ROV core sampling data, lipid sample analysis and sediment trap sample analysis. Such data are important for quantification of contaminants and sedimentation and are crucial for pre-, during- and post-drilling comparisons. Near real time monitoring included alternative sampling methods that did not fulfil true real time monitoring. This monitoring updated the situation regularly when real time observations were unavailable. In the present case this ended up as the most important tool and included the ROV based monitoring described above.

Although most of the collected information used to fulfil the obligation of the drilling permit came from near real time monitoring, the Morvin project demonstrated successfully the potential of interaction between monitoring and manipulated releases of drill cuttings. The producer of the CTS system claims they can set up systems that transfer drill cuttings over distances of up to 2 km (Rune Weltzien pers. Comm.). This clearly enhances the possibilities for running a drilling operation close to vulnerable habitats by manipulation of the release location according to the incoming information.

4. Future perspectives

Although the present monitoring concept was designed for a particular case and for protecting a specific vulnerable habitat, regulations for protection are expected to become more strict in the future. This specific case study has given a valuable insight into current monitoring technology and should initialize the overdue discussion on new developments in the fields of sensors, sensor platforms and communication technologies. In this project industry demonstrated operational capabilities to manipulate the drill cuttings disposal site and thus the likely distribution pathways of the drill cuttings in response to monitoring results. If transport of cuttings up to 2 km, as suggested by the CTS producer, is feasible, then an integrated online observation-release system should substantially enhance the ability of drilling operators to minimise impacts on vulnerable habitats. This project illustrated the importance of the development of cost-efficient real time monitoring systems for the near future. Although the real time operations failed, the near real time replacement study insured that drilling operations complied with regulations. The lessons learned may serve as important inputs into discussions on how such systems should be operated in the future. Some basic outcomes are summarized below:

- Allowing experimentation as part of monitoring

Experimentation during monitoring is risky but allows for efficient testing of concepts and technology under realistic conditions. An extended (>10 years) transition time between traditional sampling methodologies and new real time or near real time monitoring is required. The online monitoring should include the use of autonomous and semi-autonomous seafloor vehicles which operate at different distances around the integrated central observation release system. These robots would improve the evaluation of the relationship between the distribution of the mud cloud, current conditions and the photographic observations, (such as at the MRRE coral reef presented here) for assessing the exposure of vulnerable habitats. The need for validation of model output with real time methods will be reduced over time as models improve.

A major shortcoming of this monitoring program was the lack of detailed testing of equipment prior to drill commencement, as a result of project time constraints. Under the drilling timeframe constraints of the project there was no time available for realistic testing. The experience obtained through field operations has indeed been used to enhance performance and robustness of the monitoring technology and to tailor sensor packages for monitoring purposes. In a succeeding project taking place independent of operational drilling (see http://love.statoil.com), a cabled monitoring system is established partly on the basis of the experience obtained during the Morvin project.

Including advanced acoustics increased the complexity of the monitoring system. Such systems might be required when there are specific needs to monitor higher trophic marine life in the water column, but are apparently useless for monitoring re-suspended mud from drill cuttings released on the seafloor.

- Technology constraints and requirements for development

The monitoring system described here was a stand-alone system not integrated with the infrastructure of the operation of the drilling programme. Thus positioning of the equipment and the technology chosen came into conflict with the regulations and routines governing drilling operations. A real time monitoring system must be integrated into the drilling operation at an early stage of the project. This would allow an optimal distribution of sensors and systems and the most efficient solutions for communication and power delivery.

Many of the conventional sampling systems cannot produce online information. Sedimentation analysis is presently dependent on sediment traps, which in this monitoring program did not operate correctly. Simple electronic sediment meters transferring information, e.g. through an acoustic modem, are needed to secure appropriate information about the sedimentation process.

In general, reliable communication systems for sub-sea sensor networks associated with real time monitoring are mandatory. This includes reliable connection between the monitoring network and the drilling operation centre supporting an efficient feedback strategy in accordance with the drilling permit.

We used traditional methods for sampling and chemical and biological analysis. Some of these methods might in the future be replaced by sensors and/or *lab on chip* technology (Ballesteros-Gomez and Rubio, 2011; McStay et al., 2002; Mills and Fones, 2012). Such advancement might improve monitoring and replace existing technology when appropriately tested.

- Standardisation and simplification of real-time systems

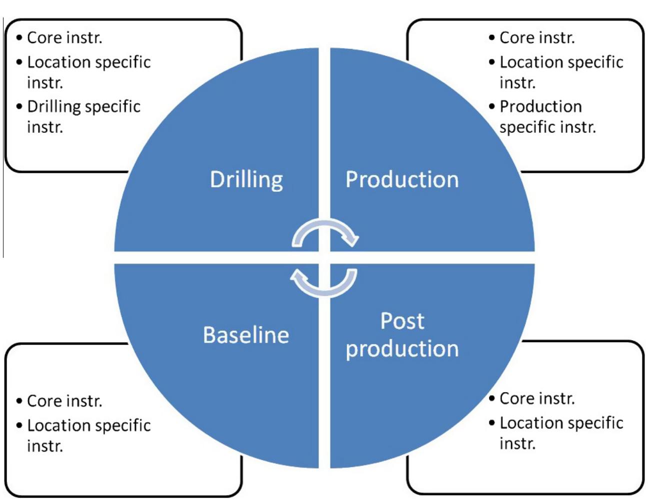

Fig. 9. Balance between standardization and specialisation in future monitoring. Core instrumentation secures a basic standardization used under all conditions and phases. Location and phase specific instrumentations are used to fulfil objectives in the monitoring associated to location and phase. This approach supports comparison of data collected during all phases and thus allows impact assessments on the marine environment when operations are carried out in different habitates. (Replace "Basline" with "Baseline" in figure).

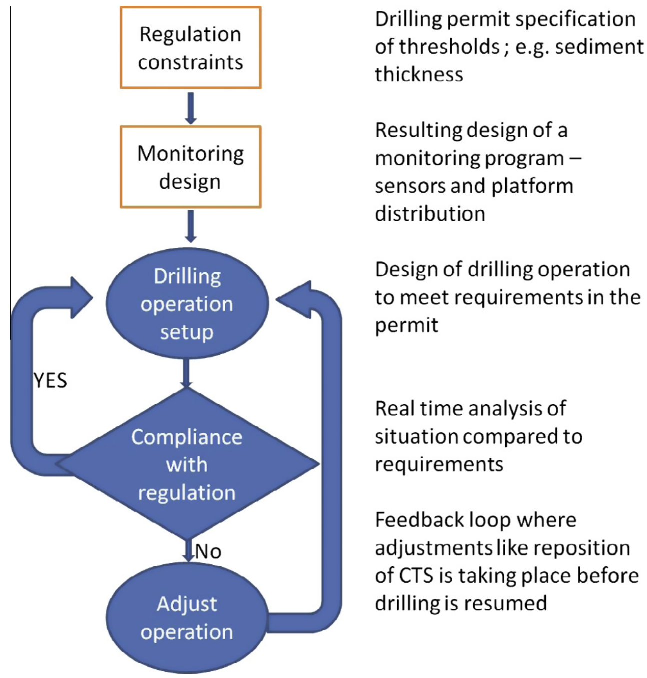

Fig. 10. Schematic illustration of the basic setup and flow of information and actions in a real-time monitoring case with feedback.

After the experimental and development stage functional standards should be established. To enable proper understanding of impact of drilling on marine life monitoring standards should include four phases; the undisturbed phase prior to drilling, the drilling and production phases and the post production phase. Each phase has its own challenges to secure power, communication and data storage. To enable a proper comparison of the state of the ecosystem during all phases, the sensor system must be operable under the constraints of each of the four phases. Functional and reliable instrumentation is essential, and as a rule, monitoring systems should be kept as simple as possible.

- Modelling

Modelling of ecosystem status needs to be an integral part of the development. This development should be an integration of existing models tailored to assimilate the data collected in all phases (Fig. 9) for each drilling location. Most importantly, by developing true real time solutions, the model should continuously update status and alarms that guide operations; e.g. the positioning of the CTS. Modelling of the interaction between drill cuttings and the spatial and temporal distribution of naturally occurring organo-mineral particles should also be integrated (see e.g. Pando et al. (2013)). The importance of real-time modelling of released drilling waste materials is further highlighted in Brönner et al. (2013). Concept for the future.

Due to the uniqueness of any drilling location a full standardization is unfeasible. More efficient could be a concept using a core instrumentation representing a minimum for all phases. In addition there would be location and phase specific sensors to fulfil specific requirements (Fig. 9). Further, a feedback loop facilitating an interaction between regulation constraints and real time monitoring results has to be developed as exemplified in Fig. 10.

Acknowledgement

We are grateful to Statoil for their support to this work including the extensive help from Rune Weltzien and the captains and crews on the support vessels. We also thank Terje Torkelsen (Metas AS) for his help with technical details of the monitoring system at Morvin and Therese Smith-Jahnsen and Grethe Tveit at the chemistry laboratory at IMR for technical assistance with the chemical analysis. The 'Hermes lander' was deployed as part of the FP6 EU-project HERMES (EC contract no GOCE-CT-2005-511234).

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.marpolbul.2014.05.007.

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