The Kosterfjord Experiment, a trial to assess the interaction of a coldwater coral reef with its environment.

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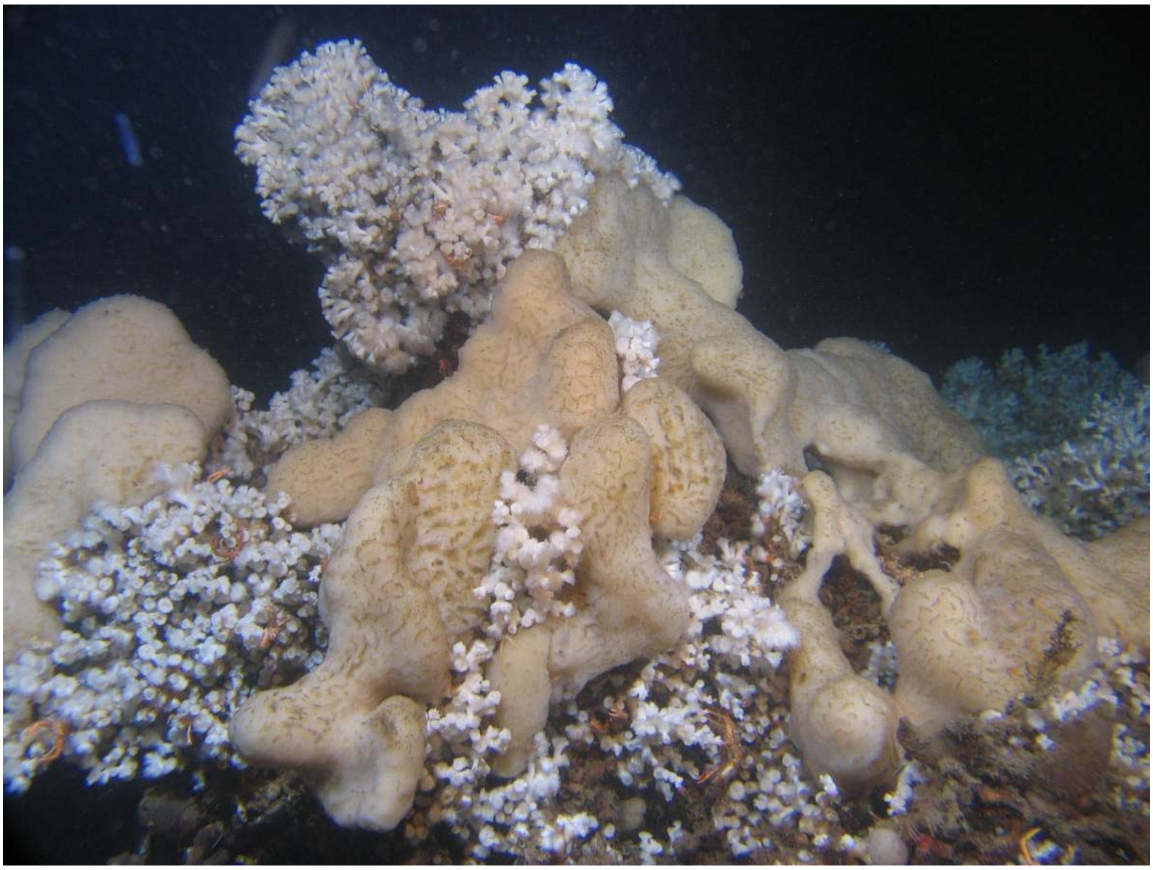

1. INTRODUCTION

Despite increased efforts in the last decade to map and explain the occurrences of cold coral communities on the NE Atlantic slope, a number of important questions still remain partly or unanswered. Examples are: which environmental factors are crucial in determining where cold-water coral reefs can be established? How does a reef of the cup coral (*Lophelia pertusa*) interact with its surroundings? What type of food is extracted from the passing water currents in what quantities? How much oxygen is used by the corals for their respiration? How do the coral reef structures modify local current patterns and the microhabitat around coral polyps?

Within the HERMES Consortium, a broad collaboration has been formed with the objective to shed more light on some of these questions, and ultimately to provide data that will make it possible to create realistic mathematical models describing the functioning of cold-water coral ecosystems. As a study area the Kosterfjord/Hvaler (NE Skagerrak) was selected where several *Lophelia* reefs have been found in the coastal deep-water channels. Advantages of this particular area are that 1) it is close to the facilities of the Tjarno Marine Biological Laboratory (TMBL, Goteborg University), 2) being protected from the ocean relative small vessels can be used 3) the relatively shallow depth allows operations with a ROV, and 4) TMBL has produced detailed maps of the coral distribution in the study area during the ACES and HERMES projects. The TMBL was also able to provide ships with a ROV to deploy equipment and sampling material. Above conditions make the Kosterfjord/Hvaler area an ideal site for intense observations on cold water corals and in-situ experimentation.

The general objectives of the Kosterfjord experiment were to measure differences in the quantity and quality of the particulate organic matter (POM) over the reef over the shorter (tidal) and longer time spans (month to year), and to determine possible relations with other environmental factors (currents, temperature, reef activity).

The detailed goals of the experiment were to:

1. Assess the long term (seasonal) variability in environmental forcing (current regime, turbidity, zooplankton densities, POM quality).
2. Provide a gross estimation of biogeochemical fluxes and respiration at the reef system.
3. Provide a quantitative analysis (biomass estimate) of biological community.
4. Experimentally determine community respiration and metabolism.
5. Shed more light on the feeding ecology of *Lophelia pertusa*
6. Obtain a set of physical oceanographic data covering the whole period in order to

    i) Assess the variability in environmental parameters at the reef, e.g. currents, temperature, salinity, O2 and turbidity,
    ii) Quantify the main processes controlling both the residual and transient currents that impact the reef,
    iii) Provide data to support the quantification of biogeochemical fluxes at the reef
    iv) Measure at the small scale flow dynamics (turbulence) at the reef for comparison to coral abundance distribution and feeding strategies.

The principal field work within the Kosterfjord experiment has been finished in the meantime. However, some additional data collection will be continued. The results and conclusions presented here are therefore a first although major step forward.

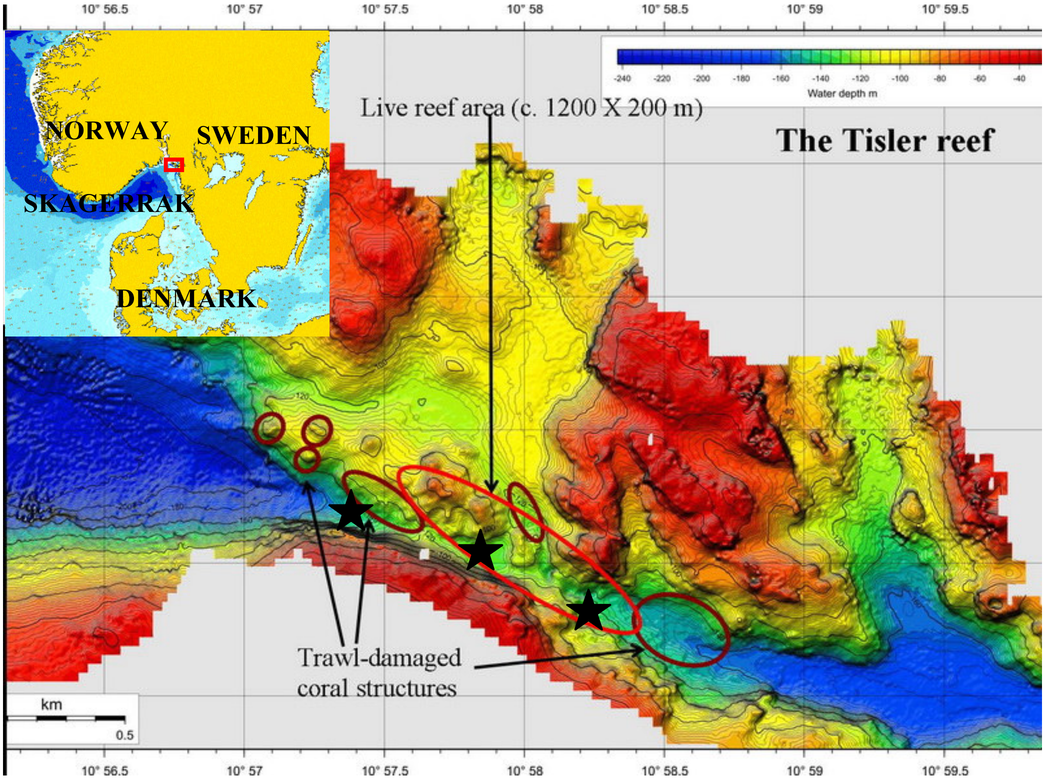

Fig. 1 *Bathymetry of the Tisler Reef. Black stars show the sampling locations i.e. SE, NW edges and the middle of the reef. Ellipses indicate areas with trawl damage (bathymetric map courtesy of Tomas Lundalv).*

2. METHODS AND MATERIALS

2.1. Sampling scheme.

The studies were concentrated on the areas largest reef, E of the Tisler islands, which is situated in the sill area of the Kosterfjord deep-water connection to the open Skagerrak (the submarine border between Norway and Sweden), east of the Tisler islands (Fig.1). This reef was first discovered and documented by the TMBL team in 2002. The living parts of the thousands of years old Tisler reef extend 1200 x 200 m laterally over a depth range of 70-155 m, making it one of the largest and most shallow known inshore reefs. It contains several color varieties of *Lophelia pertusa* corals. Thorough ROV-documentation of the area has revealed that large dead coral structures with indications of trawl damage are present in the distal parts of the reef (Fig. 1), revealing that the living reef has once had about twice the extent of the present situation. The reef was protected from trawling through Norwegian fishery regulations in late 2003. The location can be reached from TMBL in less than an hour.

The first collaborative study on Tisler reef site was undertaken between late March and early May 2006. This period was chosen because the spring bloom was expected to build up during this period. Partners from NIOZ (Gerard Duineveld and Marc Lavaleye) brought two benthic landers that were positioned at both sides of the reef, collecting data on current velocities, temperature, oxygen, chlorophyll-a content, turbidity, sedimentation and time-lapse camera observations of surrounding fauna. Partners from the National University of Galway, Ireland (Martin White and Tom Furey) deployed current meters and CTD-moorings at strategic positions on the reef in order to obtain detailed observations of current patterns and variations in hydrographical parameters (salinity, temperature, oxygen, turbidity). Partners from the University of Liverpool (Kostas Kiriakoulis, George Wolff) contributed stand-alone pumps (SAPS) for collecting large samples of particulate organic matter (POM) from the water column at various depths and locations in relation to coral distribution. Scientists from the International University of Bremen, Germany (Laurenz Thomsen, Dimitar Berov) installed time-lapse HD-video cameras for the study of coral polyp behaviour and particle flux dynamics. The local team (TMBL, Tomas Lundalv, Lisbeth Jonsson and Roger Johansson) provided background information and essential logistic support in the form accommodation, lab facilities and importantly 2 research vessels (RV's *Nereus* and *Lophelia*) plus ROV. Latter proved crucial for the accurate positioning, launching and retrieval of the various instruments.

At the start of work in late March 2006, winter still lingered in the Kosterfjord area after an unusually long and cold winter, and on arrival scientists were greeted by thick layers of snow and icy roads. During the first week of work, however, the weather changed and the snow quickly melted under the influence of heavy rains and milder weather, accompanied by dense fog forming over the still cold sea. Although the weather conditions were far from optimal, all operations at sea went very well, and all instruments were deployed according to plan. Most instruments were left to collect data at short time intervals over a period of approximately one month, and during another intense week of fieldwork in late April all instruments were successfully recovered. In early May, some of the oceanographic recording instruments were again launched in various positions around the reef, with the intention of obtaining long-term records of variations in hydrographic conditions. With the exception of a particle camera and a data logger for oxygen data on the benthic landers, all instruments worked according to plan, and the first part of the Kosterfjord Experiment was highly successful.

Partner 10 (NUIG), responsible for long-term measurements of currents and CTD data at several stations (Table 1) at the Tisler Reef, made visits to the reef in September 2006, October 2006, and July 2007 in addition to the main sampling periods in March-April 2006 and April-May 2007. This was to recover, service and redeploy moorings and current meters. A further visit towards the end of 2007 is anticipated for final instrument retrieval.

In 2007 a second concerted action took place from 25 April - 2 May. NIOZ and the University of Liverpool concentrated on the collection of near-bottom particles during a tidal cycle. For this purpose NIOZ supplied adapted SAPS pumps so that samples could be taken at short time intervals and at a fixed distance of 50 cm above the bottom. With the assistance of RV Nereus we succeeded in collecting 11 samples at three stations (at both ends and in the middle of the reef) within a period of 12 hours.

Two additional SAPS samples were collected outside the tidal cycle. SAPS samples consisted of GF/F filters through which 200 - 400 liters of bottom water had passed. NIOZ further supplied 9 single vial sediment traps to TMBL, two of which were deployed for a few days. One was collected successfully with the ROV, but the other had disappeared under suspicious circumstances (trawling?). The National University of Galway continued measuring currents, temperature and turbidity in the water column at several stations. They used ADCP's stationed at the bottom and moorings with CTD's attached at regular distances above the bottom. TMBL furnished ships, expertise to recover and deploy equipment, and made additional underwater video recording and photo shots. CTD profiles (temperature, salinity, density, turbidity and oxygen) were obtained with the ROV.

Fig. 2 *Left: RV Lophelia. Middle: RV Nereus. Right: the Sperre ROV being deployed from RV Lophelia.*

2.2. Sampling equipment and methodology

In order to achieve the aims of this experiment a suite of hydrographic and biogeochemical methodologies have been employed. Specifically, long-term deployments of ADCP current meters (with a variety of sensors), and intensive sampling of organic matter and nutrients through the tidal cycle, up and down-flow sites were carried out in parallel with benthic lander deployments.

2.2.1. Ships and ROV

Extensive use was made of the ships and ROV of the Tjarno Marine Biological Laboratory. Two ships were available for the sampling of material, and for the deployment and recovery of equipment. The RV *Nereus* was used for deployment and recovery of the NIOZ landers and the NUIG moorings plus ADCP’s. The main task of the RV *Lophelia* was to deploy smaller items using the Remotely Operated Vehicle (SPERRE SubFighter7500 DC) and for visual inspection of the placement, deployment and recovery of the heavy instruments. The ROV was equipped with online video, photographic equipment, a flexible arm with manipulator, CTD and a sonar system to locate equipment in murky water (Fig. 2).

2.2.2. Benthic Landers

Near-bed currents, fluorescence and turbidity at both ends of the coral reef were measured during a 24-day deployment of the ALBEX benthic landers (Fig. 3). Currents were measured at 0.85 m above the bottom with a Nortek Aquadopp 3D acoustic current meter. Fluorescence and turbidity were measured at the same height with Seapoint fluorometric and Optical Backscatter sensors connected to a custom built data logging device. The landers also held a Technicap PPS3/4 sediment trap with 12 vial carousel (see 2.2.6). Finally each lander was equipped with a underwater video system composed of an analogous Sony-TR2000E handycam, timer and battery pack contained in a custom built aluminium housing and a Deep-Sea Power and Light underwater light.

Fig. 3 *Both NIOZ landers to be deployed from the RV Nereus.*

2.2.3. Moorings, ADCP and other current meters

To measure the physical-oceanographic data NUIG deployed a whole array of different equipment at different times and places, covering the whole extent of the reef and the full period from late March 2006 up to Sept. 2007. A scheme of these deployments is given in Table 1 and Fig. 5. The exact positions are indicated in Fig. 6. The following instruments were used (see also Fig. 4):

i) Low-frequency (300 kHz) Acoustic Doppler Current Profilers (ADCPs) to measure overlying water column dynamics
ii) high-frequency ADCPs for near seabed dynamics and estimates of re-suspended material
iii) deployment of Seabird-SBE37 Microcat sensors for temperature and salinity measurements in the benthic boundary layer
iv) bottom mounted Aanderaa Recording Current Meters (RCM9s), equipped with turbidity and Oxygen optodes for near seabed timeseries at 80 cm above the seabed (0.8 mab)
v) a short-term deployment of a Nortek Velocimeter for direct estimates of turbulent dissipation and Reynold stresses near the seabed (Fig 4).

Fig. 4 *Left: the velocimeter taking measurements at the coral reef. Middle: an upward looking ADCP. Right: Anderaa RCM9 current meter with optical oxygen sensor positioned at reef floor.*

Equipment Type	Manufacturer	Model	Deployment Name	Deployed	Recovered	Depth	Details
ADV	Nortek	Vector	Vector 2	19/07/2007	21/07/2007	115	3200 samples per second. 5 minute bursts.
Microcat Mooring	Seabird	Microcat SBE 37	NW Mooring	30/03/2006	27/04/2006	134	4 Microcats on a mooring sampling every 5 minutes
ADCP	Nortek	Aquadopp	H-Frequency ADCP 1	27/03/2006	31/03/2006	125	5 minutes sample intervals. 80 bins with .1m interval
ADCP	Nortek	Aquadopp	H-Frequency ADCP 2	31/03/2006	25/04/2006	110	30 minute sample intervals. 60 bins with .1m interval
Current Meter, Temp, O2	Aanderaa	RCM 9	RCM9 - 1 (984)	31/03/2006	25/04/2006	120	10 minute sample intervals
Current Meter, Temp, O2	Aanderaa	RCM 9	RCM9 -2 (986)	31/03/2006	25/04/2006	102	10 minute sample intervals
TS	Seabird	Microcat SBE 37	SE Mooring	30/03/2006	27/04/2006	148	4 Microcats on a mooring sampling every 5 minutes
ADCP	RDI	Workhorse 300 kHz	L-frequency ADCP 1	27/03/2006	27/04/2006	138	20 minute sample intervals. 50 bins with .1m interval
Current Meter, Temp, O2	Aanderaa	RCM 9	SE RCM9, long-term (986)	04/05/2006	13/06/2006	150	20 minute sample interval
ADCP	RDI	Workhorse 300 kHz	L-frequency ADCP 2, long-term	04/05/2006	02/10/2006	102	30 minute sample interval. 40 bins with 2 metre interval
Current Meter, Temp, O2	Aanderaa	RCM 9	NW RCM9, long-term (984)	04/05/2006	13/06/2006	132	20 minute sample interval
ADCP	RDI	Workhorse 300 kHz	L-Frequency ADCP 3	05/10/2006	29/04/2007	120	20 minute sample interval. 40 bins with 2 metre interval
TS	Seabird	Microcat SBE 37	Microcat Mooring 3	10/05/2006	26/04/2007	122	5 Microcats on a mooring sampling every 5 minutes

Table 1 *Table of physical oceanographic instruments deployed. Continued below*

Equipment Type	Manufacturer	Model	Deployment Name	Deployed	Recovered	Depth	Details
ADCP	Nortek	Aquadopp	HF ADCP	28/04/2007	30/04/2007	116	60 bins of interval .1m. Sampling every 5 minutes
Current Meter, Temp, O2	Aanderaa	RCM 9	RCM Mooring	19/04/2007	- in situ -	152	2 Microcat units and 1 RCM 9 unit. RCM sampling every 20 minutes
Current Meter, Temp, O2	Aanderaa	RCM 9	RCM 9, 984 2	29/04/2007	- in situ -	118	RCM sampling every 20 minutes
ADCP	RDI	Aquadopp	ADCP 4	30/04/2007	- in situ -	121	25 second intervals - 40, 2 metre bins
ADCP	Nortek	Aquadopp	HF ADCP 2	19/07/2007	21/07/2007	107	20 bins of interval .1m. Sampling every 5 minutes

Table 1 *continued*

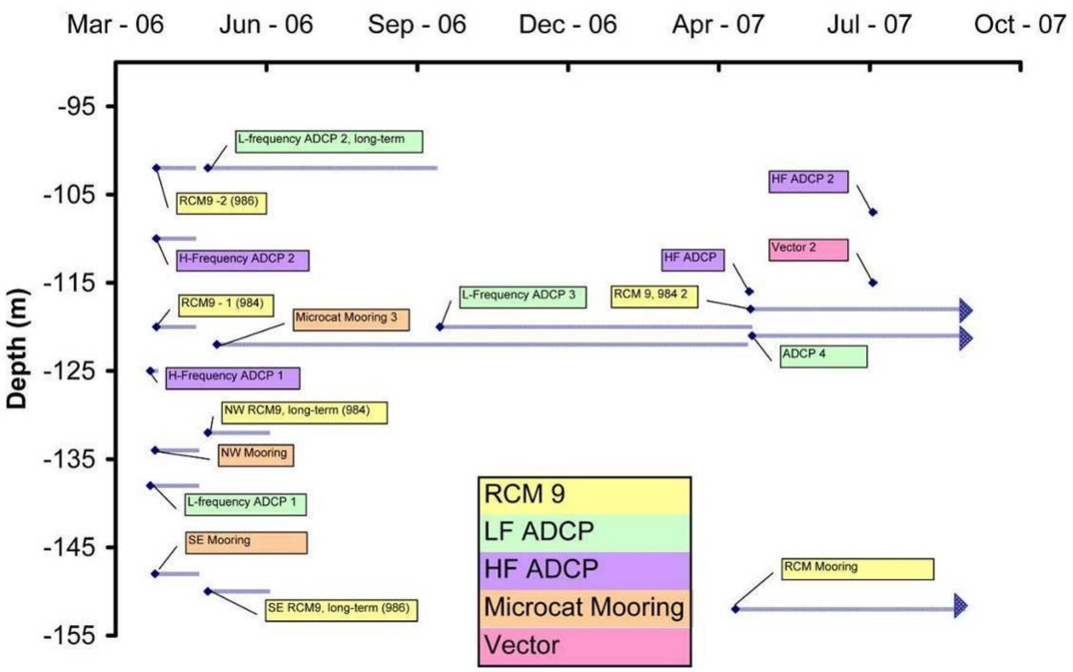

Fig. 5 *Timeline showing the times and durations of physical oceanographic deployments along with deployment depth.*

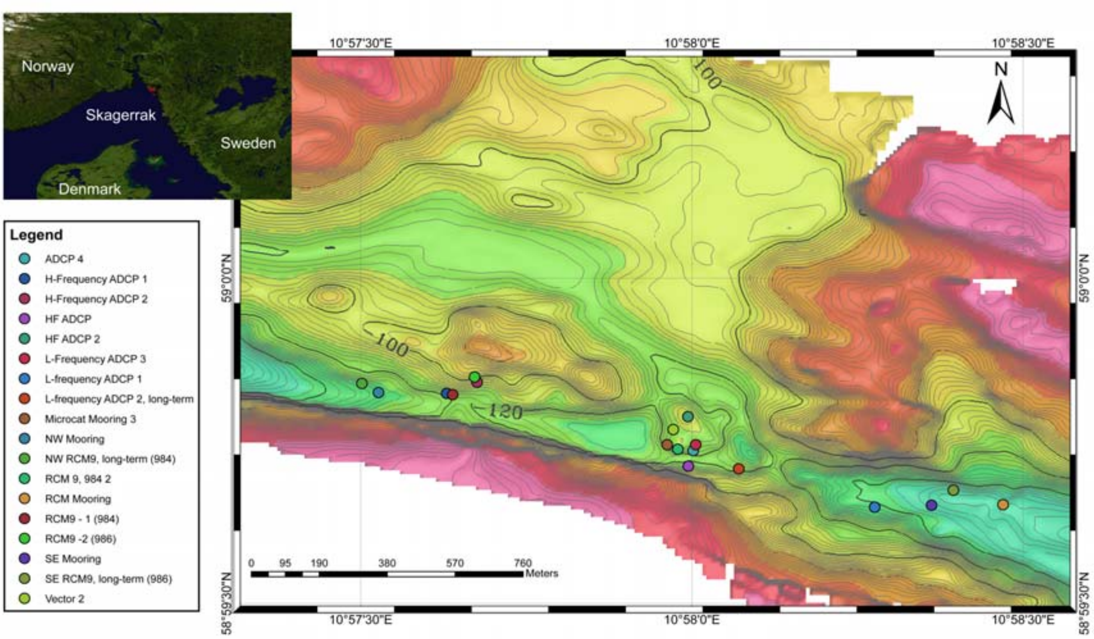

Fig. 6 *Deployment locations of physical oceanographic equipment*

2.2.4. Stand Alone Pumping Systems (SAPS) and suspended POM

Both NIOZ and University of Liverpool supplied Stand-Alone-Pump-Systems (Challenger-Oceanic) for sampling suspended POM (suspPOM) in the Kosterfjord experiment. In 2006 campaign the SAPS systems were simply fixed on steel wire and lowered to approx. 5 m above the bottom. The pumps were operated for 30 min (300-400 L of water) as close to the bottom as possible (< 10 mab) in March (30th, 31st), April (27th, 27th) 2006 on the same locations as the sediment traps. The SAPS filters (29 cm diam. GF/F) were freeze-dried on return to the laboratory. Analyses of organic carbon, nitrogen and lipid biomarkers were then performed on all freeze-dried samples. Organic carbon and nitrogen contents of all samples as well as the lipid biomarkers of near-bottom suspPOM from spring 2006 have been determined. Chlorophyll-*a* and phaeopigment concentrations of the suspPOM (SAPS) from Spring 2006 were also determined spectrophotometrically.

To save handling time and make more measurements possible per tidal cycle, and to get samples closer and at a fixed position above the bottom (1 m), NIOZ supplied adapted SAPS for the 2007 campaign. New electronic circuits, external communication ports and batteries were installed, and the SAPS were mounted in a bottom frame (Fig. 7). This set-up enabled us to collect 11 x 3 samples in one tidal cycle (see above). Lipid analyses of suspPOM from 2007 are in progress.

2.2.5. Niskin samples and suspended POM

Additional samples for susPOM samples were taken with a horizontal Niskin sampler. The settling velocities and resuspension velocities of the BBL particulate matter were measured in the lab as described in Thomsen (1998). The total hydrolysable amino acids (THAA) and hexosamines in the POM were quantified by reverse-phase HPLC on a HPLC Shimatzu system with fluorescent detector. Dauwe's degradation indices (DI) were calculated following Dauwe (1999). Also the organic carbon and nitrogen contents are measured.

Fig. 7 *Two NIOZ-SAPS systems on board RV Nereus fitted in a bottom frame as used during the spring 2007 campaign. The main body (batteries and pump) of the SAPS was placed horizontally instead of vertically while the filter unit was kept in its original (horizontal) position.*

2.2.6. Sediment traps and sinking POM

Near-bottom sediment trap material, which represents the sinking component of POM (sinkPOM), was collected with a Technicap PPS 4/3 mounted on the NIOZ landers at both ends of the “living” reef (Fig. 1). The trap opening was about 2.5 m above the seafloor and the 12 vials were exposed in sequence for 2 days each, and so covering the period 1st to 23rd April 2006. Mercury chloride was used to preserve the contents of the trap. The samples were split in two with a Folsom plankton splitter, and filtered over CA (Cellulose acetate as well as muffled GF/F (0.7µm) filters. These were than freeze-dried and weighed for mass-flux prior to further analyses. Lipid analyses of sinkPOM (2006) are in progress.

In 2007 a trial deployment of 2 single vial sediment traps was made with the ROV (Fig. 8). These conical traps have a single vial that can be closed in-situ with the ROV’s manipulator. Two of the 9 available sediment traps were deployed, but only one sample was retrieved. The other trap had disappeared.

Fig. 8 *The single-vial sediment trap at position between the corals of the Tisler Reef.*

2.2.7. Video-cameras

A video-lander composed of a Sony HDV camera (Sony HDR-HC1E) in Aanderaa housing with a time-lapse controller (MARIS II) was positioned ~1m away from a *Lophelia pertusa* coral patch with the ROV (Fig. 9). Recording of 1 minute were made every 90 minutes. Video data were analyzed with Adobe Premiere 1.5, Image J 1.36b and Adobe Photoshop CS. The change in polyp activity was quantified and related to changes in current velocities, as measured by a current meter in a close proximity to the video-lander. The relation between current velocity changes and percentage of active coral polyps was statistically evaluated.

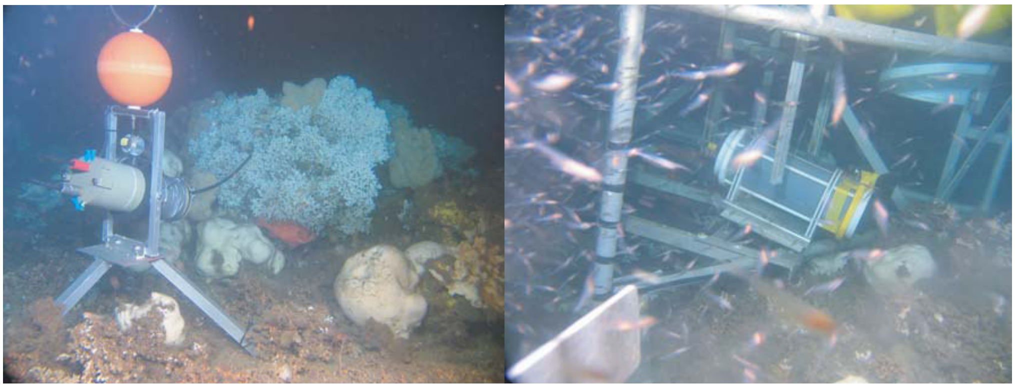

Fig. 9 *Left: video-lander with HD videocamera directed towards a coral colony for detailed monitoring of polyp behavior. Right: analog time-lapse camera attached to one of the NIOZ landers for a visual backup on data of currents and particles. Note the abundance of Euphausids (right).*

The NIOZ-landers were provided with analog time-lapse video cameras for a visual inspection of the currents (direction and speed) and for the amount and nature of the particles in the water column (Fig. 9).

3. RESULTS

3.1. Particulate organic matter (POM) (Kostas Kiriakoulakis, George Wolff)

3.1.1. Sinking POM (Benthic lander sediment traps) – Spring 2006

Sinking POC and PN values were invariably low on the first half of April (1-13/04/06) but increased (>×2) towards the end of the month (Fig. 10). This is probably associated with the onset of the phytoplankton bloom and its export to the sea floor. During the 1st half of April sinkPOC contents were slightly higher on the SE edge, but this was not statistically significant; in contrast the sinkPN values were significantly higher (albeit only slightly) on the SE edge. In addition molar C/N ratios were significantly higher on the NW edge in early April (Fig. 11), implying the sinkPOM was more degraded there. Although conclusive comments are premature at this point given the complexity of the hydrographic regime, these observations may be related to the preferential uptake of N-containing labile organic compounds (e.g. proteins, amino acids), across the reef. This is consistent with the residual water flow to the NW during this period. In the 2nd half of the month (15-23rd April 2006) the high influx of organic matter to the system probably "swamps" smaller scale (reef) effects. In addition the introduction of cold melt water towards the end of the month complicates water flow thus rendering interpretation of such observations difficult.

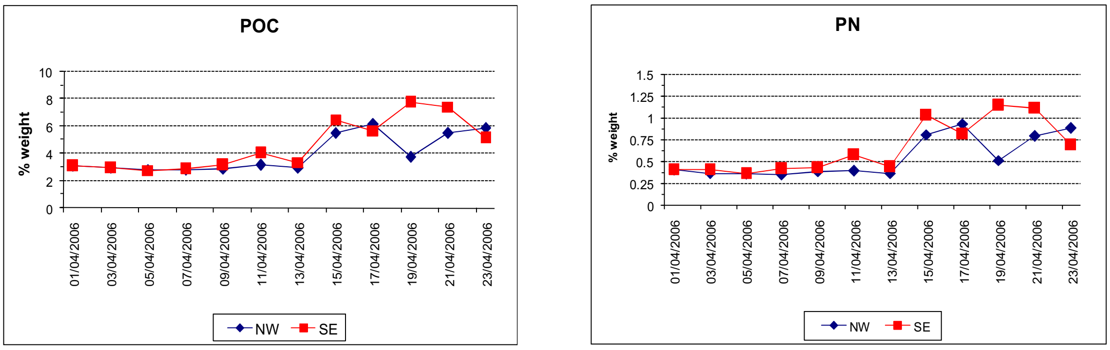

Fig. 10 *POC and PN as % weight of sediment trap material. NW and SE refer to the North Western and South Eastern edges of the "living" reef.*

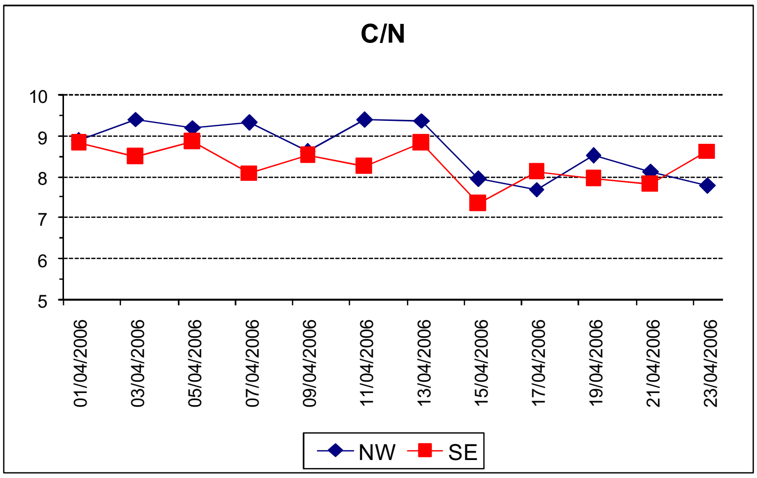

Fig. 11 *Molar C/N ratios of sinking POM. NW and SE refer to the North Western and South Eastern edges of the "living" reef.*

3.1.2. Suspended POM (SAPS) – Spring 2006

In Spring 2006 the near-bottom water (< 10 mab) at the SE edge of the Tisler Reef was frequently sampled ca. two hours before the NW edge except on 30th of April 2006, when the two edges were sampled concurrently. This latter approach was adopted in an attempt to trace the movement of suspended particles over the reef after previous observations indicated that the residual water flow was to the NW. However, parallel current measurements showed that the water flow was more complex and was, in addition, affected by incursions of cold melt water (late April 2006) that induced flow reversals. On 31st March 2006, suspended POM from the middle of the reef was also collected at the end of the day. It is not surprising that most of the parameters measured at the reef edges did not show any consistent trends (Figs 12 and 13).

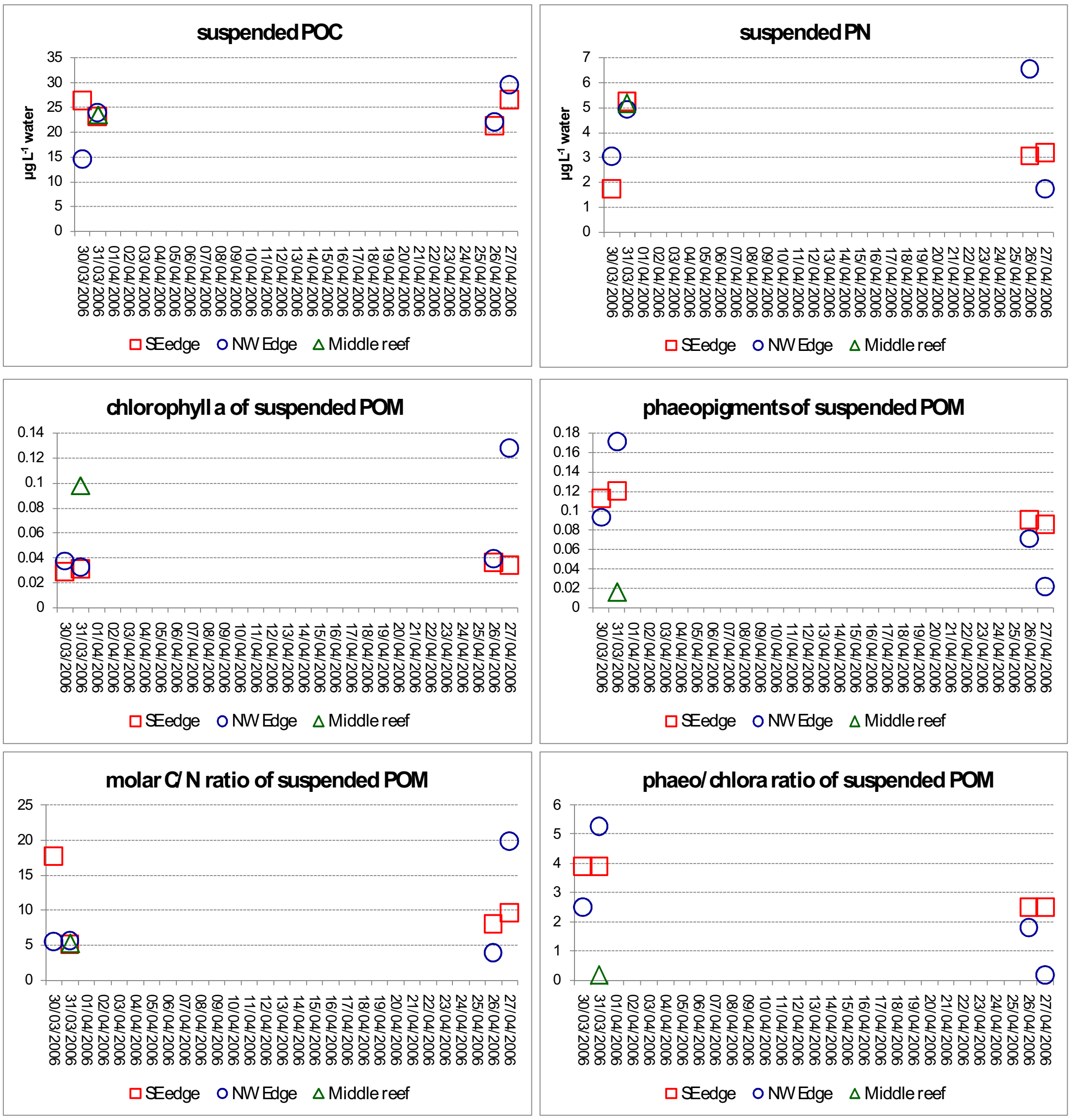

Fig. 12 *Near bottom (<10 mab) POC, PN chlorophyll-a and phaeopigment concentrations and molar C/N and phaeopigment/chlorophyll a ratios of suspended POM collected by SAPS in late March and April 2006 at the NW and SE edge of Tisler Reef. The middle of the reef was also sampled in 31 March 2006.*

although notably the middle of the reef had elevated chlorophyll-a concentrations but lower phaeopigment/chlorophyll-a ratio and lipid and essential fatty acids (EFA) concentrations (Fig.12, 13). The highest concentrations of bulk OM and lipids were measured close to the bottom in 27th of April 2006; this may be related to the sinking of the spring bloom.

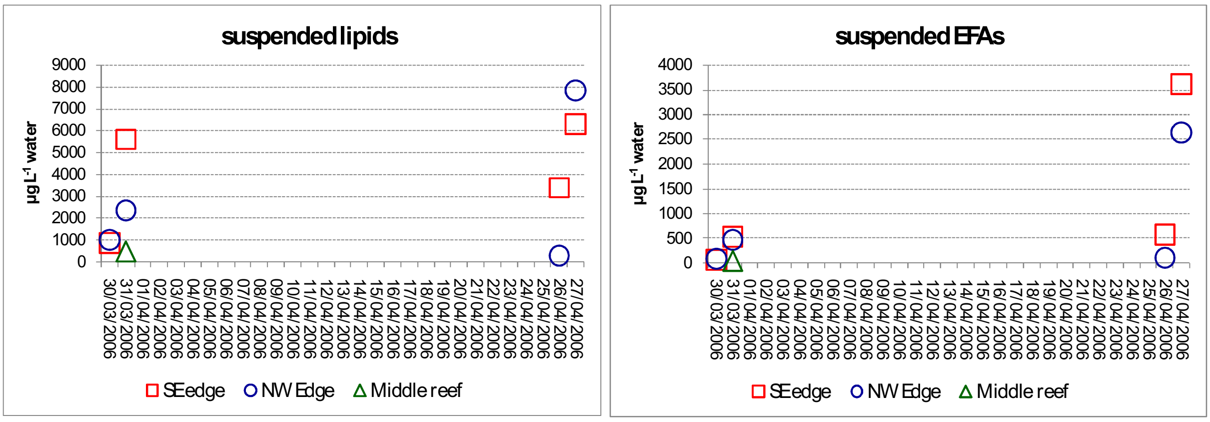

Fig. 13 *Near bottom (<10 mab) total lipid and Essential Fatty Acid (EFA) concentrations of suspended POM (SAPS) collected in late March and April 2006 at the two edges (NW and SE) of Tisler Reef. The middle of the reef was also sampled in 31 March 2006.*

3.1.3. Suspended POM (SAPS) – Spring 2007

In Spring 2007, sampling was carried out on 29th of April through the course of the day alternately at the same locations as in 2006 (i.e. SE, NW edges and middle of "living" reef) using the modified NIOZ-SAPS (Fig. 7). The proximity of the pump to the sea floor (i.e. ~1 mab) enabled closer monitoring of the water characteristics that may be affected by the corals. Initial observations show a clear increasing trend of suspended POC concentrations at the SE edge and the middle of the reef through the course of the day but this is not observed at the NW edge (Fig. 14). Suspended PN concentrations on the other hand generally decrease at the SE edge and the middle of the reef (except at 19:00h) during the day, whereas they seem to increase at the NW edge (Fig. 14). In most cases the middle of the reef seems to have lower susPOC and susPN concentrations than the edges when sampled consecutively. As for susPOC concentrations, molar C/N ratios increase during the day at the SE edge and middle of the reef, they decrease at the NW edge (Fig. 14). A common feature of these observations is that the SE edge and middle of the reef seem to "behave" in a similar manner in contrast to the NW edge. At this stage it is premature to draw any conclusions but this may be due to the different hydrodynamic regime at the two edges of the reef and may be related to the physio-biochemical impact of the reef on its immediate environment.

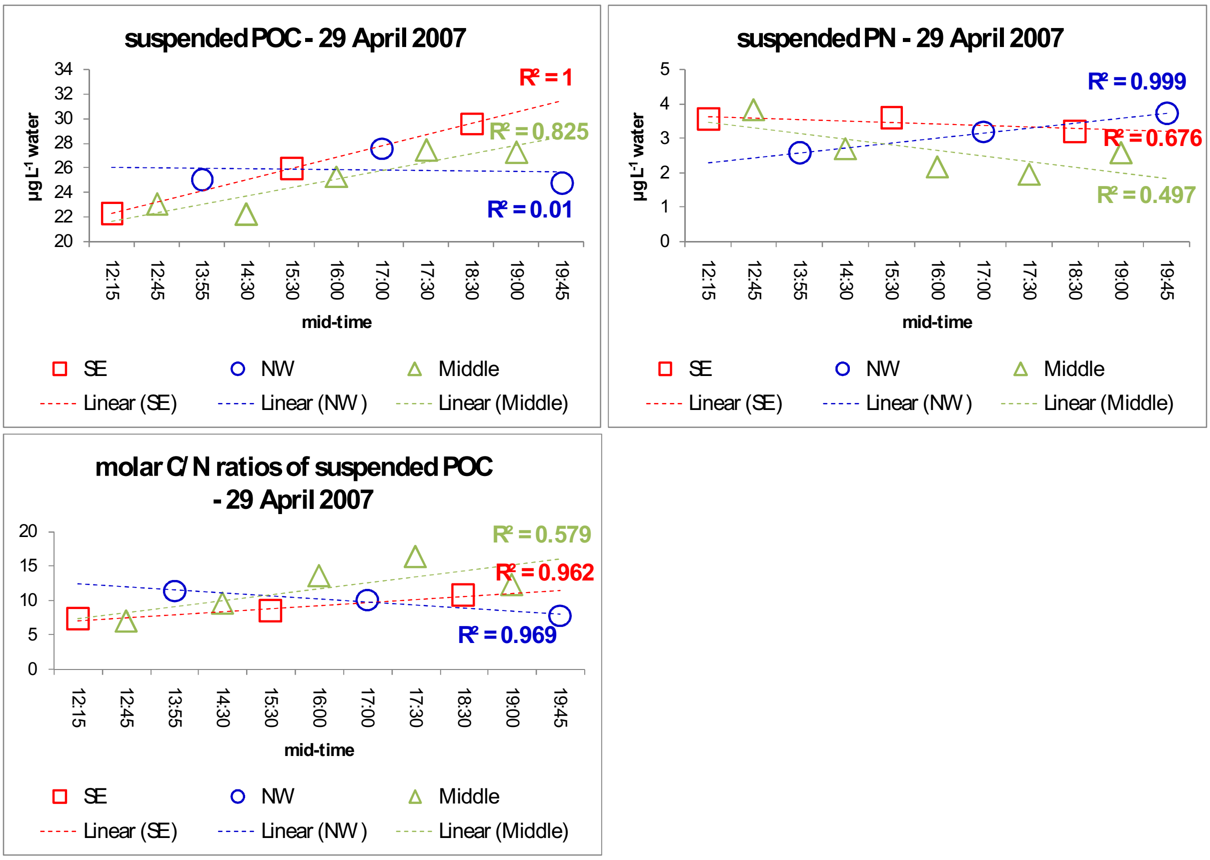

Fig. 14 *Near bottom (1 mab) POC and PN concentrations and molar C/N ratios of suspended POM (SAPS) collected in 29th of April 2007 through the course 29 April 2007 at the NW and SE edge and the middle of the "living" Tisler Reef. X axis shows mid-pumping times. Dotted lines are linear trend lines (created using Microsoft Excel 2007) for each location and R^2 values for each location are also displayed.*

3.2. Video analyses (Dimitar Berov, Laurenz Thomsen)

3.2.1.Biodiversity and macrofauna

14 taxa of animals from 8 phyla were identified (Fig.15), most abundant of which were the epifaunal squat lobster *Munidopsis serricornis* (6.7 ind. per m^2 of *Lophelia pertusa*). *M. serricornis* was observed entering in symbiotic relations with *Lophelia* – feeding on particles attached to the coral framework, hiding in cavities between branches.

Fig. 15 *Macrofauna and megafauna species filmed by the HDV lander at the Lophelia coral patch (a=Lithodes maja, b=Munida rugosa, c=Munidopsis serricornis, d=unidentified shrimp species, e= Trisopterus luscus). Scale bar is 50 mm long.*

3.2.2. Feeding behaviour and relation to current velocities

A clear relation between current velocities and coral polyp activities was established (Fig.16, 17). These results confirm that relatively high current velocities and increased flux of suspended material in the BBL are necessary for *Lophelia*'s occurence and are factors controlling the feeding behaviour of the coral. Lab flume studies with live *Lophelia* corals from the Darwin mounds (Arthur Palacz, 2006) have shown a similar relation between currents and polyp activities. The maxima of polyp activities in the two studies are quite different, i.e. 80% activity at 12-15 cm/s in our study opposed to 80% activity at ~30 cm/s in the flume study by Palacz. The difference of polyp activity implies that *Lophelia* corals at different sites are adapted to the local current regimes and have unique optimal ranges of current velocities and particle fluxes at which they are most active.

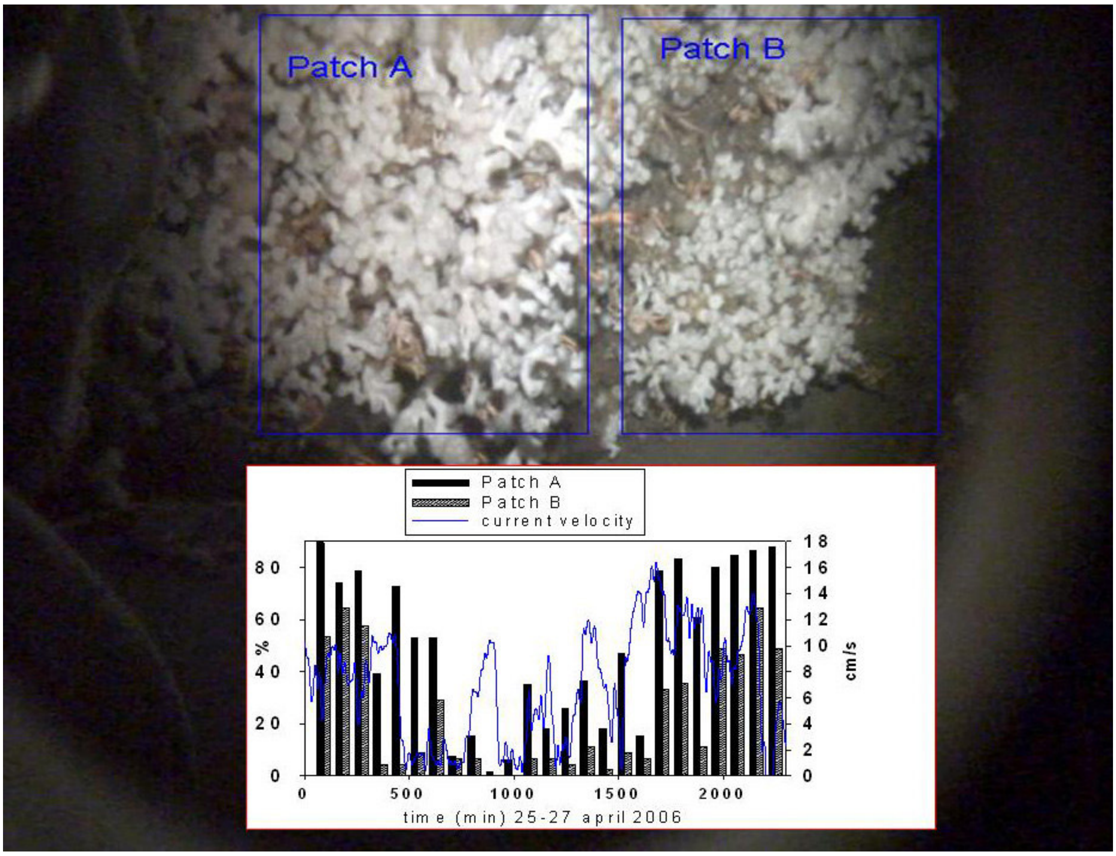

Fig. 16 *Comparison of polyp activities of a current exposed coral patch (patch A) and a patch not exposed to currents (patch B). Percentage of active coral polyps is plotted versus the current velocity (blue line). Patch A is significantly more active than patch B , which could de attributed to the higher particle flux due to better exposure to the passing currents.*

3.2.3. sPOM (Niskin bottle) as food source

Results from the resuspension velocity measurements of the sPOM collected with a Niskin bottle (see sections 2.3) show that the current velocities recorded at the study site are sufficient to resuspend the available sPOM and create a flux towards the corals.

Based on the amino acid composition data from the sPOM samples (samples provided by K. Kiriakoulakis), their degradation indexes (DI) were calculated. The DI's of sPOM from bottom water varied between -0.18 and 0.49, which are values typical for relatively undegraded coastal and ocean margin POM (Dauwe, 1999) and slightly higher than values typical for surface sediments from the Skagerrak area (Dauwe & Middelburg, 1998). The relative freshness and high protein content of the sampled sPOM indicates that it is a possible food source that can provide nutrition to *Lophelia*. Additional information on the origin of the organic matter in the sPOM will come from the C/N elemental analysis.

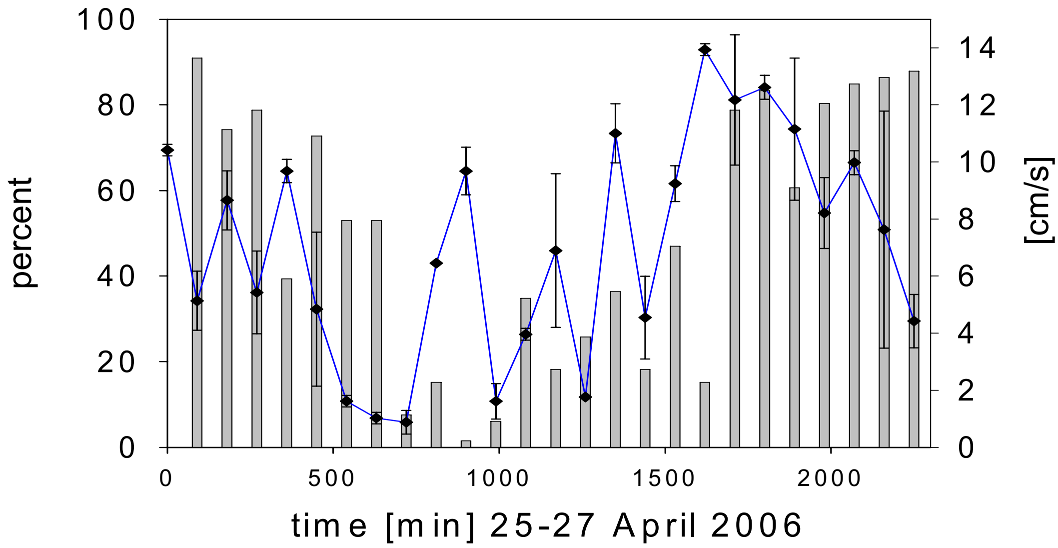

Fig.17 *Vertical bars: percentage of active Lophelia pertusa polyps in the current exposed coral patch A. Line connecting points: 20-minutes average current velocity prior to video sequence (line). Spearman's rank correlation test shows a positive correlation of the two factors (p=0,478, significance level 0.016); Kendall's rho test also reveals a positive correlation (p= 0.326, significance level 0.023)*

3.3. Benthic Lander measurements (Gerard Duineveld, Marc Lavaleye).

3.3.1. Near bottom currents

The average near-bottom current speed at the NW station was about twice as high (~0.16 m/sec) as at the SE station (~ 0.06 $m.s^{-1}$) (Fig. 18). Maximum current speed at the NW station was between 0.3-0.45 $m.s^{-1}$ while at the SE station maxima seldom reached above 0.20 m/sec. Remarkable are periods with an almost zero current speed at the NW station i.e. around 16 April and during an almost 3 day period after 22 April. Similar relaxations can be seen observed in the record from the SE station but because of the weaker currents, they are less prominent. Another striking contrast between the stations is the while at the SE end of the reef the current speed increases at 23 April to the highest values of the period, at the NW station the speed drops almost zero.

A surprising observation was that during the observation period the current direction showed no (semi)diurnal tidal change. Instead currents in the period 30 March - 22 April were almost unidirectional towards the NW (Fig 19). This was true for both stations. The few instances that the direction changed coincided with a drop in current speed to almost zero (cf. Fig.18, 19). The fact that currents were almost unidirectional in this period was very fortunate from the perspective of the Tisler experiments' aim i.e. measuring particle uptake by the reef. After the 22 April there was a distinct flow reversal at the NW station coinciding with cooling of the bottom water (see below). At the SE station more frequent erratic but short-lasting reversals were observed with a more persistent reversal at the end of the measurement period (Fig. 19, 20).

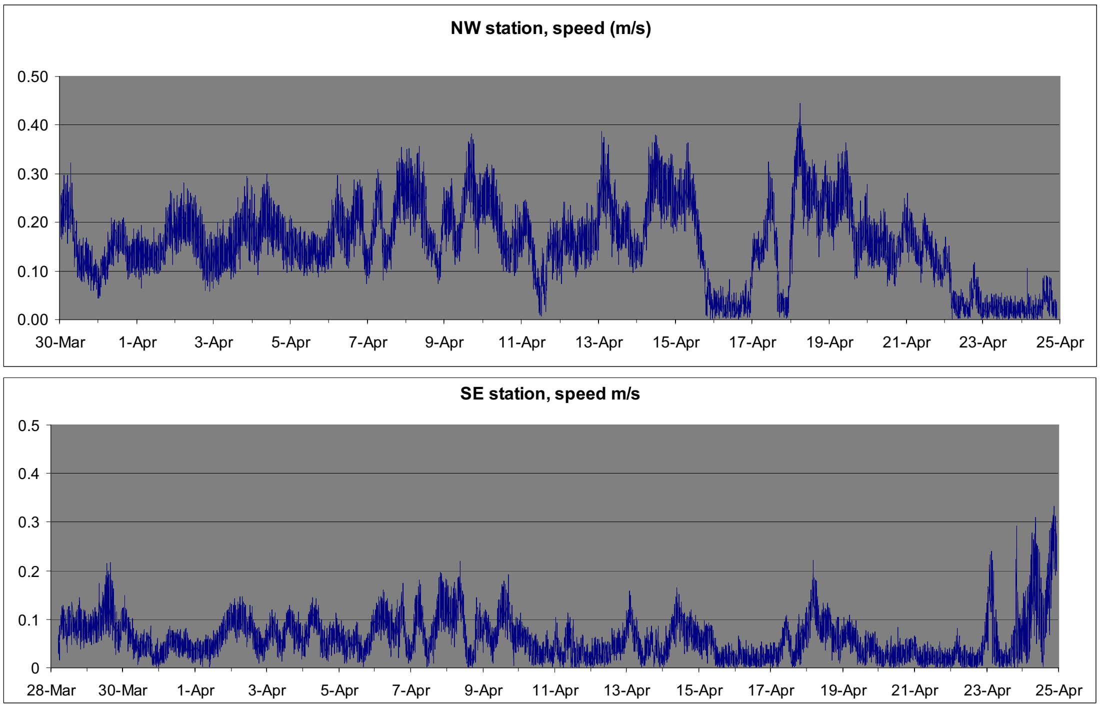

Fig. 18 *The current speed at 0.85 m above the bottom at the NW and SE station.*

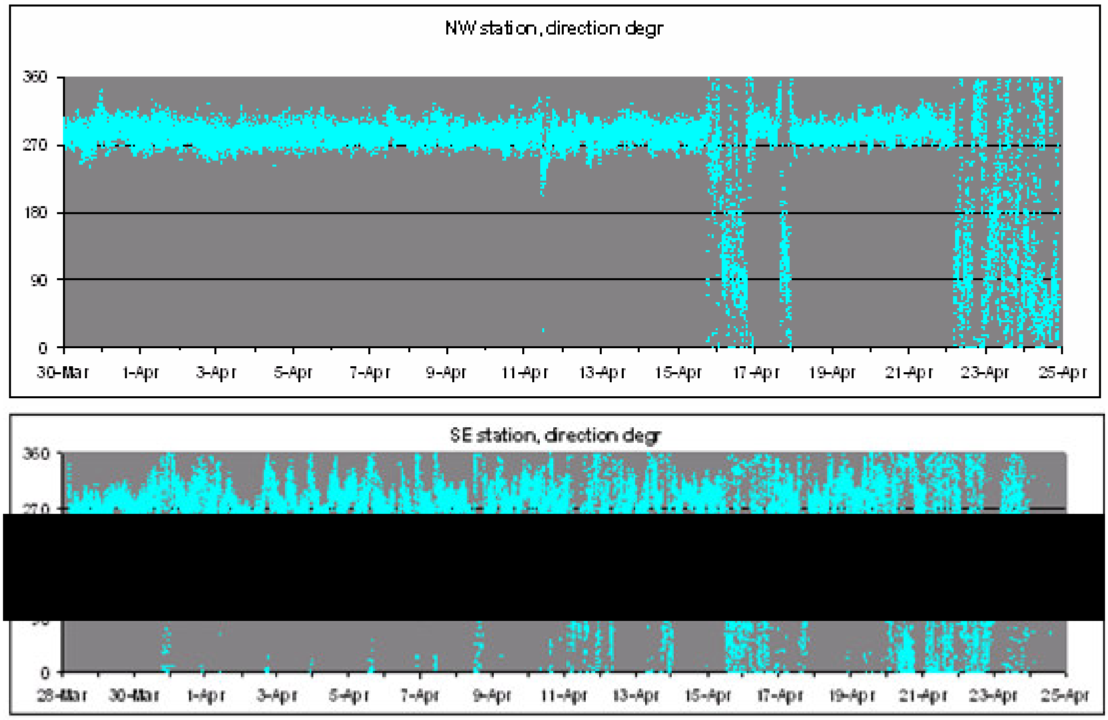

Fig. 19 *Current directions at 0.85 m above the bottom at the NW and SE station.*

The progressive vector plots from the NW station shows that during the whole period displacement of a particle would be in a NW direction (Fig. 20). The current reversal after 22 April does not affect displacement so much since current speed was very low. Particle displacement at the SE station illustrates the effect of combined reversal and increase of currents at the end of the deployment. The average displacement over the entire period was 16 $cm.s^{-1}$ at the NW station and only 4 $cm.s^{-1}$ at the SE edge (see also section 3.4.1.). This implies that it would take a particle starting at the SE edge and drifting in NW direction less than 8 hrs to cover the length of the 'living' reef area (1200 m). This estimate obviously assumes a uniform flow field. This is not the case as is demonstrated by differences in currents at the SE and NW edges. Clearly residence time of particles (e.g. deposition-resuspension cycles) is a key variable when estimating reef uptake by in-output measurements.

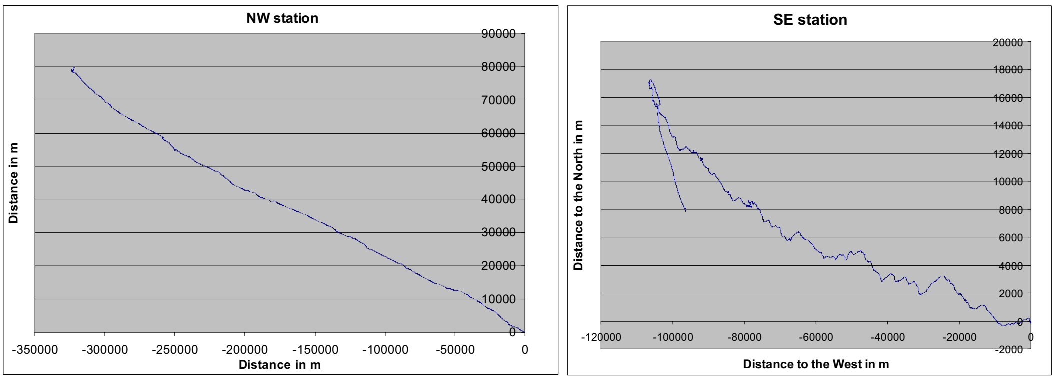

Fig. 20. *Progressive vector plots over a period of 24 days during the March-April 2006 period.*

Temperature measured by the Aquadopp current meters, showed a steady signal during the first 8 days followed by pulses of cold water (Fig. 21). These pulses became more intense towards the end of the observation period leading to overall lower temperatures near the bottom at both stations. This drop in temperature was probably caused by the increasing input of fresh melt water from land or fjord. For a discussion of the consequences of this input of melt water on the water mass over the reef and the current direction see section 3.4.1.

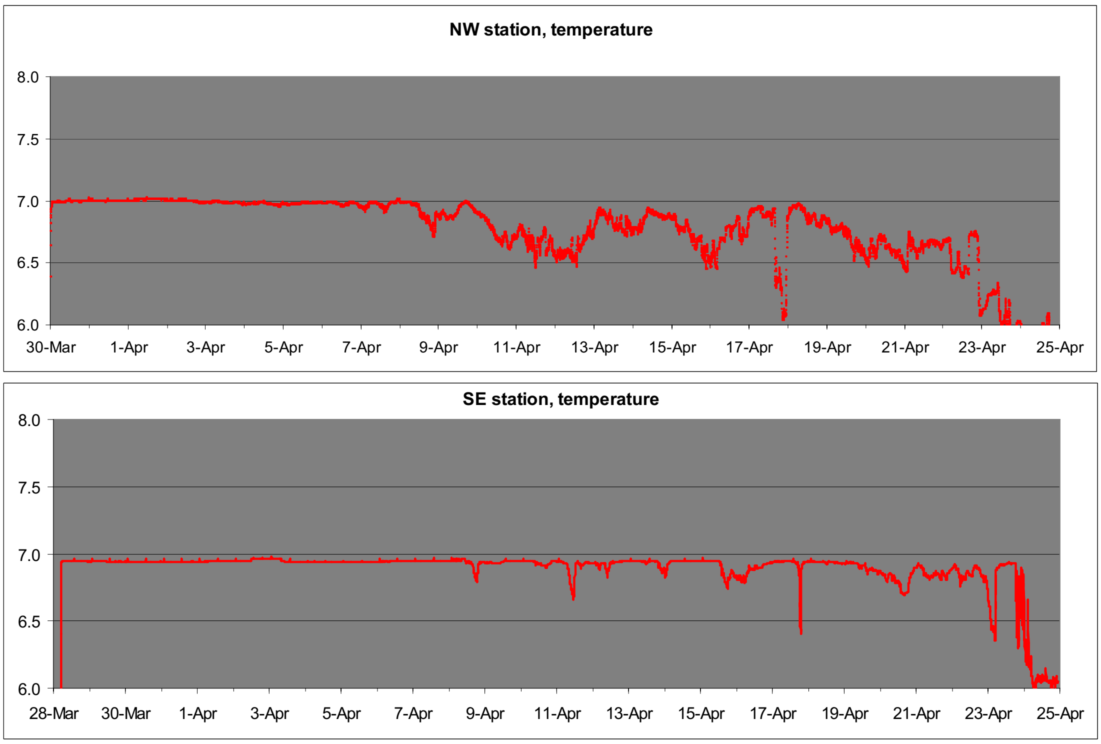

Fig. 21 *The water temperature at 1 m above the bottom at the NW and SE lander station.*

3.3.2. Near bottom fluorescence

Water column fluorescence measured at 0.85 m above the seafloor showed that the spring bloom in 2006 started with a small peak on 11 April followed by a major peak building up from 15 April onwards. Both stations yielded more or less the same pattern, but the SE station showed a stronger signal (Fig. 22). Integration of the records in Fig. 22 showed that the amount of fluorescence at the SE station was three times higher than at the NW station. Since the currents were almost unidirectional, this difference in total fluorescence could point at retention of phytodetritus by the reef. However, as fluorescence peaks appear to correspond with relaxation of the flow (Fig. 18) and probably represent sinking particles, the records in Fig. 22 cannot be taken as water column concentrations. The difference we measured between fluorescence at NW and SE strongly reflects the different frequencies of relaxation events (see Fig. 19).

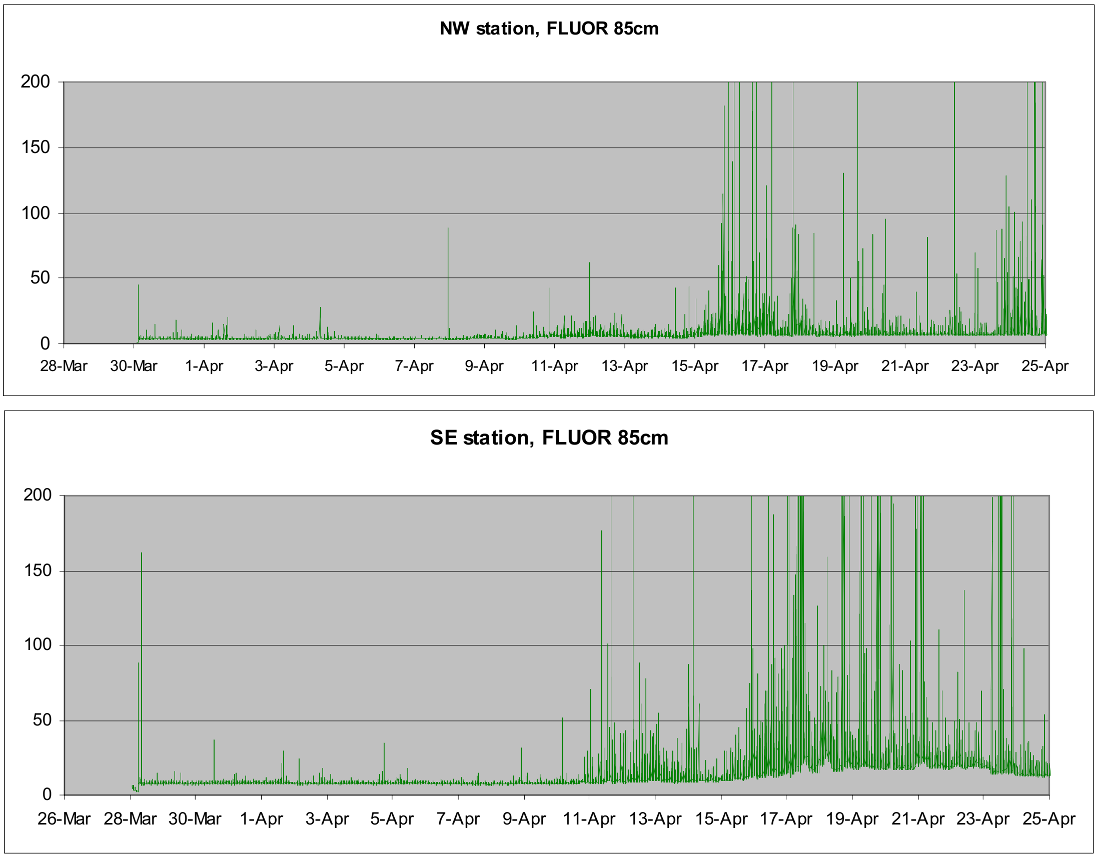

Fig. 22 *Fluorescence measured at 0.85 meter above the bottom at the NW and SE station.*

3.3.3. Near bottom turbidity

The records of the Optical Backscatter sensors from the 2 stations were different (Fig. 23). The signal at the NW station was low and smooth until small peaks occurred at 16 April. After the peaks the signal fell back to its base level. From 23 April onwards there was a more or less steady increase in the OBS signal to high levels at the end of the measuring period. At the SE station the signal was generally more spiky. Around 17 April several stronger peaks occurred but the signal returned to its base line after 24 April. Acknowledging the fact that OBS sensors are notoriously difficult to calibrate, integration of the signals showed that turbidity at the SE station was at least twice as high as at the NW station. There is no clear-cut relationship between the overall records of current speed and OBS at either station (cf. Fig 18, 23) implying that local resuspension does not contribute importantly to the water column turbidity at the reef edges. The OBS pattern instead seems partially linked to the presence of sinking phytodetrital material as peaks of OBS and fluorescence overlap. Probably a part of the OBS signal is due to flocs or particles containing fluorescent algal material. For instance, at the NW station the OBS and fluorescence peaks at 17 and 24 April coincide with relaxation of the current (Fig. 19) and enhanced fluxes in the sediment trap mounted on the benthic landers. However, in the main reef area local resuspension has been observed by ADCP (see section 3.4.3. and Fig. 29) and could represent a source of food for corals.

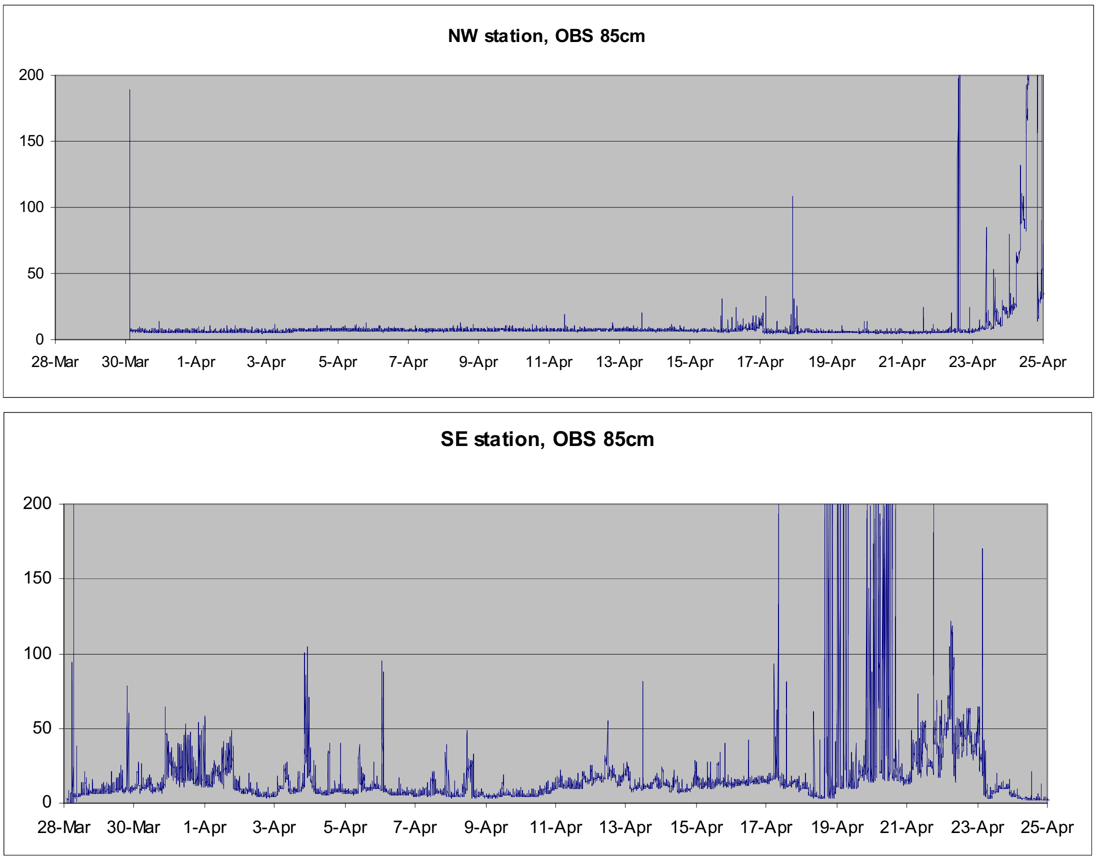

Fig. 23 *Optical Backscatter measured at 0.85 m above bottom at the NW and SE stations.*

The link between current strength and peaks in OBS, fluorescence and mass flux in the sediment trap mounted on the bottom lander, illustrates the limitation of measurements at a single height in the water column. More insight into the particle flow and retention across the dynamic shallow reef can be obtained with better coverage of the particle dynamics and concentrations in the whole water column.

3.4. Physical oceanographic measurements (Damien Guihen, Martin White).

3.4.1. General Flow

Tidal currents are small, with semi-diurnal tidal amplitudes of between 5-10 cm s^{-1}, representing neap and spring tide values respectively. These values rarely exceeded the mean (tidally averaged) residual flow strengths (Fig. 24). Tidally averaged residual currents could reach up to 30 cm s^{-1} and flow, predominantly across the sill, might be in either direction (NW towards the open Skagerak, or SE towards the inner Kosterfiord (Fig. 24). These residual flows were generally density driven, or through wind driven sea level height differences across the sill region. The results from the lower frequency ADCPs located near the sill indicated that the currents were amplified in the vicinity of the shallowest part of the sill region.

The weak tidal amplitudes have an implication for the residence time of water parcels over the reef. Tidal amplitudes of 5-10 $cm.s^{-1}$ result in horizontal tidal period excursions of between 800-1600 m respectively. Therefore for tidal currents alone, water will not be moved over greater distances than the reef extent itself. The addition of residual currents, however, can move water uni-directionally over the reef. A residual current of 3.5 $cm.s^{-1}$ will advect a water parcel by 1.6 km horizontally in the time of 1 semi-diurnal period (12.421 hrs).

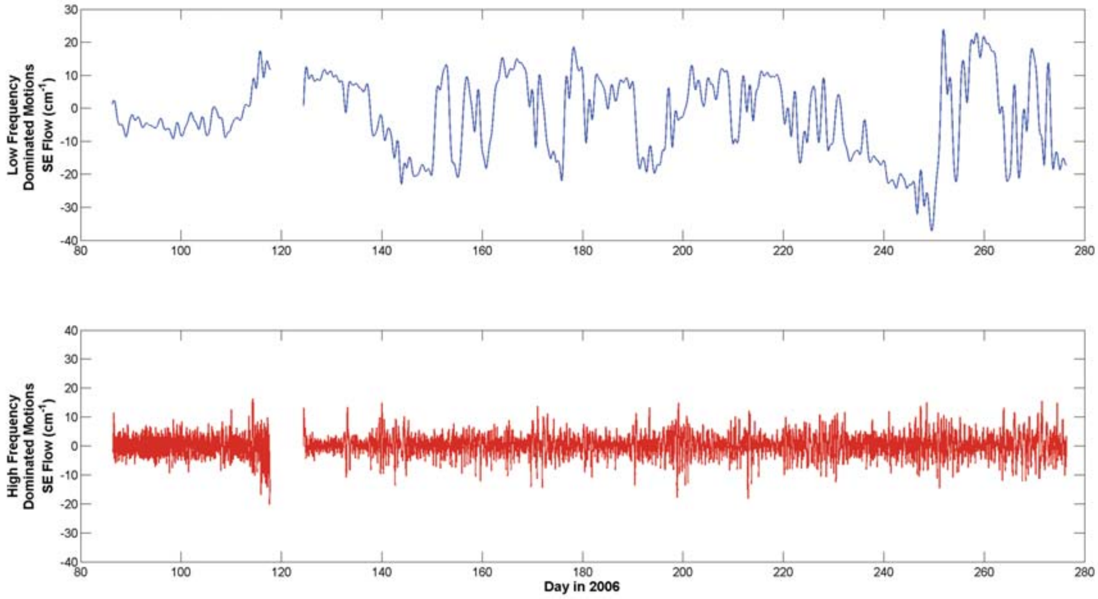

Fig. 24 *Time series of SE directed velocity component at 89 m depth measured at the sill by the 300 kHz ADCP, April-October 2006. Currents have been filtered with a 27hr filter to split the currents into low (blue, mostly tidally dominated) and high (red) frequency motions. The gap in the data represents the turnaround time of the equipment.*

An example of the importance of density forcing occurred during the spring 2006 field campaign, when measurements were made at time periods of contrasting flow dynamics (Fig. 25, 26). At the start of the measurements (end March), flow was relatively weak and directed to the northwest (Fig. 25). During the 24th of April, however, flow reversed to the southeast and increased in magnitude significantly, particularly close to the seabed. Analysis of the temperature and salinity data from the two CTD Microcat moorings deployed during this time (Fig. 26), suggested that during April, the bottom water freshened and cooled, resulting in a reduction in the water density at the sill. After the 24th April, a rapid change to colder and more saline water ensued associated with the reverse in currents. It is inferred, therefore, that the reverse in flow was a result of the reduction in density at the sill allowing deep water from the open Skagerrak to flow back into the inner Kosterfjord region after the period of flow to the NW out of the Kosterfjord.

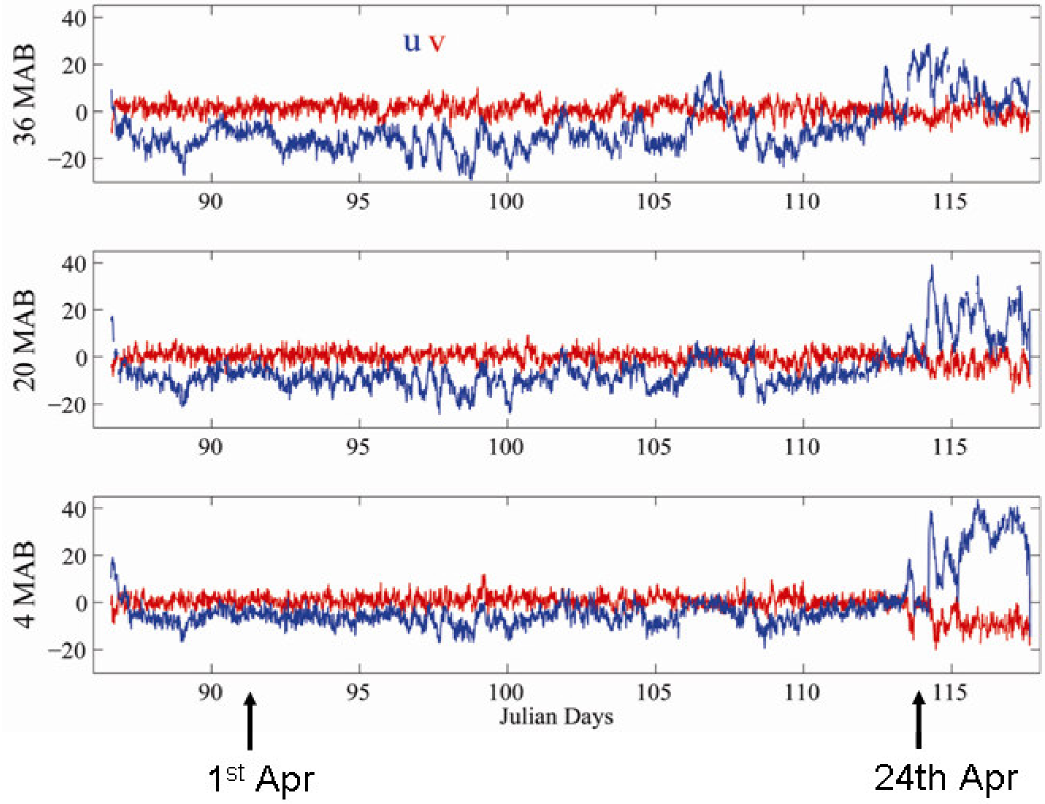

Fig. 25 *Time series of east (blue) and north (red) velocity components measured by the 300 kHz ADCP deployed to the SE of the sill region at (top) 36m, (middle) 20m and (bottom) 4m above the seabed.*

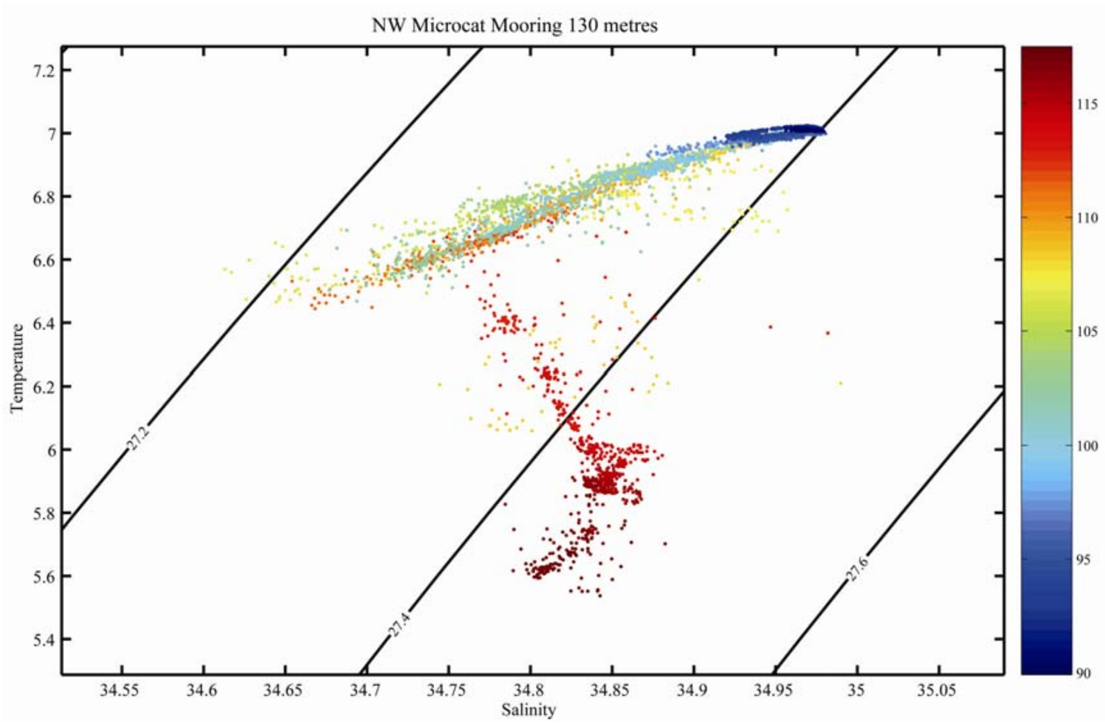

Fig. 26 *Temperature-salinity diagram for the measurements made at the NW end of the Tisler reef at 130 m water depth, 31/3/06-28/4/06. Density contours are shown in black and individual T-S points are colour coded by time (Julian Day 2006, indicated by the colour bar).*

3.4.2. Near Seabed Currents

Near seabed currents have been measured at point measurements of currents together with turbidity and O_2 as well as high vertical resolution ADCP measurements in the lower 4 m of the water column (see Fig.6, Table1). In Fig. 27 the spring 2006 time series from the RCM9s are shown located within, but towards the NW fringe of the reef, which span both combined field surveys. The currents at 80 cm above the seabed show the same trend as those indicated in Fig. 25 with the weak, relatively constant NW flow for the majority of April followed by the stronger SE return flow commencing on the 24th April. Time series of turbidity and O_2 indicated different values for both parameters measured by the two instruments due to the vertical difference in deployment depths. Both instruments do show similar trends, however. Turbidity shows a gradual rise during early April, followed by a general decrease in value although this trend is punctuated with short periods of high turbidity values. These start around the 15th April (JD 105), with the largest peak in turbidity occurring on the 17th April (JD 107), consistent with the NIOZ lander measurements (Fig. 23). Furthermore, the largest reduction in turbidity on the 17th coincides with the large sediment trap deposition in the NW benthic lander sediment trap at that time. Oxygen data show some variability throughout the measurement duration with low oxygen values measured which largely correspond to the incidences of increased turbidity, possibly indicating some response to the local fall-out of organic material after the spring bloom. High O_2 values at the end of the measurements were associated with the reverse in the main residual flow direction.

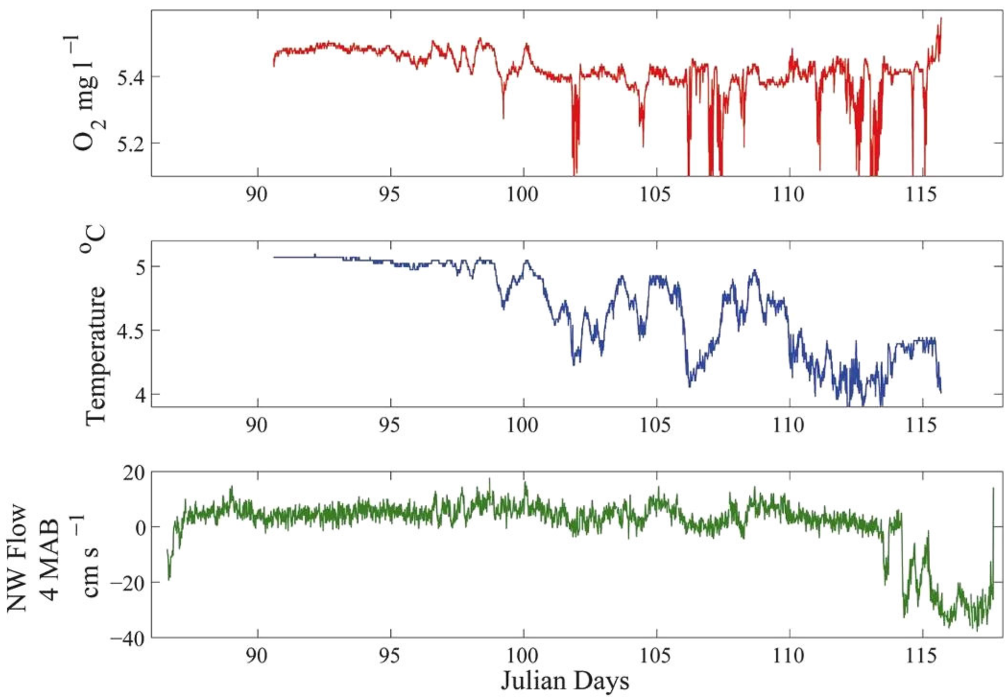

Fig. 27 *Time series of the summer NW RCM9 data showing O_2, Temperature and NW directed flow.*

Figure 28 shows the tidally averaged oxygen data against tidally averaged SE directed residual current for the measurements made during summer 2006 by the two RCM9s located at either end of the reef. The figure showed that the lowest oxygen values were generally associated with the lowest residual flow strengths, but one must also recall that these values were perhaps also associated with other processes such as the spring bloom fall-out. In general, however, oxygen values increased with residual flow strength in either direction across the sill (SE or NW). This indicated a gradient in oxygen with distance from the reef, with higher O_2 values further from the reef. On closer inspection, this oxygen gradient, or decrease in O_2 with small residual flow, was larger at the lowest flow speeds (< 3.5 cm s^{-1}). Recalling that this value of residual flow is the threshold for currents to flush the reef within one tidal cycle, this may imply that for low residual flows an enhanced O_2 reduction was measured. Spring data also showed similar patterns to those described for the summer measurements.

The difference in the two oxygen to residual flow strength gradients for currents > and < than 3.5 cm s^{-1}, may represent enhanced oxygen consumption due to reef community respiration acting on a water body that has a long residence time over the reef. A simple calculation based on the oxygen reduction of 0.1-0.2 mg/l per tidal cycle yields a value for oxygen consumption of 3.4 mol O_2 m^{-2} yr^{-1} or an equivalent carbon demand of 40gC m^{-2} yr^{-1}. This value is high compared to similar open shelf-slope regions and suggests that reef communities may play a significant role in carbon cycling on the continental shelf.

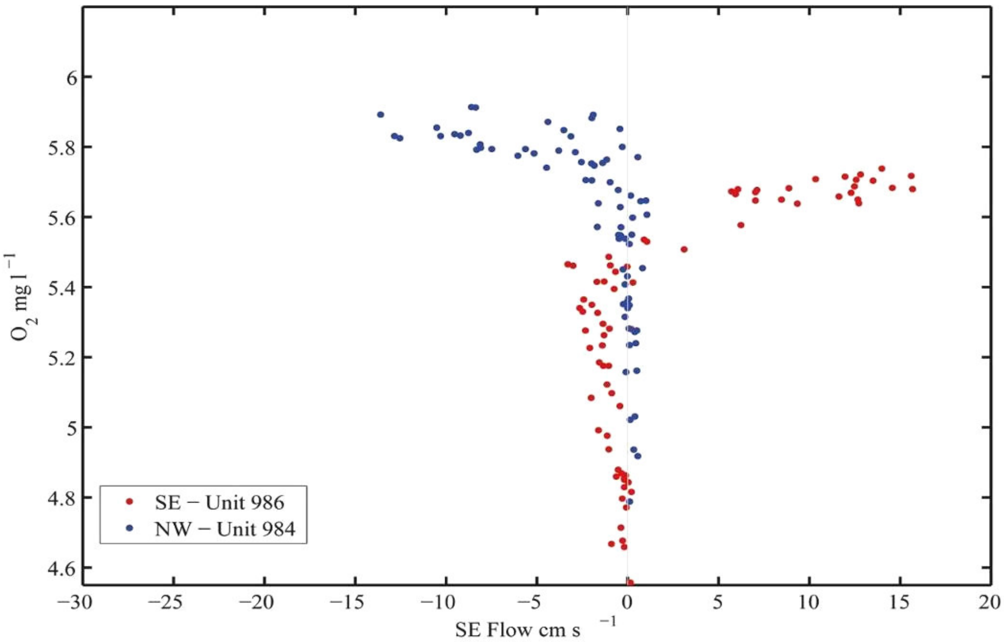

Fig. 28 *Tidally averaged O_2 values tidally averaged residual flow for both RCM9 summer (April-June) deployments (red=NW, blue=SE reef fringe).*

3.4.3. Turbulence measurements

High vertical resolution (10 cm) current measurements in the lower 4m of the water column have been made at 4 locations within the reef, although 3 of these were for short (<= 2days) duration. The most recent deployment was in conjunction with turbulence measurements made with a Nortek Velocitometer, mentioned below. Figure 29 shows an example of the 2MHz data, taken from the first 2 day test deployment. The backscatter anomaly was calculated by subtracting the mean backscatter value at any height from the instantaneous data at that height, and provides a measure of the variation in the concentration of the acoustic backscatters in the water (suspended sediment). The backscatter anomaly showed 2 large pulses of high intensity in the layer adjacent to the seabed occurring during the 29th March. These periods are associated with strong currents between 2-5 mab and a large vertical velocity shear in the lower 2 meters. Given the backscatter anomaly are found in the lower 3 meters, this might be interpreted as local re-suspension events, rather than an advective signal.

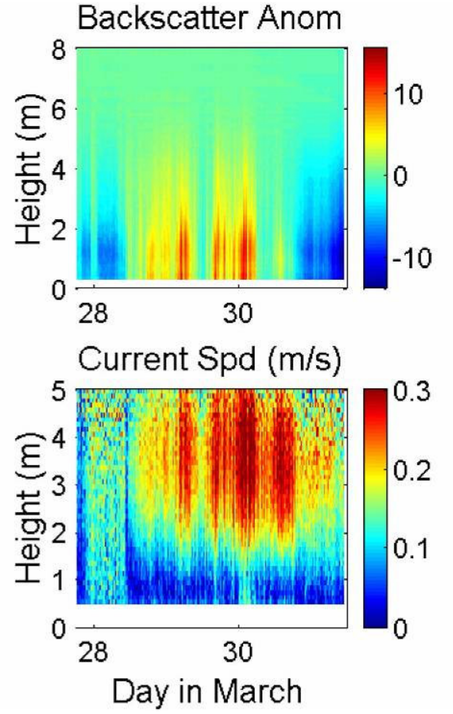

Fig. 29. *Time series of vertical acoustic backscatter anomaly from the 2MHz ADCp deployed for 2 days below main reef structure, March 2006 (top) and vertical variation of current speed (bottom). A colorbar scale for backscatter anomaly (dB) and current speed are also shown.*

Measurements of turbulence were made close to the coral heads using a Velocimeter recording three dimensional current data at a rate of 3200 samples per second. This high sampling rate will allow the calculation of turbulence at a scale not achievable with ADCP equipment. Figure 4a shows the vector in position with the sensor head at the coral. The image is being displayed on the viewing screen for the ROV onboard the R.V. *Lophelia*.

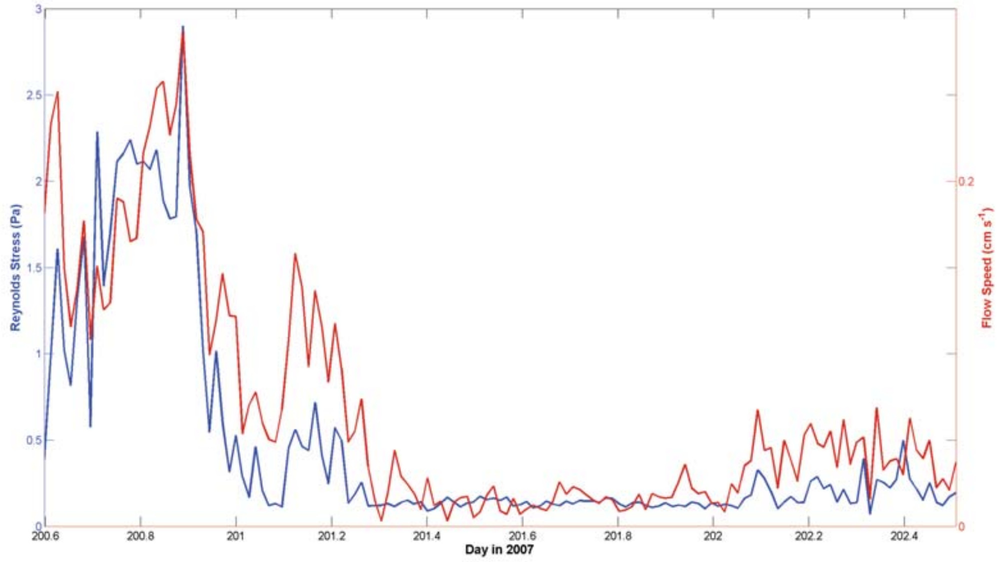

Fig. 30 *The red line shows the current speed and the blue line shows the Reynolds Stress calculated from this stress. Reynolds stress is a function of the deviation of the high resolution data from the mean.*

The velocimeter data has not yet been fully analysed and there are a number of short laboratory tests that are needed before this can be completed. Reynolds stress is an early result and one of a number of measurements of turbulence. Figure 30 shows how this stress is very closely related to the speed of the current. Further work, to be carried out shortly, will investigate the impact of reef length on turbulence.

3.4.4. Summary of the physical oceanographic data

A large amount of physical oceanographic data has now been collected at the Tisler reef in support of the multi-disciplinary field survey of the reef, as well as for some specialised experiments on the near seabed dynamics. Data return and quality to date has been very good and early results have yielded significant information on both the overall dynamics at the Tisler reef, as well as high resolution information relating to turbulent flow around individual reef components. Data has also been used to help quantify biogeochemical fluxes at the reef, although more work is required to complete this.

Results to date have shown that the tidal currents in the region are small, although amplified at the sill, and that the tidal excursions of water parcels are similar in size, or smaller than, the extent of the reef. Residual currents, driven principally by density or water level changes across the reef, are generally larger and flush the reef for residual currents of about 5 cm s^{-1} or more. At low residual flow, however, the longer residence time of the water over the reef may allow a ‘reef effect’ to be generated through the reef community respiration. This has been tentatively suggested by the initial oxygen measurements and also by some of the bio-geochemical work undertaken by the University of Liverpool.

To date, both the 300 kHz and 2 MHz ADCP data has only been quality controlled and analysed to a small degree. The initial results have suggested, however, that these data sets will provide a range of information, not only on the flow acceleration at the sill and possible internal wave generation there, but also in the near seabed turbulent dynamics and suspended material concentrations. Local re-suspension events have been observed relating to periods of high flow and near seabed vertical velocity shear (Fig. 29). Results from the 2MHz ADCPs, together with direct measurements of turbulence, also tentatively suggest the control of the individual reef structures on the turbulent dynamics, suspended particulate fluxes, and a possible directional/spatial bias in turbulent dissipation due to the local topography. This analysis is in early stages and therefore has not been reported here.

Ongoing measurements include a 3rd deployment of the RCM9s with the oxygen sensors to obtain further estimates of the community respiration in periods of low residual flow strength. In addition long term measurements with a bottom mounted 300 kHz ADCP and temperature-salinity sensors are continuing to provide a multi-year time series to assess likely inter-annual variability and individual, sporadic dynamical events at the reef. For example, measurements last winter indicated a rise in temperature occurred between the depths 90-120 m, in excess of 2°C in a matter of little over a day. ROV sampling at the end of the winter period also found numerous sponges that had died over this time period within a similar depth range. The two events may well be linked and are under investigation. The Tisler reef is also a site where limited real-time measurements are being proposed under an ESONET proposal KOSTOBS.

4. GENERAL CONCLUSIONS

1) The results of the Kosterfjord Experiment illustrate and emphasize the overriding effect of the hydrodynamic regime on the transfer of carbon rich particles to the reef floor and on the ensuing behavior of the corals.

2) The results demonstrate the importance and value of obtaining long time-series of data from complex environments, such as CWC ecosystems, in order to obtain a deeper understanding of the functioning of these systems. The necessity of long-time series is illustrated by observed events such as deep water inflow and extreme temperature event in spring and late 2006, respectively.

3) The Kosterfjord experiment exposed small-scale variations in water column characteristics. Individual micro-habitats play a significant role in modulating near seabed currents and turbulence with potentially important consequences for the particle residence time, feeding strategies and hence the distribution of live/dead coral over the whole reef. Unraveling CWC reef systems requires measurement with high spatial and temporal resolution.

4) The results at this relatively small cold water coral reef indicate that the reef plays a substantial role in Carbon sequestration. Though not yet quantified, globally CWC reefs could likewise be hotspots of mineralization activity in the ocean

5) The small-scale complexity of reef topography in combination with the fact that habitats will exert different constraints on the dynamical control of bio-geochemical fluxes, make exact quantification of fluxes a major challenge.

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