Master of Science

Course ***ISATEC***

M.Sc. Thesis in International Studies in Aquatic Tropical Ecology

Zooplankton and seston near coral reefs impacted by solitary internal waves in the Similan Islands, Thailand, Andaman Sea

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Presented to the University of Bremen, Faculty for Biology & Chemistry

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Contents

List of Figures

List of Tables

List of Abbreviations

ADCP	Acoustic Doppler Current Profiler
AWI	Alfred Wegener Institut fur Polar und Meeresforschung
C_{org}	organic carbon
CTD	Conductivity, Temperature, Depth recorder
C_{tot}	total carbon
h	hour, hours
l	liter, liters
m	meters
min	minutes
μg	micrograms
μmol	micromoles
μm	micrometers
N	Nitrogen
N_{Ox}	Nitrogen oxide (here nitrate and nitrite)
ORCAS	Ocean-Reef Coupling in the Andaman Sea
PMBC	Phuket Marine Biological Center
PO_4	Phosphates
SAR	Synthetic Aperture Radar
Si	Silicates
ZMT	Zentrum fur Marine Tropenokologie

Abstract

High amplitude solitary internal waves, or solitons, travel from West to East in the Andaman Sea. The Similan Islands, worldwide known for their coral reefs lie in the path of these solitons. The point of this study was to assess the direct and indirect impacts of internal waves on the zooplankton and seston around the Similan, and how this might affect the benthic community.

For this purpose, plankton and water samples were taken offshore in the thermocline and near the islands on the side exposed to the solitons (West) and on the sheltered side (East).

Periodically, internal waves can cause temperature drops of up to 10°C over a few minutes by 20m depth, particularly on the west side of the Similan. Their cold water contains less zooplankton and more nutrients, especially nitrates than the normal reef water. These characteristics were comparable to parameters measured in the thermocline. The solitons also presented a high sediment load and were related to an increase of barnacle larvae.

Solitons are a source of stress for the corals: they bring cold waters charged with sand and don't represent a significant supply of zooplanktonic food. This could partly explain the configuration of the coral reefs in the Similan Islands. Nevertheless, they might also benefit to the ecosystem by transporting meroplanktonic larvae from offshore and nutrients from the thermocline. Their occurrence in related to the depth of the thermocline, as such, they might not be reaching the islands all year round.

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1. Introduction

Internal waves can appear in stratified systems, like oceans and seas, along surfaces separating layers of different densities, the pycnoclines (Perry and Schimke, 1965; Osborne and Burch, 1980).

In the last fifteen years, there has been an increasing interest for those peculiar oceanographic features, due notably to the development of new satellite imagery techniques, like the synthetic aperture radar (SAR), which allows us to detect the surface manifestations (slicks or rippling) of the internal waves from space (Alpers et al., 1997).
It is now clear that internal waves are widespread all around the world, especially in coastal zones, though the low number of observations offshore could be due to the lack of images for the open ocean (Jackson, 2004).

With amplitudes that can be as big as 100 meters (Jackson, 2004), those giants travel slowly along the pycnocline until they reach an obstacle.

As direct observation of the behaviour of internal waves when they meet the shore is difficult (Nielsen et al., 2004), modelers are trying to provide us with theories about their interaction with the continental shelf. De Silva et al. (1997) found out that, like surface waves arriving on the beach, internal waves experience shoaling when the bottom depth decreases and might at some point break, generating turbulences, mixing and intrusion of water from the deep to the shallow.

1.1. Biological impact of internal waves on coastal ecosystems

Water movements of such amplitude and energy as internal waves have an influence on the organisms they meet.

First of all, internal waves displace the pycnocline, usually associated to a thermocline, up and down. In the meanwhile, they also create a vertical redistribution of phytoplankton and zooplankton associated to this interface (Haury et al., 1979). In some cases, the lower part of the waves might even allow benthic populations to reach the phytoplankton-rich layer around the thermocline (Witman et al., 1993).

Internal waves have also been presented as a vector of cross-shelf transport (Leichter et al., 1998). The rippling created by them at the surface has been proven to be able to concentrate and transport zooplankton, especially fish, crab and barnacle larvae, toward shore in several places. The swimming behaviour of these organisms might allow them to sustain their position in the surface slicks and so move with the waves (Kingsford and Choat, 1986; Shanks, 1988, 1983; Zeldis and Jillett, 1982).

In analogy to what happens in the slicks, there might be a phenomenon of concentration of particles at the bottom of the internal wave (Fig.1.1). Sediment and zooplankton might so be redistributed on the way taken by the wave (Johnson et al., 2001).

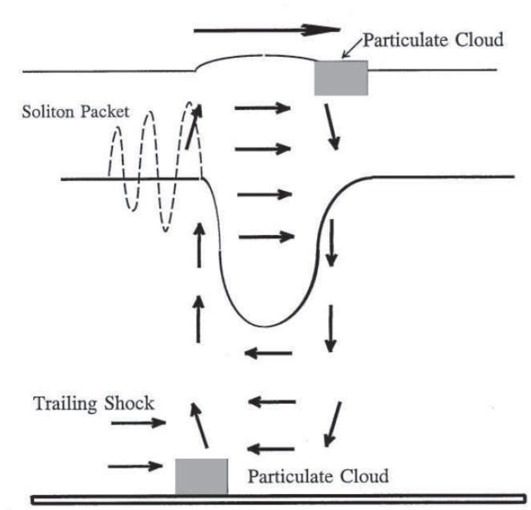

Figure 1.1.: Concentration of particles in an internal wave (Mofified from Johnson et al. (2001)) The wave is moving toward the right and we see the two zones of concentration of suspended matter in the surface slicks and at the bottom of the wave.

Another hypothesis is that the breaking internal waves, or bores, might represent a supply of food and larvae to coastal ecosystems.

From their models De Silva et al. (1997) and Sandstrom and Elliott (1984) predicted that breaking internal waves might transport cold, nutrient rich water to the shore. This was proven in a Florida coral reef where cold water from the bores entering the reef (Leichter et al., 2005) are containing up to forty times as much nitrate as the normal, warm reef water (Leichter et al., 2003). This intrusion of thermocline water is associated with a high chlorophyll a concentration (Leichter et al., 1996).

Concerning zooplankton, Pineda (1991) found indirect proofs of transport of barnacle larvae by internal bores in California but has been later discussing these results (Pineda, 1999). In Florida, calanoid copepods, crab larvae and fish larvae concentrations were higher in cold water from the bores than in reef water (Leichter et al., 1998) but there again, the author raised attention to the low number of samples taken over a short time period and the absence of comparison with zooplankton vertical distribution including above, in and below thermocline water.

1.2. Internal waves in the Andaman Sea

The Andaman Sea lies on the eastern part of the Indian Ocean between the Malay Peninsula and the Andaman and Nicobar Islands. It is exposed to a monsoon regime. The dry season (Northeast monsoon) extends from November to April. The rest of the year, the wet season (Southwest monsoon) brings rainy weather and frequent storms from the Indian Ocean.

Internal waves generated in the Andaman Sea belong to the world's biggest waves known (Alpers et al., 1997). Perry and Schimke (1965) were the first to associate the rippling stretching from horizon to horizon often seen at the surface between the Nicobar Islands and Sumatra with internal waves of extraordinary amplitude.
Those solitary waves are solitons of depression: they retain their shape and speed after colliding with each others. They usually occur in packets of five or six, the first one being the bigger (Osborne and Burch, 1980). Their amplitude can reach 80m, their length can extend to 150km and they travel along the pycnocline at a speed superior to 2m s^{-1} (Jackson, 2004).
They are generated by the tide in regions of shallow water in the western part of the Andaman Sea (Osborne and Burch, 1980). The Andaman and Nicobar Islands have a volcanic origin, around them, the seafloor suddenly rises from depth superior to 3000m to depth inferior to 200m and dives again to 2000m (see fig.1.2).

The tide, by passing over this ridge, generates a disturbance in the pycnocline, which propagates toward the West (Jackson, 2004). At least three areas have been identified as sources of internal waves: a shallow reef on the northwest coast of Sumatra, seamounts between the Andaman and Nicobar Islands and a submarine bank near the Andaman Islands (Alpers et al., 1997).

Nielsen et al. (2004) and Munk et al. (2004) encountered internal waves during their plankton surveys in the Andaman Sea. Out of CTD (Conductivity, Temperature, Depth recorder) casts, they could see that internal waves coming from the west loose in amplitude when they pass the shelf without being able to get direct evidence of breaking. On the shelf slope, at the point where the solitons interact with the bottom, they found a high abundance of zooplankton.

1.3. Mu Ko Similan National Park

The Similan are a group of nine coral islands located in the Andaman Sea, 60km away from the Thai coasts and more than 400km east of the Andaman and Nicobar Islands (see fig.1.2).

They are internationally famous for the wonderful dive sites they offer and have been classified as national park in 1982 to protect the coral reefs surrounding them from overexploitation and fishing. The Thai government even has proposed them to be listed as a UNESCO world heritage site (Sethapun, 2000).

As seen in figure 1.3, the Similan Islands lie directly in the path of internal waves travelling from the West toward the continent. Those might reach the reefs around the islands and affect them directly through a change in the water properties (Leichter et al., 2005) or indirectly, through an input of organisms.

Another special type of wave, a tsunami, hit the corals around the Similan in December 2004. By chance, the impact to the reefs was limited, except in the channels between the islands, where the damages were estimated to more than 50% (Department of Marine & Coastal Resources, 2005; Satapoomin et al., 2006).

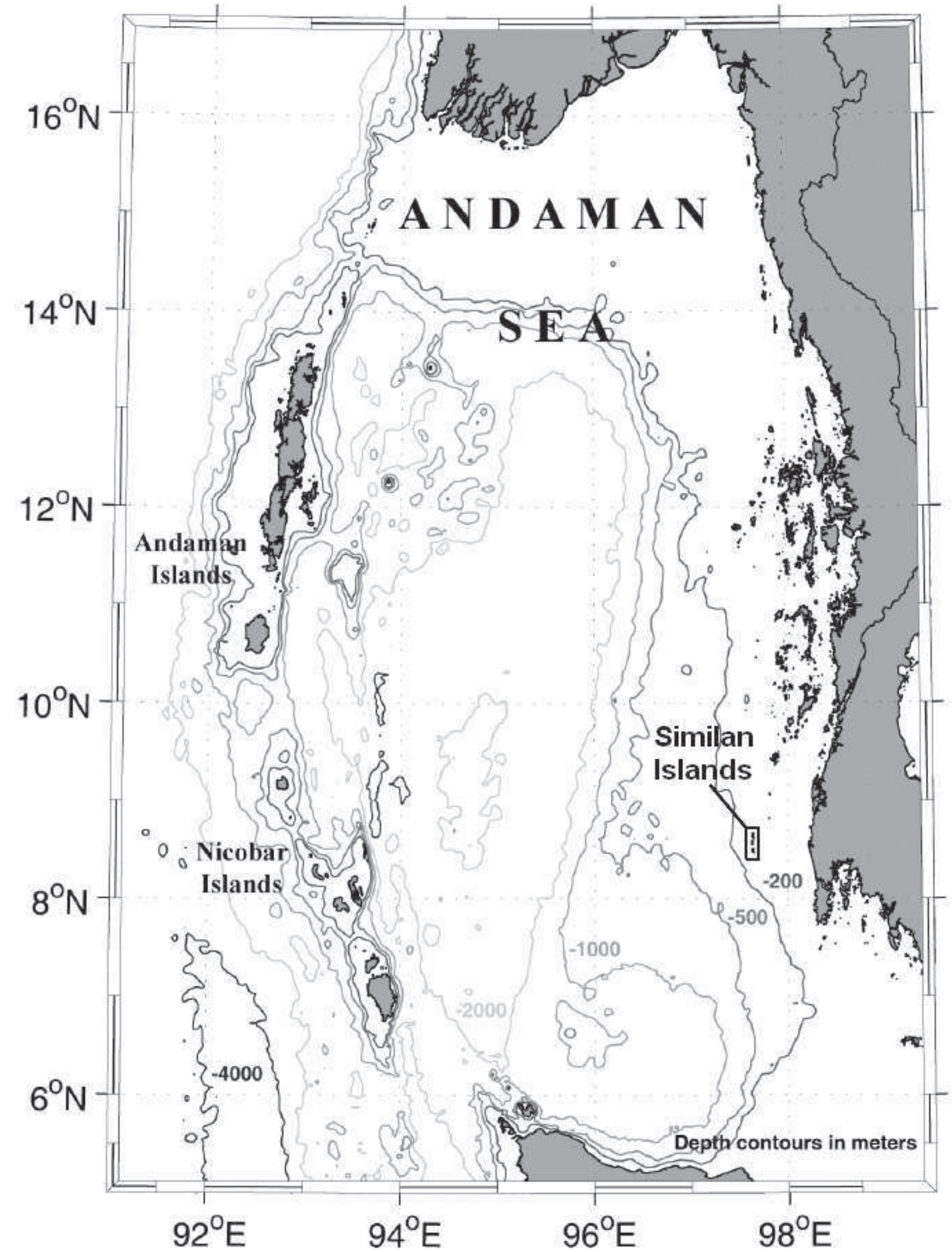

Figure 1.2.: Bathymetry in the Andaman Sea (modified from Smith and Sandwell (1997)).

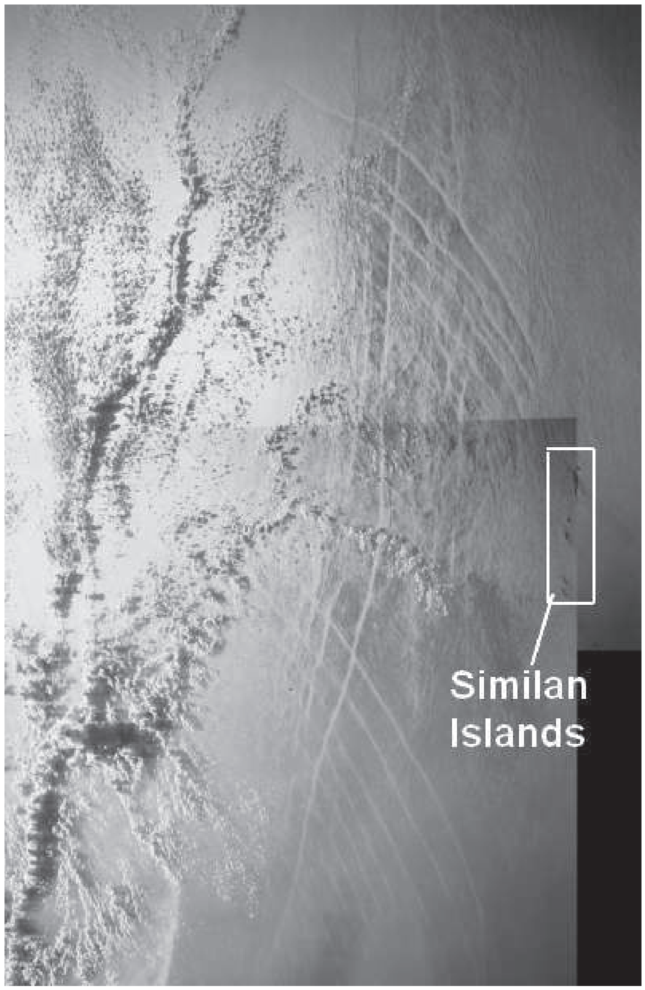

Figure 1.3.: Satellite view (SAR) of internal waves reaching the Similan Islands (modified from Jackson (2004)). We can see two wave packets coming from a South-west direction and one from the West.

1.4. Objectives, scientific questions and hypothesis

The goal of this study is to determine if the internal waves have an impact on the quantity of zooplankton and seston surrounding the Similan Islands. This could be of importance for the corals and represent a source of pelagic-benthic coupling.

- Are internal waves reaching the shore of the Similan Islands?

Before being able to quantify any impact, I will first have to corroborate the arrival of the solitons, broken or not, to the islands. Internal waves are an oscillation of the pycnocline/thermocline and are associated with variations of the temperature (Leichter et al., 2005). Sudden drops in the water temperature, associated with some other indicators, would be proofs of their penetration in the reef.

Hypothesis:
- The water temperature around the Similan shows regular variations of several degrees over a short time span.
- These temperature oscillations are associated to other phenomenon related to internal waves.

If those statements are validated, then I'll be allowed to consider their impact.

- Do the internal waves arriving on the Similan Islands represent a significant supply of holoplanktonic food and meroplanktonic larvae for the reefs?

Hypothesis:
-There is more zooplankton on the side exposed to the waves (West) than on the sheltered side (East).
- There is more zooplankton on a period with a lot of waves than on a period with very few waves on the exposed side (West).
- There is more zooplankton in the cold water of the internal waves than in the normal warm water of the reef on the exposed side (West).

There also could be an indirect effect on the zooplankton through an input of nutrient which might enhance the primary production.

Hypothesis:
- The nutrient concentration in the internal waves is higher than in the reef water.

- Are internal waves transporting seston to the reef?

Seston is a wide word used to describe the particulate matter, living and non-living suspended in the water. It includes zooplankton, phytoplankton, organic detritus and non-organic material, like sediment. In this study, due to the sampling method used, I'll consider only the particles bigger than 50μm, so that part of the seston will be excluded. Considering the seston, not only the zooplankton, will allow me to detect any other type of input of suspended matter by internal waves.

Hypothesis:
-There is more seston in the cold water of the internal waves than in the warm reef water.

To assess these statements, zooplankton and water samples were collected offshore of the Similan during a cruise to get reference values above, in and below the thermocline. The same parameters were measured as time series near the reefs of one of the Similan Islands.

2. Material and Methods

2.1. Sampling sites

In October 2007, at the end of the rainy season, a transect travelled by the PMBC's scientific vessel, the Chakratong Tongyai, allowed us to get samples from offshore. This transect crossed the Similan Islands from the East and went toward the West, in direction of the shelf break. The last sample was taken on the continental slope (see fig. 2.1).

In March 2007, December 2007 and March 2008, near-reef sampling sessions were organized from the island Ko Miang, which was chosen for its central location in the Similan and the facilities it offered. Sites were located on each side of the island: one on West, where the internal waves were supposed to arrive, one on East, which was expected to be more protected (see fig. 2.1).

2.2. Detection of internal waves reaching the Similan Islands

2.2.1. Temperature variations

In order to detect the temperature oscillations expected as proofs for the arrival of internal waves to the shore, moorings with subsurface floats were deployed by 25m depth on both sides of Ko Miang, near the sampling sites. Temperature loggers (SBE39) with sampling intervals of one minute were attached to the mooring lines every five meters, from the bottom to 5m depth.

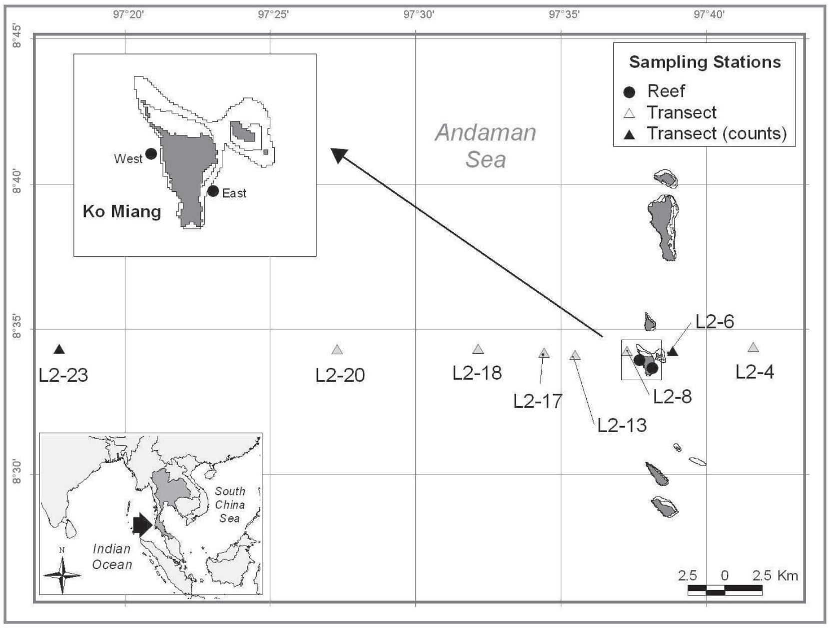

Figure 2.1.: Sampling stations around the Similan Islands. Triangles stand for off-shore samples taken during the cruise (black: analysed under the microscope, white: only filters analysed), dots represent the near-reef sites around Ko Miang. (Credit for GIS Dataset: Millennium Coral Reef Mapping Project, Institute for Marine Remote Sensing, University of South Florida (IMaRS/USF) and Institut de Recherche pour le Développement (IRD/UR 128, Centre de Nouméa))

2.2.2. Other parameters

Near the mooring lines, two Acoustic Doppler Current Profiler (ADCP) and a CTD (SBE19plus, West only) were deployed (data not presented here) to record other parameters which might be associated with the arrival of internal waves.
Observations were also made at the surface during sampling and while diving near the sampling sites.

2.3. Sampling

2.3.1. Offshore sampling

Zooplankton and seston (Multinet samples)

In order to check that there was really more plankton in the thermocline and try to find some indicators groups or special biochemical properties which might be used as a signature for offshore plankton, vertical tows were realised with a multinet (multi-plankton-sampler from Hydrobios, opening 0,25m^2, mesh 55μm, 5 nets with controlled opening and closing depth).
Eight stations were sampled along the transect travelled by the Chakratong Tongyai. The number of samples per station (number of depth intervals) and the total sampling interval varied depending on the bottom depth at the station (see table 2.1).

Table 2.1.: Offshore: Multinet samples

Station	Latitude (N)	Longitude (E)	Bottom depth(m)	Number of samples	Sampling depth(m)
L2-4	8° 34.645	97° 42.060	71	4	0-50
L2-6	8° 34.496	97° 39.155	47	2	0-25
L2-8	8° 34.467	97° 38.468	62	3	0-50
L2-13	8° 34.554	97° 35.167	69	4	0-50
L2-17	8° 34.537	97° 33.071	80	4	0-50
L2-18	8° 34.584	97° 32.136	165	4	0-50
L2-20	8° 34.554	97° 27.036	183	5	0-75
L2-23	8° 34.563	97° 17.014	340	9	0-175

Nutrients (Water samples)

Parallel to the multinet sampling, Dr Somkiat Khokiattiwong and his staff took water samples at different depths using a rosette equipped with a CTD (SBE25 with oxygen, fluorescence and PAR sensors) and Niskin bottles.

2.3.2. Near reef sampling

Zooplankton and seston (Net samples)

To find out if internal waves really bring a significant amount of plankton and seston to the Similan Islands, samples were taken in time series on each side of Ko Miang, simultaneously when possible (see table 2.2 for sampling dates).

Table 2.2.: Near-reef samples

Date	Site	Net samples	Water samples
09.03.07	East	6	6
12.03.07	West	11	6
24.11.07	West	4	0
28.11.07	West	22	0
05.12.07	West	13	0
	East	13	0
09.12.07	West	6	0
	East	1	0
10.12.07	East	13	0
08.02.08	West	0	18
11.03.08	West	12	0
17.03.08	West	12	0
	East	14	0
21.03.08	West	14	0
	East	4	0
25.03.08	West	13	0
	East	6	0

As sampling was realised from a small boat, sites were chosen depending on the availability of moored buoys installed by the national park authorities with approximately the same configuration on both sides (see figure 2.2). The western buoy (#305, coordinates: 8°34,158'N; 97°37,950'E) was anchored by 35m depth, on a gentle sandy slope with isolated coral colonies leading to granite boulders diving to 10m depth. The eastern float (#310-1, coordinates: 8°33,886'N; 97°38,413'E) was also located above a 35m deep sandy bottom, near the slope of the fringing reef covering this side of the island.

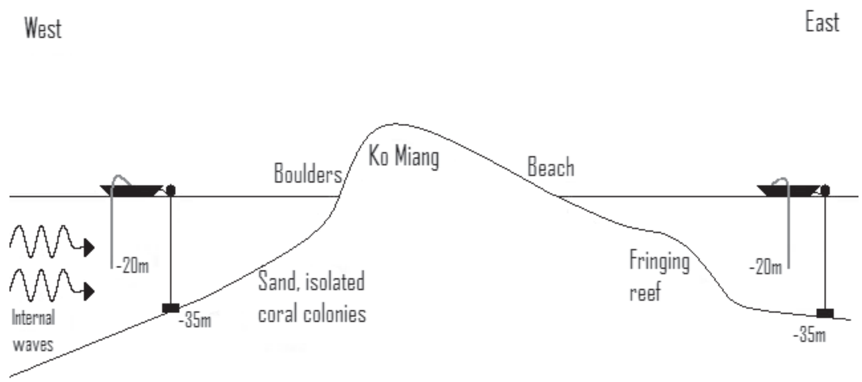

Figure 2.2.: Simultaneous sampling on both sides of Ko Miang (scale isn't respected). The arrows on the left side represent the arrival of internal waves.

Depth under the boat was varying between 30 and 40m depending on the currents and the tide. A pump alimented by a generator was used onboard to sample water through a 20m long plastic tube (diameter: 6cm). Weights were attached to the end of the tube to avoid too much movement with the current (± 0.5 m vertically). A temperature logger (SBE39 or UTBI-001) was also fixed next to the opening of the tube, temperature being used as an indicator for the arrival of the internal waves. The pumped water was filtered 5 minutes every 15 minutes through a 50μm meshed net and the material collected in the net stored in 200ml Kautex bottles in a cooling box containing ice for maximum 6 hours.

Nutrients (Water samples)

At the same time as the net samples, some water samples were taken in March 2007 and a time serie of water sampling done in February 2008 (see table 2.2).

Those water samples were taken at the same sites and using the same system as the near reef zooplankton sampling (pump and 20m tube), the water was then stored in 1l PE bottles in a cooling box containing ice until return to the island.

2.4. Analysis

The freshly taken samples conserved at low temperatures were processed as quickly as possible following those steps (see fig.2.3) :
- Division in two equal parts with a Folsom-splitter.
- One half was put into a 200ml Kautex bottle with 5% formalin and kept aside for analysis under microscope.
- The other half was processed further:
- Fractionation in two size classes for near reef samples: 50-200μm and >200μm, in four classes for offshore samples : 50-100μm, 100-200μm, 200-300μm and >300μm
- Each fraction was filtered on GF/F filters (precombusted and preweighted).
- The filters were then frozen until transport to Phuket where they were dried (24h at 60°C) and sent to Germany into hermetic bags containing silica gel.

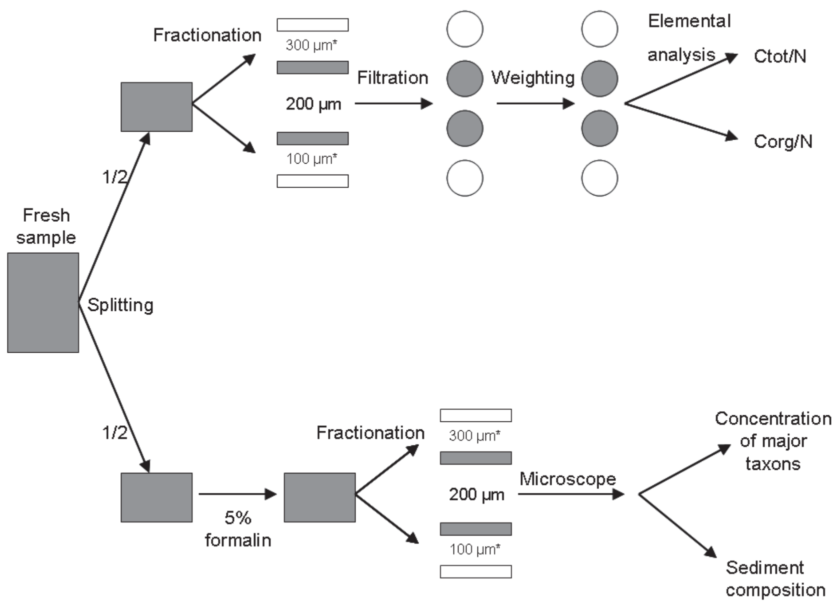

Figure 2.3.: Sample processing and analysis (white: only for offshore samples) Top: seston dry weight and elemental composition, bottom: microscopic observation of zooplankton and sediment

2.4.1. Microscopic work

Samples conserved in formalin were divided in size fractions in the same way as the filtered half (two fractions for reef samples, four for offshore samples).

Zooplankton enumeration

Each size fraction was systematically divided twice with a Folsom splitter (1/8 of the original sample), giving so four subsamples.

Major zooplanktonic taxons were identified based on Conway et al. (2003).
The number of individuals for all major zooplanktonic taxons was determined in one subsample under a stereomicroscope (magnification 25 fold) using a Bogorov chamber.
The number of individuals for rare taxons was also counted in the remaining part of the sample. From those counts, the number of individuals per fraction was recalculated for the whole sample and the concentration (individual/m^3) determined.

For the small fractions (<200μm), the counting was difficult due to the small size of the individuals. It has been then decided to make only a visual evaluation of the amount with five levels (none, very few, few, some, a lot).

Shelled organisms

In some cases (foraminifers, gastropods), it was necessary to determine if the individuals were alive at the time of sampling or only dead shells in suspension. For this, a method of staining with Bengalred used in benthos ecology was applied (Bernhard, 2000; Lutze and Altenbach, 1991).
Bengalred stains the cytoplasma (adsorption to proteins). The individuals of interest were placed in a solution of Bengalred (1g/l ethanol) a few minutes and checked under the microscope after rinsing. The organism alive at the time of sampling were appearing bright red, while the others (empty shells) remained white.

Sand

Sand particles were found in some samples. The amount of sand was evaluated using the five levels previously described (none, very few, few, some, a lot).

2.4.2. Dry weight

Dried filters were weighted on a microbalance with reading accuracy of 1μg. Dry weight of the fraction was determined by deducing the filter weight (measured on the same balance before the field trip) from the total weight. The seston concentration (mg/m^3) was then calculated.

2.4.3. C/N Ratio

The same filters used for the dry weight were split in two halves.
One half was put into a tin cup and analyzed with an elemental analyzer (NA2100, CE Instrument) for total carbon (C_{tot}) and total nitrogen (N).
The other half was put into a silver cup and phosphoric acid was added to remove inorganic carbon. It has then been analyzed for organic carbon (C_{org}) and total nitrogen (N).
From those results, the following ratios were calculated: C_{tot}/N and C_{org}/N (μg atom/ μg atom). Molecular weights of C and N were then used to calculate the atomic ratios.

2.4.4. Nutrients

On the island, the water samples were processed as follow: filtration through GF/F filters, poisoning with mercuric chloride (only samples of February 2008) and freezing.
Samples taken in March 2007 were analysed in Phuket by colorimetry and spectrophotometry following Strickland and Parson's method (Strickland and Parsons, 1972).
Samples taken in February 2008 were analysed in Germany using a continuous flow analyzer, colorimetry, fluorometry and spectrophotometry (SKALAR, method from Hansen and Grasshoff (1983)).

3. Results

3.1. Arrival of internal waves to the Similan Islands

3.1.1. Temperature oscillations

We can see on figure 3.1 oscillations of the water temperature of such a scale over such a short time that they can only be explained by the fact that internal waves are effectively reaching the Similan Islands.
In December 2007 there were few and small temperature variations (less than 2°C drop).
But in March 2008, the variations were stronger (up to 5°C drop) and more frequent even though there were some laps of time with no soliton arriving.
In March 2007 the internal waves were constantly reaching Ko Miang and caused bigger temperature decreases (up to 10°C).
The east and west sides were both reached by the cold water but the variations were smaller on east. The east side is therefore more sheltered than the west one, which is directly in the path of the internal waves.

These changes in wave strength and frequency had an impact on the mean temperature, which was clearly depending on the season, the year and the position around the island (Kruskal-Wallis ANOVA on ranks $P<0.001$+ Dunn's method, all $P<0.05$).
The maximum temperature in the reef was one degree warmer in March for both years than in December 2007. Despite this, the mean temperature was colder in March 2007 than in December 2007.
The mean water temperature in March 2008 remained higher than in December 2007.
The mean temperature on West was always lower than on East.

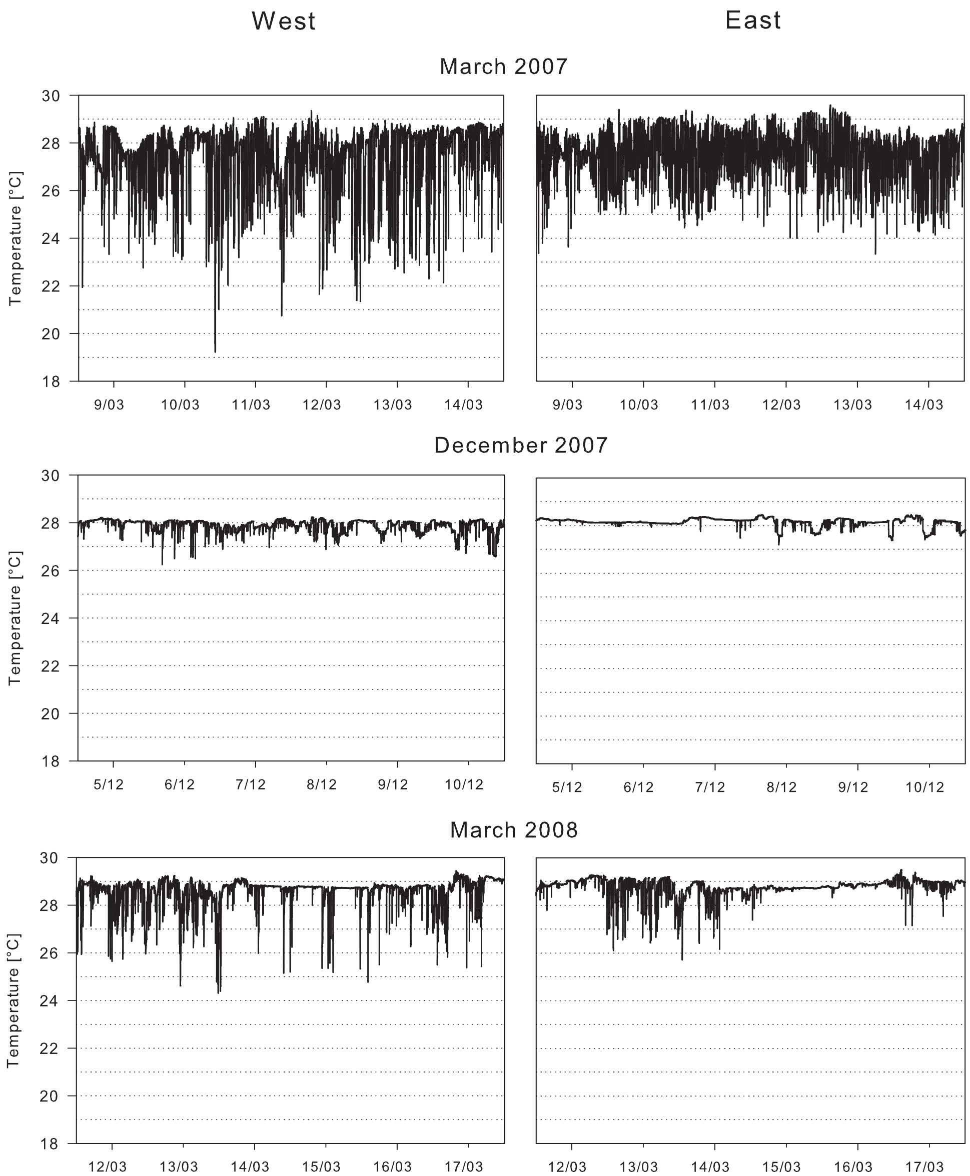

Figure 3.1.: Temperature variation on both sides of Ko Miang in March 2007, December 2007 and March 2008, temperature and time scales (7 days) are always the same. (Data from the mooring logger at 20m depth, 5m above the bottom).

3.1.2. Further evidences

The ADCP data revealed strong horizontal and vertical currents corresponding to the temperature drops. Particle load seemed higher at this moment (Claudio Richter, personal communication).
The CTD data also revealed variations in salinity, pH and oxygen concentration simultaneous to the arrival of cold water (Claudio Richter, personal communication).

The temperature variations were felt by divers through 7mm dive suits. When an internal wave arrived, a moving vertical flickering zone, like the one seen during the penetration of a thermocline, was observed, sometime charged with particles (personal observation).

At the surface, during the near-reef sampling, surface slicks could be observed in March 2007 and 2008. The time of their passage under the boat have been noted and corresponded to the temperature drops at the end of the sampling tube.

3.2. Offshore: reference values above, in and under the thermocline

3.2.1. Water properties

We can see on figure 3.2 (oxygen, salinity and fluorescence) and figure 3.3 (temperature) the parameters measured by the CTD at station L2-04 (east of the Similan Islands), L2-06 (next to Ko Miang), L2-20 and L2-23 (both quite far offshore).

The two offshore stations had a relatively well marked halocline between -20 and -30m depth, the thermocline lied a bit deeper. At stations L2-04 and L2-06, there was a slight change in temperature at around -40m which might be considered as the upper part of the thermocline.

At all stations, the oxygen concentration followed the temperature quite well, decreasing while going to deeper waters.

To note are the peaks of chlorophyll in the offshore stations at depth where the temperature starts decreasing (thermocline) until around -60m where the light was almost reduced to zero.

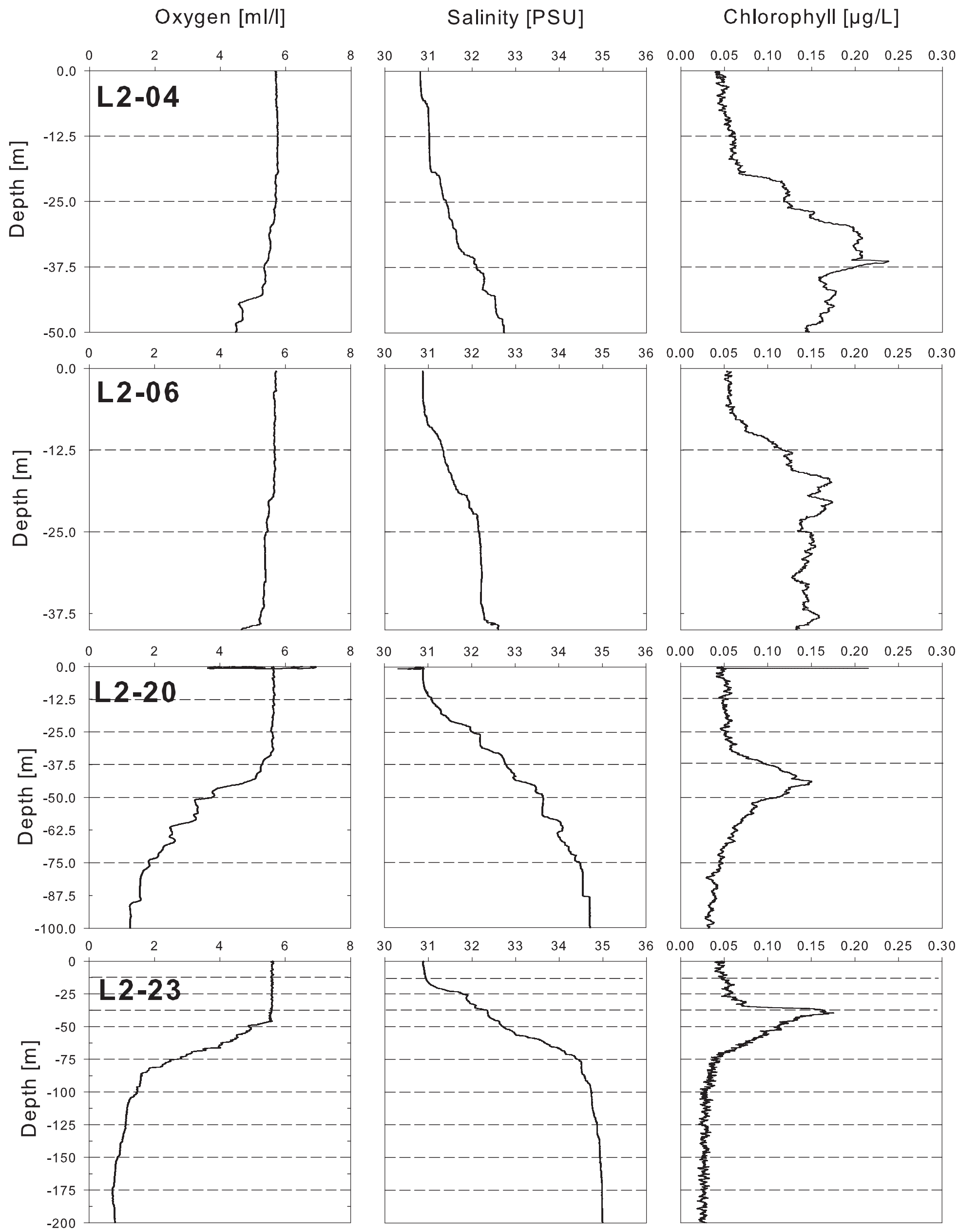

Figure 3.2.: Oxygen concentration, salinity and fluorescence (μg Chlorophyll/l) at stations L2-04, L2-06, L2-20 and L2-23 (temperature is represented on fig 3.3). Vertical dashed lines represent the sampling intervals (nets). Depth scales are different but the x-axes are the same for all stations.
(data: courtesy of Dr. Somkiat Khokiattiwong)

3.2.2. Seston dry mass

There was no sand and no benthic foraminifers in the multinet samples, the few planktonic foraminifers were all alive at the time of sampling. The seston samples were so mainly composed of zooplankton with a few phytoplanktonic organisms.

For the two offshore stations, the dry mass was getting lower with increasing depth with exception for one interval (-37.5 to -50m), within the thermocline, where the concentration reached the surface value again (fig.3.3).
In this same layer, the concentration was even greater than at the surface in station L2-04 but the tendency to decrease with depth was not evident.
Station L2-06 just showed a decrease of concentration with depth.

The size distribution revealed greater plankton size at stations L2-20 and L2-23.

3.2.3. Vertical distribution of zooplankton

The zooplankton concentration tended to follow the same distribution as the dry weight (see fig.3.4).

In all multinet samples, the copepods represented more than 80% of the plankton.
As it is often the case, calanoid copepods were the dominant group in most sample except in one deep sample (-75 to -100m) where the poecilostomatoids were more. (note the much smaller concentration of zooplankton than at the surface.)
Cyclopoids seemed more abundant in the thermocline than in the other samples.
There was relatively more big calanoids in the deeper samples.
Sapphrinidae were quite rare and didn't show a particular depth pattern.

The fraction of non-copepod zooplankton was a bit higher and more diverse at the surface than in the deep but remained quite stable through the water column.
After copepods, the dominant groups were chaetognaths and appendicularia, followed by mollusks and crustacean.
Echinoderm larvae concentrations were higher at the surface. There were few ostracods and polychaets. No barnacle larvae have been found.

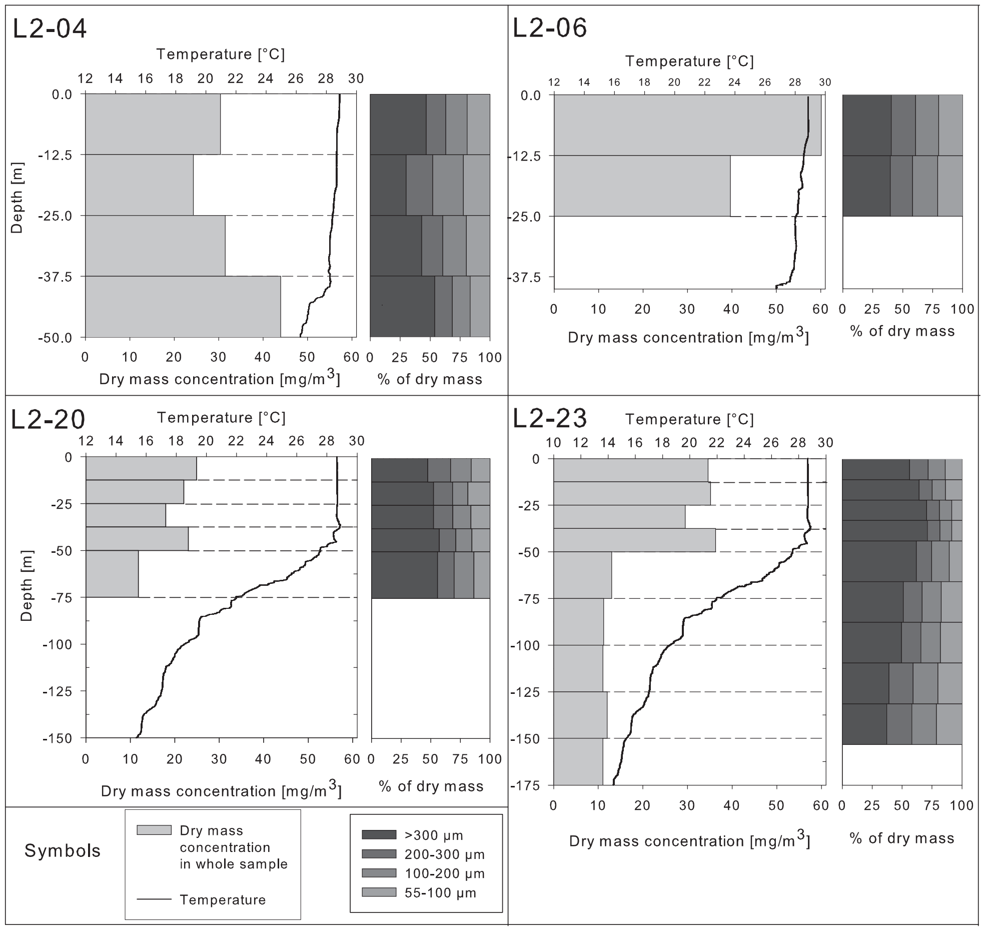

Figure 3.3.: Biomass repartition at station L2-04, L2-06, L2-20 and L2-23. For each station, the left part represent the temperature and the plankton dry mass per m^3 in each sampling interval (vertical dashed lines), the right part of the graph represent the percentage of total biomass per size fraction. Depth scale differs between the two top graphs and the two below, temperature and dry mass scales are all the same.

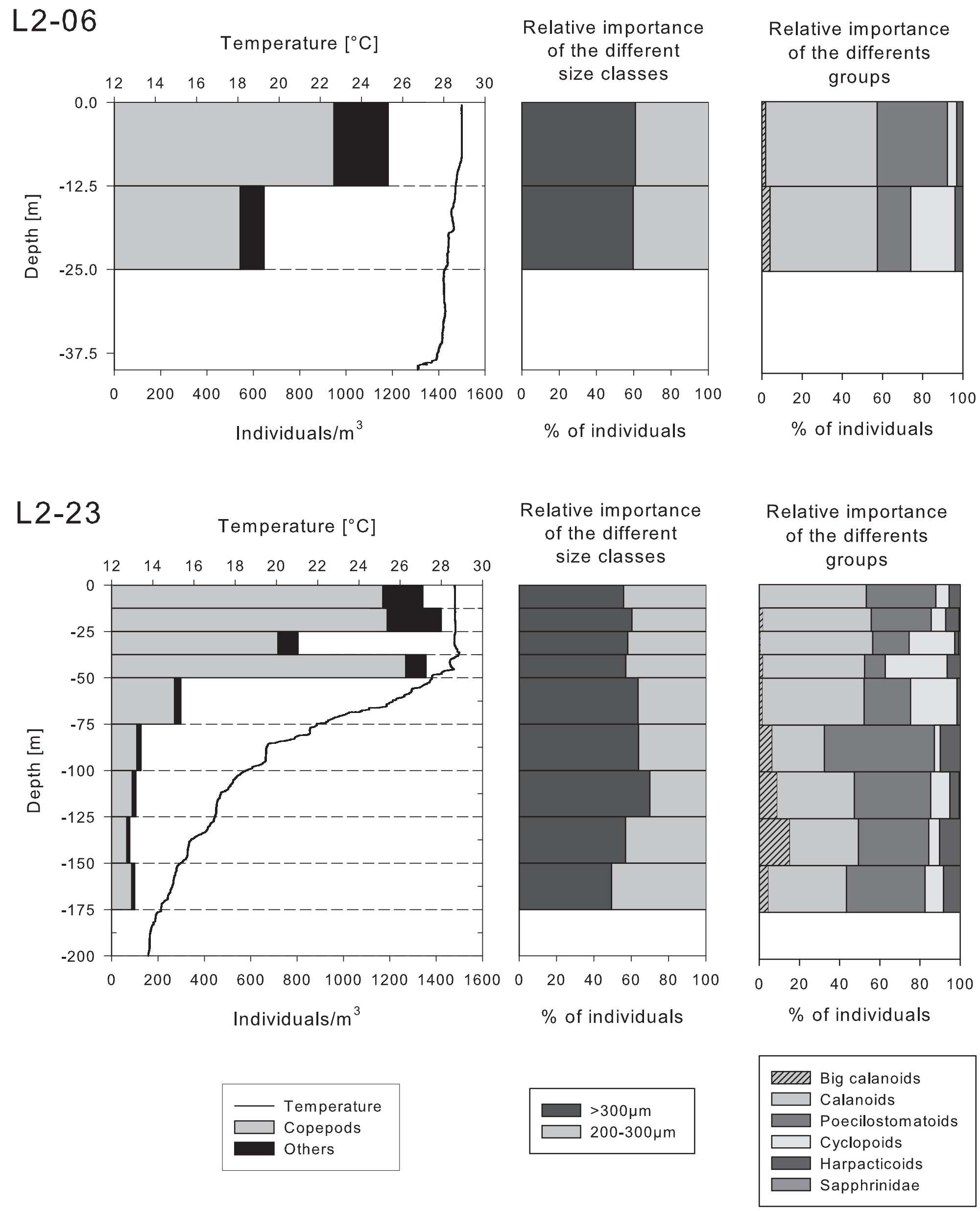

Figure 3.4.: Zooplankton concentration at stations L2-06 and L2-23 with special emphasis on copepods.

3.2.4. Nutrients concentration

Apart from ammonium, all measured nutrients showed a similar profile: a rather low concentration at the surface, greatly increasing under the thermocline(fig.3.5). N_{Ox} were almost absent in the first 30m but reached values of up to 15 μmol/l in the deep. In the thermocline, their concentration was about 5 μmol/l.
Ammonium didn't show any recurrent pattern, being mostly below detection level, it suddenly increased in some samples in the deep as well as in surface waters.
Phosphates concentrations decreased with depth toward the thermocline but increased again under it, being of about 0,5 μmol/l at the surface and reaching up to 1.4 μmol/l in deep waters. Silicates were rather constant in the 40 first meters, about 4 μmol/l and then stepped up to 40 μmol/l below 60m.

3.3. Ko Miang: near-reef zooplankton, seston and nutrients

3.3.1. Variations in zooplankton

Figures 3.6, 3.7, 3.8 and 3.10, represent the same zooplankton parameters for March 2007, the 05.12.07, the 25.03.08 and the 11.03.08 respectively. The y-axes always have the same scale.

Comparison East and West

The total zooplankton concentration wasn't significantly different between the east and the west side (t-test, P=0.770). Some days it was higher on West, other days on East, even in March 2008.

Only in March 2007 (fig. 3.6), the concentration on west (mean for the 12.03.07= 4243 individuals/m^3) was about two time higher than the concentration on east (mean for the 09.03.07= 2406 individuals/m^3).

The proportion of copepods related to the total zooplankton was generally greater than 80% but in March 2007 and 2008, the copepods had a smaller importance in the plankton on the west side than on the east side. There was no such pattern in December 2007.

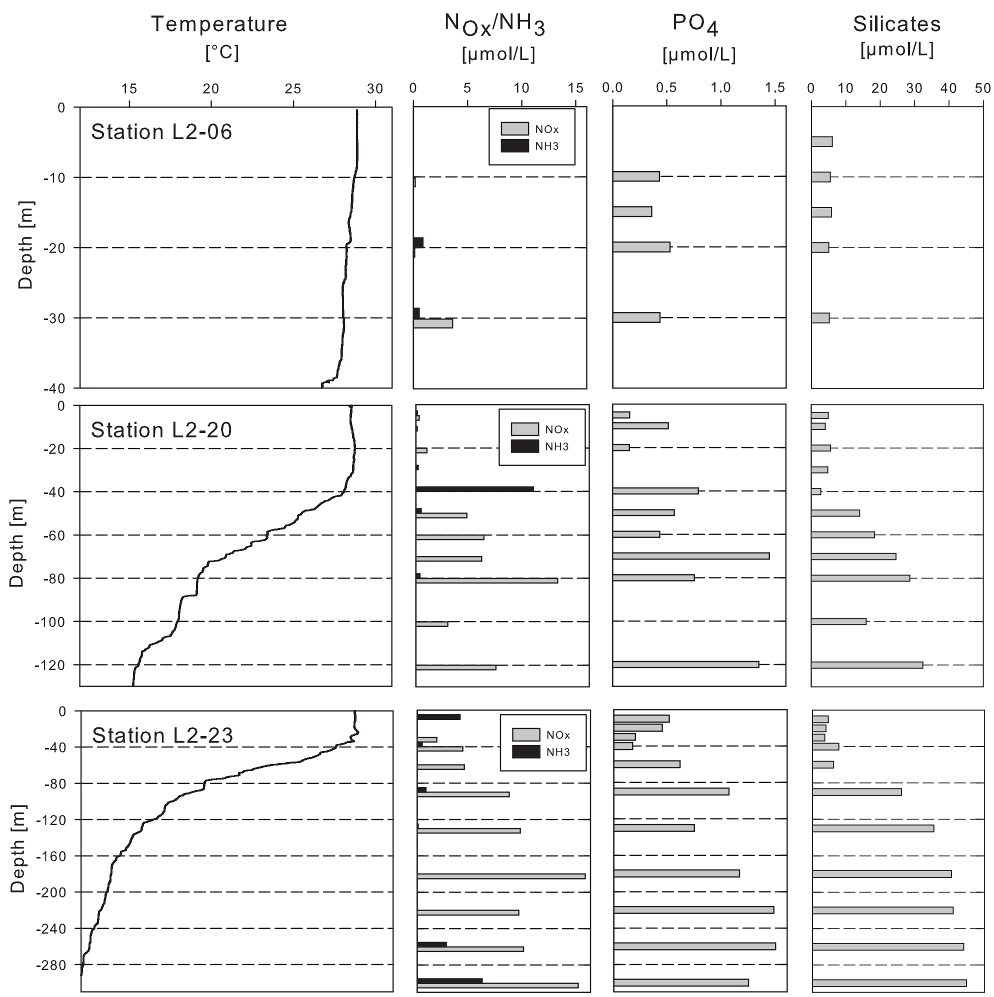

Figure 3.5.: N_{Ox}, NH_3, PO_4 and silicates vertical distribution at stations L2-06, L2-20 and L2-23 in October 2007(data: courtesy of Dr Somkiat Khokiattiwong)

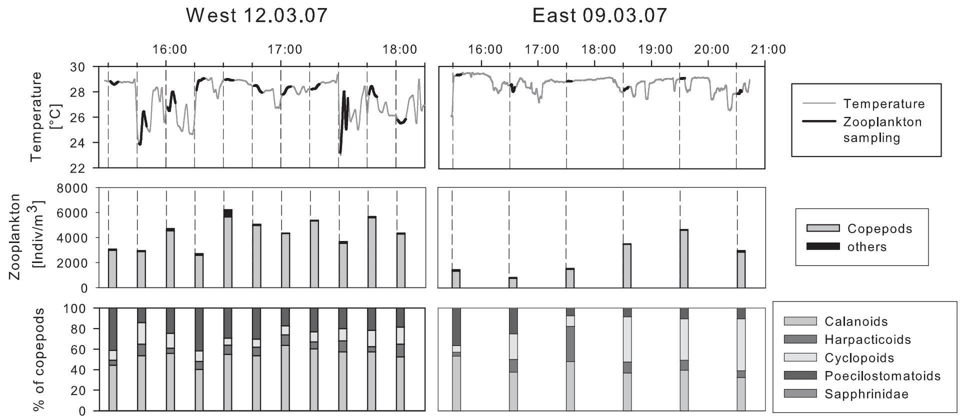

Figure 3.6.: Temperature, zooplankton concentration and composition of copepods in March 2007 on both sides of Ko Miang (two different days, different time scales).

Concerning the copepod composition, the calanoids were most of the time the dominant group. In March 2007, there was a bigger proportion of poecilostomatoids on West than on East, where the cyclopoids were present in higher proportions, but this was not the case for the other sampling days.

Comparison between December and March.

The zooplankton concentration in December 2007 wasn't significantly different from March 2008 (ANOVA P=0.102).

Kruskal-wallis ANOVAs on ranks followed by Dunn's test were conducted on all zooplankton groups only the following one showed differences.
- In the copepods, the rarest zooplankton group, the sapphrinidae were more abundant on the west side in March 2008 than in December.
- On west, the abundance of zooplankton when excluding the copepods was greater in March 2007 than in December (fig.3.7 and 3.8).
- The same pattern was found for the polychaets, barnacle nauplius and ostracods (see annexe A1).
- Echinoderms larvaes were more abundant in December, especially old pluteus really near from settlement.

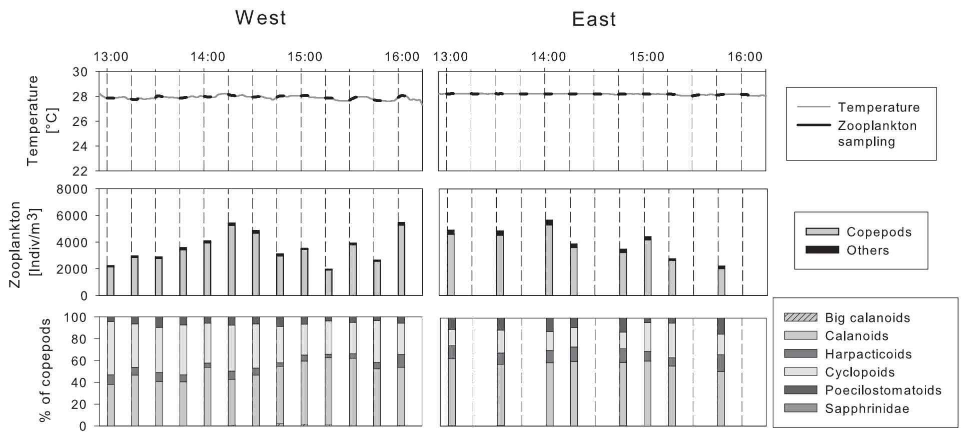

Figure 3.7.: Zooplankton concentration and composition of copepods on the 05.12.07 on both sides of Ko Miang (simultaneous sampling).

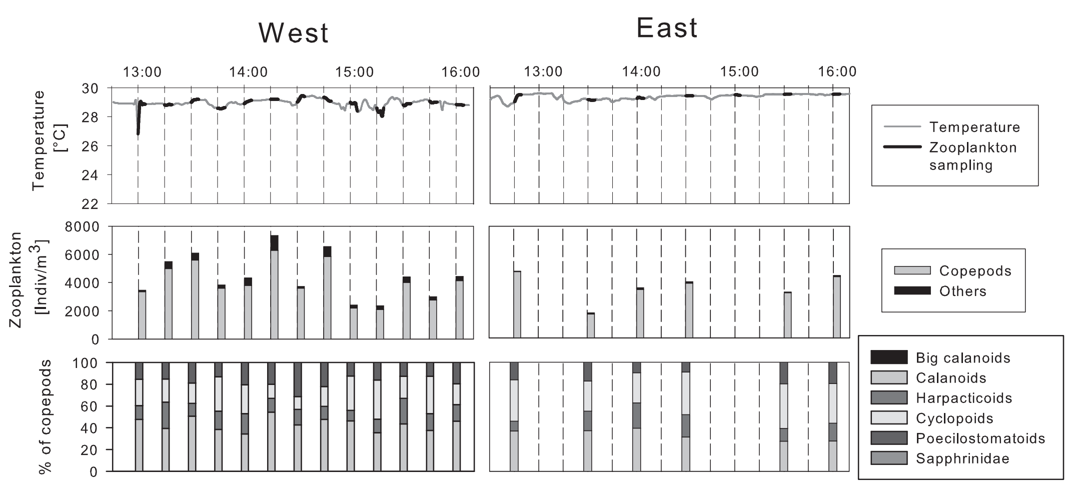

Figure 3.8.: Zooplankton concentration and composition of copepods on the 25.03.08 on both sides of Ko Miang (simultaneous sampling).

Zooplankton concentration in and out of the internal waves

A linear regression on all samples from the west side in March 2008 was conducted in order to determine if there was more zooplankton in the cold water of the internal waves than in the normal reef water (fig.3.9). The variation of temperature while the sample was taken was used as an indicator for the strength of the internal wave.

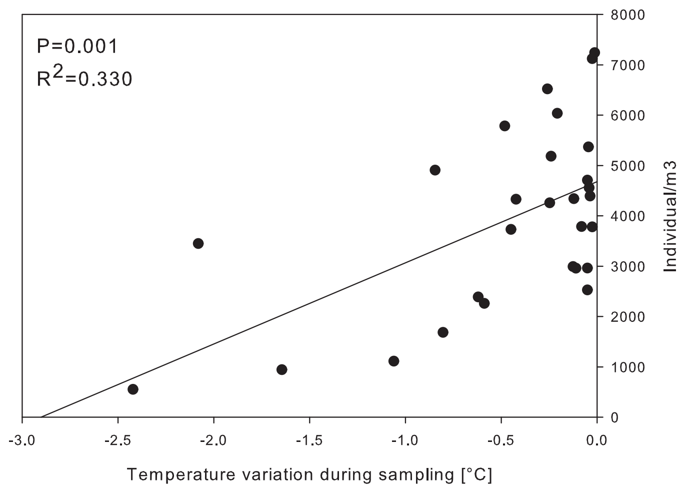

Figure 3.9.: Zooplankton concentration related to the temperature variation during sampling on the west side of Ko Miang in March 2008 (linear regression). Assumptions of normality and constant variance were respected.

There was a significant relation between the zooplankton concentration and the temperature variation: the bigger the variation (colder water), the lower the concentration (the same was true for the copepods, main component of the plankton: $P=0.002$, $R^2=0.326$).

Two waves arrived during the sampling on the west side of Ko Miang on the 11.03.08 (see fig.3.10). In the bigger one, the zooplankton concentration really dropped down and stayed low until the normal temperature was reached again. The second one created a similar drop in the copepods concentration but not in the total zooplankton because of a huge quantity of barnacle nauplius arriving to the reef.

No zooplankton group was systematically present in internal waves and absent in reef water.

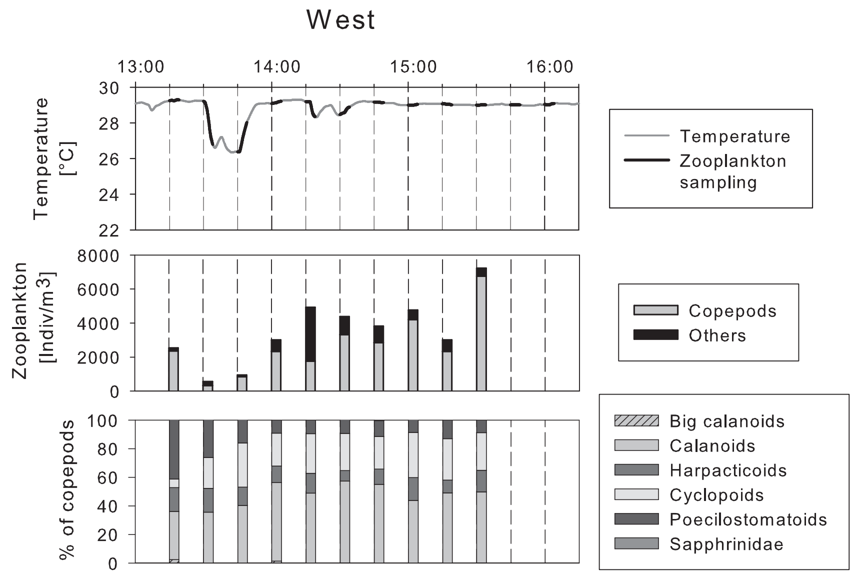

Figure 3.10.: Zooplankton concentration and composition of copepods on the 11.03.08 on the west side of Ko Miang

Comparison with multinet samples

The zooplankton concentration was much lower offshore (max= 1417 individuals/m^3) than in the near reef samples (mean= 3504 invividuals/m^3). However, some of the samples taken in the broken internal waves reached down to values really near from thermocline values.

3.3.2. Dry mass and composition of the seston

Figures 3.11, 3.12, and 3.13, represent the dry mass and the C/N composition of the seston on the 05.12.07, the 25.03.08 and the 11.03.08 respectively. The y-axes always have the same scale.

Seston dry weight

There was no significant difference in the seston mean dry weight between the eastern and the western side (Mann-Withney U-test, P=0,3543) nor between December 2007 and March 2008 (Mann-Withney U-test, P=1).

The dry weight was slightly oscillating around a value of 39 ± 7 mg/m^3 (mean for both sides on the whole sampling period).
But the seston concentration was clearly more variable on the West than on the East (F-test, P=0,0084) and more in March 2008 than in December 2007 (F-test, P=0,0121).

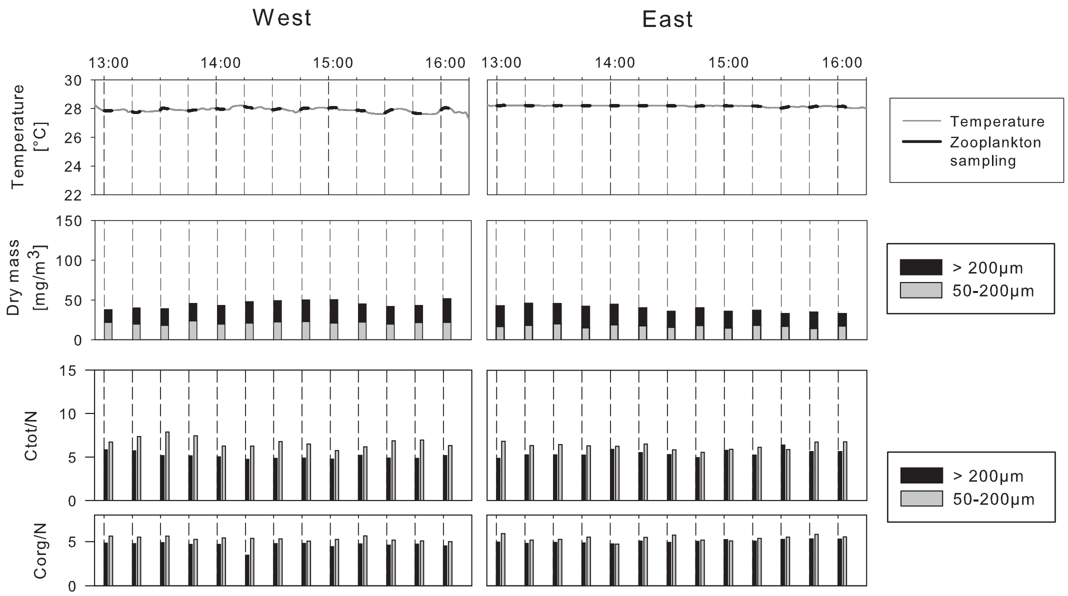

Figure 3.11.: Dry mass and C/N composition of the seston on the 05.12.07 on both sides of Ko Miang (simultaneous sampling).

To be noted are peaks of dry weight on the 11.03.08 and the 25.03.08 on West (fig. 3.13 and 3.12), which correspond to drops in temperature.

Except for two samples in internal waves (one on the 11.03.08 and one on the 25.03.08), the bigger size class represented a slightly bigger proportion of the dry weight than the smaller one.

The seston dry mass was significantly higher (t-test, P=0,004) in the near reef samples than in the offshore samples from the same depth (mean for samples taken offshore between 12,5 and 25m depth = 29 mg/m^3).

It was impossible to test the difference between reef samples and thermocline samples as there were only two samples that were taken into the thermocline. One was far below the mean in the reef (station L2-20, 23 mg/m^3), the other one was in the same range (station L2-23, 36 mg/m^3).

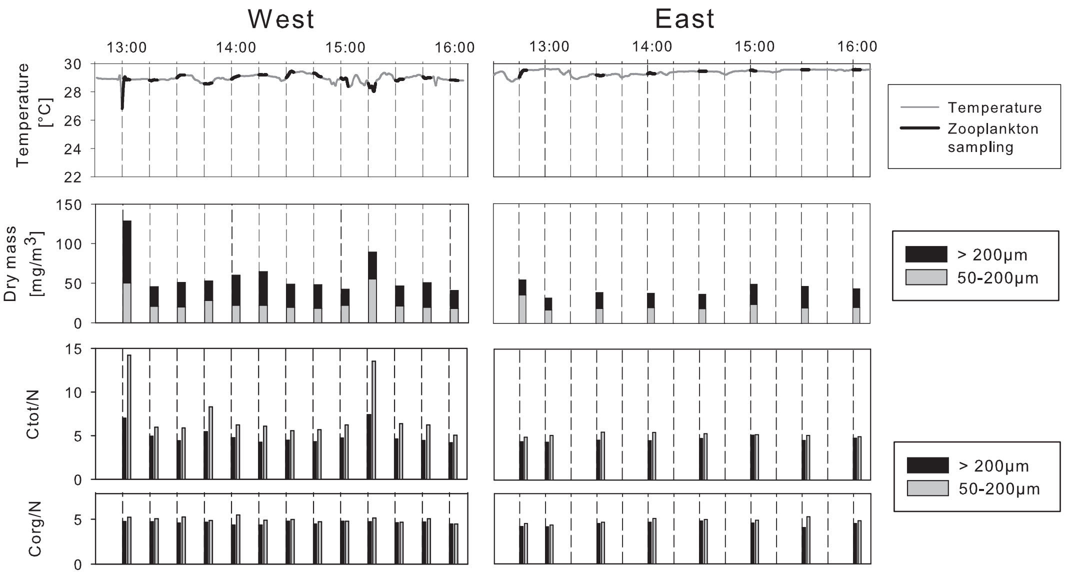

Figure 3.12.: Dry mass and C/N composition of the seston on the 25.03.08 on both sides of Ko Miang (simultaneous sampling).

C:N Ratio

The C/N ratios presented in graphs 3.11, 3.12, and 3.13 were calculated from the μg atoms of C and N.
The C_{org}/N ratios were really stable during the whole sampling period with a mean of 5.039/1. The corresponding atomic C:N ratio would be 100:23.14.

Most of the time, the smaller size fraction had a slightly higher C_{org}/N value.

Like the dry mass, there were peaks of C_{tot}/N ratios when the temperature dropped on West(see fig. 3.12 and 3.13). No such thing was observed for the C_{org}/N.

Microscopic observations of the seston

The samples which showed dry mass peaks were the ones described as containing a lot of sand in the microscopic observations. The other ones didn't contain any sand or only very few.
This sand was made mostly of debris of carbonate (corals) and shells (pteropods and foraminifers), very few quartz, which explains the simultaneous $_{tot}$/N peaks.

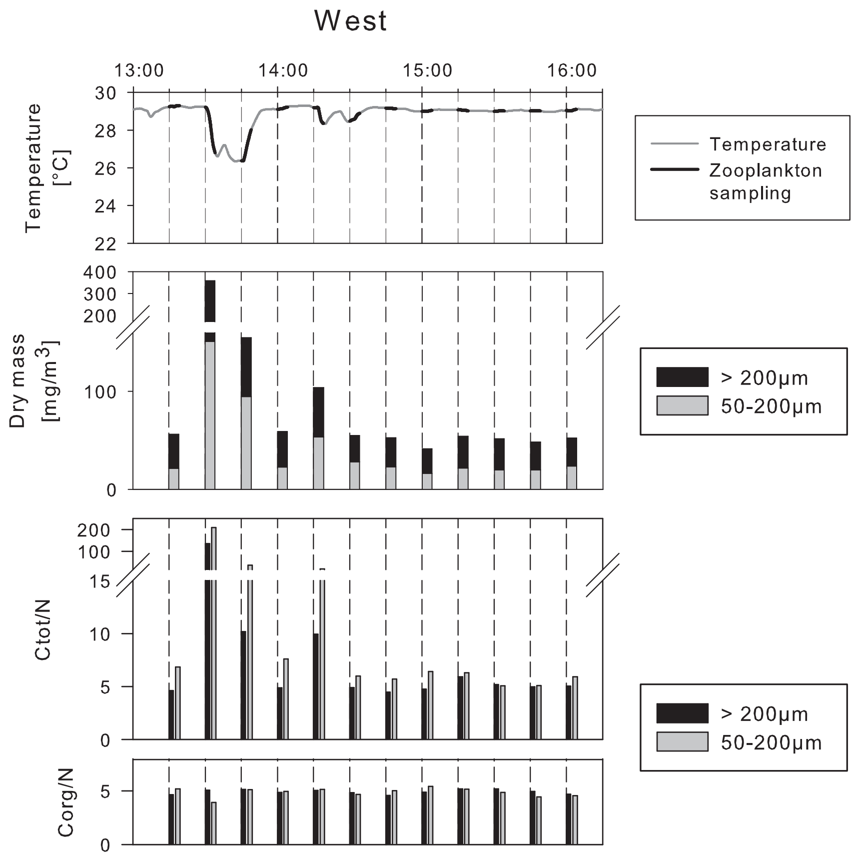

Figure 3.13.: Dry mass and C/N composition of the seston on the 11.03.08 on the west side of Ko Miang.

These samples also contained a lot of gastropods and planktonic foraminifers, which, after staining with bengalred, revealed to be only dead, empty shells.

The following planktonic forams species were identified: *Globigerina bulloides* and *-calida*, *Globigerinoides rubber*, *-sacculifer* and *-siphonifera*, *Globigerinita glutinata*, *Neogloboquadrina dutertrei*, *Globorotalia menardii* and *Pulleniatina obliquiloculata*, the six first ones being the more common (Barbara Donner, personnal communication).
Some living bentic foraminifers were also found.

3.3.3. Nutrients

In March 2007 (fig.3.14) and February 2008 (fig.3.15) N_{Ox} showed a tendency to increase greatly from almost zero to up to 4 μmol/L when an internal wave arrived on either side of the island.
Phosphates and silicates presented a similar pattern with also some variations out of any temperature drop, never reaching offshore values below 40m.
Ammonium stayed below detection limits in 2008 and didn't show a clear temperature related pattern in 2007.

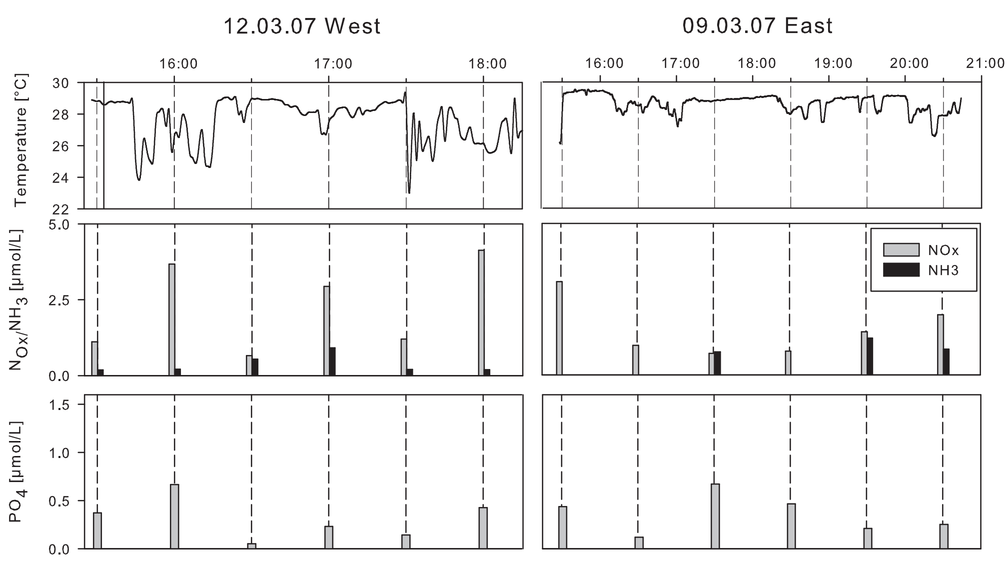

Figure 3.14.: Concentration of N_{Ox}, NH_3 and PO_4 in March 2007 on both sides of Ko Miang (vertical dashed lines represent the time of sampling).

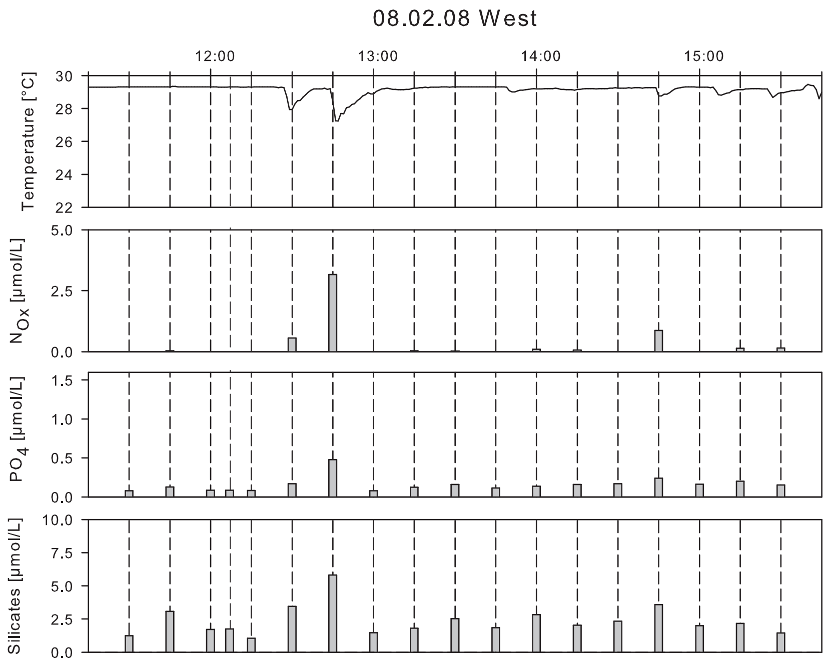

Figure 3.15.: Concentration of N_{Ox}, PO_4 and silicates on the 08.02.08 on the west side of Ko Miang (vertical dashed lines represent the time of sampling).

4. Discussion

4.1. Internal waves in the Similan Islands

4.1.1. Type of waves

The large amplitude solitons generated in the Andaman Sea are reaching the Similan Islands, causing regular temperature variations over a short time scale, up to several meters above the bottom.

There is no evidence that these internal waves are broken when they reach the central island Ko Miang . But it can be assumed, that, given their high amplitude offshore, the depth of the pycnocline and the bathymetry around the islands, they at least experienced shoaling and probably breaking on the continental slope before arriving to the Similan. In addition to this, Leichter et al. (2005) observed the arrival of both unbroken internal waves and bores to a coral reef in Florida. The bores were presenting stronger currents and higher frequency than the unbroken waves. This fits with my observations and supports my assumptions.

4.1.2. Incidence and duration

The tidal frequency of the internal waves (Osborne and Burch, 1980; Alpers et al., 1997), couldn't be observed around Ko Miang. The solitons are reaching the island more often than expected. This is probably due to the crossing of several waves packets coming from different directions (see fig. 1.3).

In Florida, the duration of the temperature drops caused by tidal bores in the reef are lasting 20 min to several hours until the thermocline water evacuates through gravity processes (Leichter et al., 1996). In the Similan, the cold water incursions generally don't exceed 15 min. This might be explained by the different type of waves observed, their speed and the configuration of the site. In Ko Miang, the internal waves seem to arrive faster and might reflect on the granite boulders located on the west side of the island, leaving as fast as they come.

There is a strong seasonality in the occurrence and strength of internal waves around the Similan. During the rainy season, the thermocline is quite deep (60-70m) due to mixing by wind and storms, while the water column is more stratified during the dry season, with a thermocline located at about 30-40m depth (Nielsen et al., 2004). In December, the thermocline must still be quite deep and the internal waves might break deeper or be reflected on the shelf slope, explaining the lower occurrence of temperature drops around the island than in March.
In March 2007, the thermocline was shallower than in March 2008 (Claudio Richter, personal communication) and the solitons reaching Ko Miang stronger. This gives further support to the relation between the thermocline depth and the occurrence of internal waves in the Similan.
As such, internal waves might not reach the islands during the Southeast monsoon.

4.1.3. Changes in water properties and their effect on corals

Leichter et al. (1996) observed variations in temperature (up to -5.4°C), salinity and current related to the arrival of tidal bore to the Florida Conch Reef.
On the west side of Ko Miang the water temperature at 20m depth can make jumps from 29°C to 19°C over a few minutes. At the same time, salinity, pH, oxygen and currents are also varying. Like in Florida, it is likely that this water comes from the thermocline.

These changes in water properties are observed on both sides of the Similan, but are more pronounced on West. The benthic community might so be more affected by the internal waves on this side.

It has been proven that temperature affects the physiology of corals (Brown, 1997; Stone, 2007). Wolanski et al. (2004) even suggested that internal waves, not light, might limit the lower depth where corals are able to grow in Micronesia.
The temperature variations associated to the arrival of solitons are a stress for the corals of Ko Miang. But they could also, by their cooling effect, be of some help for reefs to resist climate change (Mélanie Bon, unpublished data).

4.2. Effects on the zooplankton

4.2.1. Plankton as food

Internal waves don't represent a significant supply of food for the benthic community of Ko Miang.

There is less zooplankton in the cold water of the solitons than in the warm reef water. However, only 30% of the abundance data were explained by the temperature alone. There must be other factors influencing the zooplankton concentration.

Leichter et al. (1998) found that calanoid copepods, the dominant group in the zooplankton, were more abundant in the bores than in the reef water in Florida. But, as discussed in the previous chapter, the internal waves studied there were quite different from the ones arriving in the Similan.
The method used, a plankton net propelled one meter above the bottom by divers, also differs from the one used in this study. However, Pineda (1999) could prove a transport of zooplankton in warm fronts behind tidal bores by using a pumping method similar to the one I used.

As the mean zooplankton concentration remains the same in March and December, the suspension feeders aren't exposed to starvation but the availability of their zooplanktonic preys is decreasing when an internal wave arrives to the island.

4.2.2. Larval supply

The arrival of barnacle larvae to Ko Miang is related to the occurrence of internal wave. However, given that only one wave was clearly containing a huge amount of barnacle larvae, it is impossible to say if the larvae were transported by the bore itself (Leichter et al., 1998) of by the surface slicks (Kingsford and Choat, 1986; Shanks, 1986; Zeldis and Jillett, 1982).

No other larvae were found to be brought by solitons. Echinoderm larvae where even more abundant in their absence, but their concentration is usually varying a lot along the Thai coast (Suree Satapoomin, personal communication).
As within a same taxonomic group, different species might present distinct concentration patterns in internal waves, focus on species might have brought different results (Pineda, 1999).

To take in consideration is also the fact that, on the west of the Similan, the nearest island is 400km away. Though possible, it seems quite unlikely that larvae might be transported from there (Levin, 2006).
But meroplanktonic larvae released by benthic organisms in the Similan might be transported back by internal waves or even to islands located further east.

4.2.3. The thermocline, a source of plankton?

If we compare the composition of the plankton in the internal waves reaching the Similan and in the offshore samples, there is no direct evidence that thermocline zooplankton might reach the islands.
I have few replicates in the thermocline and my offshore samples were taken in October, not in March. But my results fit with previous studies (Munk et al., 2004; Satapoomin et al., 2004) who found a very low seasonal variability in the composition of zooplankton.

On the other hand, the zooplankton amount in the cold water reaching Ko Miang is very near from the concentration in the thermocline.

What is striking is that the proportion of copepods in the internal waves is lower than in the reef or in the thermocline. It might be that, due to their swimming abilities (Seuront et al., 2004), copepods escape from the solitons on the way between the shelf break and the island. This would explain the changes of composition.

There might also be a difference between offshore and near-reef samples due to the sampling methods. Pumps might face a bigger problem of zooplankton escape than nets (Harris et al., 2000). In our case, this would mean that fast swimmers are underestimated in the samples taken around Ko Miang. But as in warm reef water the non-copepods organisms don't show an unusually high proportion this shouldn't be the case in the internal waves.

There is less zooplankton offshore, even in the thermocline, than around the island. This implies that upwelled thermocline water could only bring a substancial amount of zooplankton to the reef if there is a phenomenon of concentration along the way (Johnson et al., 2001). This seems not to be the case, except for barnacle larvae, polychaets and ostracods.

However, despite the low amount of zooplankton contained in the internal waves, they could still be considered as an input if this zooplankton is somehow trapped in the ecosystem.

Another important point to mention is that the thermocline contained a lot of phytoplankton. Leichter et al. (1996) found a high chlorophyll a content in the internal bores in Florida. Internal waves could represent a supply of phytoplankton to the Similan, but this hasn't been considered here.

4.3. Seston: organic and non-organic particles

4.3.1. Elemental composition

Table 4.1 compare the atomic C_{org}:N ratio found in the Similan Islands with values given in the literature.

Table 4.1.: Values of atomic C:N ratio for plankton and seston

Reference	Group	Atomic C:N
Redfield et al. (1963)	Phytoplankton	100:15.09
Beers (1966)	Copepods	100:19.83
	Polychaets	100:25.57
	Jellyfish	100:34.41
Reviewed in Harris et al. (2000)	Zooplankton taxa	min 100:28.57
	Zooplankton taxa	max 100:7.57
Webb et al. (1975), coral reef	Seston	min 100:12.50
	Seston	max 100:27.78
This study, Ko Miang	Seston	100:23.14

As most of the phytoplankton was excluded, due to the mesh size used, it isn't so surprising to find values differing from the Redfield ratio.
If we consider only organic carbon, the main component of the seston was zooplankton. Our value fit in the range given in the literature even if it would have been expected to be a little bit lower, given that the copepods were the dominant group.

The difference in the ratio between the size fractions can be explained by a lower nitrogen content in the smaller fraction, which could be due to a higher proportion of phytoplankton or of detritus.

4.3.2. Input of sand

Internal waves are bringing sediment to the Similan Islands. It is composed of debris of corals, foraminifera and gastropods shells and contains some benthic organisms. To be noted is that the opening of the sampling tube which collected sand was located between 10 and 20m above the bottom. This gives us an idea of the energy of the solitons reaching Ko Miang.

No sediment was observed in offshore samples so this carbonate-rich sand must come from the seafloor. The resuspension process might happen on the continental slope and/or on the way from the shelf break to Ko Miang (Bogucki et al., 1997; Hosegood et al., 2004; Johnson et al., 2001).

This constant input from the deep might explain the differences in the sediment composition between the east and the west side of Ko Miang (Carin Jantzen, unpublished data).

One of the forams species observed, *Globigerina bulloides* is common in upwelling regions (Lidz, 1966) but as we had mostly dead shells and we don't exactly know where they come from, we can't draw any conclusions about them.

4.3.3. Impact on corals

The huge quantity of suspended matter transported by the internal waves to the Similan reduces the light availability for benthic organisms.

Anthony and Fabricius (2000) found out that high particle load, beside its direct stressing effect (abrasion, deposition on tissues), could lead to a switch from phototrophy to heterotrophy in corals. This acclimation capacity is species dependent. Evidences for such a switch have been found in some corals of the Similan (Cornelia Roder, unpublished data).

4.4. Nutrients supply

4.4.1. Quality and origin

Internal waves bring nitrates to the Similan Islands. They also transport phosphates and silicates but the supply is less marked.
The concentrations of N_{Ox} in the cold water of the solitons are up to 30 times the values in reef water and similar to those observed in internal bores in Florida (Leichter et al., 2005).
Amounts of nutrients in the warm reef water are in the range given in the literature for coral reefs (see table 4.2). Only nitrates are a bit higher, especially in March 2007, when Ko Miang was under a constant flow of internal waves.
When the soliton activity is less intense, nutrients arrive in form of pulses and might be available only for organisms able to assimilate them quickly.

Table 4.2.: Nutrients concentration in coral reefs(μmol/l)

Reference, hydrodynamic	Nutrient	Reef water	Cold water
Webb et al. (1975)	N_{Ox}	0.02-0.17	no
Kinsey (1979)	N_{Ox}	<0.5	no
	PO_4	0.15-0.6	no
Andrews and Mueller (1983)	N_{Ox}	0,09-0.47	no
	PO_4	0.14	no
Wolanski et al. (1988), Upwelling	N_{Ox}	0.04	up to 0.26
	PO_4	0.14	increase
	Si	1.03	?
Leichter et al. (2003), Bores	N_{Ox}	0.1-0.2	1-4
This study, Solitons	N_{Ox}	<1.0	up to 3.1
	PO_4	<0.2	up to 0.7
	Si	<3.0	up to 5.8

Offshore, the pattern of N_{Ox} and PO_4 fit with results found in previous studies (table 4.3). The concentration of nutrients increases with increasing depth.
Values found in the internal waves are the same or a bit lower than those found in the thermocline. This corroborates the hypothesis that internal waves transport thermocline water or a mix of thermocline water and surface water to the Similan.

Table 4.3.: Nutrients concentration in the Andaman Sea (μmol/l)

Reference	Nutrient	Surface	Thermocline	Deep
Nielsen et al. (2004)	N_{Ox}	<0.1	0.1-10	up to 30
	PO_4	0.05	0.05-1.3	up to 2.6
This study	N_{Ox}	<1	4 - 6	up to 15.5
	PO_4	<0.5	0.4 - 0.8	up to 1.5
	Si	<6	6 - 8	up to 45.0

4.4.2. Increase in nitrates: good or bad new?

As we see in the thermocline, a higher nutrient concentration might enhance the development of phytoplankton, and so trigger an increase of food available for the benthos around the Similan.

Ferrier-Pagès et al. (2001) found out that an increase in nitrates don't change rates of photosynthesis in corals. But a high concentration might favorise the growth of algae over corals (Wolanski et al., 1988).
The higher density of turf algae on the west than on the east side of Ko Miang might be a consequence of the nutrient input by solitons (Carin Jantzen, personal communication).

4.5. Conclusions

Internal waves, whether they are broken or not, bring cold water from the thermocline to the Similan. On their way from the shelf break, they resuspend sediment and transport it to the islands.
This process, far from bringing zooplanktonic food to the benthos, is representing a stress for the corals. It might explain, by its effects more pronounced on one side, that there is no real coral reef on the west of Ko Miang, although the impact of the Southwest moonson cannot be neglected.
Nevertheless, solitons also have a positive influence on the islands as they are bringing larvaes to the reef community. Their input of nutrient might enhance the productivity of the ecosystem but also enhance the development of algae to the detriment of corals.

These impacts are more or less pronounced along the year and might disappear during the rainy season.

Internal waves have been observed in regions rich in coral reefs, like Indonesia and it might be interesting to see if the same patterns are observed in these parts of the world.

A. Appendix

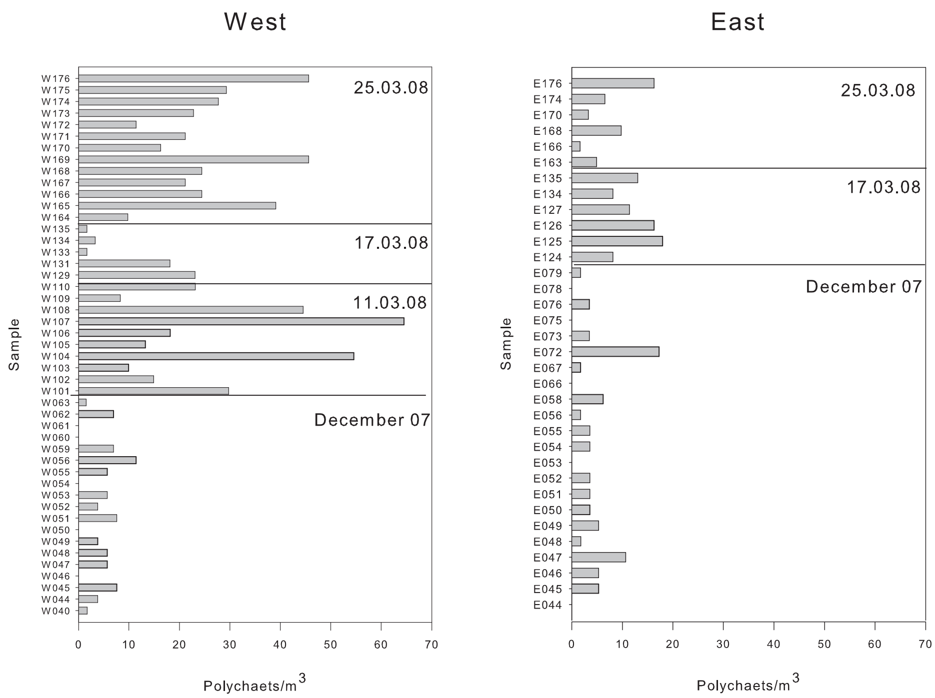

Figure A.1.: Concentration of polychaets on both sides of Ko Miang during the whole sampling period.

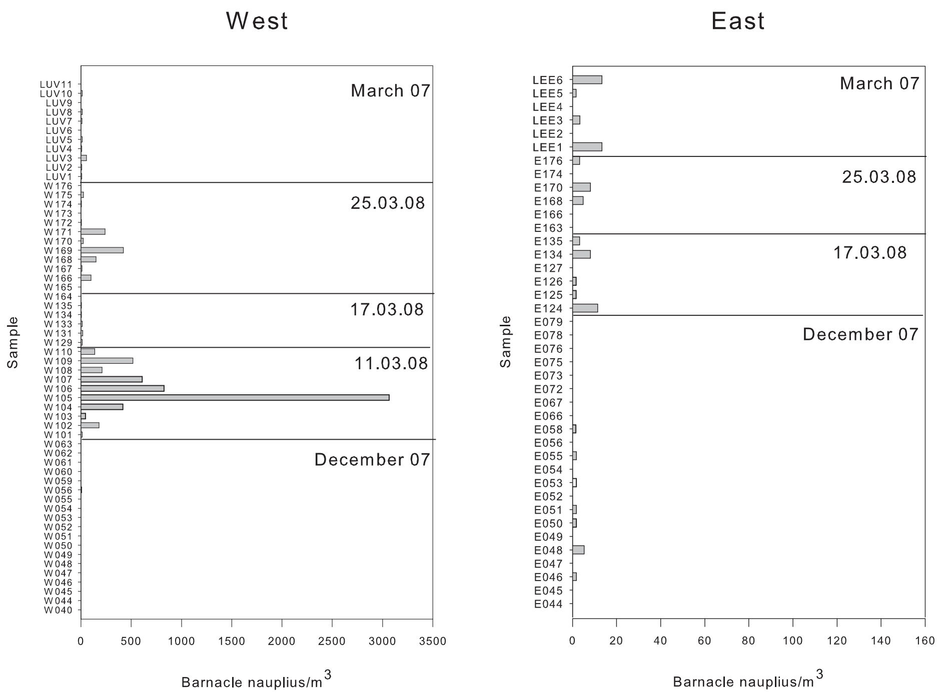

Figure A.2.: Concentration of barnacle nauplius on both sides of Ko Miang during the whole sampling period (note the different concentration scales on east and west).

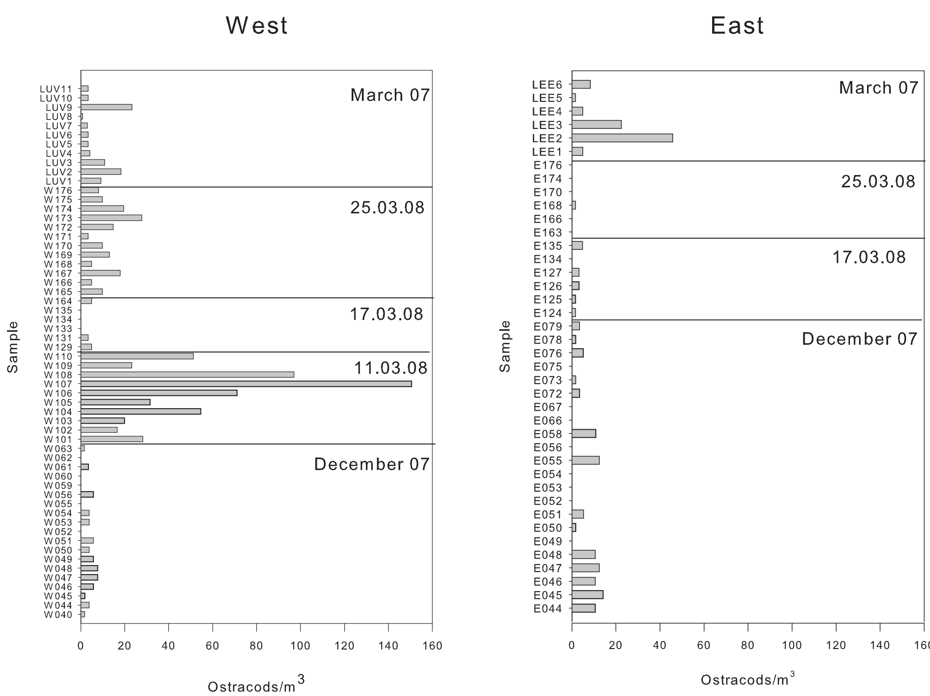

Figure A.3.: Concentration of ostracods on both sides of Ko Miang during the whole sampling period.

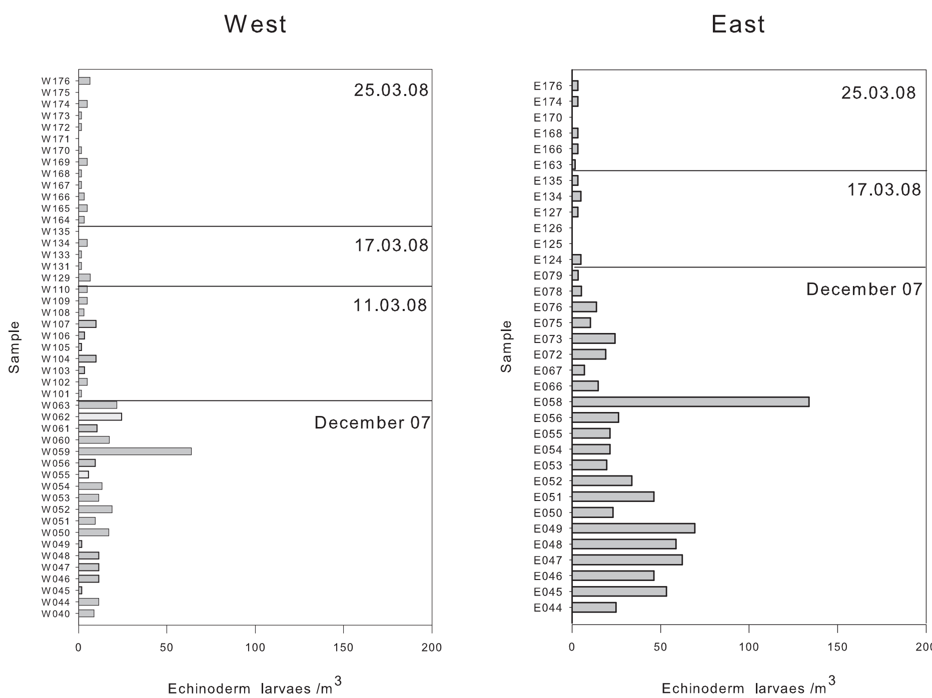

Figure A.4.: Concentration of echinoderm larvaes on both sides of Ko Miang during the whole sampling period.

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