Deployment of wireless sensor network to study oceanography of coral reefs.

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Abstract

Great Barrier Reef Australia (GBR) is affected by cold water intrusions originating in the Coral Sea and upwelled on the reef. Therefore biological interest in GBR upwelling has been driven by the view that upwelled waters rich in nutrients boost plankton production and overall productivity of the GBR system. Upwelling can be a high frequency short-duration event and therefore it may be challenging to quantify synchrony between physical and biological change impacting the reef. We deployed a Wireless Sensor Network (WSN) for in situ monitoring of upwelling. Temperature is a good proxy for upwelling however 3D dense spatial data is required to correctly describe upwelling and their impact on plankton abundance. The array of underwater sensors was deployed at various depth on the coral reef in Nelly Bay, Magnetic Island, GBR. We propose that the temperature data is communicated real time via ad hoc network using RF signal to the on-shore base station. This permits us to collect the plankton data in real-time synchronized to the temperature changes. To explore the utility of WSN we also deployed data loggers to collect temperature data from the same location. . This paper outlines the methods of the deployment of WSN for ecological research. It also describes preliminary results. Our preliminary findings did not produce sufficient evidence for upwelling however we did find that the water temperature can vary by as much as 1 °C even on a small spatial scale due to stratification of the water column. Stratification can influence depth-related abundance of plankton and the supply of food to reef associated organism however we could not confirm this with statistical confidence due to the lack of plankton data collected while water stratification was present. The use of robust real-time WSN to trigger plankton collection at the events of upwelling or stratification would have assisted with this investigation.

1. Introduction

Understanding the relationships between physical and biological oceanography is a challenging task due to very dynamic nature of the oceans. This calls for the deployment of new methods and technology in oceanographic studies that allows detecting and communicating the changes in real-time. It was proposed to deploy Wireless sensor Network to quantify the synchrony between physical and biological changes impacting the reef due to oceanic upwelling [1].

Coral reefs have incredible diversity and density of organisms and could not survive without input of additional nutrients from outside the reef [2]. Upwelling has the potential to facilitate such input and also have a great influence on the supply of planktonic food for reefs [2, 3]. Upwelling can be a high frequency short-duration event and therefore it may be challenging to quantify synchrony between physical and biological change impacting the reef. The objective of our study was to describe variation in water temperature on a tropical reef caused by upwelling and water stratification and determine the influence that physical oceanography has on distribution of plankton.

In the Great Barrier Reef (GBR), Australia, cold water intrusions come from the Coral Sea bringing nutrients into GBR waters [4]. Biological interest in GBR upwelling has been driven by the view that upwelled waters are rich in nutrients and contribute significantly to the overall productivity of the GBR system [4]. Moreover, Furnas and Mitchell [4] found strong correlation between temperature and concentrations of phosphate, nitrate and silicate in upwelled regions of GBR. The ocean fluctuations in nutrients result in variations in the growth of marine organisms such as phytoplankton [5-7]. Understanding the plankton abundance and composition within the complex GBR ecosystem is essential to understanding the GBR food chain.

Plankton is considered to be some of the most important organisms on Earth since it is a primary food producer for most aquatic life. Based on the trophic level, plankton could be divided into three broad groups: phytoplankton (producer), zooplankton (consumer) and bacterio-plankton (recycler) [8]. Understanding the phytoplankton productivity in the world ocean has recently became a major concern because of its role in CO2 recycling and therefore the effect on global climate change [9]. In addition to making a significant contribution in removing carbon dioxide from the atmosphere the phytoplankton create the foundation of ocean food chain.

The phytoplankton generally increases in biomass at the junction where frontally convergent circulation has either supplied limiting nutrients or resulted in the aggregation of plankton particles [7]. Thomson and Wolanski [10] established that strong tidal currents can pump nutrient-rich water from below the mixing layer through the reef passages onto the shelf. Such inputs of inorganic nutrients are responsible for the large fluctuations in phytoplankton biomass and overall primary production [5]. Phytoplankton blooms, defined as rapid growth, take place when upwelled waters bring nitrate, phosphate and silicate nutrients into euphotic zones [5]. Plankton species can move up and down the water column [11], thus plankton abundance should be estimated with respect to depth and appropriate 3D sampling design is important.

The upwelling can be caused by various dynamic processes in the ocean including wind, topography and tidal movements. Large scale coastal upwellings are generally driven by wind force. This type of upwellings occur when alongshore winds generate Erkman transport causing the surface waters to move offshore and be replaced by deeper nutrient-rich water that upwells close to shore [12]. High frequency coastal upwelling can also be associated with tidal jets, internal tides, internal waves and internal tidal bores [13]. The temporal and spatial variability in upwelling near coral reefs may contribute to temperature variability, the balance between locally- and remotely-derived nutrients, and the overall dynamics of coral reef system [14].

The GBR upwelling allows the cross-shelf intrusions of Coral Sea water through the reef matrix [15]. Andrews [16] used temperature to trace cross-shelf transport which in open stratified water produces a marked bottom-temperature signal. The temperature was found to mark the upwelling intrusions adequately [16]. Furnas and Mitchell [4] found that nitrate, phosphate and silicate concentrations are strongly correlated with water temperatures.

We hypothesize that changes of sea water temperature impact the abundance of plankton and propose to set up real-time monitoring of the effect of high frequency temperature changes on plankton abundance. To be able to trace the effect of high frequency temperature changes due to daily tides, stratification events and upwelling with sufficient tolerance we decided to monitor on a relatively small spatial scale compared to previous studies. We hypothesize that daily tides have similar effect on plankton abundance as previously documented upwelling but with smaller magnitude. Thus the aim of this study was to understand the effect of high frequency changes in the sea water temperature due to tidal fluctuations on plankton distribution and abundance on 3D scale at Nelly Bay, Magnetic Island, Australia.

We employed a Wireless Sensor Network (WSN) for in situ monitoring of temperature on 3D scale in order to be able to collect high quality spatial data required to fully understand the impact of temperature on the distribution and composition of plankton species. Data loggers have been deployed by Australian Institute of marine Science for in-situ monitoring of sea temperature along various reefs of GBR. Data loggers instantaneously record sea temperatures every 30 minutes and are downloaded every 6 to 12 months, depending on the site. The daily fluctuations of sea temperature in Nelly Bay, Magnetic Island were recorded by such data loggers and reached up to 2 °C difference in March 2005 (Fig. 1). When comparing temperature data from Nelly Bay to the tide chart for the same period of time (Fig. 2) we see a trend that generally high tide causes a drop in water temperature and spring tide (increase in amplitude) result in higher variations of temperature between reef flat and reef slope. However more detailed analysis over longer period of time including additional factors such as solo radiation and wind power would be required to confirm this preliminary observation. While such existing data loggers provide excellent insight into high frequency temperature variations it is difficult to measure the biological impact in real time. The data loggers store the information which can download every 6 months thus immediate collection of plankton samples in the event of high temperature variation is not possible. We therefore propose to employ WSN to allow biological data collection (plankton) at the same time.

Utilization of WSN technology is quite appropriate when dealing with very dynamic organisms such as plankton. One of the main challenges faced in plankton field studies is the fact that plankton communities are very dynamic and under favorable conditions the cells can divide quite rapidly [17]. Large short-term fluctuations in phytoplankton biomass as well as transport of matter and energy through plankton community [17] calls for a special sampling technique where sampling can be performed shortly after the potentially favorable conditions have been detected. We deployed WSN to collect 3D temperature data and communicate information about changes in the water column in real time.

2. Methods

2.1 Sensor Array

The array of sensors was deployed on 3 dimensional spatial scale with horizontal coordinates spaced out along the reef crest and reef flat and at various depths. Sensor network is a term used to describe the latest trend in electronic monitoring where each sensor contains a small computer able to manage and collect environmental data and transmit in real time [18]. Ambient Systems is a supplier of wireless mesh networking solutions that consist of chips embedded with the Ambient's networking software and radio transceiver technology [19]. In this study we used Ambient Systems smart temperature sensor solution based on one-wire devices DS18B20 from Dallas Semiconductor. The DS18B20 communicates over a 1-Wire bus that by definition requires only one data line (and ground) for communication with a central microprocessor. Each DS18B20 has a unique 64-bit serial code, which allows multiple DS18B20s to function on the same 1–wire bus; thus, it is simple to use one microprocessor to control many DS18B20s. The resolution of the temperature sensor is user-configurable to 9, 10, 11, or 12 bits, corresponding to increments of 0.5°C, 0.25°C, 0.125°C, and 0.0625°C, respectively. In this study the sensors programmed to the maximum resolution of +/-0.0625 °C.

Multiple DS18B20 sensors are connected on one-wire to a processing unit called Unode supplied by Ambient Systems (Fig. 3). The Unode also has integrated RF networking capabilities to communicate with other Unodes and the base station (see http://www.ambient-systems.net) thus allowing us to create sensor network with real time data transmission capabilities. Each string of temperature sensors is connected to a Unode (Fig. 4) and positioned underwater inside of an hydraulic cable at various depths (2 meters apart) (Fig. 5). We employed a sensor network consisting of 2 arrays with 4 Unodes each (Fig. 6). Sensor network offers several advantages over historical monitoring techniques by streamlining the data collection process, potentially minimizing human errors and time delays, reducing overall cost of data collection, and significantly increasing the quantity and quality of data on temporal and spatial scales [20].

Wireless sensor networks allow fine grained interface between the virtual and physical worlds and thus represent the future for environmental monitoring [21]. In a sensor network, each node is able to manage the collection of environmental data. This management includes interacting with other sensors to determine the data collection rates and electronic system status. The environmental data is then packaged up using standard networking protocols to broadcast into the network. This means that if the node is unable to directly contact the target base station the data can be rerouted to the target via other sensors (ad hoc network establishment). There is no hierarchy between the nodes and they can be spaced out randomly to form multi-hop mesh as long as the distances are within the signal reach. The sensors communicate unique identification number and thus the data can be tagged with three dimensional attributes (x, y and depth). The transmitting frequency band of 900 MHz was selected as the most suitable compromise between board rate, humid environment and commercial availability of transmitters [1].

Due to corrosion of underwater cables and physical damage from wave action, the temperature data from WSN was only received for 16 hours on 21st and 22nd of September thus limited my analysis.

2.2 Dataloggers

To ground-truth the data we planned to receive from WSN we also used TG3100 temperature data loggers (Gemini Data loggers UK Ltd), that were calibrated to measure temperature with ± 0.2 °C accuracy. These data loggers are manufactured in water proof packages thus we could place them on the outside of hydraulic cables containing DS18B20 sensors. We employed TG3100 temperature data loggers to record temperature data over time at two depth levels and different spatial position on reef profile. We placed data loggers on four moorings out of total 8 moorings used by WSN. The inner moorings were positioned on reef flat and outer moorings on the outer edge of reef slope.

Data loggers were attached to mooring lines at two depth levels, 1m from the sea surface and 1m from the sea floor (Fig. 5). The loggers at two depth levels were expected to detect the presence of stratification or upwelling. In total, eight data loggers were synchronized and programmed to record temperature every 10 minutes for the period from 05/09/2007 until 25/09/07.

2.3 Study site

The data on temperature and plankton was collected at Nelly Bay (146 51' 9" E 19 9' 52"S), Magnetic Island, Australia. Magnetic Island is situated about 7 km of Townsville; it is bordered by a number of sheltered bays with fringing reefs. Magnetic Island is classified as inner-shelf reef and is situated 7 km offshore. Nelly Bay's 1800m-wide sand and rubble intertidal reef crest and slope area will be used for data collection (Fig. 6). The temperature collecting nodes were spaced out along Nelly Bay reef crest and reef flat at various depths.

2.4. Temperature stratification and upwelling

We expected to detect both water stratification and upwelling during observation period. The intrusion of cool water to coastal areas often varies with lunar tides [13]. It was predicted therefore that stratification and upwelling would be greatest during spring tides. To separate these events from the temperature offset caused by calibration and resolution of DS18B20 sensors and TG3100 data loggers the threshold had to be established. Based on the resolution of TG3100 the maximum error rate would be 0.4 °C, but this level of error would be very unusual. A criterion of 0.5°C net vertical gradient from the surface temperature was recommended as a threshold to distinguish weakly stratified regions from unstratified [22]. We therefore selected this criterion (0.5°C as maximum difference between shallow and deep temperatures, ΔT) for the water column to be considered mixed. Thus stratification or upwelling were to be detected if $\Delta T \geq 0.5$ °C.

We expected to be able to detect upwelling as cold water intrusions moving vertically up and horizontally towards the shore and finally reaching the surface. It was predicted that the outer mooring sensors would detect temperature drops first and then cold water intrusions would reach inner moorings but with some time delays.

2.5 Plankton data collection

To measure the influence of water temperature on plankton abundance depth stratified plankton samples were collected next to each temperature station. I expected that depth related patterns would be greatest at spring tides and therefore plankton samples were collected on a high tide during spring tides using Niskin bottles. Niskin bottles are a common technique for small size plankton sampling; they are cylinders that can remove columns of water of known diameter and depth [23]. The Niskin bottle method was preferred for this study over collection with plankton net because it minimizes trauma and enhances the survival of phytoplankton taxa that are easily damaged or killed when they come into contact with the mesh of plankton net [24]. This method also allowed us to take samples precisely next to each temperature station which would not be possible with long tows of plankton nets. In this study I used 5-litre Niskin bottles. The water samples were collected next to each temperature station at two depth levels that corresponds with the depth of temperature loggers (1 meter from the sea surface and 1m from the sea floor). We collected plankton samples at the time of high tide during spring tides (high tide of ≥ 3.4 meters). In total we collected 40 samples over 5 days from 6^{th} to 11^{th} of September 2007.

The water bottle adequately sampled mesoplankton (0.2 mm-2 mm) and microplankton (20-200 µm). A 50 µm mesh sieve was used to concentrate 5-litre field samples into 250 ml jars. All samples were concentrated and preserved in 2-5% formalin within three hours from collection to avoid predation or decomposition.

2.6 Laboratory techniques

In the laboratory facilities samples were further filtered using 50 µm mesh sieve to a 20 ml concentrate out of which 1ml subsamples were taken. We used a modified 10 ml calibrated pipette with wide mouth (5mm) to provide wider entrance for the small organisms [24]. The 20 ml concentrate was stirred prior to taking a subsample. Manual mixing was not sufficient to mix up and break up colonial phytoplankton. Phytoplankton species which aggregated in colonies or chains were excluded from counts due to higher effect of patchiness on subsample variance. Thus only unicellular unchained species were counted and analyzed. I used Sedgewick grid which contains 1ml of subsample volume for plankton counting.

3. Results

3.1 Temperature variations and physical oceanography

The water column was generally homogeneous in September 2007 however a vertical stratification was found on some occasions at both transects (Fig. 7). The average difference between shallow and deep data loggers was 0.1 ºC which indicated that the entire study area was a mixed layer. Stratification events occurred during spring and neap tides (Fig. 7) and were most obvious at the outer sites. In contrast, the waters were well mixed at the inner sites. The maximum temperature difference between surface and near the substratum loggers was 1.2 ºC (1pm on 6th of September, Fig.7b). A 1 ºC difference on 17th of September ranked second and occurred around 4pm (Fig. 7b). The first stratification event lasted for 2 hours (12pm-2pm) and the second event on 17th of September lasted for 8 hours (11am-7pm) calculation based on critical criterion of $\Delta T \geq 0.5$ ºC.

The first stratification event occurred during spring tides (maximum amplitude of 2.7 meters) and the second event occurred during extreme neap tides (amplitude of 0.8 meters, Fig. 7). Tide amplitude therefore was not the main factor driving temperature stratification as originally predicted. This was confirmed by regression analysis that showed no relationship between the tide amplitude and stratification level represented as the difference between temperatures of shallow and deep layers of the water column ($r^2 = 0.0035$; ANOVA F=0.267; df=1,78; ns,). The data also showed that extreme spring tides (amplitude of around 3 meters) did not promote mixing of the water column more or less than tides of lower amplitude. Greatest stratification did not occur at particular phase of the tide. On some occasions stratification was greatest at low tide and others at high tide but during neap tides (Fig. 7). Peak periods of stratification were during tides of low amplitude and near low water at other times (Fig. 7).
No upwelling was detected during observation period. Despite thermal stratification the cold water did not persist at the surface. The daily temperature drops of 0.8 ºC on average did not always correlate with phase of the tide (Fig. 7). Moreover, high temperature variations between daily maximum and minimum occurred during spring tides (maximum difference of 1.3 ºC, Fig. 7) and during neap tides (maximum difference of 1.1 ºC, Fig. 7). Tidal amplitudes did not correlate to daily temperature variations ($r^2 = 0.0049$; df=1, 20; ns). Thus bigger tides did not produce greater differences between daily temperature maximum (peaks) and daily temperature minimum (drops).

3.2 Real time sensor array

The utility of a real time sensor array based on WSN technology was tested and ground- truthed
with data loggers. We compared the temperature data measured by data loggers and real time sensors on the same spatial and temporal scale (Fig. 8). Both datasets showed the same trends, however there was a temperature off set between real time sensors and data loggers of approximately 0.5 ºC (Fig. 8).

3.3 Plankton abundance

The relationships between plankton abundance and depth varied by day for most taxa. When differences were found it was generally at day one of the plankton collection (6th of Sept) when the water column was stratified by 1.2 ºC difference between shallow and deep loggers. Differences in abundance between depths were found at day one for nauplius larvae, diatom *Coscinodiscus* spp. and the dinoflagellate *Ceratium* spp. Abundance of nauplius was high in shallow waters during day one and changes in rank abundance among days resulted in a significant interaction between day and depth. Abundance of copepods varied among days with highest numbers of copepods collected at the last two days of collection period. Although there was a trend for difference of copepod abundance between depths on day two and five this was not detected by ANOVA. Main effects and interactions were not detected for other taxa probably due to high residual variants.

4. Discussion

4.1 Temperature stratification

Although we did not find sufficient evidence for upwelling in this study confirmed initial prediction that the water temperature can vary significantly even on a very small special scale thus adequate spatial resolution is required when collecting temperature data to analyse oceanographic events on coral reefs.

This study challenges the existing view that the inner shelf waters of the GBR Lagoon are generally unstratified [16, 25-27]. Wolanski et al. [26] measured the temperature across the GBR Lagoon offshore from Townsville and found that there were no vertical temperature gradients for inshore waters and some were found offshore during calm weather conditions. Wolanski et. al's [26] measurements were taken weekly from Jan 1979 to Jan 1980 over a large spatial scale. Similar observations were documented by Orr [28] in September-October 1933 in the GBR Lagoon close to Low Isles (station at 16.35ºS, 145.6ºE) in 32 meters of water where they found less than 0.1ºC gradient between surface and deep waters. Similar to Wolanski et al. (1981) Orr recorded temperature on weekly basis [28]. My study was different to previous studies of the GBR Lagoon both spatially and temporally. Stratification events that I found in Nelly Bay were short duration events lasting less than one day. For most of the observation period the waters in Nelly Bay were well mixed (less than 0.1ºC vertical gradient) and thus if the temperature was recorded weekly the stratification events most probably would not be reflected in the collected temperature data. The important implication of my study is that sea surface temperature (SST) data alone may not be reflecting the full complexity of oceanographic processes within lagoon.

4.2 Influence of stratification on plankton distribution

Thermal stratification of the water column influenced the distribution of some planktonic taxa. Stratification often affects the distribution of phytoplankton [29]. In my study there were strong trends for nauplius larvae, *Coscinodiscus* spp. and *Ceratium* spp. to be more abundant in shallow waters when the water column was stratified. Vertical differences in abundance were most obvious in nauplius larvae and *Coscinodiscus* spp, both of which were more abundant in shallow waters during stratification.

4.5 Utilization of real time WSN for oceanographic studies

The ability to explore the relationship between stratification and distribution of prey is often hampered by a lack of real-time data. We demonstrated that utilization of WSN can provide real time communication of temperature data about oceanographic events and consequently biological sampling can be planned to address specific hypothesis. For example, timely information about stratification events would facilitate exploration of the biological effect that physical oceanography has on plankton. Unfortunately due to technical problems with WSN we did not receive real-time data about the second stratification event on 17th of September and thus plankton samples were not collected. This limited our ability to do comparative analysis of plankton abundance during thermal stratification but at the same time highlighted the advantages that WSN technology can offer for plankton studies.

WSN offers several advantages over historical monitoring techniques by streamlining the data collection process, potentially minimizing human errors and time delays, reducing overall cost of data collection, and significantly increasing the quantity and quality of data both temporally and spatially [20]. Wireless sensor networks allow fine grained interface between the virtual and physical worlds and thus represent the future for environmental monitoring [21]. Future studies would be able to utilize wireless sensor network to trigger plankton collection once the water temperature anomalies were detected. The design of the system has to be more robust to be able to survive in the aggressive sea water environment [30] and temperature sensors would have to be calibrated to industry standards prior to deployment.

5.0 Conclusion

This study demonstrated that short term stratification can occur in shallow tropical waters and influence the distribution of plankton. This challenges traditional view that waters of the GBR Lagoon are always well mixed and that surface values of temperature and salinity are representative of the whole water column. Stratification was caused by cooling in shallow water at night. Greatest warming in shallow water happened during low tides and at low tide amplitude phases of the lunar cycle. The ability to observe changes in phytoplankton production at the time or shortly after physical changes in the water column is crucial to furthering our understanding of the trophic dynamics of marine ecosystems. The current study highlights the utility of real time WSN as a means of achieving this goal.

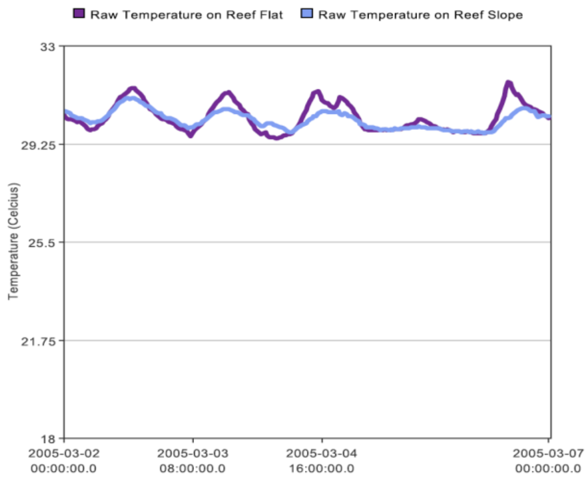

Figure 1. Graph of temperature variation for Nelly Bay for the reef flat (0 metres) and reef slope (5 metres) for the period 2nd to 7th of March 2005 automatically delivered through the www.reeffutures.org website

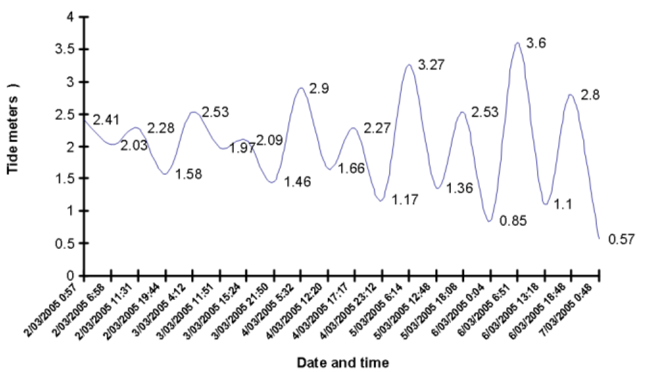

Figure 2. Graph of tidal variations for the period 2nd to 7th of March 2005 for Townsville and Nelly Bay.

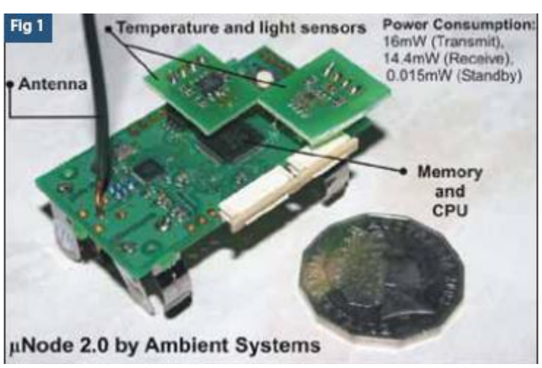

Figure 3. Unode supplied by Ambient Systems |19|

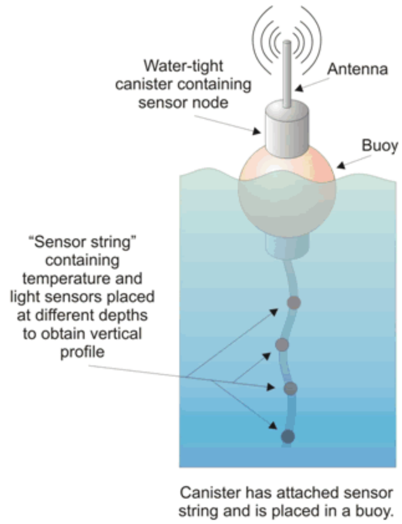

Figure 4. Sensor string design showing the position of underwater temperature sensors and RF transmitter attached to the buoy |19|

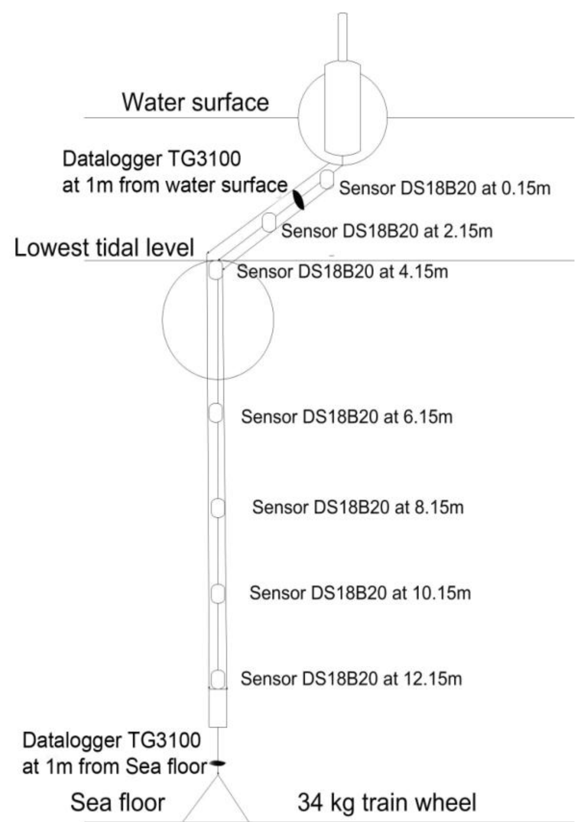

Figure 5. Diagram of the sensor buoy with seven DS18B20 digital thermistors and TG3100 dataloggers.

Figure 6. Study site at Nelly Bay, Magnetic Island, Australia. The sensor network consists of 2 transects with 4 moorings per array. Each mooring has 7 sensors deployed on vertical scale 2 meters apart (Fig. 5)

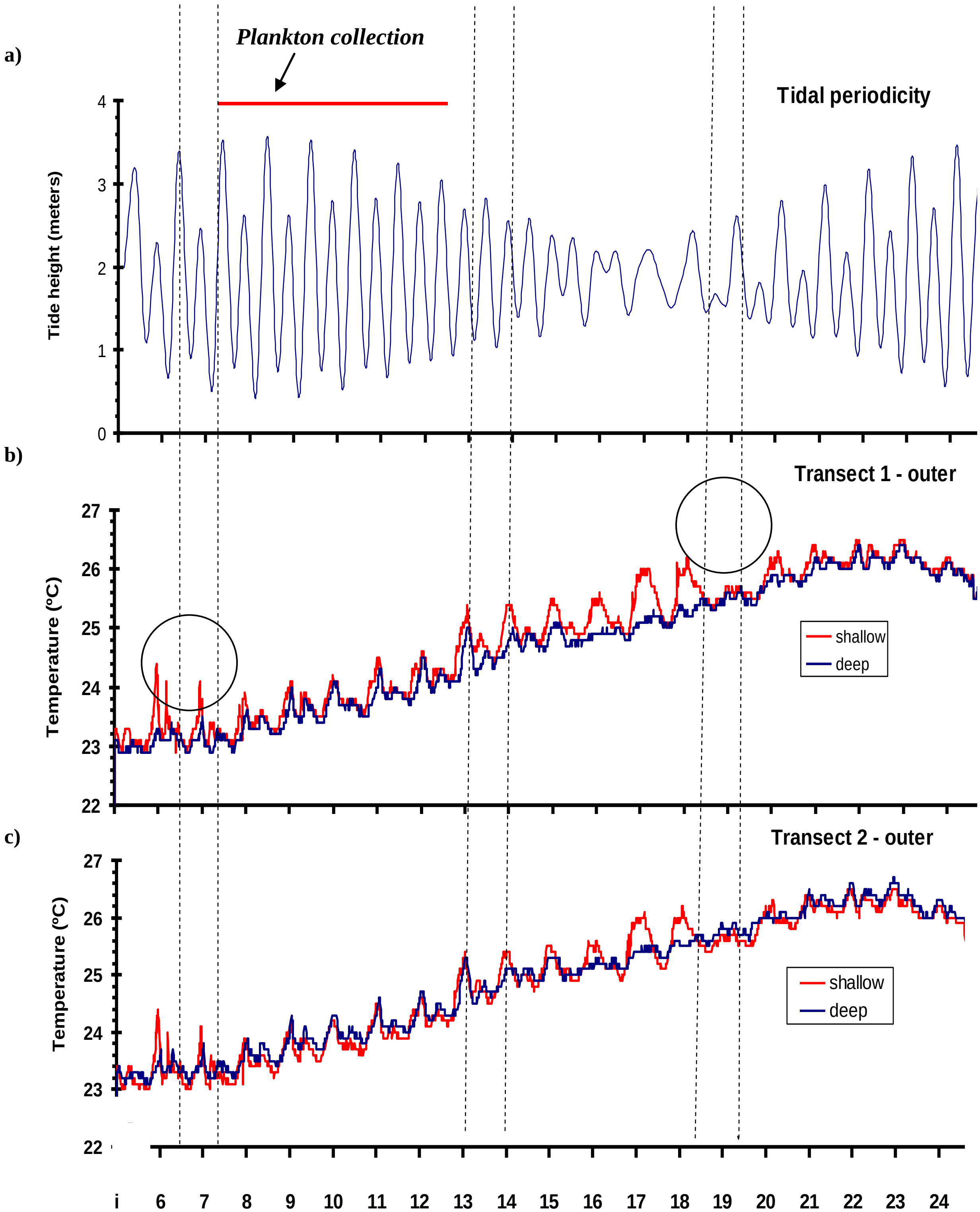

Figure 7: a) Tidal variation during 20 day period in September 2007, the red line highlights the spring tides and when plankton was collected. b) and c) Temperatures at shallow (1m from the surface) and deep (1m within sea floor) dataloggers from transect 1(b) and transect 2(c) recorded at the outer moorings (Fig.6). Circles in Fig. (b) highlight the events of water stratification. The doted lines applied to show the tidal phases during daily temperature peaks and falls on 6, 12 and 17 of September.

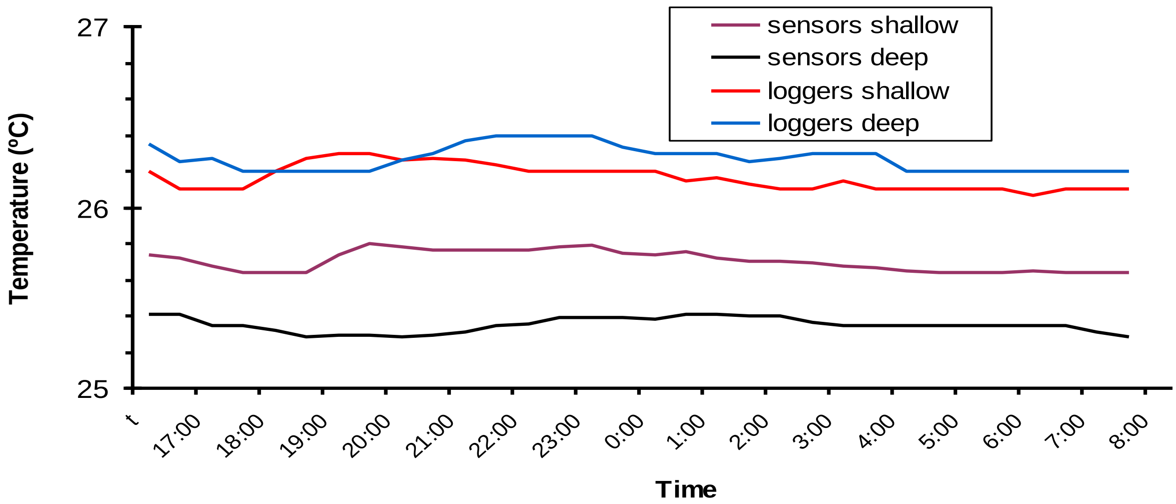

Figure 8: Temperature data collected by the data loggers (TG3100) and real time sensors (DS18B20) at the outer mooring station of transect 2 on 21st and 22nd of September 2007. The data loggers and real time sensors were fixed on the same mooring line at two depth levels: shallow (within 1 meter from the surface) and deep (1 meter from the sea floor).

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