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Current Trends in Oceanography and Marine Science

Claereboudt MR. Curr Trends Oceanogr Mar Sci: CTOMS-107.
DOI: 10.29011/CTOMS-107.100007

Research Article

Monitoring The Vertical Thermal Structure of the Water Column in Coral Reef Environments Using Divers of Opportunity

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Citation: Claereboudt MR (2018) Monitoring The Vertical Thermal Structure of the Water Column in Coral Reef Environments Using Divers of Opportunity. Curr Trends Oceanogr Mar Sci: CTOMS-107. DOI: 10.29011/CTOMS-107.100007

Received Date: 14 October, 2018; **Accepted Date:** 12 November, 2018; **Published Date:** 20 November, 2018

Abstract

Although under increasing anthropogenic pressure, the coastal areas of the world ocean in general and the coral reefs in particular are in need of accurate oceanographic description. If remote sensing provides nearly synoptic surface information, depth-resolved data collection in coral reef environments is often difficult because of equipment cost, vandalism and logistic constraints, particularly in developing countries. Volunteer divers carrying small data loggers provided a series of temperature-depth profiles sufficiently accurate to map the temporal evolution of the thermal structure of the water column in a coral reef environment. A total of 87 profiles in a popular dive site near Muscat, the capital of the Sultanate of Oman, were collected over a period of 10 months, concentrating around the summer 2010 and showed a strongly stratified water column with a temperature gradient exceeding often 5ºC around the thermocline. Strong cooling of the near-surface water during the summer were associated with rapid rises of the thermocline. Remotely Sensed Sea Surface Temperature (SST) showed much lower amplitude temperature drops during these events and comparisons with CTD acquired temperature depth profiles showed high correlation with the inexpensive logging system. This inexpensive system could be used as a national monitoring system to monitor reef temperatures in situ and issue more accurate bleaching warnings than large scale satellite-based systems.

Introduction

Although very important to the understanding of the responses of coral communities to changes in the water climate, the long-term assessment of abiotic characteristics of these water masses in coastal coral communities is often a technical and a logistic challenge. Because monitoring instruments are located well within reach of fishermen and other reef users, they may be subject to vandalism and losses [1]. Regular CTD casts are possible but when high frequency data acquisition is required they become rapidly expensive and time consuming. Fixed thermographs on the reefs have shown in some areas, particularly in Oman, the importance of short term, rapid and sometimes large changes of temperature to the ecology of the reef [2-5]. and illustrated the need for high frequency temperature sampling in this particular ecosystem. These recordings were however limited to a single depth or a few depths along the reef. Although monthly monitoring of the water column structure using CTD profiles has been successful in identifying seasonal trends in temperature and stratification in the Gulf of Oman [5]. it failed to identify the high frequency variations recorded by fixed thermographs during the same period. Data loggers attached to diving birds [6-8]. or pinnipeds in both Antarctic waters [9-11]. or the NE Pacific Ocean [12]. have provided very useful spatial and temporal information that improved our knowledge of the oceanography of the Antarctic polar ocean and more recently a citizen science approach has shown some promising results using dive profiles recorded by "dive computers" and uploaded by citizen participants on a web platform [13]. As a preliminary study for a larger national investigation, inexpensive data loggers, attached to volunteer recreational divers, were used to extract short to medium term variability in the temperature field around coral communities near Muscat, the capital of the Sultanate of Oman.

Materials and Methods

Data were collected near Fahl Island, a small island (23° 40.899'N, 58° 30.269'E) offshore the capital area of the Sultanate of Oman, and a favorite dive spots for many diving operators and by members of the Petroleum Development of Oman (PDO) dive club. During 10 months in 2010, each group of divers from the PDO dive club, attached a small data logger to one of the participant's Buoyancy Compensating Devices (BCD). These loggers, specially designed for ease of use and absence of maintenance, have a depth accuracy of approximately 30cm (resolution 1 cm) and a temperature accuracy within 0.8˚C (resolution 0.01˚C). Data collected on the small loggers (Temperature, Depth and Time) were downloaded to a computer after each dive day and stored in text format for further processing. During each dive, data points were logged every 20 seconds forming a dive profile. A 2D (time-depth) profile of the water column near Fahl Island was then assembled by time/depth kriging using the software Transform (Fortner Research). Data from the diver's loggers were compared to actual CTD casts (Idronaut-Ocean7 316) collected in the vicinity of the reef by Sultan Qaboos University Research vessel, Al-Jamiah, on two dates corresponding to volunteer dives. The 27 June 2010 and the 11 July 2010. Sea Surface temperatures were also compared to remotely sensed surface temperature in the same area (NOAA coral reef watch products, AVHRR SST. at the same time.

Results

Over a 10-month period, a total of 87 temperature profiles were logged in by the volunteer divers near Fahl Island. As several profiles were often acquired on the same day at slightly different locations around the island, only the deepest dive on any given day was considered leading to a total of 38 temperature-depth profiles extending from the surface to 35 m in depth. Over the 10-month period, temperature varied between 22˚C (February 2011) and 32˚C (August 2010). A noticeable difference between the downward and upward profiles was observed on most profiles (Figure 1). and only the upward profiles, resulting from much slower ascents of the divers, were used in the following analysis. The depth-time temperature profiles revealed a strongly stratified water column during the summer and fall (June-October) with temperature gradients often exceeding 5˚C between 5 and 20 m in depth and a relatively homogenous water column in spring and winter (May 2010 and November 2010 to February 2011). The stratified period was also interspersed with irregular and noticeable drops in the temperature of the upper water column (10-13 July, 6-8 August, 26-28 August and 2 October) During these events, surface temperature decreased from 29-31˚C down to 24-25˚C with a nearly homogenous lower water column down to 30 m in depth.

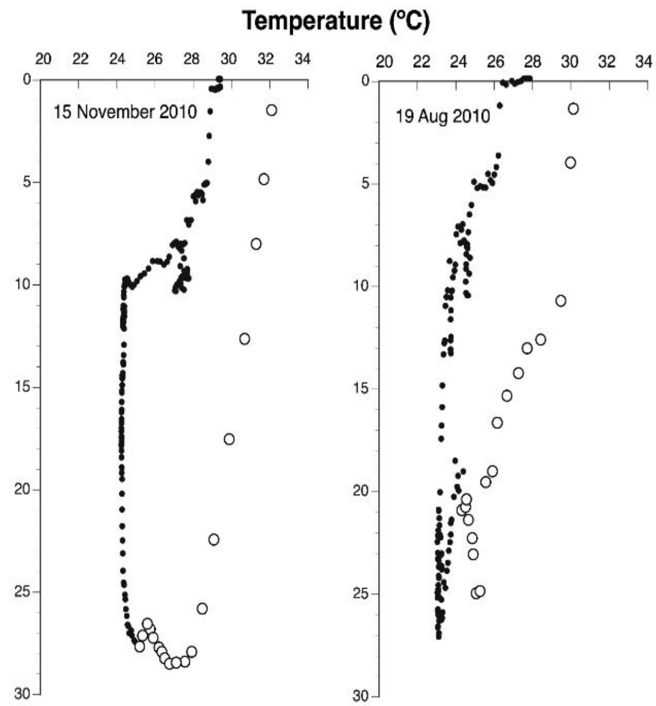

Figure 1: Typical temperature profiles recorded by the volunteer divers acquired in November and August 2010. Note the rapid descent (empty symbols; sampling period is 20s) and the hysteresis in the logger response due to a long time constant (thermal inertia) of the device. Only the upward profiles (filled symbols) were used in the analysis.

Although satellite derived sea surface temperatures for the same area showed drops in the skin temperature on these dates, the amplitude of these changes (Figure 2) were much dampened. A comparison of the SST measured using night-time imaging (AVHRR-SST product) on the same dates (within 24 hours) as the actual SST measured between 0.5-1 m in depth by the data loggers carried by divers, indicated a systematically higher temperature of the remotely sensed data (Figure 3). A comparison between CTD profiles which have been carried out near Fahl Island within 24 hours of one of the dive profiles show that the vertical structure of the water column and the temperature values recorded by the divers did not differ much from that recorded with a state-of-the-art CTD system (Figure 4) and confirmed at least on these 2 dates a well-established thermocline at 6 m and 9 m respectively.

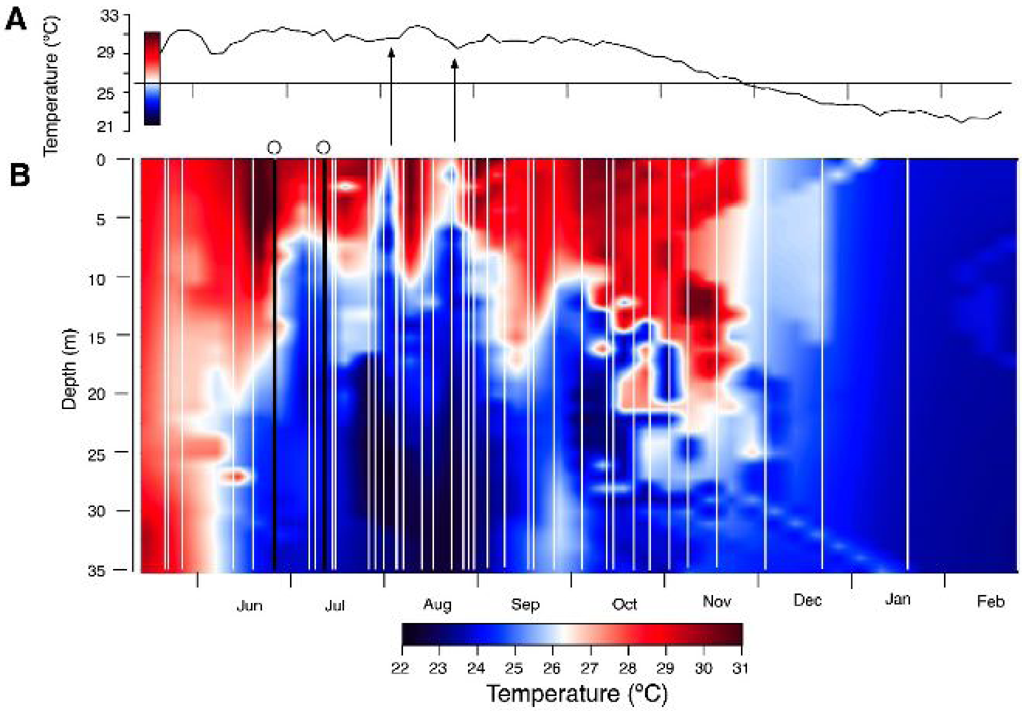

Figure 2: A. Satellite-derived Sea Surface Temperature (SST) near Fahl Island. The two arrows identify periods of large temperature drops observed on the divers' profiles. B. Time-Depth-Temperature profile near Fahl Island created by interpolation of 38 individual profiles between 20 May 2010 and the 28 February 2011. Each profile is identified by a white vertical line. The two black lines and small white disks correspond to the days at which there were also complete CTD casts in the vicinity of the reef.

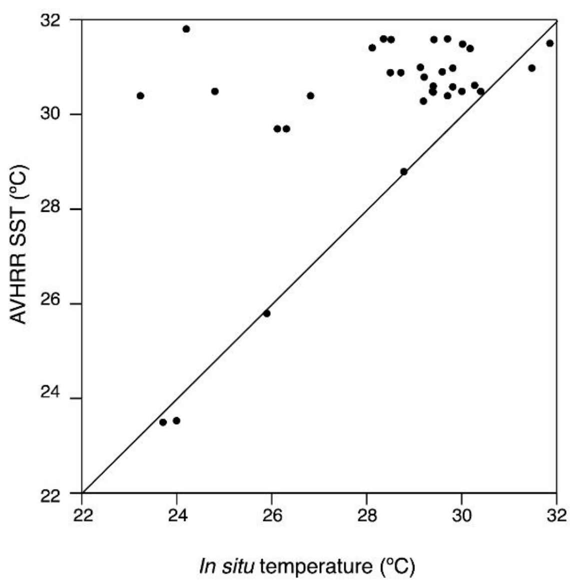

Figure 3: Correlation between satellite derived and field measured SST by the volunteer divers. The diagonal straight line represents perfect agreement.

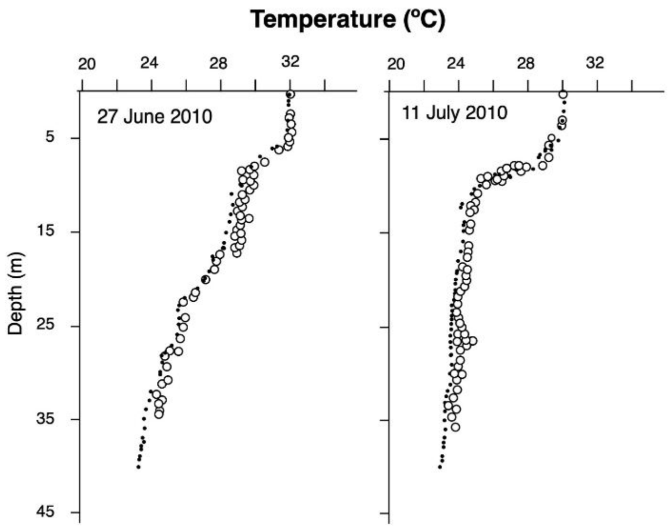

Figure 4: Ascending temperature profiles measured by volunteer divers and CTD casts on 27 June 2010 and 11 July 2010. Filled symbols represent CTD measurements and empty symbols data from instrumented divers.

Discussion

The hysteresis observed between the downward and upward profiles likely results from the typical behavior of divers combined with the large thermal inertia of the thermographs. Divers tend to dive rapidly down to their maximum dive depth but, for safety reasons, ascend considerably more slowly at a recommended maximum rate not exceeding 10 m (30 feet) per minute. In the subsequent analysis, only the upward section of each dive was thus considered from the maximum depth of the dive to the surface.

The irregular drops in temperature observed between during summer (June to October) were recorded previously in the Gulf of Oman using thermographs attached to the reef substrates. They were associated in some cases with massive fish and invertebrate mortalities and believed to correspond to rapid rises of the thermocline and exposure to low oxygen water. This is the first time however that detailed profiles showed the movement of the thermocline during such events, up to the surface on 6-8 August and 26-28 August 2010. These drops in temperatures are different in duration (a few hours to a few days) and likely caused by different processes than the well document summer upwelling that affects most of the Arabian Sea Coast of Oman under the direct influence of SW monsoon winds [14]. The sea surface temperature measured by satellite observations was only poorly correlated to the actual measured temperature. This is in contrast to observations made in Chagos where 5 m *in-situ* thermograph records matched closely remotely sensed temperature observations (AVHRR SST). In the Gulf of Oman (a.k.a. Sea of Oman), corals, typically located more than 1-2 m below the surface experience temperatures inferior (sometimes by 3-4°C) to the SST measured remotely and the risk of bleaching predicted by integrating these high SST may be overestimated [15]. Bleaching in Oman takes place but affect a much lower proportion of the coral communities than elsewhere [16]. and recovery post-bleaching is common (Pers. Observation). The observed summer rises of the thermocline from 25 m in mid-June to 8-12 m in August, when the highest sea surface temperatures are expected on the reef, may provide coral communities with a natural temperature refuge against the harmful effect of high temperatures. Similar protection from excessive thermal stress due to internal waves was reported recently from a Pacific Ocean atoll in the South-China Sea [17]. although protected corals may become more sensitive to temperature stress [18]. This emphasizes the need to create management tools that encompass local information, such as local temperature maxima, stratification, and variability of the temperature regime into the forecasting of coral bleaching events.

Although the cost of the diver carried data-logger is small (approximately 200 US$ for a single unit) in comparison to traditional CTD systems, they are also less accurate and limited in the number of variables available. They can however provide useful information to researchers working in areas regularly visited by recreational divers and provide accurate records of the temperature actually sustained by coral community during bleaching events. If this low-cost system is expanded to include professional dive operators who have daily dives in different coral communities along the coastline, monitoring much larger areas at higher temporal resolution becomes possible.

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