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Diurnal warming in shallow coastal seas: Observations from the Caribbean and Great Barrier Reef regions

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ABSTRACT

A good understanding of diurnal warming in the upper ocean is important for the validation of satellite-derived sea surface temperature (SST) against in-situ buoy data and for merging satellite SSTs taken at different times of the same day. For shallow coastal regions, better understanding of diurnal heating could also help improve monitoring and prediction of ecosystem health, such as coral reef bleaching. Compared to its open ocean counterpart which has been studied extensively and modeled with good success, coastal diurnal warming has complicating localized characteristics, including coastline geometry, bathymetry, water types, tidal and wave mixing. Our goal is to characterize coastal diurnal warming using two extensive in-situ temperature and weather datasets from the Caribbean and Great Barrier Reef (GBR), Australia. Results showed clear daily warming patterns in most stations from both datasets. For the three Caribbean stations where solar radiation is the main cause of daily warming, the mean diurnal warming amplitudes were about 0.4 K at depths of 4–7 m and 0.6–0.7 K at shallower depths of 1–2 m; the largest warming value was 2.1 K. For coral top temperatures of the GBR, 20% of days had warming amplitudes >1 K, with the largest >4 K. The bottom warming at shallower sites has higher daily maximum temperatures and lower daily minimum temperatures than deeper sites nearby. The averaged daily warming amplitudes were shown to be closely related to daily average wind speed and maximum insolation, as found in the open ocean. Diurnal heating also depends on local features including water depth, location on different sections of the reef (reef flat vs. reef slope), the relative distance from the barrier reef chain (coast vs. lagoon stations vs. inner barrier reef sites vs. outer rim sites); and the proximity to the tidal inlets. In addition, the influence of tides on daily temperature changes and its relative importance compared to solar radiation was quantified by calculating the ratio of power spectrum densities at the principal lunar semidiurnal M2 tide versus 24-hour cycle frequency representing mainly solar radiation forcing, i.e., (PSD_{M2}/PSD_{24}). Despite the fact that GBR stations are generally located at regions with large tidal changes, the tidal effects were modest: 80% of stations showed value of (PSD_{M2}/PSD_{24}) of less than 10%.

1. Introduction

Diurnal warming refers to the phenomenon where the upper few meters of the ocean heat up daily due to the absorption of solar radiation. Since the top 5 m of the ocean absorb about 60% of the incoming solar radiation (Fairall et al., 1996), the near-surface water tends to warm up more than the layers beneath. The precise distribution of the heat content, i.e., the shape of the vertical temperature profile, depends primarily on the insolation and wind mixing (Gentemann et al., 2009; Soloviev and Lukas, 1997; Ward, 2006). The averaged surface warming amplitude from measurements is modest [O(0.1 K)], as the heat is distributed into the diurnal warm layer over ten or more meters in depth. However, during low wind and strong solar radiation conditions, it is not unusual to have a surface warming >3 K, in which case the heat is concentrated in a shallow near surface warm layer (<1 m). The largest surface warming captured by satellite is >6 K (Flament et al., 1994; Gentemann et al., 2008; Merchant et al., 2008). An accurate quantification of the diurnal warming amplitude and vertical structure is important for merging satellite sea surface temperature (SST) data taken at different times of day, for more accurate SST retrieval and validation against buoy data (Gentemann et al., 2004) and correct air-sea heat flux calculation (Fairall et al., 1996).

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This study is concerned with the diurnal warming in shallow coastal waters. Shallow coastal waters refer to locations adjacent to land, with a water depth ranging from a few meters to up to 30 m, a depth comparable to the diurnal warming layer found in studies of diurnal heating in the open ocean. So far, most diurnal studies either took place far from the coastline, or made a deliberate effort to eliminate coastal data to avoid the complex coastal dynamics (Merchant et al., 2008). A few studies have examined the diurnal warming at seas or coastal regions (Bohm et al., 1991; Kawai et al., 2006), however water depths of the study locations are over 50 m, a depth far exceeding the diurnal warming layer depth. As such, the effects of bottom and local bathymetry could be viewed as negligible, and coastal characteristics were not assessed. A relevant paper on coastal diurnal warming is by Kaplan et al. (2003), where the authors examined in-situ temperature measurements from moorings located at 20–30 m depth at two offshore locations in Chile. The authors reported several coastal characteristics including tide and sea breeze effects on the diurnal warming near the coast, in addition to the influence of wind and insolation. Due to the limited number of locations however, that study was not able to examine other coastal characteristics such as bathymetry and the effects of shoreline geometry, nor to summarize the tidal effect in a statistical fashion.

Diurnal warming in coastal shallow waters is of interest for a number of reasons. First, for satellite measurements of SST at the coastal regions, only those from infrared radiometers can be used due to side-lobe contamination in the microwave radiometer measurements. Since infrared measurements are vulnerable to cloud contamination, merging multiple SST measurements taken from satellites with different overpass times is needed to reduce data loss from clouds. Knowledge of the coastal SST diurnal variation is essential for such data merging. Second, deep ocean diurnal warming has been studied extensively in recent years, with the development of physical and empirical modeling tools. Thus, extending the research towards more complex coastal cases, and studying the similarities and differences of the two is a natural next step. The third, perhaps the most important reason is that coastal shallow waters include the habitats of temperature sensitive ecosystems such as coral reefs. Coral bleaching is a generalized stress response in corals but occurs predominantly when temperature reaches an intolerable level, resulting in corals losing their symbiotic algae and turning pale to white. Mass coral bleaching events have occurred in recent years and have been closely monitored using satellite SST data (Berkelmans et al., 2004; Berkelmans and Oliver, 1999). Current coral bleaching monitoring and prediction products based on satellite measurements, such as bleaching HotSpots and Degree Heating Week (DHW) focus on the harmful effect of long-term (12 weeks, bi-weekly data) SST anomalies based on night time SST (Strong et al., 2004). However, recent studies have suggested the cell death within the coral symbiosis occurs much more rapidly (minutes to hours) than previous thought, especially during high temperature events (Dunn et al., 2004), whereas other studies have found that daily maximum temperatures correspond better to bleaching events than night temperature (Berkelmans et al., 2004; McClanahan et al., 2007). Both point to a possible link between coral bleaching and daily temperature variation at the shallow depths where corals are located. Thus a better understanding of coastal shallow water diurnal warming, both its amplitude and vertical structure is needed so that the surface measurements can be extended in a physically reasonable manner to the depths of the corals. This could improve coral bleaching prediction and monitoring.

This study characterizes diurnal warming by analyzing two in-situ datasets taken in shallow coastal waters at the Caribbean Sea and at the Great Barrier Reef (GBR) region off northeast Australia. Both datasets include multiple locations, with in-situ temperature measurements taken close to coral reefs as they were designed for monitoring coral bleaching. The Caribbean Sea dataset includes temperature measurements at multiple depths with co-located weather and light measurements at four locations. Thus, it is a good dataset to study the vertical structure of the warming, and the relationship between forcing and temperature evolution. The Great Barrier Reef temperature dataset, on the other hand, is composed of temperature measurements from hundreds of data loggers located on coral tops spanning a large geographic area. Thus, it provides an opportunity to directly measure the diurnal warming at the depth of the corals, and to study the impacts of the locations and bathymetry features on diurnal warming characteristics in a statistically sufficient way. The influence of tides on daily temperature development was analyzed for both stations, though the GBR dataset is a better dataset for studying tides as the region has larger and more spatially variable tidal amplitudes. This study aims to lead to a better understanding of the differences and similarities of diurnal warming in shallow coastal waters compared to its open ocean counterpart, both in warming characters (amplitude, vertical profiles) and environmental influences (wind, insolation, tides, location and bathymetry).

2. In-situ data

The Caribbean dataset includes measurements from four locations (Fig. 1): southwest Puerto Rico (station ID LPPR), Little Cayman Island (station ID LCIY), St Croix in the U.S Virgin islands (station ID SRVI), and Lee Stocking Island at Bahamas (station ID CMRC). The stations belong to the National Oceanic and Atmospheric Administration (NOAA)'s Integrated Coral Observing Network (ICON) program. For each station, a pylon was installed in about 7 m depth of water on sea bottom categorized as 'colonized pavement' which is flat, low-relief, solid carbonate rock with coverage of algae and coral as the structure of the pylons require at least 20 m in diameter of flat terrain for the installation of chains to brace the structure. All stations were located close to the shore (<300 m at SRVI, CMRC and LCIY, <3000 m in LPPR inside a bay). The Caribbean region has micro tidal ranges (Kjerfve, 1981). Three of the stations we study have tidal amplitudes of less than 0.4 m, while CMRC has slightly larger tidal range of 0.8 m. The station locations were chosen to be protected from dominant wind direction to avoid being pounded by high seas. No currents measurements are available. However, tidal currents are believed to be very weak due to the small tidal ranges and proximity to the shoreline, except when the location is close to a tidal inlet.

A variety of meteorological and oceanographic instruments are attached to the station pylons above and below the water-line (Table 1). Above water measurements include wind speed and direction, air temperature, air pressure, precipitation, relative humidity and light with an hourly resolution. Light intensity is measured in 3 ultraviolet wavelength bands and at visible wavelengths (PAR, photosynthetically active radiation). The broad spectrum solar radiation can be calculated from PAR assuming visible radiation represents a constant fraction ($=0.4$) of the total incoming radiation (Gill, 1982; Kaplan et al., 2003). Underwater, hourly water temperatures and depth (pressure) variations were recorded by CTD (Conductivity, Temperature, Depth Sensors) at a 'shallow depth' (1–2 m below the water surface) and at a 'deep' depth (4–6 m). At the LCIY station, only the 'deep' depth was measured hourly by CTD. For February to September 2011, 6-min resolution water temperature and depth (pressure) measurements were available at three near-surface depths (1.2 m, 1.5 m and 2 m) and a near-bottom depth (7.2 m) from four additional loggers.

The GBR dataset, on the other hand, consists of ocean bottom temperature measurements with a 30-min resolution. The loggers