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Nearshore, seasonally persistent fronts in sea surface temperature on Red Sea tropical reefs

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Temperature variability was studied on tropical reefs off the coast of Saudi Arabia in the Red Sea using remote sensing from Aqua and Terra satellites. Cross-shore gradients in sea surface temperature (SST) were observed, including cold fronts (colder inshore) during winter and warm fronts (warmer inshore) during summer. Fronts persisted over synoptic and seasonal time-scales and had a periodic annual cycle over a 10-year time-series. Measurements of cross-shore SST variability were conducted at the scale of tens of kilometres, which encompassed temperature over shallow tropical reef complexes and the continental slope. Two tropical reefs that had similar reef geomorphology and offshore continental slope topography had identical cold fronts, although they were separated by 100 km along the Red Sea coast of Saudi Arabia. Satellite SST gradients across contours of topography of tropical reefs can be used as an index to flag areas potentially exposed to temperature stress.

Keywords: barrier reef, coral reef, cross-shore SST gradient, front, Red Sea, temperature stress, tropical lagoon.

Introduction

The manner in which temperature varies in tropical reef ecosystems is an important habitat characteristic, because reef inhabitants can be particularly prone to temperature extremes. For example, tropical corals are susceptible to temperature-induced bleaching (Fitt *et al.*, 2001). However, little is known about temperature variability in reef systems such as those on the Saudi Arabian coast of the Red Sea. What is known of temperature variability in that reef system is derived from a few descriptions of *in situ* measurements and remotely sensed sea surface temperature (SST).

Early research using *in situ* observations of seawater temperature described relatively warm inshore seawater on some Red Sea reefs (Morley, 1975). Reefs north of Jeddah had weaker overheating than barrier reefs in the south, and Morley explained that this was due to the substantial barrier reef in the southern Red Sea that traps seawater on the shallow coastal shelf. Therefore, an important early concept in the temperature dynamics of tropical reefs was that water at some reef systems has little exchange with the massive offshore reservoir, causing a cross-shore temperature gradient.

Remote sensing via satellite platforms has provided a critical data source for preliminary description of environmental patterns in remote tropical reef environments such as in the Red Sea (Acker *et al.*, 2008). Previous satellite-based studies of SST in tropical reef environments focused on warm temperature anomalies, highlighting the utility of satellites in detecting habitats prone to impacts from climate change (Selig *et al.*, 2010). Remotely sensed measurements from the moderate-resolution imaging spectroradiometer (MODIS) Aqua and Terra platforms resolve SST at mesoscale resolution (Savtchenko *et al.*, 2004). Such platforms are useful in resolving gradients in ocean colour variability approximately a few kilometres from the shoreline and for assessing changes in environmental variables on synoptic and seasonal time-scales (Valente and da Silva, 2009). Therefore, they are valuable data sources when assessing the presence of SST fronts in the Red Sea (Belkin *et al.*, 2009), which we hypothesize are associated with nearshore, shallow topographic features typical of tropical reefs.

Identifying the existence of cross-shore gradients in seawater temperature and characterizing the regional scope may be important basic steps needed to recognize tropical reefs in danger of environmental impacts from climate change and temperature-induced coral bleaching. Comparing temperature of the reef with the relatively large seawater reservoir offshore provides a snapshot of spatial variability that is distinct from a temperature-anomaly index based on SST climatology (Barton and Casey, 2005). Higher temperatures onshore may be a relatively common feature of reefs and not anomalous at all. For example, higher temperatures on inshore reefs differ from the situation on outer reefs on South Pacific islands (Oliver and Palumbi, 2009). The fact that temperature is often higher in one habitat implies that the corals that live in those areas are most likely acclimated to the higher temperatures. For example, in the South Pacific, corals experiencing high seawater temperature had inherent resistance to thermal stress (Oliver and Palumbi, 2009). Such resistance is an important adaptation of corals to elevated seawater temperature in tropical reef ecosystems (Rowan, 2004).

Warmer seawater may not be the only significant feature of SST on tropical reefs, because reef cooling is also of concern for tropical reef health. Reef cooling has recently been implicated in coral bleaching on the Florida Keys (NOAA-NOS, 2010). Corals may need to cope with cool as well as warm temperatures, because it is likely that the same reefs are prone to both temperature extremes as a consequence of the effect of heat exchange on retentive shallow reef systems. For example, Morley (1975) reported cooler water inside small coastal reef flats in the Red Sea that were also subject to overheating. In this paper, MODIS SST data were analysed to detect warm and cold fronts, and the prevalence of cold fronts compared with warm fronts assessed. We highlight the utility of this metric for detecting potential periods of temperature stress in northern Red Sea tropical reefs.

Data and methods

Data compilation

Topographic data

We compiled data on the topography of the coast of Thuwal, Saudi Arabia, to define the areas of interest in our study of SST variability. The data included material from a British Admiralty chart (Chart 2659), GEBCO global bathymetric data (1 min grid, http://www.ngdc.noaa.gov/mgg/gebco/grid/1mingrid.html), and Landsat 7 images. The Admiralty chart allowed the identification of the position of tropical reefs suitable for an analysis of mesoscale SST variability. A contour plot of GEBCO bathymetric data accurately depicts the deep topographic features of the Red Sea near the study area (Figure 1). Landsat 7 data were acquired from NASA (http://landsat.gsfc.nasa.gov) and had high spatial resolution (30 m). These data were accessed primarily to acquire additional topographic data including the location of emerged land masses and submerged topographic features <20 m deep (Robinson, 1985) that could not be resolved accurately using other data sources available.

Remote-sensing SST data

The source of SST data for this study was from MODIS on the Aqua and Terra satellites that each pass over the Red Sea twice daily. On each pass, the MODIS scans and measures swaths of the Earth's surface in the thermal infrared, allowing the estimates of SST. MODIS Aqua data were available from July 2002 and MODIS Terra data from February 2000. SST data based on long- (11 μm) and short-wave (4 μm) measurements were available, but we worked exclusively with the higher precision long-wave SST and only with night-time data to reduce the signature of diurnal heating fluctuations (Robinson, 2004). Level 2 MODIS SST data were downloaded from the ocean colour data browser on the Ocean Color website, including swaths of night-time satellite passes (http://oceancolor.gsfc.nasa.gov). All swaths that covered at least 25% of the geographic area between 35.5–39.5°E and 20–24°N from the start of available data to the end of May 2009 were requested.

MODIS SST data were interpolated to a regular 0.01° latitude and longitude grid using geo-referenced latitude and longitude coordinates for swaths of SST measurements. Level 2 data are quality controlled, and gridded data with a quality flag value <2 were marked as invalid SST values before interpolating the data to a regular grid.

In all, 4050 MODIS Terra swaths and 3100 MODIS Aqua swaths fitted the search criteria. MODIS Terra satellite passes typically occurred between 22:00 and 23:30 local time. MODIS Aqua satellite passes were on average 3.5 h later, between 01:30 and 03:00 local time.

In situ *SST data*

In situ temperature data were acquired from a nearshore mooring deployed in late October 2008 and recovered in April 2009. The mooring was deployed ~300 m from shore, offshore from a coastal reef-flat (Figure 1). The mooring had an array of temperature loggers measuring temperature at 5-min intervals. The logger most relevant to this SST study was an SBE39 (Sea-Bird Electronics, Bellevue, Washington) located ~2 m below the surface.

Data analysis

Topographic data

The locations of shallow reef features were determined from the sources of topographic data described above, generating a regional depiction of coral reef and shallow topography on the Red Sea coast of Saudi Arabia. Together, the data provided adequate topographic data to define the area to subsample in the SST data. The Landsat 7 data were most useful for identifying morphological characteristics of shallow tropical reefs, and focus was on this habitat for SST analysis.

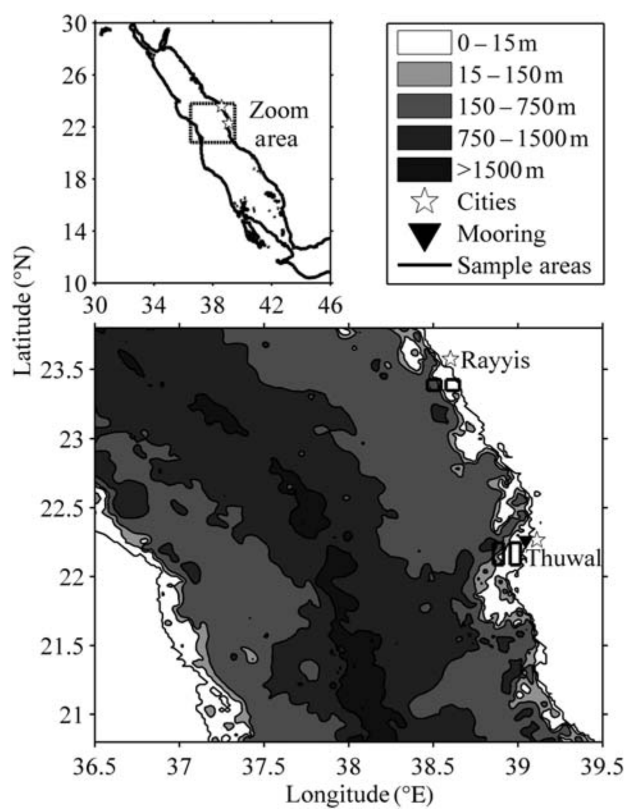

Figure 1. The study area. The large-scale map at the upper left shows the outline of the Red Sea and the zoom area depicted in the map below. The cities Rayyis and Thuwal are depicted in both maps, but the lower map also shows Red Sea bathymetry, the location of the mooring, and the SST sample areas.

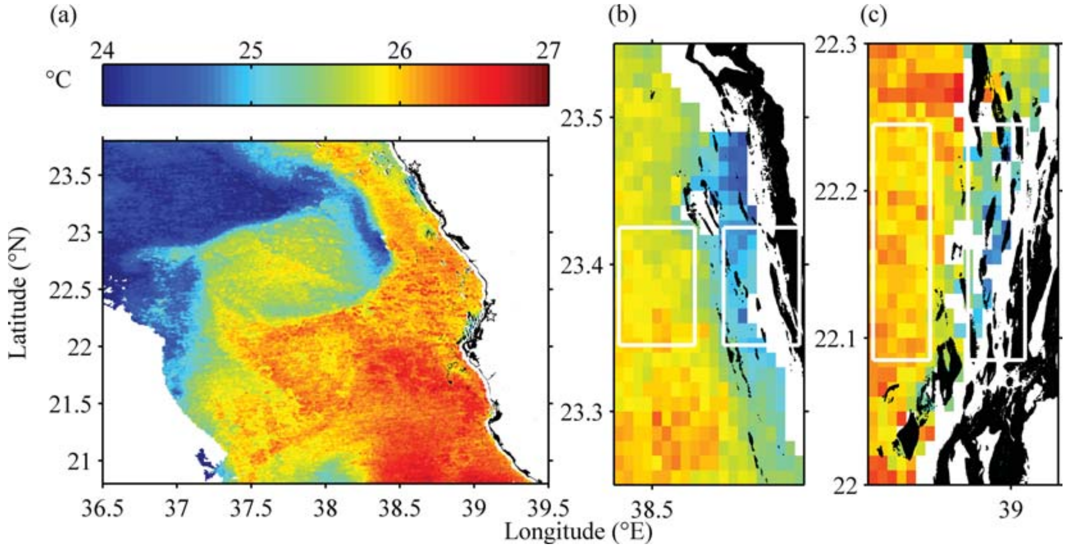

Figure 2. Mean SST map for January 2003. Colour portions are 5-d mean SST values from January 2003. Pixels are 1 × 1 km resolution SST data interpolated to a uniform latitude and longitude grid. Black markings on the Saudi Arabian coast correspond to shallow reef features, digitized from Landsat 7 images with a 30-m resolution. Stars indicate the locations of Thuwal and Rayyis, as in Figure 1. SST is cooler nearshore and in particular over dense aggregates of nearshore shallow reefs at Rayyis (b) and Thuwal (c). The white lines demarcate the offshore and nearshore sample areas in (b) and (c).

MODIS and in situ *data comparison*

We compared MODIS and *in situ* SST on a coral reef near Thuwal, Saudi Arabia. There, an area >100 km^2 is punctuated at multiple locations by shallow tropical reefs, bordered by water deeper than 150 m offshore and by land in an onshore direction. SST was subsampled from a 16 × 6 km area within this nearshore reef area (depicted in the nearshore box near Thuwal, Saudi Arabia, in Figures 1 and 2c) for comparison with the temperature sensor on the mooring just to the north of the SST sample area (Figure 1). The MODIS SST data from Aqua and Terra satellites were extracted for the duration of the mooring deployment. Every SST measurement in the nearshore sample area available during that period was compared with *in situ* temperature data from the nearby mooring. Additionally, the SST and the mooring temperature were compared with the zonal wind velocity recorded at a meteorological tower located on the coast of Thuwal, Saudi Arabia, ∼6 km northeast from the mooring (Farrar *et al.*, 2009).

Cross-shore gradients

Cross-shore gradients in SST were observed at two reefs in the eastern Red Sea near Thuwal and Rayyis, Saudi Arabia. These candidate reefs were initially identified by navigating Landsat 7 images covering the Red Sea coast of Saudi Arabia. The gradients are depicted in an image of SST representing a 5-d average from January 2003 (Figure 2). First, temperature in the 16 × 6 km grid area near Thuwal was compared, subtracting the mean SST from an area of equal size 10 km offshore (Figure 2c). Invalid values were excluded, and the number of grid points with SST data was recorded. The date and time of each swath pass was also recorded.

A second reef was identified south of Rayyis, Saudi Arabia, some 100 km north of the reef near Thuwal. The coast near Rayyis has many features similar to that bordering Thuwal (Figures 1 and 2). The Rayyis coast has many shallow reef crests near the shore and deep water directly west and offshore. SST measurements of the Rayyis reef were sampled from individual passes of the MODIS Aqua and Terra satellites over an area of 8 × 8 km, encompassing many of the shallow reef crests (Figure 2b). A cross-shore temperature gradient was calculated by subtracting the mean SST for an identically shaped area 10 km offshore from the mean over the nearshore area.

The cross-shore gradients at Thuwal and Rayyis were compared. First, 5-d binned averages of MODIS SST were plotted over the entirety of the Aqua and Terra satellite missions, which produced a multiyear time-series between late 2000 through the start of 2009. Second, a mean annual cycle in the cross-shore gradient was computed by averaging across years. The days of the year were divided into 5-d bins in which all satellite passes were grouped. As solar radiation is an important driver of SST pattern, the solar year rather than the day of the year was used to index the 5-d bins. The solar year begins and ends with the winter solstice (∼21 December) and is in phase with the trend in solar radiation. The mean and 25 and 75 percentile statistics were computed for each bin, providing a summary of the 9-year dataset. These statistics were plotted together to illustrate the SST cycle over a typical solar year and to compare and contrast the SST gradient on the Thuwal and Rayyis reefs.

Results

Topography

The shallow tropical reef features along the coast of Saudi Arabia are plotted black in Figure 2. The resolution of level 2 MODIS satellite SST data is 1 × 1 km at nadir, and usually the shallow tropical reefs had a smaller footprint. However, the onshore sample area off Thuwal, Saudi Arabia, overlaps with a dense aggregation of shallow tropical reef (Figure 2c), so it represents an average SST over a surface area covering shallow tropical reefs and surrounding water deeper than 20 m.

Comparison of MODIS and *in situ* SST

Available night-time MODIS SST data measured from Aqua and Terra satellites are plotted with *in situ* temperature data from the nearshore mooring on Figure 3. Satellite-based measurements of SST between November and March can be as much as 1°C less than the temperature at the mooring 2 m below the surface, although these two sources of seawater temperature data track each other over a 5°C range in the record.

SST is typically colder than the bulk temperature centimetres below the water surface, owing to a number of factors affecting the heat transfer from the ocean to the atmosphere (Fairall *et al.*, 1996). For the Red Sea coast, coastal breeze can enhance latent heat loss, because strong offshore wind drives air over the ocean surface, increasing the evaporation of seawater. Strong coastal wind jets reported for this period are thought to have greatly affected the heat loss from the Red Sea at a buoy 60 km offshore from the sampling area (Jiang *et al.*, 2009).

Coastal breeze was a nightly occurrence over the sampling area, as measured from a nearby meteorological tower. However, the strength of the coastal breeze was negatively correlated with the difference between *in situ* and satellite measurements of seawater temperature (unpublished data). Therefore, an enhanced cool skin temperature attributable to coastal breeze could not explain the negative bias observed in the SST measurements.

Castillo and Lima (2010) observed a similar negative temperature bias in their study of MODIS SST, but their analysis focused on the methodological bias introduced by using satellite derived SST measurements to estimate temperature on coral reefs. In general, a number of methodological problems may arise for

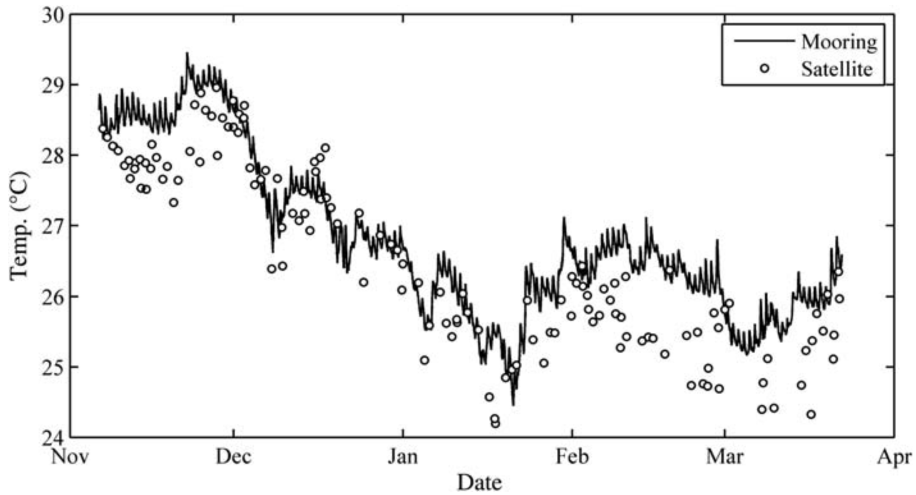

Figure 3. A comparison between *in situ* temperature data and mean SST over the nearshore reef at Thuwal, Saudi Arabia. A high frequency temperature signal from 2 m below the surface on the nearshore mooring resolves a diurnal temperature signal (mooring location depicted in Figure 1). The satellite datapoints are derived from night-time passes of the Aqua and Terra satellites over the nearshore area near Thuwal, depicted in Figures 1 and 2c.

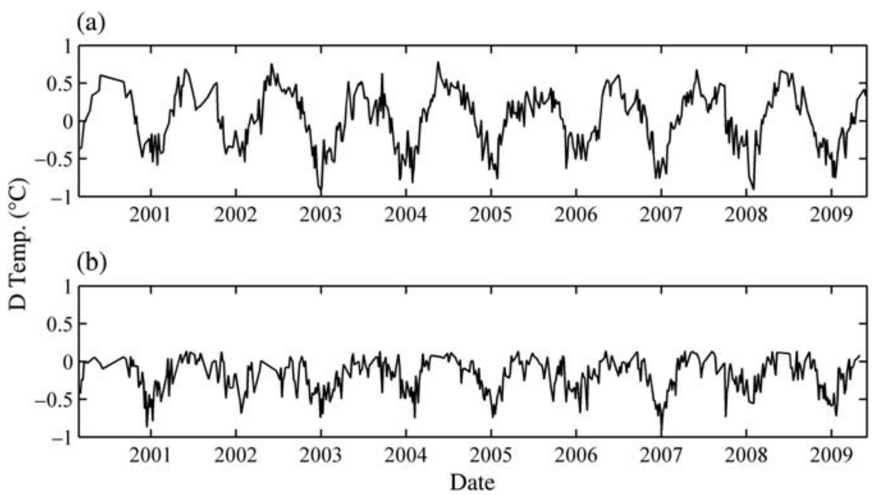

Figure 4. Time-series of cross-shore temperature gradients. (a) Cross-shore temperature gradient at Thuwal, Saudi Arabia, calculated from the difference in mean SST between a 96-km^2 area covering a portion of the inshore reef and the mean SST for a comparable area 10 km offshore (Figure 1). The MODIS Aqua and Terra satellite data are averaged into 5-d bins; data are missing for some 5-d intervals, because there were insufficient data to estimate the SST gradient. (b) Cross-shore gradient for the reef near Rayyis, Saudi Arabia. The onshore and offshore areas used in the difference calculation are 10 km apart and are each 64 km^2.

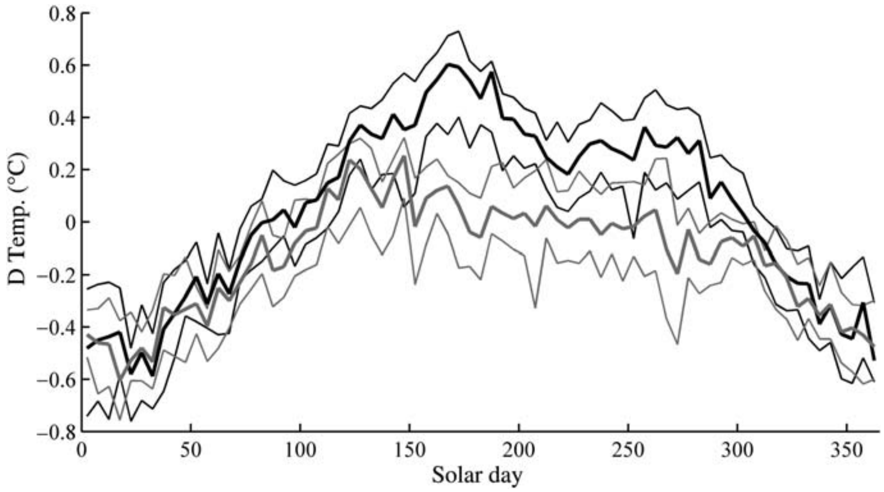

Figure 5. Averaged seasonal cycle over the solar year, indexed by the winter solstice (solar day 0 = ~21 December). SST gradient for Thuwal, Saudi Arabia (thick black line), with its associated 25th and 75th percentiles (thin black lines), and for Rayyis (thick grey line), 100 km north of Thuwal with associated 25th and 75th percentiles (thin grey lines).

satellite measurements of SST for heterogeneous habitats such as coral reefs, because satellite measurements cannot resolve temperature features that are smaller than the minimum length-scale of the satellite measurement (Robinson, 2004). In this study, we attribute some of the variability in MODIS SST estimates to methodological bias, because the difference between MODIS SST and *in situ* temperature sensor values was positively correlated with the number of invalid pixels in the MODIS SST swaths for the nearshore sampling area (unpublished data).

MODIS satellite swaths with fewer high-quality SST measurements are likely to introduce greater statistical error into SST estimates. Therefore, to remove the negative bias in the following time-series analysis, a weighted average of SST from satellite swaths was derived based on the number of high-quality pixels in each swath for the respective nearshore sampling area.

Cross-shore temperature gradients

A multiyear time-series of cross-shore SST variability near Thuwal, Saudi Arabia, has a clear annual periodicity (Figure 4a). During the boreal winter, SST inshore was colder than it was 10 km offshore. This contrasts with the relatively warmer SST on the reef in summer. The SST gradient also varied with an annual period on the Rayyis reef (Figure 4b).

A multiyear average for the SST gradient at the Thuwal and Rayyis reefs demonstrates similarities in the phase of the annual cycles (Figure 5). The SST gradient is identical at these two locations around the winter solstice (solar day 0). However, the Thuwal reef has a distinct warm SST gradient around the summer solstice (solar day ~180) which is not apparent at the Rayyis reef.

The temperature gradient around the winter solstice is demonstrated by the spatial pattern in mean SST over 5 d in January 2003 (Figure 2a–c). Gradients in SST are present at both the Thuwal and Rayyis reefs. Other reefs between Thuwal and Rayyis have SST values similar to SST offshore, indicating that the SST gradients across the Thuwal and Rayyis reefs are unique features of the region.

Discussion

Temperature on tropical reefs along the coast of Saudi Arabia is patchy, primarily dominated by small-scale gradients of the order of metres to kilometres. Cross-shore SST gradients over reef systems have sustained annual periodicities, with a regionally significant cold front around the winter solstice. We examined two nearshore reefs, because they have similar shallow topographic features. They had similar temperature patterns, although they were separated by 100 km. The Red Sea coast may be prone to small-scale SST variability as a result of the topographical complexity and alongshore variability in tropical reef geomorphology.

There are few descriptions in the literature of cold cross-shore gradients on tropical reefs. Morley (1975) described cold gradients across small coastal reef flats only a few metres to 0.5 km in size. Monismith *et al.* (2006) found cold gradients that drive gravity currents at scales of a few tens of metres. A seasonal cycle in SST is typically found on the northeast continental slope of North America, where a seasonally persistent SST cold front forms during winter at the interface between cold inshore coastal water and warm offshore water from the Gulf Stream current (Ullman and Cornillon, 1999).

SST fronts have also been described for the Red Sea (Belkin *et al.*, 2009), and the pattern is associated with the mixing of seawater across a latitudinal gradient in SST. However, the cross-shore gradient in SST is a zonal gradient at the scale of tens of kilometres, an order of magnitude greater than the latitudinal gradient of SST measured for 200 km along this region of the Red Sea (unpublished results). The cold gradient observed on tropical reefs near Thuwal and Rayyis may establish as a result of the retention of cold water over densely packed aggregations of shallow tropical reef, creating a persistent shallow lens with a distinct temperature from the area proximally located offshore. Despite the apparent discontinuity in the cross-shore SST pattern between the two reefs along the coast of Saudi Arabia (Figure 2), the two gradients reported here are strikingly similar, because they are in phase with each other and are both slightly lagged from the cycle of solar radiation (Figure 5).

The coasts off Thuwal and Rayyis are similar in that they have many small shallow reefs, which are close to land in an onshore direction and to the shelf break offshore. Tropical reefs >10–20 km from the coast do not appear to have a cold gradient throughout winter, as depicted in the 5-d average from January 2003 (Figure 2a), although the coast between Thuwal and Rayyis is punctuated by many small shallow reefs as seen in the nearshore sample areas near Thuwal and Rayyis. Therefore, the formation and persistence of the cold gradient may depend on the proximity of tropical reefs to the shore. This could be due to the tendency of these nearshore tropical reefs to retain a shallow-water lens that is relatively cold as a result of the prevailing trend of heat loss from the Red Sea during the boreal winter.

The nearshore reef formation at Thuwal seems to be particularly prone to dramatic temperature variability, with cooler temperature in winter and warmer temperature in summer. Increased temperature variability makes inshore parts of reefs more prone to temperature stress, as reflected in the stress-resistance traits of corals (Oliver and Palumbi, 2009). As factors other than the bathymetry influence nearshore circulation over tropical reefs, however, the temperature fronts created through this process may be eroded by a number of other nearshore circulation processes that cannot be characterized easily using satellite measurements alone. Therefore, we cannot explain why the warm temperature gradient was not observed at Rayyis during summer as it was in Thuwal, but it is striking how well the satellite measurements characterize repeated patterns in temperature distributions between years and in different habitats.

Satellite-derived measurements of the cross-shore SST gradient may provide a convenient index for characterizing SST variability on tropical reefs. It has been recognized that tropical reefs appear to be a complex patchwork of areas more or less prone to temperature stress. Complex spatial patterns in temperature have typically been characterized by identifying variability from average temperature through time. For example, long-term trends in seawater temperature on a fine spatial resolution provide the basis for SST climatology that is part of reef-conservation effort (Selig *et al.*, 2010). Spatial and temporal averaging, using weights based on the quality of SST estimates, reduce the resolution of SST measurements, but it can increase the reliability of SST as a measure of coral reef temperature. The persistent small-scale spatial gradients in SST may be an important and common environmental feature on tropical reefs in the region, and there could be benefit in evaluating them further to inform conservation efforts that involve the thermal adaptation of corals.

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