Late monsoon threatens coral refugia in the Andaman Sea

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Abstract

Internal waves (IWs) mitigate thermal stress and provide refugia for corals against increasingly frequent mass bleaching. However, climate events may bring uncertainty regarding the resistance of such refugia. Here, using in situ observation data in the Andaman Sea (AS), we conduct a case study in which a monsoon anomaly associated with an El Niño event threatens IW coral refugia. IW cooling in the AS coral reefs is modulated by the thermocline depth variation, which is driven, to a significant extent, by Kelvin wave signals from the equator. In the pre-monsoon period, distinct variations in IW cooling and surface heating form a time window of quickly-growing cumulative heat exposure. The El Niño induces a typical two-week delay of summer monsoon onset, which prolongs the duration of thermal stress growth and brings severe bleaching risk to corals. As global warming increases the frequency of extreme El Niño events, IW coral refugia will face great challenges in the future.

1. Introduction

Global climate change is increasing the frequency and spatial extension of mass bleaching (Hughes et al 2018), thereby threatening the persistence and diversity of coral reefs (Bellwood et al 2004, Hoegh-Guldberg et al 1999, 2007). The extreme thermal stresses induced by El Niño caused three well-known pantropical bleaching events of shallow-water corals in 1998, 2010 and 2016 (Hughes et al 2017, 2018, Sully et al 2019). In addition, studies have shown that global warming is expected to increase the frequency of extreme El Niño events and associated extreme high sea surface temperature (SST) events in the future (Cai et al 2014, 2018).

In light of this severe situation, coral conservationists are in search of natural coral refugia (Glynn 1996, Riegl 2003). High frequency temperature variations have been found to reduce coral bleaching risks (Safaie et al 2018, Green et al 2019). Internal waves (IWs) induce low temperatures, low oxygen levels, low PH values and higher inorganic nutrient concentrations in the coral reefs, influencing the morphology, primary productivity, distribution and community composition of corals (Schmidt et al 2012, Wall et al 2012, Jantzen et al 2013, 2014, 2016). By inducing strong cold-water intrusion and large-amplitude temperature variations in coral reefs (Vlasenko and Hutter 2002, Leichter et al 2006, Venayagamoorthy and Fringer 2006, Aghsaee et al 2010, Wall et al 2014), IWs can alleviate thermal stress and provide refugia for corals from thermal stress (Riegl et al 2009, Chollet and Mumby 2013, Schmidt et al 2016, Wyatt et al 2020). The corals that are exposed to IWs have been reported to have a higher species diversity than IW-sheltered corals,
where some bleaching-susceptible species have nearly disappeared (Wall et al 2014).

The Andaman Sea (AS) is an ideal experimental area for studying the influence of IWs on coral bleaching. Coral reefs in the AS are important economic resources for the surrounding countries. A peculiar submarine topography has led to the common occurrence of large-amplitude IWs amplified by tidal currents near the Andaman-Nicobar Islands (Osborne and Burch 1978, 1980, Alpers et al 1997, figure 1(b)). Coincident variabilities of high temperatures and IW cooling are critical in determining the efficacy of refugia provided by IWs. Although concurrent peak periods of IW cooling and high temperature are ubiquitous in tropical areas (Storlazzi et al 2020, Wyatt et al 2020), the variations in climate modes may introduce uncertainties into this synchronism because the variabilities in surface heating and IW cooling are driven by distinct processes. Alternating monsoon winds dominate the SST variabilities in the AS (Liu et al 2018), while the thermocline variabilities are presumably modulated by the forcing of equatorial Kelvin waves (Yu 2003, Rao et al 2010, Cheng et al 2013, 2017). In particular, the strong semiannual variability caused by equatorial westerlies (Wyrtki 1973) strongly impacts the ocean dynamics in the AS (Chatterjee et al 2017, Liu et al 2022). As shown in figure 1(a), positive SST anomalies attributed to basin-wide warming (Klein et al 1999) cover the AS during the decay phase of El Niño, potentially inducing thermal stress to the corals. In addition, El Niño events tend to delay the onset of the summer monsoon in the northeastern Indian Ocean (Li et al 2018), which potentially introduces uncertainties to the competition between high SST and IW cooling in the AS.

According to the data reported in Wall et al (2014), during the unprecedented 2010 heat anomaly in the AS, the IW-exposed corals showed a milder bleaching response than the IW-sheltered corals at all sites (figure 1(d)). However, although the mitigation of bleaching responses were significant within nearly
all species, mass bleaching nevertheless occurred even in the areas exposed to IWs. More than 80% of Pocilloporidae and Porites spp. branching bleached, while 40%–60% of Acropora spp., Porites spp. branching and others bleached in 2010 (see figure 3 in Wall et al 2014), indicating a breakdown of IW-protection. Because thermal stress is recognized as the key cause of extensive coral bleaching (Brown et al 2000), a diagnosis of heat accumulation is necessary to interpret what happened in the IW-exposed areas in 2010.

In the present study, using \textit{in situ} temperature sequences in the eastern AS from the coral reef monitoring efforts of the Phuket Marine Biological Center, we analyse the characteristics and driving processes of IW cooling and study the influence of El Niño on the evolution of heat accumulation. Taking the case in 2010 as an example, we interpret the occurrence of severe bleaching risks in the expected coral refugia during the decay phase of El Niño.

2. Data and methods

2.1. Data

Three temperature time sequences (Liu 2020) are obtained on the west sides of Miang Island (97.6335° E, 8.5621° N), Tachai Island (97.8071° E, 9.0674° N) and Surin Island (97.8409° E, 9.4125° N) (figures 1(b) and (c)), each with a duration of nearly five years, from November 2010 to June 2014. HOBO water temperature data loggers (Tidbits) with a resolution of 0.02 °C, are deployed on coral reefs on the seafloor at water depths of 20 m. The temporal interval of the sensors is 20 min, which is considered to induce a large error in the amplitude of a single IW. However, the uncertainties of IW cooling and heat accumulation at the daily level can be largely reduced by averaging a large number of samples, which are tested by a 1 min interval temperature sequence from December 2018 to April 2019 (supplementary figure S1 available online at stacks.iop.org/ERL/17/034038/mmedia). Temperature data from a moored buoy from November 2012 to May 2014 in the central AS (95.6° E, 9.6° N) are used to observe the changes in the thermocline depth and the behaviors of IWs in the deep AS (Liu 2020). The water depth at the AS buoy location is 2500 m, and the temperature sensors are set at 1 m, 10 m, 20 m, 40 m, 60 m, 80 m, 100 m, 120 m, 140 m, 200 m, 300 m, 500 m and 700 m. The sensors below 140 m stopped working from mid-March 2013 due to a battery failure. Available homochromous buoy data at 80° E on the equator from the Research Moored Array for African-Asian-Australian Monsoon Analysis and Prediction (RAMA) program (McPhaden et al 2009) are also included to study the signals from equatorial thermocline changes. The daily Optimum Interpolation Sea Surface Temperature (OISST) data (Reynolds et al 2007), sea level anomalies (SLAs) data from Archiving, Validation, and Interpretation of Satellite Oceanographic data (AVISO, Ubelmann et al 2015), and wind data from the NCEP/NCAR reanalysis (Kalnay et al 1996) are used as essential complements to the observational data.

2.2. Methods

The temperature variations are composed of the variations caused by IWs (\(T_{\text{niw}}\)) and temperature variations without IWs (\(T_{\text{niw}}\)): \(\dot{T} = T_{\text{niw}} + T_{\text{niw}}\). We use a Butterworth filter to extract the low-frequency part \(T_i\) from the raw time sequences with a cut-off set to the local inertial frequencies. As the large, unidirectional IW pulses can alter \(T_i\), we obtain \(T_{\text{niw}}\) via a restoration of a moving window root mean square (r.m.s.) value of the high-frequency variability following Wyatt et al (2020). First, we subtract \(T_i\) from the raw temperature sequence. Then, we calculate the r.m.s. for each moving window corresponding to inertial periods and added the r.m.s. to \(T_i\). We check the adjusted low-frequency time sequences and set the values exceeding the daily maximum to the daily maximum. Finally, we again low-pass filter the adjusted low-frequency time sequences to obtain \(T_{\text{niw}}\). The mean (max) error caused by the coarse temporal resolution of \(T_{\text{niw}}\) is evaluated as 0.018 °C (0.19 °C) (supplementary figure S1).

The same method is used to calculate the temperature amplitudes of IWs observed by the buoy data in the deep AS. We also calculate the displacements of isotherms \(\eta\) caused by the daily maximum IWs at the AS buoy location as \(T(z, t) = T_{\text{niw}} (z - \eta (z, t))\), where \(\dot{T}\) is the time-dependent temperature profile and \(T_{\text{niw}}\) is the background temperature profile without IWs.

To quantify the thermal stress, we employ the standard methods introduced in Wyatt et al (2020) to calculate the degree heating days (DHDs):

\[
DH = \frac{\sum_{t=-12}^{t} \dot{T}(t)}{n}
\]

where \(\dot{T}\) is the sum of temperatures that are 1 °C or more above the threshold, and \(n\) is the number of samples over which \(\dot{T}\) is summed. Threshold values are set to climatological maximum monthly mean SSTs calculated from the OISST data from 1981 to 2016. DHDs are analogous to, but more sensitive than, the degree heating week or degree heating month metrics (Wyatt et al 2020). In addition to DHDs based on observed temperature sequences, the DHDs without IW effects are calculated. The mean (max) errors of DHDs based on raw temperature sequences and temperature sequences without the influence of IWs and their differences are 0.07 °C day (0.44 °C day), 0.02 °C day (0.14 °C day) and 0.07 °C day (0.48 °C day), respectively (supplementary figure S1).
3. Results

As shown in figures 2(a)–(c), strong, frequent cooling pulses are observed at all three stations, indicating the strong influence of IWs. The temperature can decrease to 22 °C, and the maximum temperature decrease can exceed 7 °C west of Miang Island and Tachai Island. By subtracting the IW cooling from the raw temperature sequence, we acquire sequences of $T_{\text{niw}}$. $T_{\text{niw}}$ and the temperature of IW-induced intruded water have distinct variabilities and driving processes, and their differences determine the cooling effect of IWs.

The daily $T_{\text{niw}}$ values are highly consistent with the SSTs ($r \approx 0.83$), which are modulated by the surface air-sea heat fluxes associated with monsoon winds (Liu et al 2018). The temperature is warmest during the monsoon transition period in spring, especially in the spring of 2010, which is the decay phase of an El Niño, and SST and $T_{\text{niw}}$ can reach 32 °C. The seasonal high temperature in spring usually decays with the onset of the summer monsoon. In 2010, the onset time of the summer monsoon is May 17, 16 days later than the mean monsoon onset time of May 1 during 1979–2016 (Li et al 2018). Corresponding to the temperature anomalies, the DHDs are largest in the spring of 2010 and ignorable in almost all of the other seasons and years. The monsoon onset ends the fast growth of DHDs, initiating the decay of thermal stress and bleaching risks.

The temperature of the intruded water is modulated by the IW intensity and thermal stratification. The cooling effect of IWs shows uniform seasonal and interannual variabilities at the three stations. On a seasonal scale, IW cooling is strongest during the boreal spring and largely overlaps with the period of
highest seawater temperature; thus, the cooling effect of IWs is expected to provide refugia for corals from thermal stresses. However, the lowest temperature of intruded water and the largest IW amplitude coincide with the negative phase of the semiannual SLA signals, earlier than the peak of the SST, as well as the monsoon onset (figure 2(d)). Because SLAs always mirror thermocline variations (Yu 2003, Schramek et al 2018), an increase in the SLA indicates a deepening of the thermocline, and vice versa.

Although the southwest summer monsoon winds in the AS are expected to induce a deepening of the thermocline and a positive SLA, the deepening signal originating from the equator arrives much earlier than the monsoon onset (figure 2(d)), indicating potential asynchrony between IW cooling and high temperature. Especially in 2010, the onset of the summer monsoon did not occur until the positive peak of the Kelvin wave arrived in the AS, which was later than the onset of the summer monsoon in other years. The delayed onset of the monsoon and the advanced Kelvin wave enhance the asynchrony between IW cooling and high temperatures. Kelvin waves are weakened when crossing the northern tip of Sumatra due to the energy lost to the excitation of westward Rossby waves (Cheng et al 2013). Their re-enhancement in the AS indicates the contribution from alongshore winds.

As shown in figures 3(a)–(c), the cooling effects of IWs are closely related to SLAs with correlation coefficients of approximately 0.7 at all three stations. The buoy data show that the depth and amplitude of IWs in deep oceans also vary with the thermocline depth, indicating the dynamic connection of IWs in deep oceans and shallow waters. The fluctuation of the IW amplitude in deep oceans is weak relative to that in coastal areas (figure 3(d)). The buoy-observed spring IW amplitude is approximately two times greater than the IW amplitude in early summer, when the thermocline is the deepest. However, in the coastal area, the IW cooling in spring (3 °C ~ 5 °C) is nearly ten times the peak IW cooling from June to July (<0.5 °C). The trend of the IW amplitude in coastal areas is highly consistent (r ≈ 0.95) with the variation in thermocline depth represented by the 23 °C isotherm (Girishkumar et al 2013), again indicating the strong modulation of IW cooling by the thermocline.

As mentioned above, mass bleaching occurred even in potential IW coral refugia in 2010. Heat accumulation is the proximate driver of mass.
bleaching (Glynn and D’Croz 1990, Fitt et al 2001, Wyatt et al 2020). To illustrate what happened in the spring of 2010, we quantify the accumulated heat stress using DHDs relative to standard predictions of the coral bleaching threshold temperature. High DHDs exceeding 8 °C days, a criterion representing a severe bleaching risk, explain the mass bleaching that occurred in the spring of 2010 (figure 4(a)). Taking the station west of Surin Island as an example, the DHDs based on \( T_{niw} \) (DHD_{niw}) exceed 8 °C days in mid-April, which is 16 days earlier than the DHDs based on the raw temperature sequence (DHD_{raw}). Due to IW cooling, the duration of DHDs exceeding 8 °C days is shortened from 48 days to 27 days.

Severe bleaching risks appear after May 1, later than the mean onset time of the summer monsoon in this area (Li et al 2018). Before this time, the DHD reduction induced by IW cooling (DHD_{iw}) increases with DHD_{niw}, providing effective protection against severe bleaching. However, the spring of 2010 was in the decay phase of a strong El Niño, and the timing of the summer monsoon onset was delayed to May 17. As DHD_{niw} continues to increase in May, DHD_{iw} stops increasing, initiating a downtrend. Thus, under the combination of a DHD_{niw} increase and a DHD_{iw} decrease, the fast-growing DHD_{raw} eventually breaks through the protection of IW cooling and induces a severe bleaching risk during the delay of the monsoon onset.

IW cooling is determined by the temperature difference between the local water and the intruded water. As \( T_{niw} \) grows from March to May, the SLA indicates a downtrend of the thermocline depth (figure 4(b)) that tends to suppress IW cooling and enhance the accumulation of heat stress. Especially during the delay of the monsoon onset, the thermocline depth approaches its low peak, while \( T_{niw} \) maintains its high peak. Such an asynchrony between \( T_{niw} \) and thermocline depth induces the asynchrony between DHD_{niw} and DHD_{iw} and eventually causes a severe bleaching risk. The delayed monsoon onset, prolonged high SST and continuous deepening thermocline during the spring of 2010 are representative of El Niño years (supplementary figure S2).

4. Summary and discussion

Tropical corals are facing increasingly frequent large-scale mass bleaching induced by global warming and associated extreme thermal events. This situation has prompted the search for potential coral refugia and reef conversion areas. IWs are considered to be a workable ambient condition for coral conversion from global warming because they induce strong cold water intrusion into coral reefs. However, the efficiency of IWs in mitigating thermal stresses depends on the matching between the climate modes of surface warming and IW cooling. Based on in situ observations in the AS and satellite data, this study shows that a high bleaching risk occurs even in the expected coral refugia in 2010. IW cooling is strongly modulated by the thermocline depth, which has distinct driving processes with \( T_{niw} \). The El Niño-induced delay of the onset of the summer monsoon enlarges the asynchrony between high temperature and IW cooling and provides a time window for the co-existence
of the highest temperatures and inhibited IW cooling, which eventually induces severe bleaching risks to corals.

The results of this study reveal a pathway by which large-scale climate modes influence IWs and coral bleaching in coastal areas (figure 5). The equatorial westerlies excite downwelling Kelvin waves, which propagate into the AS and are re-enhanced by alongshore winds. Then, the Kelvin waves excite westward Rossby waves, which propagate into the central AS and deepen the thermocline there. A deep thermocline pushes down the IWs, hindering their intrusion into coral reefs and inhibiting IW cooling. An upwelling Kelvin wave leads to the converse effect.

Although the data show a firm relationship between IW cooling and the thermocline depth, the processes of IW propagation into coral reefs are complex. Because the vertical distribution of the water temperature is uniform in shallow waters and our sensors are deployed near the seafloor, the temperature variation caused by local isotherm fluctuations is expected to be negligible. Elevation-type IWs in coastal areas essentially propagate as gravity currents upslope to the coast, carrying cold deep water into the shallower area and losing their energy and mass in the process of overcoming the gravity, friction and drainage of the dense fluid (Venayagamoorthy and Fringer 2006). A shallower thermocline means a shorter distance to the corals and a lower temperature of the upslope surging water mass, which enhances IW cooling in coastal areas. Furthermore, the shoaling of the thermocline facilitates the shoreward propagation of IW energy by lifting the IWs.

Areas exposed to variable thermal conditions or with lower temperatures are considered to be potential coral refugia against thermal stresses under the projection of global warming (Bongaerts et al 2010, Karnauskas and Cohen 2012, Wall et al 2014, Wyatt et al 2020). However, the mesophotic depth in the Caribbean has been proven to be an unlikely refugia from climate change (Smith et al 2016). Frade et al (2018) reported high rates of deep bleaching that were attributed to a cessation of transient upwelling in the Great Barrier Reef. IW coral refugia are considered to be reliable in areas where IWs are active during anomalously warm periods (Wall et al 2014, Wyatt et al 2020). In this study, although the concomitant positive SST anomalies and negative SLA anomalies in El Niño years indicate a greater potential reduction in thermal stresses on an interannual scale, the episodic failure of IW protection induced by late monsoons warrants a comprehensive assessment of IW coral refugia.

Apart from the thermal effect, IWs have many incidental influences. IWs reduce the intensity of light, which protects shallow corals from damage by strong irradiance (Hoegh-Guldberg and Smith 1989, Brown et al 2002, Brown and Dunne 2008) but reduces the diversity of deep corals (Schmidt et al 2012). Moreover, IW-induced
resuspensions, sedimentations and nutrient variations also influence the coral reefs. This study does not consider these factors, due in part to their extraneous essential role in the time window of this study and a lack of observations. Furthermore, the intrinsic community composition has been reported to explain 30%–40% of the bleaching response (Wall et al 2014, Wyatt et al 2020), and the trends of the bleaching response among species and depths are expected to be consistent. In addition, the approximate temperature threshold of climatological SST may introduce bias into DHDs, and more in situ time series are essential for acquiring an accurate threshold.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://osf.io/u5dm8/.

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