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SEASONAL VARIATION IN WATER CIRCULATIONS AND ITS IMPACT ON THERMAL ENVIRONMENT IN A CORAL REEF AREA OF SOUTHWEST JAPAN

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Abstract: Summer and wintertime observations were conducted through deploying horizontal oceanographic time series sensors in a coral reef region of Southwest Japan to assess the existing hydrodynamic and thermal environments in relation to seasonal changes. A significant variation in water circulation and temperature distribution pattern was recorded in Shiraho reef area between two different seasons. During winter, a strong inflow of oceanic water was recorded inside the reef on a semidiurnal pattern that led to significant water temperature rising while in summer, considerable amount of sea water entered the reef area with a diurnal frequency causing water temperature slightly lower. Outside the reef, current was found to flow nearly parallel in direction to the north-south stretch of the reef.

Key words: Current, temperature, Shiraho, coral reef, Ishigaki, Japan

Introduction

Research on coastal water circulation dynamics in tropical and subtropical regions has received considerable attention in the recent past because of the importance of hydrodynamic processes in determining the short and long-term sustainability of marine and coastal ecological systems (Wolanski, 1994, 1986; Kruyt and van der Berg, 1993). The hydrodynamic processes also determine the linkage between coastal ecosystems such as mangroves, seagrass beds and coral reefs. The description of water circulation and exchange patterns in tropical and subtropical coastal waters is therefore crucial to the understanding of ecosystem dynamics and global ocean flux studies (Bowman, 1997; Swenson and Chuang, 1983; Ho, 1977). Hydrodynamics in coastal reef areas are thought to be the most complicated phenomena if the reef areas become connected or remain exposed to the open ocean (Nakaza *et al*., 2006). A number of research studies have already conducted on a variety of coral reefs. According to Andrews and Pickard (1990), water circulations in a coral reef lagoon system are mainly driven by wind, tide, and waves overtopping on the reef crest. In fringing reefs, like those of the Caribbean, wave overtopping on the reef crest and the induced inflow is considered to be the main driving force of water circulation (Roberts *et al*., 1992, 1975) while tide is thought to be the main driving force in fringing reefs in the Great

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Barrier Reef due to large tidal ranges (Parnell, 1988). Kench (1998) observed physical processes in an Indian Ocean atoll and indicated that lagoon circulation is tide dominated with flushing of the lagoon occurring through the deep leeward passages. The atoll structure was found to control both lagoon circulation and the spatial pattern of energy distribution.

Coral reef areas are known as geologically complex, and biologically productive for fish and other living organisms. However, over the past several years with increasing regularity coral reefs around the world have been affected by a phenomenon know as "coral bleaching". The global extent of and recent increase in coral bleaching have been summarized by Glynn (1993) and Brown (1987) and documented for specific region by Brown *et al*. (1996), Hoegh-Guldberg and Salvat (1995), and Cook *et al*. (1990) among many others. Many studies have suggested that elevated temperature is one of the most likely causes for coral bleaching (Winter *et al*., 1998; Brown, 1997). The degree of coral bleaching and consequent mortality has been reported to show significant variability in global and regional scales. This suggests that physical environments, such as water temperature (Berkelmans and Willis, 1999), salinity, turbidity, etc. (William and Gary, 1997; Hoegh-Guldberg and Smith, 1989), and biological environments like dominant species (Marshall and Baird, 2000; Kayanne *et al*., 1999), predatory animals, etc., in coral reefs may vary in different scales.

For detailed and quantitative understanding of the actual physical processes governing coral bleaching or any other ecological phenomena, it is needed to know the hydrodynamic and thermal environments of coral reef areas in detail, with special emphasis on the connections with offshore environments in various conditions. However, these issues have not been well addressed for the coral reef regions of the Ryukyu Islands. Tanimoto and Uda (1990) studied water circulation pattern on Nakadomari Reef, Okinawa Island, and mentioned that the current was caused by wave-overtopping on the reef crest and the effect of wind was small. Yamano *et al*. (1998) conducted observations in the Kabira reef of Ishigaki Island and pointed out that the circulation in the reef shows a marked wind influence. The authors concluded that the circulation pattern under calm wind conditions is characterized by an inflow of ocean waters into the moat over the reef crest and an outflow through a prominent channel. Nakamori *et al*. (1992) observed water circulation on Shiraho Reef, Ishigaki Island, based on field measurements of the current and study of the arrangements of coral patches. They concluded that the offshore waters enter the reef across the reef crest and return to the outer ocean directly through a channel. Nadaoka *et al*. (2001), who made the observation for Shiraho Reef of Ishigaki Island, concluded that the overall characteristics of reef currents under normal atmospheric conditions, are governed by the dynamic balance among tide, wave and wind, and river plume effects, and have close relationship with the salinity and turbidity variations. However, for the Ryukyu Islands, the variations of reef circulations between two different climatic conditions and its possible impact on temperature distributions in reef systems had not been discussed. The issues have been well addressed through the present study.

Materials and Methods

Site details: Observations were conducted in the southeast coastal region of Ishigaki Island (from about 24º 20' 18" to 24º 25' 27" north latitude and from 124º 15' 17" to 124º 21' 07" east longitude), southwest Japan (Fig. 1). The observation site included both the Shiraho reef and offshore areas outside the reef. Shiraho Reef area is hydraulically connected with the offshore area through channels namely "Tooru-guchi, Ika-guchi, Moriyama-guchi and Bu-guchi. Of all the channels, Tooru-guchi is the biggest reef gap in the study area connecting the offshore region with the reef area (Nakamori et al., 1992). The southern part of the reef is comparatively shallow than the northern region. The shallowest area namely "Watanji" is also located in the southern part that becomes exposed to air during low tide. The coastline along the study area faces to the east runs north and south. As shown in Figs. 1 and 2, the observations were made on a stretch of about 8 km along the shore, in the middle of which Todoroki river mouth is located. Water depths at the measuring stations located outside the reef were about 50-52 m.

Instrumentations: As shown in Fig. 2, the observations site includes in total 11 measuring points to record horizontal current, water temperature distributions, wave heights and tidal ranges both from reef and offshore areas. Oceanographic data were collected through the deployment of different sensors during summer (August 7 to October 27, 2001) and wintertime (February 7 to March 25, 2002) observations. Compact Electromagnetic Meters (CEMs) were deployed at seven points inside the moat of the reef area named Re1-Re7 with the help of moored buoys for time series measurement of horizontal current and water temperature at 10 minutes intervals. The sensors were set at around middle depth of the shallow reef area having the depths ranging from 1.5 to 3 m. Outside the reef, bottom moored Acoustic Doppler Current Profilers (ADCPs) having the acoustic frequency of 600 kHz each were set at four stations named Off1-Off4 to record the vertical profiles of horizontal current and the time history of water temperature fluctuations. ADCPs recorded velocity profiles over the entire depth range at 1 meter depth intervals and the time history of horizontal velocities were measured at every 10 minutes intervals.

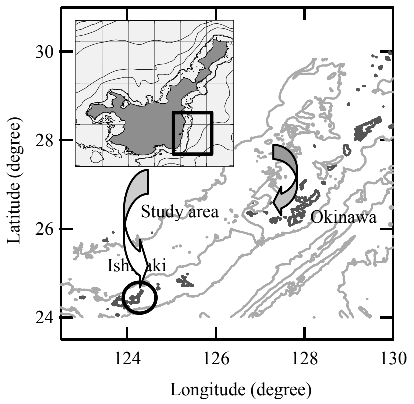

Fig. 1. Map of Ishigaki Island and location of the study area.

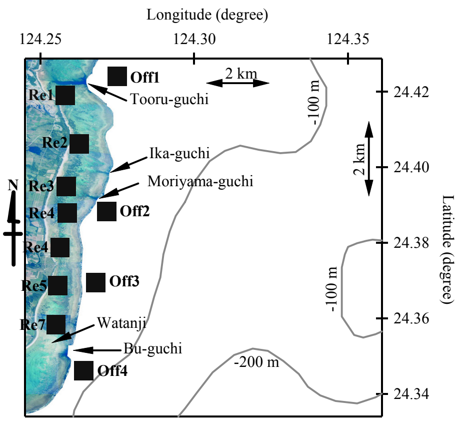

Fig. 2. Location of sensors deployed in the study area.

During the observations, wave gauges (each with a built in pressure gauge and bi-directional electromagnetic current meter) were also placed both in the reef and offshore areas at Re1 and Off1 for continuous measurement of tidal currents and wave heights at every 1 hr interval. Required atmospheric data were collected from Ishigaki Meteorological Observatory.

Results

Water circulation and temperature distribution inside the reef area during winter: Horizontal current of north-south and east-west components during February 13, 00:00 to February 15, 00:00, 2002 is shown in Figs. 3a and 3b for stations Re1 through Re7. Time series of mean tidal fluctuations of reef (station Re1) and offshore (station Off1) areas, the difference of tidal ranges between reef and offshore regions (Fig. 3c), water temperature fluctuations for stations Re1 and Re7 (Fig. 3d) and atmospheric temperature distributions (Fig. 3e) are also shown. As Fig. 3 indicates, a nearly constant and controlled water circulation pattern characterized the current structure of Shiraho reef during the winter. Figure 3c shows that there was a time lag between the reef and offshore areas especially in the initial period of tidal rising from a low tide condition. The time gap was recorded for a maximum period of about 3 hours. As the tidal level in the offshore region rose earlier than the reef area a strong inflow of oceanic water entered the reef area. During February 13, 03:30 when tidal level in the offshore region was rising (Fig. 3c) the offshore water entered the reef area through station Re1 with a significant temperature rising at this point (Fig. 3d). Later, the warm oceanic water flowed southward from station Re1 toward station re7 with a little time gap (Fig. 3a). Due to the penetration of warm sea water, temperature at station Re1 increased more then 4 ºC within a very short period of time. Contrary to this temperature rising at point Re1, water temperature in the southernmost part of the reef at station Re7 showed a gradual dropping during the observation (Fig. 3d).

During tidal rising, a short period and nearly unidirectional southward current was measured in the reef area on a semidiurnal basis. Other than the short period semidiurnal current, Figs. 3a and 3b show that water circulations in the reef areas were characterized by a northwest current at stations Re1, Re2 and Re5, a southwest current at stations Re6 and Re7 and a dominant east current at stations Re3 and Re4.

Water circulation and temperature distribution inside the reef area during summer: Figure 4 shows north-south and east-west currents in the reef area for stations Re1 through Re7, water temperature variations for stations Re1 and Re7, and atmospheric temperature fluctuations from September 3, 00:00 to September 5, 00:00, 2001. Mean tidal level fluctuations recorded at stations Re1 and Off1, and the difference of tidal ranges between stations Off1 and Re1 are also included in Fig. 4. During the summertime measurements, recorded tidal levels showed little discrepancy between the offshore and reef stations (Fig. 4c) and also the time gap between the two stations during tidal rising was little in comparison to wintertime observations. This little time gap (about 1 hour) led to a slight rise of offshore tidal level over the reef area and the inflow of low velocity south current inside the reef on a diurnal basis. When sea water entered inside the reef area then average reef and sea temperature was measured as 31 and 28 ºC respectively. With the penetration of cold oceanic water during September 3, 14:00 and September 4, 14:20 (Fig. 4a), water temperature at station Re1 got a little drop even though the temperature at station Re7 was still increasing (Fig. 4d) due to atmospheric influence.

Water circulation and temperature distribution in the offshore region: North-south and east-west currents, and water temperature fluctuations at station Off1 are shown in Figs. 5 and 6 for winter (February 13, 00:00 to February 15, 00:00, 2002) and summertime (September 3, 00:00 to September 5, 00:00, 2001) observations respectively. During winter, only near bottom temperature (Fig. 5c) was measured while for summer, temperature was recorded at four different depths (Fig. 6c). Horizontal current velocities are shown for every 10 meter depth interval starting from 10 m below the surface extending down to 50 m depth. Recorded current data depict that both during summer and winter, current field was dominated by alongshore (north-south) current. During a rising tide (Figs. 3c and 4c), current flowed southwest while for a dropping tide condition, northeast current was recorded at station Off1 both during summer and winter. Water temperature of station Off1 at different depths indicates no considerable variation with the tidal fluctuations during winter. However, during summer, recorded water temperature shows a marked rise and fall with a tidal level getting up and down respectively.

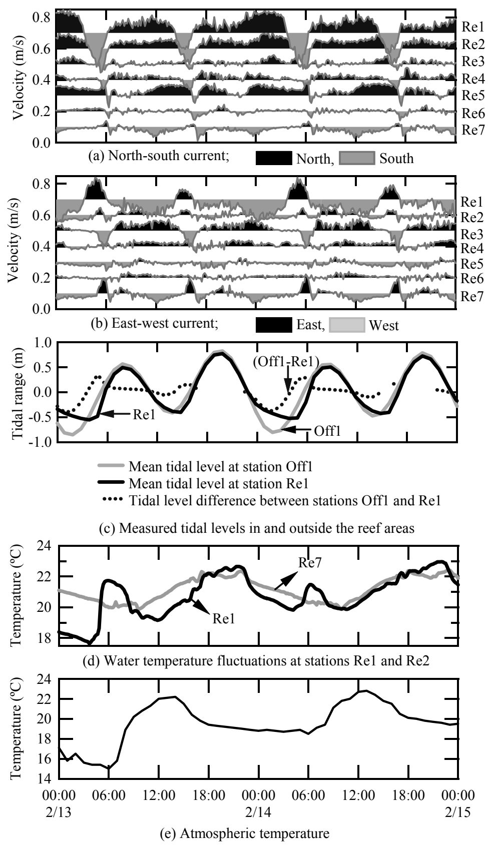

Fig. 3. Current, tidal range and temperature distributions in 2002: (a) north-south and (b) east-west currents (Re1 to Re7), (c) tidal levels (Re1 and Off1), and the difference (between Off1 and Re1) of tidal level, (d) temperature fluctuations (Re1 and Re7), and (e) atmospheric temperature variations.

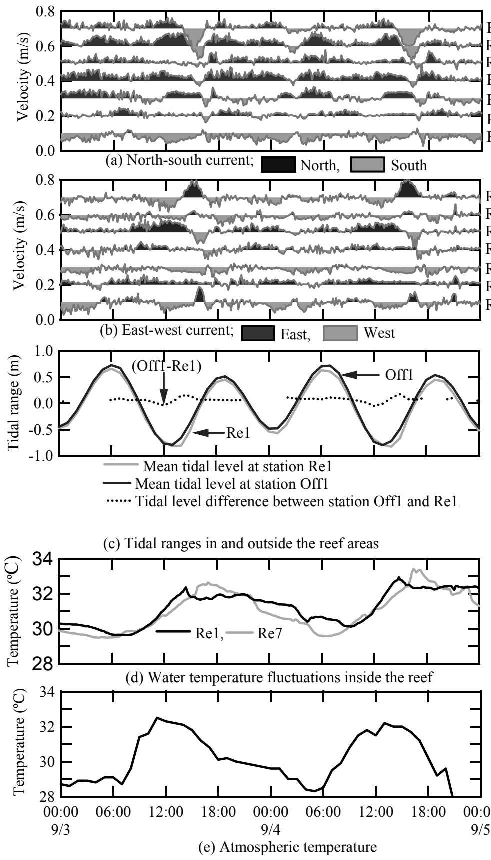

Fig. 4. Current, tidal range and temperature distributions in 2001: (a) north-south and (b) east-west currents (Re1 to Re7), (c) tidal levels (Re1 and Off1), and the difference (between Off1 and Re1) of tidal level, (d) temperature fluctuations (Re1 and Re7), and (e) atmospheric temperature variations.

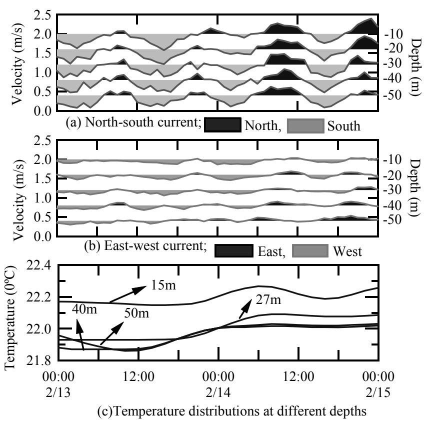

Fig. 5. Depth profiles of current and temperature fluctuations at station Off1 in 2002.

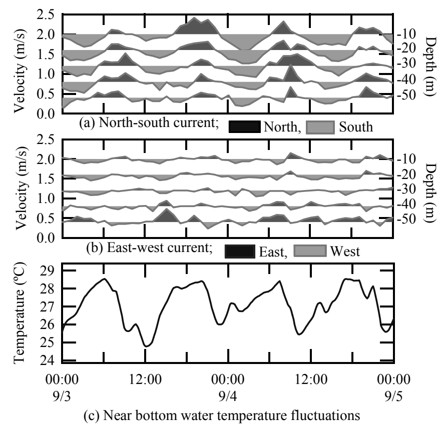

Fig. 6. Depth profiles of current and temperature fluctuations at station Off1 in 2001.

Discussion

Coral reefs occur within well-defined limits of the physical environment. Bathymetry, temperature, light, water characteristics, ocean currents and the history of sea-level change all contribute to determining the present distribution, composition and diversity of coral reef ecosystems. Therefore, the flow of oceanic water into and through coral reefs and the resulting water residence time in the reef system is a critical factor in determining community distributions and production rates in Coral Reef ecosystems both by controlling the supply of nutrients from offshore and the level of turbulence on the reef edge. Recorded oceanographic data suggest that both during summer and winter, Shiraho Reef area was characterized by controlled water circulation pattern with the difference in frequency and velocity only. Current and tidal data indicate that when tidal level in the offshore region at station Off1 started rising from a low tide condition, the tidal level inside the reef at station Re1 was still dropping with a continuation for a maximum period of about 3 hours during the winter and about 1 hour during the summer. This opposing trend in tidal fluctuations between the reef and offshore areas resulted a significant rising of offshore tidal level over the reef area. As the tidal height outside the reef edge area increased considerably, oceanic water entered the reef area particularly through the Tooru-guchi reef channel where station Re1 was located. The time lag that was recorded between the reef and offshore areas in the initial period of tidal rising made a frequency difference between the two seasons in the propagation of southward current from the northern part of the reef in station Re1 toward the southern region in station Re7. During winter, sea water temperature was comparatively warmer than reef water particularly during nighttime. The recorded water temperatures for offshore and reef areas were about 22 ºC and 17 ºC respectively. As oceanic water entered the reef area through station Re1, measured water temperature at this point showed significant rising. Contrary to this elevated temperature at point Re1, water temperature in the southernmost part of the reef at station Re7 found to drop considerably. It is already mentioned that the southern part of the study area is the shallowest zone, and this shallowness mainly helped to decrease water temperature through atmospheric cooling effects until the warm oceanic water reached here from the northern part. The rising of temperature in station Re7 was happened due to the presence of warm water flow from station Re1. A time lag is found between the north and south part of the study area both in current and temperature variations. This time lag comes from the time interval that is required for the incoming sea water to reach from station Re1 to station Re7.

Oceanic water from station Re1 turned southward and flowed parallel to the coast in the moat. The currents then converged on the southern part of Shiraho moat with southeast current at stations Re2 and Re7 and southwest current at stations Re3 through Re6. Finally the water is drained to the southern part (Nadaoka *et al*., 2001; Nakamori *et al*., 1992). As the oceanic inflow stopped, water temperature at station Re1 again started dropping sharply due to atmospheric low temperature. Later with the rising of atmospheric temperature (Fig. 3e) reef temperature also started increasing gradually, however, there was a time lag between the reef and atmospheric temperature. Nakamori *et al*. (1992) concluded that Shiraho reef flat has a single circulation unit which is comparable to a cell unit of nearshore current system. In contrast to Shiraho reef, entry and draining of sea waters in other fringing reefs of Ryukyu Islands are found to have marked differences. In that case, sea water on the reef flat is exported to the outer ocean directly through some channels like a rip current of the nearshore current system (Tanimoto and Uda, 1990).

During summer, as the tidal level outside the reef area slightly raised over the reef area, the inflow of oceanic waters inside the reef area occurred in a diurnal frequency leading to a short period southeast current at station Re1. Then southeast current gradually advanced toward the south passing stations Re2 through Re7. Strong solar radiation made the water temperature of the shallow coral reef area warmer than that of the sea during summer. So, due to the influence of incoming tidal water, temperature at station Re1 was decreased. On the other hand, temperature at station Re7 was still rising due to atmospheric influence. As southeast current propagated from station Re1, short period south, southwest, southwest, south, south and southeast currents were observed at stations Re2, Re3, Re4, Re5, Re6 and Re7 respectively with small time lag between each observation point. With a time interval when cold sea water reached station Re7 from station Re1 then water temperature at this point also started dropping. Other than the frequency difference of short period southward current, water circulation pattern inside the reef areas was almost controlled and uniform like that of wintertime.

Study results showed that the current field outside the Shiraho reef area was mainly dominated by semidiurnal tides. Harmonic tidal analysis of 8 principle tidal constituents (M_2, S_2, N_2, K_2, K_1, O_1, P_1 and M_m) indicated that M_2 and S_2 tidal components mainly influenced the general circulation pattern of the Okinawa offshore region (Kitamura *et al*., 2004). Both the incoming and outgoing currents in the offshore region were found to flow in a nearly parallel direction to the north-south stretch of the Shiraho reef area. Water circulations at the three other stations (Off2 to Off4) followed almost similar direction pattern (data not shown) as of station Off1.

Conclusion

The present study was conducted to observe the hydrodynamic and thermal environments under two different climatic conditions with a view to see whether this seasonal change makes any significant variation in water circulation and temperature distribution patterns. Under normal atmospheric condition, Shiraho Reef area was found to be characterized by an almost uniform, regular and controlled water circulation pattern both during summer and winter. The only difference that was recorded is the frequency distribution of a southern current between two different seasons. During winter, strong inflow of oceanic waters led to a semidiurnal south current in the reef while for summertime circulation, the current was measured in a diurnal frequency. Water temperature in the reef was mainly dominated by atmospheric temperature. Both the short and long-time thermal oscillations were in principle influenced by atmospheric conditions, however, the inflow of sea water contributed to increase water temperature significantly during winter. Water temperature inside the reef area slightly dropped due to the influence of incoming tidal water. Other than the reef area, current outside the reef was characterized by a semidiurnal oscillation. Both for the rising and falling tides, currents in the offshore region flowed in nearly parallel direction to the north-south stretch of reef area.

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