CHARACTERISTICS OF TIDAL CURRENTS IN THE EAST SEA OF ISHIGAKI ISLAND, SOUTHWEST JAPAN

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沖縄県石垣島白保海岸において，サンゴ礁より沖側の潮流特性を把握するための現地観測が 2001 年の夏場と 2002 年の冬場において行われている．夏場に行われた観測結果は，潮流楕円の主軸が南北方向にあること，さらに水深約 50m という比較的浅い海域においてさえも，上層と下層とで流れの様子が異なり，表層から中層までの潮流楕円の回転方向は時計回りであり，それよりも下層では反時計回りとなっていることなどを示している．さらに，水温躍層位置が低下する冬場における観測結果では，夏場得られたと同様な結果が，かなり深いところ，具体的には水深 150m 程度も深くなるところで見出されることなどを示している．

Key Words: *Tidal current, Shiraho reef, Ishigaki Island, tidal ellipse, depth averaged current, current velocity vectors, clockwise, anticlockwise, internal wave, thermocline, ellipse orientation*

1. INTRODUCTION

Mass coral bleaching is now a worldwide concern. So special attention must go toward the conservation and preservation issues of coral reef resources, as coral reef communities are so vulnerable to environmental impacts. Since, water circulation is a major factor in determining the community structures and the exchange or dispersal of materials in coral reefs (Yamano et al. 1998)[1], for any conservation, preservation or development activities, emphasis must be given in determining the water circulation pattern of the reef area.

The shallow water region outside the Shiraho coral reef edge of Ishigaki Island is bestowed with characteristic isobathymetric features. It is assumed that the water circulation of the shallow offshore region may influence the water circulation pattern and thermal environment of the reef area as the reef area becomes connected with the offshore area through the reef gaps, and also the reef area becomes flooded during high tide. It is urgent that we have more detailed knowledge on the current fields in the offshore area adjacent to the reef area before dealing with the characteristic water circulations inside the reef area. Currents in the open sea area are very complicated phenomena since the influences come to such current fields from so many factors including the local wind. In this paper, we mainly concentrated to figure out the tidal current structures in the offshore area.

Researchers from different areas of the world have been conducting research activities on a variety of coral reef and of its adjacent shallow water areas (Andrews and Pickard 1990; Atkinson et al. 1981; Frith 1981)[2)3)4)] however; there are few studies on fringing reefs in the Ryukyu Islands. Nakamori et al. (1992)[5)] observed the water circulation on Shiraho coral reef area and concluded that the offshore waters entered the reef area across the reef crest and returned to the outer ocean directly through the reef channels. Though the authors showed that the offshore water enters the reef area and contributes to the circulation patterns in the reef area to a greater extent; information about the shallow water current system in the offshore area outside the reef edge was not so detailed. Similarly, Nadaoka et al. (2001)[6] who made the observation in the Shiraho coral reef area concluded that the overall characteristics of reef currents are governed by the dynamic balance between tide, waves and wind effects. In the Ryukyu Islands, Nakaza et al. (1992)[7] also made field observations on wave and current fields in the Okinawa reefs however, the observations were conducted under typhoon condition.

Until now the researchers who have done observations in the present study area mainly put their focuses on the reef circulation pattern without investigating the current structures in the adjacent shallow water offshore region in detail. Very limited information has known about the offshore current from those research works. Present study shows the details of characteristic tidal current structures as this areas water circulation is mainly dominated by tidal influences. The results of the study could be used as good reference materials in order to know the hydrodynamic and thermal environments of the region in detail.

2. METHODOLOGY

(1) FIELD OBSERVATION

a) Location

Present study was conducted in the east sea (from about 24° 20′ 04″ to 24° 25′ 27″ in north latitude and from about 124° 15′ 19″ to 124° 21′ 07″ in east longitude) of Ishigaki Island, southwest Japan (**Fig.1**). Field observations were conducted in the offshore region outside the Shiraho reef edge area. Six measuring points named Off.1, Off.2, Off.3, Off.4, Off.5 and Off.6 were selected to measure the time history of vertical profiles of horizontal current velocity. The water depths at the measuring points range from about 52 m to 230 m.

b) Sensor deployment

Acoustic Doppler Current Profiles were deployed at the measuring points (**Fig. 1**) with the help of moored buoys for continuous measurement of vertical profiles of horizontal current velocity. The water depths at Off.1, Off.2, Off.3 and Off.4 were about 52 m while at Off.5 and Off.6; the depths were 150 m and 230 m respectively. Current velocities were recorded every 10 minutes intervals at every 1 meter from the bottom layer up to the surface at all the measuring points. At Off.1, tidal levels were measured every 1 hour interval through the deployment of bottom mounted Wave Hunter.

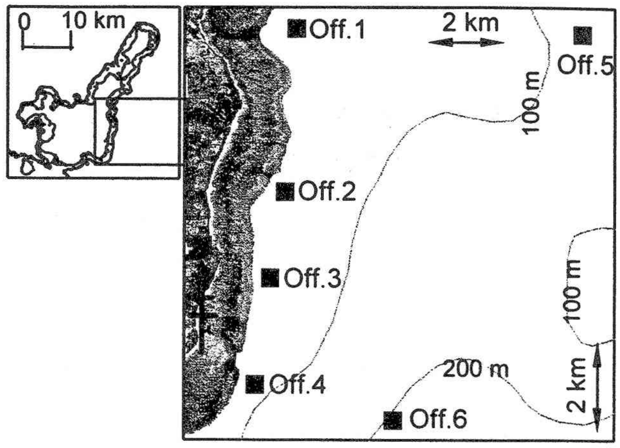

Fig. 1 Ishigaki Island and the locations of the measuring points.

Field observations were done during both summer and winter seasons. For the summer season, the observation duration was from August 10 to October 27, 2001 and current velocities were measured at Off.1, Off.2, Off.3 and Off.4.

On the other hand, during a wintertime observation, current velocities and tidal ranges were measured at Off.1, Off.3, Off.5 and Off.6 from February 7 to March 25, 2002.

3. RESULTS & DISCUSSIONS

(1) DEPTH AVERAGED TIDAL CURRENTS

Figure 2 shows the velocity vectors of depth averaged tidal currents in the offshore area at Off.1, Off.3, Off.5 and Off.6. Current velocities are shown from March 2 12:00 to March 3 02:00. As already mentioned horizontal current velocities were recorded at every 1 meter from the bottom up to the surface layer. Depth distributions of horizontal tidal current velocities are averaged in **Fig. 2**.

Figure 3 shows mean tidal levels in the offshore area at Off.1. Current velocity vectors shown in **Fig.2** correspond to the marked tidal levels of **Fig.3**. The downward and upward arrows close to the markers on **Fig. 3** indicate low and high tide conditions respectively.

Figure 2 shows that during March 2, 12:00, depth averaged tidal currents in the offshore area at Off.1, Off.3, Off.5 and Off.6 were flowing in almost northern direction, as it was low tide condition in the sea (**Fig. 3**). Since low tide was continuing, two hours later on March 2, 14:00, currents at Off.1, Off.3 and Off.5 flowed northward however, at Off.6 northeastern current was found. **Figure 2** shows that

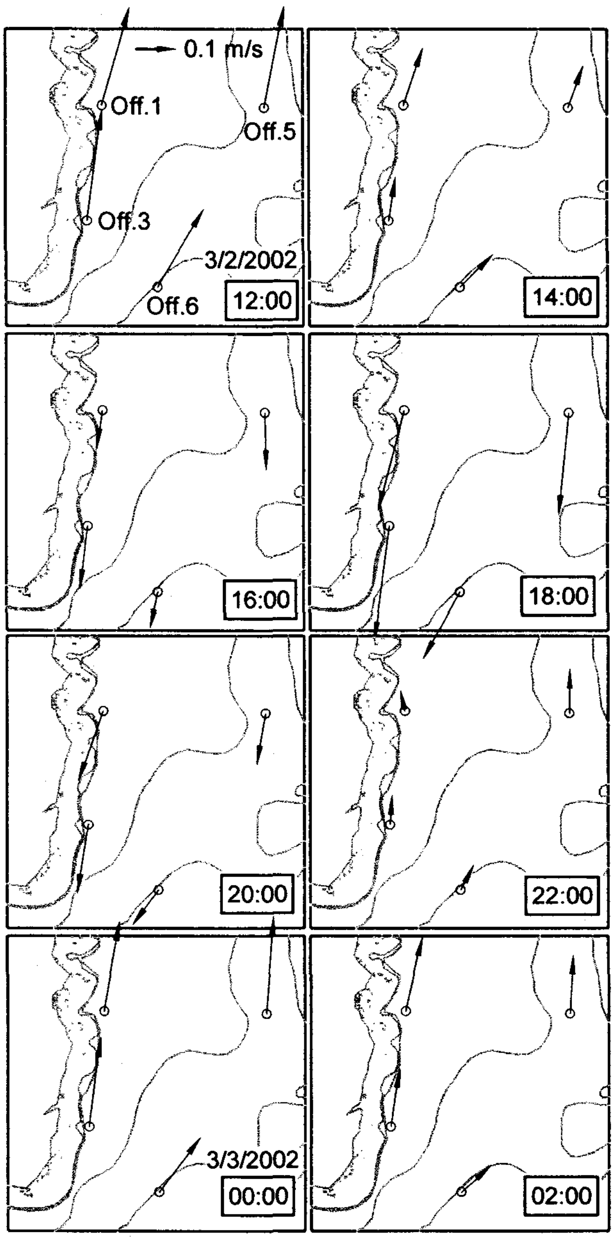

Fig. 2 Depth averaged current velocity vectors in the offshore area.

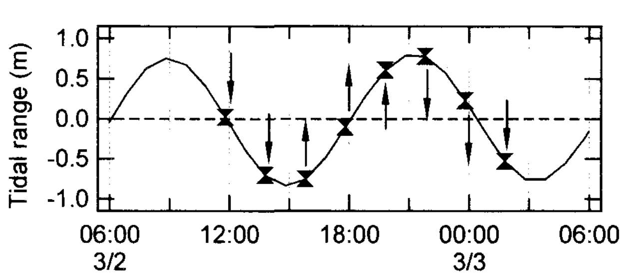

Fig. 3 Mean tidal levels at Off.1.

during low tide depth averaged tidal currents were heading in nearly parallel directions to the north-south stretch of the Shiraho coral reef area except at Off.6 where the tidal current direction remained parallel with the adjacent isobaths.

As the tidal level started rising, during March 2 16:00, tidal currents in the offshore area at all the measuring points were flowing toward the southern direction with a comparatively lower velocity. Two hours later on March 2 18:00, southward tidal currents at Off.1, Off.3 and Off.5 became more progressive with the continuation of tidal level rising. That time, tidal current at Off.6 was slightly shifted to the southwest from its earlier southern direction.

During March 2 20:00, tidal current velocity vectors showed southern direction except at Off.6 where a southwestward current was prominent. This is also evident for high tide condition that currents at Off.1, Off.3 and Off.5 were nearly parallel to the north-south stretch of the reef area while at Off.6 tidal current direction remained parallel to the adjacent isobaths.

As low tide started again, during March 2 22:00, tidal current direction turned toward the north. More progressive northward tidal currents were seen through **Fig. 2** during 00:00 and 02:00 on March 3 similar to the depth averaged tidal current directions during 12:00 and 14:00 on March 2.

Figure 2 shows that depth averaged tidal current directions in the offshore area during both low and high tide conditions were almost parallel to the north-south stretch of the reef area except current at Off.6. Tidal current direction at Off.6 stayed parallel with the adjacent isobaths.

Study results showed that the tidal current fields of the study area were mainly dominated by semidiurnal tidal components. The analyses of eight major harmonic tidal components such as M_2, S_2, N_2, K_2, K_1, O_1, P_1 *and Mm* clearly indicated that M_2 and S_2 tidal components were the two most dominating tidal components there.

(2) DISTRIBUTIONS OF M_2TIDAL ELLIPSES AT DIFFERENT DEPTHS IN THE OFFSHORE AREA DURING WINTER

Though the depth averaged tidal current directions in the offshore area were mainly toward the south and north directions during high and low tide conditions respectively, orientations of the tidal ellipses and the directions of the major axes at different depths of water, indicated the existence of different directional currents in the upper and bottom layers of water.

Figure 4 shows the orientations of the tidal ellipses at Off.1, Off.3 and Off.5. The tidal ellipses are shown during the wintertime filed observation of February 7 to March 25, 2002. For Off.5, tidal ellipses are shown at different depths of water starting from 10 m below the surface down to 5 m above the bottom. For Off.1 and Off.3, tidal ellipses are also shown from 10 m below the surface down to 2 m above the bottom. The upward and downward arrows on the tidal ellipses in **Fig. 4** indicate clockwise and anticlockwise directions respectively.

Clockwise rotations of the tidal ellipses were found from 10 m below the surface down to 80 m depth in **Fig. 4** at Off.5 where the major axes of the ellipses were almost in north-south directions. The lengths of the major axes gradually decreased from the surface toward the deep regions however, in the bottom layer, the lengths of the major axes were increased instead of decreasing. The length of the minor axis was almost zero at 100 m depth from where the ellipse rotation was turned to an anticlockwise direction from their previous clockwise direction.

When the tidal ellipse rotation was turned to an anticlockwise direction starting from 100 m depth toward the bottom layer of Off.5, the ellipse orientation started turning gradually from north-south direction toward east-west direction and finally near the bottom the major axis attained nearly east-west direction.

From the viewpoints of tidal ellipse orientations and their rotational directions at Off.5, it is assumed that strong east-west directional currents were existed there, which followed internal wave propagation.

Figure 4 also shows the tidal ellipse orientations of M_2 tidal component at Off.1 and Off.3. At Off.1, ellipse rotation is clockwise from the surface layer down to 45 m depth. After that ellipse rotation was turned to an anticlockwise direction. Major axes of the ellipses lay almost in north-south directions from the surface down to the bottom layer making nearly a parallel direction to the north-south stretch of the reef zone.

At Off.3, tidal ellipses showed a major north-south directional current from the surface down to the bottom layer like Off.1 (**Fig. 4**) and the rotation directions of the ellipses were clockwise from 10 m below the surface down to 35 m depth. From 45 m depth toward the bottom, ellipse rotation was in an anticlockwise direction.

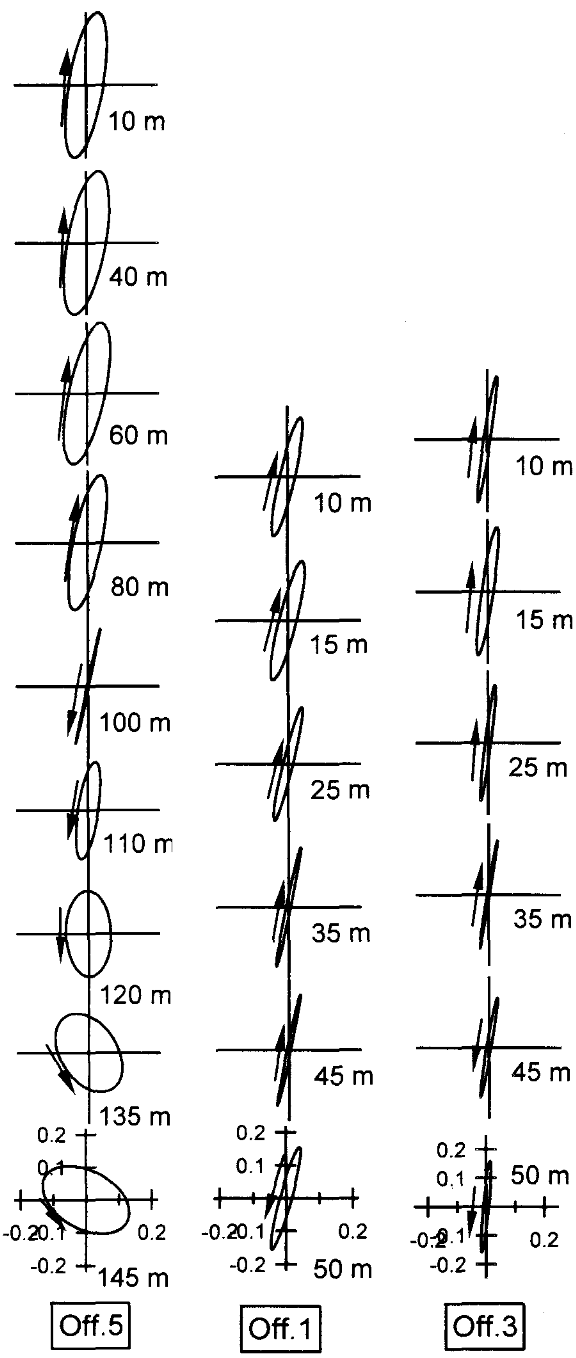

Fig. 4 Tidal ellipses at Off.5, Off.1 and Off.3.

Tidal ellipse orientation at Off.6 (data not shown) was also similar to those of Off.1 and Off.3 and at this three measuring points, study results don't show the propagation of internal waves rather the ellipse orientation is assumed to be due to the bottom friction effects.

(3) DISTRIBUTIONS OF M_2TIDAL ELLIPSES AT DIFFERENT DEPTHS IN THE OFFSHORE AREA DURING SUMMER

Tidal ellipses of M_2 tidal component at Off.1, Off.2 and Off.3 are shown in **Fig. 5** during the summertime field observation of August 10 to October 27, 2001. For all the measuring points, ellipses are shown from 10 m below the surface down to 50 m depth. The upward and downward arrows on the ellipses indicate the clockwise and anticlockwise directions respectively.

Figure 5 shows that from 10 m below the surface down to 25 m depth at Off.1, the major axes of the ellipses stayed in a principle north-south direction and the rotational directions were clockwise. From 35 m depth, the rotation was changed to an anticlockwise direction and the major axes of the ellipses started gradual inclining toward the east-west direction, which became more prominent near the bottom layer of the water body.

Tidal ellipses orientations at Off.1 showed an interesting feature of current velocity distributions having the depth of around 52 m. In the upper and lower layers, clearly different directional currents became apparent. This is assumed to be due to the existence of internal wave propagation. As it was a summer season, the thermocline was formed in a shallow depth of water comparing to winter season.

Tidal ellipses were rotating in a clockwise direction at Off.2 from 10 m below the surface down to nearly the bottom layer and the major axes of the ellipses were almost in north-south directions. As the lengths of the major axes were gradually declining from the surface layer toward the bottom and ellipses were rotating in a clockwise direction almost throughout the entire water column, bottom friction effects were likely to influence the ellipse orientation at Off.2.

Figure 5 also shows the distributions of tidal ellipses at different depth layers of Off.3. The ellipses were rotating in a clockwise direction from 10 m below the surface down to 30 m depth. From 45 m depth, anticlockwise directional pattern was observed. The major axes of the ellipses showed north-south directions from the surface layer toward the bottom and the lengths of the major axes were gradually decreasing from the surface down to the bottom layer. Though **Fig. 5** shows very little inclination of a major north-south direction toward east-west direction, at Off.3 bottom friction effects are also assumed to influence the orientations of the tidal ellipses like Off.2.

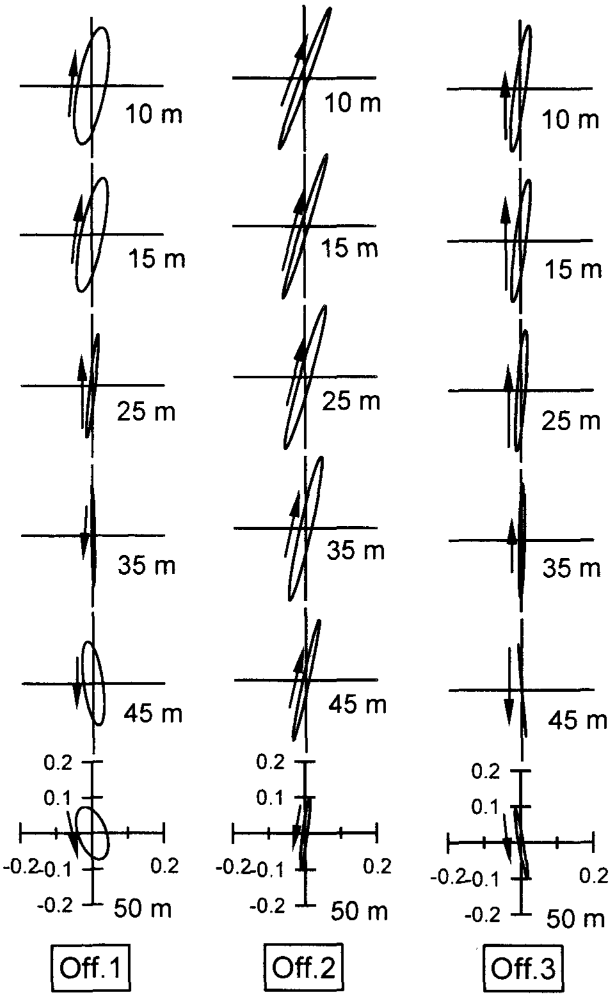

Fig. 5 Tidal ellipses at Off.1, Off.2 and Off.3.

4. CONCLUSIONS

Acoustic Doppler Current Profilers and other necessary sensors were deployed in the east sea (adjacent to Shiraho coral reef area) of Ishigaki Island, southwest Japan to measure the vertical profiles of horizontal current velocity distributions and also the tidal levels. Both summertime and wintertime field observations were conducted there during 2001 and 2002 respectively.

Tidal analyses of eight major tidal constituents (M_2, S_2, N_2, K_2, K_1, O_1, P_1 *and Mm*)showed that the current fields of the study area were dominated by semidiurnal tidal components and the dominant influences came from M_2, *and* S_2.

During low tide, the depth averaged tidal currents flowed in northward direction at all the measuring points except at Off.6 where northeastward current was observed. On the other, during high tide, tidal current flowed toward the south to the exception of Off.6 where the current was followed by southwestern direction.

Study results show that the depth averaged tidal currents in the offshore area flowed in nearly parallel directions to the north-south stretch of the reef area during both low and high tide conditions. Tidal current at the measuring point Off.6 was the only exception to this.

Tidal ellipse orientations in the study area showed different distribution patterns during winter (2002) and summertime (2001) observations. During winter, ellipse distributions at the measuring points close to the reef edge areas (Off.1 and Off.3) showed clockwise rotation directions from the surface down to the bottom layers. The major axes of the ellipses stayed in north-south directions at these measuring points having the depths of around 52 m. For the measuring point Off.6 (230 m depth), same results were found similar to Off.1 and Off.3.

Ellipse distributions at Off.5 (150 m depth) showed interesting phenomena during winter. From the surface up to middle layers, tidal ellipses were rotating in a clockwise direction and the major axes of the ellipses lay in north-south directions. In the bottom layer, anticlockwise directional tidal ellipses were found at Off.5 where the major axes showed almost east-west directions. These phenomena are assumed to be due to the propagation of internal waves. To clarify these internal wave phenomena further research is required which is our next target.

During summer (2001), field observation was done only near the reef edge areas. Ellipse distributions at all the measuring points were almost similar except at Off.1. Here at Off.1, we found similar ellipse distribution pattern as of Off.5 in winter. However, the current velocity in the bottom layer was not so strong at Off.1 comparing to Off.5, the trend of changing the rotational direction from clockwise to anticlockwise and the tendency of the major axis in turning toward the east-west direction from the north-south direction indicate the existence of internal wave propagation at Off.1 during summer.

A different distribution pattern of the tidal ellipses at Off.1 during winter and summertime observations occurred due to the depth difference of thermocline layer formation. During wintertime observation, as the thermocline was formed in a deeper layer, tidal ellipse distributions at Off.1 didn't indicate the propagation of internal wave. This time at Off.5, study results indicated internal wave propagation.

Contrary to this, during summer as the thermocline was formed in a comparatively shallow depth; tidal ellipse distributions indicated the existence of internal wave at Off.1.

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