EFFECTS OF INTERNAL TIDE ON CURRENTS AND WATER TEMPERATURE IN CORAL HABITAT AREA

Muhammad Abdur ROUF, Eizo NAKAZA, Ryutaroh KUDAKA, Yoshihisa AKAMATSU, Toshiaki MIYAGUNI and Liliane KOTLER

Department of Civil Engineering and Architecture, University of the Ryukyus, Nishihara, Okinawa, Japan

沖縄本島源河海域において，比較的強い内部潮汐の存在が見いだされ，それが浅海域であるサンゴ礁海域の水温環境に及ぼす影響を現地観測により明らかにしている．流れの観測は，水深約 100 mの比較的深海部からサンゴ礁縁部の水深約 50mまで岸沖方向に設置した ADCP を用いて行われている．海底面近くに固定された ADCP による流れや水温データは，沖側からサンゴ礁海域まで，内部潮汐の伝播に伴う水温の変動を受けることを示している．また，流れおよび水温変動のスペクトル解析結果は，内部潮汐および水温変動がかなり高周波側に比較的高いエネルギーのピークを持ち，非線形性の強い現象であることを示し，内部潮汐の崩壊による乱れの影響の可能性を示唆している．

Key Words: *Internal tides, tidal currents, water temperature, water mixing, reefs, coastal environment, Okinawa.*

1. INTRODUCTION

Dynamics of coastal ocean is characterized by a variety of hydro-physical processes where internal tide is one of key processes. The characteristics of internal tide generation may vary from place to place, depending on the bottom inclination and on density stratification as given by the Brünt-Väisäla frequency. The energetic internal waves become a regular feature on continental shelf and slope region and are potentially capable of enhanced mixing, particularly near the seabed where current shear can be large. Comprehensive review has been made regarding internal tide observations[1)] as well as generation and formation of modes[2)]. So far, internal tides have been observed on many continental margins such as along the southern coast of Japan in Sagami and Suruga Bays[3),4)] and in Zanpa near Okinawa[5)].

Genka bay (GB) is located in Okinawa Main Island, the biggest island in Ryukyu archipelago, situated in south of Japan and lying in subtropical region. The area has following unique features: suitable habitat of endangered species such as Sweet fish (Ryukyu-Ayu); presence of coral habitat; the two declared marine protected area; fishing and sea agriculture activities. Coral in the Ryukyu Islands is prone to various threats such as coral bleaching and red silt pollution[6)]. During world wide coral bleaching event of 1998, a relatively weaker coral bleaching was noticed in Sekisei lagoon (The largest coral habitat area in Okinawa prefecture). Physical environment that effects on the flow regime was highlighted as a factor for that weak bleaching[7)]. Specifically, coral bleaching becomes particularly likely when the water becomes stratified, with warm water absorbing solar radiation and sitting in a stable fashion on top of underlying cooler water[8),9)]. The physical conditions that cause vertical mixing of the water column often mitigate coral bleaching[9)]. Zanpa coast, close to the GB, has been studied recently and found the existence of active internal tide characterized by the cool bottom water penetrating towards the shore[5]. According to the fact above, it is anticipated that the physical ocean processes may have significant influence on the habitats of present study. Internal tide especially is responsible for cooling by vertically mixing water.

Considering the importance of GB as well as protection of its marine resources, comprehensive field observations were made for the first time to explore the characteristic tidal current structures with the focus on internal tide and variability of physical variables in GB. Few characteristics such as barotropic and baroclinic current of GB has already been reported by authors[10)].This paper particularly addresses more detail about the characteristics of internal tidal current and cooling system due to the passage of internal tide in shallow coral habitat area.

2. OBSERVATIONS

(1) Details of observation site

Observations of the present study were carried out in the north western coastal region of Okinawa Island, located southwest of Japan. The main island of Okinawa and the surrounding seabed topography are presented in **Fig. 1**. Coastal shelf region of the study area has a gradual slope with the depth ranged from 25-100m and may be treated as critical slope whereas most part of the Okinawa Island follows narrow continental shelf. Survey area perspective is pointed out in the **Fig. 1** depicting reef areas, reef edge, major rivers and creeks connected to the bay as well as four sites of observations. A bird eye view of the bathymetry of the study area is also shown in **Fig. 2**. Field observations were conducted at area about 1 km from the shore extending about 8 km towards the offshore. The first site (St.1) is at 26.7472N, 128.003W with a water depth of 110m; the second site (St.2) at 26.7278N, 128.035W with a water depth of 60m; the third site (St.3) is at 26.6958N, 128.061W with a water depth of 50m; and the fourth site (St.4) is at 26.7181N, 127.999W with a water depth of 60m. St.3 is representing the nearest observation site of coral reef edge whereas St.2, St.4 and St.1 are representing subsequent offshore observation sites from the coast. The coastline along the study area faces to the north-west and runs broadly from south-west to north-east. This makes the area like bay and is surrounded by coral reef.

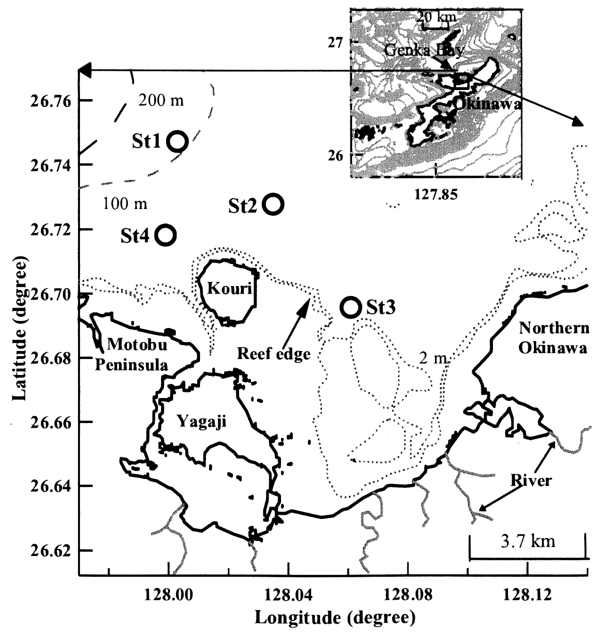

Fig. 1 Location of the measuring points. Inset shows the Seabed topography around Okinawa Island

(2) Data collection

Acoustic Doppler Current Profilers (ADCP) and ADCP-Wave made by RD instruments as well as Aquastic Doppler Profilers (ADP) made by NORTECK were deployed in the study area to obtain the time series of vertical profile of horizontal velocities. ADCP 300KHz was deployed in St.1 and St.4, ADP 500KHz in St.2 and ADCP-Wave 600KHz in St.3. ADCPs were positioned in up-ward looking mode and configured to sample with a 10min time ensemble and average over 2 meters depth cell. Measurements covered over 80% of the water column depth at both sites considering the center of the first good data cell above the seabed and the center of the last good data cell above the seabed. Near surface data obtained by a bottom-mounted ADCP was not in consideration as near surface data is normally contaminated because of the beam angle to vertical. The deployment was between September 9 to November 7, September 9 to November 30, September 26 to December 6 and September 9 to November 29, 2007 at St.1, St.2, St.3 and St.4 respectively. Sea level data were obtained from http://www.saltwater.jp. Particularly, Nago observation records were considered for collecting sea level data.

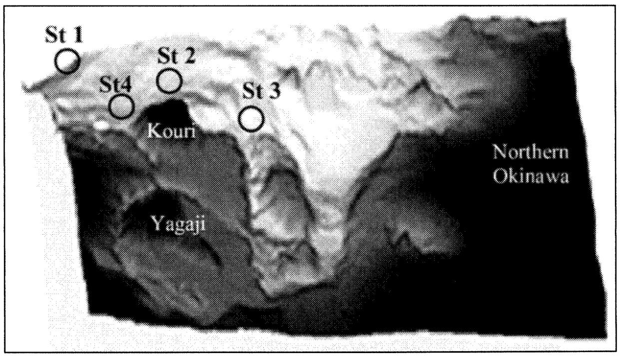

Fig. 2 Birds eye view of Genka bay bathymetry and location of measuring points.

3. RESULTS AND DISCUSSIONS

(1) Near bottom water temperature fluctuations

Bottom temperature following ten minutes interval obtained at station 1-3 together with sea level (record from Nago Observatory) following hourly record between September 27 and October 6, 2007 are shown in **Fig.3**. Modulations of temperature fluctuations were related with spring-neap cycle where the fluctuations were intensified at the same time following tidal oscillations.

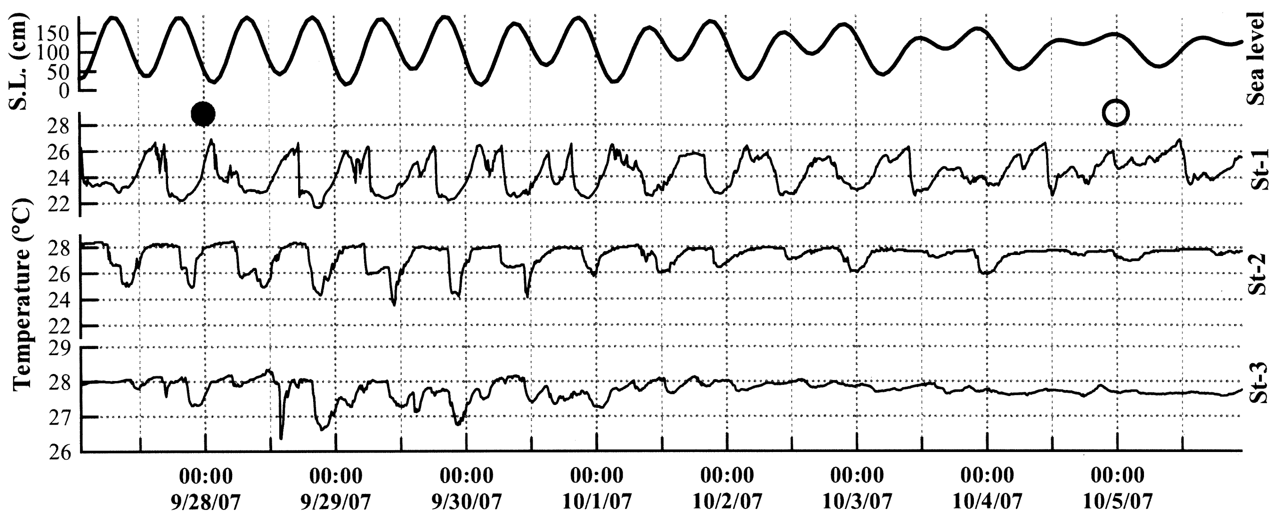

Fig. 3. Time series (ten minutes interval) of bottom water temperature at Station 1-3 together with hourly sea level (at Nago observatory) distribution between September 27 and October 6, 2007. Solid circle indicates spring tide and blank circle neap tide. Temperature scale for station 3 (St-3) is different from those for station 1 (St-1) and station 2 (St-2).

But the magnitudes of temperature fluctuations were different among three stations and the range of that magnitude decreased towards the coast. Offshore Station 1 shows highest magnitude, mid shore station 2 represents relatively lower magnitude and near shore station 3 depicts the lowest magnitude. The most significant feature in the temperature records was a predominance of semidiurnal period fluctuations, which also noticed in the sea level records at the top of **Fig 3**. The time variations of temperature records did not correspond to regular sinusoidal current compared to the sea level. Even, the station 3, closest to the shore, showed a certain extent of oscillation following semidiurnal period. This oscillation pattern indicates that offshore bottom water has some influence on bottom layer of even near shore shallow region following temperature transmission.

(2) Vertical structure of horizontal current and bottom temperature trend

Previous chapter addresses the significant influence of offshore bottom water temperature on bottom water temperature change in shallow area following transmitted cool water from offshore to shallow area. To clarify more details, vertical structure of horizontal current, sea level and bottom temperature records are incorporated here following hourly averaged data to observe the propagation patterns between 0:00 and 23:00 of September 28th, 2007. Horizontal current represents the baroclinic component calculated by subtraction from individual layer current to barotropic (depth averaged current). **Fig. 4-6** shows the vertical structure of horizontal current for (a) east-west and (b) north-south component at stations 1~3, respectively. A solid line at the top and dotted line at the bottom represents the sea level and bottom temperature, respectively. The dark and light field portions indicate the eastward (northward) and westward (southward) currents respectively.

Fig. 4(a) indicates the east-west current where there was a strong eastward current near the bottom layer at around 6:00 and 17:00 and **Fig. 4(b)** indicates the north-south current where there was a strong southward current at the bottom layer during the same time. Considering both east-west and north-south component, according to **Fig 4 (a and b)**, a strong southeast (i.e., shoreward phase) current found at the bottom layer at 6:00 and 17:00 and transmitted upwards with decreasing bottom water temperature. During that upward transmission, southeast current at the bottom layer was replaced by a northwest (i.e., offshore ward phase) current at 11:00 and 21:00. This northwest current also transmitted upward but with increasing bottom water temperature. This phenomenon reveals the existence of cross shore current with internal tide in a continuous stratification field throughout the profile at station 1 and was responsible for changing water temperature (around 5°C) at the bottom layer as shown in **Fig 4**.

Fig. 5 shows the vertical structure of horizontal current at mid-shore station 2. Similar to station 1, if east-west **(Fig. 5(a))** and north-south **(Fig. 5(b))** component considered together, there was also an existence of cross-shore internal tidal current in a continuous stratification field as a strong southeast current found at the bottom layer at 5:00 and 17:00, transmitted upward with decreasing bottom water temperature and are replaced by north-west current at 11:00 and 23:00 and followed upward transmission with increasing temperature. Since the intensity of cross-shore internal current velocity at

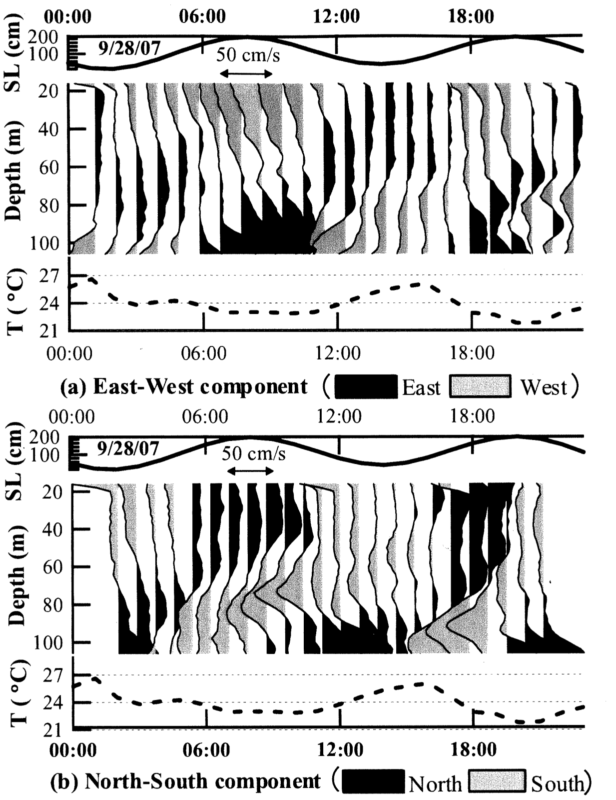

Fig. 4 Vertical structure of horizontal current distribution for Station 1. (a) east-west and (b) north-south component. Solid and dotted line represents sea level and bottom temperature respectively.

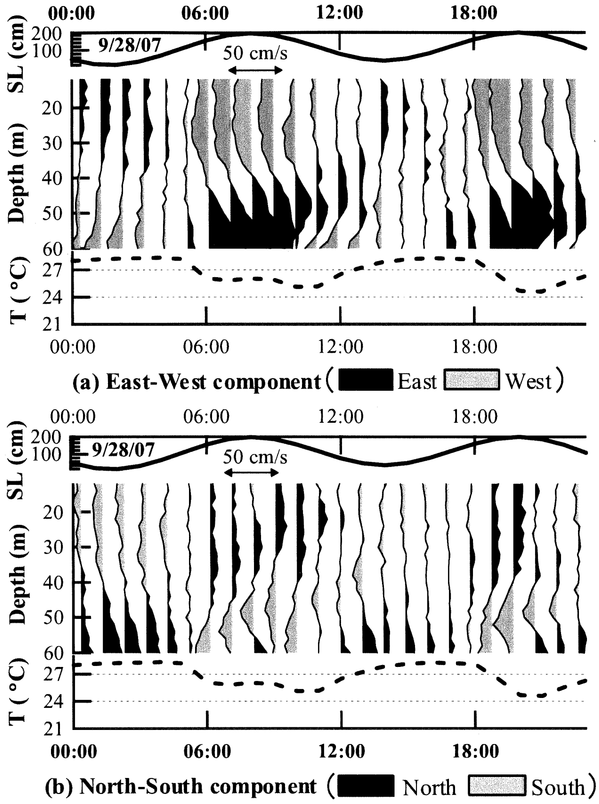

Fig. 5 Same as Fig. 4 except at Station 2.

station 2 was relatively lower than that of station 1, hence the temperature change at the bottom layer of station 2 was found as 3.8°C, which was lower than that of station 1.

Even at station 3, which is close to the shore and belongs within the vicinity of coral reef edges, there was cross-shore current, though it was very weak. For clear understanding, different current velocity and temperature scales are used for station 3 in **Fig. 6**. As shown in **Fig. 6 (a and b)**, a clear southeast current was found at the bottom layer at 19:00 and transmitted upward with decreasing temperature and were replaced by north-west current at 23:00 and followed upward transmission with increasing temperature. Irregularity of water temperature and propagation phase was found most of the time especially at 14.00 that might be due to the penetration of river current but was not investigated in this study. Temperature change was found very little (around 1.3°C) due to low intensity of cross-shore internal current at this station comparing with station 1 and station 2. It is supposed that almost all internal tidal energy may be used for mixing the water body and disappear dramatically between station 2 and station 3, hence water temperature change was lower at station 3. As shown in **Fig. 4~6**, cross-shore internal tidal current plays a significant role for cooling the water even in

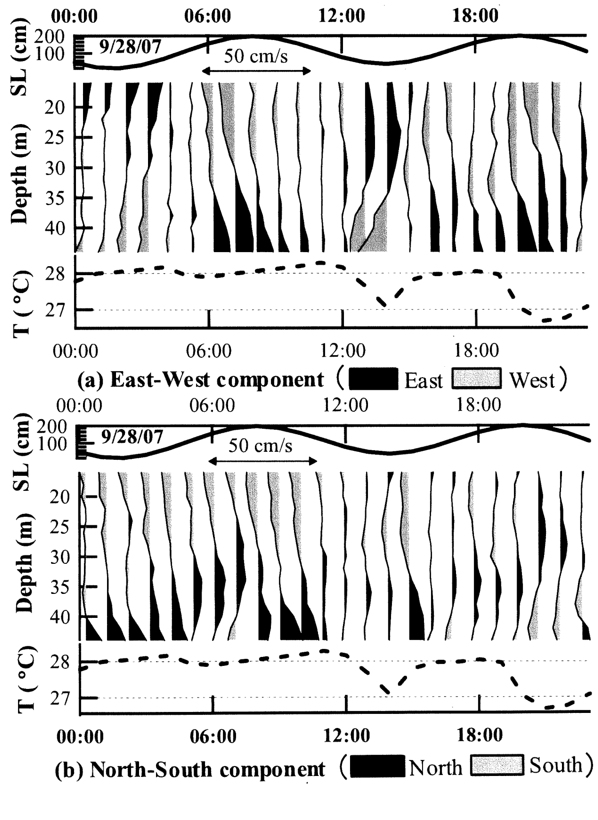

Fig. 6 Same as Fig. 4 except at Station 3.

shallow coral habitat area.

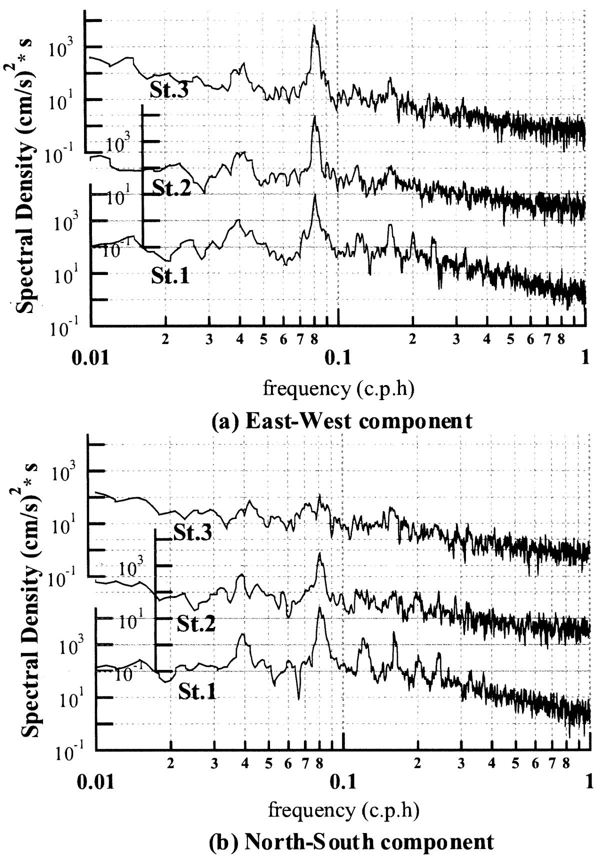

Fig. 7 Frequency spectra of the bottom current fluctuations at Station 1-3. (a) East-West and (b) North-South component. (St.1, St.2 and St.3 represent the station1, station2 and station3 respectively).

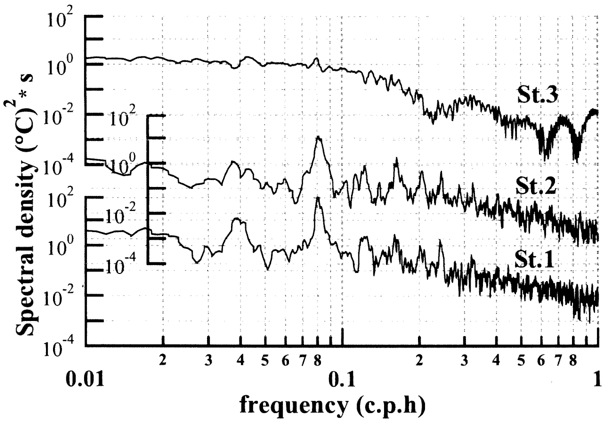

Fig. 8 Frequency spectra of the bottom water temperature fluctuations at Station 1-3. (St.1, St.2 and St.3 represent the station1, station2 and station3 respectively)

(3) Bottom current spectra

Bottom current fluctuations of east-west component and north-south component at Stations 1-3 are shown in **Fig. 7** to further verify the existence of internal tide. Spectrum was calculated on series of respective 8192 data (time step of 10 minutes). Energy of diurnal and semidiurnal fluctuations were found higher than other tidal fluctuations both in east-west and north-south component at Stations 1-3. A decreasing trend of energy levels found at respective frequencies from offshore St.1 to near shore St.3. Remarkably, energy at higher frequencies were also noticeable in St.1, St.2 and even St.3. This phenomenon corroborates the existence of internal tide that shows nonlinearity even in near shore region.

(4) Bottom water temperature spectra

As shown in **Fig. 4-6**, temperature fluctuations are related to the propagation of internal tides. **Fig. 8** shows the power spectra of bottom temperature fluctuations at Station 1-3. Spectrum was calculated on series of respective 8192 data (time step of 10 minutes). Similar to current spectra, nonlinearity of bottom water temperature fluctuations was noticeable at higher frequencies in all stations. There were strong peaks at semidiurnal and diurnal frequencies and also at higher frequencies of both St.1 and St.2 but remarkably very weak in St.3. This phenomenon indicates the lack of restoration force for internal tide and hence little temperature change at St.3 as shown in **Fig.6**.

4. CONCLUSION

Profiling measurements have been carried out in the Genka bay of Okinawa from September-December, 2007 at four stations to study the characteristics of internal tidal current and its likely associated cooling system. According to the analysis, the results can be summarized as follows.

(1) Time series of bottom temperature follows a certain extent of semidiurnal oscillation pattern and depicts the influence of offshore bottom water to even near shore shallow region following cross-shore ward temperature transmission.

(2) Vertical structure of horizontal current along with bottom temperature trend and sea level records show clear existence of cross-shore internal tide which decrease or increase the bottom temperature following its in and outgoing phase respectively.

(3) Energy spectra of bottom water temperature and current also recognizes the existence of internal tide, which indicates nonlinearity following their large amplitudes.

Internal tide and its influence on the cooling system may persist throughout the summer season in Genka Bay. This phenomenon will not be same in winter and needs further investigation. Results described in this study have to be taken in consideration for sustainable coastal management initiatives in Genka bay.

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REFERENCES

1) Huthnance, J., M.: Internal tides and waves near the continental shelf edge, *Geophys. Astrophys. Fluid Dyn.*, 48, pp.81-106, 1989.
2) Filonov, A. E., and Lavín, M.F.: Internal tides in the Northern Gulf of California. *Journal of Geophysical Research*, 108 (C5), 3151, doi:10.1029/200JC000761, 2003.
3) Kitade, Y., and Matsuyama, M.: Characteristics of internal tides in the upper layer of Sagami Bay. *Journal of Oceanography*, 53, pp.143-159, 1997.
4) Kitade, Y., and Matsuyama, M.: Semidiurnal internal tide observed over Ohmuro-Dashi, the northern part of the Izu Ridge. *Deep-Sea Research*, 49 (I), pp.1309-1320, 2002.
5) Nakaza, E., Rahaman, S. M. B., Kitamura, Y., Pawlak, G., and Tsukayama, S.: Cross-shore internal waves in Zanpa coastal region of Okinawa Island. *Journal of Waterway, Port, Coastal, and Ocean Engineering*, 132 (1), pp.36-46., 2006.
6) Mitsui, J., Nadaoka, K., Hamasaki, K., Ueno, M., Kimura T., Harii, S., Paringit, E. C., Tamura, H., Suzuki, Y., Kumagai, W., Yasuda, N., Ishigami K., and Iizuka, H.: Field measurements and analysis of currents and fine sediment, thermal and coral larvae transport in Sekisei Lagoon, Okinawa, Abstract, *10th International Coral Reef Symposium.* Okinawa Convention Center, Okinawa, Japan, p.108., 2004.
7) Furushima, Y., Yamamoto, H., Maruyama, T., Ohyagi, T., Yamamura, Y., Imanaga, S., Fujishima, S., Nakazawa, Y., Shimamura, A.: Necessity of bottom topography measurements in coral reef regions. OCEANS '04. MTTS/IEEE TECHNO-OCEAN '04, 2, pp.930- 935, 2004.
8) Nakaza, E., Rahaman, S. M. B., Tsukayama, S., Kitamura, Y., and Tamashiro, K.: Temperature distributions in a coral reef area and the influences from internal waves. Abstract, *10th International Coral Reef Symposium.* Okinawa Convention Center, Okinawa, Japan, p.109., 2004.
9) Heron, M. L., Skirving W. J., and Heron, S. F.: Coral bleaching limitations by wave-induced vertical mixing at He Reef Front. Abstract, *10th International Coral Reef Symposium.* Okinawa Convention Center, Okinawa, Japan, p.107., 2004.
10) Ryutaro, K., Masatumi O., Rouf, M., Liliane, K., Naomi, O., Nakaza E.: Sea current and water quality in Genka bay of Okinawa. *Annual Journal of Civil Engineering in the Ocean*, Vol. 24, pp.621-625, 2008. (in Japanese).