Circulation Pattern and Thermohaline Structures of Waters Off Pulau Tinggi, Johor

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ABSTRACT

This paper discusses the circulation pattern and thermohaline structures of waters around Pulau Tinggi based on a survey conducted during a period of 16 ï 19 August 2004. To get an overall coverage, a total of eight transects extending outward from the island were established. The measurements were conducted at three stations for each transect. The current profiles were measured using the Nortek Acoustic Doppler Current Profiler (ADCP) while the salinity, temperature and pressure were determined using the Idormar Conductivity ï Temperature- Depth (CTD) probe. A Minitroll pressure gauge was also deployed at the jetty of Kampung Pasir Panjang to monitor sea level fluctuation due to tide during the measurement period. An Aandera Automatic Weather Station (AWS) was also set up at Kampung Pasir Panjang to measure various atmospheric parameters including wind speed and solar radiation. Overall, the ADCP data indicate that regardless of tidal cycle, the current were predominantly southerly or southeasterly with average speeds of between 30 ï 50 cm s^{-1}. The prevailing winds were mostly southwesterlies i.e. nearly opposite to the current directions, with average speeds between 2-4 ms^{-1}. In the upper layer of about 5 ï 10 m, the current speeds were lower apparently due to the influence of the prevailing winds. In the bottom layer of about 5 ï 10 m from the seabed, the bottom friction slowed the current. The current flow patterns indicate a typical pattern of a flow around an island with wake formation at the southern-end of the island. Generally, the water the thermohaline structures at all sampling stations were similar. The temperature range was between 28.9^{o}C at the surface to 28.3^{o}C at depth of 25 to 30 m. The salinity range was between 32.15 at the surface to 32.45 at the bottom. Generally, the water masses at the inner stations were cooler and saltier than those at outer stations. However, measurements at other stations also indicate spatial variability of temperatures and salinities. The depth-profiles of temperatures and salinities indicated a typical structure of about 5 m mixed upper layer follow by a strong gradient between 5 to 10 m and uniform temperature and salinity below 10 m. Turbulent flow due to wind influence at

upper layer and due to bottom friction at bottom layer may responsible for the homogeneities of properties at these two layers.

ABSTRAK

Kertas kerja ini menghuraikan corak peredaran arus serta struktur termohalin di sekitar perairan Pulau Tinggi berdasarkan pencerapan yang dilakukan pada 16-19 Ogos 2004. Sebanyak lapan trasek yang mengunjur keluar dari pulau telah ditentukan untuk mendapatkan litupan yang menyeluruh. Pencerapan dilakukan di tiga stesen sepanjang setiap transek. Profil arus diperoleh dengan menggunakan Nortek Acoustic Doppler Current Profiler (*ADCP*) *manakala saliniti, suhu dan tekanan pula ditinjau dengan menggunakan prob* Idormar Conductivity ï Temperature- Depth (*CTD*). *Tolok tekanan* Minitroll *pula diletakkan di jeti Kampung Pasir Panjang untuk mendapatkan bacaan ayunan paras laut berkenaan dengan pasang surut sepanjang tempoh pencerapan.* Aandera Automatic Weather Station (*AWS*) *juga telah dipasangkan di Kampung Pasir Panjang untuk pencerapan parameter-parameter atmosfera termasuk kelajuan angin dan sinaran solar. Secara umumnya, data cerapan ADCP menunjukkan bahawa peredaran arus di sekitar Pulau Tinggi adalah dalam arah menuju selatan ataupun barat daya dengan kelajuan sekitar 30-50 cm* s^{-1} *tanpa bersandarkan kitar pasang surut. Angin yang dicerapkan adalah angin barat daya dengan kelajuan purata 2 – 4* ms^{-1} *i.i hampir bertentangan dengan arah aliran arus. Pada paras atas sekitar kedalaman 5 – 10 m, kelajuan arus adalah berkurangan disebabkan oleh pengaruh tiupan angin. Pada paras bawah sekitar 5 – 10 m dari dasar laut, geseran dasar melambatkan aliran arus. Corak aliran arus memaparkan corak tipikal aliran mengelilingi sebuah pulau dengan perkembangan keracak pada penghujung selatan pulau. Struktur termohalin di semua stesen cerapan adalah serupa secara umum. Julat suhu adalah sekitar 28.9*^{o}*C di permukaan laut dan 28.3*^{o}*C pada kedalaman sekitar 25 hingga 30 m. Saliniti berjulat antara 32.15 di permukaan laut dan 32.45 di dasar. Umumnya, jisim air apa stesen berdekatan pantai adalah lebih sejuk dan masin berbanding dengan jisim air di stesen yang semakin jauh ke laut terbuka. Sesungguhnya, cerapan bagi stesen-stesen lain turut memaparkan perubahan reruang suhu dan juga saliniti di persekitaran perairan Pulau Tinggi. Profil kedalaman suhu dan saliniti menunjukkan struktur tipikal dengan 5 m lapisan campuran atas diikuti dengan kecerunan mendadak antara 5 hingga 10 m dan suhu serta saliniti adalah seragam di bawah 10 m. Aliran bergelora akibat pengaruh angin ke atas lapisan atas serta geseran dasar di bawah adalah bertanggungjawab ke atas kehomogenan ciri-ciri pada dua lapisan ini.*

Keywords: circulation pattern; thermohaline; Acoustic Doppler Current Profiler (ADCP); Conductivity ï Temperature- Depth (CTD); Automatic Weather Station (AWS); Pulau Tinggi

Introduction

Pulau Tinggi lies approximately 32 km southeast of Mersing, Johor. The island is about 6 km long and 4 km wide with its land elevation peaks to the highest point of about 625 m above sea level. The island, which has been gazetted as a marine park in 1994, is rich with marine flora and fauna. As in other marine ecosystems, the islandös rich and diverse marine ecosystem is very much influenced and probably constrained by various physical conditions of its waters including current circulation and temperature-salinity ranges. Current patterns and thermohaline structures can be important for various biological and chemical processes in the ecosystem. Current circulation, for example, can be important for larval dispersal and pollutant transport (e.g. Tsanis and Wu 1995; Cowen et al. 2003). The existence of coral and sea grasses around the island is probably influenced by the water circulation around the island.

The water circulation forms an integral part of dynamical processes in waters around an island and the tidal cycle could very much be part of this circulation. In coastal sea, tidal current is likely to reverse direction during opposite phases of tidal cycles. Another interesting feature is the island wake, a phenomenon that is likely to be produced when water flows around an island. Depending on several dynamical factors, a circulation flow around an island may produce a wake (Wolanski et al. 1984; Tomczak, 1988). The circulation at Pulau Tinggi may also be part of the large-scale circulation of the South China Sea (SCS) sea. There have been only a few reports of current and circulation patterns in the SCS including those of Dale (1956), Wyrtki (1961), Brown (1973) and Liew et al. (1987). Generally, the circulation in the South China Sea is very much influenced by the monsoon system. During the northeast monsoon period, the current in waters off the east coast of Peninsular Malaysia is mostly southerly while during the southwest monsoon period the direction is northerly. However, the circulation pattern may also vary interannualy (Wu et al. 1998). There appears to be no earlier work of direct current measurement in waters around this island.

Material and Methods

The survey was conducted during a period of 16 to 19 August 2004. A total of eight transect lines extending outward was established in waters around the island (Figure 1). There were three measurement stations in each transect with the distance between stations was about 500 ï 1000 m. For transect A for example, station A1 was located near to the island while A3 was the outer station. An additional station in the channel between Pulau Nanga Kecil and Pulau Apil was also established. The location of a station was determined using a handheld global positioning system (GPS).

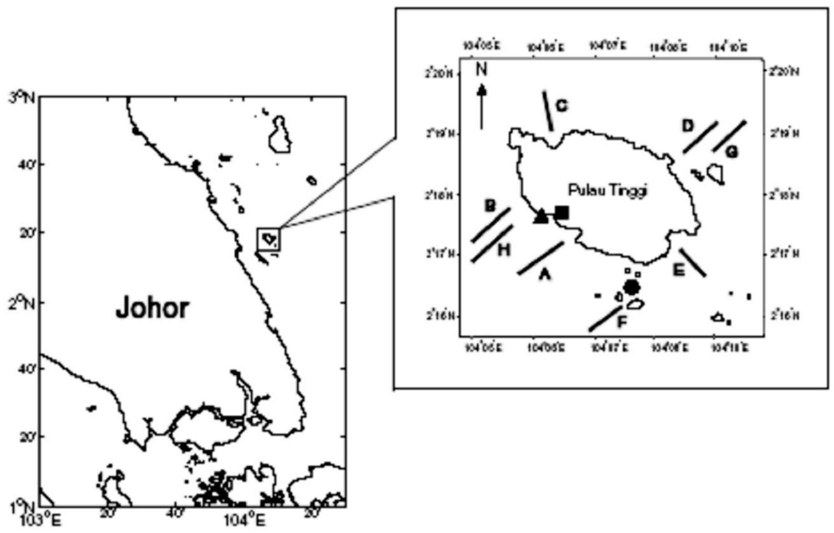

FIGURE 1: The Map Indicating the Approximate Location of the Sampling Transects. The Dot Indicates a Sampling Station at the Channel Between Pulau Nanga Kecil and Pulau Api. The Triangle and Square Indicate the Locations Minitroll Pressure Sensor and the AWS, Respectively

The current speeds at each sampling point were measured using a Nortek Acoustic Doppler Current Profiler (ADCP). This ADCP probe has a frequency range of 1 MHz with a maximum profiling range of 25 m. The ADCP was clamped downward looking to the side of a ship with the ship anchored during the sampling period. The ADCP was pre-programmed to profile 25 layers of 1 m depth each. The ADCP profiled the current in each layers for every three minutes with 60 seconds averaging time for each observation. The ADCP measurements at each station were conducted for about 30 minutes. During the same period, an Idormar Conductivity-Temperature-Salinity (CTD) probe was lowered into the water to profile temperature and salinity. A Minitroll pressure gauge was also deployed at the jetty of Kampung Pasir Panjang to monitor sea level fluctuation due to tide during the measurement period. For measurements of various atmospheric parameters (e.g. wind speed and direction and solar radiation) an Aandera Automatic Weather Station (AWS) was set up at Kampung Pasir Panjang at an interval of 5 minutes.

Results

Figure 2 shows the sea level fluctuation due to tides from 22:04:30 15 August 2004 to 06:29:00 19 August 2004. As indicated, the tide in Pulau Tinggi was a mixed type with predominantly semi-diurnal category. Also shown are the approximate the sampling periods of each transect line with respect to the tidal cycles. Transect A, C and E were sampled in the morning when the tidal condition was approaching a higher high water (HHW). Transect B, D and F were sampled in the afternoon when the tide was receding to a higher low water (HLW). The sampling in the channel was conducted from 10:10 to

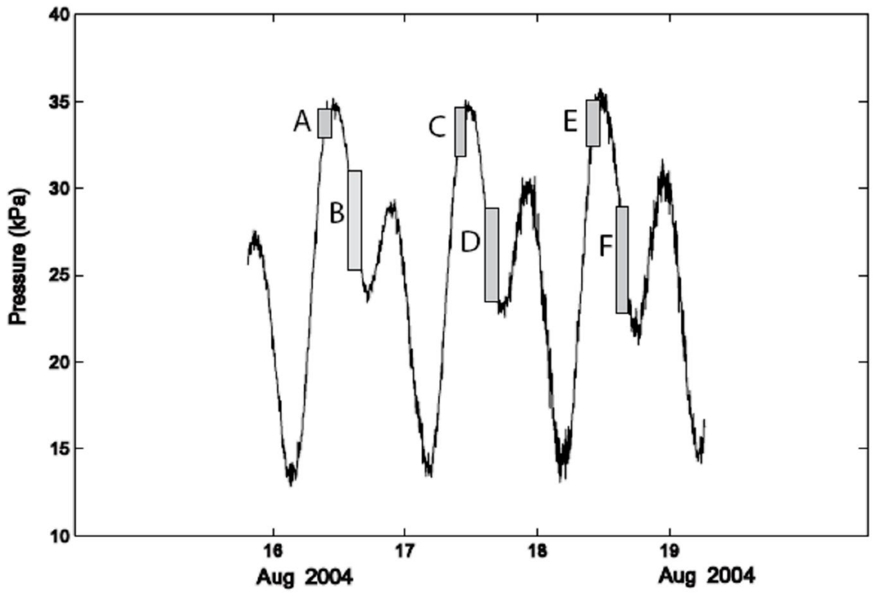

FIGURE 2: Sea Level Fluctuation (in term of pressure) During the Four Sampling Days. The Vertical Bars Indicate Relative Sampling Period at the Transects Indicated by the Alphabets

10:52 19 August 2004. Similar to the sampling period of transects A, C and E, the sampling in Transect G was conducted from 11:23 to 13:28 19 August 2004 i.e. when the condition was approaching a HHW. The sampling in Transect H was done at night i.e. from 20:55 to 23:50 19 August 2004 when the tidal condition was approaching a lower high water (LHW). Figure 3 shows the stick plots of wind for each of the four sampling days. Except during early morning of 16 August 2004, the prevailing winds were predominantly southeasterly with speeds ranging from 2 to 6 ms^{-1}. Figure 4 shows the solar radiation from 0800 to 1800 for each of the sampling days. The radiations were lower in the morning but increased to a maximum value at about 1 ï 2 pm in the afternoon. Fluctuations in the reading may associated with cloud coverage.

A total of 24 ACDP measurements were carried out during the four days sampling period. The current stick diagram and current speed depth profile were plotted for all the 24 measurements. The currents at inner stations of depth < 10 m appeared to be very weak and with no particular direction. This may represent the frictional boundary around the island. However, the current speed increased steadily with the direction became apparent in middle and outer stations of more than 15 m depth. Figure 5 shows the current stick plot at various depths for outer stations of transect A, B and C. The current directions at these stations were either southerly or southeasterly, with a maximum speed of about 50-60 cm s^{-1}. The currents at middle stations were similar to the outer ones while those at inner stations were much weaker without particular direction. The currents at stations D2, E3 and at the channel appear to be different (Figure 6). At D3, the current measurements indicated southeast flow while at the channel the water appeared to be stagnant. However, at E3 the condition appeared different with rotating current flows as indicated by the sticks.

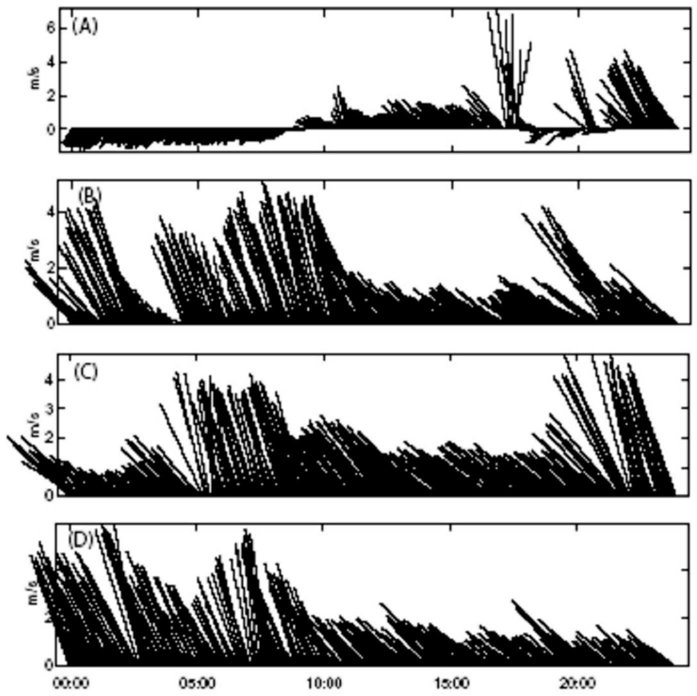

FIGURE 3: Prevailing Wind for the Four Sampling Days. Sticks Pointing Upward Indicate Southerly Wind. (A) 16 Aug 2004, (B) 17 Aug 2004, (C) 18 Aug 2004 and (D) 19 Aug 2004

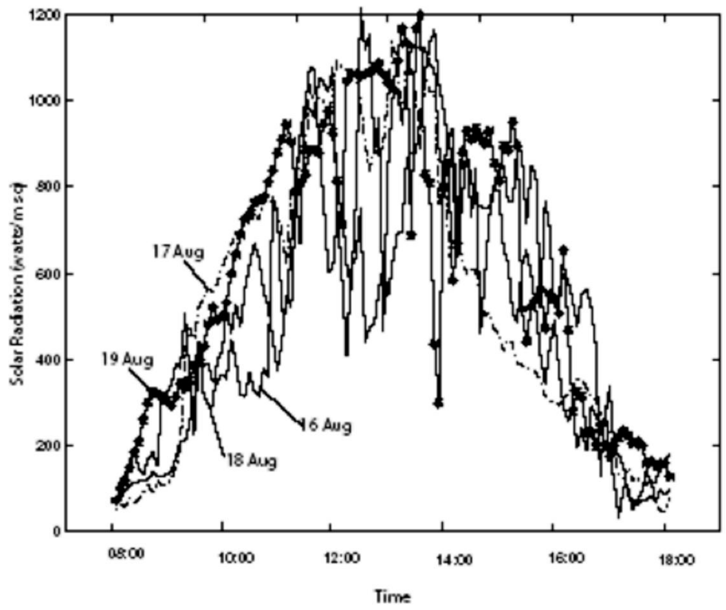

FIGURE 4: Solar Radiation Measured at the Height of 10 m from 0800 to 1800 During the Four Sampling Days

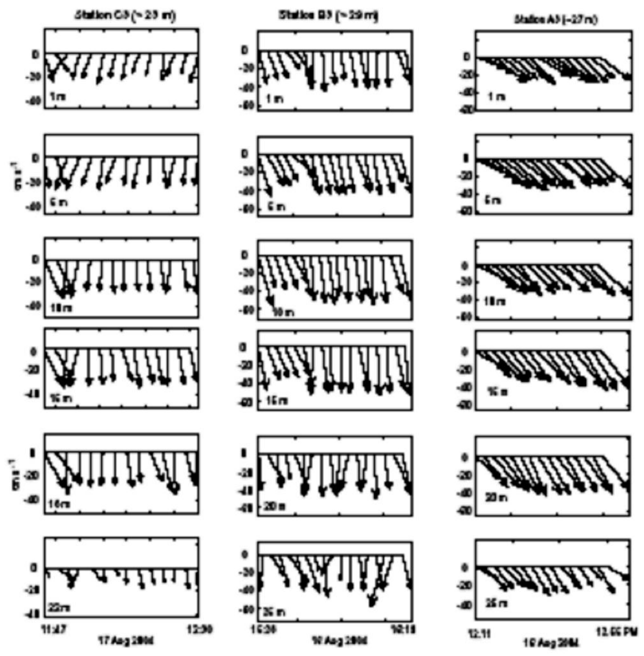

FIGURE 5: The Current Sticks at Various Depths for the Outer Stations of Transect A, B and C. Sticks Pointing Downward Indicate Southerly Current (i.e. flowing to the south)

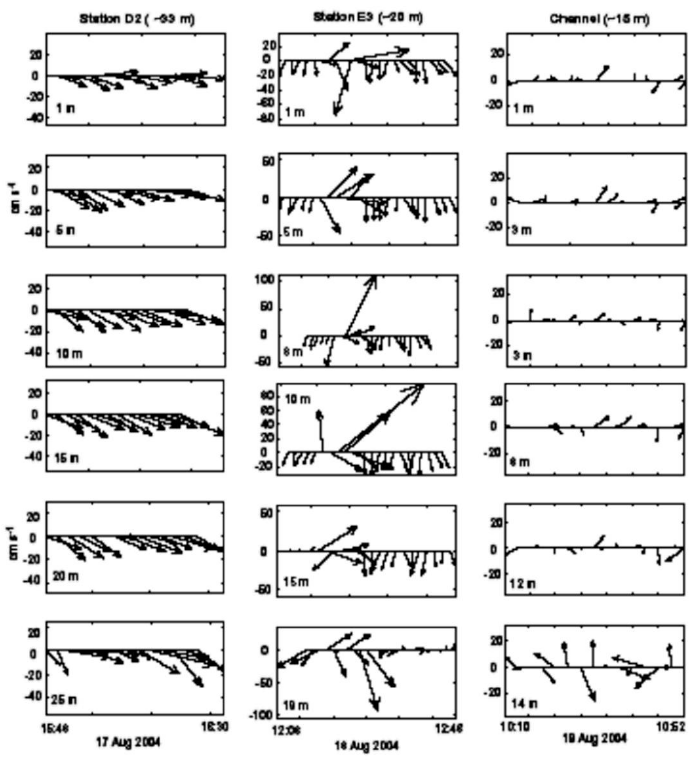

FIGURE 6: As in Figure 5, Except for Transects D and E as Well as Measurements at the Channel

Figure 7 shows the current speed depth-profile as well as the u and v velocity components of Station C3. The current speed depth-profiles at other stations were similar. The current speed increased with ~ 20 cms^{-1} at the surface to ~ 30 cms^{-1} at a depth of about 15 m. Below 15 m the current speed decreased gradually but below 20 m the speed reduced rapidly to nearly zero at 22 m. The current speed profile from the seabed to a depth of about 15 m represents a typical bottom boundary layer in which the speed is very much influenced by the bottom friction. However, the speed reduction in the upper layer is obviously due to wind influence. The prevailing winds during the sampling period were predominantly southeasterly i.e. nearly opposite to the direction of the current. The opposite winds slowed down the current speed by ~ 10 cm s^{-1} at the surface. Interestingly, the wind influence reached to a depth of about 14 m.

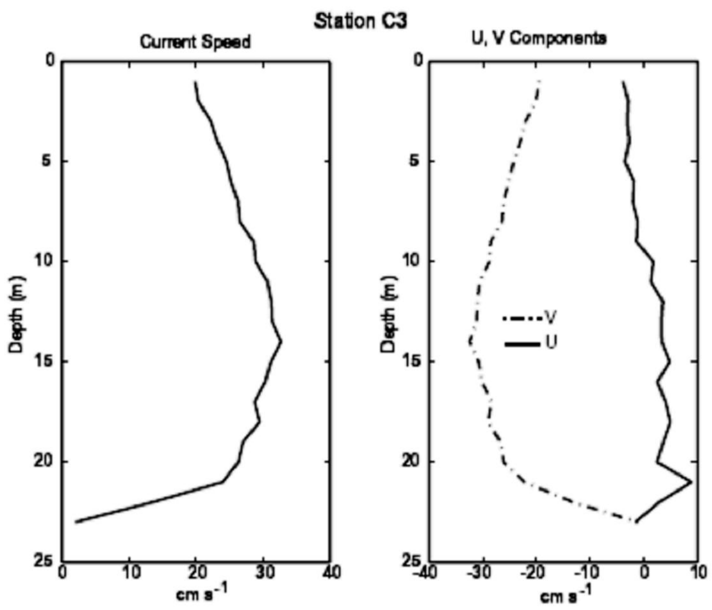

FIGURE 7: The Current Speed-Depth Profile at Station C3

Despite consistent flow patterns at other stations, the current measurements at station H2 appeared to be opposite to those at other stations (Figure 8). For the upper layer of about 10 ï 15 m, the flows were predominantly northerly i.e. opposite to the current patterns at station B2 and B3 while at the bottom layer the currents were much weaker.

The CTD measurements were plotted into temperature-depth profile, salinity-depth profiles and T-S diagram. Figure 9 show the temperature-depth profiles at transects A and B. The temperature-depth structures at the two stations were similar despite different time of measurement. At the relatively shallow inner stations, the temperatures were 28.5°C. At middle stations, the temperatures at the surface to a depth of about 5 m were around 28.55°C. Below 5 m, the temperatures were uniform at around 28.45 °C to the bottom. However, the surface temperatures were warmer at the outer stations i.e. around 28.9°C. The temperatures were uniform for depth < 5 m whereas below this depth, the temperatures changed drastically to about 28.5°C at depth of ~ 10m. Below this depth, the temperatures appeared to be uniform. The salinity-depth profiles between the two stations appeared slightly different. The salinity at inner and middle stations for transect A appeared to be slightly higher i.e. around 32.5 psu. At the outer station, the salinities were slightly lower i.e. around 32.3 psu with no apparent variation with depth. However, the salinities at B2 and B3 clearly showed increasing trend with depth. The salinities at the inner stations were similar to those at A1 station. The thermohaline structures of water masses at transects A and B were shown in Figure 11. The sigma-t values were between 20.3 ï 20.4 kg/m^3 at inner stations while at outer stations the values were between 19.7 ï 20.4 kg/m^3.

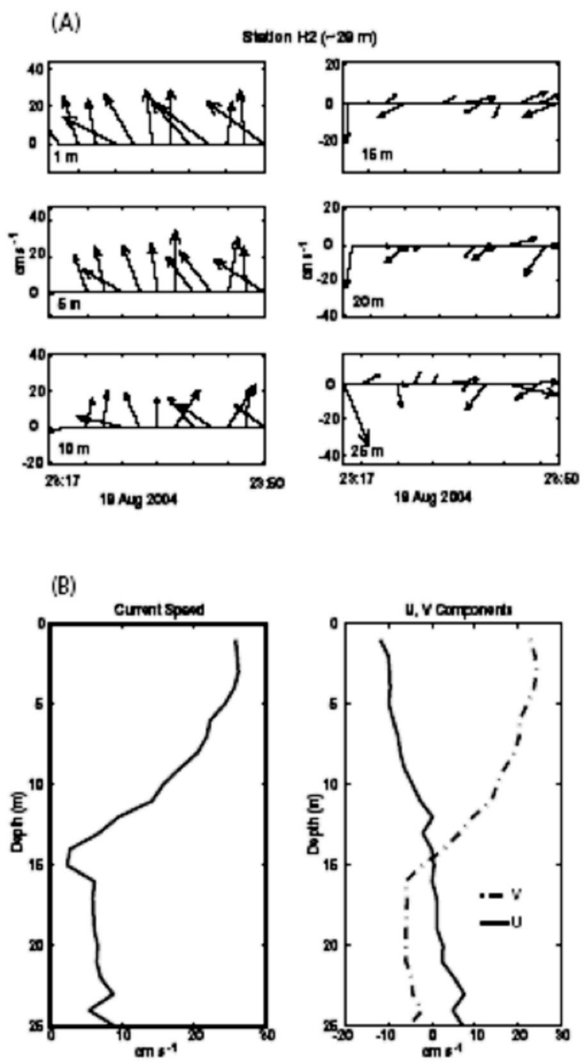

FIGURE 8: (A) The Current Sticks Plot at Various Depths for H2 Station.
(B) The Current-Depth Profile at the Station

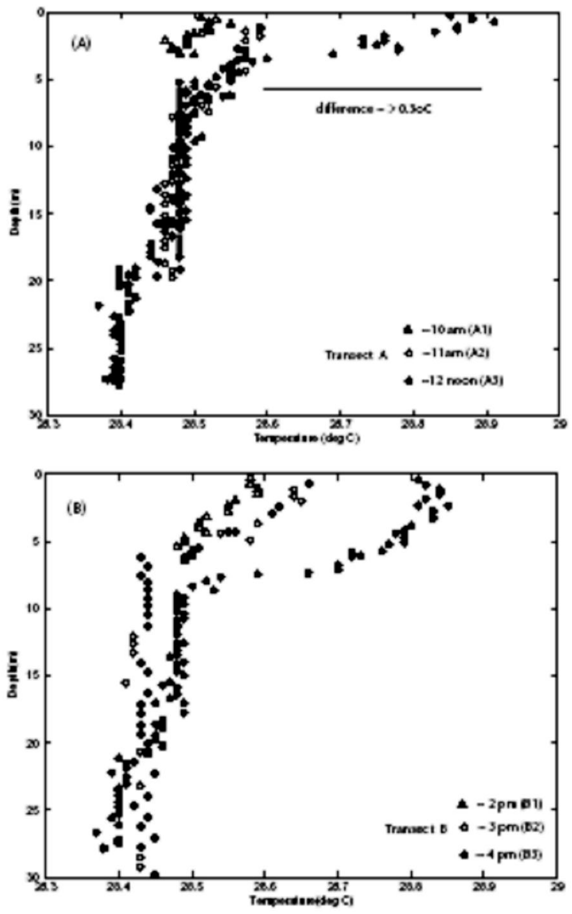

FIGURE 9: Temperature-Depth Profiles for Transects A and B

Discussion and Conclusion

The current stick plots for stations in transect A, B, C, A, F, and D (as well as those at transects G and E) indicated southerly ï southeasterly current encountering the island. This is a typical flow around an island that may or may not produce island wakes at the southern-end of the island (Tomczak 1988). If the wakes were to be formed, the wakes would be located in the southern parts of the island i.e. in the vicinity of transect E. Indeed, the ñrotatingò current captured by the ADCP in station E3 (Figure 6) may represent an eddy that passed by during the sampling in station E3. Interestingly, the maximum speed of the eddy reached 100 cm s^{-1} i.e. about five times faster than background velocity. From a theoretical point of view, the effect of an island on the flow field depends on the relative importance of the inertial and frictional forces (Tomczak 1998). If the frictional dominates, the particles will be dragged along the islandôs coast. If the inertial force dominates the particles will be thrown off from their paths and the flow will separate from the island.

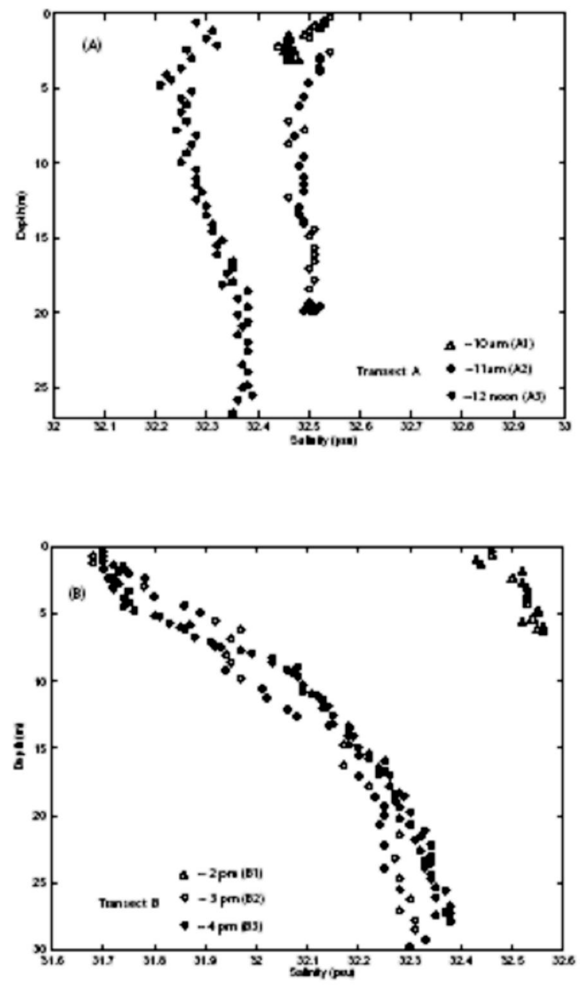

FIGURE 10: As in Figure 9 Except for Salinity

Generally, incorporating the current patterns in all transects and arguments of wake formation, the flow pattern around the island may be represented schematically as shown in Figure 12. The agreement between the current patterns in transects A, C, E, and G (i.e. when the tide was rising and getting to a HHW) and transects B, D and F (i.e. when the tide was receding and getting to HLW) seems to suggest the circulation pattern in Figure 12 does not change or reverse during period of opposite tidal phases. However, the current patterns of the top 10-15 m in transect H (i.e. during the rising of the second tide to LHW) seems to suggest otherwise (Figure 8). Could this be due to wind stress in the northerly direction during the sampling period in transect H? The extent of that northerly current to ~ 10 m depth seems to suggest the influence of wind stress. The wind patterns during the sampling at this transect were predominantly southeasterly with comparable speed to those during the sampling at station C3 (Figure 3).

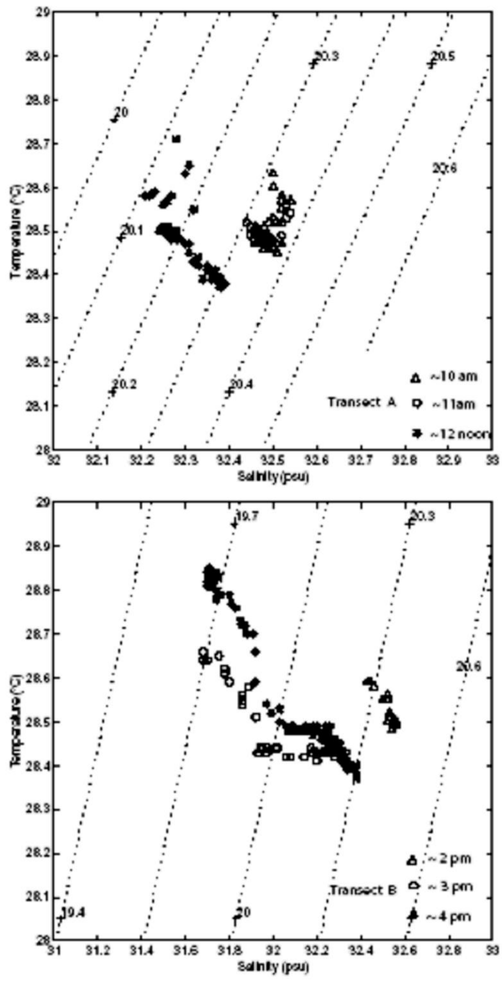

FIGURE 11: The T-S Diagram for Water Masses Sampled at (A) Transect A and, (B) Transect B

However, if the general circulation around this island is as depicted in Figure 12, it was certainly opposite to the general circulation in the South China Sea during the southwest monsoon season. Based on surface current report compiled by Wyrtki (1961), the upper circulation during the month of August (i.e. during the southwest monsoon) is northerly. Could the circulation in the island during the period be an intermittent feature of the large-scale circulation in the South China Sea or could it be part of a coastal counter current in the area? These questions require further investigation. There is also a possibility that the current reverses direction when the tidal condition recedes to lower low water (LLW). To ascertain this, a continuous measurement of the current for several tidal cycles is needed. This can be achieved by deploying the ADCP upward looking at the sea bed. However, with many sampling stations and water depths of 20-30 meters, an ADCP deployment can be a risky exercise.

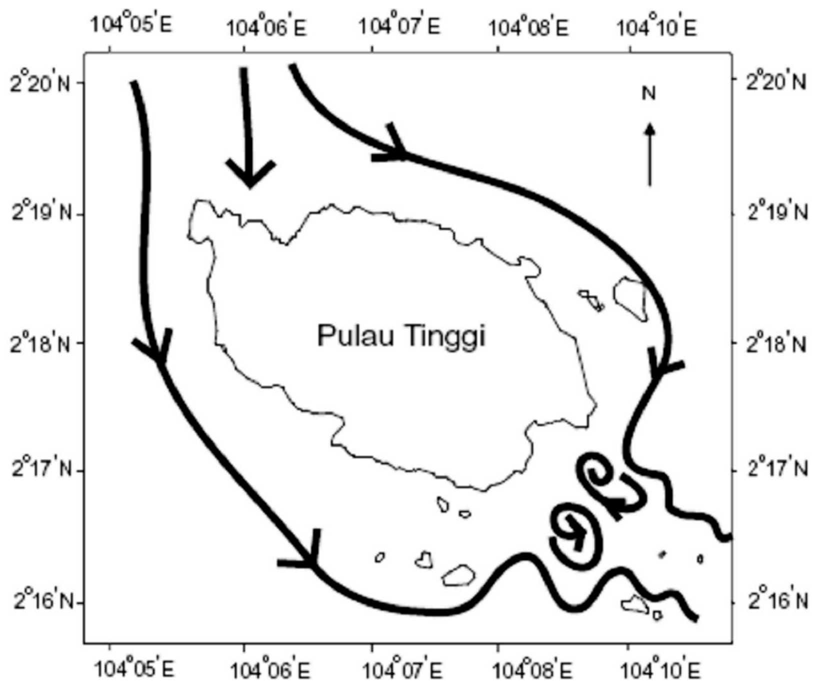

FIGURE 12: The Schematic Representation of the Circulation Around the Island Based on Current Patterns Measured at Various Transects. The Occurrence of Eddies in the Southern Part of the Island Indicate the Island Wake Phenomenon

Generally, the temperatures at the surface layer tended to be uniform and warmer near the island. At the outer stations, the temperature appeared to be slightly cooler. A strong temperature gradient existed at depth between 5-10 m. Below 10 m, the temperatures were uniform with depth. The relatively uniform temperature at the surface layer and at the bottom layer could be due to turbulent mixing associated with wind at the surface and friction at the bottom. The similarity of temperature-depth profiles between transect A and B seemed to suggest that other component in the heat budget may be important. For the inner station, for example, measurements taken at A1 (i.e. at about 10 am) were similar to those at B1 taken at about 2 pm. As indicated in Figure 4, solar radiation peaked at around 1 ï 2 pm. One would expect temperatures at B1 would be warmer. This suggests that other factor such as mixing, evaporation, infrared radiation at the surface, and conduction may be important in removing the heat from the surface layer. Interesting the salinity at inner stations the salinity appeared to be slightly higher than the outer stations. One would expect the salinity at inner station would be lower due to fresh water input from land. This is the case in some of the stations indicating spatial variability of water properties around the island.

The preliminary results presented in this paper represent a snap-shot of the circulation pattern and thermohaline structures in water around the island. It may take several visits to get a better picture of the conditions. For better understanding, modeling approach can also be undertaken.

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