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THE CHARACTERISTICS AND ORIGIN OF WATER MASSES ALONG THE SABAH COAST

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ABSTRACT

A definition of water mass characteristics and its origin along Sabah coastal waters is presented based on 55 CTD casts cruises in July 2009 combined with five Argo profiling floats at surrounding seas. The T-S relation in Sabah waters including South China Sea, Sulu Sea and Celebes Sea show existences of eight water masses. By referring to the earlier water mass characteristics of the region, we found water masses in the surface mixed layer with strong mixed of Open Sea Water (OSW), Continental Shelf Water (CSW) and Tropical Surface Water (TSW). Below the layer of this active mixing is a zone of rapid transition called the Seasonal Thermocline Water (STW). Meanwhile, the Maximum Salinity Water (MSW), Permanent Thermocline Water (PTW), North Pacific Intermediate Water (NPIW) and Deep Water (DW) were found at the depth range from below the seasonal thermocline to about 1000 m. This definition is important for an improved understanding of geographical positions of different water masses which contained valuable information in the study area which is not well understood.

KEYWORDS: Sulu Sea, South China Sea, Celebes Sea, Water Mass, Sabah waters

1.

INTRODUCTION

Sabah is part of Borneo and located in the northern part of the island. Sabah coastline faces the South China, Sulu and Celebes Sea and is part of South Asia Waters (Wyrtki, 1961). These three sea basins are separated by islands and sill which create a unique geographical settings for water masses exchanges. Along Sabah coastline, the Sulu Sea is separated from the SCS by 420 m deep sill. On the other hand, the Celebes Sea connected through Balabac straits and freely connected to the Pacific Ocean on its Western side..

The circulation in the SCS, Sulu and Celebes Sea was first described by Wyrtki (1961), based on earlier hydrographic observations, sea level records, and ship drifts, and later simulated by several basin scale models (Liu et al. 2008). According to these earlier studies the circulation in the SCS is chiefly forced by monsoon, cyclonic in winter and anticyclonic in summer has play important roles in the sea surface temperature variability of the SCS. Recent studies (Cai & He, 2010) further suggest that there is a highly positive correlation of seasonal circulation between the Sulu Sea and the southeastern SCS.

Earlier, water properties (temperature, salinity, oxygen concentration, etc.) has been used as passive tracer to provide direct pathways of water masses and temperature on isopycnal surfaces is uniquely defined by salinity. Rojana-anawat et al. (2001) have

Table 1 Water mass characteristic of the different water bodies according to several authors: Deep Water (DW),

Water mass	Temperature (°C)	Salinity	Study Area	Water depth (m)	Author/Year
DW	2.5-5	34-35	Vietnamese EEZ	>900	Rojana-anawat et al. 2001
PTW	10-15	34-35	Vietnamese EEZ	180-400	Rojana-anawat et al. 2001
MSW	15-20	>34.5	Vietnamese EEZ	100-200	Rojana-anawat et al. 2001
MSW	17-19	>34.3	Vietnamese EEZ	100-200	Dippner & Loick-Wilde 2011
STW	20-27	34-35	Vietnamese EEZ	50-150	Rojana-anawat et al. 2001
OSW	25-29	33-34	Vietnamese EEZ	>40-50	Rojana-anawat et al. 2001
NCSW	23-27	31-33	Vietnamese EEZ	10-<30	Rojana-anawat et al. 2001
SCSW	29-31	27-33	Vietnamese EEZ	10-<30	Rojana-anawat et al. 2001
NPIW	7-9	34.4-34.5	SCS & northern Philippine Sea	480-500	Qu et al. 2000
NPTW	17.7-18.2	>34.3	SCS & northern Philippine Sea	120-150	Qu et al. 1998,2000
TSW	25-30	33.5-34.5	Lat EQ-15N Long 120-140E	Surface layer	Qu et al 1999

Permanent Thermocline Water (PTW), Maximum Salinity Water (MSW), Seasonal Thermocline Water (STW), Open Sea Water (OSW), Northern Continental Shelf Water (NCSW), Southern Continental Shelf Water (SCSW), Continental Shelf Water (CSW), North Pacific Intermediate Water (NPIW), North Pacific Tropical Water (NPTW), and Tropical Surface Water (TSW).

identified seven different characteristic water masses in the Western SCS. While further analysis by Dippner and Loick-Wilde (2011) has gave a redefinition of water masses which serve as end members of mixing. The definition of previous study in the South-East Asia waters which serve as our basic reference are given in Table 1. Additionally, Qu et al. (2000) have studied water mass distribution by analyzing historical hydrographic data in the SCS included near the coast of Sabah waters.

Despite considerable modification of characteristics as a result of mixing, interestingly waters of both salinity maximum and minimum of North Pacific origin were traced on the density surfaces around 25.0 and 26.73, respectively.

In this short article, physical observations are presented from the 30-days voyage expedition along Sabah waters and water mass definition was classified with respect to the earlier classification of Rojana-anawat et al. (2001), Dippner and Loick-Wilde (2011) and Qu et al. (2000). Additionally, five Argo profiling floats at surrounding Sabah seas were used to demonstrate the unique water masses interconnectivity of surrounding seas including South China Sea, Sulu Sea, Celebes Sea, Philippines Sea and Pacific Ocean. The article is aims to give an overview of water mass definition along Sabah Coastal water and surrounding seas, which no peer reviewed paper has been published on this topic. However, the results may have some limitations because measurements with extensive coverage both in space and time were not used.

2. DATA AND METHODS

The study area covers the Sabah waters, which include SCS, Sulu Sea and Celebes sea. The data used in this study are CTD data and Argo profiling float data. The sampling stations during cruise and the trajectories of Argo profiling floats are shown in Fig. 1. The CTD data obtained aboard Malaysia Royal Navy vessel "KD Perantau". The cruises took place in the exclusive economic zone (EEZ) of Sabah water during southwest monsoon in July 2009. Overall, a total of 55 stations and CTD casts were collected. Observations were carried out covering the area from 112°-120°E and 4°-8°N. In terms of data, conductivity (C), temperature (T), depth (D), and dissolved oxygen (DO) were measured at each station using an SBE 19Plus CTD profiler. The specifications of the profiler are as follows: temperature accuracy is 0.005 °C and

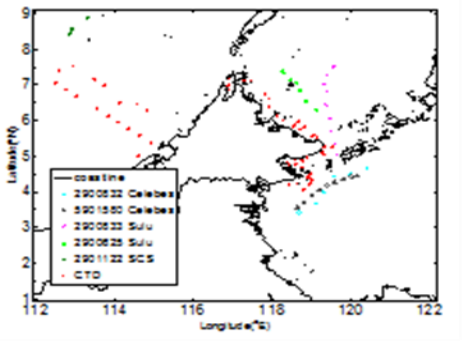

Fig. 1 Map of the Sabah surrounding seas with 55 CTD station (+) cruises in July 2009 and floating trajectories of five (5) Argo profiling floats. The stars represent the start point of Argo floats and the different marks show the selected profiles used for water mass analysis.

temperature resolution is 0.0001 °C; conductivity accuracy 0.0005 S/m and conductivity resolution 0.00005 S/m; pressure accuracy is 0.1% of full scale range and pressure resolution is 0.002% of full scale range; dissolved oxygen sensor accuracy is 2% of saturation. The CTD sampling interval is 4Hz and measurement were made down to maximum depth of 800 m.

In addition, five Argo profiling floats at surrounding seas in an area from 112°-121°E and 3°-10°N were analyzed. These data were collected and made freely available by the international Argo project which provide temperature (T), Salinity (S), pressure (P) of the world oceans over broad spatial scale. The Argo data were obtained from the online Global Data Assembly Centers of the Argo project at www.argodatamgt.org and include profile data, metadata, trajectory data and technical data. To insure the accuracy and reliability of these data, real-time and delayed mode quality control were made beforehand in accordance with the Argo Data User Manual version 2.3, 2010. Since the Argo floats drifting in the ocean freely, the range of the

Argo Profiles	Max. Depth (Meter)	Period	Start Measurement		Area
			Latitud	Longitud	
2900625	1270.3	22 Oct. 2007 – 19 Nov. 2007	7.383	118.249	Sulu Sea
2900832	1209.3	17 Oct 2008 – 6 Nov 2008	4.652	120.397	Celebes Sea
2900833	1212.4	18 Jan 2009 – 18 Feb 2009	7.514	119.547	Sulu Sea
2901122	1205.8	21 Jan 2009 – 14 Feb 2009	8.531	112.895	SCS
5901580	510.2	21 Jun 2009 – 29 Jun 2009	4.458	120.154	Celebes Sea

data for the studied area can be ensured, and there will be too much data to analyze for water mass studies if all data are used. Thus, only the available Argo floats data at Sabah waters and surrounding sea were used for the analysis purpose. Table 2 display all Argo floats information, which data is only available in Sabah waters. Note that the distribution of the Argo float data (covered beyond EEZ of Sabah water) is quite different from the CTD profiles data (covered only Sabah coastal water).

For analysis purposes, the study area is divided into 3 major territorial waters. 1. The South China Sea on Sabah west coast, 2. The Sulu Sea at Sabah north east coast and, 3. Celebes Sea at Sabah southeast coast. All CTD profiles and the Argo floats data were merged together to compose an overall T-S diagram. Water mass analysis distribution was analysed with T-S diagram to identify specific water masses which serve as water mass properties drifting in the ocean

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Water mass analysis distribution was analysed with T-S diagram to identify specific water masses which serve as water mass properties for mixing between water masses.

3. RESULT

3.1 Temperature and Salinity Profile

The vertical distribution of temperature and salinity from 55 CTD casts and five Argo floats data as shown in Fig. 2 and Fig. 3, respectively. The maximum depth of CTD cast were ~800 m the cruise and ~1200 m from Argo floats data. Both do not cover the whole water depth of more than 2000 m.

Since the Sabah water is situated in the tropical zone, sea-surface temperature is consistently high. Both observation from CTD and Argo floats data shown sea-surface temperature (below 50m) ranges only for 2°C between 30 to 28°C. Nonetheless, the temperature ranges increase significantly between 100-300m depth. Gradual drop of temperature from both data showed that the upper water column is persistently well stratified. The surface water of vertical distribution show that Argo float 2900625 (measurements in October-November 2007 in Sulu Sea) was lower than Argo float 2901122 (measurements in January-February 2009 in SCS) by a margin of about 2°C.

The vertical distribution on the 50 m level show that the surface salinity is rather low from CTD cast data compared to Argo float data by a margin of about 1 PSU. The lowest salinities are found along the coastline towards the Sulu Sea, especially near Pulau Bangi. Because of the low salinity water

influence, CTD cast data shown a very huge ranges of surface salinity especially at the firs 100m depth (32-34.5 PSU). At subsurface around 100m depth, salinity maximum was spotted from Celebes Sea data, which signaled a presence of unique water mass that carry high salinity water into the region possibly originate from central Pacific.

3.2 Water Mass Definitions

T-S diagram of the Sabah waters was drawn with the temperature and salinity profiling from 55 CTD casts and data from five Argo floats as shown in Fig. 4 (a) and (b), respectively. Argo floats 2901122 (measurements in January-February 2009 in SCS), 2900832 and 5901580 (measurements in

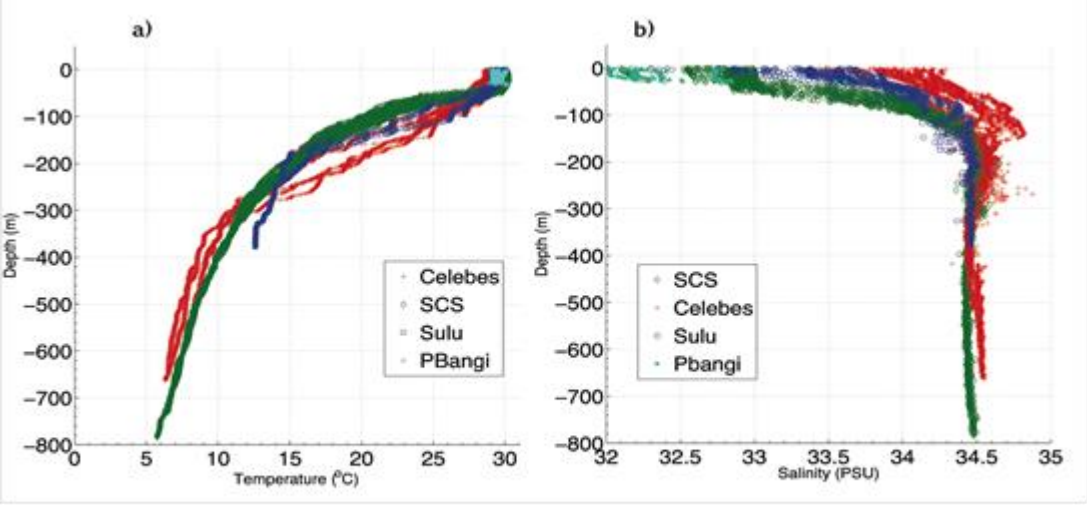

Fig. 2 : Profiles of (a) temperature and (b) salinity of CTD cast data in coastal area of Sabah Waters

October-November 2008, Jun 2009, respectively in Celebes Sea) shows that the T-S diagram is a reverse 'S' in shape, which means the water structure here was high temperature and low salinity in surface, and high temperature and high salinity in subsurface. Meanwhile at intermediate level, less-low temperature and salinity and low temperature less-high salinity in deep layer.

In the upper ocean, from the classical concept of water mass analysis, the characterization of water masses is not as easy because of the surface mixed layer is an essential element of heat and freshwater transfer between the atmosphere and the ocean and the influence of river outflow along the Sabah coastline created by monsoonal climate. We suggest the new definition for two local upper waters which can be identified from the T-S diagram of Fig. 4 (a) and (b), one is Continental Shelf Water (CSW) and the other Open Sea Water (OSW). CSW was characterized by temperature between 29-31°C and salinity between 27-33.5 PSU which covers CTD data at coastal area that is shallower than 40 meter. The OSW, found at coastal area where the depth is greater than 40m, characterized by temperature between 25-29°C and salinity between 32.5-34 PSU are seen in both data sets.

The Seasonal Thermocline Water (STW) occurs from both data sets in SCS, Sulu Sea and Celebes Sea at a depth between 50 to 100 m depth, its temperature was between 20-27°C with salinity range 34-35 PSU. These results indicate that this water exists in Sabah surrounding seas. In addition, previous study by Qu et al. (1999) have identified the Tropical Surface Water (TSW) which is traced confined primarily south of 15°N include Sulu Sea and Celebes Sea, a water mass with temperature 25-30°C and Salinity between 33.5-34.5 PSU. TSW is seen in both data sets and these results prove the straight line in the TS-diagram indicates more mixing between STW and TSW instead the existence of an own water mass.

The surface water in the SCS connects freely with those in the East China Sea, the Java Sea, the Sulu Sea and the western Philippine Sea. However, subsurface waters flow into the SCS primarily from the western Philippine Sea through the Luzon Straits as a

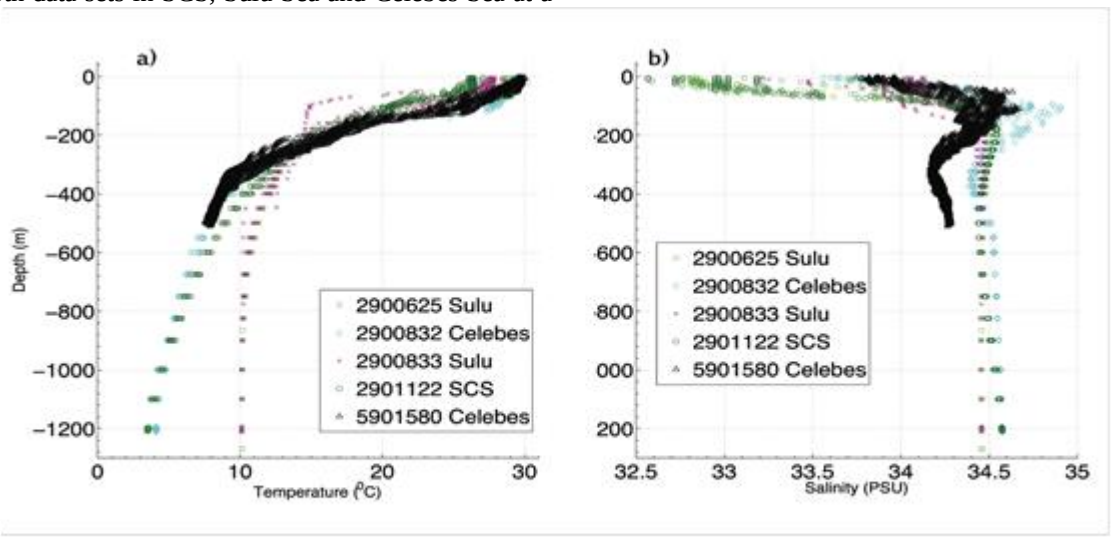

Fig. 3 : Profiles of (a) temperature and (b) salinity of five (5) Argo profiling floats data of Sabah surrounding seas Waters

40m, characterized by temperature between 25-29°C and salinity between 32.5-34 PSU are seen in both data sets.

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as a result of the shallow sill depths connecting the other sea to SCS (Wong et al. 2007 and Qu et al. 2009). The CTD cast data and The Argo floats 2901122, 2900832 and 5901580; both data sets, appears as salinity maximum at around 150 m in the SCS and Celebes Sea, which has been named Maximum Salinity Water (MSW). The MSW was characterized by temperature between 15-20°C and salinity greater than 34.5 PSU as observed by Rojana-anawat et al. (2001) in the central area of the Vietnamese upwelling. Further analysis by Dippner and Loick-Wilde (2011) gave the new temperature range of MSW to the range of 17-19C and extend the salinity range S>34.3 which covers all data and defines as end member. This water has its origin in the North Pacific, a wide density range of 23.5 – 25.5 and is called North Pacific Tropical Water (NPTW) by Qu et al. (2000). There is little indication that this water extends into Sabah surrounding seas.

The Deep Water (DW) occurs from Argo float data 2900832 and 2901122 at a depth greater than 1000 m, its temperature was between 2.5 to 5°C with salinity range >34.5 PSU. Between DW and MSW masses, a local minimum occurs at 180 to 400 m depth in both data sets, its temperature was between 10 to 15°C with salinity range 34 to 35 PSU which has been named Permanent Thermocline Water (PTW).

The North Pacific Intermediate Water (NPIW), which appears as salinity minimum, centered around 500 m with density range of 26.5-27.0 are seen in both data sets in the SCS and Celebes Sea but not in Sulu Sea. This water has also can be traced to its source in the subpolar regions in the North Pacific (Qu et al. 2000). There is little indication that this water extends into SCS and Celebes Sea.

With this definition, obviously the overlapping between rectangles mark on STW, TSW and OSW can be considered as mixed water masses. In general, the Argo float data support the overview of water mass definition in the Sabah offshore covered SCS, Sulu Sea and Celebes Sea, whereas the CTD cast data support the water mass definition along Sabah coastal area.

4. **DISCUSSION**

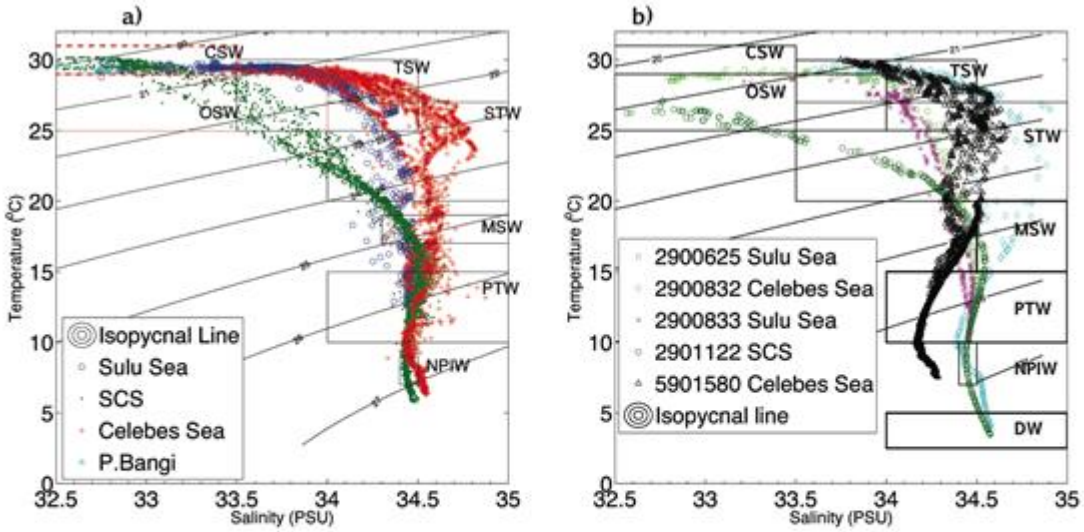

Fig. 4 : T-S diagram of (a) all CTD cast data and (b) five (5) Argo profiling floats in Sabah surrounding seas. The solid rectangles mark the T-S range of water masses according to previous study in the South-East Asia waters and dash rectangles mark the T-S range of redefined water masses CSW and OSW. The thin lines of Isopycnal line denote potential density of 20 to >27.

The water mass definition of Sabah waters are slightly differ at the ocean surface from both of these data sets, first, the CTD cast which has covered Sabah coastal water only; second, the Argo float which has covered beyond EEZ of Sabah waters. For instance, the salinity range of ocean surface from CTD cast data was lower in the Sabah coastal water compared to Argo float data in the Sabah offshore approximately 1 PSU. In the upper ocean, the separation of water mass is not as easy because of the influence of river outflow along the Sabah coastline created by monsoonal climate. The simulation results as observed by Jakobsen et al. (2007) indicate that during North East monsoon and South West monsoon, the salinity distribution at Kota Kinabalu, Sabah are significantly influenced by the river outflow in the Sulu Sea and Brunei Bay, respectively.

Most water masses are formed at the ocean surface. This is a region of strong mixing, which produces uniformity of properties above a layer of rapid property change. The surface mixed layer which usually occupies the uppermost 50 - 150 m showed mixing water mass between CSW, OSW and TSW. The water mass definition in the upper layer is too obscure to define due to strong mixed between each water mass, where ocean circulation is predominantly forced by monsoonal winds. At this stage, it seems desirable to analyze more data of T-S in the upper layer of the ocean for the entire Sabah waters to define an own water mass instead of mixing water mass.

Recent study shows evidence that waters of both the salinity maximum and the salinity minimum exist at around 150 m and 500 m, respectively. Identical with several earlier observation by Wyrtki (1961) and Qu et al. (2000), we found these waters can be traced around Sabah waters along density of 25.0 and 26.73, respectively. Several hypotheses have been raised concerning the mechanism of the intrusion of Pacific waters near the coast of Borneo including SCS, Sulu Sea and Celebes Sea. Based on a series of numerical experiments, Metzger and Hurlburt (1996) suggested that the mean Luzon Straits transport is mainly a function of the large–scale forcing of the Pacific and the model geometry in the Sulu Sea. According to Qu et al. (2000), these waters were showed strong property gradients of in the Luzon Straits. Temperature and Salinity of NPTW decrease along the coast south of China, east of Vietnam, and near the coast of Borneo salinity maximum (<34.575) is no longer well pronounced. This modified NPTW forms the MSW in the upwelling area. NPIW seems to be better conserved and transported for a greater distance than NPTW, presumably because of weak mixing below the seasonal thermocline. Further analysis according to Qu et al. (2000), the intrusion of high-salinity NPTW occurs only in winter when NE monsoon is fully developed, whereas the low-salinity NPIW enters SCS only in spring when the intrusion of NPTW is weakest.

5. CONCLUSION

Perious study only concentrate on the northern part of Sulu Sea and SCS in proviing defenition of water masses. Definitions of coastal waters along Sabah coast in this study provide new information on type of water masses that provide the continuity of water mass that occupy all three seas surrounding the area. Presence of NPIW in the region also has shown how dynamic is the region as one of the intersection of the throughflow from the Pacific Ocean.

Generally, definition of water mass via temperature and salinity is problematically in the upper layer of the ocean because neither temperature nor salinity is an absolute conservative property due to heat fluxes at the air-sea interface and due to precipitation and evaporation. Nevertheless, in an area with such a high variability, those data sets might be useful in providing a general overview of the water mass definition in the study area that is not well understood.

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