Refining of Water Masses at Sarawak Waters, Malaysia

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Abstract
Water mass identification is essential to understand the dynamics of water circulation. The waters off Sarawak are influenced by the northeast and the southwest monsoons. We studied the physical oceanography of the South China Sea along these waters, from data collected during the Prime Marine Scientific Expedition 2009. The expedition was organized by the Malaysian Ministry of Science, Technology, and Innovation through the National Oceanography Directorate. The physical properties of seawater were obtained using the 'Conductivity-Temperature-Depth' (CTD) profiler from the ocean surface to a water depth of 523 meters. Measurements were recorded from 62 stations, with the furthest offshore distance being approximately 471 kilometers from the nearest point of Sarawak's mainland. The aim of this study is to identify the mass features of Sarawak waters. We employed the T-S diagram and refined the water masses based on previous studies conducted in the South China Sea. The constructed vertical salinity and temperature profiles showed that salinity increases towards the sea bottom, whereas temperature decreases as water depth increases. Five water masses were identified off Sarawak waters, namely Continental Shelf Water (CSW), Open Sea Water (OSW), Maximum Salinity Water (MSW), Permanent Thermocline Water (PTW), and Water Mass 1 (WM1). WM1 is derived from the mix of OSW and MSW masses. Results of this study are useful for studies in primary productivity and the distribution of marine resources in these waters.

Keywords: Vertical profiles, T-S diagram, water mass, Sarawak waters, South China Sea

Introduction
The water characteristics of the South China Sea (SCS) area are subject to seasonal monsoons.

From November to March, the Northeast monsoon dominates the SCS region, causing strong northeasterly wind stress in Malaysian waters. The Southwest monsoon dominates this area from April to August, driving a northward coastal current off the east coast of Malaysia (Akhir, 2012). During this monsoon, the surface current starts flowing northeasterly from the west coast of Borneo Island along the coast of Sarawak (O'Neil & Eason, 1982). Siripong (1984) stated that the surface current during the transition period between the Northeast and Southwest monsoons in May was weaker and varied in direction compared to ordinary monsoons. Therefore, the vertical and horizontal structures of the water properties in the SCS may change during different seasonal monsoons. Vertical structures off Sarawak waters were discussed by Manson et al. (2018).

The properties of seawater, such as temperature and salinity, have been used as guidelines or passive tracers to provide direct pathways of water masses (Arsad & Akhir, 2013). A water mass in the ocean is defined based on water temperature (°C) and salinity (PSU) characteristics. A water mass is an identifiable body of water with a common formation history that has a distinctive narrow range of temperature and salinity from surrounding waters (Marghany, 2012). Song (1994) explained that a single water mass can occupy a particular oceanic region, but at the same time, several water masses can be present at an oceanic location as the water masses mix and spread across that area. Each water mass is first identified by its water characteristics, followed by observing the ocean process that created that specific characteristic. It is then necessary to compile temperature, salinity, and water depth to understand the differences in water masses. One of the standard methods for water mass identification is based on a temperature-salinity (T-S) diagram (Marghany, 2012). According to Dippner and Loick-Wilde (2011), definitions of water masses for areas with high variability of ocean parameters are useful to understand the complexity of the biological system, such as plankton in upwelling areas.

Akhir (2012) identified higher phytoplankton density in the coastal areas of Sarawak during the southwest monsoon. A comparison of prokaryotic communities in the surface waters of the eastern South China Sea (SCS) revealed that surface microbial community patterns in Sarawak waters exhibited a more distinctive composition and metabolism (Song et al., 1994. This might be related to water mixing and the properties of seawater. However, the study of the physical characteristics of Sarawak waters is limited to understanding the vertical and horizontal features of water, such as water mass definition.

Previously, the study of water masses on the Sarawak coast was conducted by Saadon et al. (1998a) during the Southeast Asian Fisheries Development Centre (SEAFDEC) cruise held in 1997. Another study on temperature and salinity profiles off Sarawak waters was discussed by Saadon et al. (1988b) during the Matahari Expedition in 1985. Manson et al. (2018) elaborated on the temperature and salinity profiles of Sarawak waters, defining the water properties at different depths. These water properties were analyzed for water mass definition and classification based on studies by Qu et al. (1999; 2000) in the western SCS, Rojana-Anawat et al. (2001), Dippner and

Loick-Wilde (2011) in Southeast Asia waters, and Arsad and Akhir (2013) in Sabah waters. Thus, the objective of this study is to redefine the water masses based on the previous study done in SCS and to identify the water mass features in Sarawak waters, Malaysia.

Methodology

Study Area

The Prime Marine Scientific Expedition 2009 (PMSE '09) took place over 44 days between June and July 2009 in the waters of Malaysian Borneo, encompassing the South China Sea (SCS), the Sulu Sea, and the Celebes Sea. The expedition aimed to collect coastal and offshore oceanographic data and was organized by the Ministry of Science, Technology, and Innovation (MOSTI) through the National Oceanography Directorate (NOD), in close collaboration with the National Hydrographic Centre, Royal Malaysian Navy (RMN), and local universities. During the expedition, physical oceanographic data collected in the SCS within Sarawak waters were analyzed to identify water masses at depths less than 500 m, covering a survey area from 2.8737°N to 4.4446°N and 109.9034°E to 113.3421°E (Figure 1).

Water temperature and salinity were measured at 62 stations located approximately 50 km to 471 km off Sarawak's mainland (Figure 1). In this study, sampling stations closer to the shoreline of Sarawak waters, with a water depth of less than 50 m, are considered shallow waters, while those located further offshore with water depths greater than 50 m are designated as deep water (Manson et al., 2018). Measurements were conducted during the southwest monsoon in June 2009, using an SBE 19Plus Conductivity-Temperature-Depth (CTD) profiler, recording temperature and salinity data from the sea surface down to 523 m water depth.

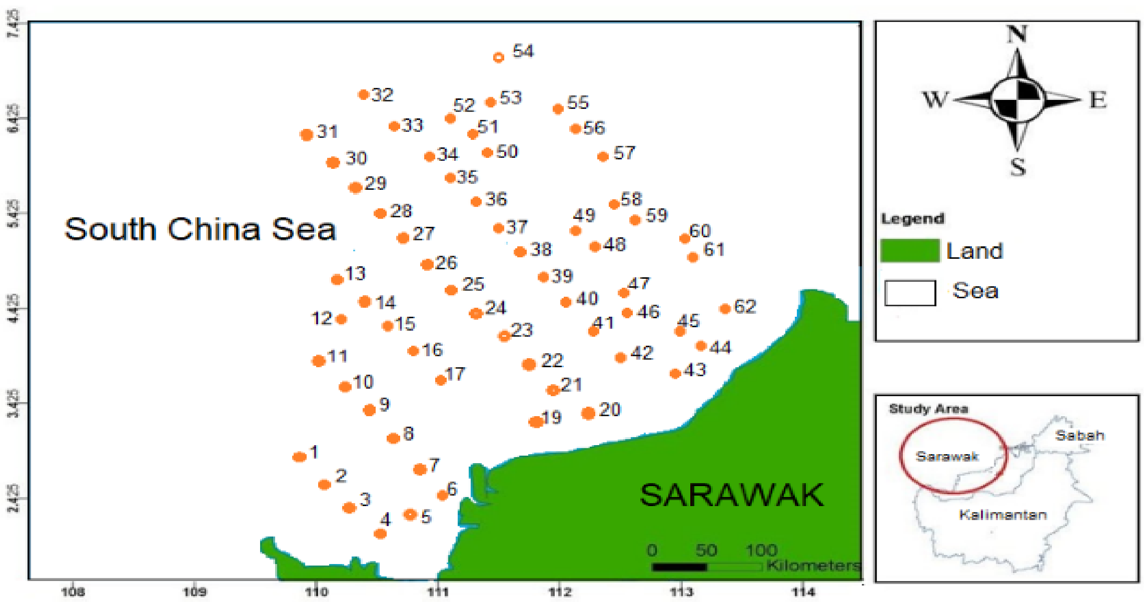


Figure 1. Location of 62 Stations at Sarawak Waters

Data Analysis

The temperature and salinity data were compiled using Microsoft Excel to create temperature-salinity (T-S) diagrams, identifying the water characteristics of the study areas. T-S diagrams were also employed to mark the water mass distribution based on specific water mass classifications in the SCS published by Qu et al. (1999; 2000), Rojana-Anawat et al. (2001), Dippner and Loick-Wilde (2011), and Arsad and Akhir (2013).

Water mass distribution in the SCS, particularly along the Philippine coast, was identified based on the relationship between potential temperature versus salinity and dissolved oxygen versus salinity data (Qu et al., 1999; 2000). Qu et al. (2000) recognized water masses in this area as Tropical Surface Water (TSW), North Pacific Tropical Water (NPTW), South Pacific Tropical Water (SPTW), and North Pacific Intermediate Water (NPIW). Characteristics of the Antarctic Intermediate Waters (AAIW) were also found in this region as part of the Indonesian throughflow (Wrytki, 1961). Rojana-anawat et al. (2001) classified water masses along the Vietnamese waters of the western SCS as Deep Water (DW), Permanent Thermocline Water (PTW), Maximum Salinity Water (MSW), Open Sea Water (OSW), Seasonal Thermocline Water (STW), Northern Continent Shelf Water (NCSW), and Southern Continental Shelf Water (SCSW). Dippner and Loick-Wilde (2011) redefined water mass characteristics in SCS as DW, PTW, MSW, OSW, and Mekong/Gulf Thailand Water (MKGTW), while Arsad and Akhir (2013) discovered two local water mass characteristics in east SCS: the upper layer of Sabah waters known as Continental Shelf Water (CSW) and OSW. These water mass definitions were done by comparing the temperature and salinity values to the measured data from the CTD. The range of temperature and salinity values were overlaid with the T-S diagram from the expedition to redefine and determine the specific water masses of Sarawak waters. The temperature and salinity range of the earlier water mass definitions in the SCS were also adjusted to present information specifically for this study.

Results and Discussion

Definitions and Reconstruction of Water Mass in the South China Sea (SCS)

The water masses in the SCS are influenced by their location and sources of water. For instance, the Mekong/Gulf Thailand Water (MKGTW) mass is primarily affected by the Mekong River at Gulf Thailand. The uppermost layer of the SCS typically constitutes a surface layer with uniform hydrographic properties, known as the surface mixed layer (Song et al, 1994). The construction of the T-S diagram for Sarawak waters reveals that salinity vertical profiles increase towards the sea bottom, while temperature decreases as water depth increases (Figure 2).

Water mass definitions identified by Qu et al. (1999) and Qu et al. (2000) along the Philippine coast of the SCS were plotted on the constructed T-S diagram for Sarawak waters (Figure 3a). However, none of these water mass definitions fit this T-S diagram. Nevertheless, the three water masses (OSW, MSW, and PTW) identified by Rojana-anawat et al. (2001) are fitted to the T-S diagram (Figure 3b).

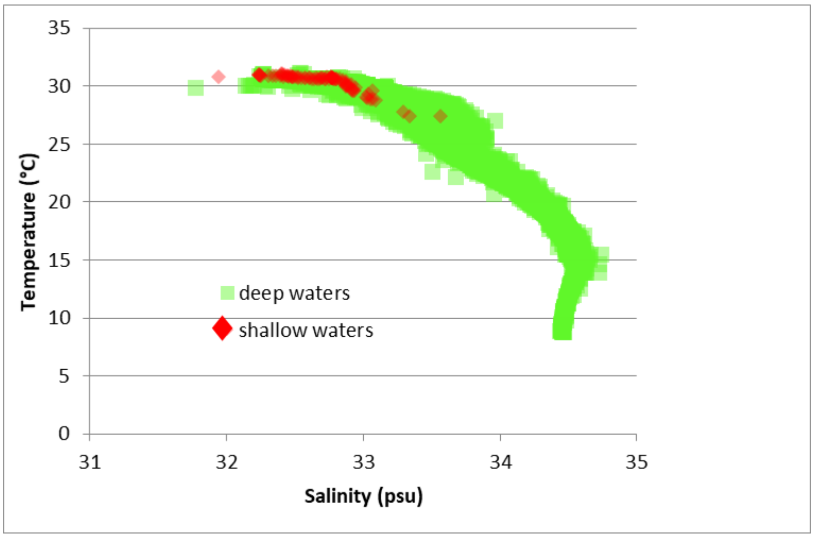
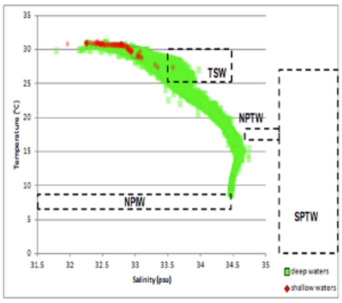
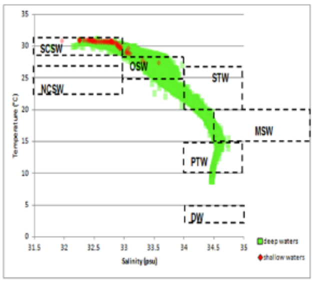


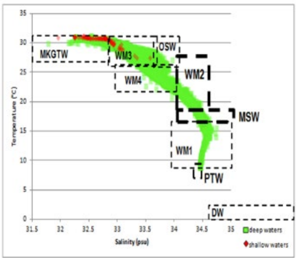
Figure 2. T-S diagram of Sarawak waters



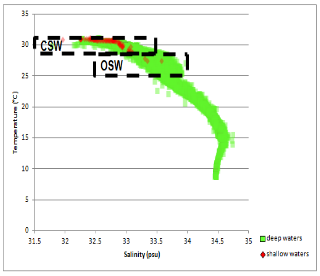
a: Water mass classification by Qu et al. (1999; 2000)



b: Water mass classification by (Rojana-anawat et al. (2001)



(c): Water mass classification by Dippner & Loick-Wilde (2011)



(d): Water mass classification by Arsad & Akhir (2013)

Figure 3. Water mass classification based on previous studies carried out at SCS; Tropical Surface Water (TSW), North Pacific Tropical Water (NPTW), South Pacific Tropical Water (SPTW) and North Pacific Intermediate Water (NPIW), Northern Continent Shelf Water (NCSW), Seasonal Thermocline Water (STW), Permanent Thermocline Water (PTW), Deep Water (DW), Continental Shelf Water (CSW), Open Sea Water (OSW), Water Mass (WM), Maximum Salinity Water (MSW), Mekong/Gulf Thailand Water (MKGTW) and Southern Continental Shelf Water (SCSW).

The water masses (WM1 and MSW) identified by Dippner and Loick-Wilde (2011) and the water masses (CSW and OSW) reported by Arsad and Akhir (2013) all fit well with the T-S diagram of Sarawak waters (Figure 3c-d). Based on the redefinition of water masses within the SCS, five water masses (CSW, OSW, WM1, MSW, and PTW) were matched with the water masses of Sarawak waters during the Southwest monsoon in June 2009 (Figure 4).

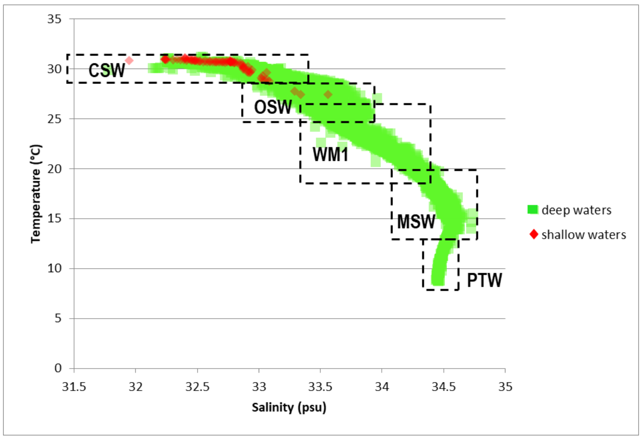


Figure 4. T-S diagram of all CTD casts in Sarawak waters with labeled classification of water mass identified in the SCS. The dotted rectangular labeled on the T-S ranges diagram is the best match to describe the water masses off Sarawak waters.

Water Mass Definitions and Reconstruction of Sarawak Waters

The water characteristics and newly redefined water mass characteristics in the SCS are summarized by Arsad & Akhir (2013) and Dippner & Loick-Wilde (2011). The layer of the sea is divided into surface, middle, and bottom layers (Table 1). The upper 50 m water depth is known as the surface layer. This layer is covered by two distinct water masses: the CSW and the OSW. The CSW is present in Sarawak waters, with temperature and salinity ranging between 29°C to 31°C and 27 psu to 33.5 psu, respectively (Arsad & Akhir, 2013). The OSW is found in deeper waters between 57 m to 75 m. However, traces of these water masses are also found in shallow waters (for example, St. 8 starting from 37 m depth) with temperature and salinity ranging from 25°C to 29°C and 32.9 psu to 34.1 psu, respectively.

The middle layer of the SCS, originally classified by Dippner & Loick-Wilde (2011) as Water Mass 2 (WM2) (Table 1), is redefined as the middle layer for Sarawak waters, known as WM1. This water mass is derived from the mixing of OSW and MSW water masses, with a wider range of salinity (33.4 to 34.4 psu) compared to WM2 with a salinity range of only 34.1 to 34.6 psu. However, both water masses have a similar temperature range from 19 to 28°C.

The bottom layer water masses of the SCS are identified as MSW and PTW (Table 1). The MSW water mass is characterized by a temperature and salinity range of 13°C to 20°C and 34.2 psu to 34.8 psu, respectively. The PTW is usually located between the water masses of MSW and DW (Dippner & Loick-Wilde, 2011). It is detected when an obvious thermocline formation occurs in the T-S diagram at deeper waters (Figure 2). There are increases in temperature and salinity for PTW at Sarawak waters compared to the PTW defined by Dippner & Loick-Wilde (2011) due to a significant thermocline formation in the T-S curve (Figure 3c). The new definition of PTW is located below the MSW layer where the temperature ranges between 8°C and 13°C, and salinity ranges from 34.4 psu to 34.7 psu. The minimum temperature of 8°C shows that the PTW is located in the deeper waters of Sarawak coastal areas.

Table 1. Redefinition of water mass and its characteristics in Sarawak waters based on previous studies in the SCS.

Ocean layer	Water mass	Temperature (°C)	Salinity (psu)	Source	Water mass re-definition	Redefined temperature (°C)	Redefined salinity (psu)
Surface layer	CSW	29-31	27.0 33.5	Arsad & Akhir (2013)			
	OSW	25-29	32.5 -34.0	Arsad & Akhir (2013)	OSW	25-29	32.9-34.1
Middle layer	WM2	19-28	34.1-34.6	Dippner & Loick-Wilde (2011)	WM1	19-28	33.4-34.4
Bottom layer	MSW	17-19	>34.3	Dippner & Loick-Wilde (2011)	MSW	13-20	34.2-34.8
	PTW	7-9	34.4-34.5	Dippner & Loick-Wilde (2011)	PTW	8-13	34.4-34.7

The bottom layer water masses of the SCS are identified as MSW and PTW (Table 1). The MSW water mass is characterized by a temperature and salinity range of 13°C to 20°C and 34.2 psu to 34.8 psu, respectively. The PTW is usually located between the water masses of MSW and DW (Dippner & Loick-Wilde, 2011). It is detected when an obvious thermocline formation occurs in the T-S diagram at deeper waters (Figure 2). There are increases in temperature and salinity for PTW at Sarawak waters compared to the PTW defined by Dippner & Loick-Wilde (2011) due to a significant thermocline formation in the T-S curve (Figure 3c). The new definition of PTW is located below the MSW layer where the temperature ranges between 8°C and 13°C, and salinity ranges from 34.4 psu to 34.7 psu. The minimum temperature of 8°C shows that the PTW is located in the deeper waters of Sarawak coastal areas.

The salinity profile of Sarawak waters increases with water depth. The maximum salinity at a water depth of approximately 500 m from the sea surface is 34.8 psu (Manson et al., 2018). The overlapping area, marked as rectangles of the OSW and MSW, was identified at the middle layer of SCS (Figure 4). In this study, the occurrence of mixing water masses is defined as Water Mass 1 (WM1), where the temperature and salinity range from 19°C to 28°C and 34.4 psu to 34.7 psu, respectively (Table 1). Therefore, no DW was detected, as defined by Rojana-Rawat et al. (2001). The DW usually exists at a water depth of more than 900 m. In this study, the temperature and salinity data were measured only down to a maximum water depth of approximately 523 m.

Redefinition of Water Masses in Sarawak Waters

Water masses such as CSW and OSW, as defined by Arsad and Akhir (2013) in Sabah waters, also occupy the uppermost layer of Sarawak waters, characterized by a temperature range of 29°C to 31°C and a salinity range of 27 psu to 33.5 psu (Table 1). These water characteristics perfectly align with the surface layer of the T-S diagram of Sarawak waters. It is suggested that a similar water mass is found in the surface waters of both Sabah and Sarawak. The newly defined OSW in Sarawak waters shares the same temperature range of 25°C to 29°C and a salinity range of 32.9 psu to 34.1 psu. The OSW water mass dominates Sarawak waters and has been consistently defined in previous studies within the SCS area. For instance, Rojana-Anawat et al. (2001) characterized the temperature range as 25 to 29°C and a salinity range of 33 to 34 psu in Vietnamese waters. It was later redefined by Dippner and Loick-Wilde (2011) in the same study area (Vietnamese waters), with a slight increase of 1°C in the temperature range and a smaller range of salinity. This study suggests that OSW in Sarawak waters is more saline compared to the water characteristics in Sabah as defined by Arsad and Akhir (2013).

The water mass at the middle layer of Sarawak waters exhibits similar characteristics to the MSW and PTW defined by Dippner and Loick-Wilde (2011). It likely originates from the Northwest Pacific Ocean, where the MSW and PTW are named as NPTW and PTW water masses, respectively, on the Philippine coast (Qu et al. 2000). The MSW was initially distinguished by Rojana-Anawat et al. (2001) with a temperature range of 15 to 20°C and a salinity range of more than 34.5 psu. However, according to Dippner and Loick-Wilde (2011), the temperature range set by Rojana-Anawat et al. (2001) is unclear, and the salinity range is too small. The MSW in Sarawak waters is distinguished by a redefined temperature and salinity range of 13 to 20°C and 34.2 to 34.8 psu, respectively. The temperature and salinity range are not as wide as the MSW in Vietnamese waters.

Conclusion

The surface layer in the study of Sarawak waters aligns best with the water characteristics defined by Arsad and Akhir (2013), while the middle and bottom layers closely resemble the water characteristics defined by Dippner and Loick-Wilde (2011). Five types of water masses (CSW, OSW, MSW, PTW, and WM1) have been identified in Sarawak waters. WM1 represents a mixed water mass of OSW and MSW detected between the OSW and MSW layers. However, both Qu et al. (1999; 2000) and Rojana-Anawat et al. (2001) generally do not fit with the T-S diagram of Sarawak waters, where the T-S range is distinctly different compared to these findings. The number of water masses in Sarawak waters could potentially be higher with further measurements towards the sea bottom. Water masses may also vary with data measurements carried out during different seasonal monsoons, such as the northeast monsoon. It is suggested that further studies on water mass definition be conducted during different seasonal monsoons such as intermonsoon and northeast monsoon. A comprehensive understanding of water masses would enhance biological knowledge, including primary productivity and the distribution of marine resources in this area.

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