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The Influence of the Andaman Sea and the South China Sea on Water Mass in the Malacca Strait

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Abstract : The Malacca Strait is an important waterway link between the Indian Ocean and the South China Sea. It is also an important fisheries area for the neighbouring states. Improved understanding of the water mass variations over the monsoon seasons can lead to better management of this water body. The purpose of this paper is to present the seasonal variations in the water mass properties in the Strait. Data from the World Ocean Database for the Strait was utilised to assess the seasonal variation in temperature, salinity and dissolved oxygen. The data indicated the introduction of cool, deep, saline water from the Andaman Sea during the Southwest Monsoon. During the Northeast Monsoon the situation reversed and there was ingress of lower salinity water mass from the south. This may be attributed to the larger river discharge experienced during the Northeast Monsoon and the introduction of lower salinity water from the South China Sea. The influence of the Andaman Sea and the South China Sea is supported by the variation in the T-S plots for the Malacca Strait. This indicates that although very saline water characteristics are fairly consistent over the year, identifiable as the Andaman Sea water, the lower salinity water characteristics separate into two distinct masses, one representing the South China Sea water and the other representing freshwater influence from river inflows. This is especially discernible in the Northeast Monsoon and in the subsequent Inter-monsoon period. Such results have implications for the movement and exchange of materials between the Andaman Sea and the South China Sea via the Malacca Strait.

Keywords : *Strait of Malacca, water mass, Andaman Sea, South China Sea, monsoon, salinity, temperature, dissolved oxygen*

1. Introduction

The Malacca Strait represents an important link between the Indian Ocean, the Andaman Sea, the South China Sea as well as the Java Sea. Thus it can be an important conduit for interaction and transfer of water properties between the various seas. The Malacca Strait is also important for the fisheries resource of its neighbouring states. As the Southeast Asian region is affected by Monsoon winds, wind-driven water movements can occur in the Strait. From previous observations, it is known that during the Northeast Monsoon, water from the South China Sea penetrates at least into the southern sector of the Malacca Strait (CHIA *et al.* 1988; PANG and TKALICH, 2003) and that there is incursion of the Andaman Sea from the north (LIONG, 1974; FAIRBRIDGE, 1996; TOMCZACK and GODFREY, 2003). The movement of these water masses may be found from investigation of the physical properties of seawater, such as salinity, water temperature and dissolved oxygen. The first two parameters are regarded to behave conservatively in mixing processes, while dissolved oxygen can be regarded as quasi-conservative. A vast amount of ocean data for the area is available from Ocean Data bases such as the World Ocean Data Center (WODC), National Oceanographic and Atmospheric Agency (NOAA), National Ocean Data Center (NODC) of the United States. An understanding of the physical-chemical variations over the monsoon seasons can lead to better management of this waterway resource. A

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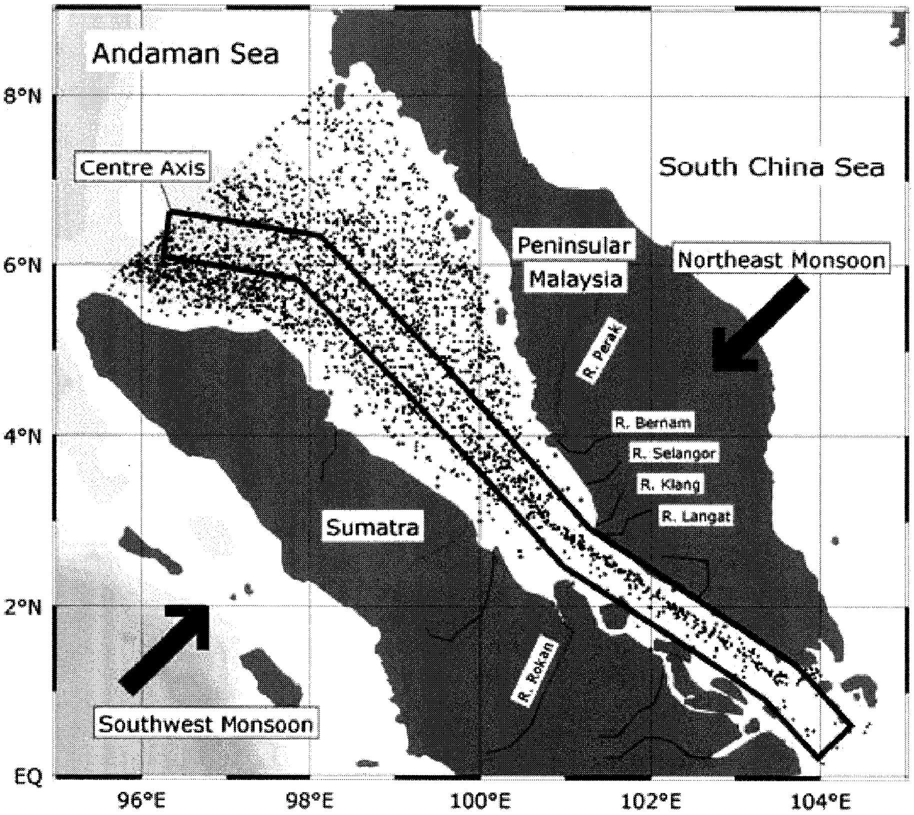

Fig. 1. Location of the Malacca Strait study area and location of stations from the World Ocean Data Base 2001. The centre axis of the Strait used for vertical section plots is also indicated.

previous analysis of the seasonal variations (IBRAHIM *et al.*, 2003) had indicated the importance of the Andaman Sea to the Malacca Strait circulation. The purpose of this paper is to present the seasonal variations in the water mass properties in the Strait. A mechanism for the variations is also proposed.

2. Methods

Water temperature, salinity and dissolved oxygen data for the Malacca Strait were obtained from the World Ocean Data Base (NOAA, 2001). Stations whose coordinates placed on land, as delineated by the ODV (Ocean Data View) high-resolution global coastline and topography file "odvmpOP_coast GlobHR_w32" based on ETOPO5 (0.2×0.2 degree grid), were omitted. Stations indicating sampling at deep depths (greater than 150 m depth) in the shallow southern sector of the Strait were also omitted. The final dataset, comprising 4,476 stations (Fig. 1), were supplied by 558 cruises carried out between 1889 and 2001. This resulted in a total of 95,063 samples of the Malacca Strait waters. The data availability by month and for different years is shown in Fig. 2.

ODV (mp) 1.4 software (SCHLITZER, 2003) was used to process the data and to create contour plot visualizations. The visualizations are presented in two forms: seasonal surface variations and axial section (Fig. 1) variations of water temperature, salinity and dissolved oxygen along the Malacca Strait. The data were separated into four seasonal groups (Table 1) to represent the different monsoonal periods. The monsoonal periods defined here are delayed by one month from the traditional climatic divisions for Malaysia, as the response of the sea is expected to lag behind that of the

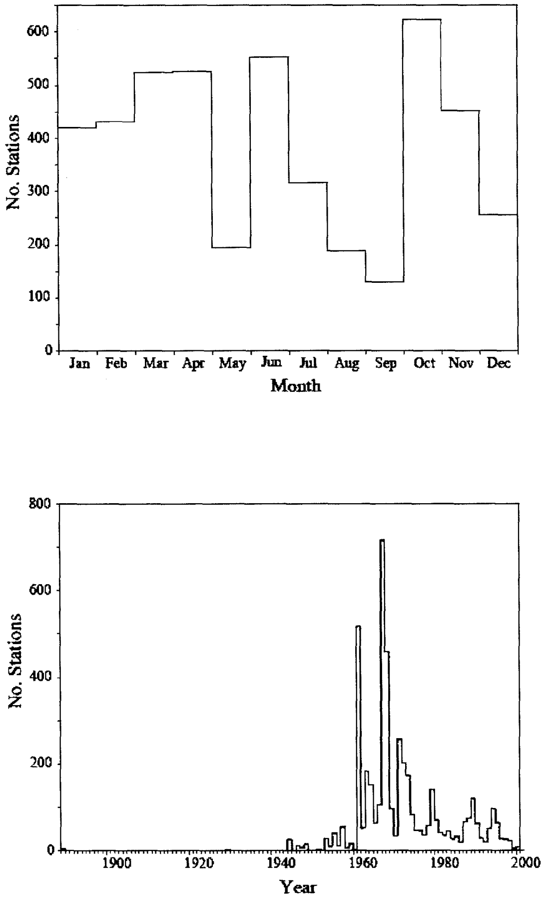

Fig. 2. Temporal distribution of station data in the Malacca Strait. (a) The number of stations data available by month. (b) The number of stations data available year by year.

atmosphere. In addition, coincidentally, division into the four monsoonal periods defined in Table 1 also resulted in some uniformity in the amount of data available for each season (Table 2). As the number of variables (water temperature, salinity and dissolved oxygen) increase, the number of stations and samples reduces.

3. Results and Discussion

Three formats are used to present the results of visualisation of the water temperature, salinity and dissolved oxygen data separated into the four seasons: a surface contour plot, a contour plot in the vertical section through a defined centre axis, and temperature-salinity plots. The data were also grouped into the four seasons. These data visualisations indicated the sequential change in water movement through the Strait during the different seasons.

The contour plots in Fig. 3 show the horizontal variation in surface water temperature, salinity and dissolved oxygen in the Strait. These figures indicate the importance of freshwater inflow in the central section of the Malacca Strait. The central portion of Peninsular Malaysia has several large river systems (Perak, Bernam, Selangor, and Klang-Langat Rivers) (Fig. 1) which drain a substantial part of the peninsula. The Rokan estuary in Sumatra (Fig. 1) also drains into the centre of the Strait. During the Northeast Monsoon (Fig. 3a), the large low salinity plume may be explained by the higher rainfall and subsequent river discharge. The isohalines in the central portion of the Strait veer northward with the coast on the right hand indicating the net flow direction from the South China Sea entering through the southern end. This situation is reversed in the Southeast Monsoon season (Fig. 3c) when there is a clear indication of the intrusion of high salinity Andaman Sea water from the north. The Southwest Monsoon period is drier than the Northeast one and the influence of river discharge is reduced. However, in the second Inter Monsoon during September to November (Fig. 3d) there is also an area with lowered surface salinity in the southern portion of the Strait. The reasons for this are unclear and need to be investigated further. The data here are primarily from samples taken during a single cruise in November 1957. A clearer picture may be obtained by considering the vertical variation in water temperature, salinity and dissolved oxygen. This may be obtained by considering contour plots in the vertical along a centre axis of the Strait, as indicated in Fig.1.

Figure 4 shows the vertical variation in water temperature, salinity, density (σ_t) and dissolved oxygen in the Strait along a 30 km wide centre axis. The interlacing of lower salinity water at the surface with higher salinity water at the bottom can be discerned by the sigma-shaped salinity contour lines in the figures for all four seasons. Fig. 4a indicates the pervasive

Table 1 Monsoon periods used for sea data separation.

Season	Period (months)
Northeast Monsoon	December, January, February (DJF)
Inter-Monsoon	March, April, May (MAM)
Southwest Monsoon	June, July, August (JJA)
Inter-Monsoon	September, October, November (SON)

Table 2 Data distribution among the four Monsoon periods.

	Northeast Monsoon (DJF)			Inter-Monsoon (MAM)			Southwest Monsoon (JJA)			Inter-Monsoon (SON)		
Variable	T	TS	TSO	T	TS	TSO	T	TS	TSO	T	TS	TSO
Cruises	157	21	10	157	16	9	153	12	3	157	12	5
Stations	1105	339	296	1131	213	141	1052	73	51	1188	71	55
Samples	18092	2035	1803	26821	1365	791	25206	538	330	24944	615	469

influence of the less saline South China Sea water through the whole Strait during the Northeast Monsoon. The dissolved oxygen values indicate the fairly uniform nature of the upper layer of the Strait despite the much fresher waters observed in the central portion of the Strait. With the start of the Inter Monsoon (Fig.4b), however, the Andaman Sea water starts to intrude into the Strait. Salinity increases, reaching maximum values during the Southwest Monsoon (Fig. 4c). During the following Inter Monsoon (Fig. 4d) salinity in the southern sector decreases and the salinity contours move northward in the Strait. This increase in freshwater may be partially attributed to the intrusion of lower salinity South China Sea water (HUSAIN et al., 1986; LIEW *et al.*, 1987). The area of interlacing between the two water masses starts from the north entrance of the Malacca Strait and extends down to the constriction of the funnel-shaped Malacca Strait. This latter area also coincides with the rise of the topographic sill in the Strait.

The intrusion of the South China Sea water into the Strait is generally regarded to be a result of onshore Northeast Monsoon winds resulting in increased throughflow into the Malacca Strait (YANAGI *et al.*, 1997). We may invoke a similar mechanism for the intrusion of the Andaman Sea water into the Strait. We may hypothesise that during the Southwest Monsoon, the Indian Ocean water is moved onshore into the Andaman Sea and into the Malacca Strait due to the sea level difference between the Indian Ocean and the South China Sea (YANAGI *et al.*, 1997). The normally cold, deep, saline water of the Andaman Sea is moved into the shallower Malacca Strait and is mixed upward into the water column. This is indicated by the deeper layer of oxygenated water during the Southwest Monsoon season (Fig. 4c) compared to the very stratified condition during the Northeast Monsoon season (Fig. 4a).

The influence of the South China Sea and the Andaman Sea on the water mass characteristics of the Malacca Strait is also supported by an analysis of the temperature-salinity plots for the whole Strait when they are separated into the four seasons. Three different origins of water masses may be distinguished based on location and salinity values: the salty Andaman Sea (AS) water from the northwest, low salinity surface water from river fresh water (FW), the South China Sea (SCS) water entering from the southeast. They are presented in Fig. 5. In particular, in Fig 5a, during the Northeast Monsoon, the three bodies of water in the Strait are distinctly separated. The trend of relative dominance of the water mass, dependent on the number of samples available in each water mass, may also be noted. This is particularly true for the FW water mass which almost disappears during the Southwest Monsoon (Fig. 5c) and the second Inter Monsoon (Fig.

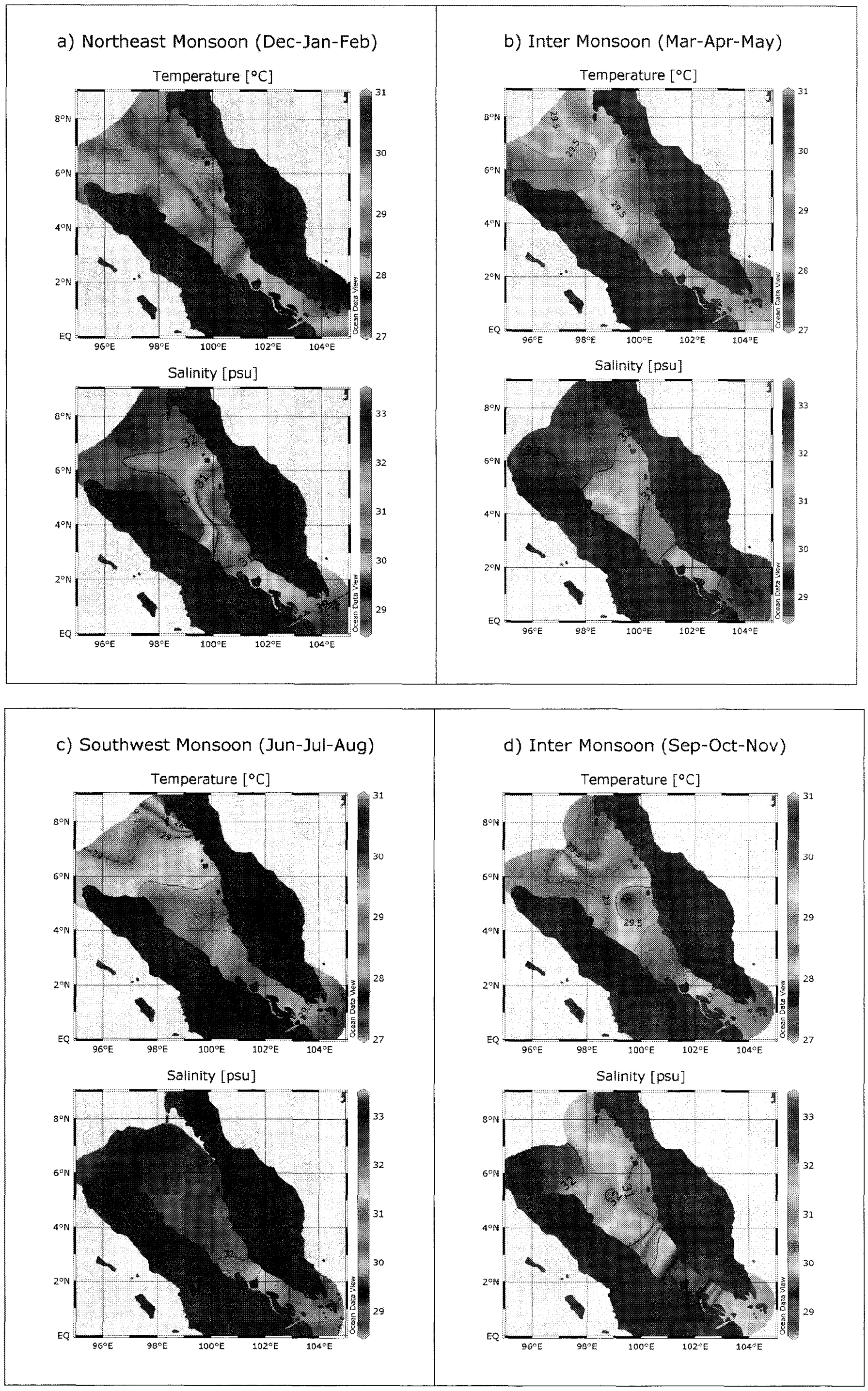

Fig. 3. Seasonal horizontal variations in surface water temperature and salinity in the Malacca Strait. (a) Northeast Monsoon season. (b) Inter Monsoon season. (c) Southwest Monsoon season. (d) Inter Monsoon season.

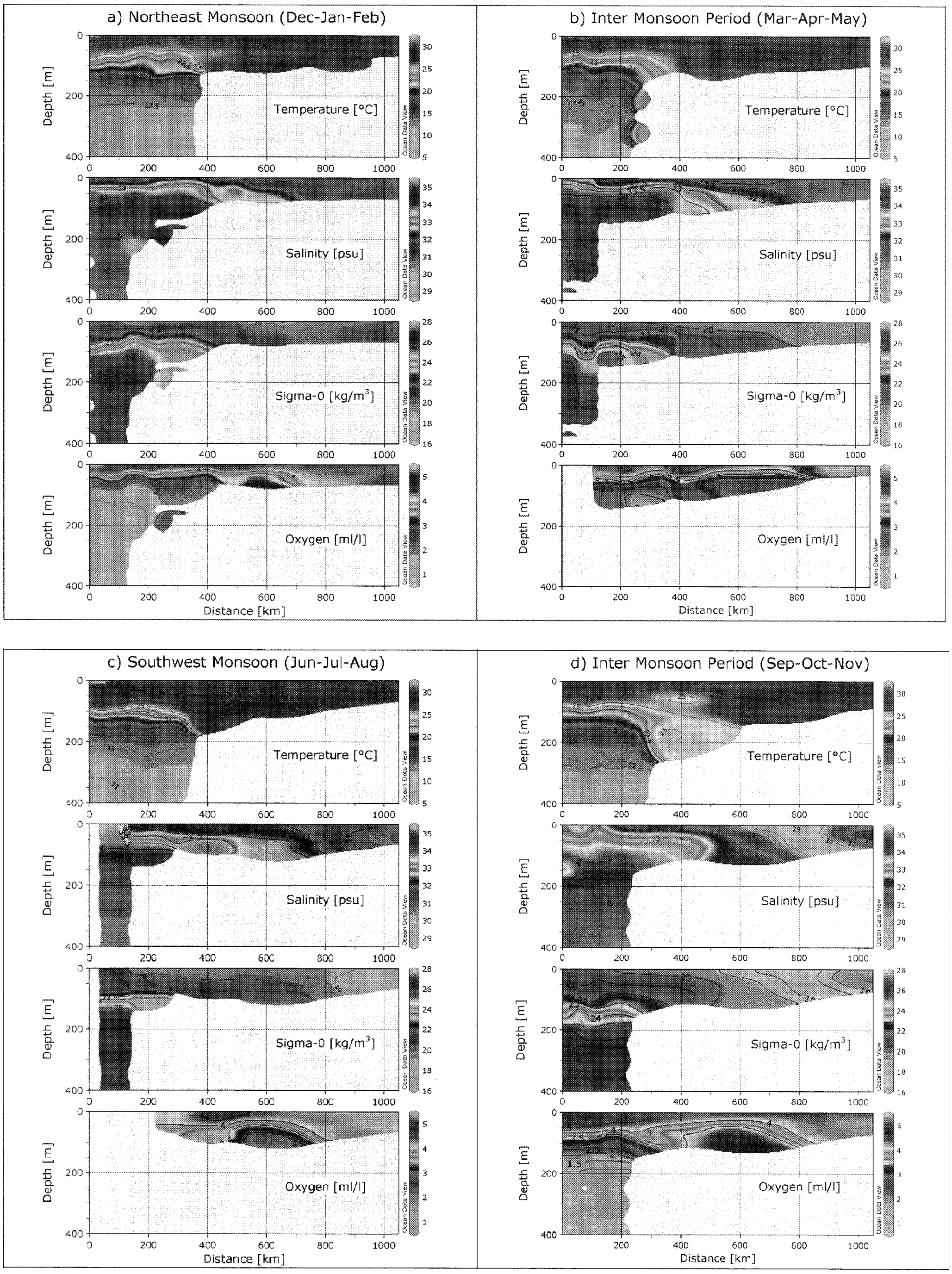

Fig. 4. Seasonal vertical variations in water temperature, salinity and dissolved oxygen in the Malacca Strait. (a) Northeast Monsoon season. (b) Inter Monsoon season. (c) Southwest Monsoon season. (d) Inter Monsoon season.

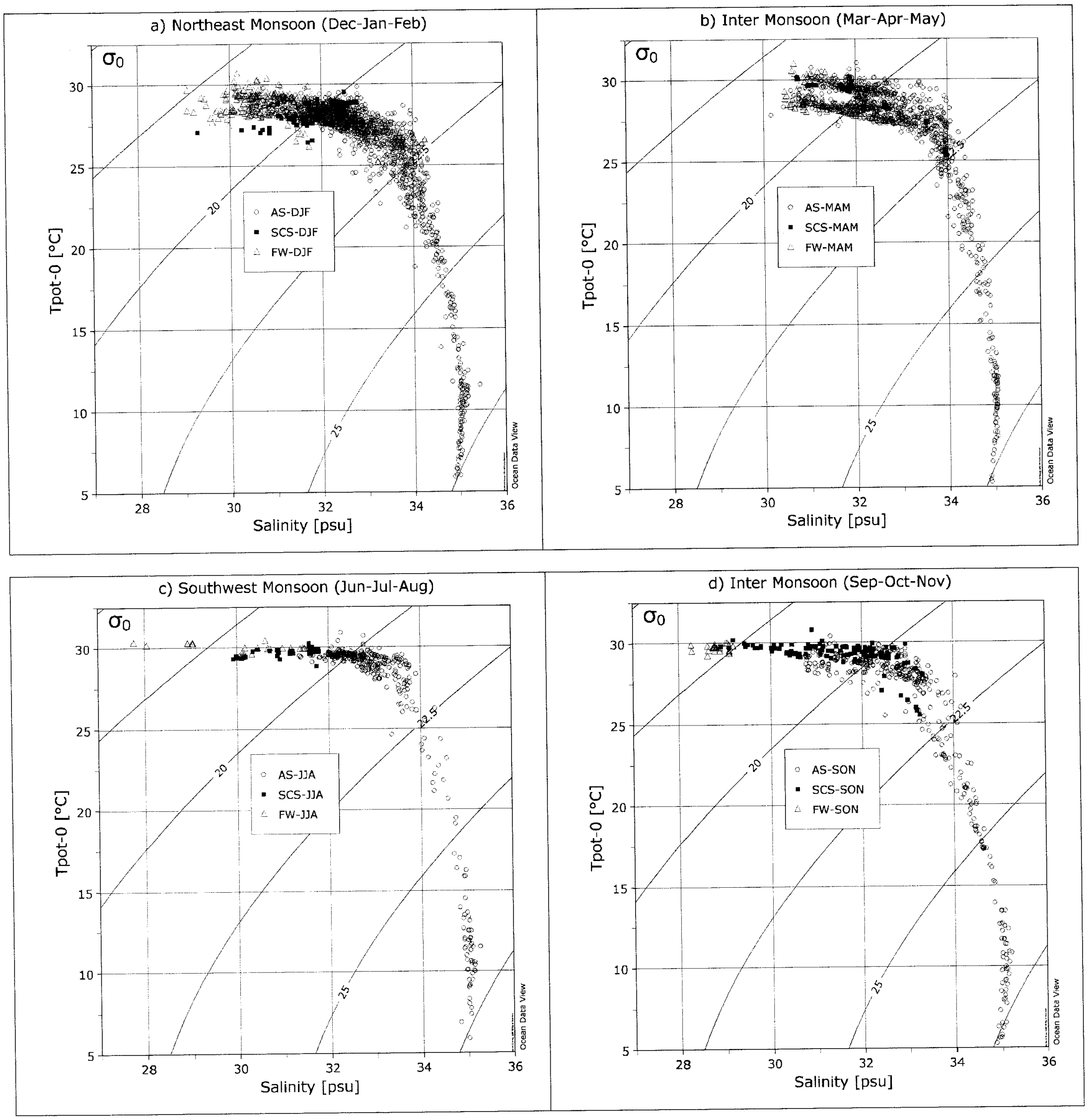

Fig. 5. Seasonal temperature-salinity plot for the Malacca Strait. (a) Northeast Monsoon season. (b) Inter Monsoon season. (c) Southwest Monsoon season. (d) Inter Monsoon season.

5d) of September-October-November. The South China Sea (SCS) water mass is also in retreat. During the Southwest Monsoon, then, the water mass in the Strait is primarily affected by the Andaman Sea (AS) characteristics, while during the Northeast Monsoon the South China Sea (SCS) and the fresh water (FW) input from rivers dominate in the surface waters.

The pattern of variation in water mass in the Strait may be compared to the movement of saline and fresh water in the estuary. At the start of high tide, the sea water will flow into an estuary and push the fresh water further upstream. At the end of high tide, the sea water retreats, flowed by the riverine fresh water flows. In an estuary, the driving force is the tidal elevation which changes the water presuure gradient force along the river channel. In the Malacca Strait the change in the pressure gradient force needs to be coupled to seasonal change. We postulate that the seasonal change is the Monsoon wind and resultant sea surface slope.

We may postulate a wind-driven oscillating pump (Fig. 6) as a mechanism to explain the variation in the movement of the Andaman Sea and the South China Sea in and out of the Malacca Strait. The movement may be generated by the altering pattern of Monsoon winds over the region. Similar mechanism has been proposed to explain the flow of the South China Sea Warm Current (CHAO *et al.*,1995) and the reversal of flows in the Singapore Strait (PANG and TKALICH, 2003). During the Northeast Monsoon the prolonged blowing of strong Northeasterly winds over the South China Sea results in elevated sea levels off the East Coast of Peninsular Malaysia due to wind stress over the South China Sea (YANAGI *et al.*, 1997). Such difference in sea level intensifies the throughflow into the south of the Strait and pushes the Andaman Sea water out of the Strait (Fig 6a) and can contribute to the flow of the North Equatorial Current (TOMCZAK *et al.*, 2003) across the Indian Ocean. Higher rainfall and the resultant higher surface runoff result in low salinity at the water surface in the Malacca Strait. During the Southwest Monsoon, the southwesterly winds blow along the Indian Ocean and across the Andaman Sea. This may result in elevated sea level around the northern end of the Malacca Strait and the Andaman Sea water flows into the Strait. In addition, sea levels along the east coast of Peninsular Malaysia are depressed compared to sea levels along the west coast (YANAGI *et al.*, 1997). These factors would result in the Andaman Sea water intruding further south into the Malacca Strait, causing the Strait water to become more saline. The extreme relative movement of the three water masses after each Monsoon is followed by a period of relaxation in each of the Inter Monsoons. This relative movement over the seasons is illustrated by Fig. 6. Information on the pattern of water mass variations in the Strait can assist in mapping movement of water masses and indicate the movement or transport of materials. This study indicates that in the Northeast Monsoon period the Malacca Strait is strongly influenced by waters from the South China Sea. Thus we may postulate that materials from the South China Sea flow into the Strait during the Northeast Monsoon. During the Southwest Monsoon, the Andaman Sea water enters at least midway into the Strait before retreating during the Northeast Monsoon. Mixing of the Andaman Sea water mass with the South China Sea water mass in the Strait may provide a means of transport of materials from the South China Sea into the Indian Ocean via the Andaman Sea. The fresh water input from rivers into the Malacca Strait may also be transported in this manner. The variation in water mass movement may have implications in terms of transport of pollutants and nutrients through the Strait. This in turn may affect the ecological health of the Strait and have impact on its aquatic resources. A better understanding of the movement of water masses through the Strait can assist in identifying potential resources of pollutants and prioritising which sources need to be managed or controlled first.

4. Conclusion and Summary

Comparison of seasonal variations of water temperature, salinity, and dissolved oxygen in the Malacca Strait indicates the importance of not only the South China Sea but also the Andaman Sea in influencing the movement and characteristics of the Strait water. River flow due to rainfall also appears to introduce significant amounts of freshwater input into the Strait. A wind generated mechanism for the intrusion of the Andaman Sea water in the Strait is proposed. This needs to be investigated further. The possibility of similar effects on other parameters, especially nutrients (LIONG, 1974), could have consequences for the behaviour in fisheries resources in the Strait.

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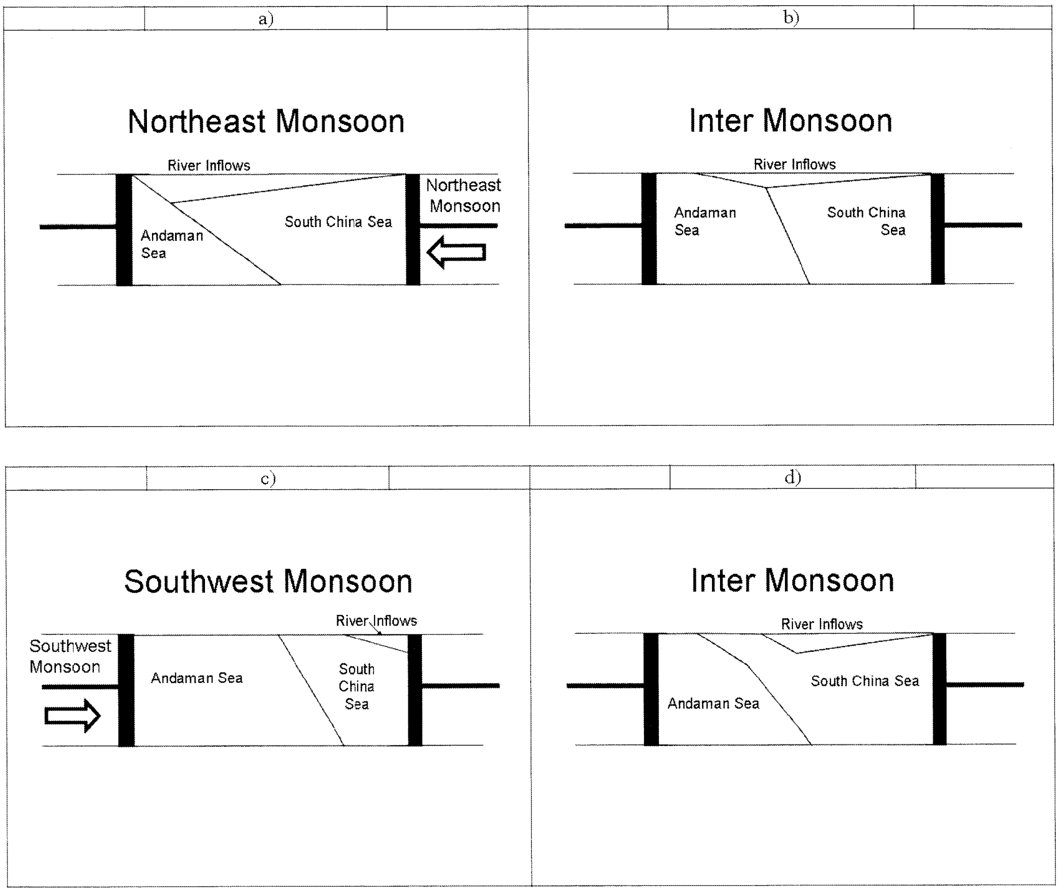

Fig. 6. Proposed mechanism for the seasonal variations observed in the Malacca Strait. (a) Northeast Monsoon season. (b) Inter Monsoon season from Northeast to Southwest. (c) Southwest Monsoon season. (d) Inter Monsoon season from Southwest to Northeast.

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