Movement of Water Across Passages Connecting Philippine Inland Sea Basins

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Date submitted: March 2, 2006; Date accepted: November 6, 2006

ABSTRACT

Advection of Pacific water to the inland seas is through a number of straits bordering the archipelago. Movement of water was demonstrated by temperature-salinity diagrams plotted for a number of stations situated along the various passages. As water from the Pacific flowed through the straits its characteristic T-S profile was modified as it mixed with waters of different properties. This was best seen along the San Bernardino-Verde Island transect where strong surface flow during the NE monsoon resulted in separation of profiles at the surface indicating dilution as water moved away from the source. For deeper water, the erosion of the subsurface salinity minimum and maximum representing the core of the intermediate waters showed transport. These waters were restricted by shallow sill along the eastern coast of the country and limited to a depth of 441m by the sill across the Mindoro Strait.

Keywords: temperature, salinity, water mass, inland sea, T-S profile, water transport

INTRODUCTION

Water masses are identified by their characteristic combination of properties (Pickard and Emery, 1990). From temperature and salinity alone, four different water masses in the upper 1000m (Fig. 1) are found around the Philippine archipelago (Udarbe-Walker et al, 2003; Amedo et al., 2002; Qu et al., 1998; Bingham and Lukas, 1995; Fine et al., 1994). At the surface, warm and fresh water corresponds to the Tropical Surface Water (TSW) that forms at the surface of the Inter Tropical Convergence Zone. A subsurface layer with maximum salinity is equated with the core of the North Pacific Tropical Water (NPTW) and below this the North Pacific Intermediate Water (NPIW) is recognized by its minimum salinity value. The cold deeper layer with increasing salinity towards the bottom

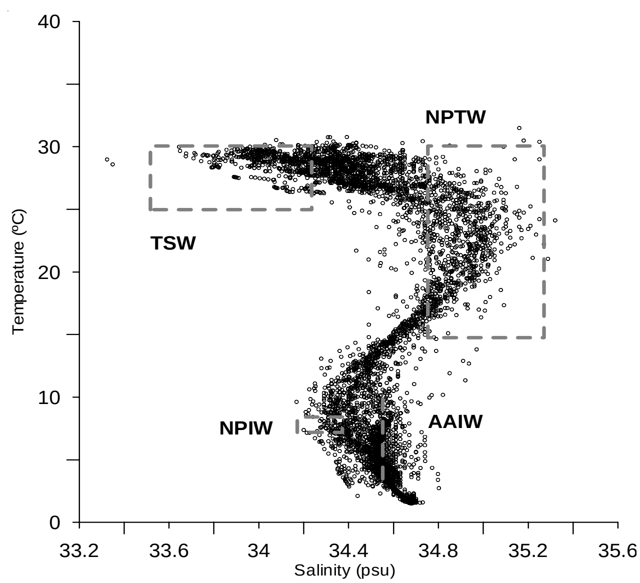

Figure 1. Temperature - salinity scatter plot of water east of the Philippines. Dashed boxes indicate property ranges of the different water mass present in the region. These are the Tropical Surface Water (TSW), North Pacific Tropical Water (NPTW), North Pacific Intermediate Water (NPIW) and the Antarctic Intermediate Water(AAIW).

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is identified with the Antarctic Intermediate Water (AAIW) that moves into the region from the south. Pacific water moves into the inner basins through various passages surrounding the archipelago and flow was inferred from the spatial distribution of properties described in the previous sections.

Temperature-salinity (T-S) diagrams are commonly used in oceanography to trace movement of ocean water (Tolmazin, 1985). As water moves farther away from its source (in this study the Western Pacific) extreme salinity values characterizing the core of the water mass decreases.

Transport of water between basins was inferred from the transition of water property distributions from one basin to its neighboring basin. Based on T-S curves plotted for stations on transects sampled along passages, flow direction and seasonal variation was determined.

METHODS

The Temperature-Salinity (T-S) diagram introduced by Helland-Hansen in 1916 (Sverdrup et al. 1970) was used to identify water masses present in the area and traced its movement from the Pacific to the inland basins. Waterways linking the open ocean to the inner seas were identified. These were the San Bernardino and Surigao Straits along the eastern coast of the Philippines, Sibutu Passage on the southeastern end of the Sulu Archipelago, Balabac Strait off the southern end of Palawan and the Mindoro Strait on the northwest.

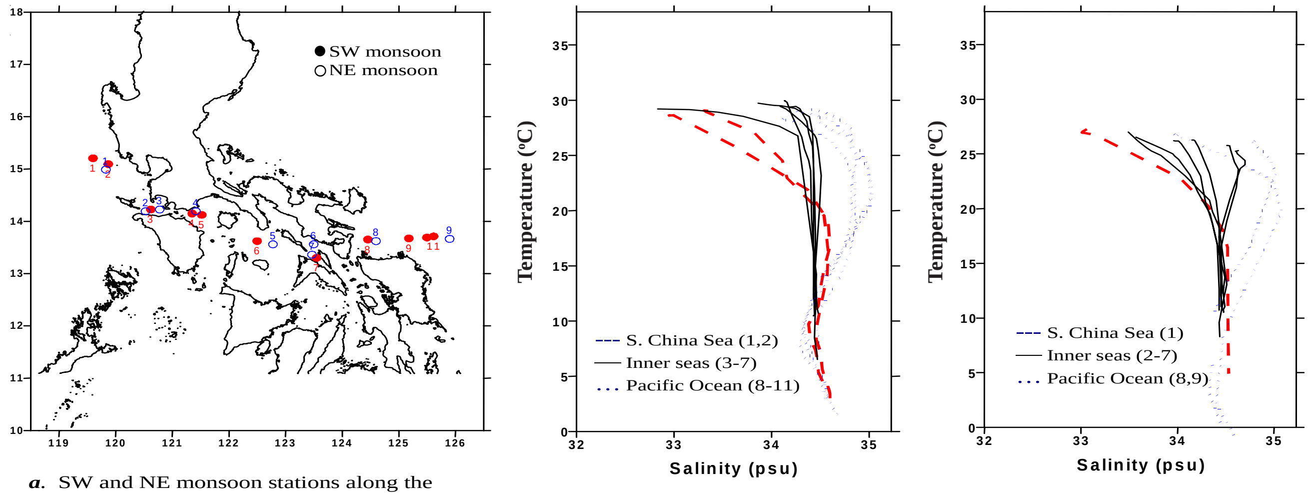
Data was extracted from the Word Ocean DataBase 2001 (Conkright et al 2002) produced by the National Oceanographic Data Center (NODC-NOAA). Water temperature and salinity for stations along the various passages were extracted. Information sampled from single cruises (done within the same year or consecutive months) was preferred. However, in its absence, data from other cruises were used. The data was sorted to season (monsoon) to show variation brought about by prevailing weather patterns. Temperature and salinity were plotted against each other and plots for a particular water way was combined to indicate behavior of the curves with respect to neighboring stations.

RESULTS

Water masses exhibit temperature and salinity characteristics that can identify them as they move in and out of the basins. Profiles for different stations along passages between basins are shown in Figures 2 to 6 with data taken during the SW and NE monsoons designated as b and c, respectively. Little deviation is observed between the seasons except for the surface layer that has relatively higher temperature and slightly lower salinity during the SW monsoon months.

Temperature-salinity profiles across the eastern straits that allow Pacific water access to the archipelago are illustrated in Figures 2 and 3 for the San Bernardino and Surigao Straits respectively. For San Bernardino, data were collected all the way to the South China Sea through the Ticao Pass, Burias Strait, the northern edge of the Sibuyan Sea and the Verde Island Passage. Along this transect four groups representing stations with similar T-S diagrams were noted. The easternmost stations (Fig. 2a stn 8-11) displayed patterns characteristic of Pacific water with relatively high salinity, a subsurface salinity maximum located at 100-200m and a salinity minimum at 400-500m. At the other end of the transect, stations 1 and 2 showed profiles similar to that of the South China Sea with salinity extrema (lower than the Pacific) found between 150 and 200m and a salinity minimum at 500m. Along the waterways linking the San Bernardino to the Verde Island Passage, the remaining stations (3 to 7) had a range of surface salinity values that decreased with distance from the San Bernardino Strait. Temperature-Salinity plots for these stations were near vertical with a wider range of values observed during the NE monsoon (Fig. 2b).

As with San Bernardino, the eastern stations (Fig. 3 stn. 1-2) across the Surigao Strait showed distinct Pacific water characteristics. Salinity maximum and minimum values were observed at 100-150m and 300-500m respectively. West of these, stations located along the shallow Surigao shelf (SW monsoon stn 3-5, no stations for the NE monsoon) can be differentiated from those within the Bohol Sea (stn 5-8). Unlike San Bernardino, where no distinct subsurface salinity maximum and minimum values were observed, high salinity was present in the shallow stations at 50 to

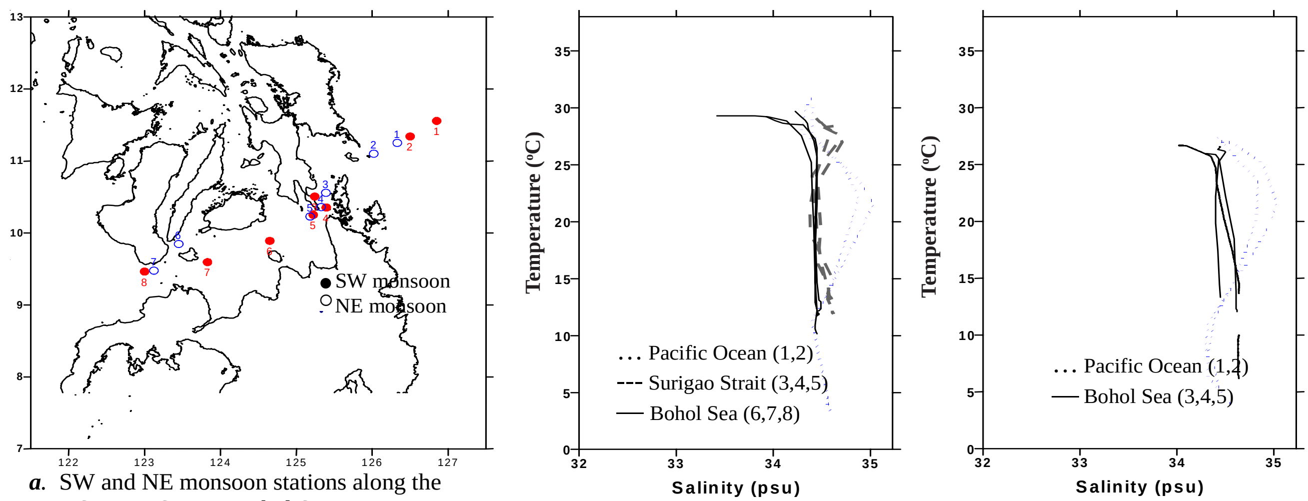


a. SW and NE monsoon stations along the Verde Is. – San Bernardino transect.

b. SW monsoon

c. NE monsoon

Figure 2. Temperature-salinity diagrams for stations along the passage from the South China Sea to the Pacific running through the Verde Is. and San Bernardino Strait. SW monsoon station 1 extracted from cruise WOD98_49003566 (1941); 2,4 WOD98_26000000 (1929); 3,5,6,7 31000586 (1949); 8 WOD98_31008482 (1974); 9 WOD98_49001338; 10 WOD98_49001316 (1965); 11 WOD98_13009650 (1966). NE monsoon stations 1 to 8 from cruise WOD98_31000586 (1949); station 9 WOD98_49003393 (1934).



a. SW and NE monsoon stations along the Surigao Strait – Bohol Sea transect.

b. SW monsoon

c. NE monsoon

Figure 3. Temperature-salinity diagrams for stations along the passage from the Pacific Ocean to the Bohol Sea running through the Leyte Gulf and Surigao Strait. SW monsoon stations 1,2 extracted from cruise WOD98_66001300 (1968); 3 to 5 cruise WOD98_31008482 (1974); 6 to 8 cruise WOD98_31000586 (1949). NE monsoon stations 1,2 from cruise WOD98_66001301 (1969); 3,5 cruise WOD98_32008478 (1974) and station 4 from cruise WOD98_31000586 sampled in 1949.

100m decreasing to a minimum value at 75 to 125m. Beyond this minimum, salinity gradually increased towards the bottom. Across the Bohol Sea no distinct maxima was seen. Instead, salinity increased gradually before dropping monotonically towards the bottom at around 200m. Aside from the usual shift in surface temperature and salinity brought about by the change in season, a significant variation in pattern between SW and NE monsoons can be seen with lower salinity extremes recorded during the NE monsoon.

From the eastern straits Pacific water eventually replenishes the surface waters of the Sulu Sea via the Bohol Sea, Guimaras and Tablas Straits. Access to the Sulu Sea however is not limited to these waterways since three other passages allow movement of Pacific water into the basin. Pacific water feeds the basin by way of the Sulawesi Sea through the Sibutu Strait on the SW tip of the Sulu Archipelago, from the South China Sea via the Mindoro Strait on the north and the Balabac Strait off the SW end of Balabac Is., Palawan. Figure 4 illustrates the T-S curves for transects made across the Sibutu Strait. Influence of Pacific water can be seen from the profiles of the southern stations (Fig. 4b stn. 6-8 and 5c stn. 4) with salinity maximum at 100 to150m and minimum salinity at 300 to 400m. Stations 1 to 3 located in the deeper sections of the Sulu Sea show a gradual increase in salinity with depth while stations 4 and 6 (SW monsoon) on the Sibutu shelf although having the same pattern as the former exhibited lower salinity values.

The northern access to the Sulu Sea and consequently other inland basins is through the Mindoro Strait. The outer stations (Fig. 5b stn.1-2 and 6c stn. 1) show relatively low surface salinity characteristic of South

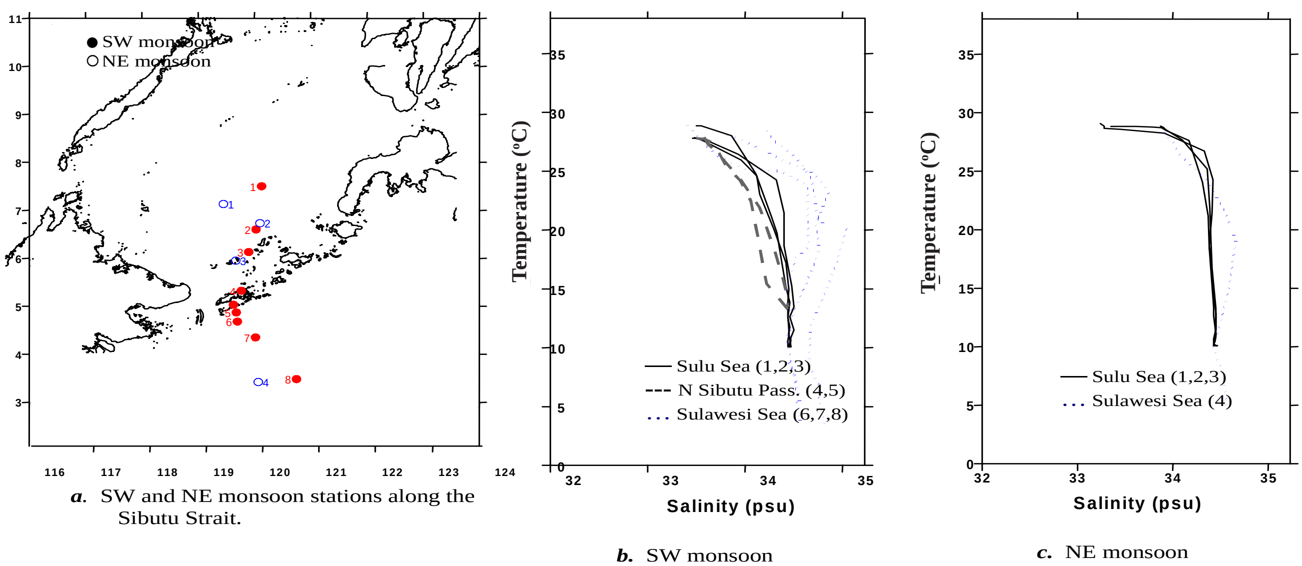


Figure 4. Temperature-salinity diagrams for stations along the Sibutu Passage that links the Sulawesi (south) to the Sulu Sea (north). SW monsoon data extracted from cruise WOD98_64000198 sampled in 1929. NE monsoon stations from cruise WOD98_31000586 sampled 1947.

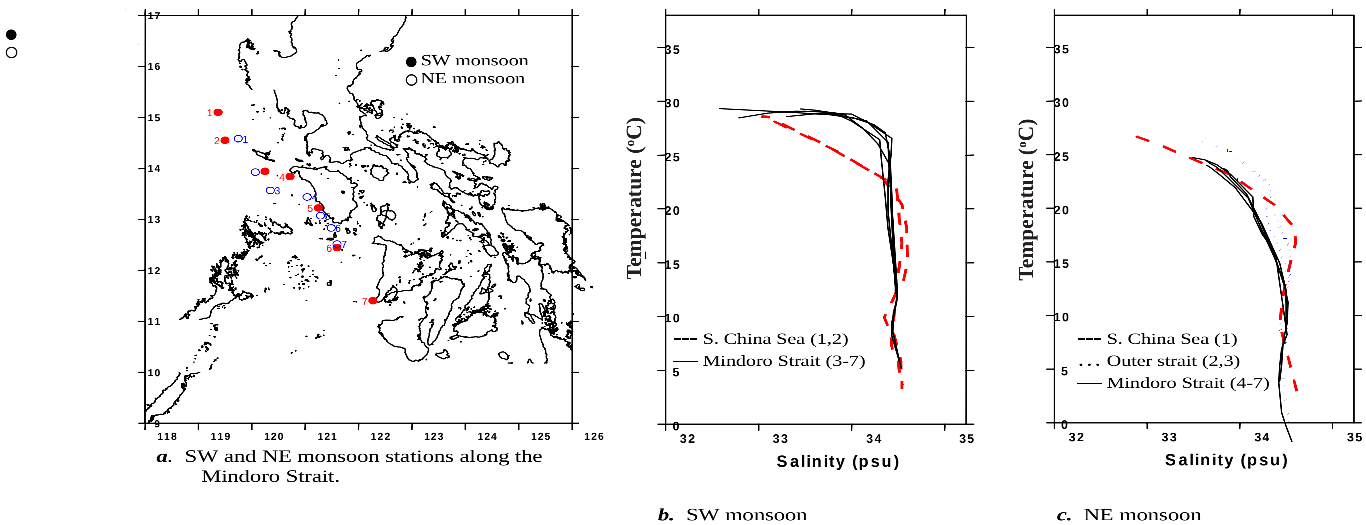
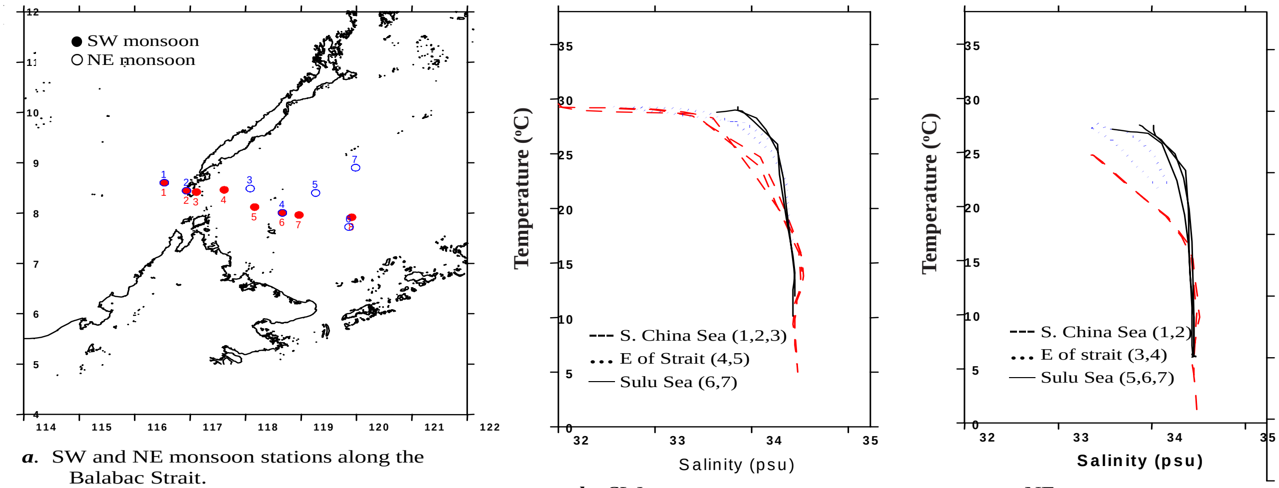


Figure 5. Temperature-salinity diagrams for stations along the Mindoro Strait linking the South China Sea to the Sulu Sea and other inland basins. NE monsoon stations and SW monsoon stations 3 to 7 extracted from cruise WOD98_31000586. SW monsoon stations 1 and 2 samples 1941.



a. SW and NE monsoon stations along the Balabac Strait.

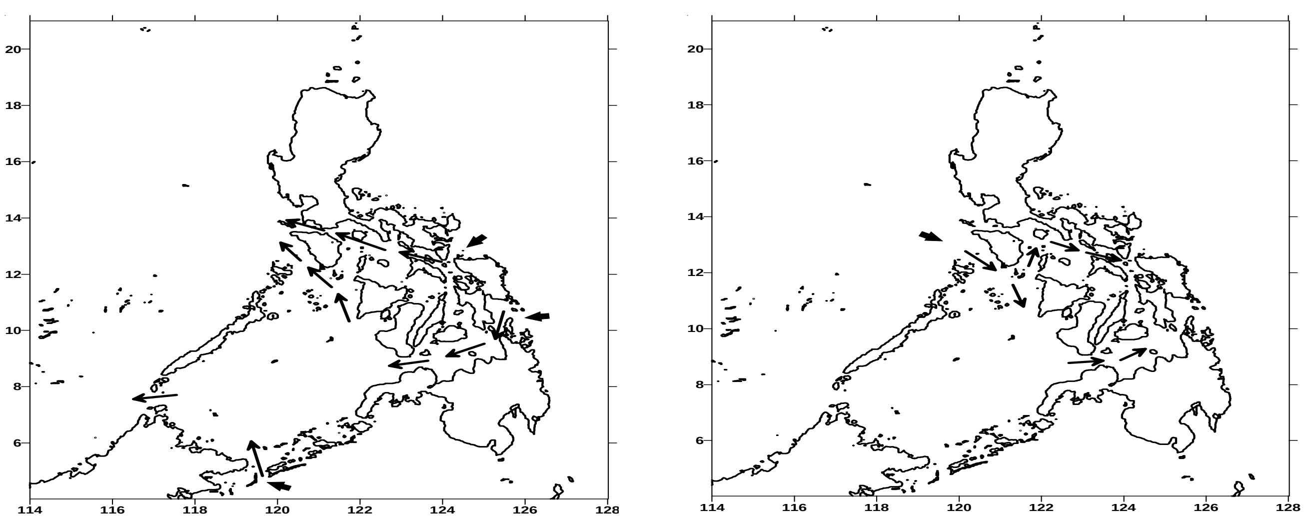
b. SW monsoon

c. NE monsoon

Figure 6. Temperature-salinity diagrams for stations along the Balabac Strait that links the South China Sea to the Sulu Sea. Data extracted from cruise WOD98_31000586. SW monsoon stations. 1, 2 6 sampled in 1949; 3, 4, 5, 8 sampled 1948. NE monsoon stations 1 and 2 sampled 1949; stations 3 to 7 sampled 1948.

China Sea water with maximum and minimum salinity values at 150 to 200m and 400m, respectively. The other stations have maximum salinity at 75 to 100m that dropped almost monotonically to the bottom. The NE monsoon profiles however show a third group of stations (stn. 2-3) with higher surface salinity than the more southern stations indicating a possible alternate source of water. Although the Mindoro Strait is the primary link of water to the inland seas, the Verde Island Passage may have significant input to the surface layer particularly during periods of strong westward flow.

The Balabac Strait SW of Palawan is a relatively shallow passage between the Sulu Sea and the southern section of the South China Sea. Western stations (Fig. 6b stn 1-3 and 6c stn 1-2) show T-S plots typical of the South China Sea with low salinity compared to the Pacific and extreme salinity of 34.48 to 34.52 psu at 200m and minimum value of 34.43 to 34.45 psu at



a. Surface water

b. Deep water below 300m

Figure 7. Inferred net flow of water across the various passages linking the Pacific. Sulawesi and the South China Seas to the inland basins.

400m. East of Balabac, T-S patterns mimic distribution for the Sulu Sea with a near vertical drop from a salinity maximum at 50 to 75m. NE monsoon profiles illustrate decreasing salinity from the central basin of the Sulu Sea towards the Balabac shelf with the vertical profile at station 3 indicating a well mixed column from surface to bottom.

DISCUSSION

The shallow sills along the eastern coast of the country hinder the flow of the intermediate water masses entering the archipelago. The salinity minima and cold deeper layer characteristic of these water masses are therefore absent from the T-S plots across the San Bernardino and Surigao Straits (Fig. 2 and 3). Only the upper layers are present showing decreasing salinity away from the source (Pacific). Decrease in the salinity gradient is more pronounced during the NE monsoon since the flow from the Pacific is strongest this time of the year (Wyrtki, 1961). This is depicted in Figure 2c where a gradient of decreasing surface salinity is observed farther away from the Pacific. In contrast during the SW monsoon (Fig. 2b) the surface salinity gradient is weaker within the inner passages indicating reduced flow from the Pacific. Amedo et al., (2002) observed similar anomalies in the course of their analysis of water characteristics taken from the Ticao Pass and adjacent water ways leading away from the Surigao and San Bernardino Straits. Intense mixing likewise accounts for the homogeneous nature of the water column as shown by the vertical to near vertical behavior of plots west of the straits.

Although unable to flow through the eastern straits, the NPIW is reported to influence the deep water of the Sulu Sea (Quadfasal et al., 1990). This water mass feed the inner basins through the Mindoro Strait from the South China Sea by way of the Luzon Strait. Its subsurface salinity minima can be seen in plots for the outer station of the Verde Is.-San Bernardino (Fig. 2), Mindoro (Fig. 5) and Balabac (Fig.6) transects and can be traced further into the Mindoro Strait at depths of 400 to 500m. As with the eastern straits, shallow sills across the two other passages hinder the flow of deep water to the Sulu Sea.

By tracing the erosion of core properties of water masses, it is possible to infer direction of the general flow through the strait (Wust (1935) as described in Sverdrup, et al., 1970). The high salinity values of the inner stations along the Mindoro Strait (Fig. 5b and c) at shallower depths relative to the outer stations indicate movement of water from the Sulu Sea to the South China Sea. In contrast, below 125m a reverse flow into the Sulu Basin can be inferred by the change in salinities relative to each other. The change in direction between the South China Sea and the Mindoro Strait is due to different forces acting on the water column. At the surface movement of water towards the South China Sea is due to wind stress induced by the monsoons and the prevailing easterlies. Below the surface, the horizontal pressure gradient force due to the difference in density between the South China Sea and the Sulu Sea causes a shift towards the Mindoro Strait. Relatively low density of the Sulu water is the result of turbulent mixing from sill over flow and other lesser-understood processes that might be occurring with the basin.

This behavior is present in both SW and NE monsoons although plots for the SW monsoon aside from being warmer, show a more vertical curve which is associated with intense mixing brought about by the SW winds. The NE monsoon stations 2 and 3 off Mindoro likewise display higher salinity compared to the inner stations (Fig. 5c). This is most likely the result of mixing of Sulu Sea water with water flowing out from the Verde Island Passage. Relatively higher salinity is expected since water from the passage would have traveled a more direct route from the Pacific that has higher salt content. The wide variation in salinity at the surface is due to periodical changes at the frictional layer and is normally disregarded in the analysis (Tolmazin, 1985). Next to the Mindoro Strait, the Sibutu Passage has the deepest sill allowing entry of deep water into the Sulu basin. It connects the Sulu Sea with the Sulawesi Sea that is fed from the Pacific by the Mindanao Current (Qu et al., 1998). As with the Mindoro Strait, direction of flow is inferred by the concentration of core properties. The inference however should be made with caution since the inner stations are also influenced by waters flowing into the basin from other sources (e.g. Balabac, Mindoro, Bohol, etc.). The decrease in salinity from outer to inner station for the column of water down to about the sill depth (275m) shows a general flow towards the Sulu Sea during the SW monsoon.

Conversely, the NE monsoon profile shows a two directional flow with the upper layer to about 125m flowing out of the Sulu basin and the deeper layer moving into the basin. Metzger and Hurlburt (1996) suggest that transport through the Sibutu Passage is associated with the shift in the bifurcation latitude of the North Equatorial Current. The northward migration of the bifurcation latitude towards the end of the SW monsoon (autumn) intensifies transport of the Mindanao Current bringing Pacific water towards the Sulawesi Sea. Transport is reduced in spring (end of NE monsoon) when the bifurcation latitude moves southward (Qiu and Lukas, 1998).

The core of the NPIW can be seen at 400-500m in the Sulawesi Sea stations but it is not clear from the charts whether the NPIW is able to move into the Sulu basin. The large difference in T-S characteristic between the Sulawesi and the rest of the Sibutu transect stations suggests a limited exchange between the Sulu and Sulawesi Seas. This could be due to the location of the Sibutu Strait relative to the eastward flow south of the Sulu Archipelago which transports water from the Pacific to the Sulawesi.

SUMMARY AND CONCLUSION

The movement of water through the various passages linking the open seas with the inland basins was demonstrated by the series of T-S profiles plotted for samples along these waterways. As water from the Pacific flowed through the straits its characteristic T-S profile was modified as it mixed with waters having different properties. Where transport was strong, the gradients between the T-S curves were wider indicating dilution farther away from the source. This was most obvious for the surface layer of the San Bernardino Strait during the NE monsoon (Fig. 2c). Reduced flow during the SW monsoon on the other hand showed a narrower spread of the profiles (Fig. 2b).

Advection of the NPTW and NPIW from the Pacific to the other basins was suggested from the erosion of the subsurface salinity maximum and minimum that indicates the core of these water masses. Restricted by narrow sills across the eastern straits, the NPTW rejuvenates the inland basins through the Mindoro Strait by way of the South China Sea (Fig. 5). The 441m sill across the Mindoro Strait however, prevents lateral flow of the NPIW from feeding the inland basin. Its characteristic salinity minimum is not evident in the T-S profiles of the inner seas.

The net flow of surface and deep water below 300m across the various passages linking the Pacific, Sulawesi and the South China Seas to the inland basins is illustrated in figures 7a and b respectively.

ACKNOWLEDGMENTS

This study is part of the first author's MSc research that looked at how Pacific deep water influences the hydrographic character of Philippine inland seas. Presentation of the paper at the 8th National Symposium for Marine Science was made possible by a travel grant provided by Conservation International.

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