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Seasonal variation in the behavior of tailing wastes in Buyat Bay, Indonesia

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Abstract

Seasonal variations in temperature, salinity, sigma-t and light transmittance were investigated in Buyat Bay, Indonesia, related to the dumping activity there. More than 2000 tons per day of tailings were disposed through a Submarine Tailing Disposal (STD) method at 82 m depth in Buyat Bay. An 80 m depth of the assumed pycnocline was not well confirmed. The seasonal variability of temperature, salinity and sigma-t showed the pycnocline of 40–135 m at the deepest observation station (140 m) during 1997. Furthermore, the Mixed Layer Depth was in good agreement with the wind stress, and the wind stress affected the spreading of tailings there. The outlet of submarine tailing disposal must be below 135 m in Buyat Bay.

Keywords: Buyat bay; STD; Pycnocline

1. Introduction

Buyat Bay is located in Minahasa Regency, North Sulawesi, Indonesia. The bay connects to the Moluccas Sea which is closed in the south by a ridge from Celebes to New Guinea with the islands of Taliabu, Mangole and Obi (Fig. 1a). The region and the bay are influenced by tropical monsoon climate with high rainfall during the northwest monsoon (December to February) and an extended arid season during the southeast monsoon (June to September). The character of the tropical monsoon climate influences the oceanographic condition of the bay.

Very few studies have investigated the oceanographic condition in Buyat Bay, except the mining company report which disposes tailings to the bay and obtained oceanographic data with the purpose of pollution control as emanated by the government. The location which is adjacent to the Moluccas Sea, Buyat Bay is relatively open towards the North Pacific Ocean enabling its water masses a free entrance, while it is closed against the Indian Ocean. Wyrtki (1961) and Gordon et al. (1994) revealed that the most powerful branch of the current in the Moluccas Sea from the western Pacific Ocean was strong during the southeast monsoon and weak during the northwest monsoon. In addition, regarding satellite data, the long term mean local wind, which reaches its maximum in August, drives deeper the surface mixed layer in Buyat Bay and as a result deepens a pycnocline as well.

Safe disposal of mining waste, including tailings, is generally recognized as the single largest environmental disturbance from the mining industry worldwide and a major expense for mining companies. Since March 1996, a mining company, Newmont Minahasa Raya (NMR) started the production and applied the Submarine Tailing Disposal (STD) to discharge about 2000 tons of tailings each day into Buyat Bay. The tailings are disposed through a pipe that runs along 8000 m from the shore into Buyat Bay to a depth of 82 m below the sea surface (Fig. 1b). The company believes that the depth is just 2 m below the acceptable minimum level for STD discharge that is under the pycnocline of 80 m depth.

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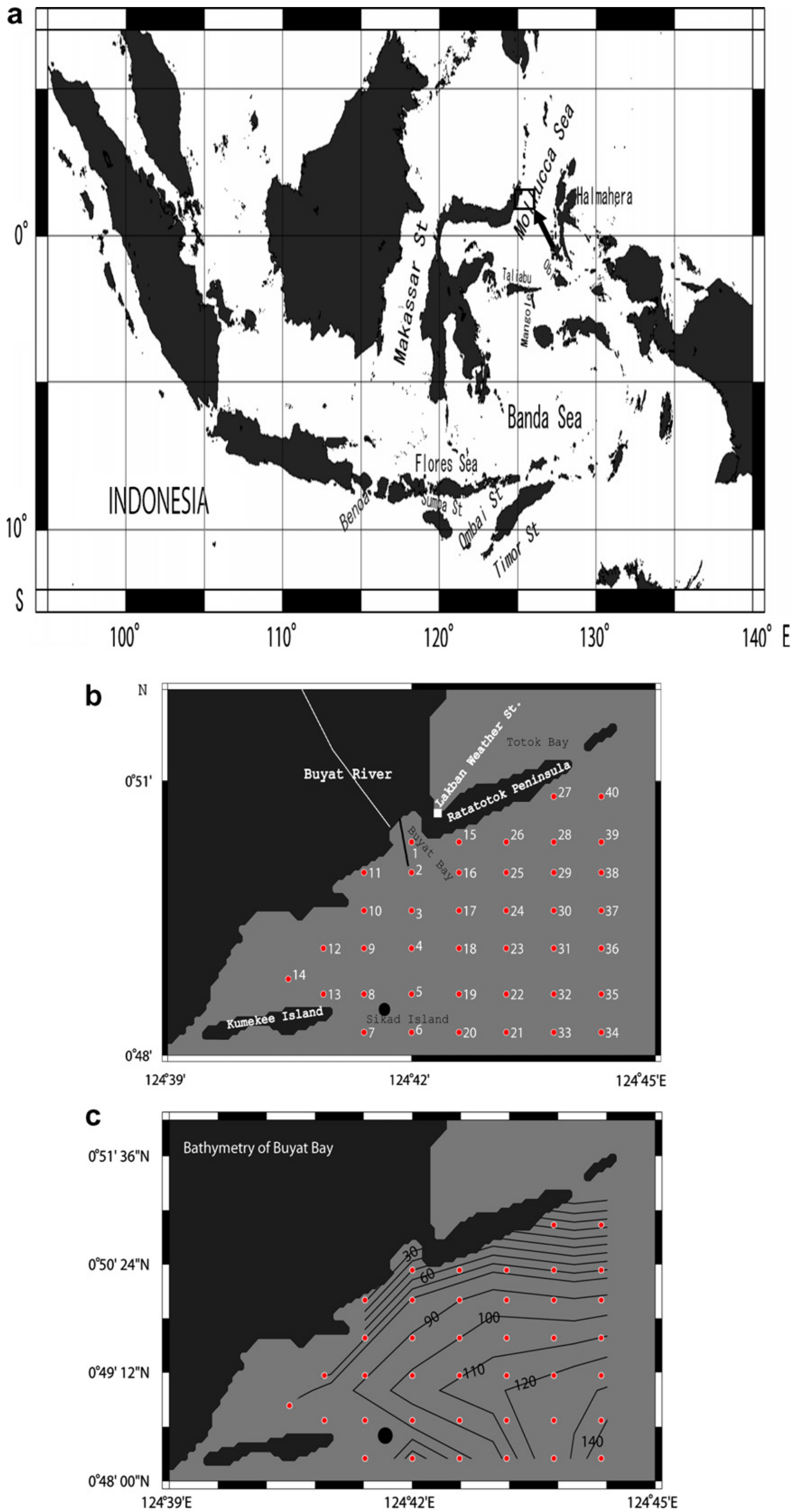

Fig. 1. (a) Indonesia Archipelago and Buyat Bay which is shown by an arrow; (b) observation stations. The thick line across the stations shows the pipeline of the tailing wastes; (c) bathymetry. The numbers in figure show the depth in meters.

Tailings pose environmental threat not only due to their volume but also because of their toxicity which contain sulfides as well as metals such as cadmium, copper, iron, lead, manganese, mercury, silver and zinc. STD is very popular among mining industries in the Western Pacific region such as the Philippines, Indonesia, Fiji, and Papua New Guinea. The aim of STD is to deposit tailings in deep stratified waters where it is likely that the tailings will be trapped below the surface mixed layer and flow as dense slurry to a deposition site on the deep ocean floor. Depositing tailings on the sea floor will be less likely to oxidize and leach out toxic metals due to low oxygen availability and, in addition, marine life at these depths is not so abundant, nor is important to the human food chain.

It is believed that the disposal tailings below the pycnocline (STD) could inhibit the vertical mixing into the surface layer and trapped the tailings below the layer. Hence, STD is safe for the marine life. However, it was found that fish diversity near the discharging area had declined. The number of fish species caught by the fishermen was 59 species before the operation of STD in Buyat Bay. However, it was reduced to 13 species or approximately 22% of the initial condition within 1 year of STD operation. Furthermore, there was a negative impact on the fishing ground of traditional fisherman, in that previ-

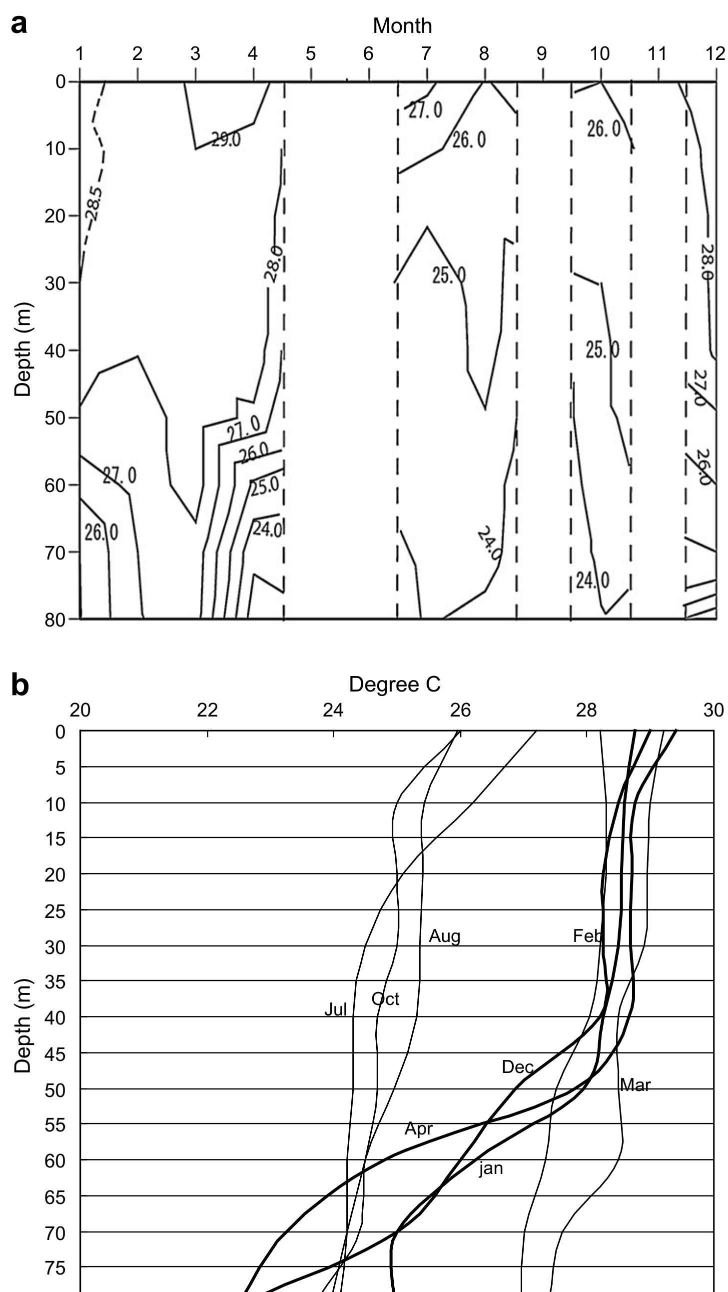

Fig. 2. (a) Monthly vertical distributions of temperature at Station 2 of Buyat Bay in 1997; (b) profiles of temperature at Station 2 of Buyat Bay during January, February, March, April, July, August, October and December 1997.

ously they were able to catch fish within 75 m but recently they have to go further up to 1.2–4.5 km from the coastline. It means that the fishermen have to perform an extra effort and add operational cost to fish offshore (Anonymous, 2000).

Prisetiahadi and Yanagi (2006) studied the distribution of tailings in the southern coastal sea of Sumbawa Island, Indonesia, and claimed that the tailing spread by vertical mixing in the surface layer and by seasonal currents below the pycnocline. The work showed that mean sea level has a marked negative effect on the mixed layer depth (MLD) or pycnocline, that is, the higher mean sea level corresponds to the deeper MLD or pycnocline and vice versa. Furthermore, they suggested that the density gradient criteria to determine the pycnocline was $0.03\ \mathrm{m}^{-1}$, rather more than proposed by Levitus (1982) which varied from 0.01 to $0.125\ \mathrm{m}^{-1}$, and Price et al. (1978) proposed $0.02\ \mathrm{m}^{-1}$.

The present research was undertaken in order to understand the influence of the seasonal variability of ocean environment at the dumping site on the fate of the tailing wastes there. Discussions on temperature, salinity, and sigma-t for seawater stratification, on light transmittance related to the detection of tailing plumes were conducted.

2. Observations

The observations were carried out monthly at 40 stations (Fig. 1b) in the study area during the year 1997 except for May, June, September and November with no data. The bathymetry of the observation area (Fig. 1c) ranged between 10 m and 140 m and station 34 is the deepest station. The data were obtained by using a CTD (Conductivity, Temperature and Depth profiler) with transmissometer for the vertical profiles of water temperature, salinity and light transmittance. Sigma-t was calculated from water temperature and salinity using the usual state equation.

Monthly wind data, heat flux (sensible, shortwave, long wave and latent), precipitation and relative humidity were obtained from NOAA-CIRES climate diagnostics center which covers the study area of 124–126°E, 0.5– 2°N (http://www.cdc.noaa.gov/cdc/reanalysis/reanalysis.shtml). Rainfall data were obtained from Lakban Port meteorology station near the study area (see Fig. 1b).

Net heat flux (Q_s; W/m^2) calculated by using the bulk formula (Yanagi, 1999) as follows:

$$Q_s = Q_A - Q_B - Q_e - Q_h$$

where Q_A denotes the shortwave radiation from the sun, Q_B long wave radiation from the ocean, Q_e latent heat

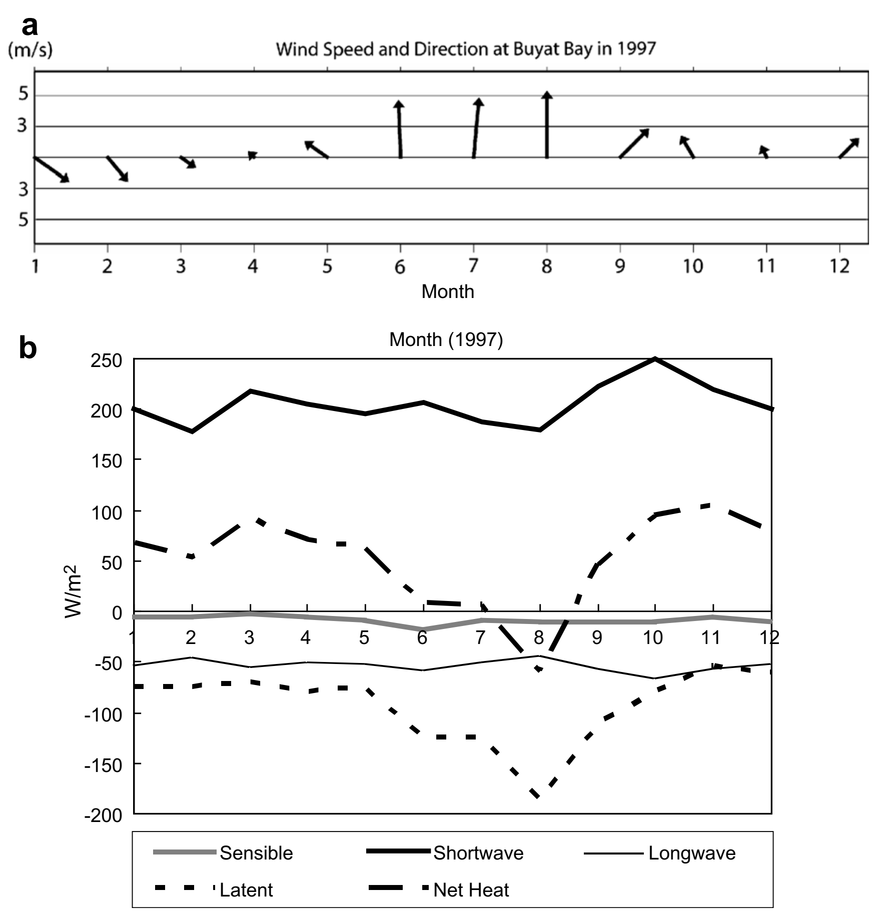

Fig. 3. Wind speed and direction (a) and heat flux (b) over the area of Buyat Bay (124–126°E, 0.5–2°N) obtained from NOAA-CIRES climate diagnostics center in 1997.

transfer due to evaporation and Q_h sensible heat transfer due to heat diffusion.

Meanwhile, evaporation (E) was estimated (Yanagi, 1999) by

$$E = k(E_s - E_a)W$$

where k denotes the evaporation coefficient (=0.17 mm day^{-1} hPa^{-1} m^{-1} s; Ishizaki and Saitoh, 1978), E_s and E_a the saturated moisture pressure at the sea surface in hPa and the moisture pressure in the air in hPa, respectively, and W is wind in m s^{-1}. Then, saturated moisture pressure over water could be estimated through the sea surface temperature.

3. Results and discussion

3.1. Temperature

The observed vertical profiles of water temperature at Station 2, which is the nearest station to outlet of STD, are shown in Fig. 2a. The sea surface temperature (SST) in Buyat Bay ranged between 25.7 °C in August and 29.8 °C in April in 1997 (Fig. 2a). The largest net heat flux in October (Fig. 3b) has a phase lag of about π/2 to the warmest SST in April.

From Fig. 2a, the sea water temperature stratification was observed during January to April with high SST (28.5–29.5 °C) at the surface layer, about 28.0 °C at

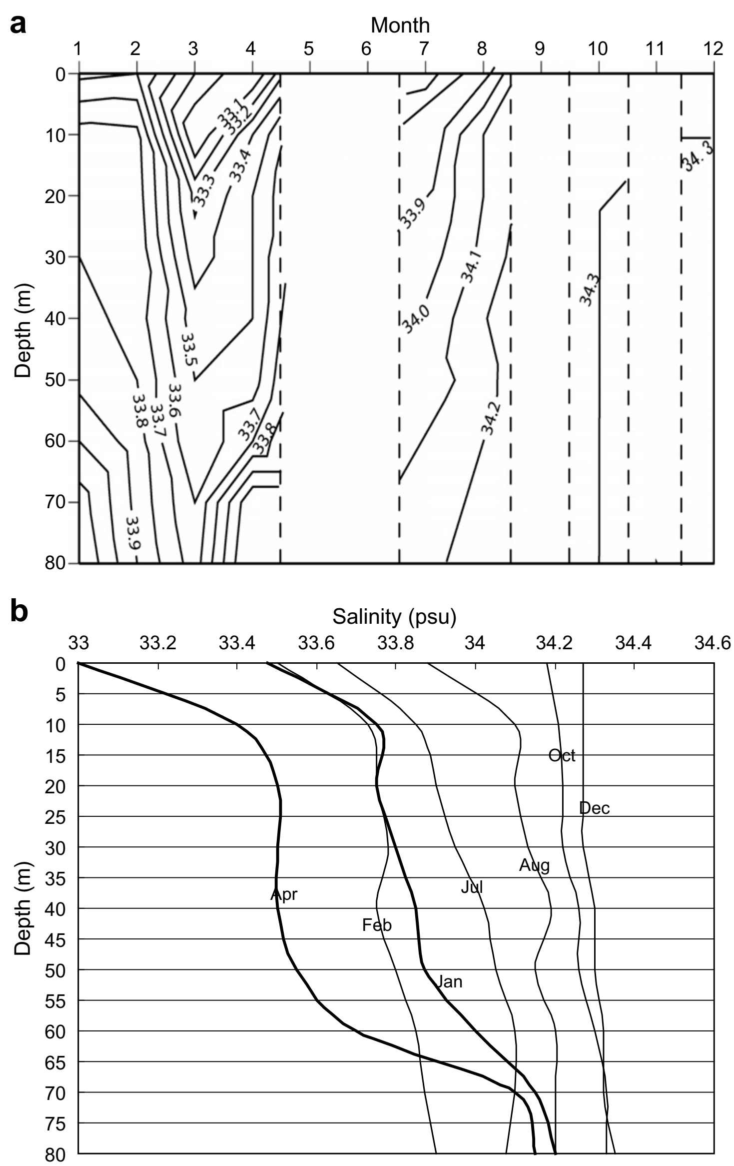

Fig. 4. (a) Monthly vertical distributions of salinity at Station 2 of Buyat Bay in 1997; (b) profiles of salinity at Station 2 of Buyat Bay during January, February, March, April, July, August, October and December 1997.

45 m depth and about 27.0–24.0 °C between 55 m and 80 m depth. While, during July to October no stratification existed and a low SST (26.0 °C to 27.0 °C) was observed at the surface. A thermocline, which is recognized by rapid decrease of temperature, was between 50 m and 70 m in January, 45 m and 75 m in April and 40 m and 80 m in December, but there was no thermocline in July (Fig. 2b) when the strong south wind blows (Fig. 3a).

3.2. Salinity

The sea surface salinity (SSS) is controlled primarily by the balance between evaporation and precipitation. A low salinity occurs due to rain and river discharge. SSS in Buyat Bay was between 33.0 psu and 34.3 psu (Fig. 4a). The highest SSS was in December and the lowest was in April. It was observed that SSS was high, 34.0 psu, during July to August, meanwhile, SSS was low, 33.0–33.5 psu, during January to April (Fig. 4a). Regarding the data of precipitation (P), evaporation (E) and ($P - E$), recorded near the study area (Fig. 5), the months with low SSS indicated a large ($P - E$), but the months with high SSS indicated a negative ($P - E$). Having studied the vertical profile of salinity as shown in Fig. 4b, the definition of the halocline could be easily obtained from the graph. Only April showed the existence of a halocline, at depths of 0–10 m and 50–70 m, while in January it was at depths of 50–70 m. The deeper halocline could not be found in the rest of the months and salinity was homogenous in the whole layer in October and December.

3.3. Sigma-t

Since the density of sea water depends on temperature and salinity, all processes that alter temperature or salinity influence the density. At the surface, the density is decreased by heating and rainfall and increased by evaporation. Seasonal variability of sea surface density (SSD) showed less dense seawater during January to April (20.5–21.0) and increased from July to October (21.5–22.0) (Fig. 6a).

Furthermore, the distribution of the density of the ocean waters is characterized by vertical stratification. During January to April, sigma-t was between 21.5 and 23.0 at 50–80 m depth, whereas during July to December sigma-t was between 22.5 and 23.0 at 50–80 m depth (Fig. 6a).

It was observed that August had the heaviest SSD due to lowest SST and high SSS. The seasonal density variability is mainly dominated by the water temperature (Figs. 2a, 4a, and 6a). It indicates a bigger influence of temperature compared to salinity in defining sigma-t value. In addition, stratified seawater occurred during January, April and December but not during July and August (Fig. 6c). The strong stratification was observed during April when strong thermocline and halocline developed.

3.4. Pycnocline

Heat conduction to the lower layer by seawater itself is extremely slow, so only a small proportion of heat is transferred downward by this process. The main mechanism of transferring heat to deeper part near the sea surface is turbulent mixing by winds and waves, which establishes a

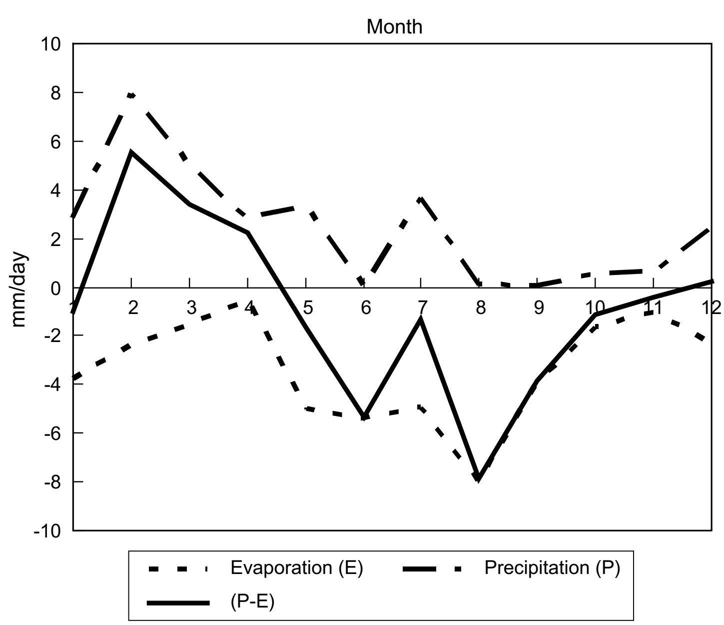

Fig. 5. Precipitation over evaporation in the area of Buyat Bay (124–126°E, 0.5–2°N) obtained from NOAA-CIRES climate diagnostics center in 1997.

Mixed Layer Depth (MLD). The homogenous layer or MLD has been defined in the literature by a number of criteria, depending on objectively prescribed degree of homogeneity of the mixed layer properties. The simplest and the most traditional method is the temperature difference (relative to the sea surface) which varies from 0.02 °C to 1 °C. Levitus (1982) used the vertical gradient of 0.006–0.1 °C m^{-1} or the maximum curvature in temperature profile. However, the most trustworthy way in defining MLD is by using the density difference (or its gradient) which should be resulted from the combined temperature and salinity effects on vertical stratification. In this regard, Levitus (1982) suggested that the density difference criteria vary from 0.01 to 0.125 m^{-1}, while Price et al. (1978) proposed 0.02 m^{-1}, and Prisetiahadi and Yanagi (2006) applied 0.03 m^{-1}. Here, 0.03 m^{-1} will be utilized in the present research to define the lower limit of MLD or the top of pycnocline. The top of the pycnocline was defined based on the sigma-t profile which showed rapid increase of sigma-t gradient (Fig. 6b and c). The rapid increase of sigma-t gradient in the upper 25 m is considered as sub pycnocline which is not our research concern and the major pycnocline, that is below 40 m, is investigated in this paper.

Having made the analysis based on the 0.03 m^{-1} criterion and rapid increase of sigma-t gradient, the pycnocline layer was at about 54–75 m in January, 67–75 m in March, 50–80 m in April, 54–65 in October, and 46–80 m in December at Station 2 in the study area (Fig. 6b and c). Moreover, the maximum sigma-t gradient was exhibited at 62 m in January and April, 70 m in March, 60 m in

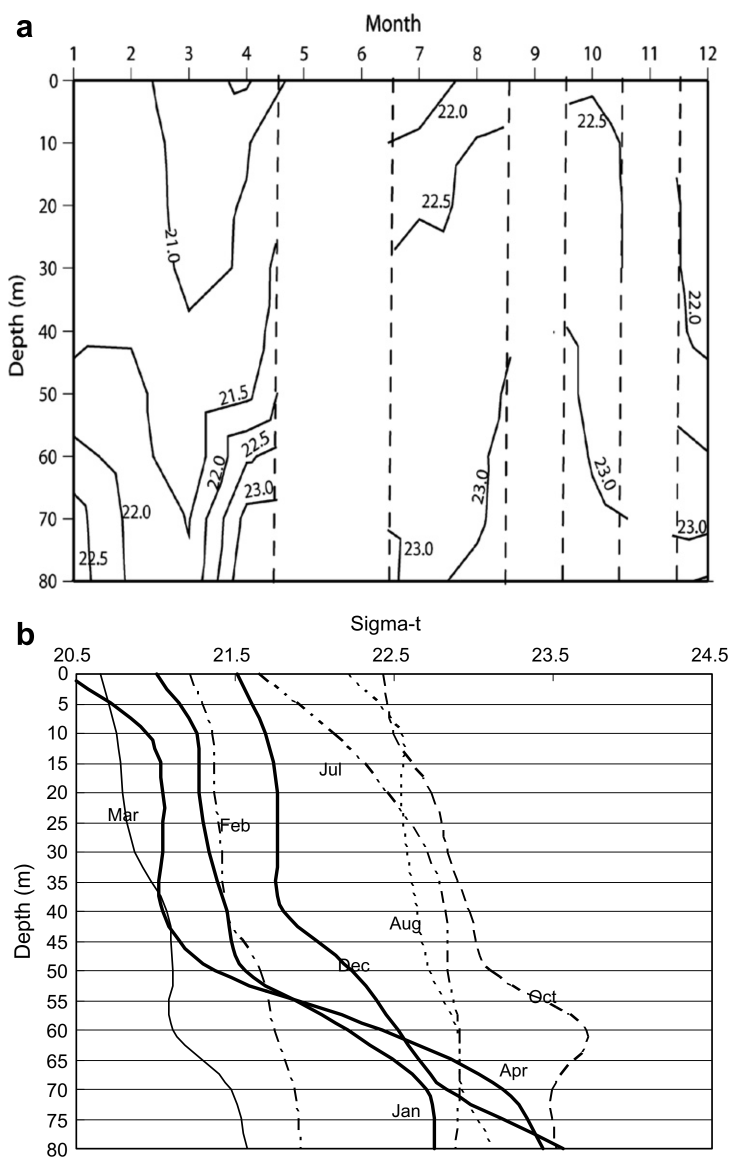

Fig. 6. (a) Monthly vertical distributions of sigma-t at Station 2 of Buyat Bay in 1997; (b) profiles of sigma-t and (c) sigma-t gradient at Station 2 in January, February, March, April, July, August, October and December 1997.

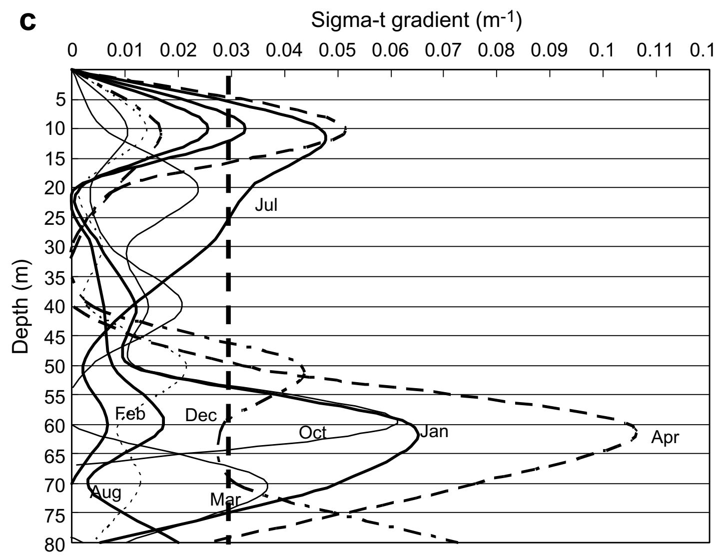

Fig. 6 (*continued*)

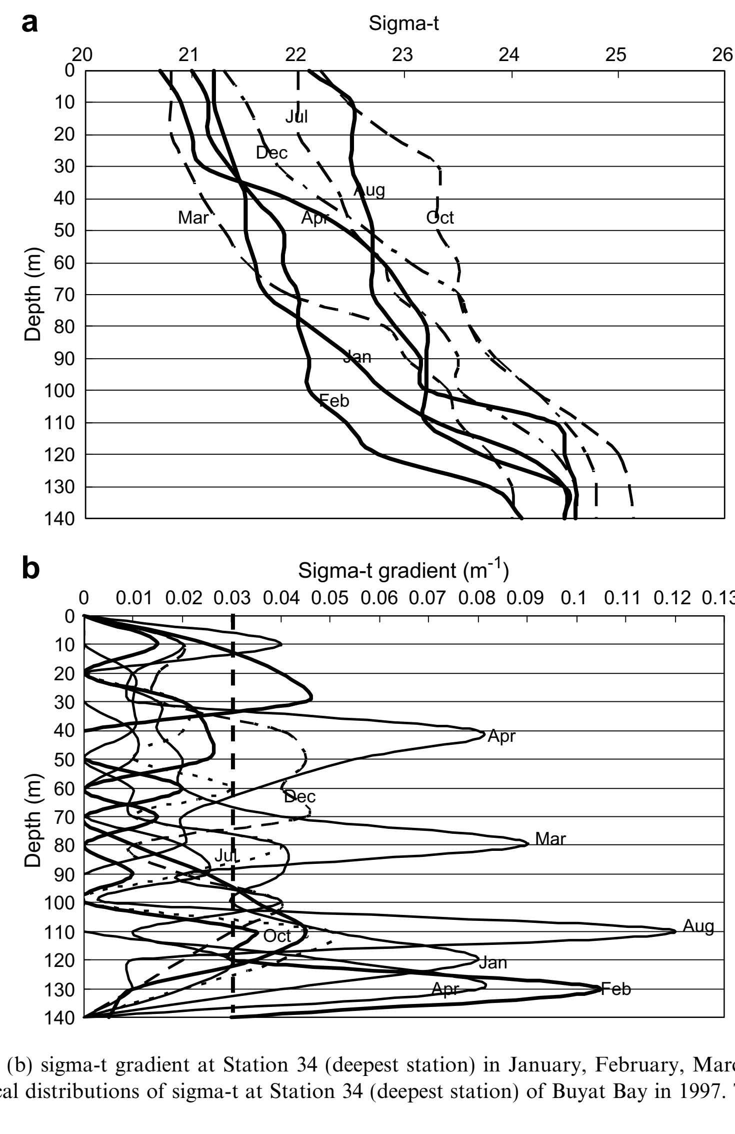

Fig. 7. (a) Profiles of sigma-t and (b) sigma-t gradient at Station 34 (deepest station) in January, February, March, April, July, August, October and December 1997; (c) monthly vertical distributions of sigma-t at Station 34 (deepest station) of Buyat Bay in 1997. Thick dash lines indicate the top and bottom of pycnocline.

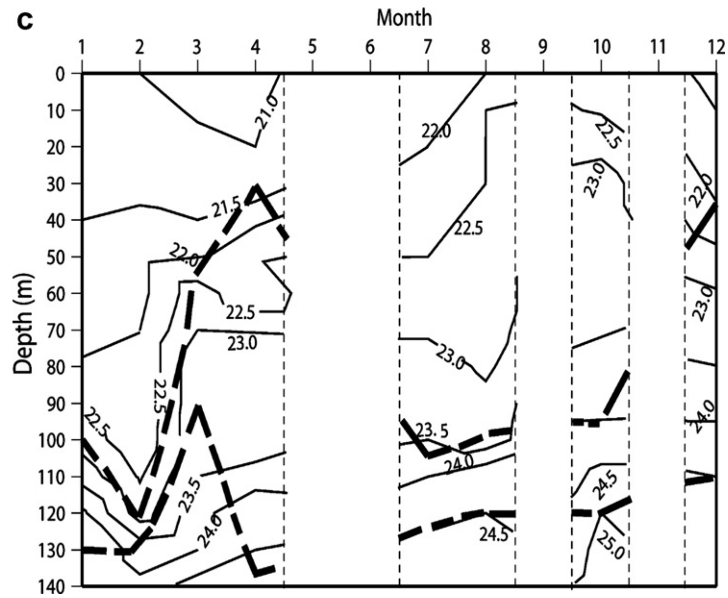

Fig. 7 (*continued*)

October and 80 m in December at Station 2 (Fig. 6c). The investigation of the seasonal variation in the pycnocline at Station 34 (deepest station) was conducted, because the major pycnocline in July and August could not be found at Station 2. Monthly sigma-t profiles at Station 34 are shown in Fig. 7a. At this deepest station, a major pycnocline was found in all months. The pycnocline was exhibited approximately at 100–130 m in January, 120–135 m in February, 65–90 m in March, 35–60 m and 120–135 m in April, 105–125 m in July, 100–120 m in August, 95–120 m in October, and 35–75 m and 95–110 m in December (Fig. 7a and b). In addition, the maximum gradient of sigma-t was found at 120 m in January, 130 m in February, 80 m in March, 40 m in April, 110 m in July, August and October and 70 m in December (Fig. 7b). The seasonal variation in the top of pycnocline shown in Fig. 7c was in well agreement with the wind speed near the study area, that is, the stronger wind speed lead to more vertical mixing and the pycnocline deepening: about 3 m s^{-1} and 100 m MLD in January, 0 m s^{-1} and 30 m MLD in April, 5 m s^{-1} and 100 m MLD in August, and 2 m s^{-1} and 30 m MLD in December (Figs. 3a and 7c).

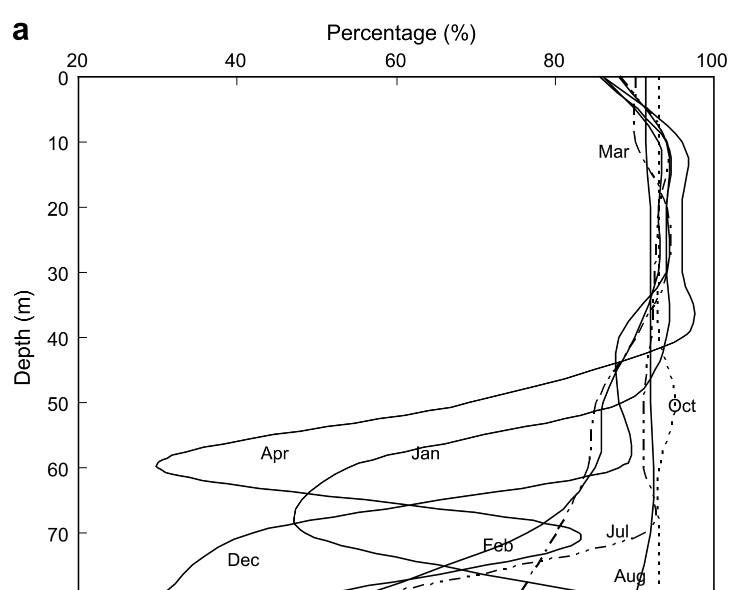

Fig. 8. (a) Profiles of light transmittance (%) at Station 2 in January, February, March, April, July, August, October and December 1997; (b) vertical distributions of light transmittance (%) along Stations 1–6 in January, February, March, April, July, August and December 1997; (c) monthly vertical distributions of light transmittance (%) at Station 2 of Buyat Bay in 1997, and the position of top of pycnocline and the center of tailing waste plume; (d) horizontal distributions of light transmittance (%) in January, April, July and December 1997. Dash lines indicate an area below 80% of light transmittance.

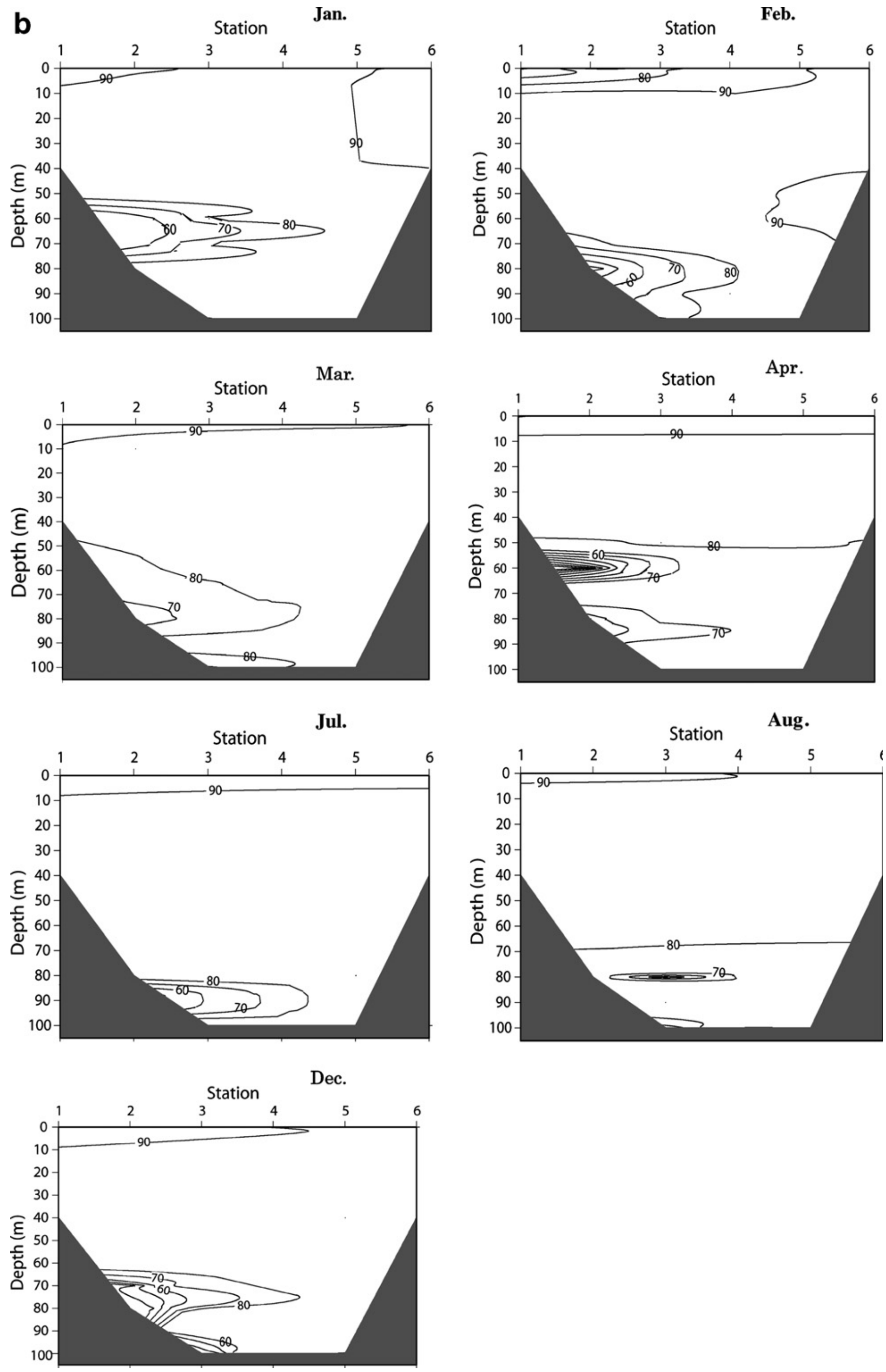

Fig. 8 (*continued*)

From Fig. 7c, the seasonal variation in the top of pycnocline is clearly shown. It gives an impression that during the transition periods, March to May and November to December, an unstable and weak wind stress resulted in a shallower pycnocline. On the other hand, July to October had a strong and stable south wind which resulted in a deeper pycnocline.

3.5. Light transmittance

Low light transmittance (LT) corresponding to high particulate concentration in the seawater can be used to track the tailing wastes. The investigation on the LT profile was conducted (Fig. 8a). The similar pattern exhibited in relation to MLD or pycnocline (Fig 6b) during January,

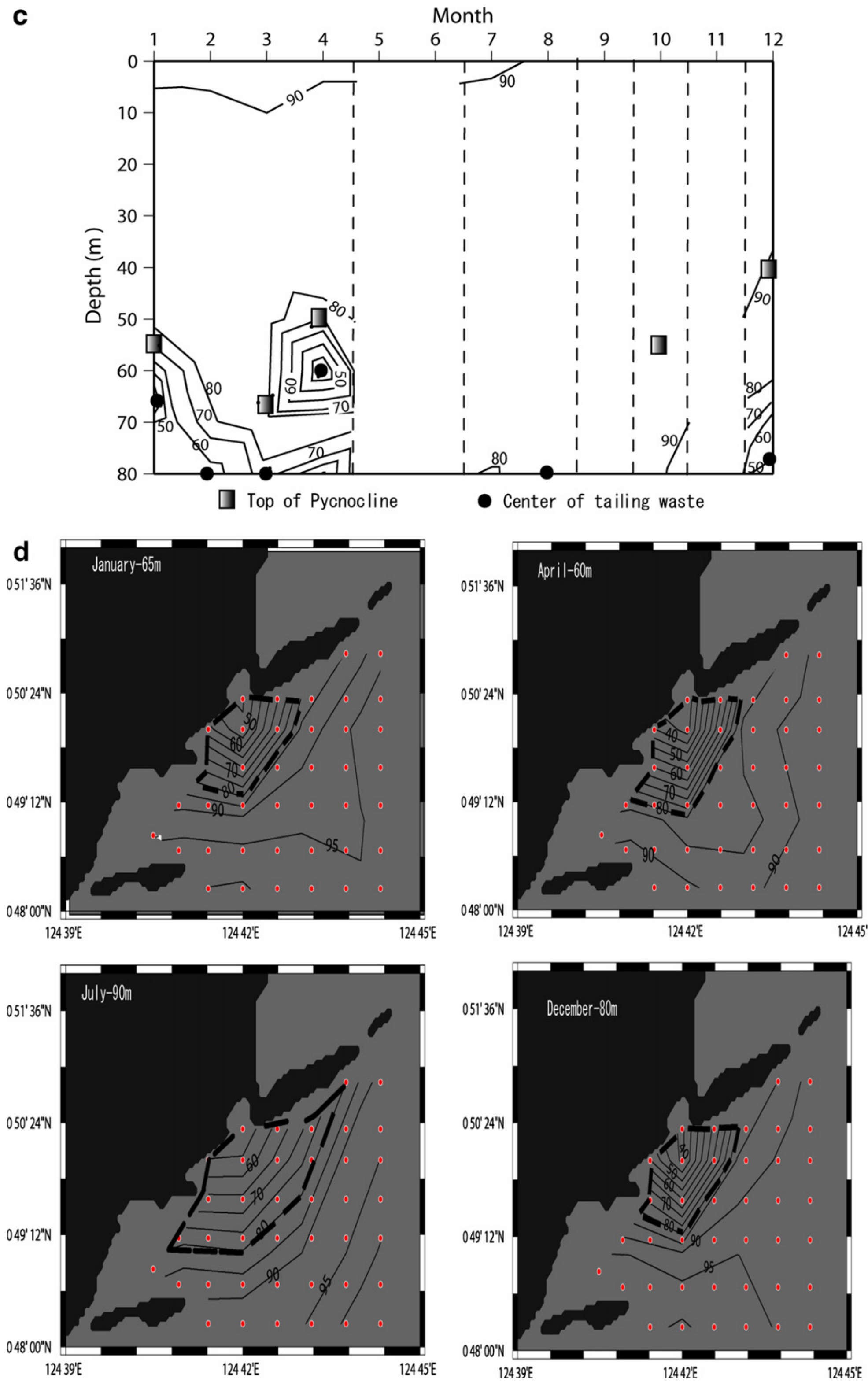

Fig. 8 (*continued*)

April, July and December. In the upper layer or MLD, LT was absolutely high, meanwhile along the pycnocline LT was found to be very low. The low LT or high concentration of tailing wastes in the lower layer indicated no vertical mixing with the upper layer in January, April and December. However, low LT was not detected in other months when no sharp pycnocline existed at Station 2 (Fig. 6b and Fig. 8a).

Vertical distributions of LT along Stations 1–6 in January, February, March, April, July, August, and December are shown in Fig. 8b, however we could not obtain LT data in October 1997. From Fig. 8b, tailing wastes were not observed at the surface except in February due to high precipitation (Fig. 5). Then, it was observed that tailing plumes were detected in various depths during the year, 65 m in January, 80 m in February, March, August and December, 60 m in April, and 90 m in July.

Seasonal variability of tailing wastes in the study area was well correlated with the seasonal variability of density. A well stratified seawater in January, April and December prevented tailing wastes from being mixed in the water column and stayed below pycnocline (>55 m in January, >50 m in April and >40 m in December) as shown in Fig. 8c. When the top of pycnocline existed below 82 m at Station 2, the center of the tailing existed at 80 m or below, while the top of pycnocline existed above 82 m at Station 2, the center of tailing existed 10 m or 35 m below the top of pycnocline.

Horizontal distributions of LT were investigated at different depths in January (65 m), April (60 m), July (90 m) and December (80 m) associated with low LT detected from the vertical distribution at Station 2, where the outlet of the disposal pipeline is situated (Fig. 8d). High concentration of tailing wastes (below 80% of LT) was spreading up to Station 4 southward in all months and extended over up to Station 27 to the north-east from the outlet (Sta. 2) in July and up to Station 26 in January, April and December. In addition, it was spreading south-westward till Station 12 in July. Based on these facts, July had the widest area of high concentration of tailing wastes compared to January, April, and December. It may be due to that July had the strongest south wind which might have generated the southward current in the subsurface layer.

It is indispensable to find a permanent pycnocline near the study area for better practice of STD. If the disposal tailing wastes under the bottom of permanent pycnocline, it would be safe throughout the year because no vertical mixing occurred as a result of strong barrier which inhibits water movements. STD in Buyat Bay must be carried out below 135 m from Fig. 7c.

4. Conclusion

Seasonal variation in temperature, salinity and density were investigated at Buyat Bay in relation to the monsoon. The most important finding in the present results was the existence of pycnocline at deepest station between 40 m and 135 m. The pycnocline development was related to the wind stress and it influenced the spreading of tailings. The outlet at 82 m depth should not be presumed as a safe disposal site as applied by the mining company because of the existence of a deeper pycnocline in Buyat Bay. The finding of a permanent pycnocline as a disposal site of tailings should be prominently encouraged as the best solution. In this regard, at least 135 m depth should be considered as the bottom of permanent pycnocline that would be safe for STD operation in Buyat Bay. This finding would be well informed to the Ministry of Environment of Republic of Indonesia for better application of a safe STD in the current site in the future.

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