Mixing Stages of Water Masses in the Western Equatorial Pacific

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Abstract

The mixing stages of water masses in the western Equatorial Pacific are examined by the aid of T–S curves for 370 stations. The original water types related to the region under consideration are determined from materials excluding those of stations in an area between 13°N and 3°S. T–S curves for stations located between 13°N and 3°S can be classified into five groups according to the pattern or mixing stage, corresponding to five geographical divisions nearly parallel to the latitude. The mixing ratio between water types in five divisions are determined. The boundary zone between the water masses from the north and the south is on ca. 6°N, where salinity is roughly homogeneous with depth. The latitudinal change of T–S curves are shown by the aid of average curves for every two degrees of latitude (Fig. 6).

1. Introduction

It is a well-known fact that the three water masses, the western North Pacific Central water mass, the Equatorial Pacific water mass, and the western South Pacific Central watter mass, meet in the western Equatorial Pacific and the mixing stages are complicated. The general feature of the hydrographical conditions in this region is discussed by Takahashi (1959) using materials obtained by the Kagoshima-maru and the Keiten-maru in oceanographic surveys which were performed yearly between 1952 and 1956 including EQUAPAC and IGY projects, but the mixing stages of water masses are not discussed in detail. In past days, the water masses north of the Equator were analyzed by Koenuma (1937) with T–S curves derived from the materials obtained by the Mansyu. In the present paper, the water masses and the pattern of mixing in the western Equatorial Pacific will be discussed by the aid of T–S curves depicted from a number of materials. These materials have been obtained from the expeditions performed by the following vessels: Kagoshima-maru and Keiten-maru of Kagoshima University in 1952–1959: Kosyu, Katuriki, and Komahashi of the Imperial Japanese Navy Hydrographic Department in 1936–1937; Orsom III of the Institut Francais D'Oceanie in 1956–1958; Snellius of the Netherlands Hydrographic Department in 1929–1930. From these surveys, 370 stations are conveniently picked up, as shown in Fig. 1. Making use of these materials, the mixing stages of water masses are examined, although the deep water can not be discussed on account of the shortage of deep water observations.

2. Original Water Types

In the tropical region of the North Pacific, a temperature-salinity curve has an inverted form of the letter 'S' characterized by a salinity maximum at a depth of ca. 100–150 m and a salinity minimum at a depth of ca. 500–600 m; the former corresponds to the upper water and the latter to the subarctic intermediate water. Koenuma (1937) is of the opinion that the origin of the upper water is found on the surface around 20°–30°N and 160°–180°E and that it is transported to Saipan Island area by the northeast trade wind, sinking to ca. 100–150 m due to high density. Among the present selected data, several materials obtained at stations located between 20°N and 13°N are plotted in Fig. 2a & 2b. At a depth of 100–150 m the water around ca. 15°N (Fig.

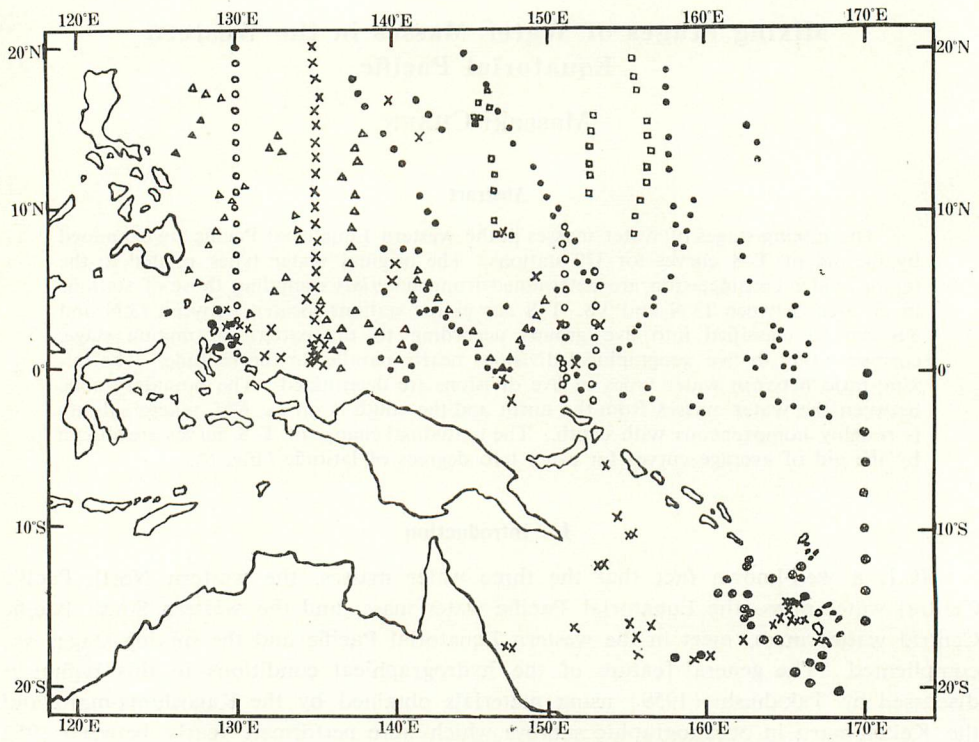

Fig. 1. Map showing the stations. Symbols: circles, Kagoshima-maru; crosses, Keiten-maru; triangles, Katuriki; dots, Kosyu; squares, Komahashi; cirles including crosses, Orsom III; circles including triangles, Snellius.

2a) shows higher maximum of salinity than that around ca. 20°N (Fig. 2b). This fact seems to suggest that the original water type of the salinity maximum is located rather nearer to the former than to the latter on account of the extending direction. As shown in Fig. 2a, the mean values of the temperature, T, and of the salinity, S, of the upper water are ca. 24.6°C and ca. 35.33‰ respectively. On the other hand, the subarctic intermediate water of low salinity sinks at the subarctic convergence and extends toward the south, and the mean values of the temperature and of the salinity of this water are determined from Fig. 2b as ca. 7.0°C and ca. 34.13‰ respectively. According to Koenuma (1937), salinity minimum is found at the layer of ca. 800 m in the water near the Hachijo Island.

In order to discuss the mixing stages of water masses, it is necessary to determine the original values of the water types related to the region under consideration, because a water mass is formed from the mixture of certain water types. The original values of the two above-stated water types can be derived from the character of T–S curves, which have an inverted form of the letter 'S'. Each curve has three nearly straight parts, similar in their pattern. Extending these three straight parts, we can obtain two intersections which show the respective original water types. The procedure is illustrated in Fig. 2a & 2b. The approximate original values of the temperature and the salinity obtained by this procedure are ca. 25.0°C and ca. 35.45‰ in the upper water (Fig. 2a), and ca. 7.0°C and ca. 34.00‰ in the subarctic intermediate water (Fig. 2b). Koe-

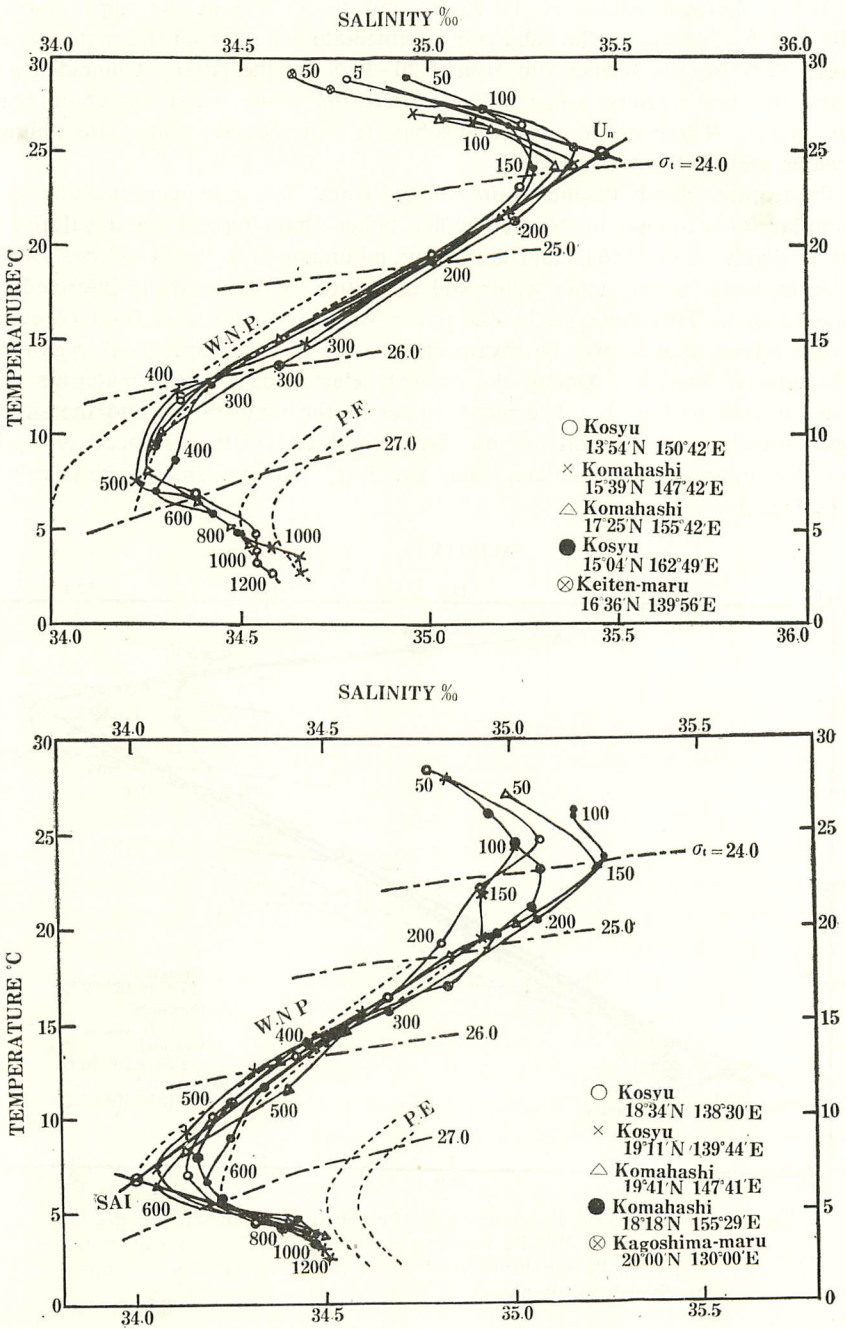

Fig. 2 a, b. Examples of T-S curves in the northern area than 13°N in the western Pacific. Observing depths are entered. W.N.P., western North Pacific Central water mass; P.E., Pacific Equatorial water mass; these two are shown by Sverdrup, et al. a : upper ; b : lower.

numa (1937) obtained values of T=25.5°C and S=35.50‰ in the upper water, and T=6.5°C and S=34.00‰ in the subarctic intermediate water, from the materials obtained around 15°N for the former and around 20°–30°N for the latter. Coincidence of the values for the low salinity water indicates that the lower water has come from the subarctic water. These upper water and subarctic intermediate water are abbreviated as Un-water and SAI-water hereafter.

In the tropical South Pacific, mainly in the Coral Sea, a temperature-salinity curve has a similar form to that of North Pacific, being characterized by a salinity maximum at a depth of ca. 150 m and a salinity minimum at a depth of ca. 800 m; the former corresponds to the upper water and the latter to the antarctic intermediate water. According to Thomsen (1935), the upper water is found at a layer of ca. 150 m near Tahiti Island, and it may be transported to the western Equatorial region by the South Equatorial current. Among the present selected data, some materials for this region are plotted in Fig. 3. The mean values of the temperature and the salinity of the upper water in this region are ca. 24.0°C and ca. 35.95‰ respectively, whereas those of the antarctic intermediate water ca. 5.6°C and ca. 34.42‰ respectively, as shown in Fig. 3

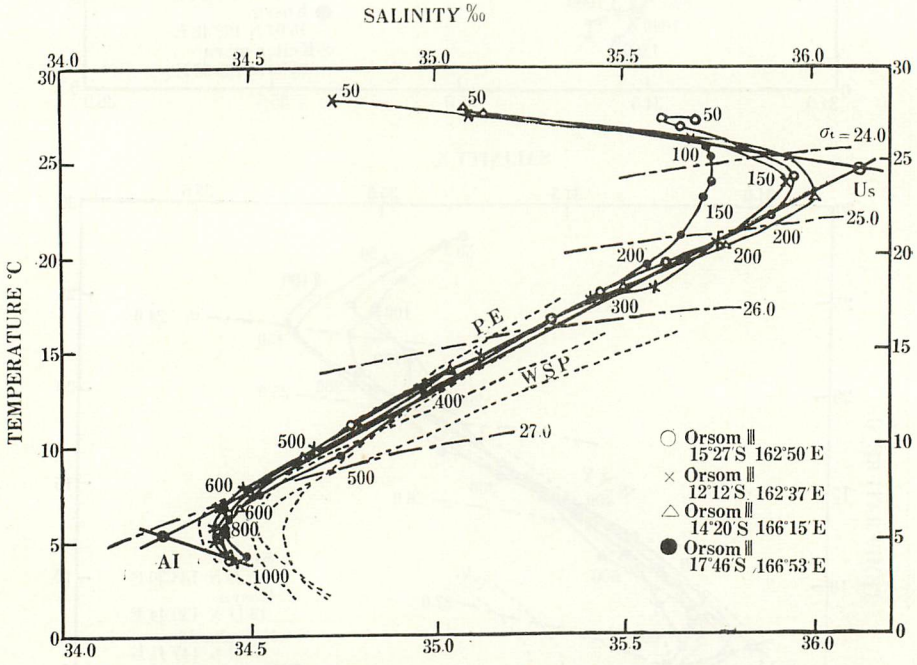

Fig. 3. Examples of T-S curves in the Coral Sea. Observing depths are entered. W.S.P., western South Pacific Central water mass; P.E., Pacific Equatorial water mass; these two are shown by Sverdrup, et al.

The original values of the two water types are determined by the same procedure as before. The procedure is illustrated in Fig. 3. The approximate original values of the temperature and the salinity obtained by this procedure are ca. 24.6°C and ca. 36.13‰ in the upper water, and ca. 5.4°C and ca. 34.27‰ in the antarctic intermediate water. These values farily coincide with Koenuma's values of T=24.4°C and S=36.20‰

in the upper water, derived from the materials obtained by the Planet (Koenuma, 1937), and with Thomsen's values of T=5.2°C and S=34.30‰ in the antarctic intermediate water, derived from the materials obtained by the Dana (Thomsen, 1935). These upper water and antarctic intermediate water are abbreviated as Us-water and AI-water hereafter.

3. Pattern of T–S curves and Mixing Stages of Water Masses

All the present selected data, excepting those treated in the preceding section, are plotted in T–S diagrams. The T–S curves are similar for the stations located within a certain geographical area, and can be classified into five groups, although they have different forms according to the rate of the mixture of the original water types. It is convenient, therefore, to divide the region under consideration into several subregions according to the pattern of the T–S curves in order to study the mixing stages of water masses in a wide extent of the ocean. The boundaries of these subregions are shown in Fig. 4.

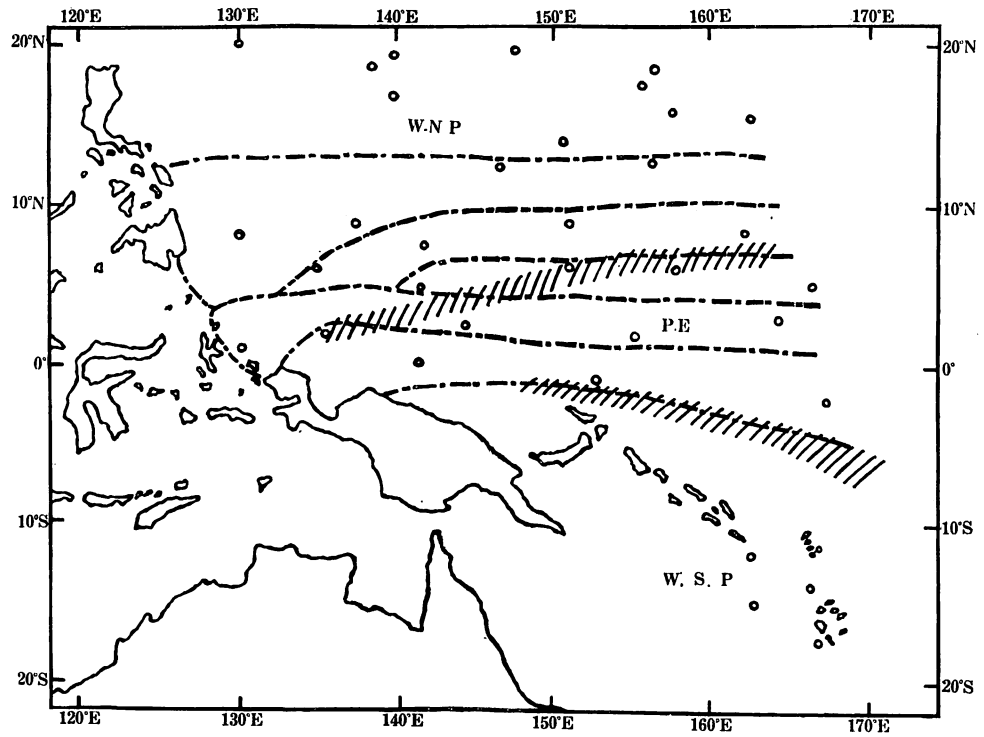

Fig. 4. The boundaries between five geographical divisions corresponding to five groups of T–S curve. Circles indicate the stations used in Figs. 2, 3, 5.

i) The First Group

Examples belonging to this group are shown in Fig. 5a. The region within which the T–S curve belongs to this group is found in a wide region to the east of Mindanao Island extending between 5°N and 12°N, narrowing in the farther east delimited by 13°N and 10°N (see Fig. 4). The Un-water is clearly found at a salinity maximum at ca. 100–150 m and the SAI-water is found at a salinity minimum at ca. 300 m. The latter mixes with the surrounding waters more rapidly than the Un-water. Below

the SAI-water, at a depth of ca. 400–500 m, the second maximum of salinity is found, indicating the incorporation of the water of low temperature and high salinity. According to Koenuma, (1937), the origin of this water of low temperature and high salinity is found in a region north-east of New Zealand and it extends northwestward to the North Pacific below the Us-water. The original values of the temperature and the salinity of this water are 14.0°C and 35.45‰. This water is denoted as the Ws-water. Judging from the T–S curves derived from the materials obtained by the Orsom III in the South Pacific, this water is not found to the south of ca. 6°S along the meridian of 170°E, but it can be found to the north of 5°S on the same meridian. Therefore, its origin must be located far east of 170°E, if this water extends northwestwards across the Equator. The second maximum of salinity at a depth of ca. 400–500 m stated above indicates the mixture of the Ws-water with the AI-water at a rate of 1 : 3 (Fig. 5a). The T–S curves below ca. 400 m in this region coincide with those of the so-called Pacific Equatorial water mass.

ii) The Second Group

Examples belonging to this group are shown in Fig. 5b. This group is found in an area extending east-westerly between 10°N and 7°N, bending south to 5°N to the west of 140°E (see Fig. 4). There is no salinity minimum due to the SAI-water in this region. Below the depth of ca. 200 m, the variation of the salinity with depth is hardly found. The Un-water is still found at ca. 100 m, and the water of ca. 150 m is a mixture of the Un-water and the SAI-water at a rate of 1 : 1.

iii) The Third Group

Examples belonging to this group are shown in Fig. 5c. This group is found in an area delimited by 7°N and 4°N to the east of 140°E, but it is not found to the west of 140°E. (see Fig. 4). The salinity minimum already vanishes in the second group. In this third group, the salinity maximum also disappears. Thus, the variation of salinity with depth is barely found from the surface to the deep layer (ca. 1000 m). Below ca. 300 m, the pattern of the T–S curves are not uniform. This region may be the boundary between the water masses from the north and from the south. The water of ca. 150 m is derived from the mixture of the Un-water and the SAI-water at a rate of 1 : 1. The waters of ca. 200–300 m and ca. 400 m are derived from the mixture of the SAI-water and the Ws-water, and of the Ws-water and the AI-water at a rate of 1 : 1 and 1 : 1.7 respectively.

iv) The Fourth Group

Examples belonging to this group are shown in Fig. 5d. This group is found in an area extending east-westerly between ca. 2°–4°N to the east of 135°E, in the western part it widens southerly to the Equator around 130°E (see Fig. 4). The Us-water characterized by a salinity maximum is found at ca. 150 m. Below this layer the salinity decreases rather sharply, probably under an influence of the SAI-water from the north. The water of ca. 250 m is derived from the mixture of the Us-water with the SAI-water at a rate of 1 : 2. And the water of ca. 300 m and of ca. 400 m are derived from the mixture of the SAI-water and Ws-water, and of the Ws-water and the AI-water at a rate of 1 : 1 and 1 : 2 respectively. The T–S curves below ca. 300 m in this region fairly coincide with those of the so-called Pacific Equatorial water mass.

v) The Fifth Group

Examples belonging to this group are shown in Fig. 5e. This group is found in an area between 1°N and 3°S, but it is not found to the west of 134°E partly delimited by the coast of New Guinea (see Fig. 4). The water between ca. 200m and 300 m are

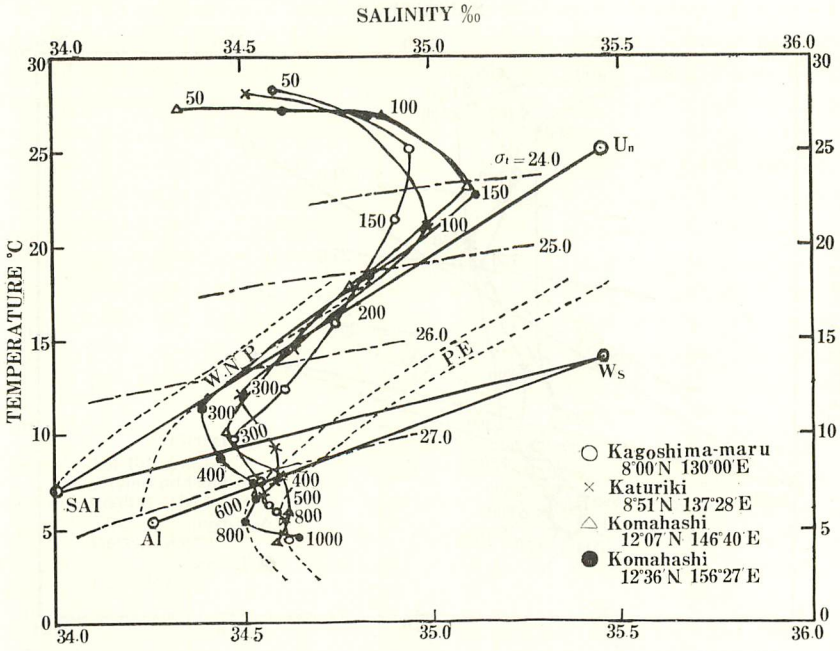

Fig. 5 a. Examples of the first group of T–S curves. Observing depths are enterd. W.N.P., western North Pacific Central water mass ; P.E., Pacifiic Epuatorial water mass.

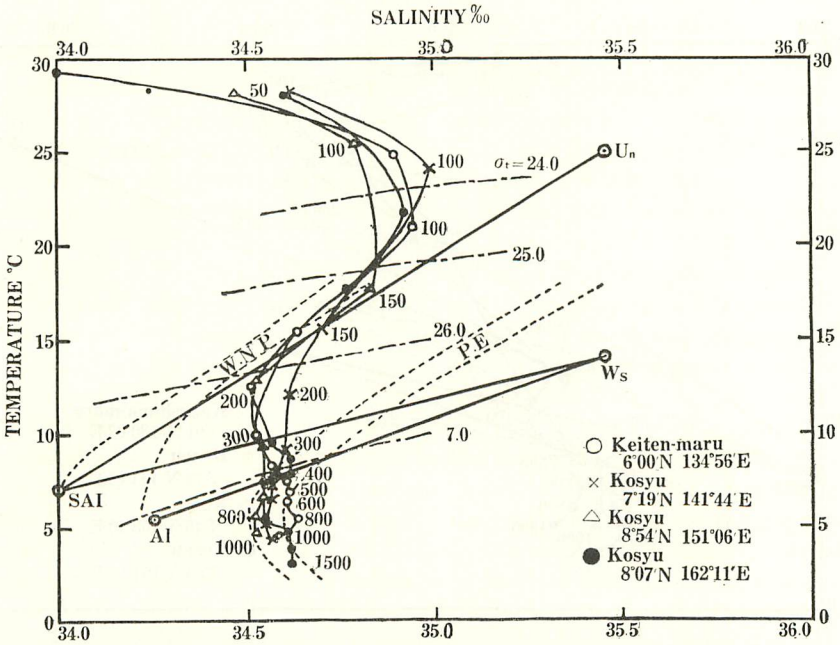

Fig. 5 b. Examples of the second group of T–S curves. Observing depths are entered. W.N.P., western North Pacific Central water mass ; P.E., Pacific Equatorial water mass.

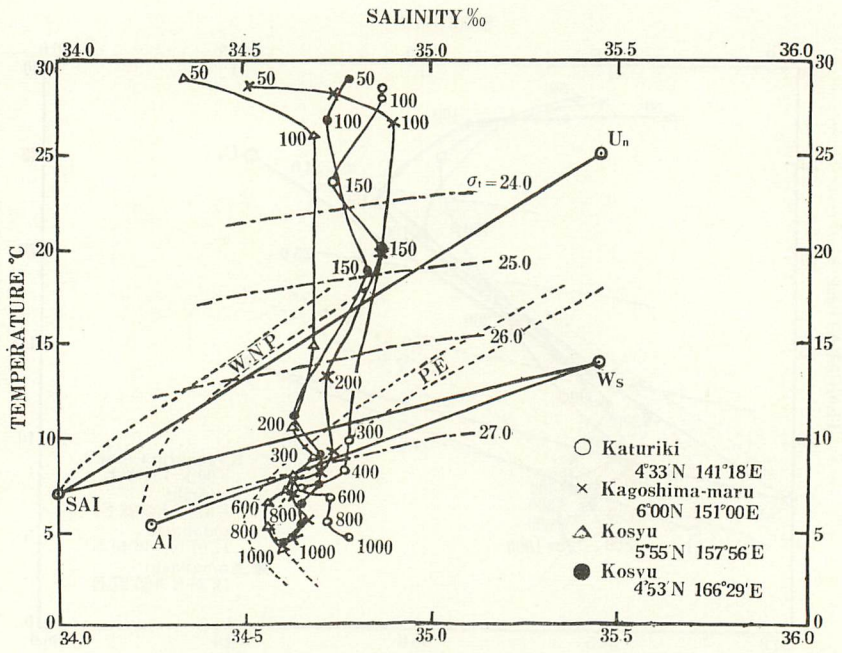

Fig. 5 c. Examples of the third group of T–S curves. Observing depths are entered. W N.P., western North Pacific Central water mass; P.E., Pacific Equatorial water mass.

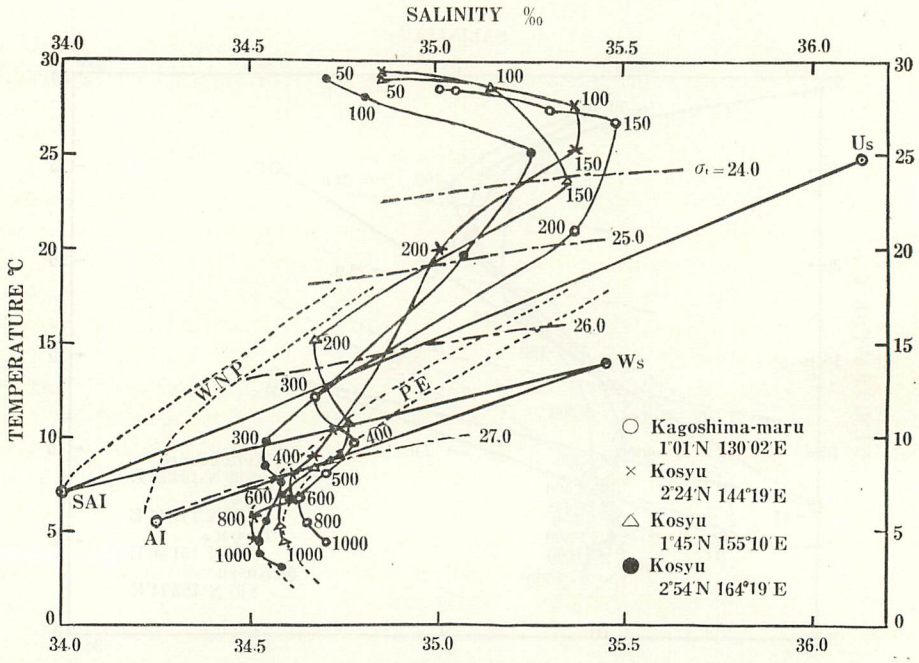

Fig. 5 d. Examples of the fourth group of T–S curves. Observing depths are entered. W.N.P., western North Pacific Central water mass; P.E., Pacific Equatorial water mass.

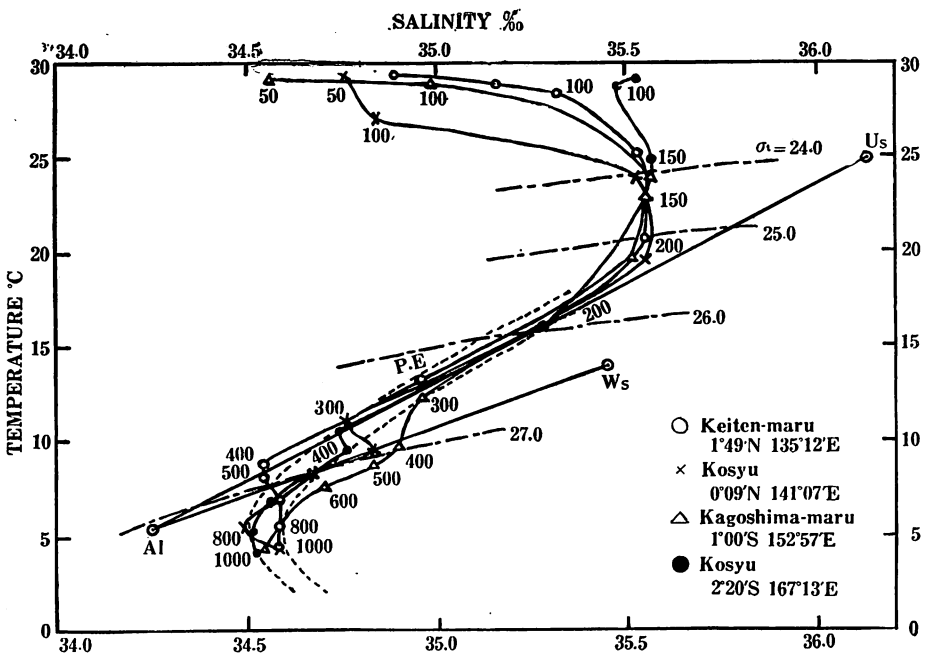

Fig. 5 e. Examples of the fifth group of T–S curves. Observing depths are entered. P.E., Pacific Equatorial water mass.

derived from the mixture of the Us-water and the AI-water. The water of ca. 400–500 m is derived from the mixture of the Ws-water and the AI-water at a rate of 1 : 1.5. The AI-water characterized by a salinity minimum can clearly be found at ca. 800 m. The T–S curves in this region coincide with those of the so-called Pacific Equatorial water mass.

4. Latitudinal Change of Mixing Stage of Water Masses

It may be concluded from the discussion in the previous section that in the western Equatorial Pacific the mixing of water masses advances in the nearly north-south dirc-tion. Accordingly, it is convenient to draw the approximate T–S curves at every latitudes for understanding the mixing processes of water masses. Barnes *et al.* (1948) roughly draw the approximate T–S curves which changes with latitudes, and show the transitional stages between the western North Pacific Central water mass and the Equatorial Pacific water mass. Using the present selected data, the average T–S curves below a depth of 200 m for every two degrees of latitude to the east of 140°E are drawn in Fig. 6. The transitional stages of the mixing process of water masses are seen clearly in the figure. The salinity difference with depth becomes indistinct gradually with latitudes from north to south and it almost vanishes at ca. 6°N (the third group). The temperature of ca. 200m at this latitude is much lower than that of the surrounding waters. The region around this latitude may be considered as a center of the waters of the North and the South Pacific.

The average T–S curves in the Coral Sea are shown in Fig. 7 for the sake of comparison with those of the above stated waters. The average T–S curve above ca. 500 m in 20°–18°S shows a pattern intermediate between the T–S curves of the Pacific Equatorial water mass and that of the western South Pacific Central water mass, wher-

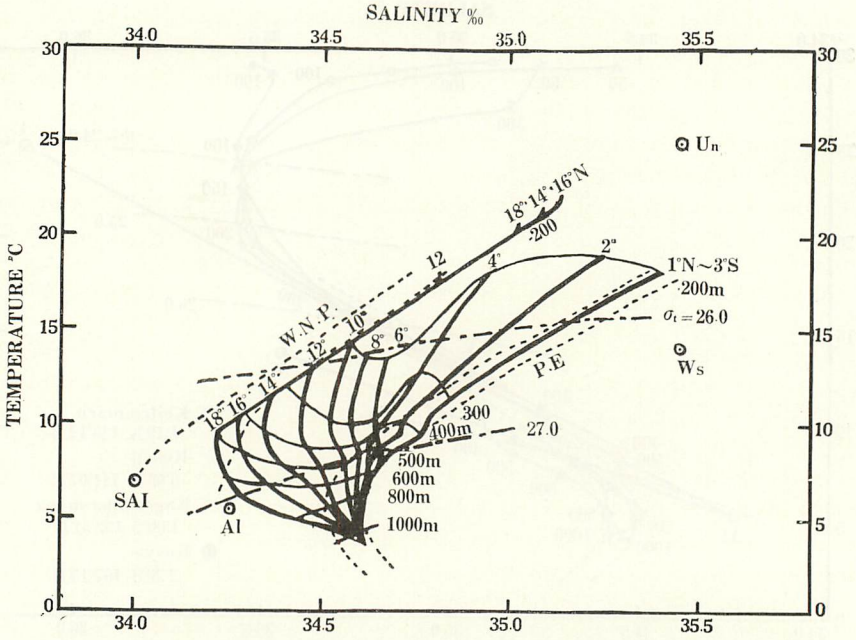

Fig. 6. Average T–S curves for every two degrees of latitude in the area between 18°N and 3°S to the east of 140° E. W.N.P., western North Pacific Central water mass; P.E., Pacific Equatorial mater mass.

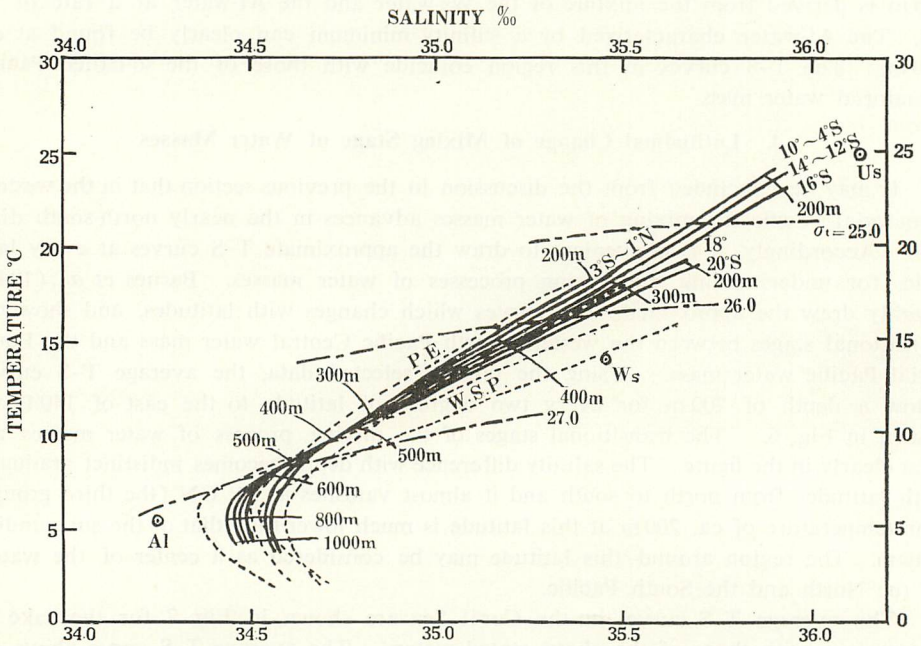

Fig. 7. Average T–S curves in the Coral Sea. W.S.P., western South Pacific Central water mass; P.E., Pacific Equatorial water mass.

eas below ca. 500 m it coincides with that of the western South Pacific Central water mass. When the water mass extends toward the north, the T–S curve above 500 m approaches to that of the Pacific Equatorial water mass, but below ca. 500 m it still keeps the pattern peculiar to the western South Pacific Central water mass. However, the T–S curve at 10°S both above and below 500 m coincides with that of the Equatorial Pacific water mass and this situation continues as far as 4°S. Between 3°S and 1°N the water is much lower in both temperature and salinity than the southern water.

5. Conclusion

370 observations are employed for the study on the mixing stages of water masses in the western Equatorial Pacific. Original water types are determined from materials excluding those of stations in an area between 13°N and 3°S and the results are as follows: northern upper water (Un), T=25.0°C and S=35.45‰; subarctic intermediate water (SAI), T=7.0°C and S=34.00‰; southern upper water (Us), T=24.6°C and S=36.13‰; antarctic intermediate water (AI), T=5.4°C and S=34.27‰.

T–S curves for stations located between 13°N and 3°S can be classified into five groups according to the pattern of T–S curve or mixing stage, corresponding to five zonal divisions nearly parallel to the latitude. In the first group of T–S curve, the salinity maximum of the Un-water at ca. 100–150 m and the salinity minimum of the SAI-water at ca. 300 m are found. Below the SAI-water, the second maximum of salinity due to Ws-water is found at ca. 400–500 m, the mixing ratio between the Ws-water and the AI-water is 1 : 3. In the second group the salinity minimum of the SAI-water almost vanishes and the variation of the salinity with depth is hardly found below a depth of ca. 200 m, although the salinity maximum of the Un-water is still found at ca. 100 m. In the third group the salinity maximum also vanishes. This stage is found around ca. 6°N, which may be considered as the boundary zone between the water masses from the north and from the south. In the fourth group the salinity maximum of Us-water from the south is found at ca. 150 m, while an influence of the SAI-water from the north is found below the Us-water. The ratio of mixture between them is 2 : 1 at ca. 250 m and that between the SAI-water and the Ws-water is 1 : 1 at ca. 300 m. In the fifth group the salinity minimum of the AI-water is found at ca. 800 m. The mixing ratio between the Ws-water and the AI-water is 1 : 1.5 at ca. 400–500 m. The latitudinal change of T–S curves is shown by the aid of average T–S curves for every two degrees of latitude (Fig. 6). For the sake of comparison, average T–S curves in the Coral Sea are also shown (Fig. 7).

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