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Some observations on the temperature inversion off Kangaroo Island, southern Australia

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Abstract

During the 1975—1976 expedition by the R. V. Kaiyo Maru of the Fisheries Agency of Japan, the temperature inversion was observed at several stations off Kangaroo Island in the southern Australian waters from November 28—December 8, 1975. The inversion occurred in the layer near the sea bed on the continental shelf and in the intermediate layer (100—200 m) off the continental edge. The properties of inversion water differed from station to station, as evinced by the temperature variation of 14. 0—15. 7℃, the salinity of 35. 4—35. 8‰ and the thermosteric anomaly of 150—170 cl/ton. The thickness of the inversion layer off the continental edge is of about 110 m. The most remarkable temperature inversion was about 0. 8℃, observed on the continental shelf. The inversion layer is inevitably accompanied by the increase of the salinity. Accordingly, the layer is not vertically unstable. It is inferred that the temperature inversion water originates from the surface water with higher density in the gulf or coastal water region, where the evaporation is prominent in summer season. It is presumed that the surface water sinks in the gulf or coastal region, and spreads on the continental shelf and further on the isosteric surface at the intermediate depth off the continental edge. It appears that such a process of the movement of the water with high density brings in the temperature inversion at a part of the continental shelf or its adjacent offing regions, where the heavy water encounters sharply with water of different origin from the offing region.

Introduction

The oceanographic observation by the R. V. Kaiyo Maru of the Fisheries Agency of Japan, as a part of the survey of trawl fishing grounds, was carried out in the waters around Australia during November 1975—January 1976. In this observation the temperature inversion was found unexpectedly in the southern Australian waters.

Hitherto, some observations have been carried out in the southern Australian waters in order to examine the environment of the fishing ground during the tuna season. As for the noticeable phenomena in the southern Australian waters, it has been pointed out that upwelling occurs mainly in the offing of the coast along Kingston—Portland at the southeast of Kangaroo Island in summer (HYND and ROBINS, 1967). The temperature inversion, however, has not been reported from the southern Australian waters.

In the waters of the northeast of Japan, the temperature inversion appears remarkably in the zone of oceanic front (Polar Frontal Zone), where two waters with different properties contact each other, as reported by KURODA (1957). HAMON (1967) reported that the tempera-

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ture inversion frequently appears in the intermediate layer of the Indian Ocean and is presumably connected with the spreading of the Red Sea water. Nagata (1968) after examining the inversion phenomenon in the sea to the east of Honshu, Japan, remarked that the temperature inversion of small scale might be usually unstable and of short duration.

In the present paper, the feature of the temperature inversion has been examined based on the data obtained during the survey of the Kaiyo Maru, and the mechanism of the formation of inversion was also studied using the data published by CSIRO, Australia along with those of the Kaiyo Maru. The published sources of data are listed in Table 1.

Table 1. The sources of data utilized.

Year	Month	Vessel	Cruise	Source
1961	Feb.—Mar.	Gascoyne	G2/61	OCR No. 10, 1966
1963	Mar.	Gascoyne	G2/63	OCR No. 22, 1967
1964	Feb.	Gascoyne	G2/64	OCR No. 34, 1967
1965	Feb.	Gascoyne	G2/65	OCR No. 43, 1968
1965	Mar.—Apr.	Gascoyne	G5/65	OCR No. 46, 1967
1975	Nov.—Dec.	Kaiyo Maru		JODC Code No. 49752901

OCR: Oceanographic Cruise Report, CSIRO, Australia
JODC: Japan Oceanographic Data Center

Results and discussion

The oceanographic stations observed aboard the R. V. Kaiyo Maru in the southern Australian waters are shown in Fig. 1. The investigations were carried out mainly in the Great Australian Bight and at a few stations in the offing region. The water temperature was measured by means of the reversing thermometers, BT and XBT. The errors of those measurements by each method are ±0.02℃, ±0.2℃ and ±0.2℃ respectively. The magnitude of temperature inversion in the vertical profile is larger than the measuremental error at ST. 90, ST. 92, ST. 93, ST. 94, ST. 95 and ST. 96. At ST. 91, which is located between ST. 90 and ST. 92 as shown in Fig. 1, the temperature inversion could not be recognized distinctly.

Fig. 2 shows the vertical temperature profile recorded by the BT at ST. 93 where the depth of sea is 150 m. It is clear from this figure that the water temperature falls irregularly from 16.9℃ at the surface to 14.2℃ at about 100 m depth and then rises to 15.0℃ near the bottom. The temperature inversion of about 0.8℃ occurs between the minimum at 100 m depth and the maximum near the bottom. It is noteworthy for oceanographic structure in this region that the BT record shows an irregular pattern in the temperature profile, too small in scale to be detected by serial observations. Fig. 3 shows vertical profiles of temperature, salinity and thermosteric anomaly at stations where temperature inversion was indicated. At ST. 94 (Fig. 3-a), where the most remarkable inversion was found among stations observed by the serial hydrographic casts, the temperature showed the minimum value 14.32℃ at 62 m depth and then rose to 14.86℃ near the bottom (154 m). The temperature

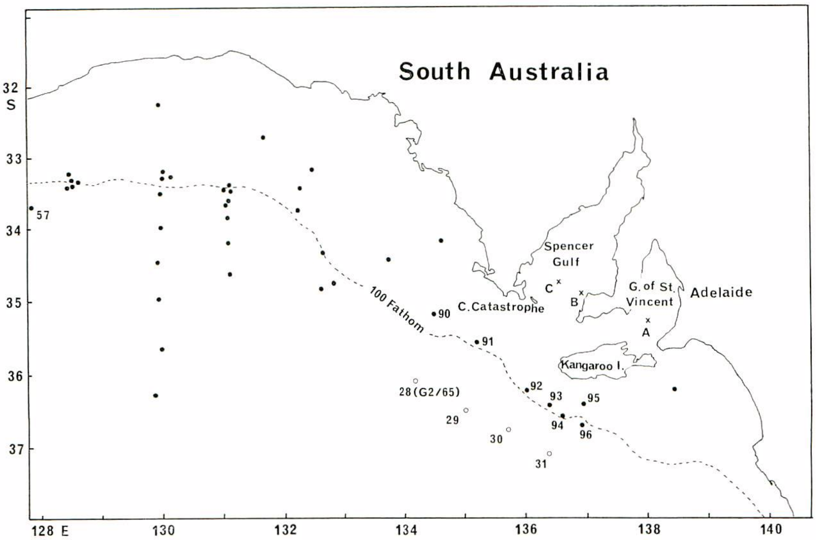


Fig. 1. Location of stations. Solid circle shows the station observed by the R.V. Kaiyo Maru. Open one shows the station observed by the R.V. Gascoyne (G2/65). A, B and C show the stations where the evaporation ΔE is estimated.

inversion of 0.54℃ occurs between 62 m depth and near the bottom. At ST. 92 (Fig. 3-b), the minimum temperature 14.08℃ was observed at 117 m depth and the temperature increased with depth, the maximum being 14.38℃ near the bottom (141 m). The temperature inversion shows 0.30℃ at this station. However, the observation did not reach the bottom but limited to the depth of 14 m above the bottom, so that the actual bottom temperature is presumably higher than 14.38℃. Consequently, it is estimated that the actual temperature inversion is larger than 0.30℃. At every station on the continental shelf the observation did not reach the bottom but terminated at the depth above it. Therefore, it is considered that the temperature inversion may be less remarkable as compared to the actual state. At ST. 96 (Fig.

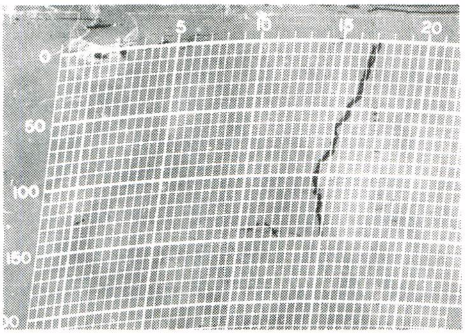


Fig. 2. Temperature profile at ST. 93 by BT record.

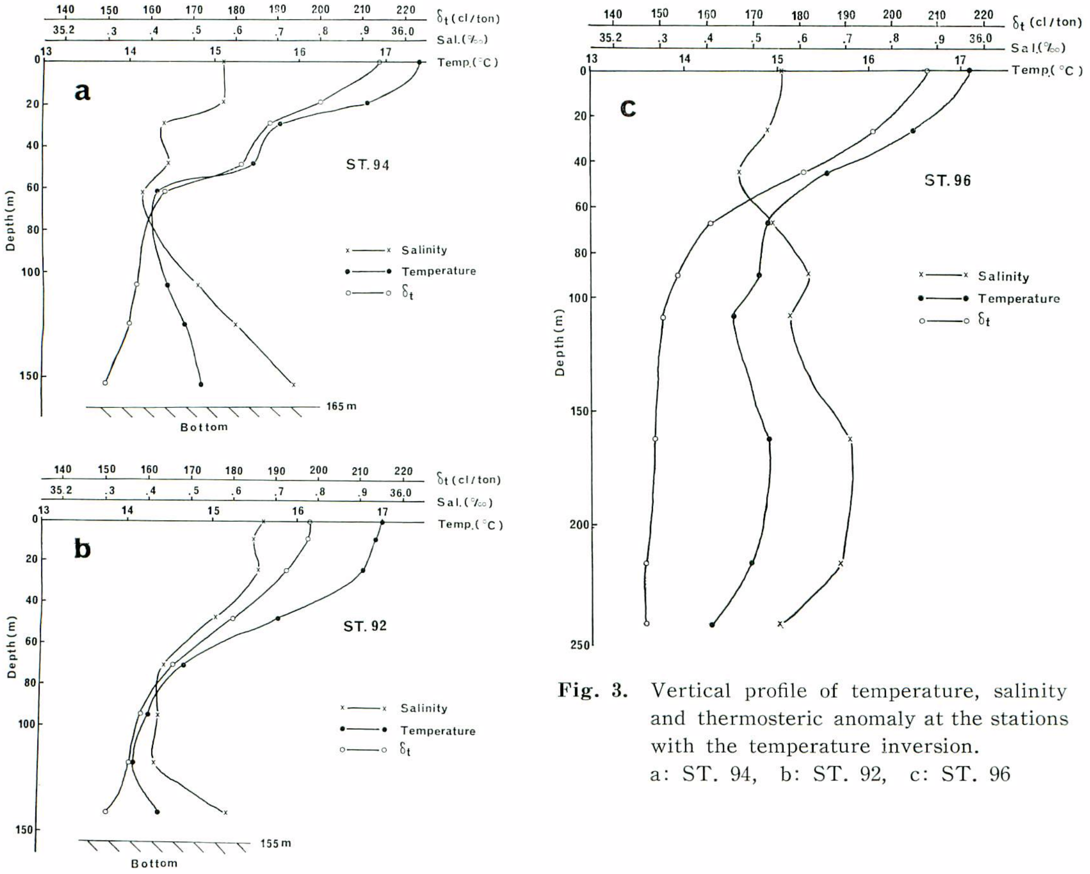


Fig. 3. Vertical profile of temperature, salinity and thermosteric anomaly at the stations with the temperature inversion.
a: ST. 94, b: ST. 92, c: ST. 96

3-c), on the continental slope, the temperature showed the minimum value of 14.54°C at 108 m depth and the observed maximum value 14.92°C at 162 m depth. Although the magnitude of the temperature inversion is comparatively less, the inversion layer, in which the temperature is higher than the minimum value, is recognized down to about 220 m depth. The thickness of this layer is about 110 m and somewhat thicker than that on the continental shelf.

It should be noted that the temperature rise corresponds to the increase of salinity. At ST. 94 where the temperature inversion is distinct, the depth of the minimum temperature corresponds to that of the minimum salinity 35.58‰. Increasing downward from this depth, the salinity attains a value of 35.74‰ near the bottom. The salinity increases in the inversion layer by 0.36‰ from the minimum to maximum. At ST. 92, just as in ST. 94, the depth of the minimum temperature corresponds to that of the minimum salinity and the salinity increases downward from this depth. In the lower layer below about 100m depth at ST. 96, both the minimum and maximum of temperature and salinity occurred simultaneously at the same depth. However, the minimum and maximum salinity observed in the upper layer, at 45 m and 90 m depths, do not correspond to the minimum and maximum temperature in spite of the vertical irregularity of temperature at those depths. The higher salinity of the depths between 108 m and

220 m corresponds to the layer of the temperature inversion. Also at ST. 90 and ST. 95, the increase in salinity can be found, but the temperature inversion is not well defined (Fig. 4). As shown in Fig. 3, the thermosteric anomaly shows a smooth pattern vertically decreasing from the surface to the bottom, in spite of the irregularity seen in the profiles of the temperature and the salinity. It is indicated that the layer of temperature inversion is not unstable due to the conspicuous vertical increase of the salinity. However, the vertical gradient of the thermosteric anomaly is comparatively less in the layer of the temperature inversion. Therefore, it is suggested that the vertical stability of the temperature inversion layer is lower than in the other layers and the water of the inversion layer is liable to be mixed vertically. The water properties of the inversion layer vary from station to station. The temperature, salinity and thermosteric anomaly are 14.0—15.0℃, 35.4—35.8‰, and 150—170 cl/ton at stations (ST. 92—ST. 96) off Kangaroo Island and 15.6—15.7℃, 35.6—35.7‰ and 165—170 cl/ton at ST. 90 southwest of the Cape Catastrophe.

The dissolved oxygen in the inversion layer is scarcely different from the upper layer and shows values higher than 90% in the saturation percentage. This fact indicates that the water of the temperature inversion layer is comparatively fresh.

Fig. 4 shows the T-S curve at stations where the temperature inversion was observed and the T-S relation of the offing water (oceanic water). The range of the T-S relation of the offing water is presented in the figure by the broken line, to facilitate comparison with

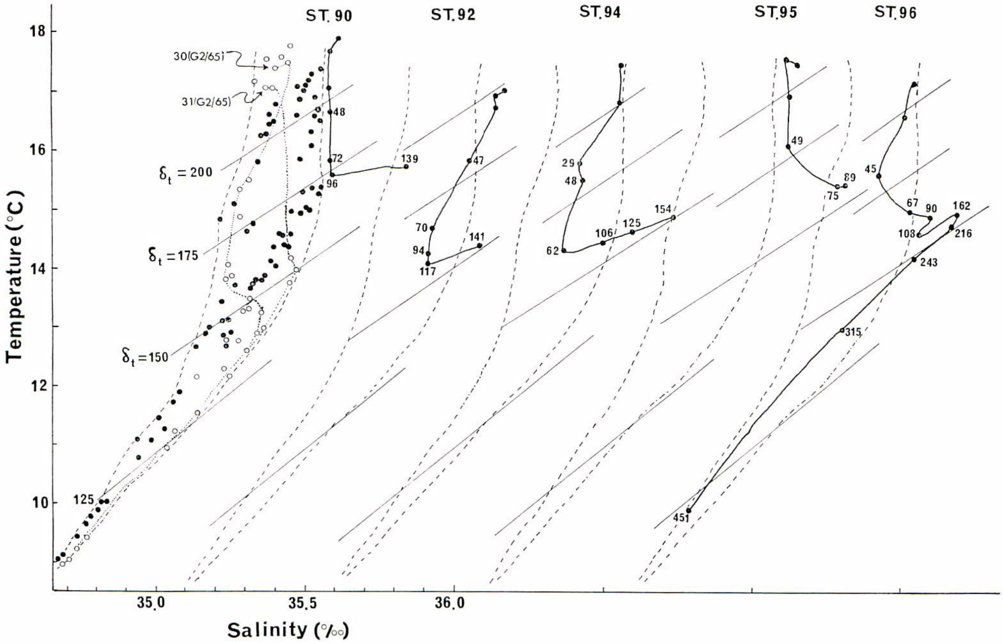


Fig. 4. T-S relation of the water in the offing region on the southern Australian waters and T-S curve at the station with the temperature inversion. The salinity scale is for ST. 90. Subtract 0.5‰ from this scale for the other stations by right side in figure. Numerals affixed to the T-S curve indicate the observed depth in meter,

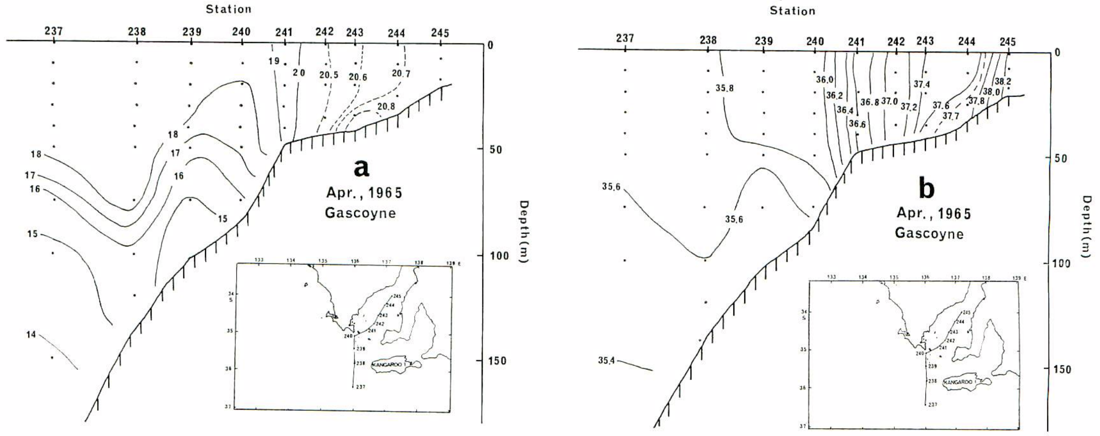
that having the temperature inversion. The T-S curves, except ST. 95, roughly coincide with the T-S relation in the offing water as for the upper layer, shallower than 100 m depth. Furthermore, the T-S curve deeper than about 250 m shows the coincidence with the T-S relation of the offing water as indicated at ST. 96. However, the T-S relation of the inversion water does not coincide with that of the offing water. Accordingly, it is obvious that comparatively warm and saline water forming the inversion layer is a peculiar water-type which does not exist in the water mass in the offing region. ST. 95 is the nearest station to the Kangaroo Island among all the stations and shallower than 100 m. The temperature is 15.34℃ and salinity 35.81‰ in the bottom water at this station. These values of temperature and salinity are comparatively higher than those of the temperature inversion water near the bottom or of intermediate layer at the other stations around the Kangaroo Island. From these evidences, it is inferred that the warm and saline water forming the inversion layer originates from the coastal region of the shallower depths. However, it should be noted that the temperature inversion at ST. 95 is of very low magnitude as compared with the other inversion although this station seems to be located nearest to the origin among all the stations where temperature inversion was observed. For the formation of the temperature inversion as mentioned above, it is necessary that relatively cold and dilute water occupies the upper layer while relatively warm and saline water exists in the lower layer.

WYRTKI and ROCHFORD (1971) show that the surface temperature and salinity are generally lower in the southward offing region than those in the northward coastal region in the southern Australian waters. Therefore, it is considered that relatively cold and dilute water above the inversion layer originates from the surface water of the southward offing area. The obscureness of the temperature inversion at ST. 95 appears to be caused by a feeble intrusion of relatively cold and dilute water originating from the offing area. The distinct temperature inversion is mainly shown at deeper stations on the continental shelf and the station on the continental slope, that is located immediately adjacent to the offing of the continental shelf. Accordingly, it is suggested that two waters encounter reciprocally on the marginal region of the continental shelf, and thus they form the sharp inflection point of the minimum temperature and minimum salinity as shown in the T-S curves at ST. 90, ST. 92, ST. 94 and ST. 96. Relatively warm and saline water seems to spread on the sea bed of the continental shelf and on the isosteric surface in the intermediate layer of the continental slope. Therefore, the movement of this water should indicate a complex pattern in the T-S curve of the intermediate layer as seen at ST. 96.

The existence of the temperature inversion in southern Australian waters is examined by the oceanographic data published by CSIRO, Gascoyne Cruise G2/61, G2/63, G2/64, G2/65 and G5/65. These cruises were carried out during the summer season from February to April, a few months later than the Kaiyo Maru Cruise. These stations observed by the Gascoyne were mainly located on the western region of Kangaroo Island. And few stations were observed on the southern region of Kangaroo Island where the temperature inversion was found in the Kaiyo Maru Cruise. Regarding the data obtained by the Gascoyne Cruise, a small scale temperature inversion is noticed at some stations in the Spencer Gulf and the Gulf of St. Vincent.

Every temperature inversion was accompanied by the salinity increase such as the temperature inversion observed off Kangaroo Island by Kaiyo Maru.

Fig. 5 shows the distribution of temperature, salinity and thermosteric anomaly on the vertical section from the inner part to the offshore of Spencer Gulf, based on the data obtained by Gascoyne Cruise G5/65. As to the temperature distribution, it is noteworthy that the temperature near the bottom is higher than that of above the bottom as shown at ST. 242, ST. 243 and ST. 244 in the Gulf. The magnitude of this inversion is comparatively less from 0.04℃ at ST. 242 to 0.26℃ at ST. 243. As shown clearly from the salinity in the vertical section, the salinity near the bottom is also higher than that above the bottom. The temperature and salinity of the inversion water fall with the increase of depth from the inner part to the head of the Gulf. The pattern of the temperature and the salinity distribution suggests that the relatively warm and saline water intrudes along the bottom toward the offing from the inner part of the Gulf. The lower thermosteric anomaly near the bottom indicates that the inversion layer is vertically stable in spite of the temperature rise near the bottom. The



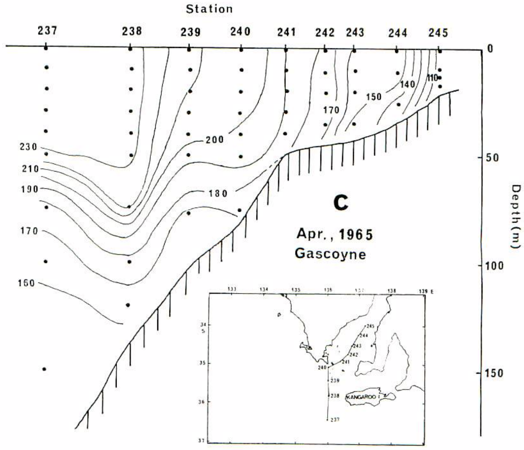


Fig. 5. Distribution of the water properties on the vertical section toward the offing from inner part of the Spencer Gulf.
a: Temperature
b: Salinity
c: Thermosteric anomaly

trend of the thermosteric anomaly distribution also suggests that there is a water of lower specfic volume (heavy water) moving towards the offing near the bottom of the inner part of the Gulf.

Fig. 6 shows the surface salinity in the Spencer Gulf and its adjacent region in summer season (February) depicted by data of the G2/65 cruise. It is a distinctive feature that the surface salinity is higher in the coastal region than that of the offing region. Especially, remarkable value of salinity, higher than 37.2‰, is recorded at the inner part of Spencer Gulf. By means of the data of the G5/65 cruise which was about a month later than G2/65 cruise, it is shown that the surface salinity became 38.25‰ in the inner part of the Gulf. The salinity increase as mentioned above appears to be caused by the intense evaporation from the sea surface during that period.

Table 2 shows the temperature and the salinity observed at three stations, which were visited by both the cruise G2/65 and G5/65. The salinity increase from February to March or April could be recognized not only at the surface but in the whole water column from surface to bottom. Now, assuming that the advectional effect is negligibly small, the salinity variation in the water column depends on the evaporation (or precipitation), ΔE, and the total salt content in a unit water column remains unchanged from February to March or April. Therefore,

$$\rho s\int_0^{Z_m} S_f(z)dz-\rho s\int_0^{Z_m-\Delta E} S_{m\cdot a}(z)dz=0 \qquad \cdots\cdots\cdots\cdots(1)$$

where ρ is the density of sea water, s the surface area of water column, Z_m the depth to which the surface mixing reaches during the period from February to March or April. At these three stations, possibly Z_m is the depth to the bottom. $S_f(z)$ and $S_{m\cdot a}(z)$ stand for the vertical salinity in February and March or April, respectively. Here, the average value of $S_f(z)$ and $S_{m\cdot a}(z)$ being written with $\bar{S}_f$ and $\bar{S}_{m\cdot a}(0\leqq z\leqq Z_m)$, the equation (1) is replaced approximately as follows:

$$\rho s\bar{S}_f Z_m-\rho s\bar{S}_{m\cdot a}(Z_m-\Delta E)=0 \qquad \cdots\cdots\cdots\cdots(2)$$

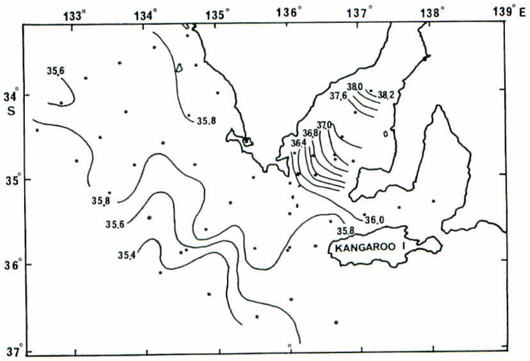


Fig. 6. Salinity distribution at the surface in summer (March—April, 1965).

Table 2. Temperature and salinity variation from February to March or April at three stations A, B and C where the evaporation ΔE is estimated. Value with asterisk shows one interpolated.

St.	A(35°18′S, 138°00′E)				B(34°51′S, 136°56′E)				C(34°45′S, 136°33′E)			
Date / T.S. / Depth	Feb., 4		Mar., 29		Feb., 9		Apr., 3		Feb., 8		Apr., 3	
	Temp.	Sal.	Temp.	Sal.	Temp.	Sal.	Temp.	Sal.	Temp.	Sal.	Temp.	Sal.
0(m)	19.44	36.148	20.50	36.726	20.34	36.992	20.68	37.298	19.99	36.854	20.51	37.138
10	.47	.168	.17	.733	.34	.989	.65	.311	.99	.857	.47	.162
20	.47	.183	.03	.920	.35	.989	.62	.312	.99	.858	.49	.166
30	.62	.451	.07	.940	.36	.984	.59	.315	20.00	.862	.51*	.168*
40					.36	.985	.60	.317	.00	.860	.52*	.189*
	ΔE=49 cm in 54 days				ΔE=35 cm in 54 days				ΔE=33 cm in 55 days			

Thus, ΔE is given by the following relation

$$\Delta E=\frac{(\bar{S}_{m\cdot a}-\bar{S}_{f})}{\bar{S}_{m\cdot a}}\cdot Z_{m} \qquad \cdots\cdots\cdots\cdots(3)$$

The thickness of evaporation, ΔE, at the three stations is estimated by the equation (3) as shown on the bottom line in Table 2. It indicates the large value, about 6—10 mm per day, on the basis of these estimations. It appears that remarkable evaporation is brought about on this region during the summer season. The saline water formed by evaporation shows high density (heavy one). Moreover, since the precipitation is not so much in autumn and winter, it is considered that the saline water formed by evaporation in summer becomes denser as a result of cooling.

Fig. 7 represents schematically the summarized water movement on the southern Australian waters obtained from the results described above. In the coastal and gulf region, the density of the surface water increases remarkably due to intense evaporation and then vertically homogeneous water is formed by means of the convective mixing from the surface to the bottom. Heterogeneity, however, is seen horizontally; the shallower the station is, the higher are both salinity and density. Eventually, convective mixing water formed in the shallower region of the coast and gulf descends along the sea bed of the continental shelf, because it has higher density than that in the deeper region. The offshore water with relatively lower temperature and lower salinity moves into the coastal and gulf region as the compensation current accompanied with sinking of the surface water of the coastal and gulf region. Thus, it is considered that the temperature inversion appears in the region where two waters meet and stratify sharply; one with relatively higher temperature on the bottom layer originating from the inshore Gulf, and the another with lower temperature on the surface layer originating from the offing.

The salinity maximum layer unaccompanied by the temperature maximum is recognized around the $\delta_t=150$ cl/ton, as seen at ST. 30 and ST. 31 (G2/65) in Fig. 4. As shown in Fig. 1, these stations are located at the adjacent region of the station where the temperature inversion was observed. The water of this layer seems to extend from the water of the temperature inversion layer. In the offing region, it is considered that heavy water formed in

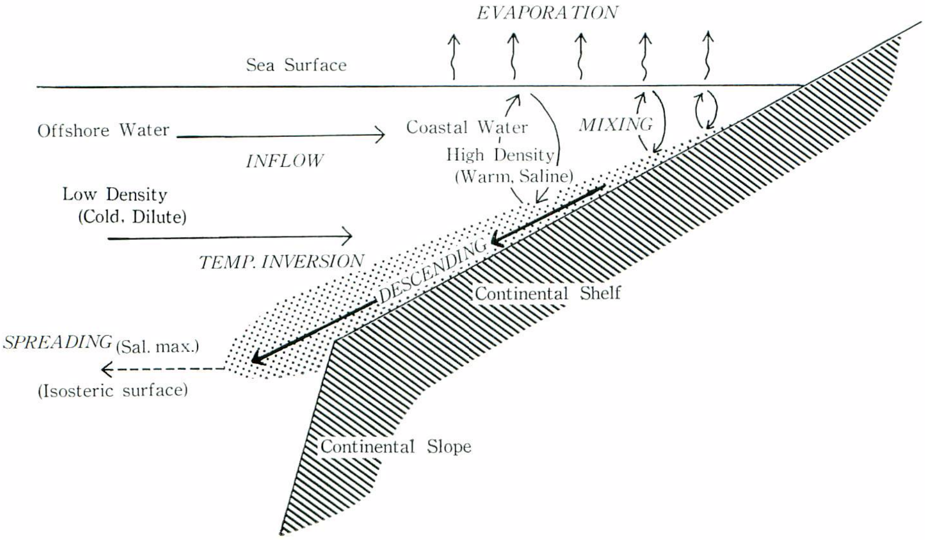


Fig. 7. Schematic diagram of the water movement.

the coastal and gulf region spreads on the isosteric surface of the intermediate layer. The water at ST. 91 is occupied by the offshore water from the surface to the bottom whereas the inshore water exists in the bottom layer at other adjoining stations. This might possibly indicate that there is geographical difference between main routes of the inflow of offshore water and the outflow of inshore water. It is considered that such a movement of two waters with different properties make the complex oceanographic condition in the offings of the Spencer Gulf and Kangaroo Island.

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南オーストラリア，Kangaroo 島沖の水温逆転について

木谷浩三

要約

水産庁調査船開洋丸による昭和50年度の新漁場開発調査航海における11月28日—12月8日に，オーストラリア南岸のカンガルー島沖でいくつかの水温逆転層が観測された。この水温逆転層は，陸棚域では，底層に，そして陸棚斜面域では，中層 (100～200m) に見られた。逆転層水の海水特性は，水温 14.0～15.7°C，塩分 35.4～35.8‰，比容アノマリー (δ_t) 150～170 cl/ton の範囲に見られた。逆転層の厚さは，陸棚上では約 90 m，陸棚斜面でも約 110 m であった。水温の逆転は，陸棚上の BT 観測点で得られた 0.8℃ が最大であった。これらの水温逆転は，必らず塩分の著しい増加を伴なっていて，鉛直的には不安定となっていない。

水温逆転層水の起源は，夏季蒸発の活発な南オーストラリアの沿岸，内湾域の表層水と考えられる。すなわち，沿岸，内湾域で形成された高密度の表層水は沈降し，陸棚底に沿って降下し，さらに陸棚斜面上では等密度面に沿って中層に拡散するものと想定される。この高密度水が，沖合域を起源とする比較的低温な水型と陸棚上や陸棚斜面上の一部で鋭く接することにより，水温逆転をもたらすものと考えられる。