Temperature Inversions in the Equatorial Pacific

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Abstract

The study of the temperature inversions which have been observed in the Equatorial Western Pacific suggests that they are essentially derived from the structure in laminae of the waters in the thermocline layer. Some temperature inversions are bound to the northern boundary of the subtropical water of the South Pacific and are due to the isentropic penetration in this water of colder and less saline waters of northern origin; others are the manifestation of a convergence towards the equator of the meridional component of the velocity, in the core of the Equatorial Undercurrent.

INTRODUCTION

During the year 1967, from March to July, the r.v. *Coriolis* from the centre ORSTOM in Nouméa, performed four cruises (Cyclone 2, 3, 4, 5) along the meridian 170° E from 20° S to 4° N. In the equatorial region (4° S–4° N), hydrological casts were made each 30 nautical miles. Bathythermal profiles were taken each 10 nautical miles with a bathythermograph, except during cruise Cyclone 5. Temperature inversions were noticed on several of these BT records within the thermocline layer, in the equatorial region where the latter has a large depth extension (150–200 m). Austin (1954) had already observed temperature inversions close to the equator at depths between 150 and 200 m. Montgomery and Stroup (1962) have noticed that these inversions, at the level of which no inversion of the thermosteric anomaly is observed, are bound to strong meridional gradients of the salt content. Similarly, Stroup (1954) has pointed out temperature inversions bound to vertical salinity gradients.

The inversions which are considered in this paper concern layers thinner than 15 m where the temperature increase with depth does not exceed 1°C. Moreover, these inversions are stable with respect to the gravity forces, as it has been shown by hydrographic samples (see fig. 1).

Fig. 2 gives the distributions of inversions in a meridional plane during cruises Cyclone 2, 3, and 4. Two kinds of inversions can be distinguished: one corresponding to inversions bound to a real increase of the salinity versus depth, another corresponding to inversions located in the core of the Equatorial Undercurrent. All the temperature inversions do not belong to these types, but the existence of these two types can help to understand the inversions and their meaning in terms of the meridional circulation.

Oceanography of the South Pacific 1972, comp. R. Fraser. New Zealand National Commission for UNESCO, Wellington: 1973.

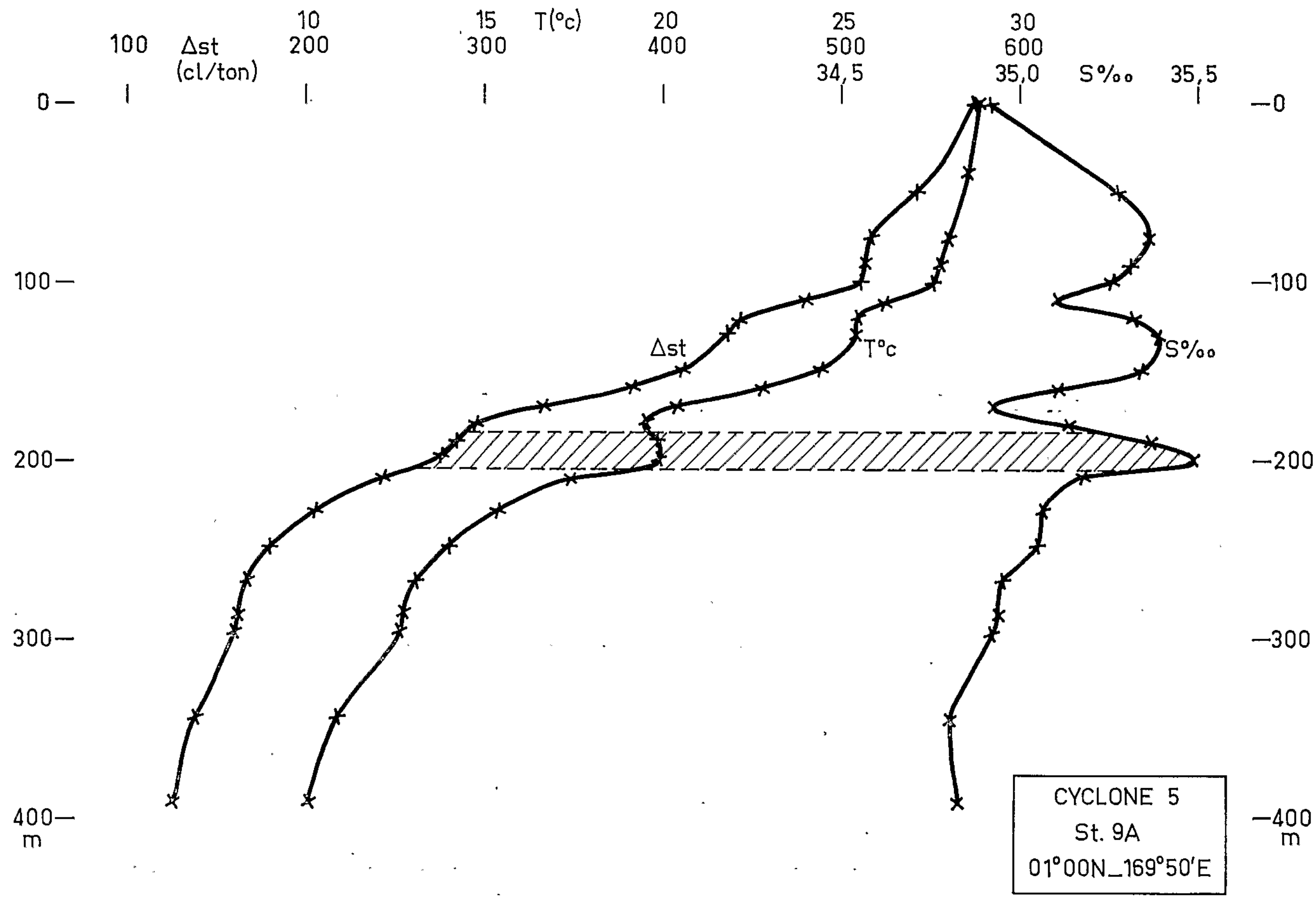

FIG. 1. Vertical profiles of temperature, salinity, and thermosteric anomaly.

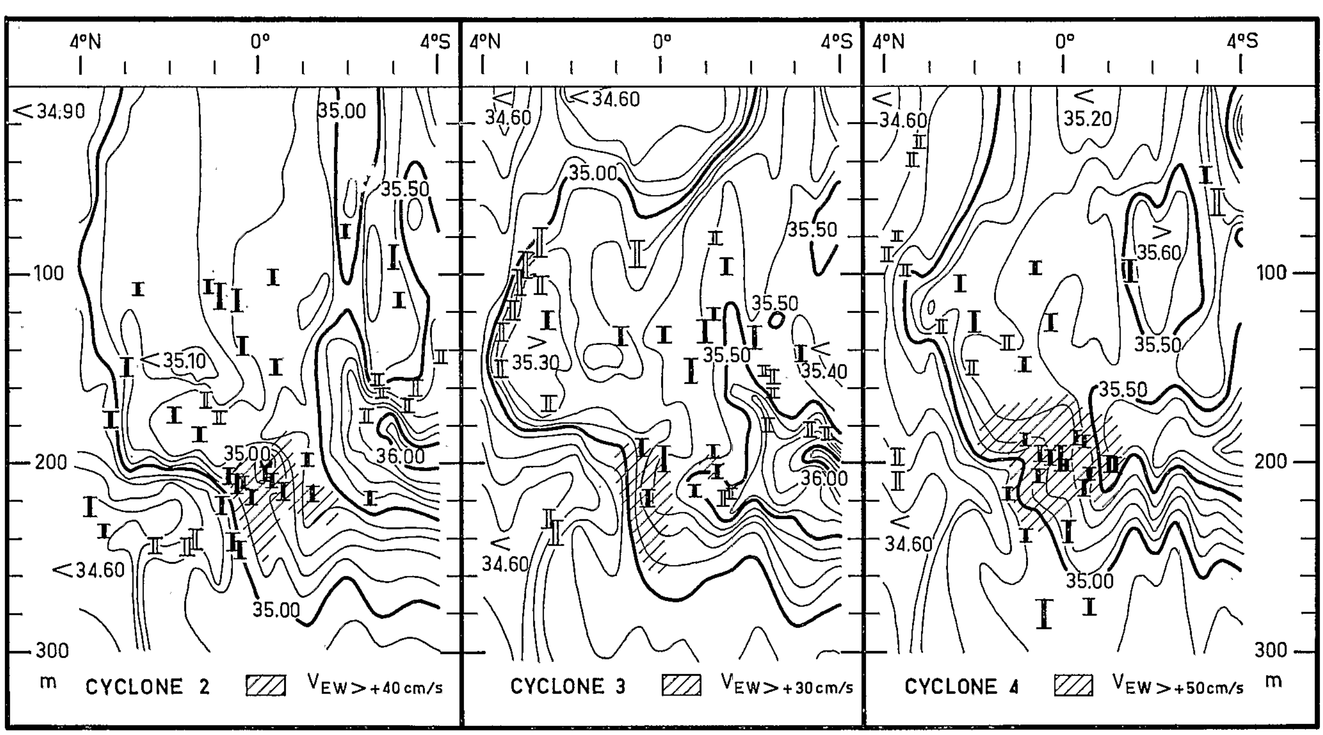

FIG. 2. Meridional distribution of salinity from 4° S to 4° N along the meridian 170° E during cruises Cyclone 2 (March 1967), Cyclone 3 (April 1967), and Cyclone 4 (June 1967). Hatched areas indicate the core of the eastward Equatorial Undercurrent. Heavy full dashes indicate temperature inversions, and the open ones inversions bound to salinity increase versus depth.

In any water mass, the thermosteric anomaly is a function of the temperature and the salinity, so one can write:

$$\overrightarrow{\text{grad}}\ \triangle ST = \frac{\partial \triangle ST}{\partial S}\ \overrightarrow{\text{grad}}\ S + \frac{\partial \triangle ST}{\partial T}\ \overrightarrow{\text{grad}}\ T \quad (1)$$

where $\frac{\partial \triangle ST}{\partial S} < 0, \frac{\partial \triangle ST}{\partial T} > 0.$

Setting $K_S = -\frac{\partial \triangle ST}{\partial T}$ and $K_T = \frac{\partial \triangle ST}{\partial T}$,

then (1) can thus be written as follows:

$$\overrightarrow{\text{grad}}\ \triangle ST = - K_S\ \overrightarrow{\text{grad}}\ S + K_T\ \overrightarrow{\text{grad}}\ T \quad (2)$$

If one considers stable temperature inversion between two homogeneous particles, with positive sense from the cold particle to the warm one, grad T is positive and grad $\triangle$ ST is negative. As the gradient vectors are collinear, the following condition can be obtained from equation (2):

$$\text{grad } S \geqslant \frac{K_T}{K_S} \text{ grad } T > 0 \quad (3)$$

that is to say, with depth positive downwards, the vertical salinity gradient is positive.

HYPOTHESIS ON INVERSION FORMATION

Inversions Bound to Salinity Gradients

Let us consider a thin isohaline layer of high salt content coming through an isohaline water mass of low salinity. This penetration is supposed to be isentropic, in such a way that the specific volume would be a strictly decreasing function of the depth for any value of the temperature (on fig. 3A, the distribution of these two water masses, on fig. 3B their T-S diagrams). A temperature inversion is observed on the T-S diagram at the very end of the tongue (on fig. 3C, the T-S diagram along the vertical line I-II). This inversion may not be observed elsewhere because vertical gradients, smoothed by turbulent diffusion, would not be strong enough. Likewise if we consider a low salinity water tongue coming through a water mass of higher salt content, temperature inversion can be observed. In both cases, temperature is found to be bound to a strong positive gradient of salinity if depth is taken positive downwards.

K_T = 30 cl/ton/°C and K_S = 72 cl/ton/‰ for S = 35.00‰ and T = 25.0°C which are values close to the ones measured in the front regions observed during the cruises Cyclone. For these values and a temperature inversion of 0.5°C in 10 m, we find:

$$\frac{\partial S}{\partial z} \geqslant \frac{K_T}{K_S} \frac{\partial T}{\partial z} = 2.10^{-2}\ ‰/\text{m}$$

that is to say an increase of the salinity at least equal to 0.2‰ for 10 m, which represents a relatively important vertical gradient of salinity.

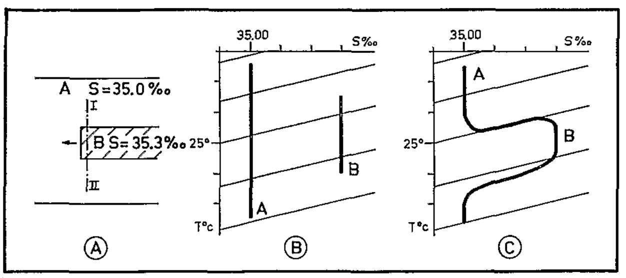

Fig. 3. Simplified schema of formation of temperature inversion.

Observed inversions satisfying these conditions are numerous. They seem to be due to the meeting of northern water mass with the South Subtropical Water mass of the salinity maximum.

Inversions Bound to Advection Region

Stommel and Fedorov (1967) have pointed out the existence of very thin horizontal laminae, isothermal, and isohaline, extending from 2 to 20 nautical miles horizontally, and from 2 to 40 m vertically. They have studied their movements, the probable time scale and dissipation time; they have shown how temperature inversions can be formed with such a structure. They have suggested that with four of these thin laminae located in two different horizontal planes and superposed in pairs, a temperature inversion can be formed when the space distribution of their specific volume brings out a new disposal of these laminae along the same vertical line. Figs 4A and 4B adapted from their study give two examples of the proposed mechanism by which temperature inversions are formed.

But obviously, a temperature inversion is not obtained from any original arrangement of temperature and salinity: there are necessary conditions given by inequality (3). In the meridional plane where data have been collected during cruises Cyclone, the meridional salinity gradient must have the same sign as the meridional temperature gradient, and the latter must be the inverse of the meridional thermosteric anomaly gradient.

Such a process can be applied to the formation of temperature inversions located in the core of the Equatorial Undercurrent.

Actually, the formation of an inversion when there is meeting of two water masses of very different salt content, is only a particular aspect of the general hypothesis of Stommel and Fedorov (1967). In fact if we consider four laminae with the initial properties and set as shown on fig. 5, their final disposal along a vertical line will give a temperature inversion by the penetration of a saline water mass, the T-S diagram of which is figurated by dots 2–4, in a less saline water mass with T-S diagram pointed by dots 1–3.

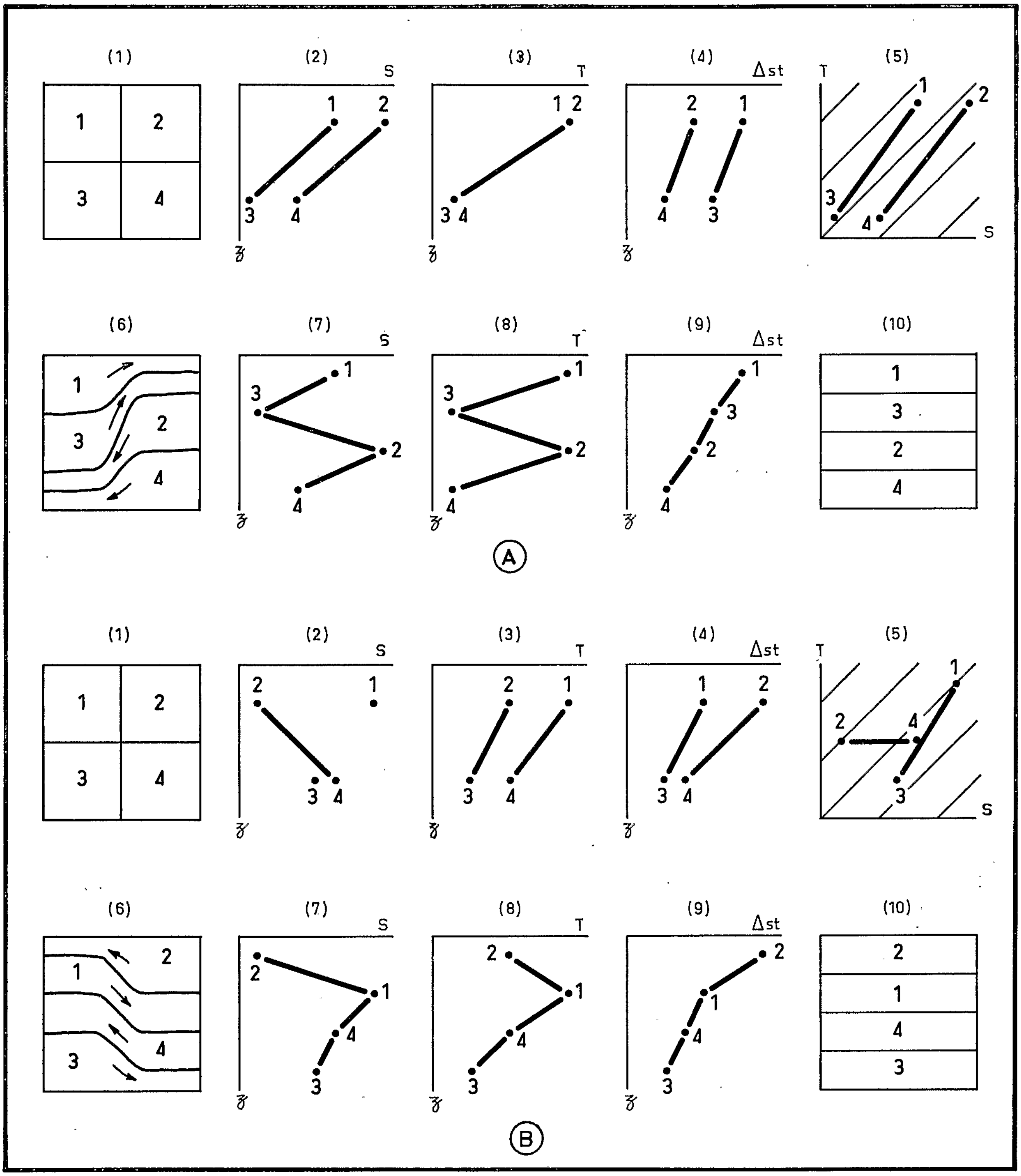

FIG. 4. Simplified schema of formation of temperature inversion according to Stommel and Fedorov (1967). (1) initial disposal of the laminae. (2), (3), and (4) respectively values of temperature salinity and thermosteric anomaly. (5) T.S. diagram with isanosteric lines. (6) movements of the four laminae. (7), (8), and (9) respectively vertical temperature, salinity, and thermosteric anomaly profiles. (10) final disposal. In (2), (3), (4), (5), (7), (8), and (9) the lines joining the points do not correspond to real values as the laminae are supposed homogeneous.

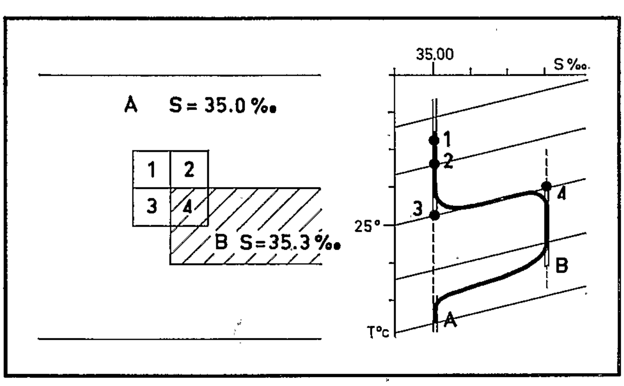

FIG. 5. The hypothesis of Stommel and Fedorov (1967) applied to the isentropic penetration of a salted water mass in a less salted water mass.

DISCUSSION

The data from cruises Cyclone 2, 3, and 4 have been used to check the reality of the mechanism proposed above. For each couple of hydrographic stations framing a temperature inversion, temperature and salinity values have been interpolated at two depths, 20 m spaced, one above and the other below the mean depth of the selected inversion. The corresponding computed values of the thermosteric anomaly define the properties of the four laminae in the initial disposal. The initial state and the final state are confused in this method, the aim of which is to see whether the inversion corresponds to a proper laminae structure at the hydrological stations which frame it. The interpolated values of temperature and salinity do not represent the initial situation since the inversion is already observed. But, as the observed temperature inversions do not in practice seem to spread out more than 20 nautical miles, one may think that the situation does not change at about 15 nautical miles from each side of the inversion and that only the very ends of the laminae are combined in order to give an inversion.

The final disposal on a vertical line is obtained by putting the thermosteric anomaly values in decreasing order. With this new arrangement, a vertical temperature profile can be drawn, and a temperature inversion is found or not. For the inversions found in such a way, meridional gradients of temperature, salinity, and thermosteric anomaly have been estimated in order to verify that the conditions of formation are fulfilled. The results are given in table 1. For all the cases, the meridional gradients of salinity and temperature, respectively $\frac{\partial S}{\partial y}$ and $\frac{\partial T}{\partial y}$, have the same sign and the meridional gradient of thermosteric anomaly has the opposite sign.

In table 1, values of $\frac{\triangle S}{\triangle z}$, which is an estimation of the vertical salinity gradient close to an inversion, are given. Actually, $\triangle S$ is the salinity difference between the two interpolated values of one of the two stations located on each side of the inversion, $\triangle z = 10$ m.

Although $\frac{\triangle S}{\triangle z}$ is not the vertical salinity gradient at the depth and the latitude of the inversion, it is supposed to be an acceptable approximation, usable as an element of the formation of an inversion and also giving indications on the meridional circulation.

As shown on fig. 6, the meridional gradient of the northward component of the velocity $\frac{\partial v}{\partial y}$ and the vertical salinity gradient, $\frac{\triangle S}{\triangle z}$ are correlated. Positive values of $\frac{\partial v}{\partial y}$ correspond to a local acceleration of the northward component and consequently represent a tendency for the water to diverge, and they are associated with positive values of $\frac{\triangle S}{\triangle z}$. On the contrary, negative values of $\frac{\triangle S}{\triangle z}$ are associated with negative values of $\frac{\partial v}{\partial y}$, which implies a convergence.

Consequently, when $\frac{\triangle S}{\triangle z}$ is positive, temperature inversions are possible because the necessary con-

TABLE 1

Cruise	Latitude	Depth	$\frac{\partial S}{\partial y}$ 10^{-}‰/m	$\frac{\partial T}{\partial y}$ 10^{-6}°C/m	$\frac{\partial \Delta ST}{\partial y}$ 10^{-3}cl/t/m	$\frac{\Delta S}{\Delta z}$ 10^{-}‰/m	$\frac{\partial v}{\partial y}$ 10^{-6} S^{-1}
Cyclone 2 ..	0° 11′ S	155	+ 0,51	+ 0,61	−0,017	+ 2,9	+ 0,2
,, ..	0° 22′ N	220	+ 1,74	+ 2,52	−0,074	+ 2,9	+ 0,2
,, ..	0° 52′ N	240	+ 5,40	+ 5,57	−0,276	− 4,2	− 1,7
,, ..	0° 52′ N	250	+ 4,80	+ 3,24	−0,284	− 4,2	− 1,7
,, ..	1° 41′ N	245	+ 2,07	+ 4,32	−0,069	+10,8	+ 1,8
,, ..	3° 11′ N	145	+ 3,10	+ 1,26	−0,184	−11,6	− 2,7
,, ..	3° 11′ N	155	+ 4,25	+ 6,48	−0,112	−11,6	− 2,7
Cyclone 3 ..	3° 48′ S	180	− 5,94	− 5,60	+0,260	+32,2	+ 4,8
,, ..	3° 48′ S	190	− 6,74	− 2,60	+0,408	+32,2	+ 4,8
,, ..	1° 40′ S	205	+ 2,75	+ 7,20	−0,005	+ 3,0	− 3,8
,, ..	0° 16′ N	210	+ 2,34	+ 3,80	−0,080	− 2,0	− 0,8
,, ..	0° 16′ N	220	+ 2,74	+ 9,20	−0,02	− 2,0	− 0,8
,, ..	2° 23′ N	225	+ 6,03	+ 3,67	−0,045	+14,5	+ 0,3
,, ..	3° 21′ N	105	+10,05	+12,67	−0,334	+14,9	− 1,5
Cyclone 4 ..	0° 23′ S	215	+ 4,30	+ 7,40	−0,140	+ 8,0	+ 1,5
,, ..	0° 09′ N	200	+ 3,09	+ 8,00	−0,025	− 4,2	− 2,1
,, ..	0° 32′ N	205	+ 4,65	+ 0,10	−0,312	+ 8,3	+ 1,4
,, ..	0° 42′ N	205	+ 3,60	+ 9,62	−0,029	+ 5,2	+ 0,8
,, ..	2° 04′ N	150	+ 0,83	+ 6,30	−0,139	+ 2,3	+ 3,0

dition from inequality (3) is filled, but when $\frac{\Delta S}{\Delta z}$ is negative and a temperature inversion is observed there are clues for a convergence. This seems to be the case of temperature inversions observed in the core of the Equatorial Undercurrent.

However, among the temperature inversions which have been considered only half have been found to be associated with the proper hydrological structure of adjacent waters. This low proportion can be explained by the fact that hydrological stations are distant by 30 nautical miles from each other, and because the salinity values are not vertically continuous, though samples have been taken every 20 m and sometimes every 10 m. Temperature, salinity, and thermosteric anomaly values at the four selected points around an inversion may not, in every case, represent the system of four homogeneous water masses giving a temperature inversion, because, according to Stommel and Fedorov (1967), the dimensions of these particles are 2 to 20 nautical miles horizontally and 2 to 40 m vertically.

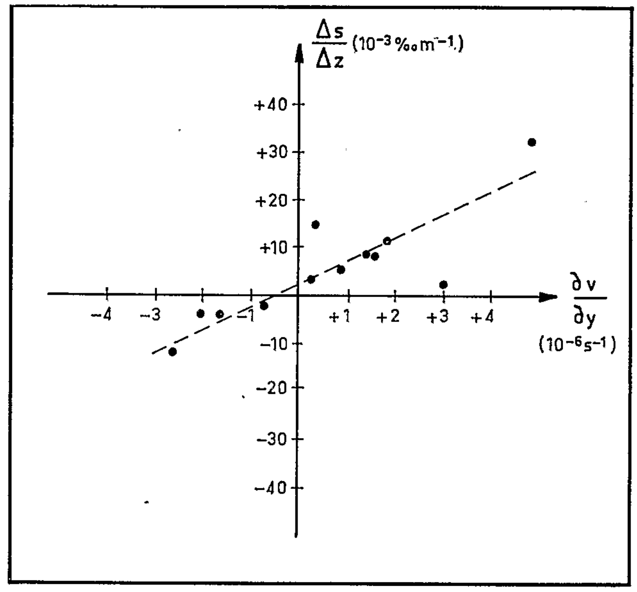

FIG. 6. Vertical gradient of salinity plotted against northward component of the velocity.

CONCLUSION

The temperature inversions found close the boundary between two water masses of very different salinity, can be considered as fairly good clues of the reality of the hypothesis of Stommel and Fedorov (1967) on a possible mixing process: isothermal and isohaline laminae escape from the two water masses and combine, this combination can then produce temperature inversions. Such a mixing process has been observed by Turner (1967) during laboratory experiments.

Temperature inversions located in the core of the Equatorial Undercurrent do not seem to be bound to salinity increase versus depth. From what has been shown before, it is possible to think that they are manifestations of convergence of waters in the zone of maximum eastward flow. Such a result agrees to the scheme of meridional circulation which has been proposed by Fofonoff and Montgomery (1955) or by Yosida, Nitani, and Susuki (1959) (see fig. 7).

As far as the meridional circulation at 170° E is concerned, some elements of it can be found in data collected during Cyclone cruises: the equatorial upwelling and surface divergence (Rotschi, 1968), the two superficial convergences, on both sides of the equator, bound to thermal fronts (Rotschi, Hisard, Rual, 1968), the subsurface divergence in the eastward flow linking the North Equatorial Counter Current and the Equatorial Undercurrent (Oudot, Hisard, Voituriez, 1969).

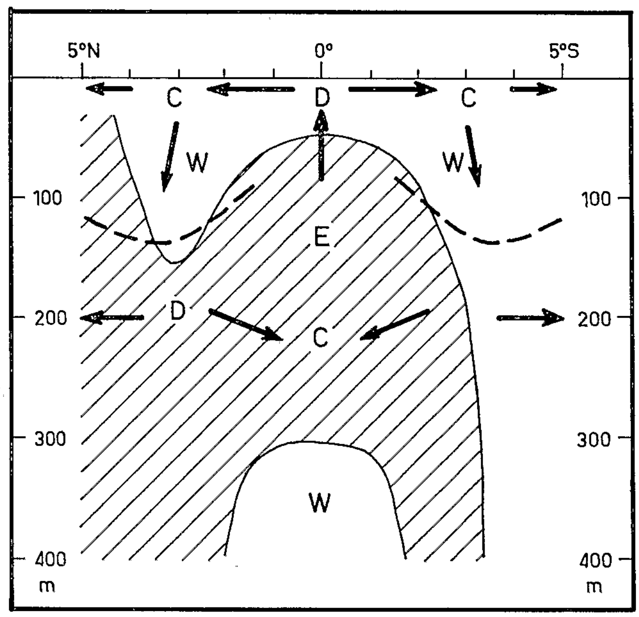

FIG. 7. Schematic meridional circulation at 170° E. Hatched area indicate eastward flow. C and D respectively indicate convergence and divergence. Dashed line represent the upper limit of the thermocline.

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