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The 'Warreen' Sections; Temperatures, Salinities, Densities and Steric Heights in the Leeuwin Current, Western Australia, 1947–1950

M. A. Greig

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THE "WARREEN" SECTIONS; TEMPERATURES, SALINITIES, DENSITIES AND STERIC HEIGHTS IN THE LEEUWIN CURRENT, WESTERN AUSTRALIA, 1947-1950

M. A. GREIG, J. S. GODFREY, P. SCHNEIDER and K. R. RIDGWAY

Division of Oceanography
CSIRO Marine Laboratories
GPO Box 1538, Hobart, Tasmania, 7001
Australia

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Abstract

Eleven hydrographic sections were taken westward from Fremantle (32°03'S) across the continental shelf, in 1947-50. Despite defects in the data, the sections are useful because they are the only systematic time series to date of hydrographic observations across the Leeuwin Current. They confirm the unusual nature of the Leeuwin Current compared to other eastern boundary currents, give some useful indications of seasonal behaviour, and illustrate the difficulty of estimating the total transport of the current.

Introduction

Between 9 November 1947 and 6 October 1950, the CSIRO Division of Fisheries undertook eleven hydrographic sections from R.V. "Warreen" along 32°03'S, due west from Fremantle, Western Australia (CSIRO Division of Fisheries 1951, 1952; Rochford, 1969a). On each cruise, several stations were taken over the continental slope (Fig. 1). The data set is of some interest as it has since been found that the very narrow Leeuwin Current flows through this region (e.g. Andrews 1977, Cresswell and Golding 1980). There are some questions regarding the accuracy of this data set, discussed below; but there is quite good agreement on broad-scale features between "Warreen" data and later results, and the "Warreen" data remain unique for their fine scale resolution of the Leeuwin Current. They thus provide a useful provisional guide to the likely average fine-scale hydrographic structure of the Leeuwin Current until such time as a similar set of sections can be undertaken with modern equipment; they may also be useful in designing such sections, and are of historic interest as the first known direct measurements of the Leeuwin Current.

In this report, we present temperature-salinity (T-S) relationships, and vertical sections of temperature, salinity and density anomaly for the eleven individual cruises (Figs 2-12). We also show surface temperature, salinity and geostrophic velocity from individual cruises (Figs 13a-k). The T-S relationships are generally consistent with later results, with rather greater scatter. Steric heights at 0, 50, 100, 200 and 300 db are calculated relative to 450 db (Fig. 14); the annual averages of the steric heights over the bins used by Godfrey and Ridgway (1985) are in good agreement with their results, but the "Warreen" results suggest that the fine structure that Godfrey and Ridgway did not resolve may be very important.

The overall T-S relationship is shown in Fig. 15a, while Figs 15b-d show vertical sections of annual average temperature, salinity and density anomaly from the "Warreen" data. More exactly, the quantities plotted are the constant components from a one-harmonic least-squares best fit to the annual cycle at each depth and location.

The annual average temperature section of Fig. 15b, extended 360 km seaward by use of annual average temperature at 32°S, 110°E from Rochford (1969b), is shown in Fig. 16a. (Note the different horizontal and vertical scales in the two figures). It is contrasted with similar sections, drawn to the same length and depth scales, for the California Current near Ensenada

(Fig. 16b); and for the Benguela Current, South West Africa at 26°S (Fig. 16c). While the provisional nature of Fig. 15a is again emphasised, the great difference between the Western Australian current system and other eastern boundary flows can be seen very clearly in this figure.

Details of the data

Each section consisted of six stations on the inner shelf (reported in CSIRO 1952) and six stations on the shelf break and in the open ocean (CSIRO 1951), each with a standard (nominal) location. The inner-shelf stations were mostly confined to data in the top 10 m only. Celestial navigation was used, and accuracy of each position was not recorded; errors of 10-20 km are quite likely beyond the shelf break, particularly in the longshore direction.

Data were collected by use of Nansen bottles with reversing thermometers in the traditional way (e.g. Sverdrup et al., 1942). Chlorinities (salinities) were determined by the Mohr chemical titration method (Oxner, 1920). Temperatures and salinities are believed to be accurate to ≃ 0.015°C and 0.03°/₀₀, respectively.

Protected thermometers were not available at the time, so depth was estimated from the length of wire and the surface wire angle; the error in this procedure is not known, but comparison of average "Warreen" results with averages from later data (see Section 4 on steric height) suggests that the errors are not likely to alter the qualitative nature of the results.

Temperature-salinity properties

The temperature-salinity relationship for each cruise is shown in Figs 2a-12a; Figure 14 shows this relationship for all data from all cruises. In addition, on each of these plots the mean T-S curve for latitude 30°S longitude 100°E (Ridgway and Loch, 1985) has been drawn and bracketed with the curve for one standard deviation.

These figures show that the data are mainly within one or two S.D. of the mean, but that a few points are well outside these limits and different from other values obtained on the same cruise. Such anomalous points (chosen by eye) are present in three cruises:

- Cruise 7

  Two values on the T-S curve from the outer section at 113°30'E (Fig. 8a) at 250 m and 415 m, and a third from the station at 114°17'E at the surface.

- Cruise 10

  Two anomalous points are apparent in the T-S diagram (Fig. 11a): one in the station at 113°30'E at 812 m and the other in the 114°17'E station at 840 m.

- Cruise 11

  One anomalous value is present in the T-S diagram for this cruise (Fig. 12a) at the inshore station 115°05'E at 627 m.

We have not corrected these values in the salinity or density plots.

Results for individual sections

The temperature, salinity and density anomaly (σ_t) for the first section (9-10 Nov. 1947) are shown in Figs 2b-d. Only the data from the six outer stations are shown. Figs 3b-d to 12b-d show comparable plots for each of the other 10 sections.

Temperature, salinity and σ_t plots are fairly similar in general characteristics, but there is usually a very well defined pycnocline, whereas the thermocline is not so well developed. This is because salinity generally has a maximum, near 35.8°/₀₀, at 50-200 m depth. The error in depth measurement is likely to increase with depth, and may have been serious when the vessel took measurements in strong currents (i.e. when wire angles were large). Thus the deep structure in Fig. 12 may be spurious. Figs 13a-k show surface temperature, salinity and (offshore from 115°05'E) geostrophic velocity relative to the bottom of each cast; the temperature and salinity data are in this case shown right into the innermost station, ≃ 5 km from Fremantle. While the geostrophic currents are not quantitatively reliable due to errors in depth measurement, the qualitative pattern should be useful.

Temperature and salinity scales vary from diagram to diagram. The surface temperature usually shows a maximum slightly inshore from the fastest southward-flowing surface current; however, this inshore displacement may be an artefact of the finite horizontal resolution in these sections. Temperatures increase westwards over the shelf, in all but one case (12 Dec. 1948). The surface salinity generally has a minimum near the peak of southward current, as would be expected from Rochford (1969b); its behaviour over the shelf is erratic, and probably relates to the coastal runoff in the days or weeks preceding each section.

Steric height data

All but 4 of the 55 hydrographic stations beyond the shelf break extended to 450 db or greater. Figs 14a-d show individual steric height observations at

0, 100, 200, and 300 db, relative to 450 db (referred to below as $D_{0/450}$, $D_{100/450}$, $D_{200/450}$ and $D_{300/450}$ respectively). Rings around a data point indicate that a salinity value is in doubt. The full curved lines in Fig. 14 join the mean values at each station, and the error bars indicate 95% confidence limits on these means, estimated as $2/\sqrt{10}$ standard deviations. In Fig. 14, the means are simple averages over the available data; the data are sufficiently evenly distributed with respect to time of year for this to be a good approximation to the annual mean.

The vertical dashed lines in Fig. 14 represent the edges of the bins used by Godfrey and Ridgway (1985), and the horizontal dashed lines show the mean annual steric heights they obtained within each bin. It can be seen that at all levels and in all bins, the average steric height from the "Warreen" data within a bin is surprisingly close to the average obtained by Godfrey and Ridgway - and their data set did not include the "Warreen" data. However, the very marked increase in slope of annual average steric height as the shelf is approached was not resolved by Godfrey and Ridgway's relatively coarse bin spacing; thus their estimate of 2×10^6 m^3 s^{-1} for the Leeuwin Current transport may be a serious underestimate. For example, the geostrophic transport relative to 450 db between 113°30' and 115°05'E is 5.8×10^6 m^3 s^{-1}; and if the geostrophic flow between 114°53' and 115°05'E is assumed to hold in to the shelf (as assumed by Reid and Mantyla, 1976), the transport between 113°30'E and the 100 m isobath is 8.9×10^6 m^3 s^{-1}. However, these large transports may in part be spurious, deriving from some systematic error in depth measurement.

Annual average sections of temperature, salinity and density

Figure 15a shows the T-S relationship with all points included, and Figs 14b-d show annual average sections of temperature, salinity and density. The structure apparent in Figs 1-11 is largely smoothed out; contours are nearly horizontal, except quite close to the continental shelf edge, where they slope downwards.

The temperature sections of Figs. 15a-c have already been described in the Introduction.

Conclusion

While the error sources discussed earlier limit the usefulness of these results, two important conclusions emerge quite clearly. First, with presently available data, the annual average mass transport of the Leeuwin Current cannot be determined even within a factor of two. A quite large observational effort, with closely spaced current meters and/or hydrographic stations, would be needed to improve on this situation. Secondly, the narrowness of the current compared to other eastern boundary currents is emphasised in Fig. 16, which also suggests that the geostrophic currents may extend fairly deep in the nearshore zone.

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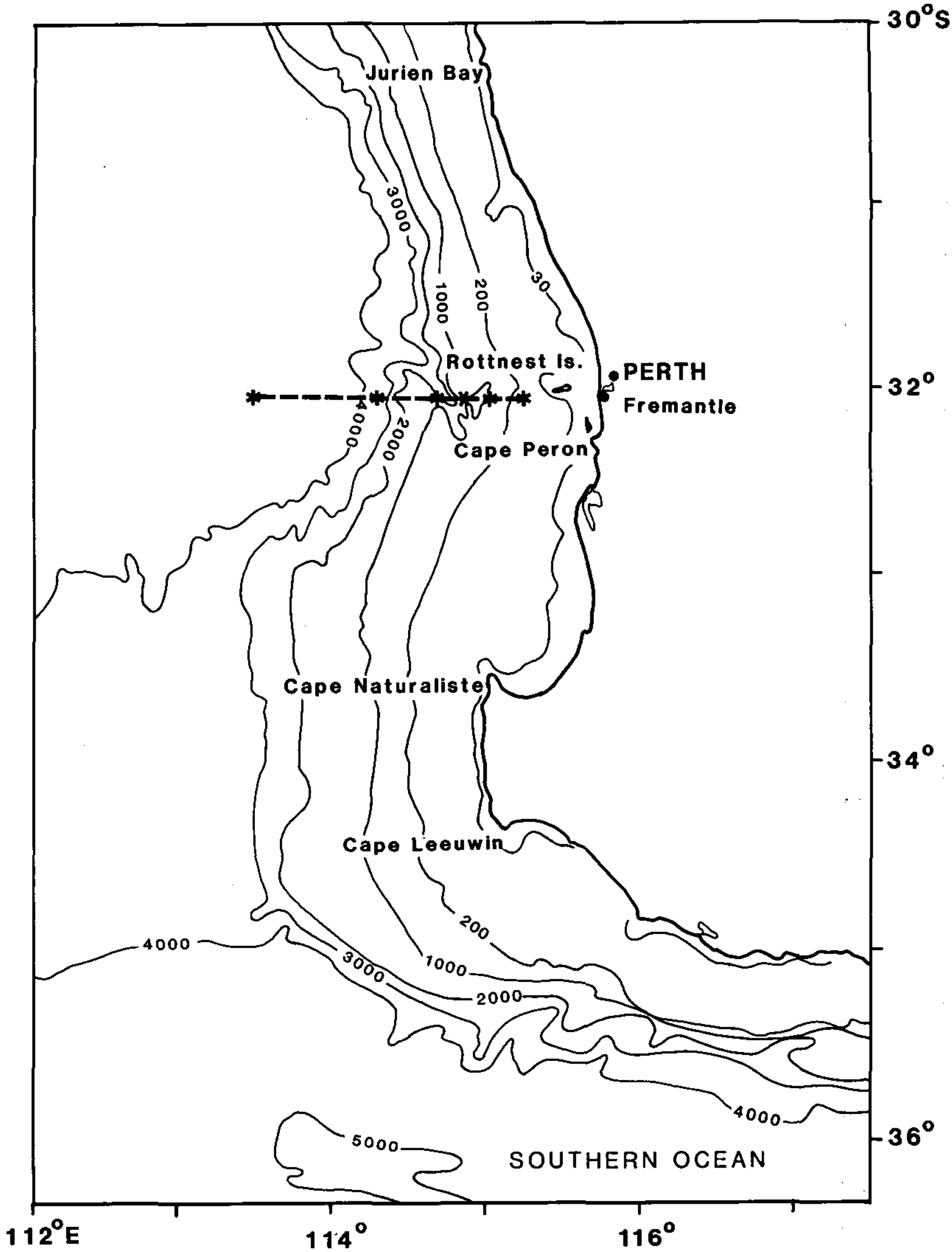


Figure 1: Location of the "Warreen" Sections. Crosses show station locations.

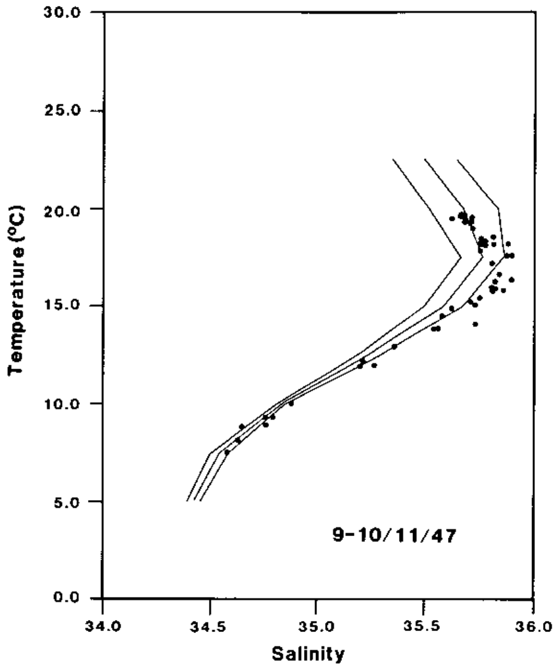


Figure 2a: T-S relationship for data of 9-10 November 1947 at 32°03'S

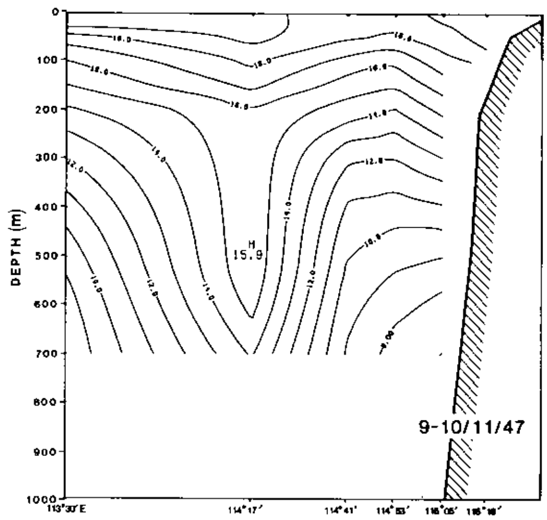


Figure 2b: Temperature section, 9-10 November 1947

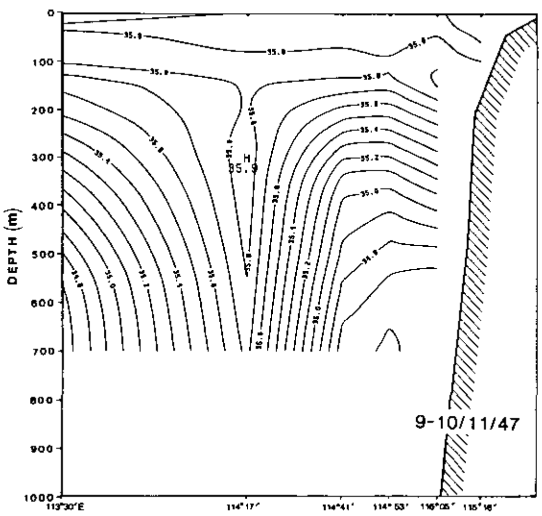


Figure 2c: Salinity section, 9-10 November 1947

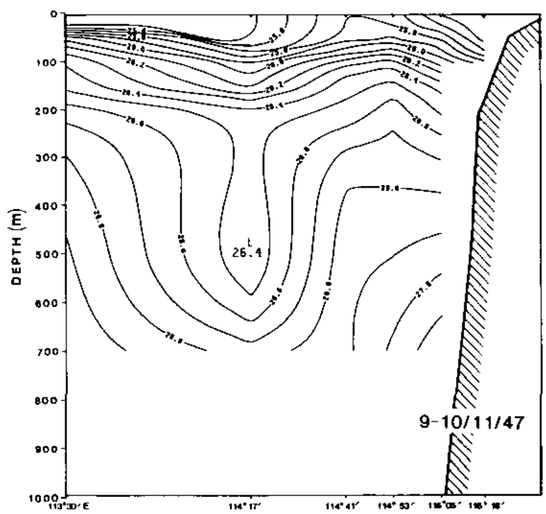


Figure 2d: Density anomaly (σ_t) section, 9-10 November 1947

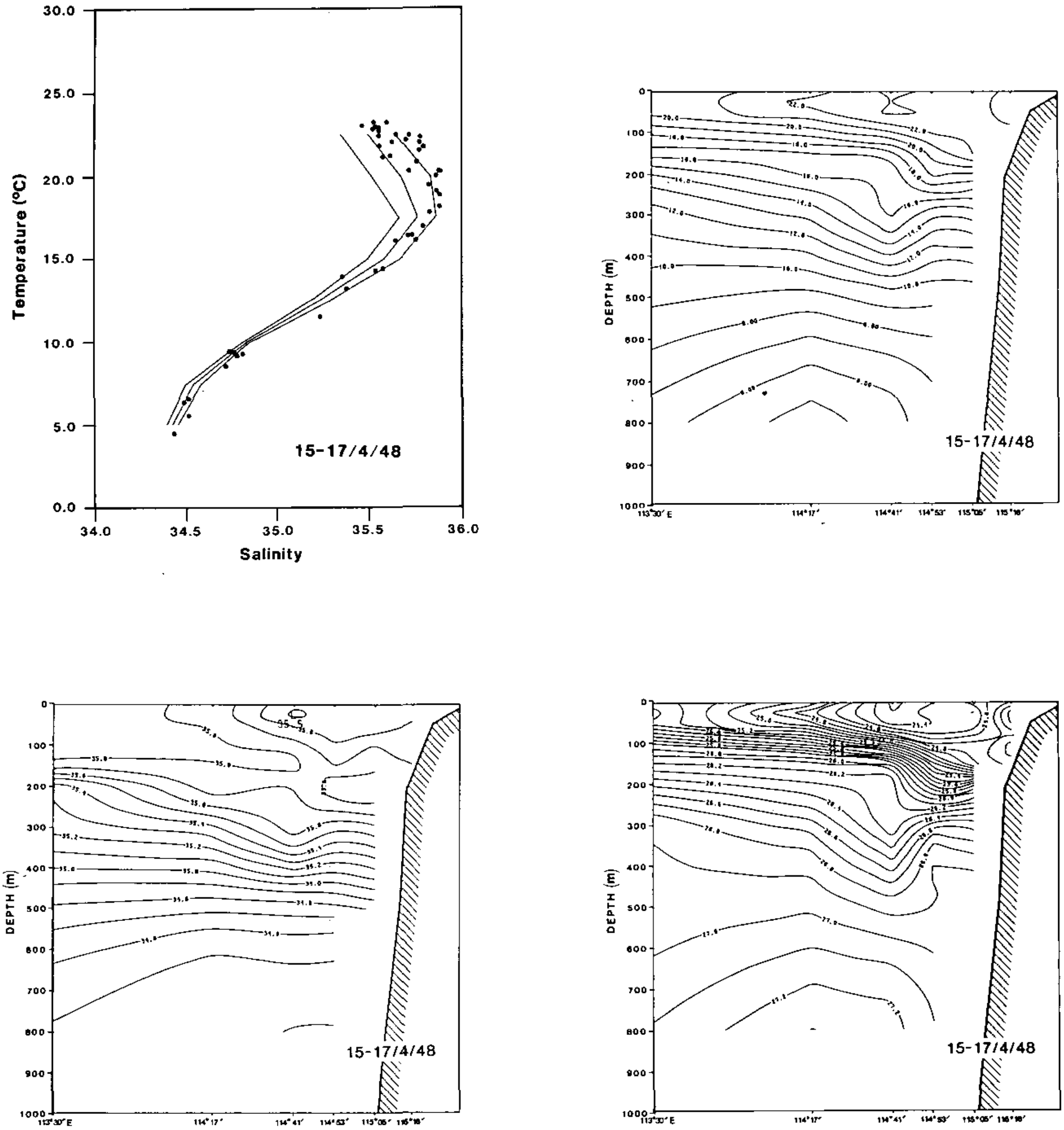


Figure 3: As for Fig. 2, 15-17 April 1948

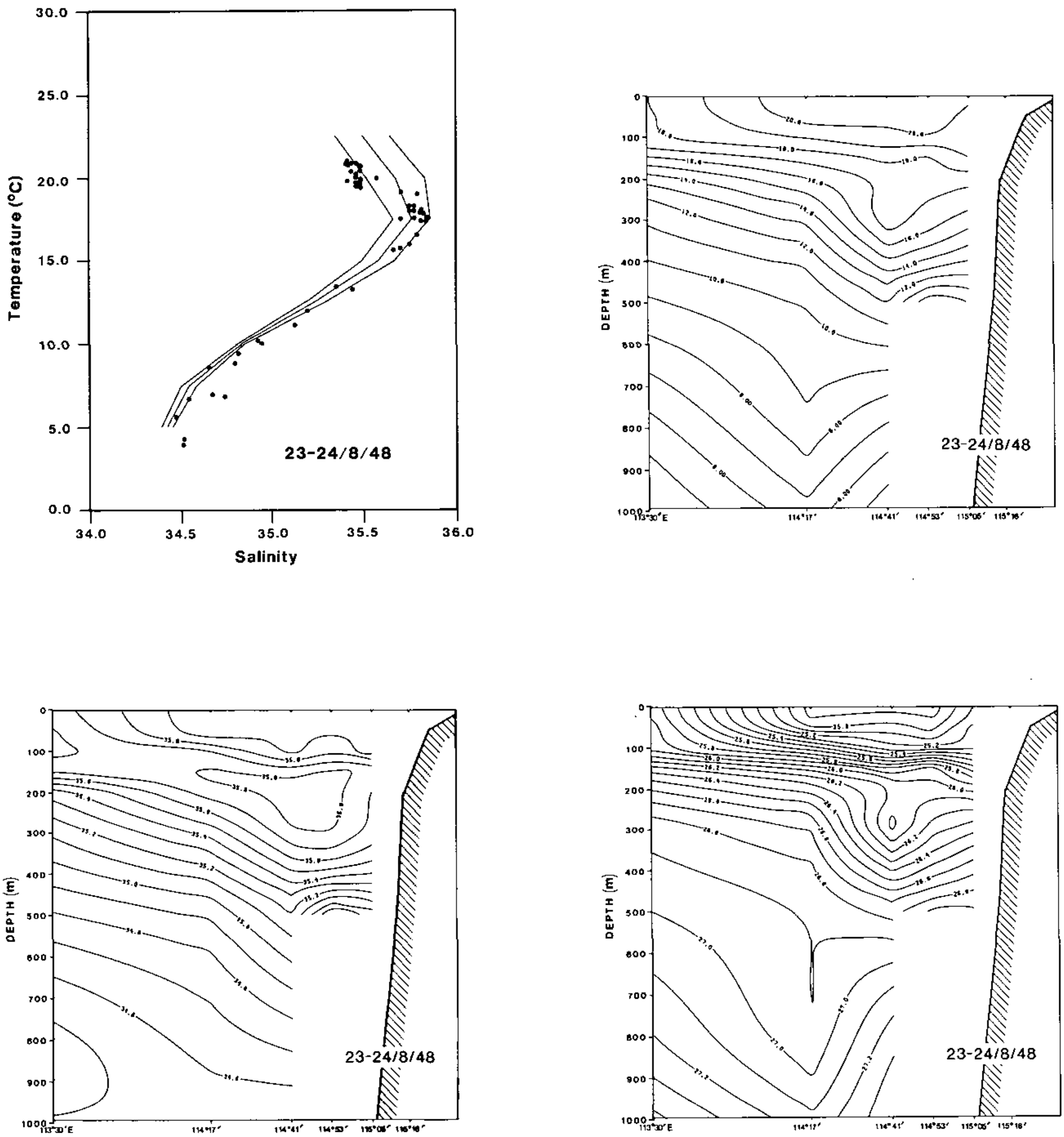


Figure 4: As for Fig. 2, 23-24 August 1948

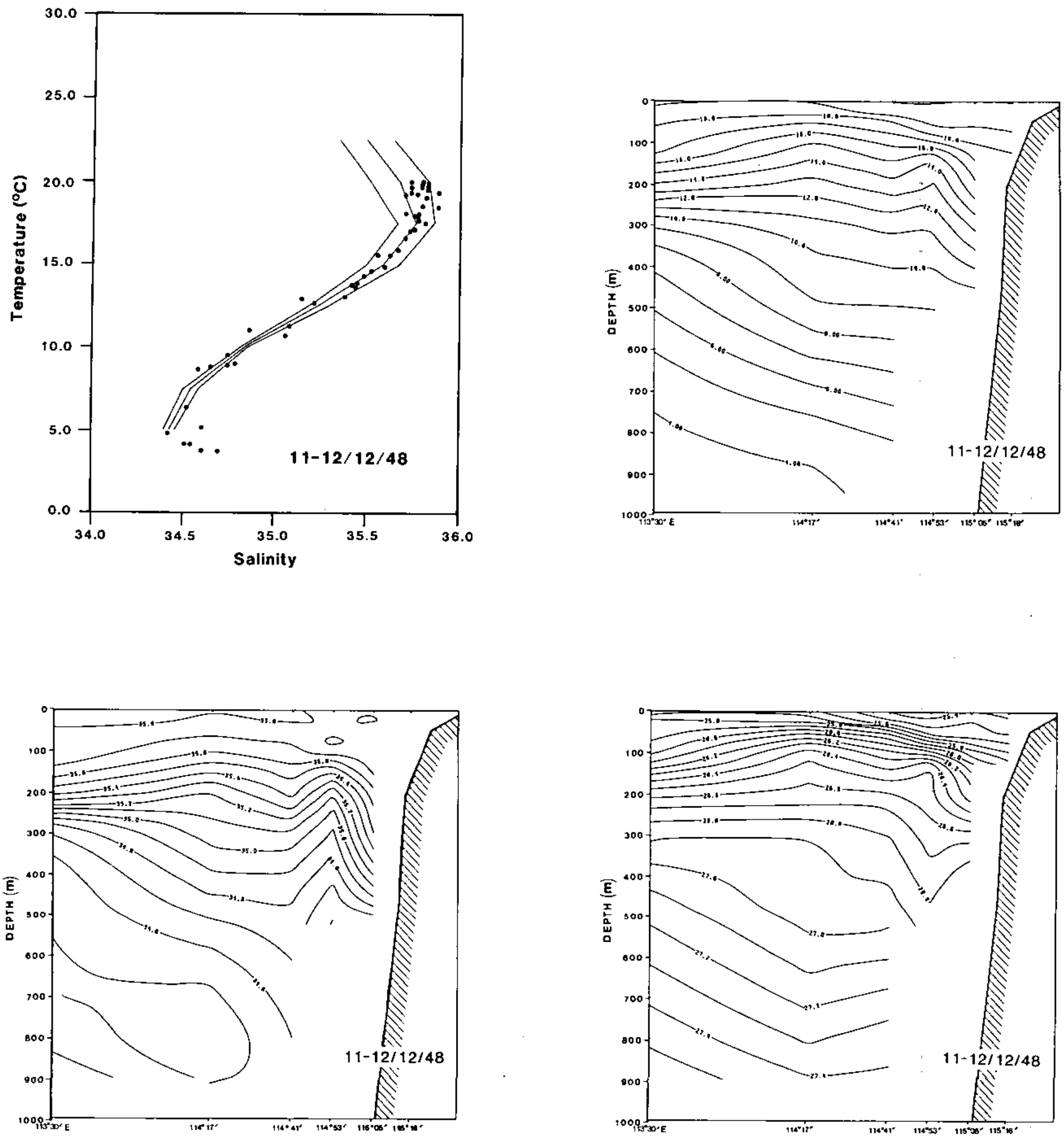


Figure 5: As for Fig. 2, 11–12 December 1948

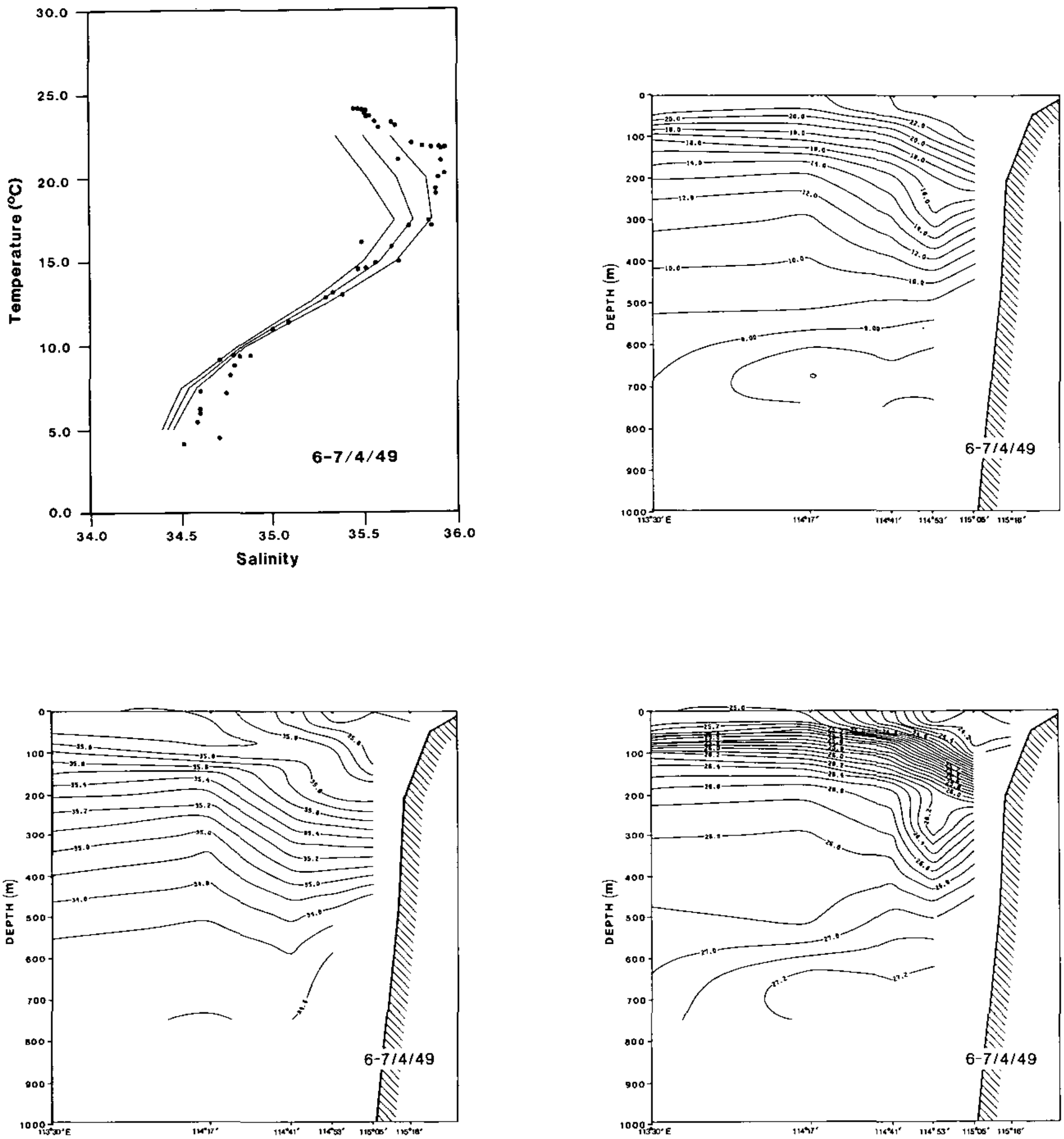


Figure 6: As for Fig. 2, 6-7 April 1949

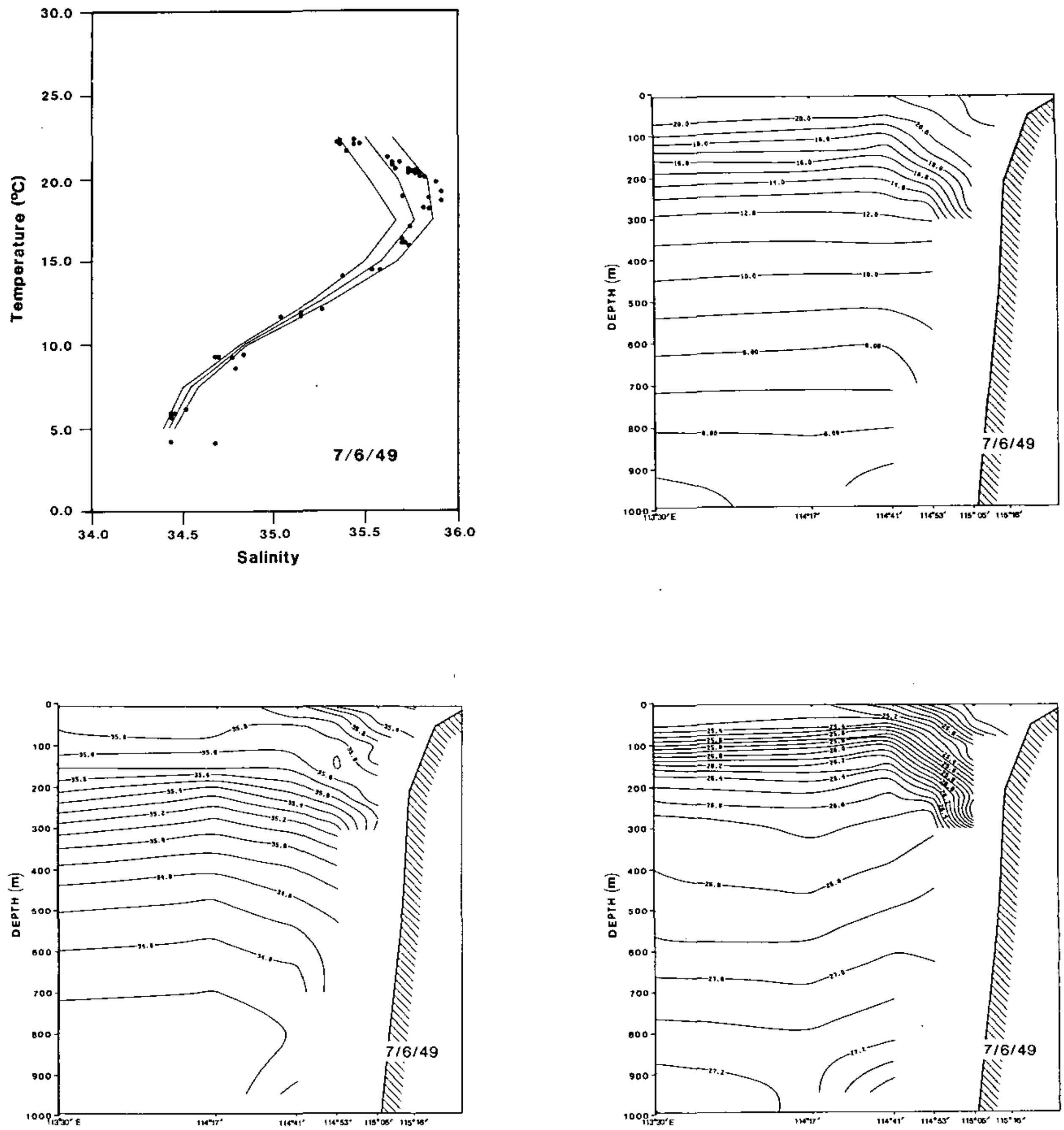


Figure 7: As for Fig. 2, 7 June 1949

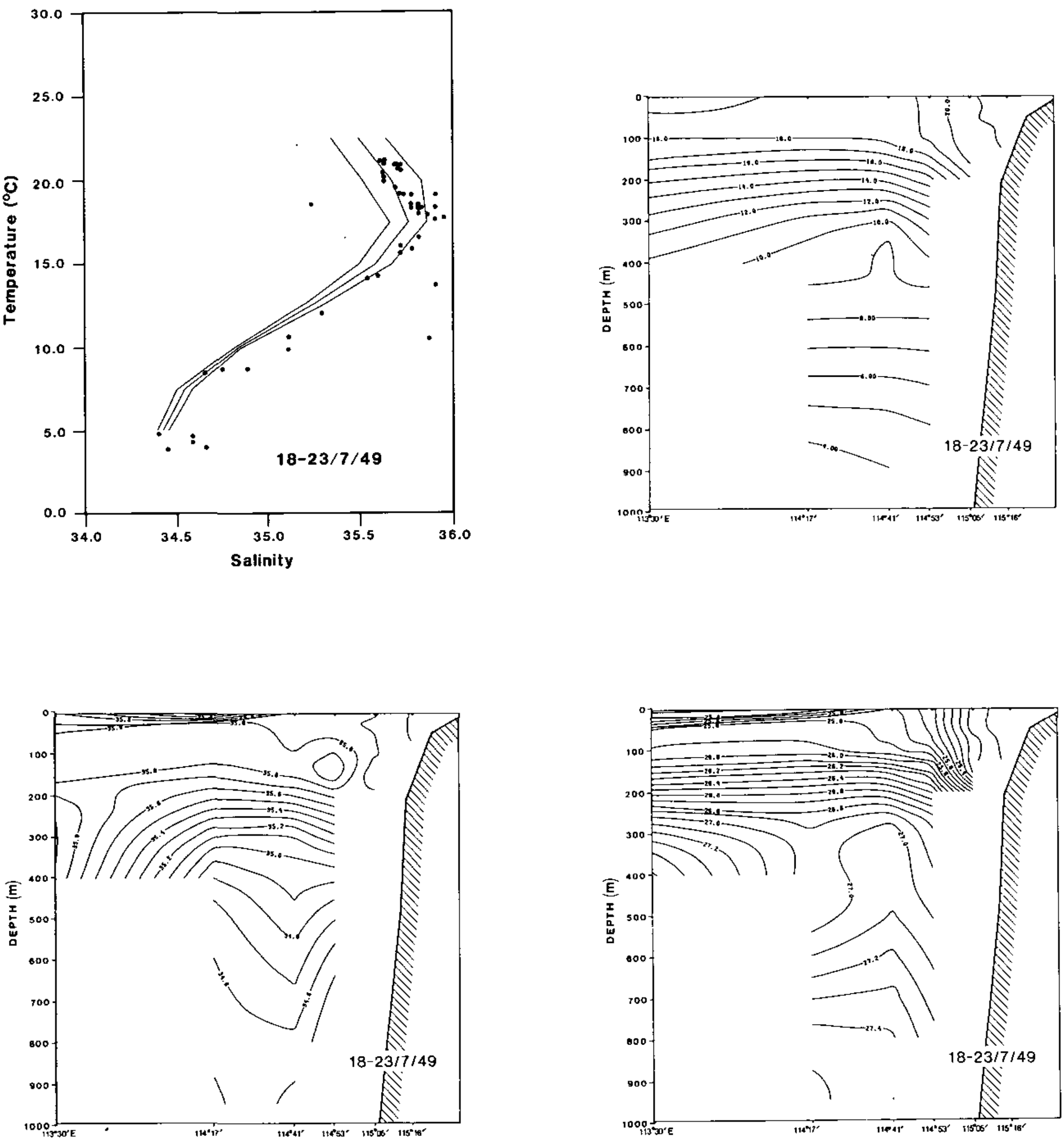


Figure 8: As for Fig. 2, 18-23 July 1949

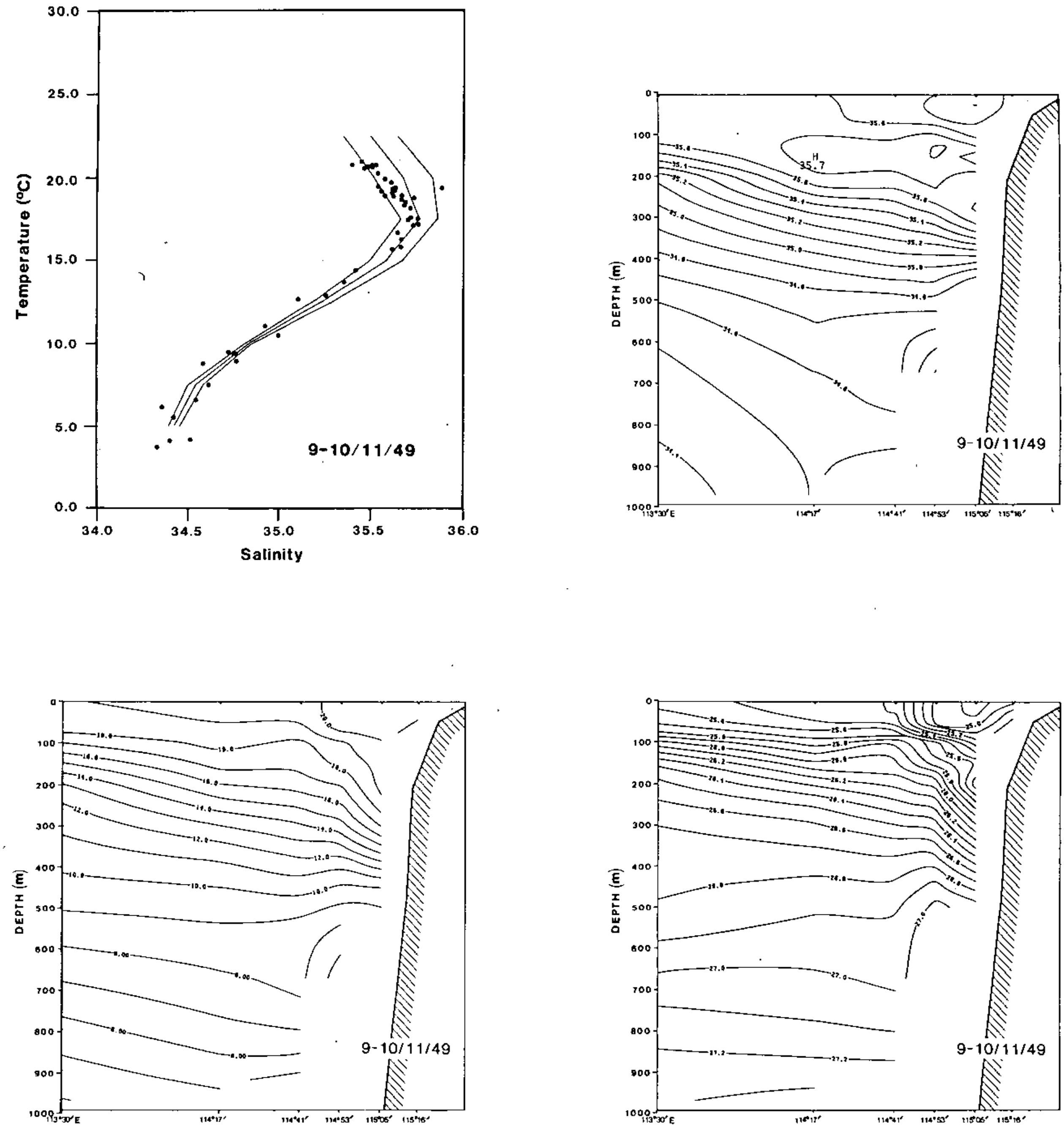


Figure 9: As for Fig. 2, 9-10 November 1949

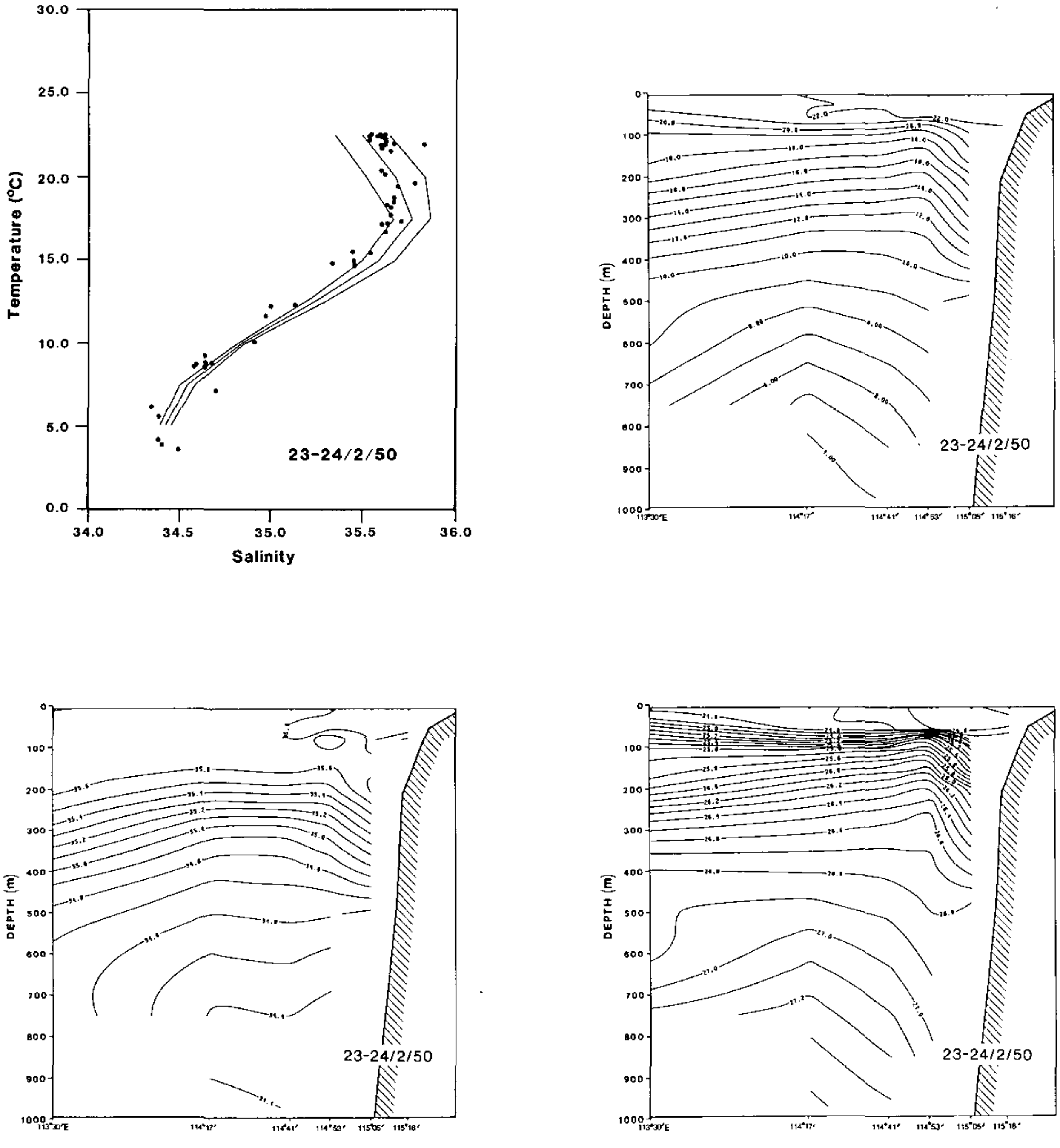


Figure 10: As for Fig. 2, 23-24 February 1950

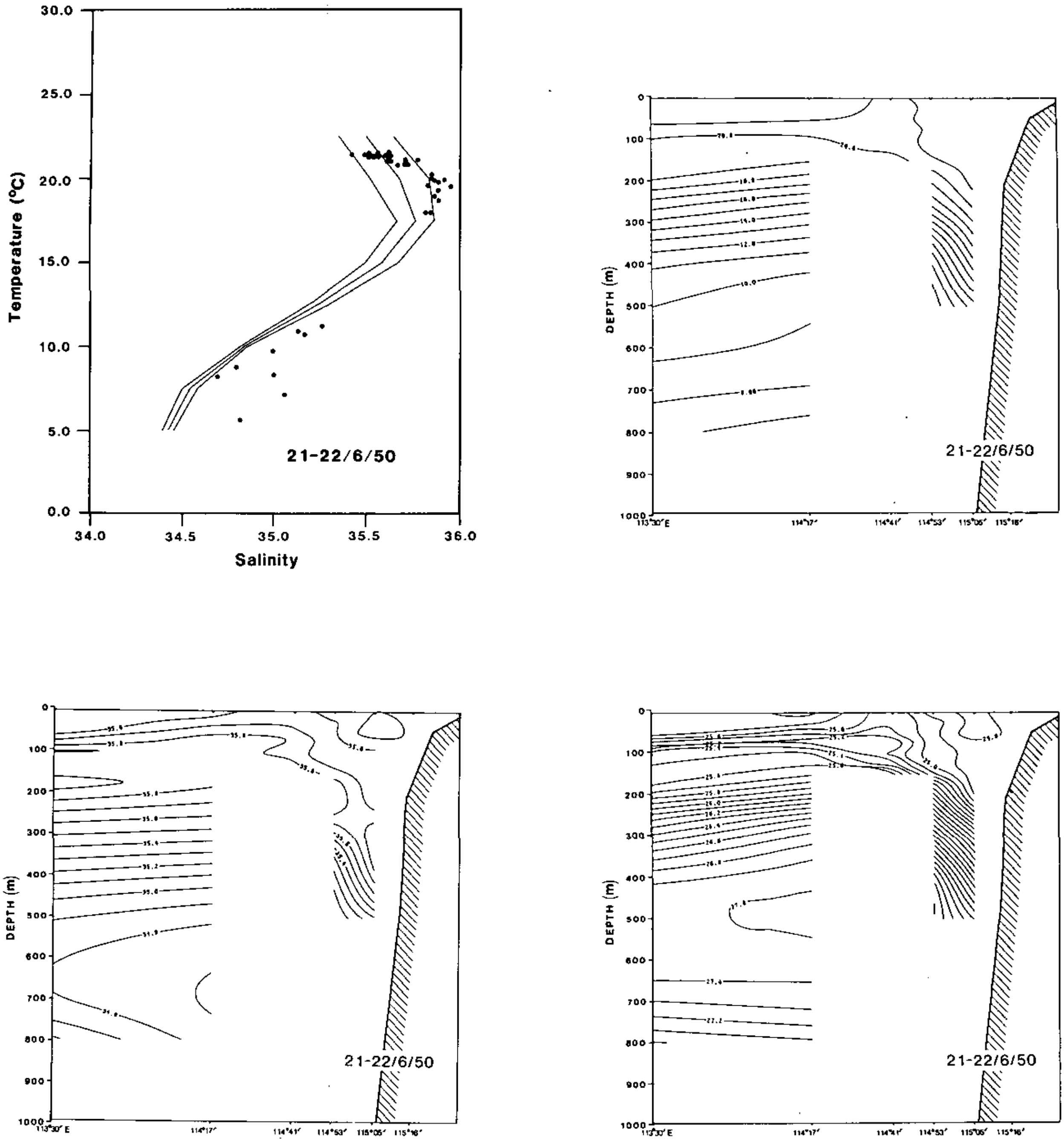
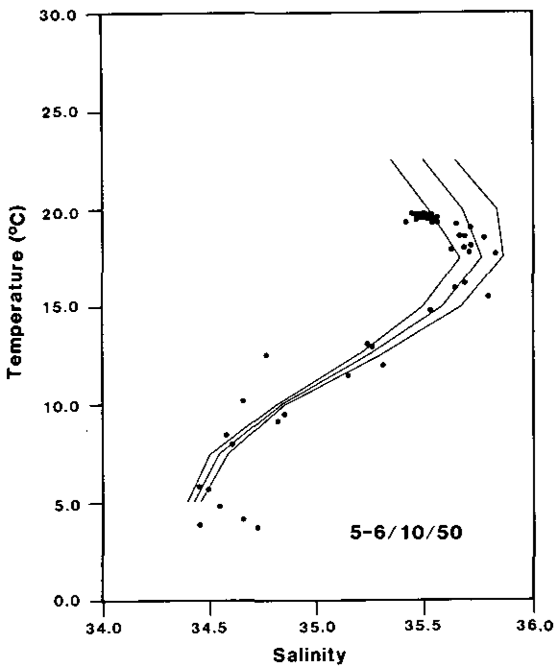
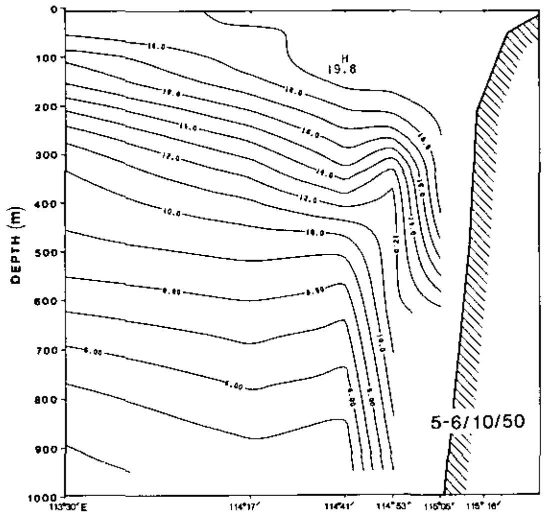
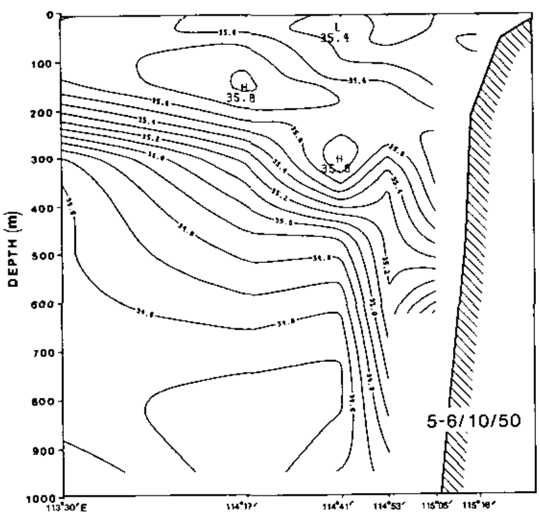


Figure 11: As for Fig. 2, 21-22 June 1950







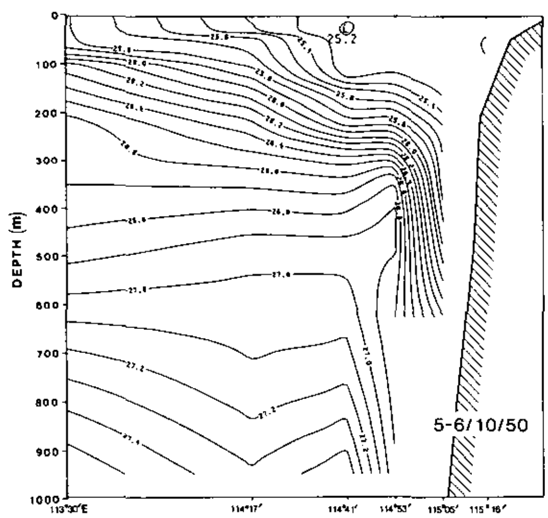


Figure 12: As for Fig. 2, 5-6 October 1950

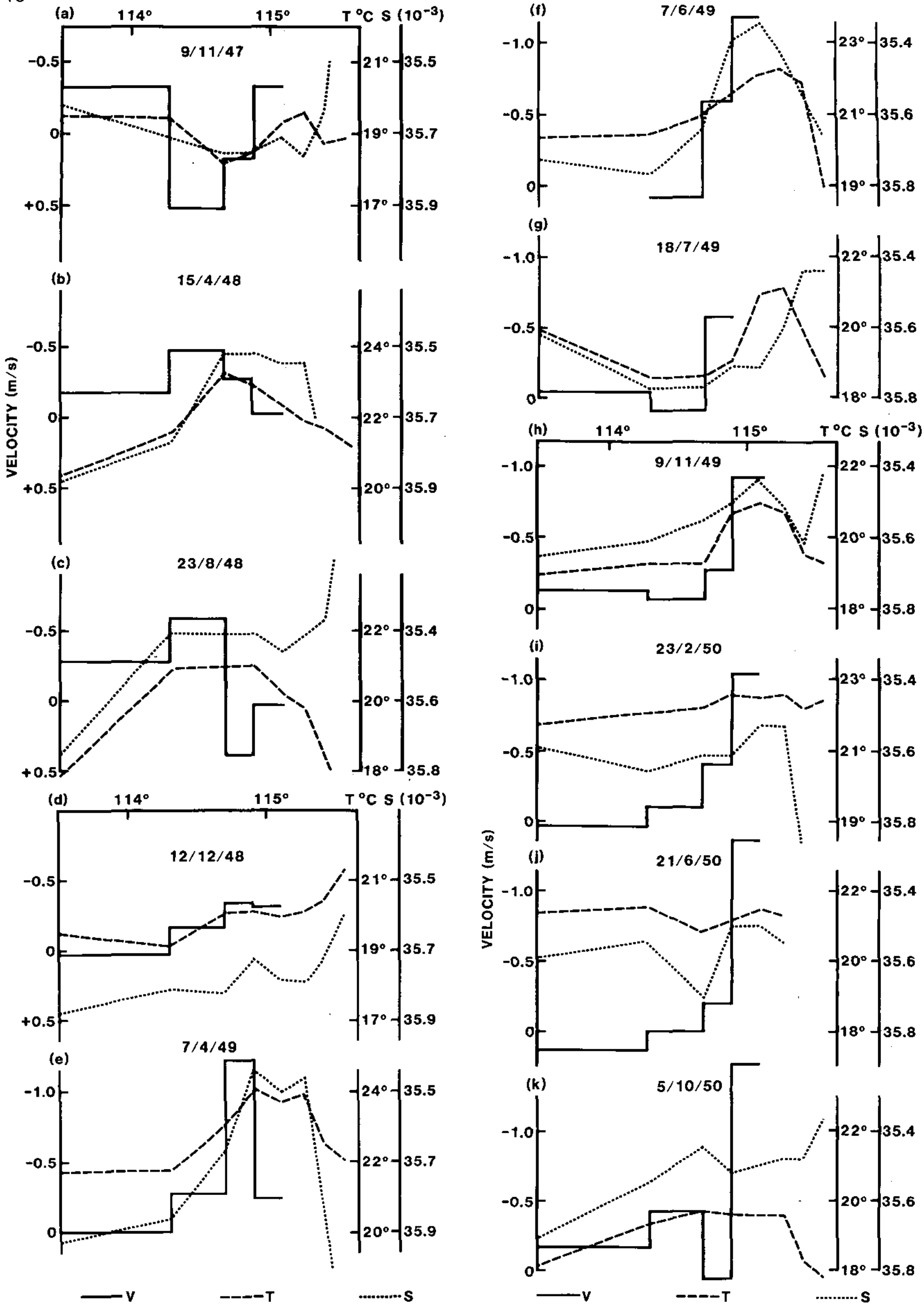


Figure 13a-k: Curves of surface geostrophic velocity relative to the bottom of the cast (full line); surface temperature (dashed line) and salinity (dotted line), for each of the sections of Figs 2-12. Velocities are negative to the south.

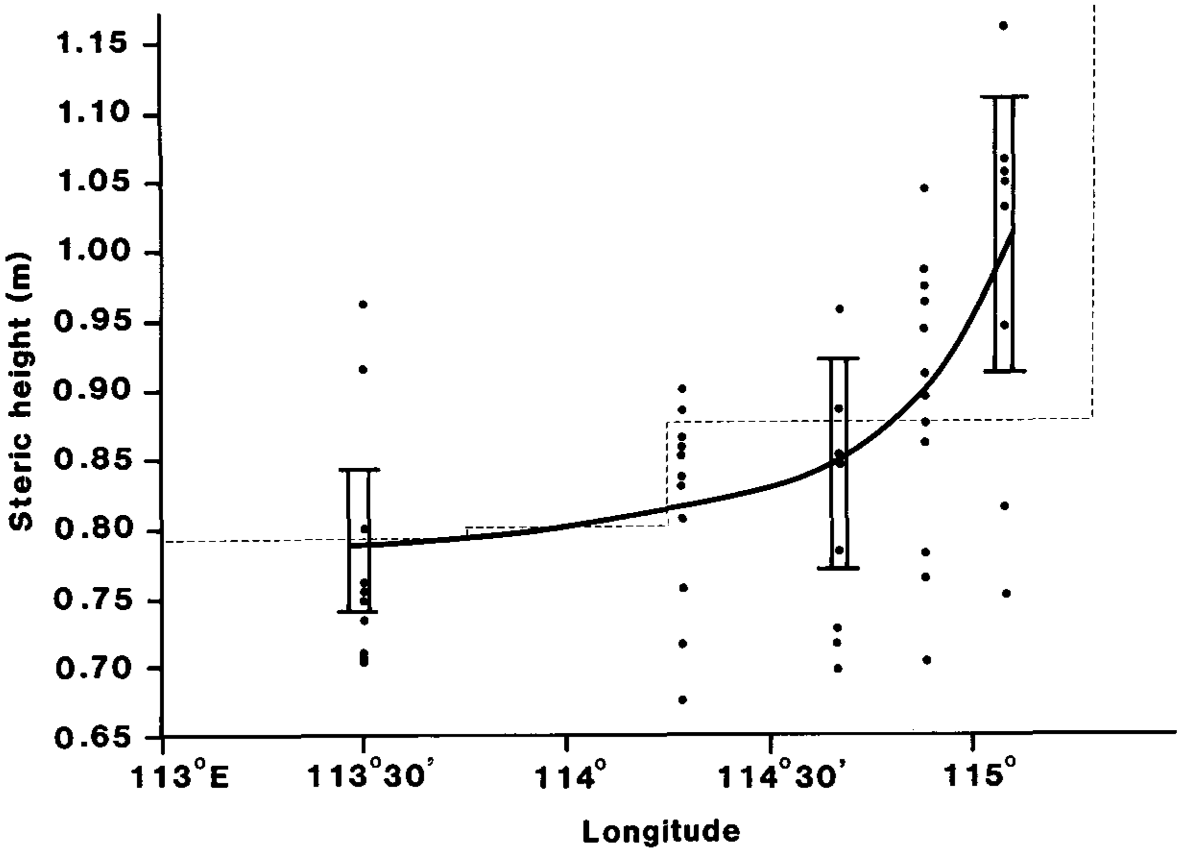


Figure 14a: The dots show all individual values of surface steric height relative to 450 db, from the "Warreen" data, in meters; the solid line connects average values, while the vertical bars show 95% confidence limits at each longitude. The vertical dashed lines represent the boundaries of Godfrey and Ridgway's (1985) bins, while the horizontal dashed lines give the annual average they found in the line of bins centred at 31.45°S

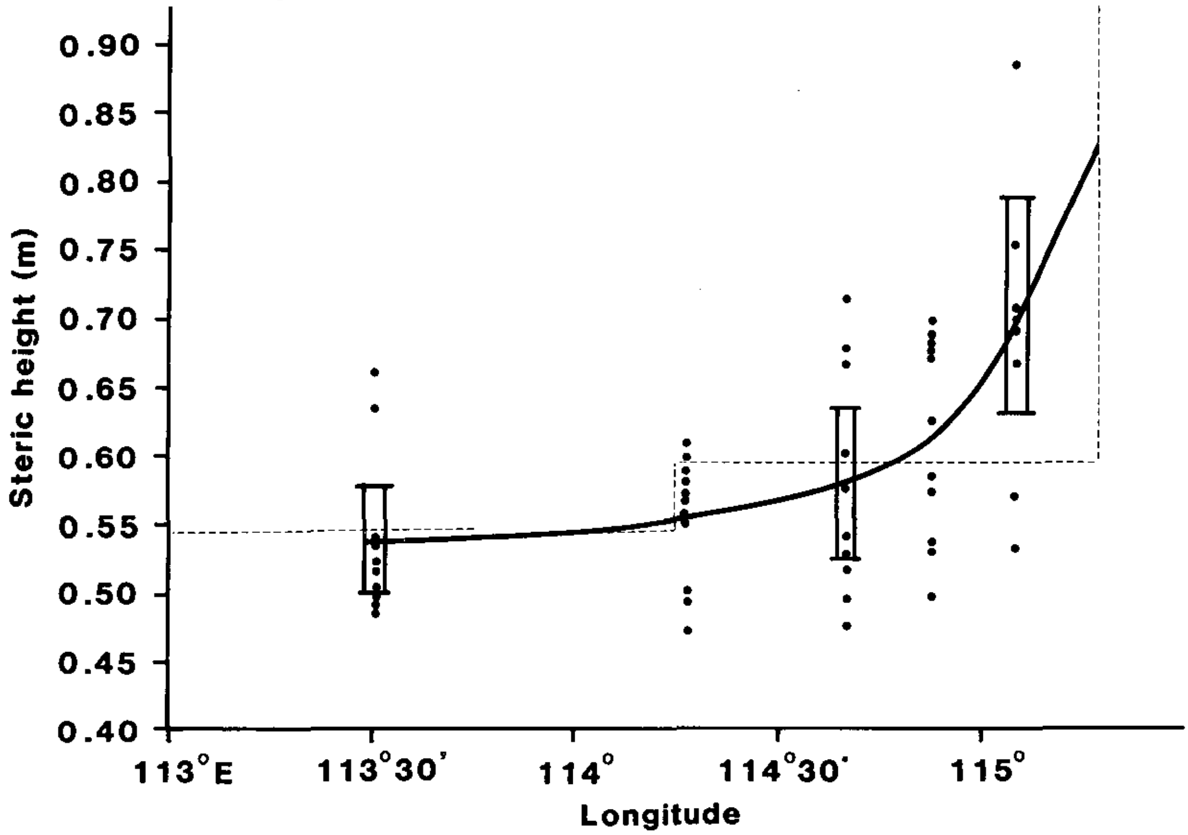


Figure 14b: As for Fig. 14a, but showing the comparable values at 100 m depth

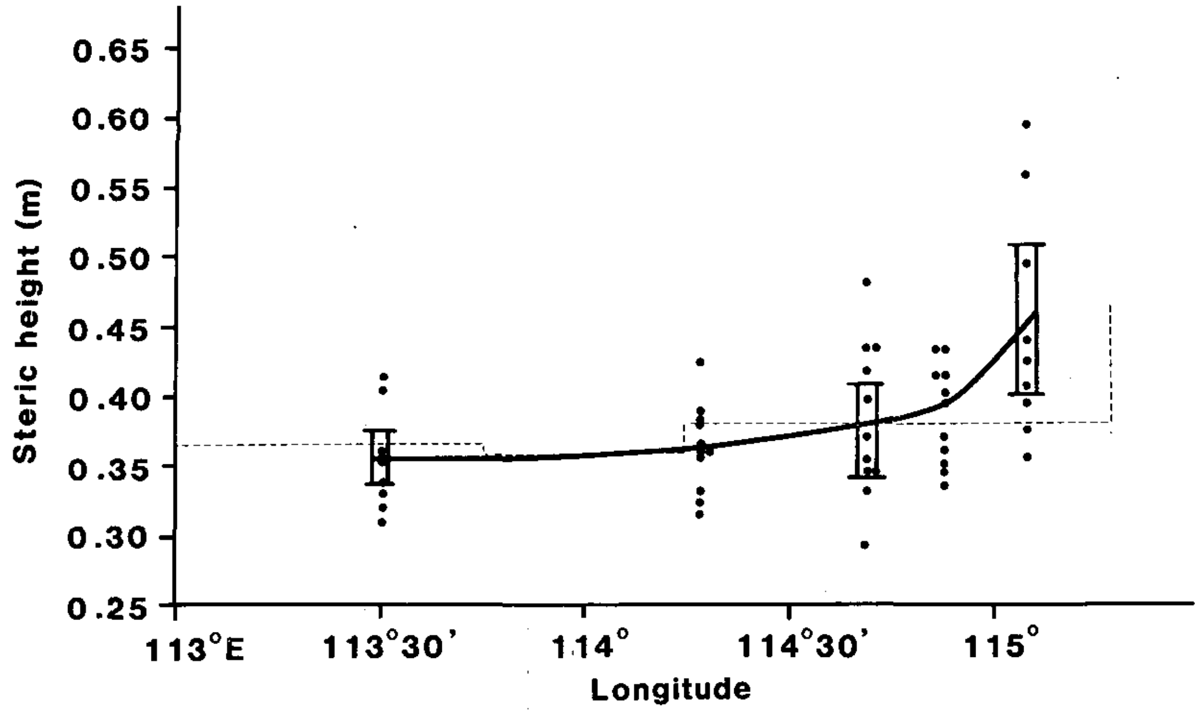


Figure 14c: As for Fig. 14a, but showing the comparable values at 200 m depth

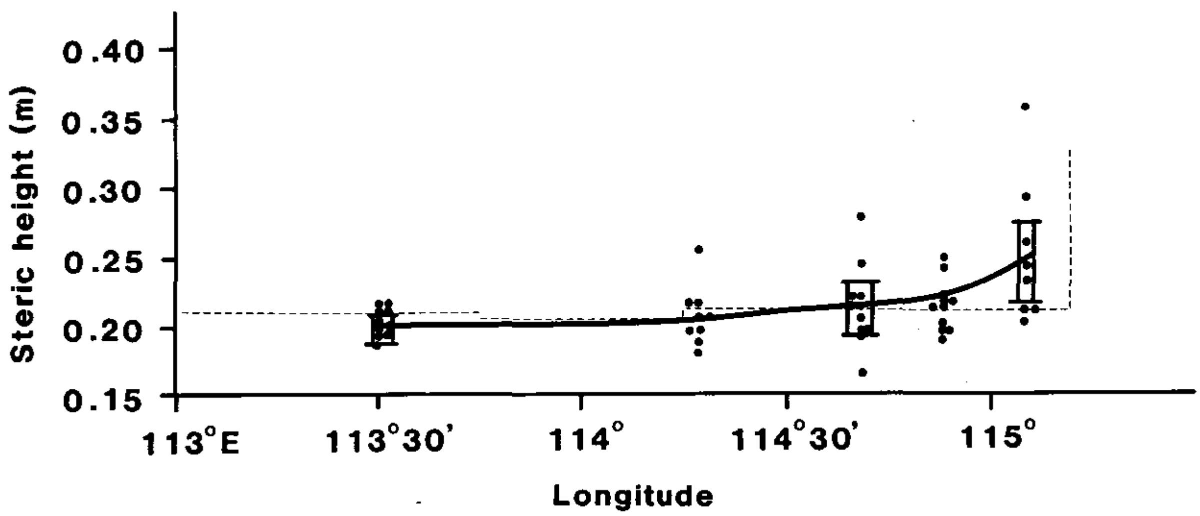


Figure 14d: As for Fig. 14a, but showing the comparable values at 300 m depth

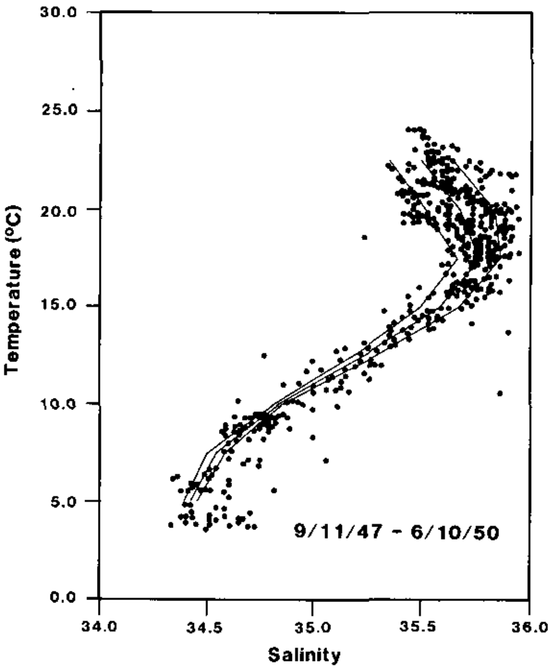


Figure 15a:

Temperature-salinity data, all stations

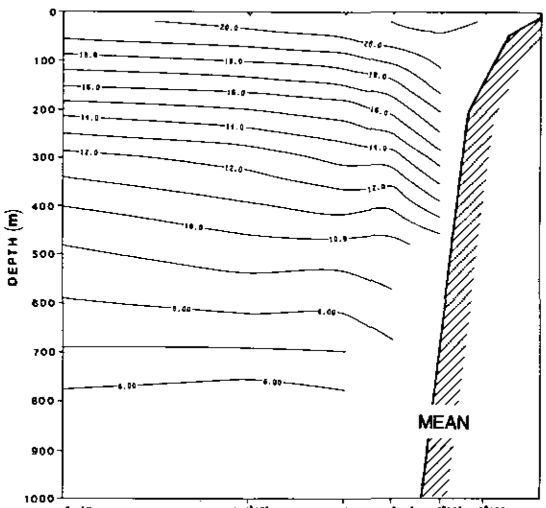


Figure 15b:

Annual mean temperature, all stations

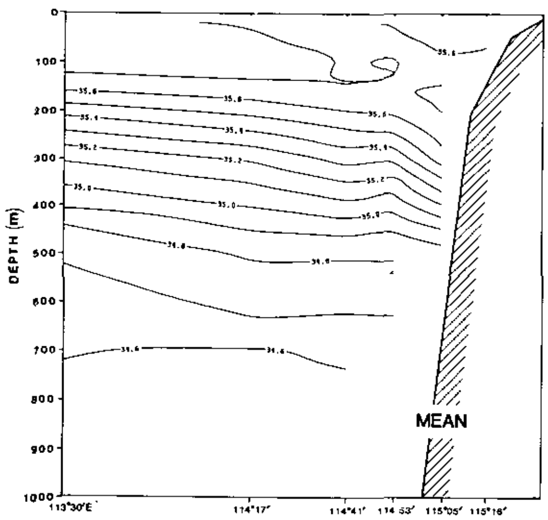


Figure 15c:

Annual mean salinity, all stations

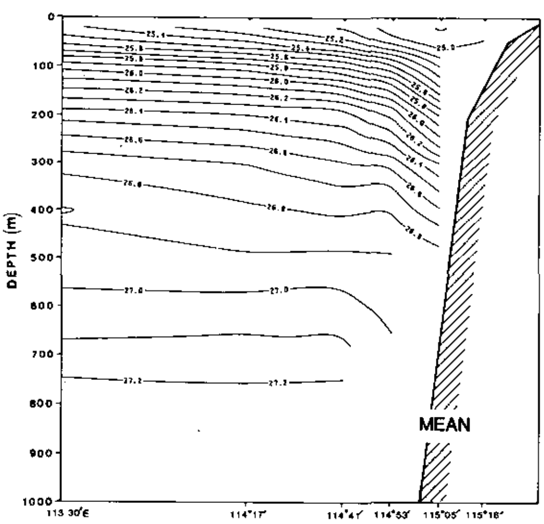


Figure 15d:

Annual mean density anomaly, all stations

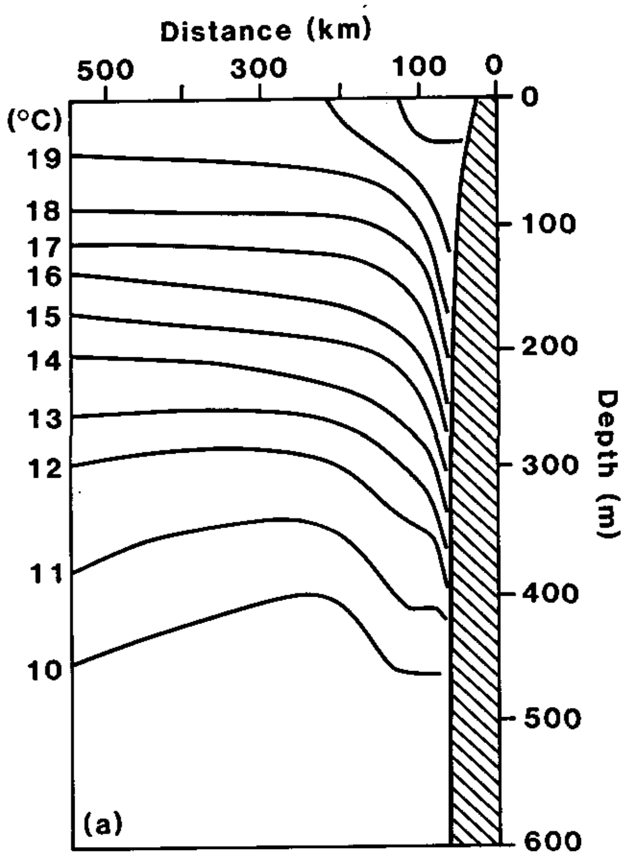


Figure 16a:
Annual average temperature, along a section at 32°S off Western Australia. Between the coast and 113°30'E, "Warreen" data have been used; values at 110°E have been taken from Rochford (1969b)

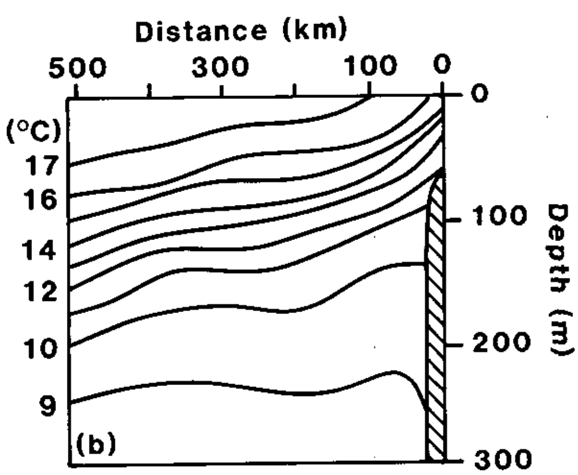


Figure 16b:
Annual average temperature, along a section at 30° - 31°N out from California. From Wyllie and Lynn (1971)

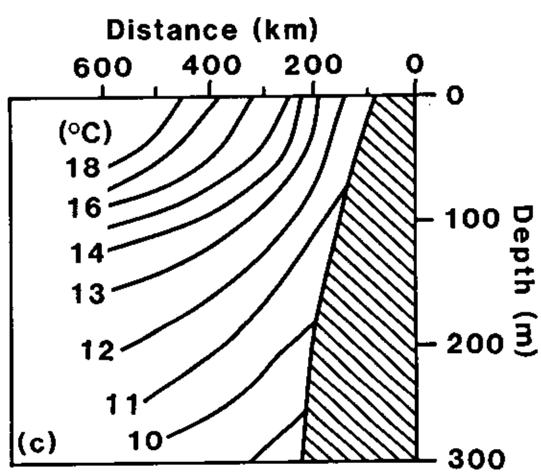


Figure 16c:
Annual average temperature, along a section at 26°30'S off the South African coast. Adapted from Schell (1970)

CSIRO
Marine Laboratories

comprises

Division of Oceanography
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HEADQUARTERS
Castray Esplanade, Hobart, Tas
G.P.O. Box 1538, Hobart, Tas 7001,
Australia

QUEENSLAND LABORATORY
233 Middle Street, Cleveland, Qld
P.O. Box 120, Cleveland, Qld 4163

WESTERN AUSTRALIAN LABORATORY
Leach Street, Marmion, WA
P.O. Box 20, North Beach, WA 6020

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