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Seasonal Influx of Nitrates to the Slope and Shelf Waters off North-West Australia

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Abstract

From mid-1982 to early 1984, CSIRO made nine oceanographic cruises within a 30,000 sq km rectangle of coastal and offshore waters off north-west Australia.

Results from these cruises have shown:

(a) Nitrate enrichment by direct surface upwelling was not detected during this period.
(b) In summer and autumn, nitrate-rich tropical waters influxed into the slope and shelf-bottom zone, with very little effect on surface nitrates.
(c) In winter, downwelling of coastal waters into mid-depth subtropical waters (both of which are nitrate-poor) kept nitrates at very low levels in slope and shelf waters.

Earlier CSIRO cruises in the North West Shelf region of Australia found much the same seasonal pattern of nitrate distribution throughout the region well to the north of the 1982-84 site.

No consistent connection between the direction of longshore currents and the nitrate concentrations in NW Shelf waters in summer was found. Generally, however, nitrates in summer were in higher concentration near the upper part of the shelf break, and available for onshore transport by a variety of physical processes, including internal waves and tidal currents. Because nitrates in winter were in low concentration along the shelf break, it was difficult to see how any physical process could transport nitrates in quantity into the shelf water. Upwelling pulses at the shelf break could not be linked in every case with nitrate-enrichment episodes within the shelf region in summer.

Questions relating to the ability of biological populations on the shelf to take advantage of transient pulses of nitrate-enriched water in summer and to maintain high production in the absence of nitrate in winter will require further investigation.

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1. INTRODUCTION

Since 1935, when Schott claimed that upwelling occurs in the Austral spring off north-west Australia, little relevant oceanographical data was collected to substantiate this until the early 1960s. Rochford (1962), largely on the basis of limited surface phosphate anomalies, concluded that upwelling did occur in September in north-west Australia; Wyrtki (1962), on the basis of two winter cruises with limited access to the near-shore region, considered that upwelling was only likely to occur off north-west Australia on the rare occasions when "the general wind pattern deviates considerably from average". He considered the December to March period offered the best prospects for upwelling to occur. Later Rochford (1977), using more extensive data, found no evidence for upwelling off north-west Australia, although there was biological evidence for some form of enrichment, which required explanation (Tranter and Kerr 1977). Continuous interest from Taiwan and other countries in the fishery potential of the North West Australian shelf region was further evidence of biological production being higher than the generally low level in most of the waters surrounding Australia (Bain 1982).

During the period of the CSIRO study, continuous temperature records between 23.5 m and 120.5 m depth, adjoining the CSIRO W3 station (Fig. 1), were obtained (Holloway and Nye 1985). These records show that pulses of cold water occurred during the summer of 1982-83. The possible role of these pulses in the nitrate enrichment of the North West Shelf is examined in this paper.

The relative importance of a number of physical processes in maintaining an adequate supply of nitrates in North West Shelf waters have been reviewed by Holloway et al. (1985). They favoured tidal-induced onshore transport (given certain biological conditions) as the most likely year-round mechanism for the transfer of nitrates from a deep offshore nitrate pool adjoining the shelf break into the shelf waters.

However, the results from nine cruises made in the CSIRO study site (Fig. 1) during 1982-84 show that this nitrate pool undergoes large seasonal changes in depth; in winter especially it limits the supply of nitrates by physical processes to the North West Shelf. These seasonal changes are documented in this paper.

2. DATA

Table 1 List of cruises

Cruise	**Dates**	**Where used**
Soela 4/82	31/7 to 2/8/82	Figs 3, 5, 6,
Soela 5/82	10/10 to 15/15/82	Figs 9
Soela 6/82	12/12 to 15/12/82	Figs 7, 8, 9
Soela 1/83	23/2 to 28/2/83	Figs 7, 8, 9
Soela 2/83	19/4 to 24/4/83	Figs 3, 7, 8, 9
Soela 3/83	21/6 to 24/6/83	Figs 5, 6, 9
Soela 4/83	2/8 to 25/8/83	Figs 5, 6, 9
Soela 5/83	22/10 to 31/10/83	Figs 9
Soela 1/84	25/1 to 26/1/84	Figs 8, 9
Diamantina 2/61	6/5 and 9/5/61	Figs 10, 11
Diamantina 1/62	21/2 and 22-23/2/62	Figs 10, 11

The positions of the stations to be occupied on each cruise (Table 1) are shown in Figure 1. The two sections running offshore are called the "Western" and "Eastern" sections. A much less detailed section utilising the two outermost stations of these two sections and the station fairly regularly occupied at 18°30'S 117°30'E is called the "Offshore Section". The approximate position of the 200 m isobath serves to delineate onshore from shelf-break and oceanic stations.

Nitrates were determined at all stations on each cruise and were used therefore as a measure of overall nutrient levels, despite the lack of other nitrogenous constituents.

Silicates were also routinely measured, but since they correlated well with nitrates, have not been utilised as an additional nutrient characteristic.

3. MAJOR WATER MASSES

Two water masses largely control the salinity, oxygen and nitrate characteristics of the waters below 100 m in the offshore region of the CSIRO study site: a high-salinity, well-oxygenated, nitrate-poor water mass originating in the subtropical south-east Indian Ocean (full lines, Fig. 2) and a low-salinity, poorly oxygenated, nitrate-rich water mass originating in the tropical east Indian Ocean to the north of the site (dashed lines Fig. 2). These two water masses also dominate the subsurface characteristics of waters along 110°E (Rochford 1967) some 600 km to the west. Upwelling of deeper waters to the surface or near-surface, or the mixing of deeper with surface water can have only a very limited effect on the nutrients whenever the subtropical water mass is present. On the other hand, the low-salinity tropical water mass can, because of its low density, spread over the subtropical water mass and increase the nitrate content of the upper 100 m column. When this happens the potential for nitrate enrichment of surface or near-surface water is greatly increased.

Any seasonal changes in the distribution of these two water masses within the study site would largely control the nutrient concentrations in the subsurface layers, thereby controlling the degree of enrichment by upwelling or mixing.

4. SEASONAL CHANGES IN THE NORTH/SOUTH DISTRIBUTION OF WATER MASSES

By late winter the subtropical water mass extends almost to the north-east limit of the CSIRO site (Fig. 3a). From early summer through to mid-autumn, the tropical water mass gradually extends southward, leaving only a small remnant of the sub-tropical water mass in the south-west of the site (Fig. 3b).

Some of these seasonal changes in the distribution of these two water masses could be caused by onshore-offshore displacement, but this is not considered a major cause in view of the predominant south-west or north-east orientation of currents offshore (Holloway and Nye 1985).

Along 110°E, seasonal changes in the boundary between these two water masses follow a different pattern (Rochford 1967). In winter, along 110°E the subtropical water mass lies at its southernmost position, in contrast to the northernmost positioning in the CSIRO site. In summer, the positioning of this water mass along 110°E and in the CSIRO site is reversed (Fig. 4).

Large-scale changes in the major current systems off north-west Australia (Rochford 1967) are thought to be responsible for these reversals in the distribution of the subtropical and tropical water masses in the CSIRO study region (Fig. 4).

The southward drift in summer of the tropical waters of north-west Australia has recently been substantiated (Godfrey and Ridgway 1984; Holloway and Nye 1985). From summer to early autumn, the tropical water mass, with a relatively high nitrate content, occupies most of the upper 200 m of water in the CSIRO site. Near-surface nitrate enrichment is therefore potentially greater during summer than winter.

5. SEASONAL CHANGES IN SALINITY AND NITRATES ALONG THE WESTERN AND EASTERN SECTIONS

Along the western section during winter, the salinity of nearshore surface waters is increased by evaporation. As they lose heat, they sink to the bottom. These nearshore bottom waters of high salinity and negligible nitrate content spread offshore across the shelf (Figs 5a-c) and downwell at the shelf break against the upper margin of the subtropical water mass. As a result, nitrate-richer waters (greater than 5 µg at/l) lie deeper along the slope region than offshore. A similar pattern of salinity and nitrates exists along the eastern section in winter (Figs 6a-c), with little potential for nitrate enrichment of the shelf waters.

Along the western section in early summer (Fig. 7a), salinities within the subtropical salinity maximum are much reduced. The tropical salinity minimum and its nitrate-rich waters now extend well into the bottom and mid-depths coastal zone. There is no indication of downwelling onto the shelf break, although isolated pockets of high-salinity bottom waters still exist.

Along the eastern section in early summer (Fig. 8a), the subtropical salinity maximum has all but disappeared. The tropical salinity minimum extends well into the coastal zone, with nitrate-rich waters at around 50 m depth in the mid-shelf region. However, a strong salinity gradient against the coastal margin, prevents these nitrate-rich waters from extending further into the nearshore region. This onshore movement of nitrate-rich tropical waters continues through January (Fig. 8b), February (Figs 7b and 8c) and April (Figs 7c and 8d), especially in the eastern section.

Less downwelling (as evidenced by the salinities) onto the shelf break region occurred along the western section in August 1983 (Fig. 5c) than in August 1982 (Fig. (5a). Nitrate-rich water was found much further into the shelf region in August 1983. The extent of such winter downwelling could cause year-by-year variations in the availability of nitrates in the slope/shelf region of NW Australia.

6. CHANGES IN NITRATES WITH TIME AND LATITUDE ALONG THE WESTERN AND EASTERN SECTIONS

A time/latitude plot of the nitrates at 50 m on the Eastern Section (Fig. 9a) shows that the transfer of nitrate-rich waters into the coastal margin occurred only between December and March in 1982-83 and again in January 1984. The uplift occurred within a depth range of 75-150 m (i.e. on or around the shelf break).

Along the Western Section (Fig. 9b) the uplift occurred earlier in October but terminated in March 1983, as in the Eastern Section. The uplift was confined to much the same coastal margin as in the Eastern Section. Nitrate values during the uplift period were lower in the Western than in the Eastern Section.

Relative to the surface value of 6 µg at/l of nitrate found during upwelling off Laurieton NSW (Rochford 1975), these nitrate peaks at 50 m are quite small.

7. DISCUSSION

(a) "Upwelling" as the principal contributor to "summer nitrate enrichment" of slope and shelf bottom water

Between December 1982 and April 1983 three pulses of cold water (less than 21°C) were recorded at 120.5 m at the North Rankin site. They coincided with weak currents to the north-east (Holloway and Nye 1985). The pulse of cold water at the North Rankin site in December 1982 coincided with a sharp drop in temperature at 100 m and an increase in nitrates at 50 m, at the shelf-break stations along both sections (Fig. 9c).

The nitrate enrichments at 50 m in February and April 1983 (Fig. 9c) did not, however, coincide with the pulses of cold water at the North Rankin site; these latter events preceded the nitrate enrichments by some 3-4 weeks (Fig. 9c).

If cold water pulses at depths are always associated with the "upwelling" of nitrate-rich waters onto the shelf break of the North West Shelf, the observed nitrate enrichment at 50 m during cruises 1/83 and 2/83 must be the residue of a nitrate "upwelling" induced by cold water pulses offshore some 3-4 weeks earlier. How this could be possible in the face of the strong tidal currents and mixing (Holloway 1983) of this region requires further investigation.

(b) Longshore currents and the nitrate enrichment of slope and shelf bottom-water

(i) "Summer"

Nitrate enrichment at 50 m was found along the eastern section during all four Soela cruises between December 1982 and January 1984 (Fig. 9a); between December 1982 and April 1983 it was found on all three cruises along the western section (Fig. 9b). Along the western section the first cruise coincided with a flow to the north-east at the North Rankin site (Fig. 1). The other two enrichments occurred during a period of transition from the Leeuwin Current to the South West (February 1983) to a weak current to the north-east and during a strong Leeuwin Current (April 1983) (Holloway and Nye 1985).

It must be concluded, therefore, that the direction of longshore currents off the North West Shelf study site, which cause elevation (flow to north-east) depression (flow to south-west) of nitrate-rich waters along the shelf margin, were not essential precursors to the two onshore nitrate-enrichment episodes in February and April 1983. It may be that the December nitrate-enrichment was only coincidentally associated with the current to the north-east.

The alternation between weak currents to the south-west and to the north-east between December and April (Holloway and Nye 1985) probably allows a general uplift, rather than a depression of colder, nitrate-richer waters against the slope margin. In combination with lack of downwelling of nearshore bottom waters onto the slope region (Section 5) and the prevalence of lighter, generally nitrate-richer, tropical waters in the near-surface layers offshore, a favourable environment would be set up for one or more physical processes (Holloway et al. 1985) to transport nitrates into North West Shelf waters from this offshore nitrate pool.
Tidally induced internal waves with onshore velocities of around 55 cm s^{-1} (Baines 1981) and tidal currents with onshore and offshore flows of around 25 cm s^{-1} (Holloway 1983) are likely to be the major transporters.

When such a bolus of nitrate-enriched water is transported onshore as a bottom current beneath the strong summer thermocline, biological assimilation of these nitrates must be effective within periods as short as 12 hours before the nitrates are mixed and dissipated by tidal mixing or currents moving offshore.

Little appears to be known about the ability of the biological communities of the North West Shelf to maintain a steady level of production under these conditions of transient nitrate enrichment. Conventional oceanographic cruises as practised during 1982-84 will not shed any further light on this problem during the "summer" months.

(ii) "Winter"

Between May and November 1982 a combination of a strong Leeuwin Current to the south-west (May to July) and downwelling of nearshore waters of negligible nitrate concentration onto the slope region (at least from June to October) kept nitrates at 50 m below a concentration of 0.5 µg at/l and commonly at zero near the surface (Figs 9a and b).

This should imply that biological production is also very low during the "winter". Measurements of carbon-fixation rates (Kabanova 1968, CSIRO 1963, 1964a, 1964b) in North West Shelf waters indicate on the contrary that "winter" production of these waters is not only higher than "summer", but also high relative to the adjoining east Indian Ocean.

If high biological production can be maintained during "winter" in North West Shelf waters despite a near-absence of nitrates, then a very unconventional type of biological production must have become established in these waters. The ability of some microorganisms to fix nitrogen from the water and therefore be independent of nitrates might be the starting point for such an unconventional cycle of biological production.

If these high 1964 carbon fixation rates in "winter" are confirmed by further investigation, it will be necessary to examine what type of biological production in these tropical North West Shelf waters could account for these high rates, even in the absence of nitrates in the Shelf waters.

As in "summer", conventional oceanographic cruises will not provide the right sort of data to solve these problems.

(c) Seasonal changes in the profiles of chlorophyll a in relation to nitrates

Typical profiles of chlorophyll a during stratified (i.e. "summer") and non-stratified (i.e. "winter") periods have been prepared by Hallegraeff and Jeffrey (1984) from three Soela cruises in North West Shelf waters, between June 1980 and June 1983.

The "summer" profile of chlorophyll a, based upon December cruise data, (Hallegraeff and Jeffrey, 1984; Fig. 2b) had maximum values of between 0.5 and 0.6 µg l^{-1} at around 50-60 m within the nitrate-enriched bottom-shelf waters (Fig. 8) beneath the thermocline. Above the thermocline, cholorphyll a values were around 0.2 µg l^{-1}, with nitrates at close to zero values.

The two "winter" profiles of chlorophyll a, both based upon June cruise data, were very dissimilar. One profile in June 1980 (Hallegraeff and Jeffrey, 1984; Fig. 2d) shows values around 0.2 µg l^{-1} distributed evenly from the surface to around 100 m, with nitrates quite low (< 1.0µg at/l) to around

75 m. The other "winter" profile (Hallegraeff and Jeffrey, 1984; Fig. 2c), in much shallower shelf waters, had chlorophyll a values of between 0.5 and 0.7 μg l^{-1}, despite nitrates of less than 0.5 μg at/l at all depths.

The "summer" profile shows clearly that chlorophyll a production is maximised in the nitrate-enriched bottom shelf waters. The two "winter" profiles are quite contradictory, one supporting the concept of low chlorophyll a production when nitrates are low, but the other showing relatively high chlorophyll a production, with no significant increase in nitrates.

More information on seasonal changes in chlorophyll a and other production indices are required not only to sort out the contradictory nature of the "winter" profiles, but also to decide unequivocally the relative contribution of summer bottom production and winter mixed-column production to the overall biological characteristics of North West Shelf waters.

(d) Applicability of results from CSIRO site to the whole North West Shelf

Stations along two sections to the northeast of the CSIRO site (Fig. 4) were occupied on earlier CSIRO oceanographic cruises. Although not in sufficient detail to show structural features across and around the shelf break, these sections display much the same broad oceanographic features as those in the 1982-84 CSIRO site.

Along section B (Fig. 4) the winter pattern has a subtropical salinity maximum encroaching onto the slope region with downward displacement of the 5 and 10 μg at/l nitrate isolines against the slope margin (Fig. 10a). The summer pattern shows the reversal to a weaker offshore salinity maximum and an upward elevation of the 5 and 10 μg at/l isolines into the upper slope region (Fig. 10b). This seasonal pattern is similar to that in the CSIRO site (Section 5).

In the winter along Section A (Fig. 4), further to the north, the deeper salinity maximum offshore was poorly developed but the nitrate isolines were depressed as in Section B, near the shelf break (Fig. 11a). In summer the nitrate isolines were at similar depths at the two offshore stations (Fig. 11b) along Section A, but near-bottom data at station 18 were insufficient to show uplift of nitrates into the shelf region, although the relatively high bottom values of nitrates at Station 17 suggest such a possibility.

Earlier CSIRO data show, therefore, that to at least as far north as 14°S the same seasonal alternation in the north/south extent of subtropical and tropical waters in conjunction with local processes could control the nitrate content of the shelf break and nearshore bottom waters, although the pattern is less evident along Section A (Fig. 1).

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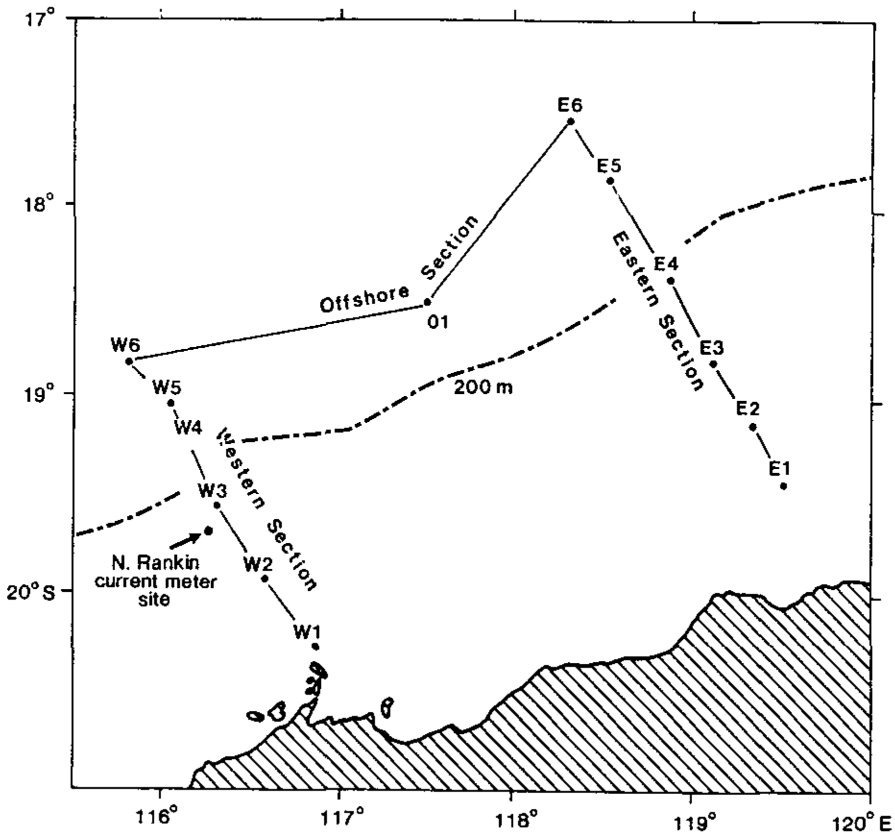


Figure 1. Location of stations in the CSIRO study site. The position of the north Rankin current meter station is also shown.

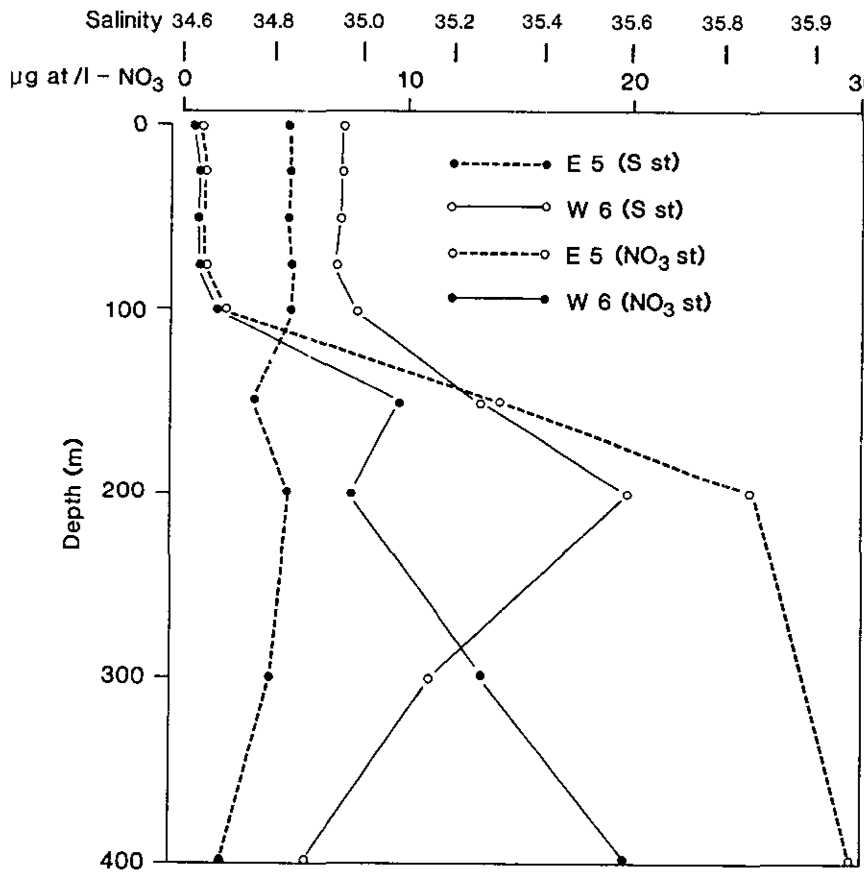


Figure 2. Representative winter profiles (August '82) at stations (W6) and (E5) (Fig. 1), showing the large decrease in nitrates within the core of the subtropical salinity maximum (solid lines); dashed lines are for the low-salinity tropical water mass.

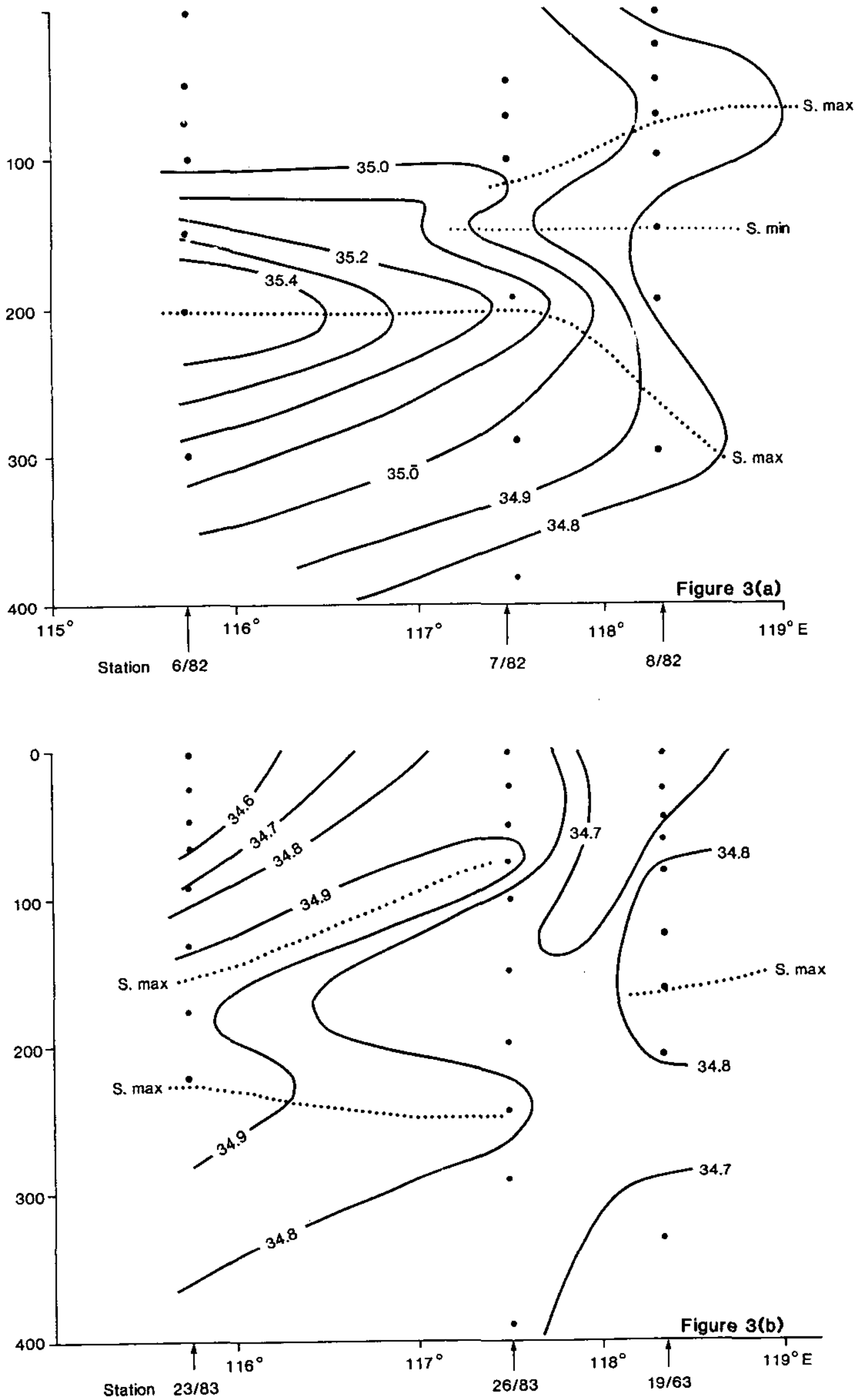


Figure 3. Salinity distribution along the offshore section (Fig. 1) late winter (August 1982) (a) mid-autumn (April 1983)

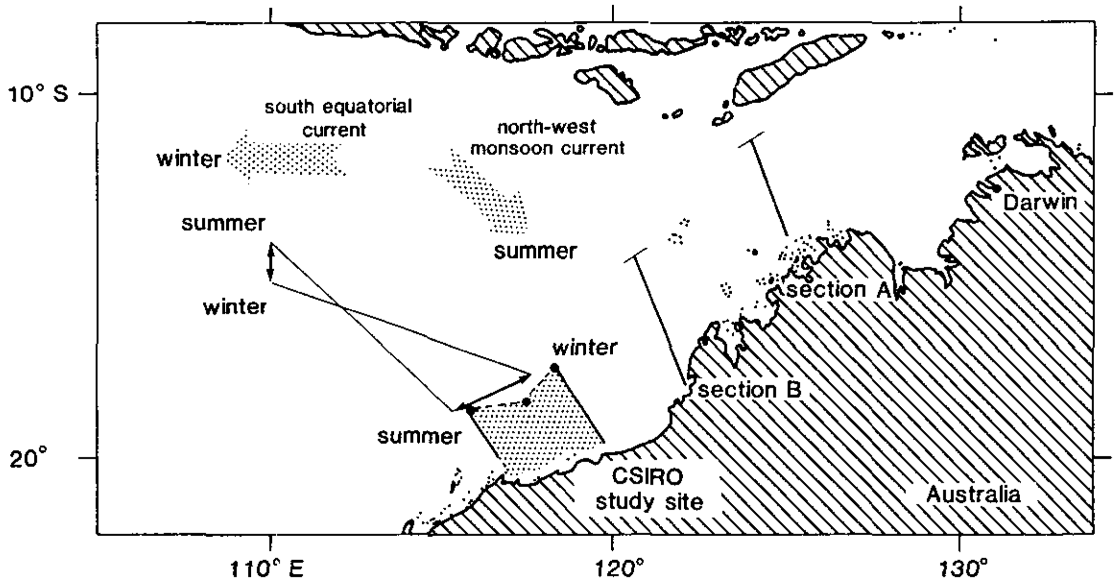
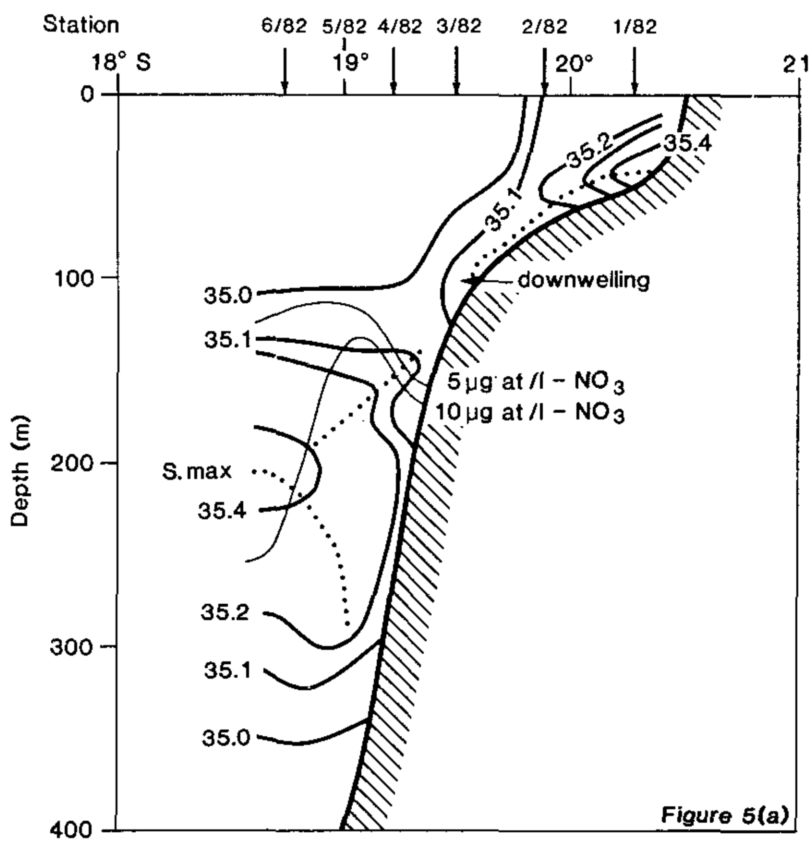


Figure 4. Chart of the seasonal shift in position of the boundary between the subtropical and tropical water masses within the CSIRO study site, relative to the shift in this boundary along 110°E. The location of Sections A and B (Figs 10 and 11) are shown.



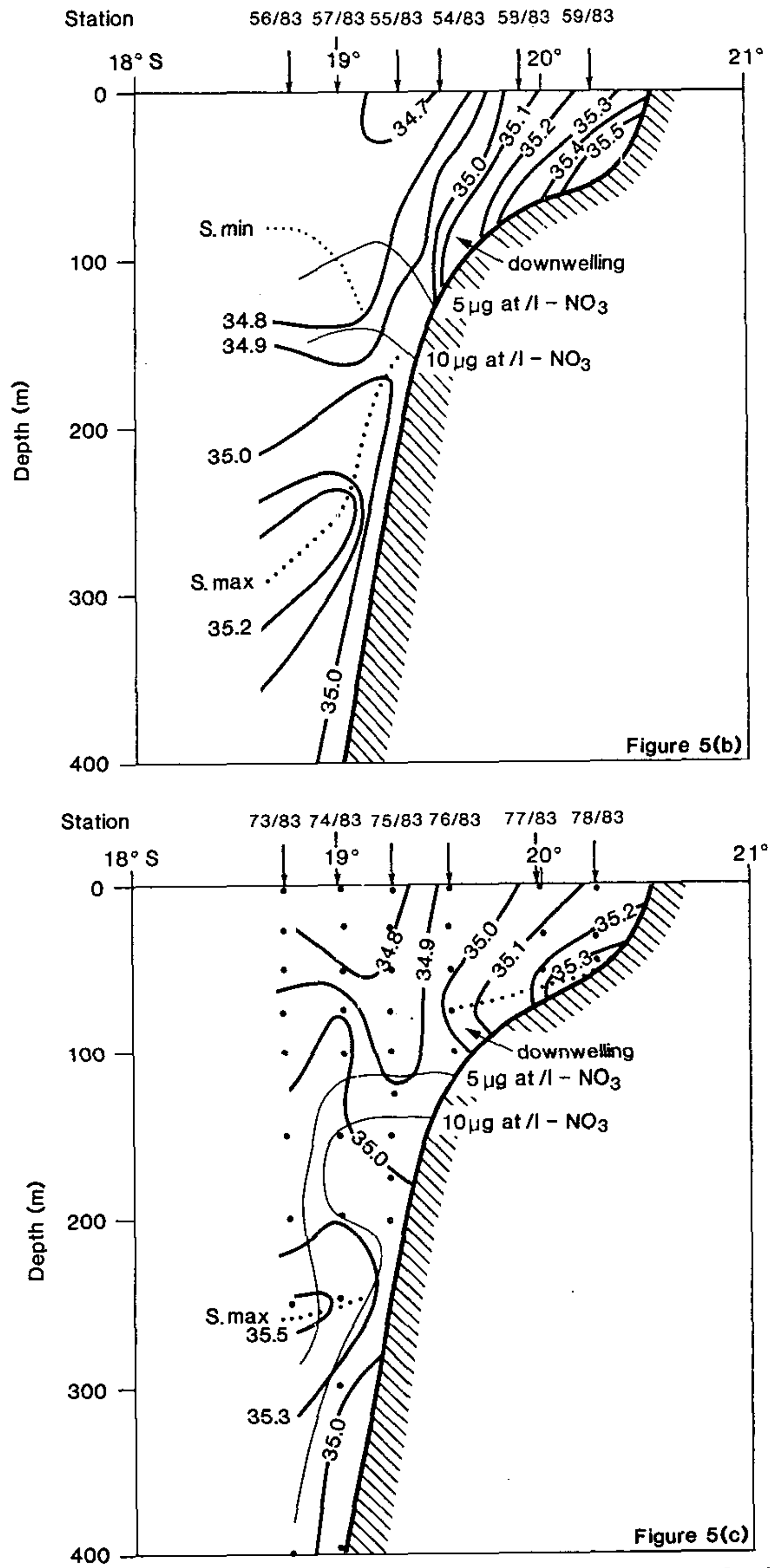
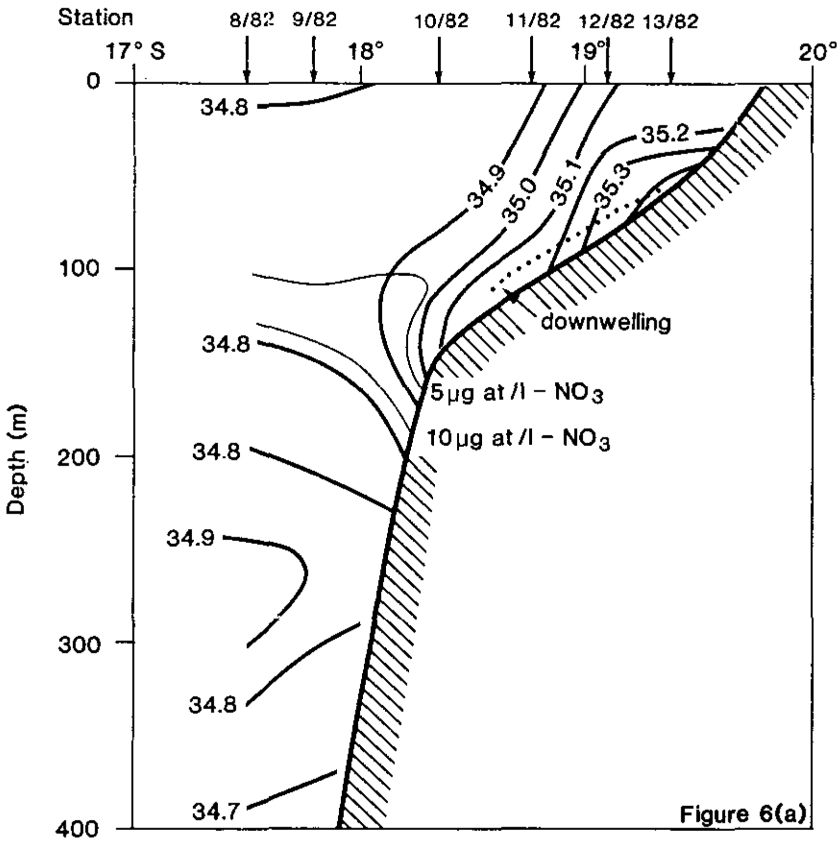
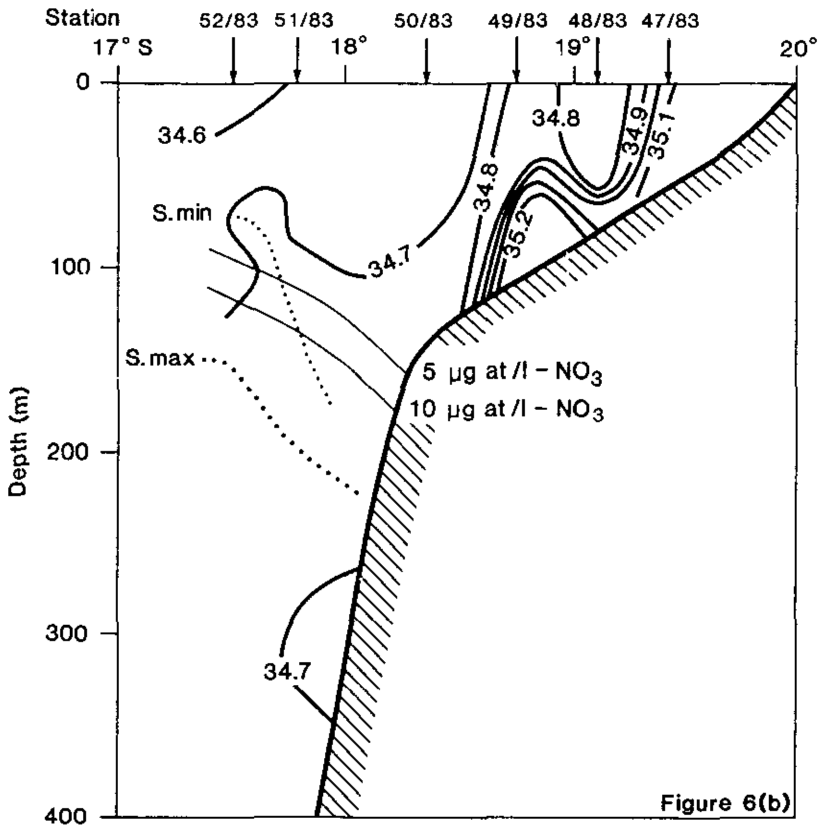


Figure 5. The winter distribution of salinity and selected nitrate isolines along the western section (Fig. 1)

(a) August 1982
(b) June 1983
(c) August 1983


Station
8/82
9/82
10/82
11/82
12/82
13/82
17° S
18°
19°
20°
0
100
200
300
400
Depth (m)
34.8
34.9
35.0
35.1
35.2
35.3
34.8
34.8
34.9
34.8
34.7
downwelling
5 µg at /l - NO3
10 µg at /l - NO3
Figure 6(a)


Station
52/83
51/83
50/83
49/83
48/83
47/83
17° S
18°
19°
20°
0
100
200
300
400
Depth (m)
34.6
34.8
34.9
35.1
S. min
34.7
34.8
35.2
S. max
5 µg at /l - NO3
10 µg at /l - NO3
34.7
Figure 6(b)

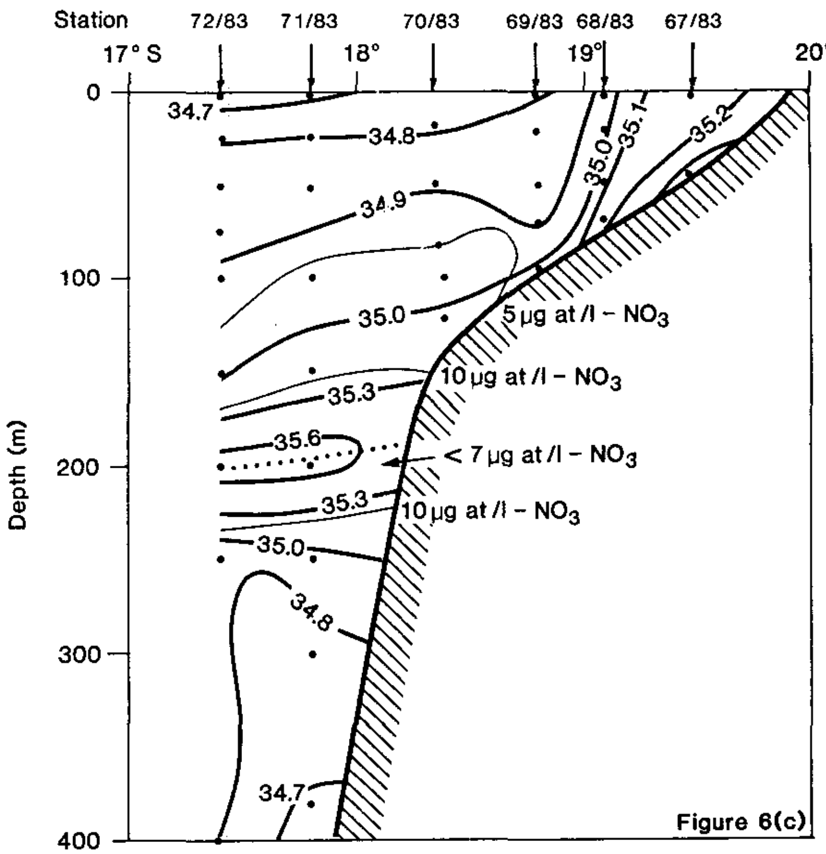
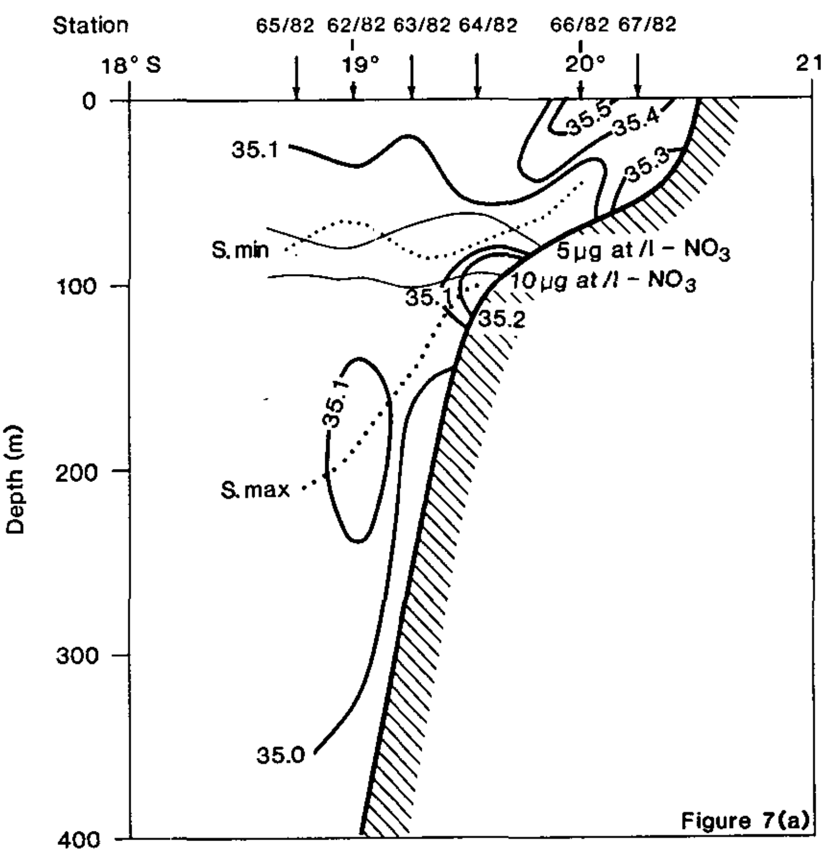
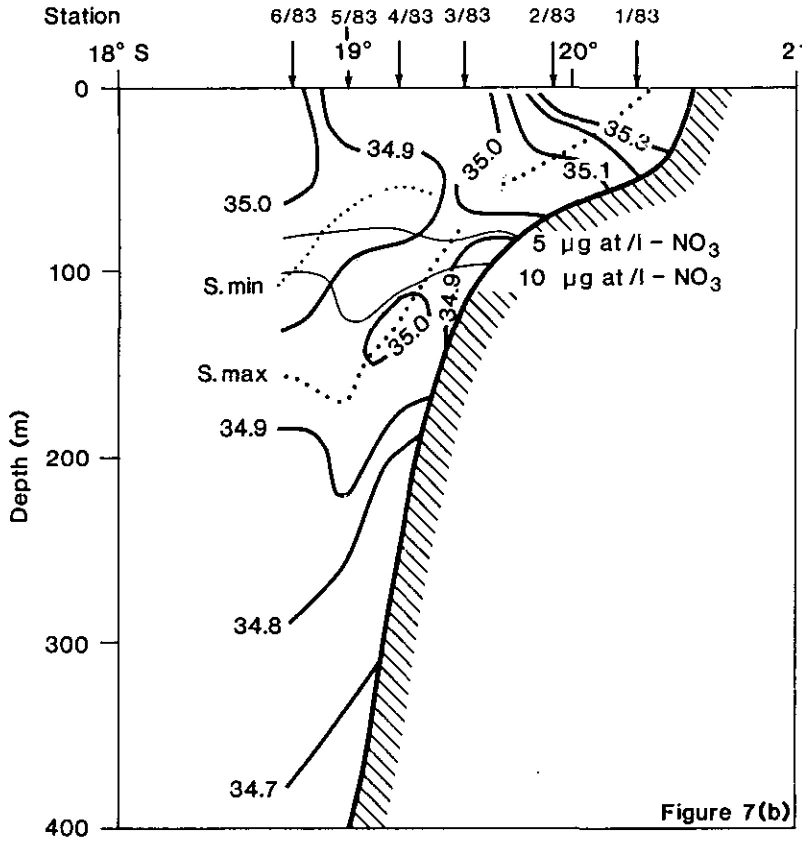


Figure 6. The winter distribution of salinity and selected nitrate isolines along the eastern section (Fig. 1)

(a) August 1982
(b) June 1983
(c) August 1983





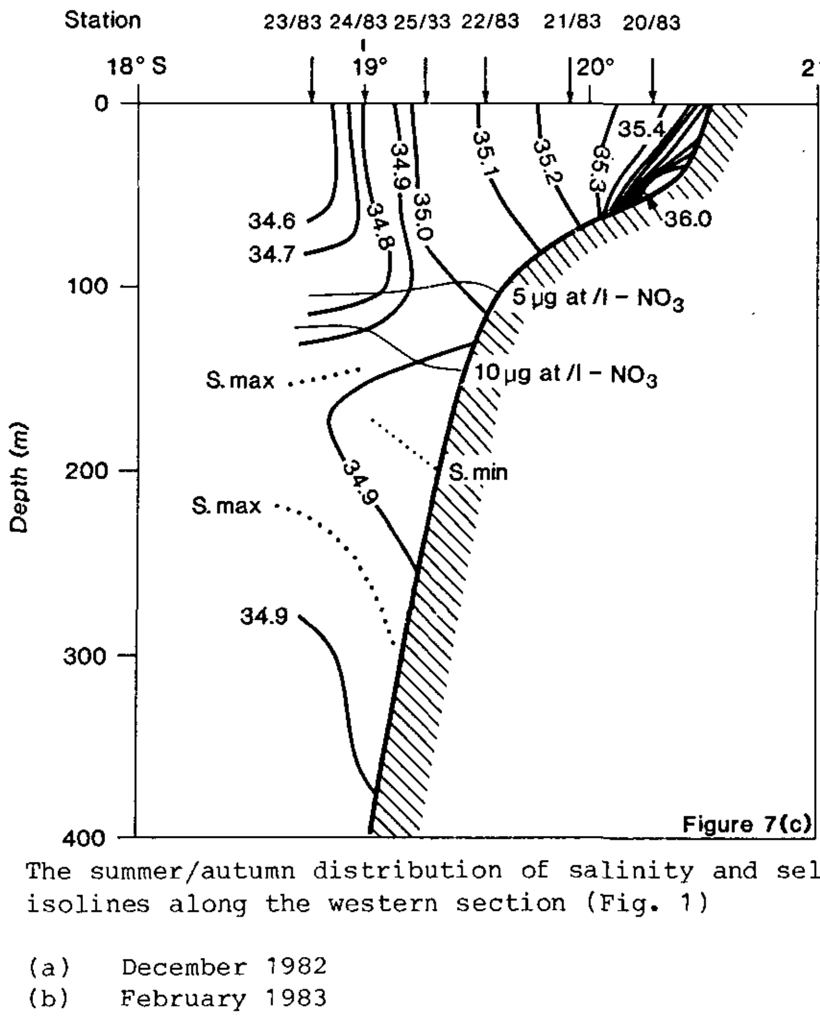


Figure 7. The summer/autumn distribution of salinity and selected nitrate isolines along the western section (Fig. 1)

(a) December 1982
(b) February 1983
(c) April 1983

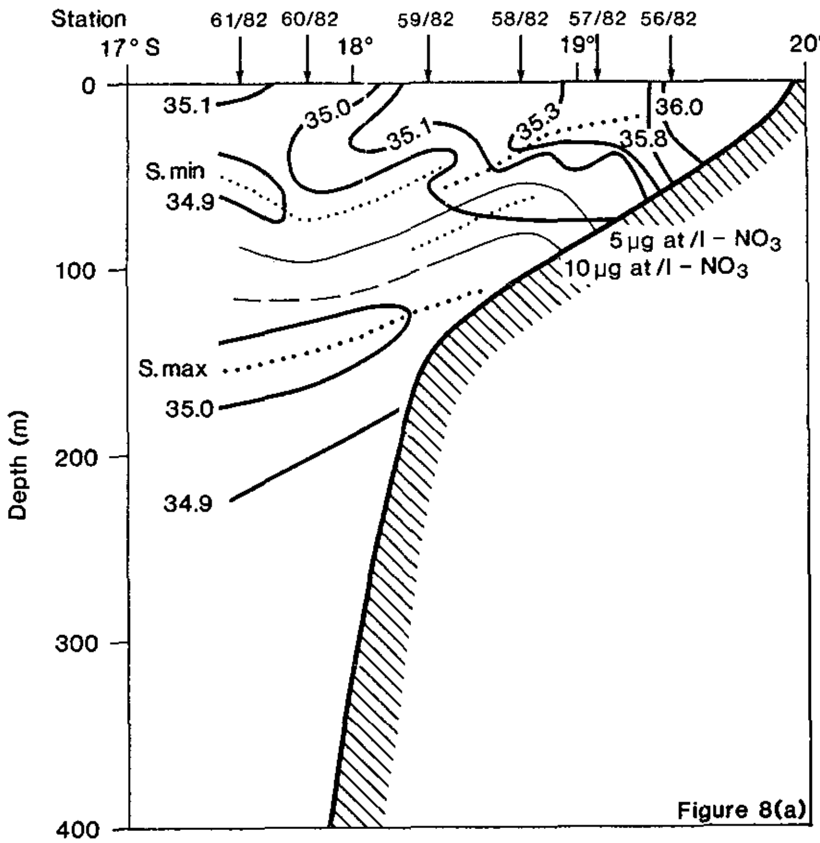


Figure 8(a)

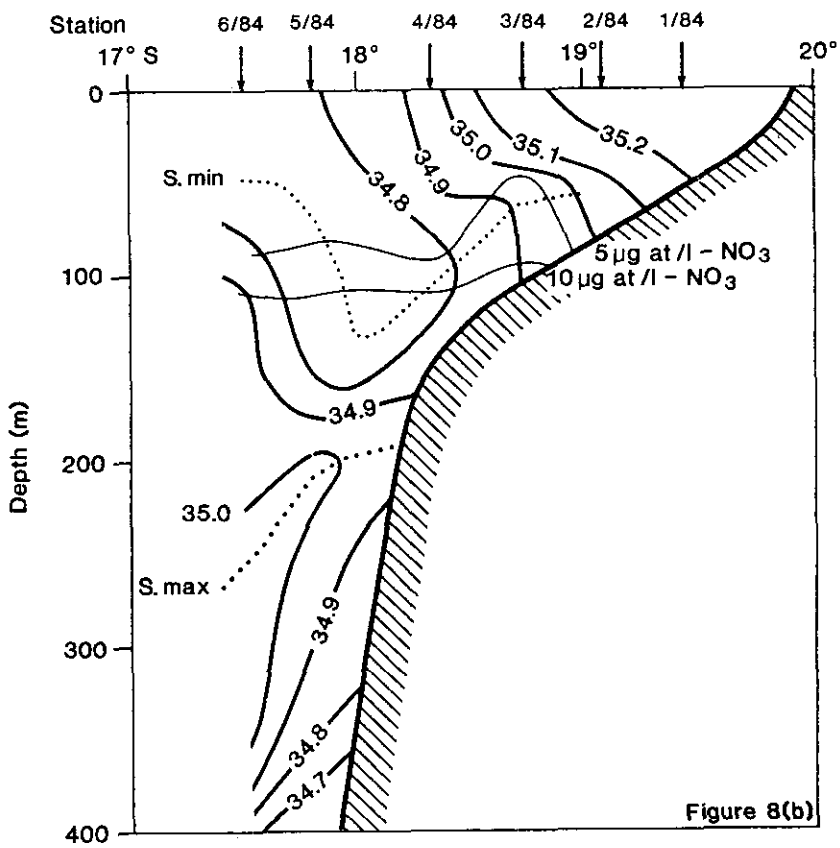


Figure 8(b)

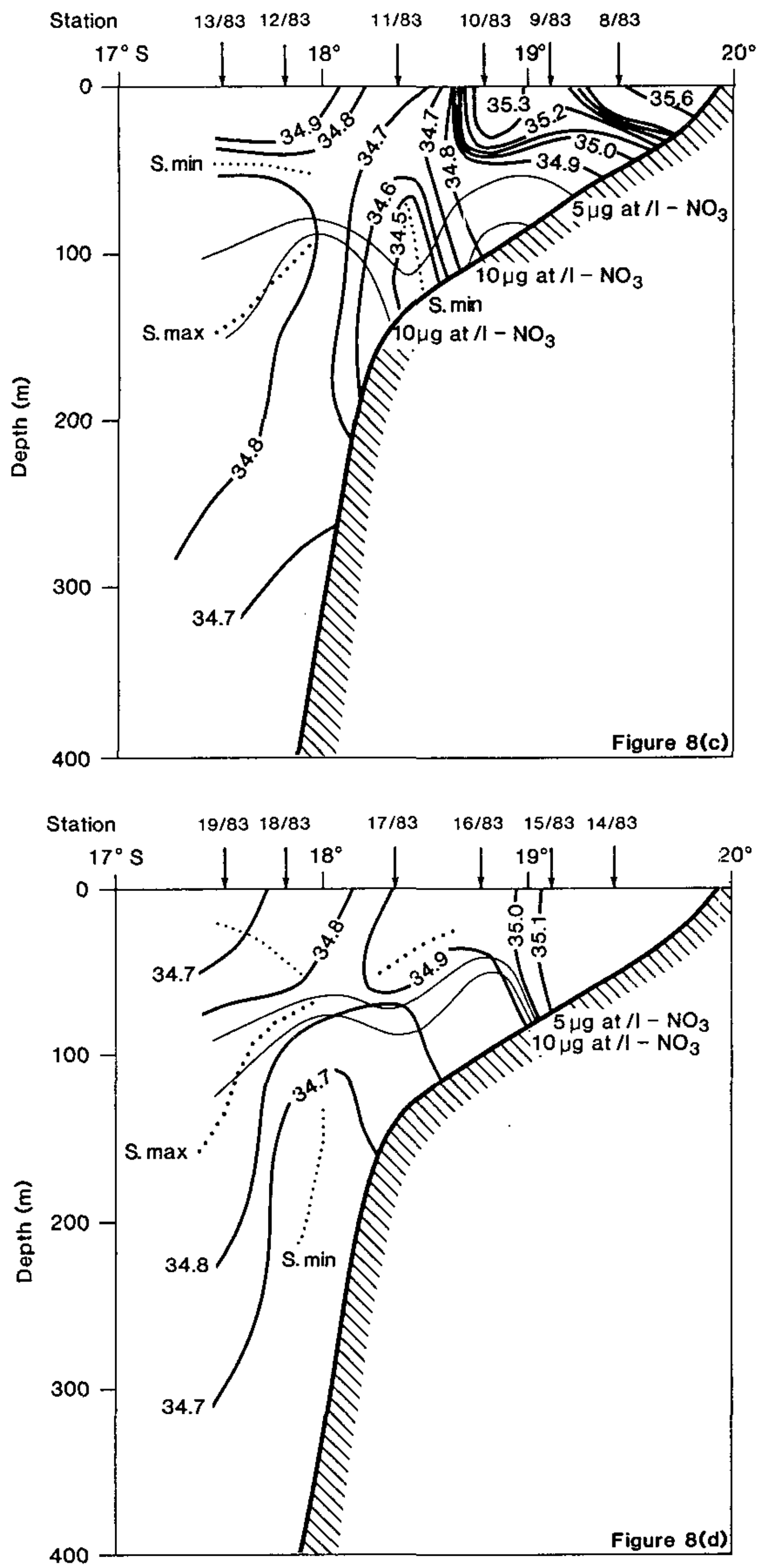


Figure 8. The summer/autumn distribution of salinity and selected nitrate isolines along the eastern section (Fig. 1)

(a) December 1982 (b) January 1984

(c) February 1983 (d) April 1983

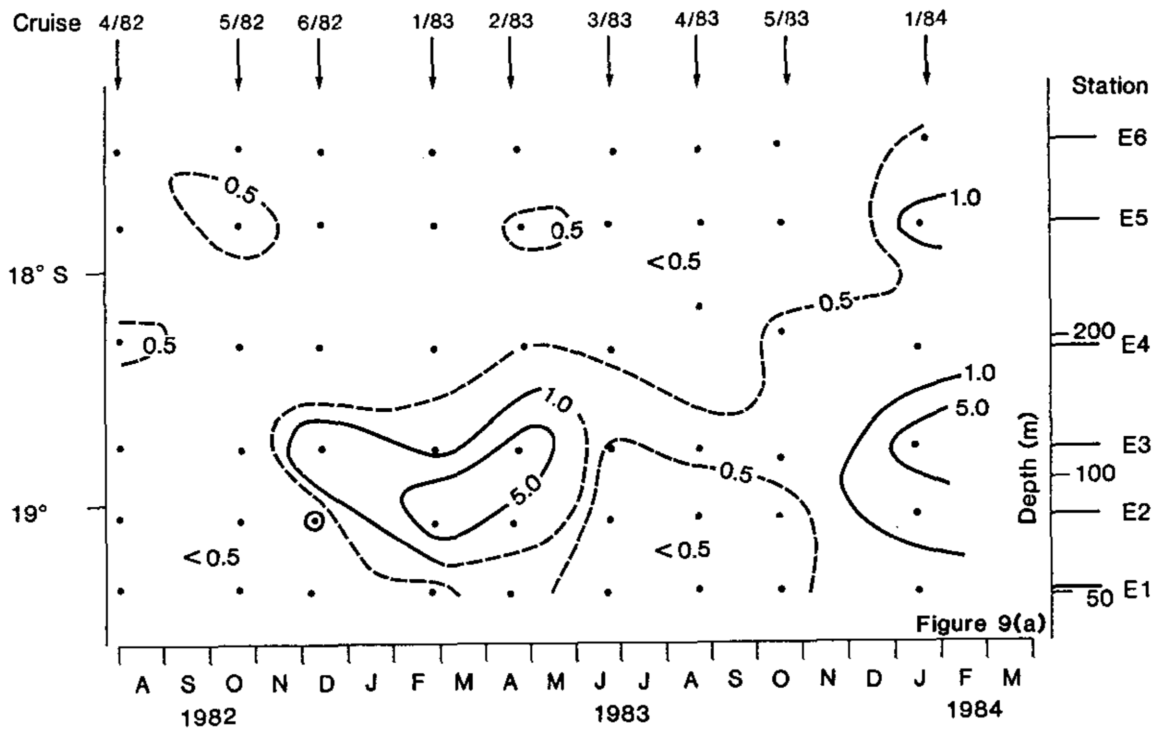


Figure 9(a)

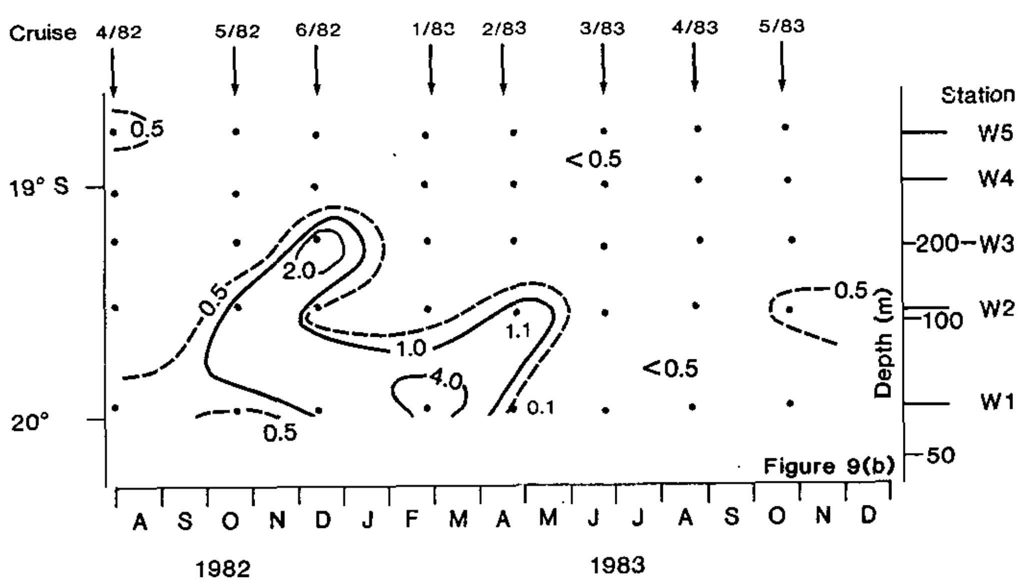


Figure 9(b)

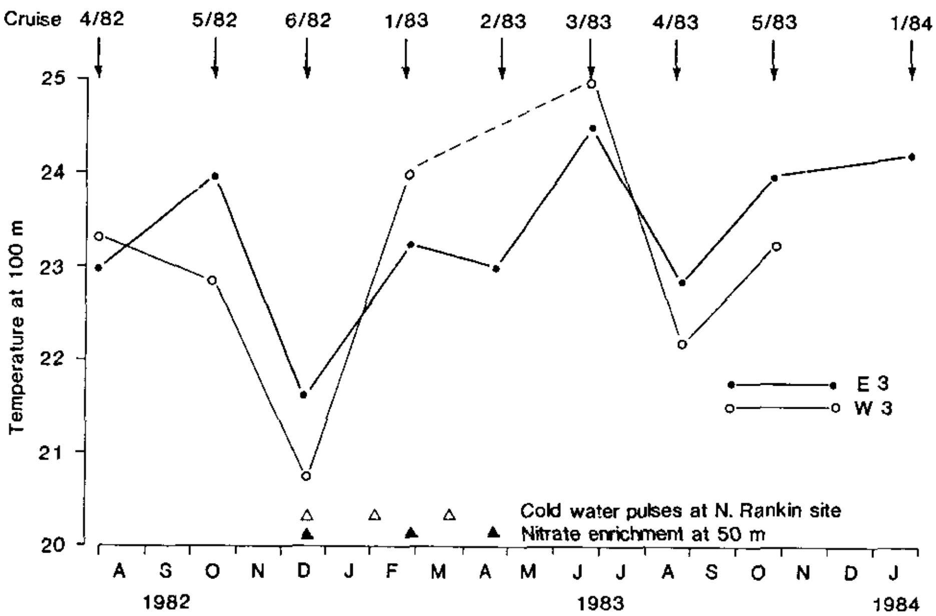


Figure 9(c)

Figure 9. The time/latitude distribution at 50 m

(a) of nitrates (μg at/l) along the eastern;
(b) of nitrates (μg at/l) along the western section of Fig. 1

The approximate positions of selected depth contours along these sections are shown

(c) Seasonal changes in temperatures at 100 m at the shelf break stations [(E3) (W3) Fig. 1].

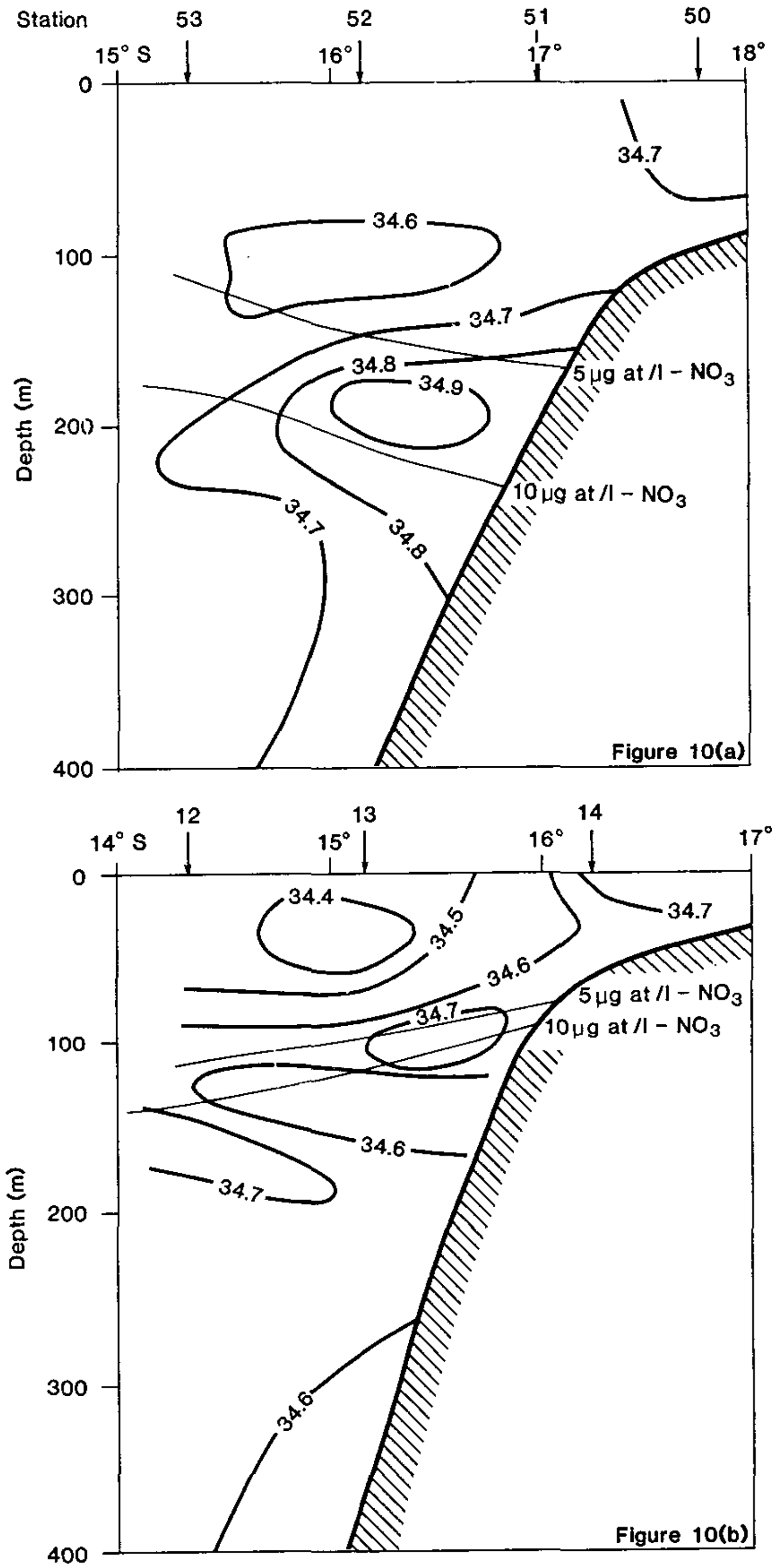


Figure 10. The distribution of salinity and selected nitrate isolines along Section B (Fig. 4).

(a) in winter - May 1961
(b) in summer - February 1962

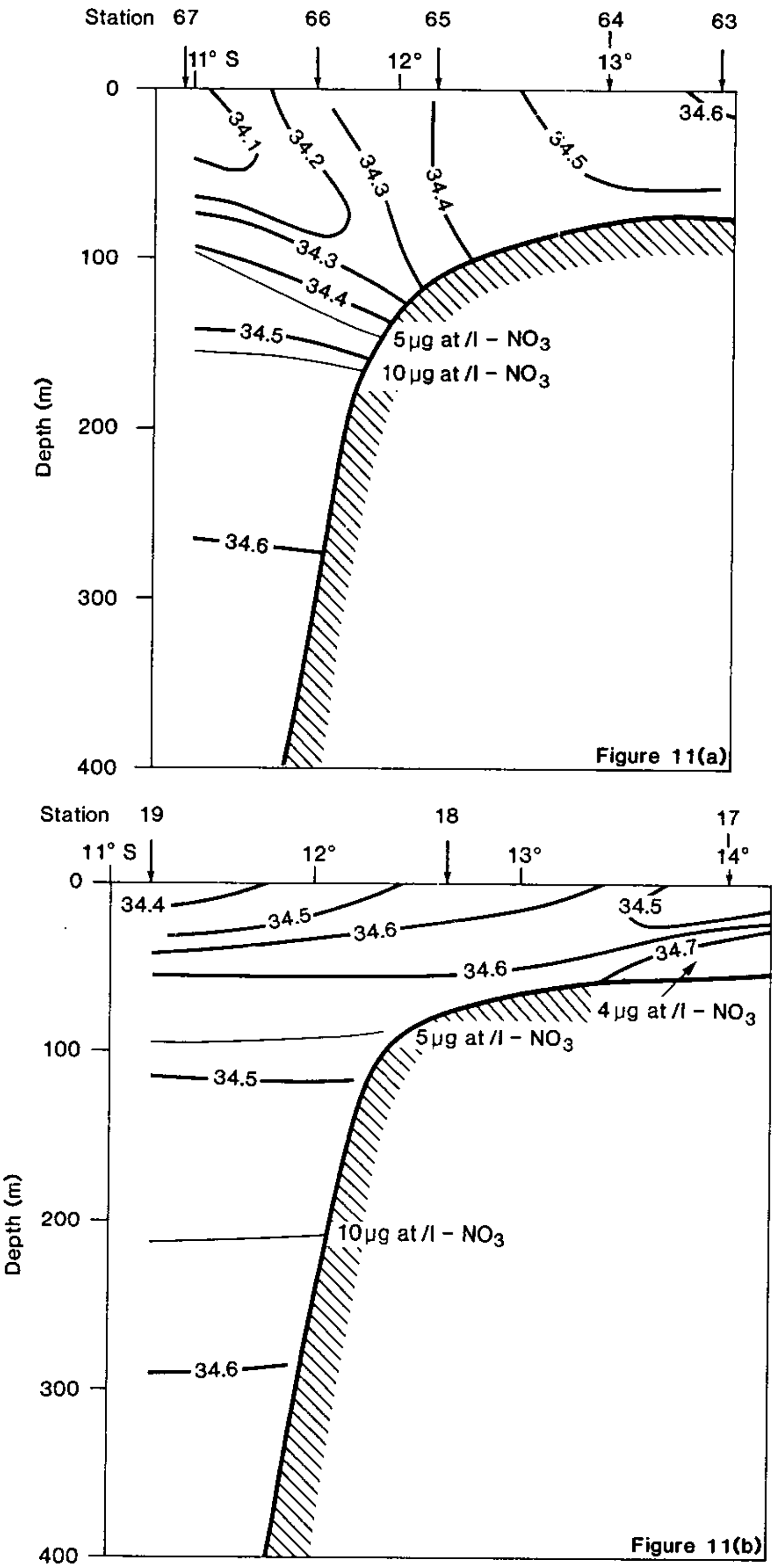


Figure 11. The distribution of salinity and selected nitrate isolines along Section A (Fig. 4)

(a) in winter - May 1961
(b) in summer - February 1962

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