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# Monitoring of Great Barrier Reef Waters; Some Oceanographic Requirements

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# MONITORING OF GREAT BARRIER REEF WATERS; SOME OCEANOGRAPHIC REQUIREMENTS

**D.J. ROCHFORD**

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## Abstract

Surface and subsurface sea temperatures and salinities have been recorded by CSIRO and AIMS in the Great Barrier Reef and western Coral Sea since 1974. The time series have highlighted several oceanographic features of importance in the planning of any long-term monitoring of the physical and chemical characteristics of these waters.

Some evidence that supports the identification of two zones in GBR waters off Townsville is presented. The inner zone experiences some maximal effects of land and local inputs, while the outer zone experiences signficant exchange with the adjoining Coral Sea.

Along the outer margin of the GBR, deeper slope waters welled to the surface in the Palm Passage in November 1980. Previous upwellings, if any, might not have been detected.

In June 1980 Coral Sea surface waters penetrated well into the Palm Passage. Earlier studies of the mid-winter dynamics of the Coral Sea off the GBR had shown, in several years, a general westward drift into the GBR region at around 19°S. This influx of surface Coral Sea waters into the GBR may possibly, therefore, be a persistent feature. In 1981, however, no such influx occurred off Townsville and no data were available elsewhere along the GBR to determine if the influx occurred at another locality.

Strategies for long-term monitoring within these two zones are suggested.

## CONTENTS

# INTRODUCTION

The lack of a systematic time-series of oceanographic observations of the Great Barrier Reef (GBR) was drawn attention to by Pickard (1977) in his summary of the knowledge of temporal and spatial changes within the region. Pickard was obliged to use Orr's 1928-29 Low Island measurements as his major source. Pickard also pointed out the lack of information on "interaction between the waters of the lagoon and those of the Coral Sea outside".

To rectify this situation, CSIRO set up a series of monitoring stations within the region in the mid-1970's. Up until 1983, these stations regularly monitored temperatures, salinities and some nutrients. After 1983, several stations were discontinued.

Whilst these GBR monitoring stations were operating, the CSIRO ships of opportunity program (SOOP) was measuring sea-surface temperatures (SST) and salinity along a shipping route some 300 km to the east of the GBR. Unfortunately this program was discontinued in 1982.

During 1975 and 1978 the Australian Institute of Marine Sciences (AIMS) repeatedly measured oceanographic characteristics of GBR waters at three near shore stations off Townsville. During 1980 and 1981 AIMS also ran a series of oceanographic cruises that covered a much wider area of the GBR, from off Townsville to its outer margin, than had earlier cruises.

These data collected by CSIRO and AIMS, which were not available to Pickard, make possible a closer examination of the seasonal changes in the waters of the GBR, and western Coral Sea, of oceanographical zonation across the GBR, and of mechanisms for exchange between waters of the GBR and western Coral Sea.

At a meeting on future research needs in the GBR (Baker, et al. 1983), a long-term monitoring program of these GBR waters was considered highly desirable. Results in this paper, however, suggest that more exploratory data may be needed before the sites for such a monitoring program can be selected.

## DATA SOURCES AND STATISTICS

SST and salinity data collected by the CSIRO SOOP (See Piip 1974 for details) in the western Coral Sea and data on temperatures and salinities at surface-subsurface depths from the monitoring stations in the GBR, are available on request from the CSIRO Division of Oceanography, Marine Laboratories, Hobart, Tasmania.

The locations of the CSIRO GBR sampling sites and of selected 1° square Coral Sea comparison sites are shown in Fig. 1. The areas covered by the AIMS cruises in 1976-77 and in 1980-81 are indicated on the inset to Fig. 1.

The AIMS temperature and salinity values are published in Ikeda _et al._, 1980 and Bellamy _et al._, 1982. Monthly means of SST and salinity, the number of observations per month, and the standard deviations about the mean for the CSIRO and AIMS monitoring data are given in Tables 1 and 2.

Similar statistical information for the 1° square monitoring sites in the western Coral Sea is listed in Table 3.

## RESULTS

### 1. Changes with time at fixed sites in the GBR and western Coral Sea

#### *(a) Sea-surface temperatures*

The maximum summer SSTs at the three northernmost GBR and Coral Sea sites (Fig. 1) were not significantly different (Figs 2, 3 and 4; Table 1) from those in the western Coral Sea (Table 3). However, for most of the rest of the year the western Coral Sea SSTs were consistently warmer. This was especially so in winter when the Coral Sea SSTs in the north were some 1°C warmer (Fig. 2) and in the south some 2.7°C warmer (Fig. 4).

At the southernmost comparison site (Fig. 1), by contrast, Coral Sea SSTs were 1° to 1.5°C warmer than those of GBR waters for most of the year, including summer (Fig. 5). The magnitude of the standard deviations in the SSTs at both the GBR and the comparison 1° square Coral Sea positions (Tables 1 and 3) suggests, however, that such differences in SST could be smaller or larger in some years. Interannual changes in the mean annual SST of this western Coral Sea region, which can be as much as 2°C over a ten-year period (Rochford, in preparation), would contribute to this variability.

Until sufficient long-term data are available for GBR waters to provide better statistical information, the differences in mean SSTs exhibited in Figs 2 and 5 may have only limited significance.

### (b) Surface salinity

Within the GBR, mean surface salinities oscillate from a marked minimum during the monsoon rain season (December to March) to a maximum in spring/early summer (July to December) when evaporation losses are in excess of rainfall (Pickard, 1977). Mean surface salinities in the western Coral Sea follow the same annual timetable (Figs 2 to 5), although the mean annual oscillations are much smaller.

At the three northern sites (Figs 2 and 4) the annual minimum salinities occur within the GBR, but south of 19°S (Fig. 5) the annual minimum salinities are found in the western Coral Sea. This latitudinal difference is the result of the East Australian Current transporting less saline waters southward in summer into the western Coral Sea off the southern region of the GBR. The monsoonal rains are also much less intense in this southern section of the GBR (Pickard, 1977).

The magnitude of the standard deviation around the mean monthly salinities (Tables 1 to 3) indicates, as for the SSTs, quite large interannual differences both within the GBR and the adjoining western Coral Sea. However, it is unlikely that the latitudinal differences between the GBR and western Coral Sea salinities would be reversed in any year.

## 2. Changes with time along transects from the outer to the inner GBR off Townsville

AIMS oceanographic cruises in the vicinity of Townsville collected sufficient data to examine the seasonal changes during 1980-81 along Palm Passage transect (Fig. 1 inset) and the changes over six months of 1981 along a Magnetic Passage transect (Fig. 1 inset).

### *(a) Palm Passage transect*

The maximum SSTs occurred in March, with little variation in value along the length of the transect (Fig. 6). The minimum SSTs occurred in August at the inner end of the transect and in September at the outer end. The inner SSTs were some 2°C colder than those at the outer end during this minimum period. A minimum SST at Station 13 in November 1980 (Fig. 6) is attributed to upwelling (Section 4(b)).

Surface salinites changed seasonally in a much more irregular manner than did SSTs. From a minimum during the monsoon season in January, surface salinities increased at a uniform rate along the length of the transect until March (Fig. 7). In April-May, however, salinities increased from the centre of the transect in April to terminate in May at the inner end of the transect.

A low-salinity event that appeared at the outer end of the transect in June reduced surface salinities considerably along the length of the transect in mid-winter (Fig. 7). (See Section 4(a).) From August through to November, surface salinities increased during the high evaporative season (Pickard, 1977). The lower surface salinity at Station 13 in November 1980 is attributed as is the SST minimum, to upwelling (Section 4(b)).

### *(b) Magnetic Passage transect*

During 1975-78 AIMS occupied three monitoring stations off Townsville (Fig. 1 inset). Monthly means of these data were combined with the six months of sampling in Magnetic Passage during 1981 to show the seasonal changes from very close inshore to the outer margin of the GBR, along a Magnetic Passage transect (Fig. 1 inset).

Seasonal changes in SSTs (Fig. 8) along the Magnetic Passage transect followed much the same pattern as those along the Palm Passage transect (Fig. 6), with maximum temperatures predominantly in March and minimum temperatures in July, one month earlier than along the Palm Passage transect. In July there was a gradient of some 4°C between inshore and offshore ends of the Magnetic Passage transect. The demarcation between the colder inshore waters and the warmer offshore waters occurred principally around Station 42 (Fig. 1), some 80 km from the coast along the Magnetic Passage transect (Fig. 8). Along the Palm Passage transect, a similar demarcation was found around Station 12 (Fig. 1), also at about 80 km from the coast (Fig. 6). (See Section 3.)

Seasonal changes in surface salinities were much more pronounced near the coast along the Magnetic Passage transect than offshore (Fig. 9). As for SSTs, the demarcation between the near-shore, highly variable, salinity pattern and the more stable salinity pattern offshore occurred around Station 42.

The salinities offshore of this demarcation increased uniformly across the transect until at least June 1981 (Fig. 9), with no evidence of the low salinity event in May-June encountered offshore along the Palm Passage transect (Fig. 7) some 16 km away in the previous year. Possibly, therefore, this 1980 mid-winter low-salinity event is not a persistent feature of the seasonal salinity pattern of the Townsville region of the GBR. (See also Section 4(a))

## 3 Annual ranges of SST and salinity in the waters of the GBR and western Coral Sea

Along a composite transect of the Palm Island passage and the much earlier Townsville nearshore station data (Fig. 1 inset), the annual SST range varied from high values nearshore to near-constant, much lower, values at between 80 km to 400 km offshore (Fig. 10). Off Townsville, therefore, GBR waters are separable (in terms of their annual SST range) at around 80 km offshore into an inner zone with an annual range greater than 5°C and an outer zone with an annual range of between 4°C and 5°C, which is similar to the annual range of SSTs in the adjoining Coral Sea.

At around 80 km offshore, the water along this composite transect deepens more rapidly with distance offshore (Fig. 10). The mean annual surface salinity range also separates, at around 80 km offshore, into an inner zone of high values and an offshore zone of much lower and near-constant values, much as did the SST range (Fig. 10). Apparently, then, there is a boundary about 80 km offshore between onshore GBR waters, which are largely influenced by local processes of heating, cooling, dilution and evaporation, and offshore waters which additionally exchange more freely with the waters of the western Coral Sea.

As the annual ranges of SST and salinity at the Low Island, Lizard Island and Heron Island CSIRO monitoring sites agree reasonably well with the ranges off Townsville at equivalent distances offshore (Fig. 10), it is possible that separation into onshore and offshore zones is a general feature of the GBR as a whole. However, more information will be required to substantiate this and to establish the oceanographic and meteorological significance of the two zones.

The annual SST ranges Pickard (1977) derived from the nearshore regions of the GBR are, for the most part, greater than 5°C. These ranges fit, therefore, into the proposed onshore zone (Fig. 10).

## 4 Influx of western Coral Sea waters into the Great Barrier Reef off Townsville

### *(a) Surface influx*

In June 1980 there was a sudden, shortlived influx of low-salinity waters into the outer margin of the Palm Passage transect (Section 2(a)). Seasonal changes in surface salinity show (Fig. 11) that this sudden decrease in surface salinity also occurred to a lesser extent at the southernmost outer margin of the AIMS survey area in June 1980 but, more significantly, showed up in the SOP mean surface-salinity pattern in June within the square 19°-19°59'S and 152°-152°59'E some 400 km offshore. As salinities for 1980 were not available for this square, the mean value was used. Within the AIMS June 1980 survey area, the low-salinity tongue extended inshore to at least 80 km from the coast, with the core south of the Palm Passage transect (Fig. 12). A chart of the June surface salinity distribution in the western Coral Sea and GBR shows (Fig. 13) that the tongue of low-salinity waters may have originated south of Papua New Guinea, and broadened and spread onshore around the latitude of Townsville.

At Willis Island during May and June 1980, a low-salinity event was observed in early June (Fig. 13 inset), preceding the low-salinity influx into the GBR later in June. Scully Power (1973) (using data from 1968-1971) showed from the dynamic height anomalies of the surface relative to 1500 m that, north of around 19°S (the latitude of the Townsville region), most of the mid-winter flow was directed westward onto the GBR and to the north along the margin of the GBR. This suggests that the 1980 influx in June may not be an isolated event but a persistent feature of the mid-winter dynamics. However, the non-occurrence of this low-salinity influx into the GBR off Townsville in June 1981 (or any other month) (Section 2) suggests either that this westward drift of Coral Sea waters does not reach the GBR each year or that Coral Sea waters reach the GBR at different locations along the GBR, depending upon interannual changes in wind patterns or for other reasons.

### *(b) Subsurface inflow*

Periodic uplift of colder and relatively rich slope waters to within 50-100 m of the surface of the outer GBR off Townsville has been documented by Andrews and Gantien (1982) and by Andrews (1983(a), 1983(b)). Kelvin waves of much shorter period also cause uplift of these slope waters off the same region of the GBR (Wolanski and Pickard 1983). These studies have not shown that these uplifts carry deeper waters to the surface in the true upwelling pattern found off the northern NSW coast in the spring and early summer (Rochford 1972, 1975).

However, there was one instance in late spring (November 1980) when these uplifted waters did upwell to the surface within Palm Passage (Fig. 6 Station 13). Considering the sampling interval along this passage, it is possible that similar upwellings could have occurred earlier in spring, but not have been detected.

The sequence of events leading to the November 1980 upwelling is shown in Figs 14 to 16. Along the outer margin of the Palm Island Passage, between August and November 1980, surface salinities increased in parallel with the salinities of a subsurface salinity maximum (Subtropical Lower Water) (Fig. 14). The increase in salinity of these subsurface waters is the result of uplift of waters from within the offshore subsurface salinity maximum at around 150 m into the shelf region of the Passage (Figs 15 and 16). By November 1980 these colder, high-salinity waters had upwelled to the surface around Station 13 (Fig. 16).

Unfortunately, no appropriate data from other years or localities along the GBR are available to establish whether this uplift and upwelling is widespread.

These periodic uplifts of high-salinity, subtropical Lower Layer waters could also have a stabilising effect on the salinity balance of the outer GBR towards the end of each year. This would explain the low standard deviations of the maximum mean salinities at the CSIRO sites (Table 1) despite the larger standard deviations of the salinities during the monsoon rain season.

## LONG-TERM MONITORING OF GBR WATERS

The results of this study highlight the large degree of inhomogeneity in SST and salinity across and along the length of the GBR. Such inhomogeneities create problems in selecting not only representative monitoring sites but also the number of such sites. However, the results do suggest the oceanographic requirements that need researching before instituting any long-term fixed monitoring program.

The first requirement is for a more extended study of the possibility that the GBR can be divided, oceanographically, into an inner and an outer zone (Sections 2 and 3).

The second requirement is for oceanographic surveys or deployment of oceanographic instrumentation along the major passages into the GBR, particularly in the winter and spring months, to establish the extent of direct surface influx and subsurface uplift and/or upwelling of deeper western Coral Sea waters into the GBR (Section 4).

If the two zones across the GBR are a general feature of the GBR, and if the influx of Coral Sea waters into the GBR occurs as a result of a combination of direct and subsurface movements, the two zones require different monitoring strategies.

Monitoring of the outer zone could initially be carried out from ships of opportunity (SOOP), including coastal steamers, fishing and tourist boats, as well as the larger maritime fleet. Surface temperatures could be measured manually but preferably by thermographs; salinities would have to be determined by salinometers from samples collected at the same time as the temperature is noted.

As often as possible oceanographic sampling along the length of the major passages connecting the GBR and the western Coral Sea should be carried out to supplement the surface sampling. If the pattern of influx was consistent along the length of the GBR and was clearly manifest in the surface SOOP values, it might be possible in time to reduce the number of such passages sampled.

Monitoring of the inner zone, in which the influence of local processes and of any man-made inputs predominate, would need a different and more difficult strategy to implement. It would have to be concentrated on sites and regions of major input of either existing or potential pollutants. Depending upon the flood cycles and how the intensity of local agricultural and industrial practices varies during the year, it would probably be necessary to compare several inner-zone sampling sites over a number of years before choosing representative sites. Sampling would also have to include a wide range of properties, including pollutants, rather than relying on the oceanographic properties applicable to the offshore zone.

In parallel with the monitoring of offshore GBR waters, monitoring of the western Coral Sea should be continued by ships of opportunity out of Queensland ports and by any other means.

Tables 1 - 3

Figures 1 - 16

Table 1 Monthly means, standard deviations and number of observations ($n$) of SST and salinity at CSIRO monitoring stations in the GBR

| Month | Booby Is. (10°36'S 141°54'E) 1977 - 1982 | | | | | | Lizard Is. (14°42'S 145°29'E) 1974 - 1982 | | | | | | Low Isles (16°23'S 145°34'E) 1977 - 1982 | | | | | | Heron Is. (23°25'S 152°07'E) 1976 - 1982 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | SST | | | Salinity | | | SST | | | Salinity | | | SST | | | Salinity | | | SST | | | Salinity | | |
| | Mean | SD | $n$ | Mean | SD | $n$ | Mean | SD | $n$ | Mean | SD | $n$ | Mean | SD | $n$ | Mean | SD | $n$ | Mean | SD | $n$ | Mean | SD | $n$ |
| JAN | 29.38 | - | 1 | 34.19 | - | 1 | 29.00 | 0.07 | 9 | 34.97 | 0.64 | 10 | 28.23 | 0.98 | 10 | 33.13 | 3.03 | 10 | 26.58 | 0.66 | 7 | 35.57 | 0.20 | 7 |
| FEB | 29.15 | - | 2 | 32.57 | 0.76 | 4 | 28.90 | 0.48 | 9 | 34.56 | 0.68 | 9 | 29.11 | 0.68 | 10 | 32.59 | 3.72 | 10 | 26.95 | - | 2 | 35.60 | - | 2 |
| MAR | 29.19 | 0.42 | 4 | 30.64 | 2.72 | 3 | 28.96 | 0.65 | 9 | 34.23 | 0.91 | 9 | 28.50 | 1.07 | 10 | 33.43 | 1.35 | 10 | 26.61 | 0.48 | 5 | 35.36 | 0.10 | 5 |
| APRIL | 28.57 | 0.75 | 6 | 33.34 | 1.07 | 6 | 27.42 | 1.36 | 6 | 34.29 | 0.95 | 6 | 27.18 | 1.12 | 10 | 33.83 | 0.56 | 8 | 26.12 | 0.62 | 4 | 35.38 | 0.14 | 4 |
| MAY | 27.53 | 0.66 | 3 | 34.36 | 0.70 | 3 | 26.00 | 0.78 | 6 | 34.93 | 0.32 | 6 | 25.05 | 0.91 | 8 | 34.81 | 0.22 | 8 | 24.66 | 0.87 | 6 | 35.50 | 0.14 | 6 |
| JUNE | 26.41 | 0.80 | 6 | 34.89 | 0.46 | 5 | 25.36 | 0.90 | 8 | 35.20 | 0.15 | 8 | 23.44 | 1.46 | 12 | 34.73 | 0.64 | 14 | 23.08 | 0.48 | 7 | 35.57 | 0.08 | 7 |
| JULY | 25.12 | 0.47 | 3 | 35.04 | 0.34 | 3 | 23.98 | 0.78 | 7 | 35.41 | 0.12 | 7 | 22.56 | 1.25 | 12 | 35.09 | 0.27 | 10 | 21.93 | 0.70 | 10 | 35.62 | 0.09 | 10 |
| SEPT | 25.73 | 0.46 | 5 | 32.57 | 0.61 | 5 | 24.94 | 0.28 | 5 | 35.31 | 0.13 | 4 | 23.71 | 0.81 | 7 | 35.30 | 0.19 | 7 | 22.02 | 0.59 | 10 | 35.61 | 0.10 | 10 |
| OCT | 25.99 | 0.61 | 5 | 35.73 | 0.20 | 5 | 25.41 | 0.66 | 10 | 35.38 | 0.21 | 11 | 25.23 | 0.60 | 8 | 35.46 | 0.19 | 8 | 22.74 | 0.56 | 8 | 35.68 | 0.03 | 8 |
| NOV | 27.29 | 0.76 | 5 | 35.64 | 0.39 | 5 | 26.72 | 0.92 | 5 | 35.34 | 0.22 | 5 | 26.90 | 0.82 | 8 | 35.33 | 0.22 | 9 | 24.66 | 0.80 | 6 | 35.70 | 0.08 | 6 |
| DEC | 28.72 | 0.73 | 6 | 35.40 | 1.05 | 6 | 27.67 | 0.90 | 12 | 35.39 | 0.16 | 12 | 28.56 | 1.14 | 9 | 35.44 | 0.27 | 9 | 26.03 | 0.90 | 9 | 35.60 | 0.22 | 8 |

Table 2 Monthly means, standard deviations and number of observations of SST and salinity at AIMS Stations 1, 2 and 3

| Month | AIMS Station 1 (19°11'S 146°55'E) 1975–1978 | | | | | | AIMS Station 2 (18°59'S 147°05'E) 1975–1978 | | | | | | AIMS Station 3 (18°46'S 147°16'E) 1975–1978 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | SST | | | Salinity | | | SST | | | Salinity | | | SST | | | Salinity | | |
| | Mean | SD | $n$ | Mean | SD | $n$ | Mean | SD | $n$ | Mean | SD | $n$ | Mean | SD | $n$ | Mean | SD | $n$ |
| JAN | 28.73 | 0.36 | 4 | 33.68 | 0.66 | 3 | 28.44 | 0.62 | 5 | 35.01 | 0.11 | 4 | 27.85 | 0.64 | 2 | 34.99 | 0.25 | 2 |
| FEB | 28.63 | 1.19 | 6 | 31.89 | 2.58 | 6 | 28.58 | 0.78 | 9 | 34.39 | 1.05 | 9 | 28.12 | 0.55 | 6 | 34.77 | 0.44 | 5 |
| MAR | 29.84 | 1.44 | 5 | 30.96 | 1.11 | 7 | 28.82 | 0.92 | 9 | 33.42 | 1.49 | 9 | 28.52 | 0.39 | 5 | 35.56 | 0.92 | 5 |
| APRIL | 26.83 | 1.57 | 3 | 33.17 | 1.07 | 4 | 27.37 | 0.77 | 7 | 34.70 | 0.45 | 7 | 26.8 | 1.25 | 3 | 34.68 | 0.22 | 3 |
| MAY | 23.60 | 0.82 | 3 | 33.88 | 1.14 | 3 | 24.77 | 0.82 | 9 | 34.63 | 0.55 | 6 | 25.38 | 0.57 | 5 | 34.76 | 0.14 | 4 |
| JUNE | 21.33 | 1.10 | 4 | 34.07 | 0.55 | 5 | 22.89 | 1.17 | 8 | 34.85 | 0.42 | 8 | 23.03 | 0.42 | 4 | 35.11 | 0.26 | 4 |
| AUG | 20.67 | 0.66 | 6 | 35.26 | 0.07 | 7 | 21.81 | 0.92 | 11 | 35.39 | 0.14 | 11 | 21.90 | 0.62 | 5 | 32.28 | 0.02 | 5 |
| SEPT | 23.13 | 1.56 | 6 | 35.47 | 0.15 | 8 | 23.44 | 0.93 | 8 | 35.38 | 0.18 | 11 | 23.78 | 0.70 | 5 | 35.19 | 0.07 | 7 |
| OCT | 25.23 | 0.66 | 7 | 35.88 | 0.18 | 7 | 24.86 | 1.04 | 11 | 35.48 | 0.19 | 10 | 25.20 | 1.36 | 8 | 35.22 | 0.05 | 8 |
| NOV | 28.04 | 1.21 | 8 | 35.78 | 0.37 | 8 | 26.70 | 1.10 | 10 | 35.46 | 0.16 | 10 | 26.6 | 0.90 | 6 | 35.25 | 0.07 | 6 |
| DEC | 29.83 | 1.51 | 4 | 35.74 | 0.37 | 7 | 28.0 | 1.15 | 10 | 35.33 | 0.17 | 12 | 28.36 | 1.17 | 5 | 35.14 | 0.16 | 7 |

Table 3 Monthly means, standard deviations and number of observations of SST and salinity at selected 1° SOP squares in the western Coral Sea and off Willis Is.

| Month | 10°-10°59'S, 147°-147°59'E<br>1966-1982 | | | | | | 14°-14°59'S, 150°-150°59'E<br>1966-1982 | | | | | | 16°-16°59'S, 152°-152°59'E<br>1966-1982 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | SST | | | Salinity | | | SST | | | Salinity | | | SST | | | Salinity | | |
| | Mean | SD | *n* | Mean | SD | *n* | Mean | SD | *n* | Mean | SD | *n* | Mean | SD | *n* | Mean | SD | *n* |
| JAN | 29.13 | 0.45 | 54 | 33.90 | 0.96 | 53 | 29.01 | 0.59 | 46 | 34.83 | 0.21 | 40 | 28.54 | 0.76 | 65 | 35.17 | 0.23 | 75 |
| FEB | 28.92 | 0.63 | 42 | 34.16 | 0.65 | 36 | 28.76 | 0.61 | 37 | 34.86 | 0.31 | 37 | 28.78 | 0.73 | 52 | 35.00 | 0.25 | 52 |
| MAR | 28.80 | 0.65 | 49 | 34.11 | 0.41 | 36 | 28.90 | 0.61 | 46 | 34.86 | 0.27 | 44 | 28.52 | 0.60 | 62 | 35.02 | 0.28 | 56 |
| APRIL | 28.55 | 0.46 | 51 | 34.31 | 0.63 | 35 | 28.33 | 0.68 | 40 | 34.83 | 0.21 | 34 | 27.62 | 0.74 | 59 | 34.94 | 0.29 | 57 |
| MAY | 27.75 | 0.53 | 49 | 34.62 | 0.53 | 44 | 27.37 | 0.72 | 47 | 34.90 | 0.36 | 47 | 26.75 | 0.72 | 62 | 35.05 | 0.19 | 58 |
| JUNE | 26.90 | 0.56 | 53 | 34.81 | 0.27 | 52 | 26.40 | 0.74 | 35 | 34.93 | 0.31 | 34 | 25.85 | 0.73 | 63 | 35.14 | 0.30 | 60 |
| JULY | 25.90 | 0.51 | 69 | 35.03 | 0.30 | 67 | 25.93 | 0.89 | 34 | 35.06 | 0.31 | 34 | 25.34 | 0.77 | 58 | 35.11 | 0.24 | 57 |
| AUG | 25.60 | 0.47 | 57 | 35.07 | 0.22 | 54 | 25.42 | 015 | 37 | 35.16 | 0.24 | 37 | 24.85 | 0.71 | 53 | 35.22 | 0.20 | 54 |
| SEPT | 25.83 | 0.55 | 50 | 35.07 | 0.27 | 49 | 25.98 | 0.76 | 38 | 35.08 | 0.22 | 38 | 25.46 | 0.89 | 61 | 35.17 | 0.23 | 59 |
| OCT | 26.57 | 0.92 | 43 | 35.12 | 0.24 | 39 | 26.93 | 0.92 | 41 | 35.16 | 0.22 | 41 | 26.25 | 0.96 | 56 | 35.21 | 0.22 | 55 |
| NOV | 27.87 | 1.17 | 51 | 34.79 | 0.52 | 40 | 27.94 | 0.86 | 35 | 35.14 | 0.15 | 35 | 27.35 | 0.76 | 48 | 35.20 | 0.15 | 47 |
| DEC | 28.90 | 1.44 | 29 | 34.44 | 0.79 | 22 | 28.72 | 1.11 | 27 | 35.09 | 0.25 | 27 | 27.95 | 1.00 | 58 | 35.21 | 0.17 | 57 |

Table 3 (cont.)

| Month | 19°-19°59'S, 152°-152°59'E 1966-1982 | | | | | | 23°-23°59'S, 153°-153°59'E 1966-1982 | | | | | | Willis Is. 16°18'S, 149°59'E 1966-1982 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | SST | | | Salinity | | | SST | | | Salinity | | | SST | | | Salinity | | |
| | Mean | SD | *n* | Mean | SD | *n* | Mean | SD | *n* | Mean | SD | *n* | Mean | SD | *n* | Mean | SD | *n* |
| JAN | 28.04 | 0.73 | 40 | 35.14 | 0.38 | 40 | 27.28 | 0.93 | 95 | 35.35 | 0.27 | 95 | 28.61 | 0.96 | 30 | 35.23 | 0.15 | 33 |
| FEB | 27.82 | 0.68 | 38 | 35.19 | 0.22 | 38 | 27.43 | 0.63 | 80 | 35.26 | 0.22 | 79 | 28.81 | 0.88 | 30 | 35.10 | 0.17 | 32 |
| MAR | 27.84 | 0.77 | 25 | 35.20 | 0.23 | 24 | 27.18 | 0.64 | 88 | 35.31 | 0.19 | 75 | 28.77 | 1.44 | 32 | 35.08 | 0.17 | 33 |
| APRIL | 26.89 | 0.57 | 37 | 35.24 | 0.20 | 35 | 26.18 | 0.65 | 89 | 35.32 | 0.15 | 88 | 27.93 | 1.04 | 33 | 35.10 | 0.17 | 34 |
| MAY | 25.78 | 0.43 | 41 | 35.31 | 0.16 | 41 | 24.71 | 1.10 | 74 | 35.37 | 0.15 | 73 | 26.21 | 1.00 | 33 | 35.12 | 0.19 | 30 |
| JUNE | 24.79 | 0.59 | 31 | 35.23 | 0.18 | 32 | 23.53 | 0.78 | 89 | 35.41 | 0.12 | 84 | 25.86 | 0.95 | 29 | 35.19 | 0.21 | 28 |
| JULY | 24.41 | 0.11 | 37 | 35.30 | 0.25 | 37 | 23.35 | 0.66 | 74 | 35.41 | 0.15 | 72 | 24.97 | 0.79 | 23 | 35.28 | 0.24 | 20 |
| AUG | 23.82 | 0.81 | 36 | 35.38 | 0.27 | 36 | 22.76 | 0.60 | 84 | 35.45 | 0.14 | 82 | 25.02 | 1.10 | 25 | 35.33 | 0.21 | 25 |
| SEPT | 24.17 | 0.70 | 39 | 35.35 | 0.22 | 39 | 23.05 | 0.81 | 82 | 35.46 | 0.15 | 80 | 25.52 | 1.14 | 26 | 35.40 | 0.26 | 25 |
| OCT | 25.18 | 0.79 | 51 | 35.36 | 0.21 | 51 | 24.28 | 0.57 | 101 | 35.41 | 0.15 | 93 | 26.10 | 1.09 | 26 | 35.33 | 0.18 | 26 |
| NOV | 26.08 | 1.00 | 33 | 35.30 | 0.17 | 33 | 25.65 | 0.65 | 73 | 35.41 | 0.18 | 72 | 27.57 | 1.28 | 21 | 35.33 | 0.18 | 21 |
| DEC | 27.48 | 1.14 | 29 | 35.28 | 0.24 | 29 | 26.71 | 0.67 | 79 | 35.39 | 0.19 | 78 | 28.33 | 1.28 | 23 | 35.29 | 0.16 | 23 |

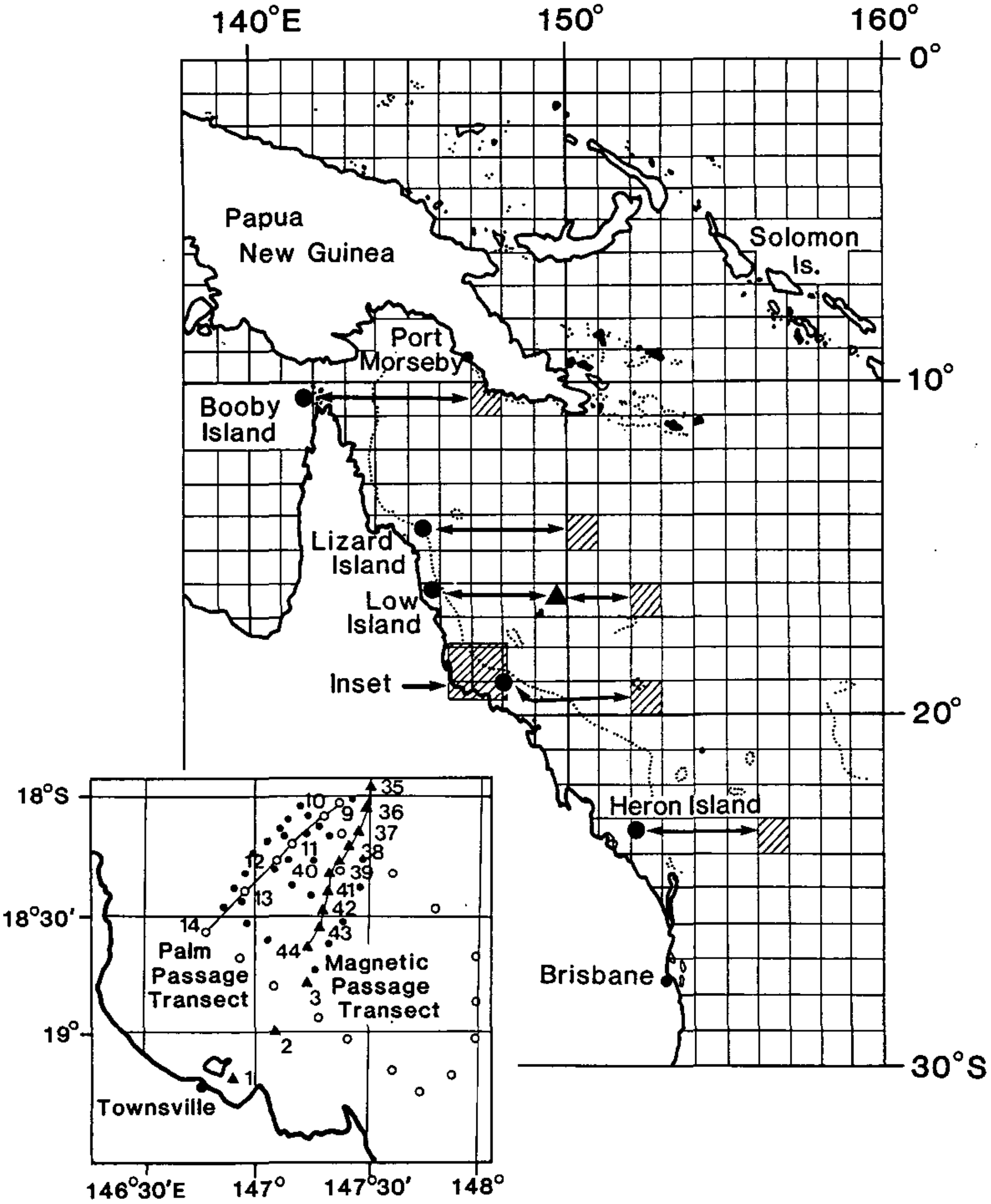

**Figure 1** Positions of the CSIRO fixed monitoring sites in the GBR and the 1° square SOP comparison sites.

*Inset* Locations of the AIMS sampling stations and the Palm Passage and Magnetic Passage transects

1975 - 1978
1980 - 1981
x 1981

Details of these stations are given in Ikeda *et al.*, 1980 and Bellamy *et al.*

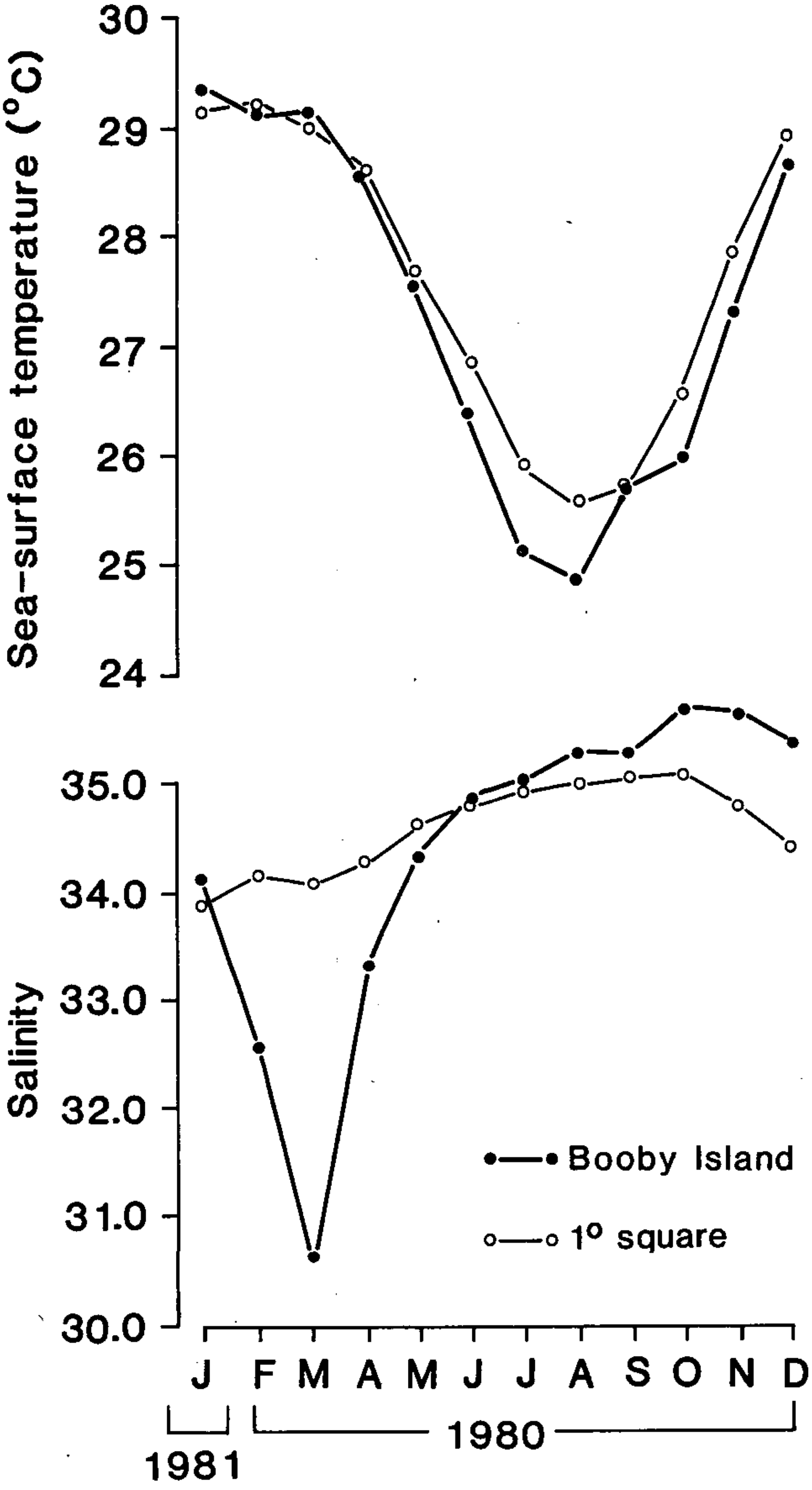

**Figure 2** The mean monthly cycle of SST and salinity at the Booby Island station and 1° square (10°-10°59'S, 147°-147°59'E)

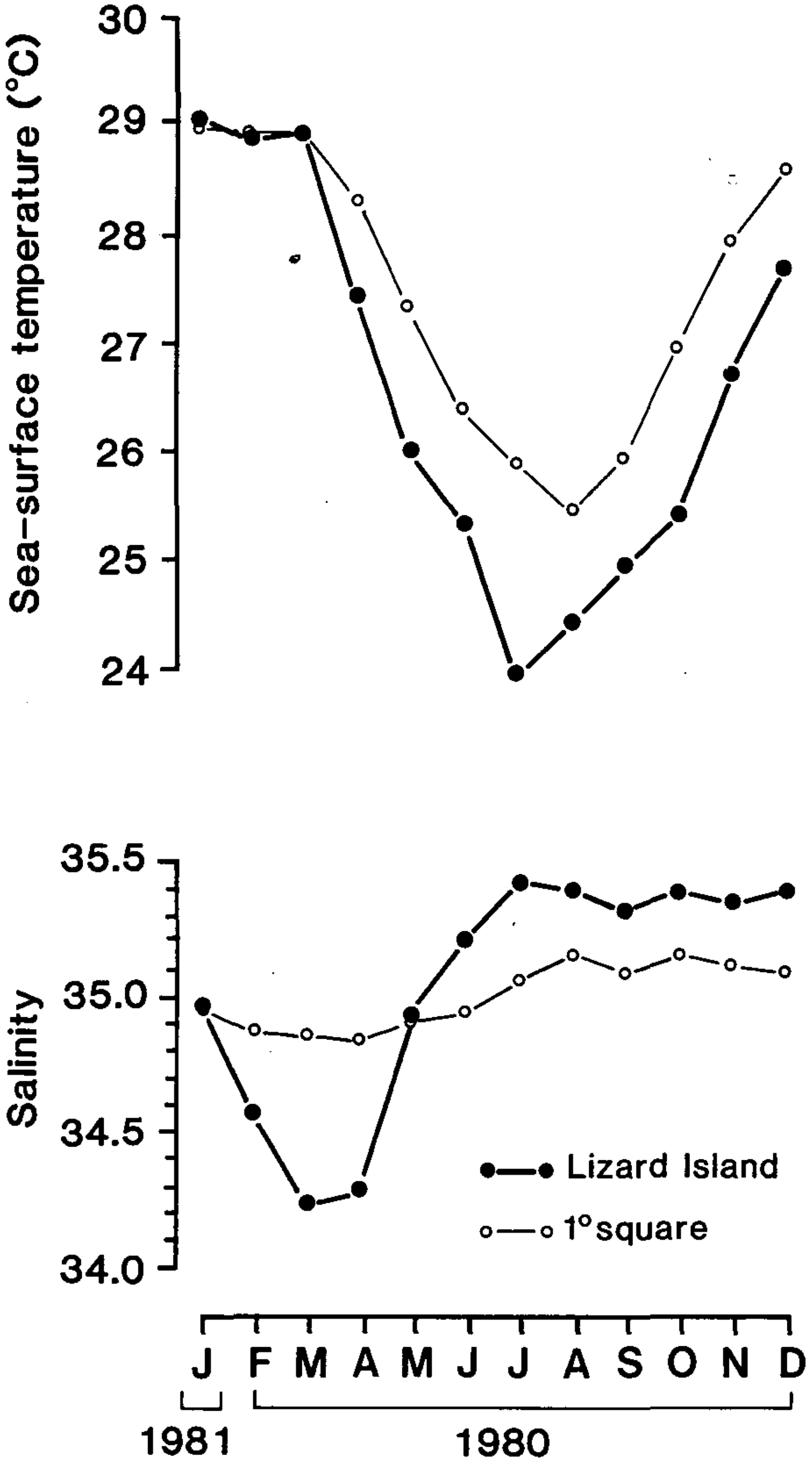

**Figure 3** The mean monthly cycle of SST and salinity at the Lizard Island station and 1° square (14°-14°59'S, 150°-150°59'S)

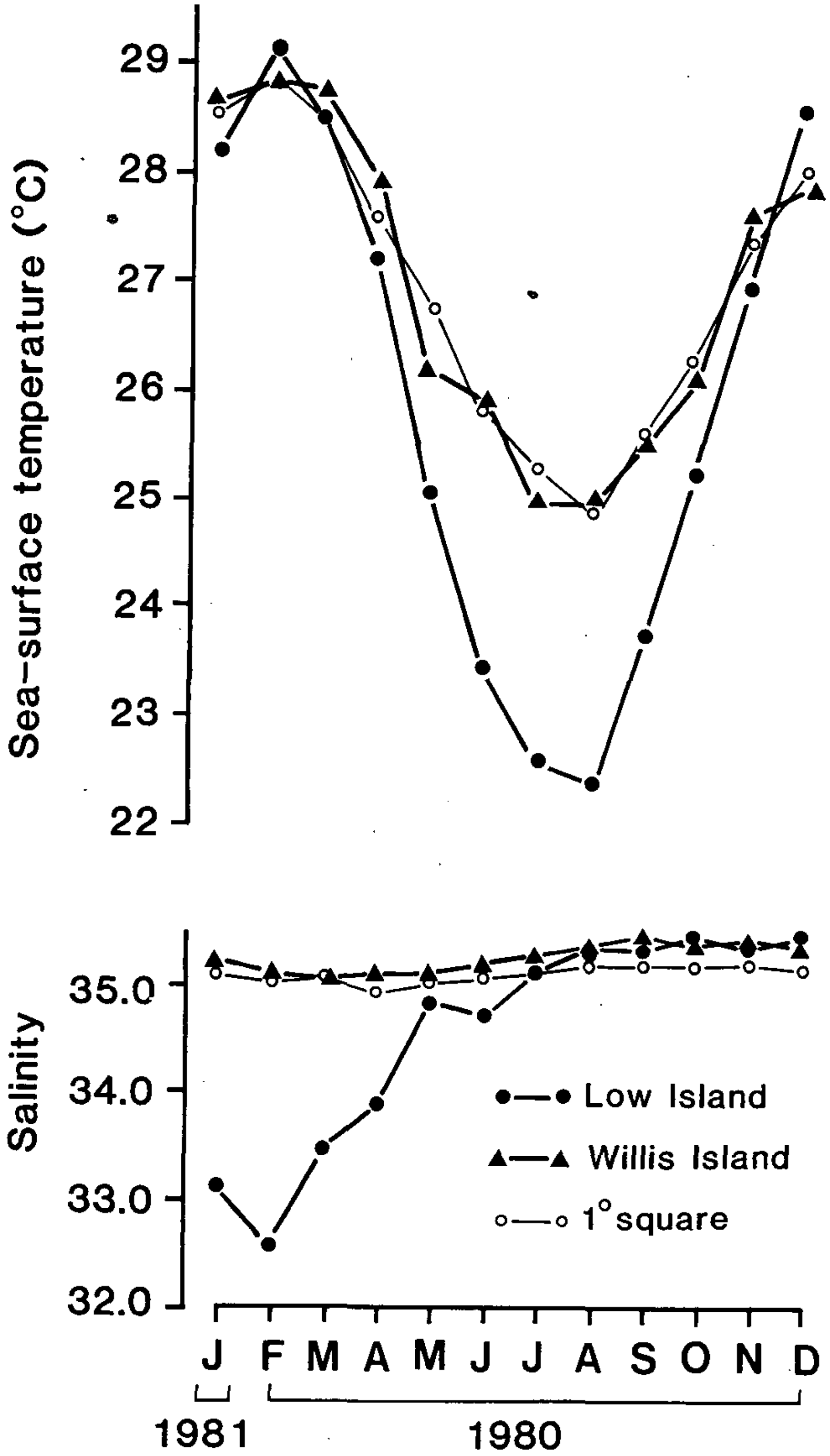

**Figure 4** The mean monthly cycle of SST and salinity at the Low Island and station 1° square (16°-16°59'S, 152°-152°59')

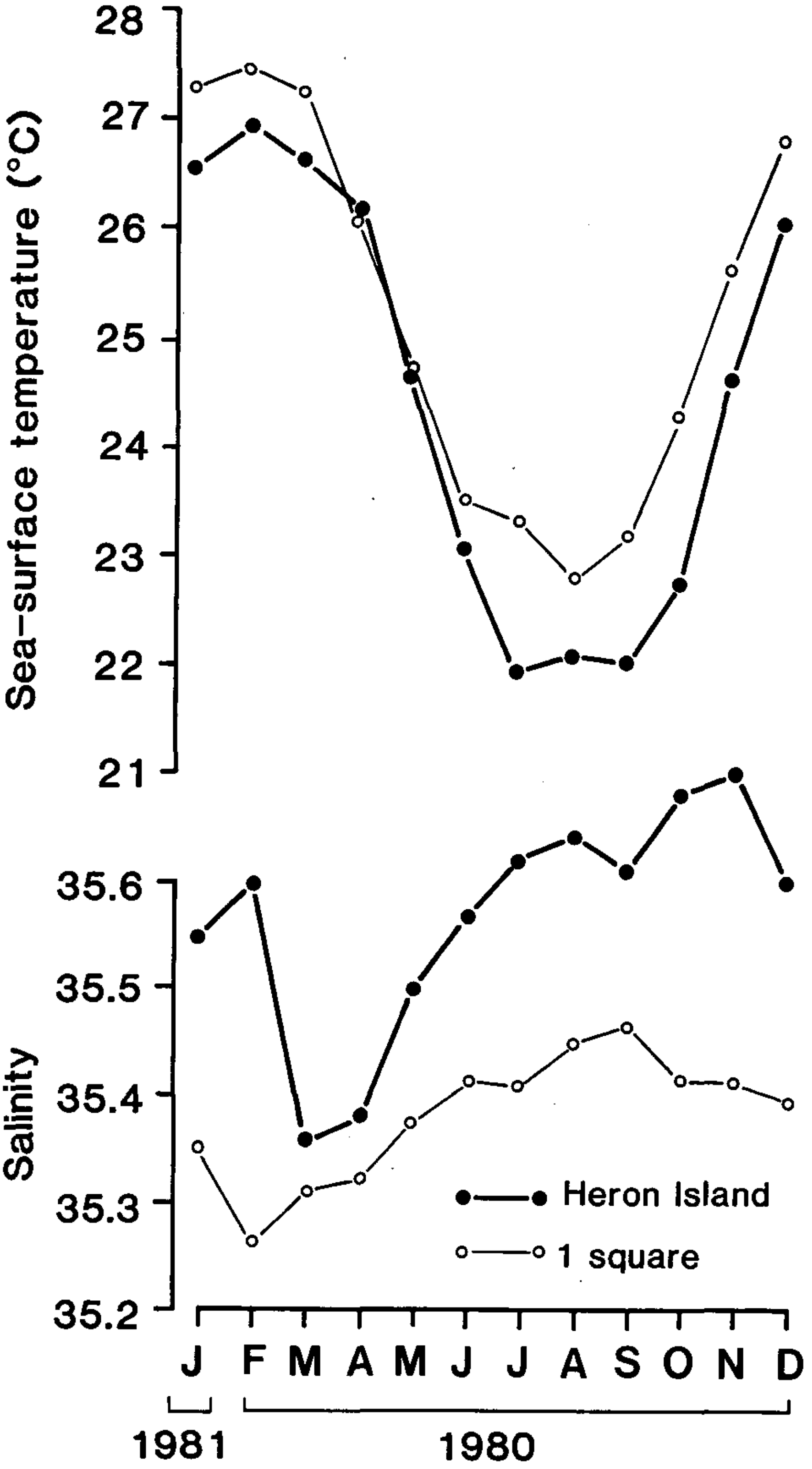

**Figure 5** The mean monthly cycle of SST and salinity at the Heron Island station and 1° square (23°-23°59'S, 153°-153°59'E)

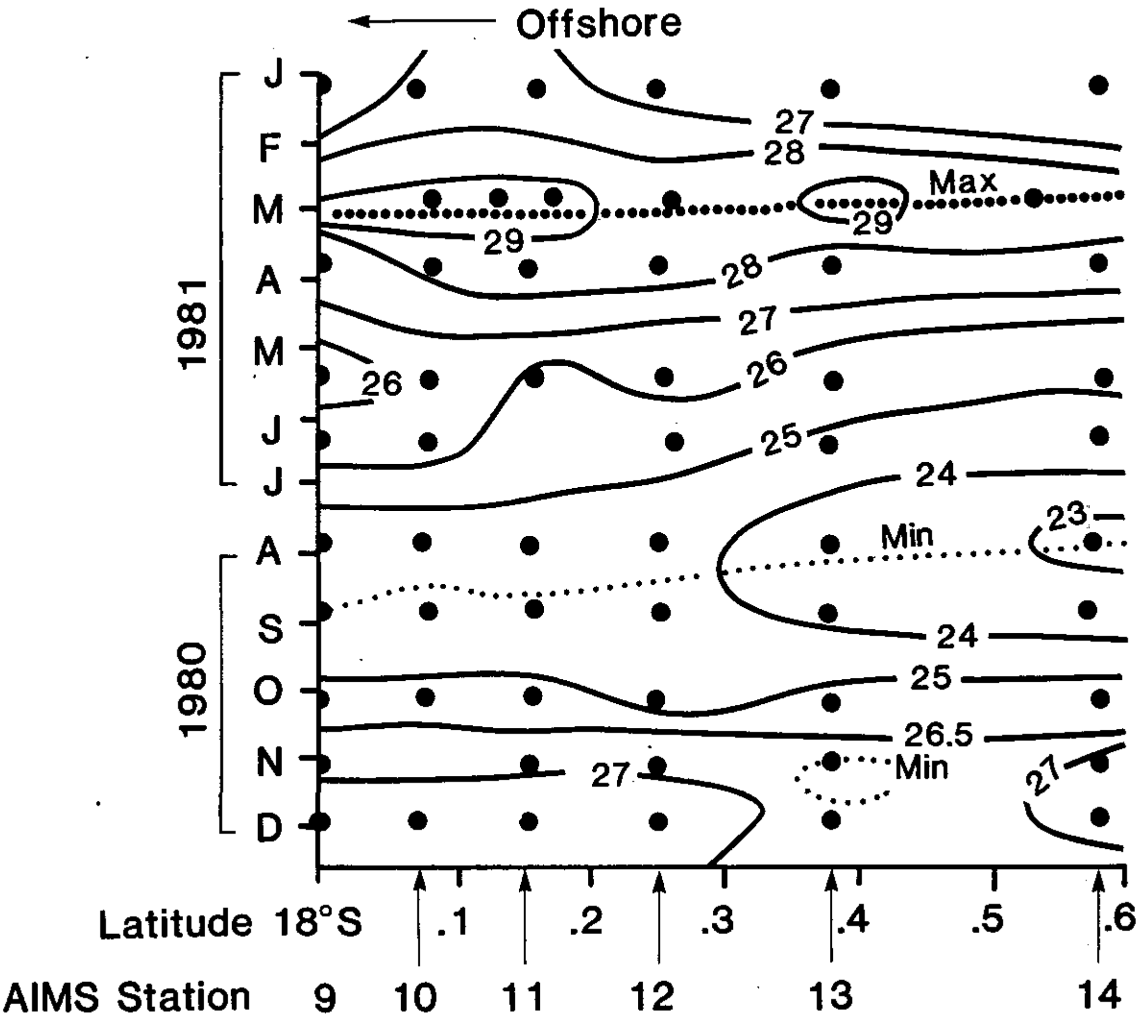

**Figure 6** Sea-surface temperature as a function of time and position along the Palm Passage transect, 1980-1981

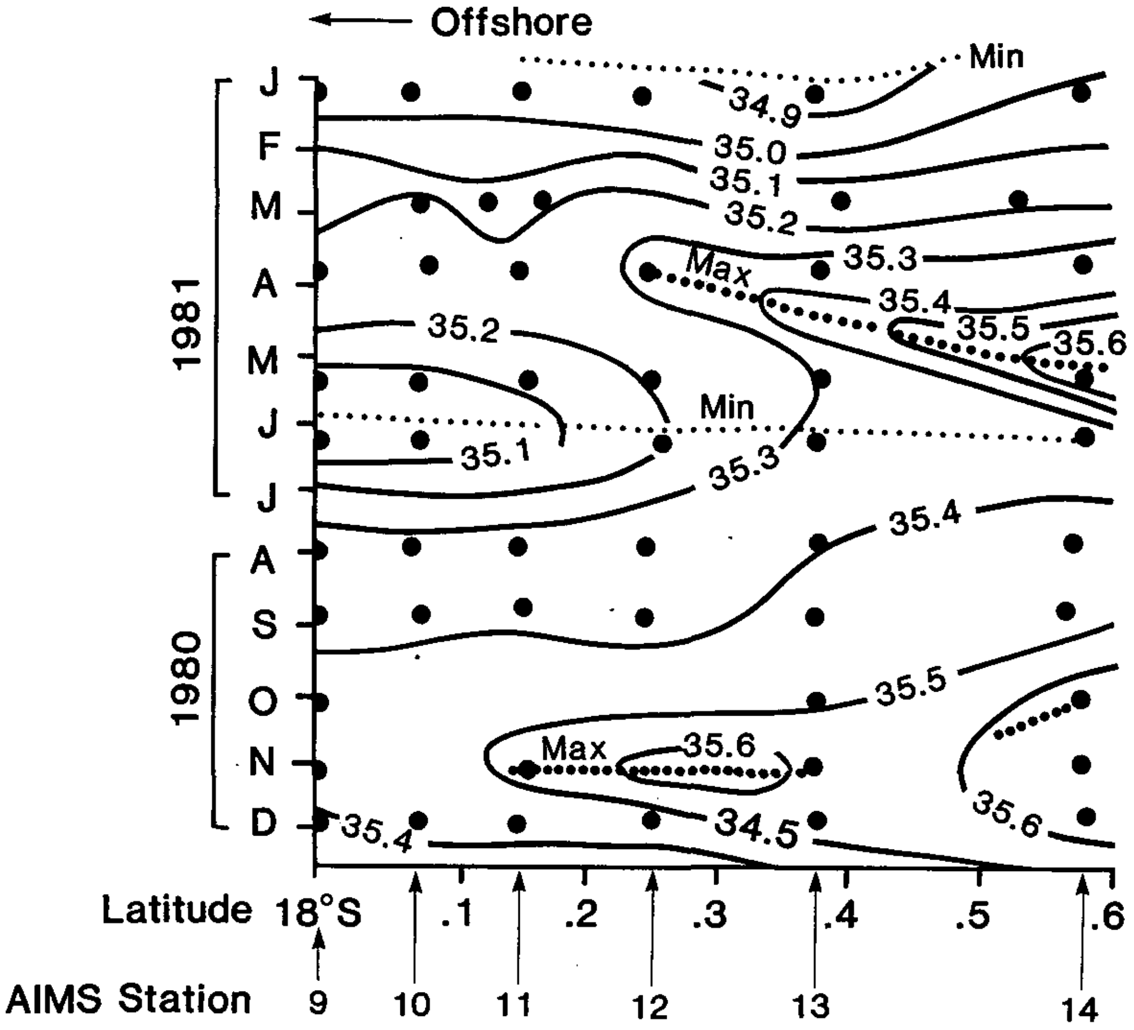

**Figure 7** Surface salinity as a function of time and position along the Magnetic Passage transect, 1980-1981

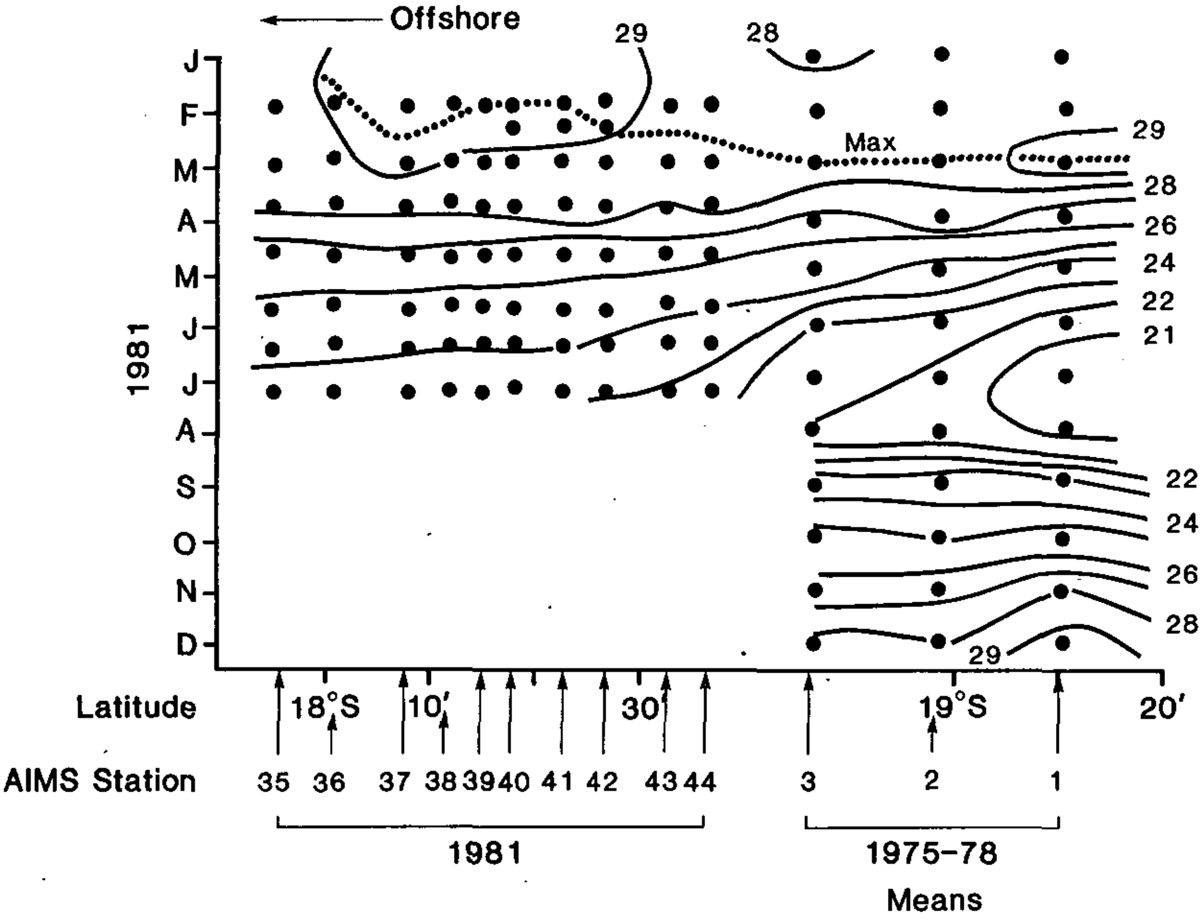

**Figure 8** Sea-surface temperature as a function of time and position along the Magnetic Passage transect, 1981

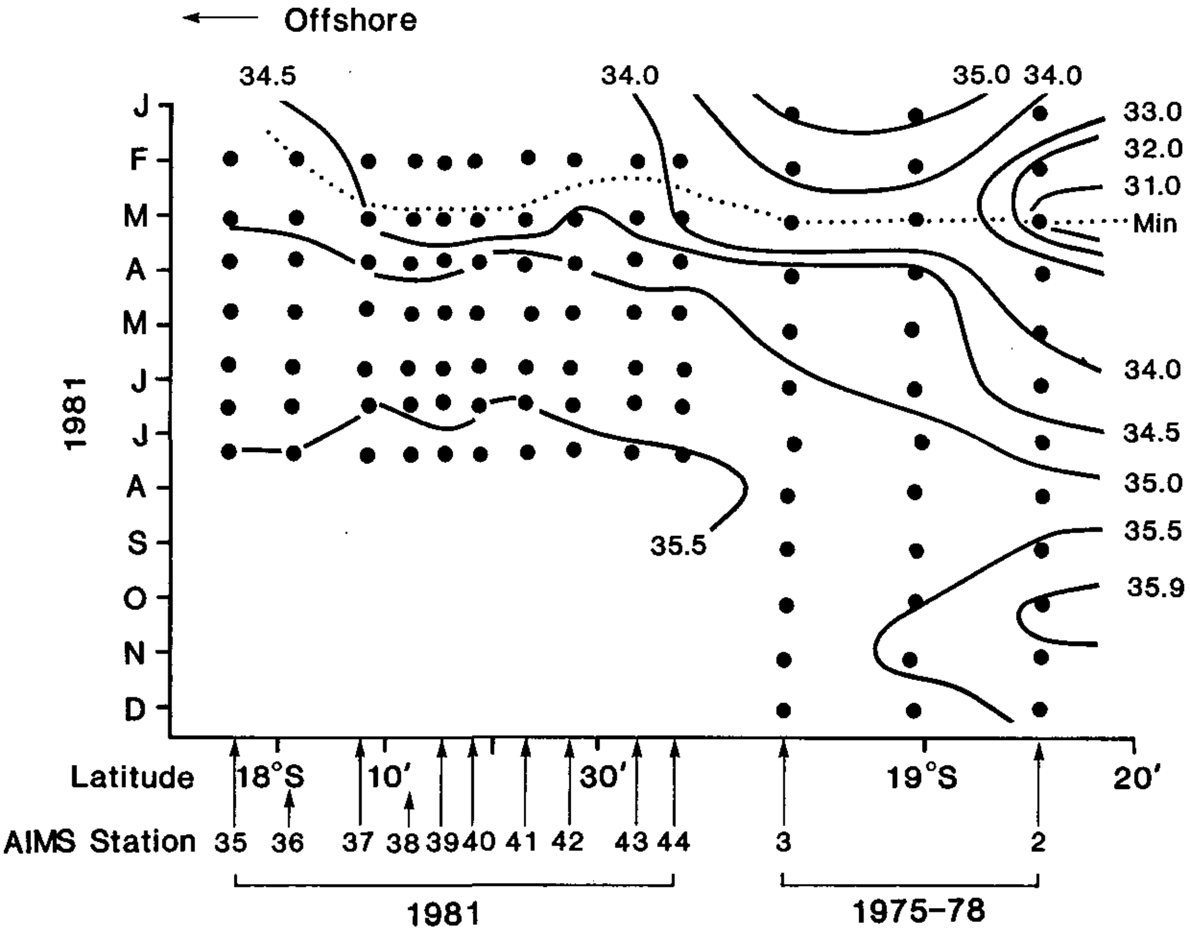

**Figure 9** Surface salinity as a function of time and position along the Magnetic Passage transect, 1981

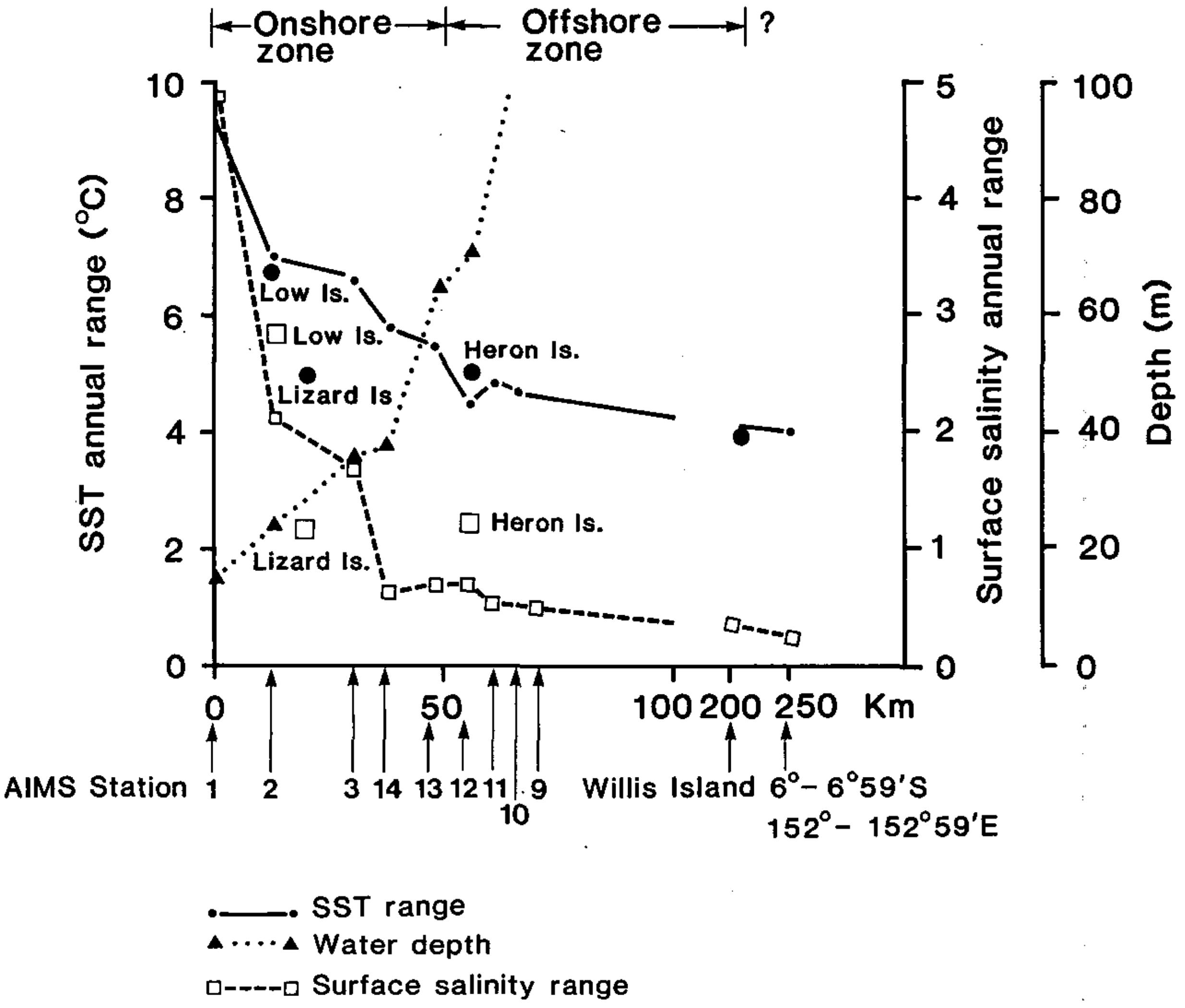

**Figure 10** Changes with distance from the coast off Townsville of the annual sea-surface temperature range, the depth of water and the annual surface salinity range. The corresponding values of the SST and salinity ranges are shown for Low, Lizard, and Heron Islands.

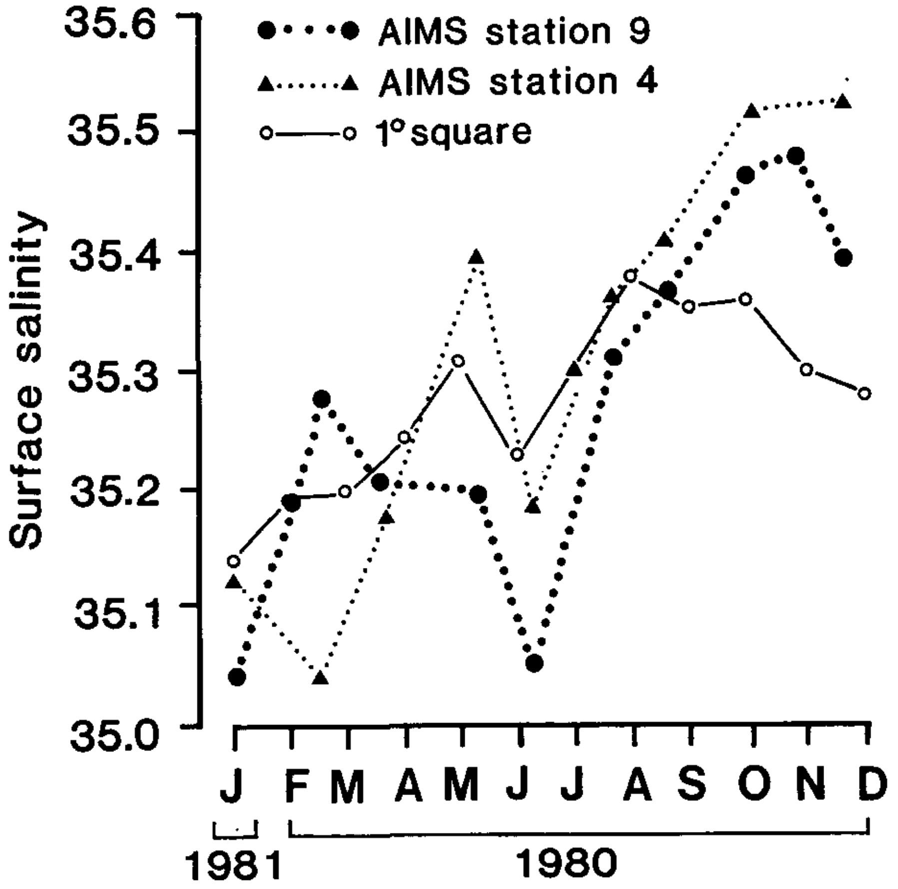

**Figure 11** Changes during 1980-1981 in the surface salinity at AIMS stations 9 and 4 (see Fig. 1) and in the mean monthly surface salinity on the CSIRO 1° square (19° 19°59'S, 152°-152°59'S)

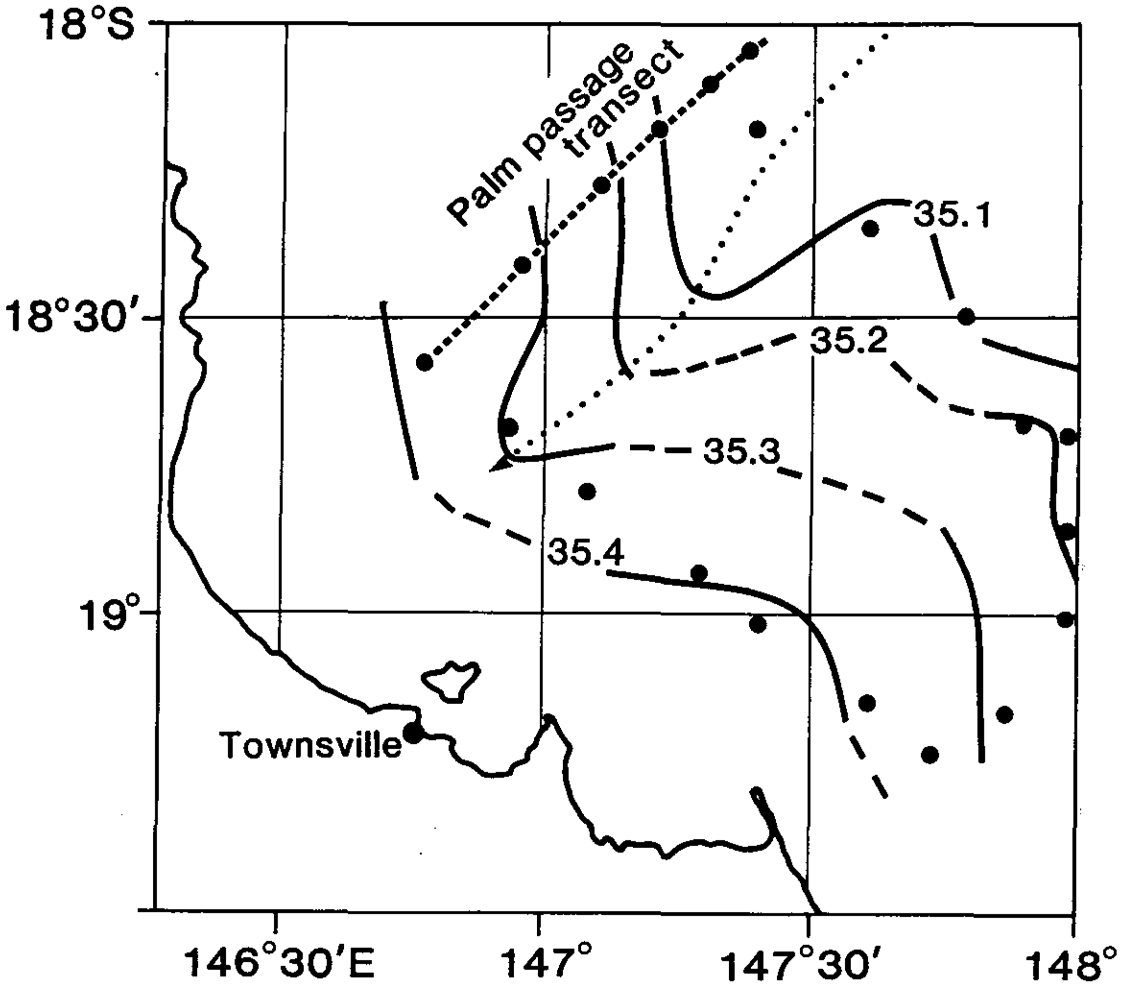

**Figure 12** The surface distribution of salinity off Townsville in June 1980

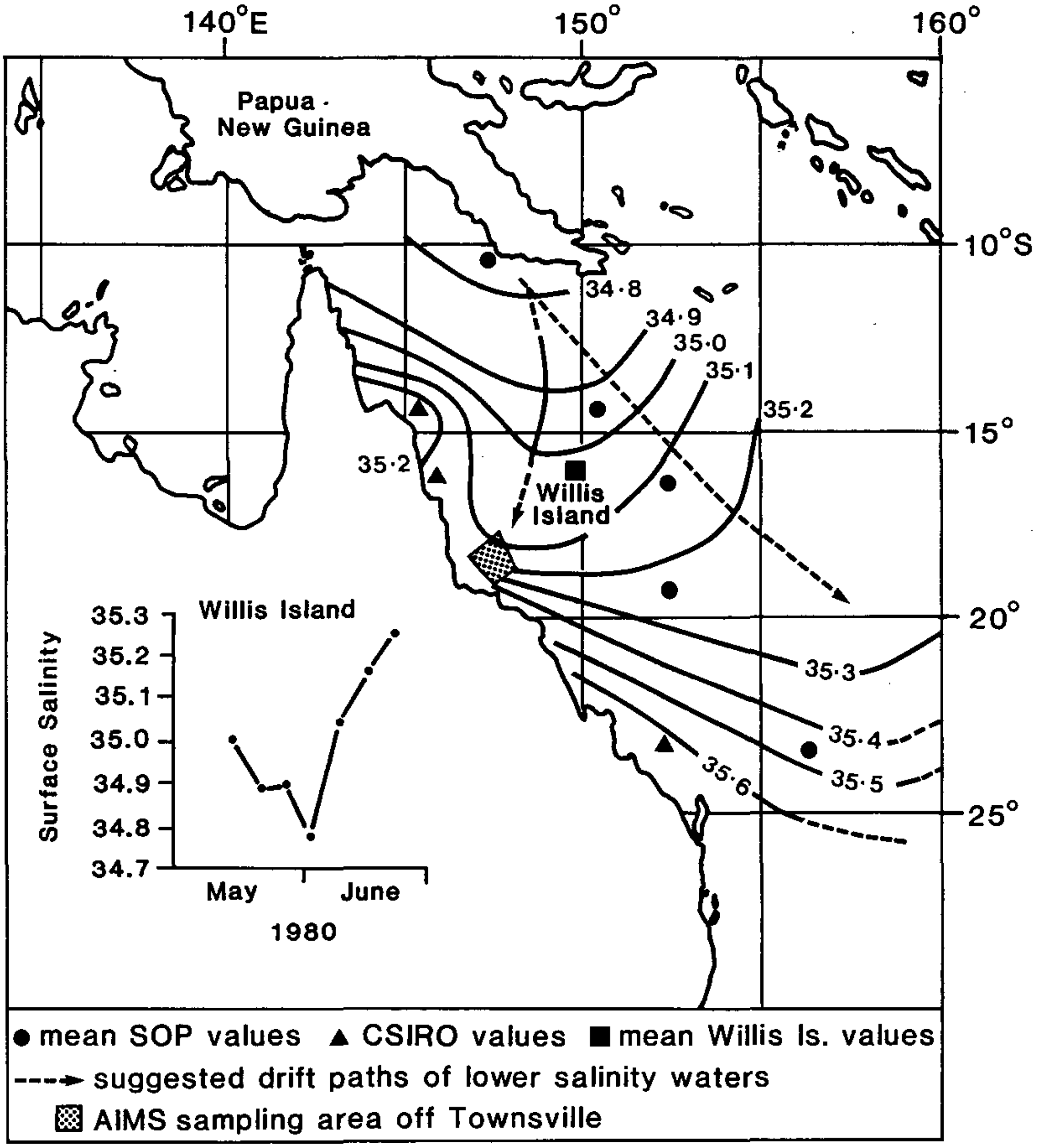

**Figure 13** The mean surface distribution of salinity in June 1980 in the northwest Coral Sea: SOP, CSIRO and Willis Island values. Inset Surface salinity at Willis Island May-June 1980. The arrows indicate the suggested drift paths of the lower salinity waters

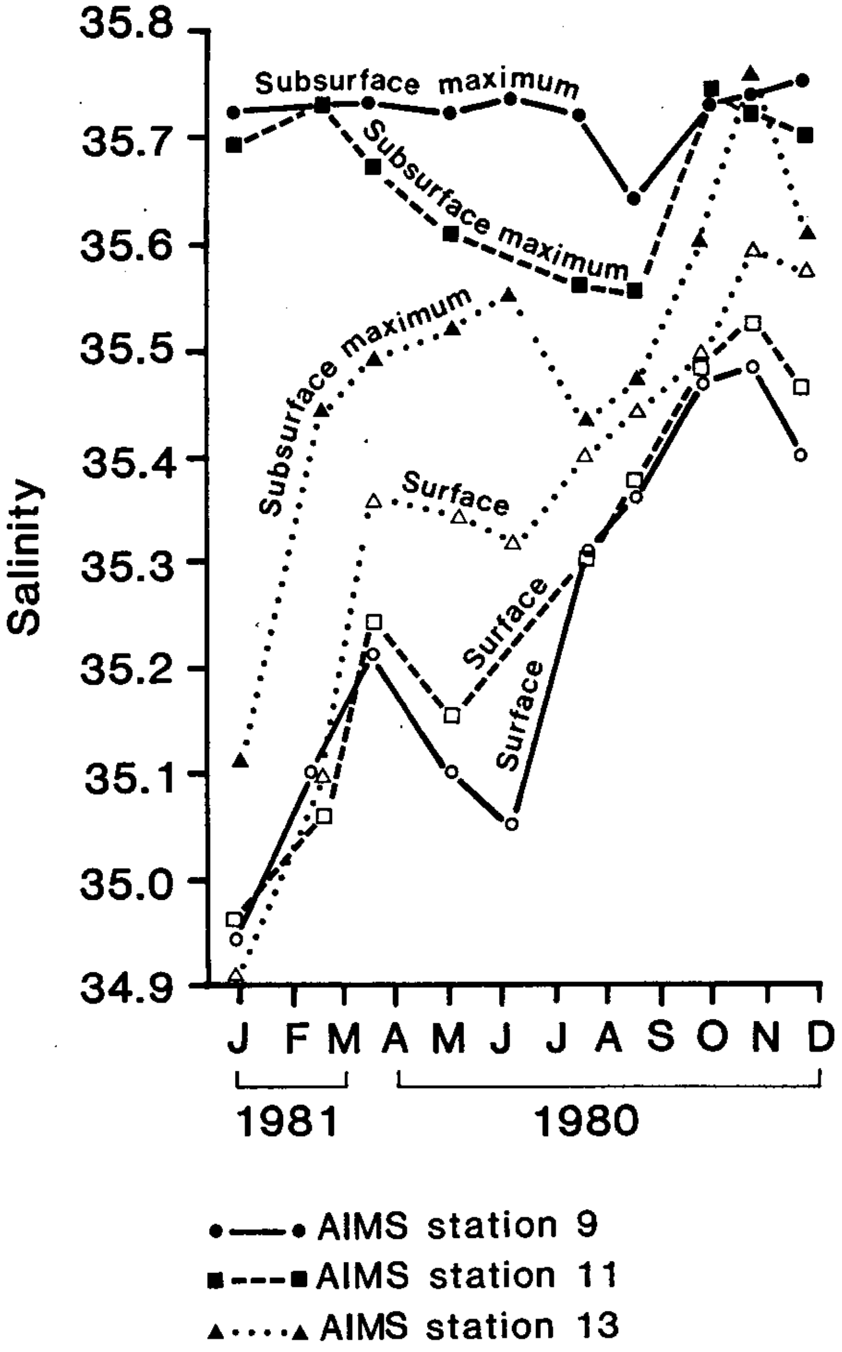

**Figure 14** The changes during 1980-1981 in the surface salinity and subsurface salinity maxima at AIMS stations 9, 11 and 13 along the Palm Passage transect

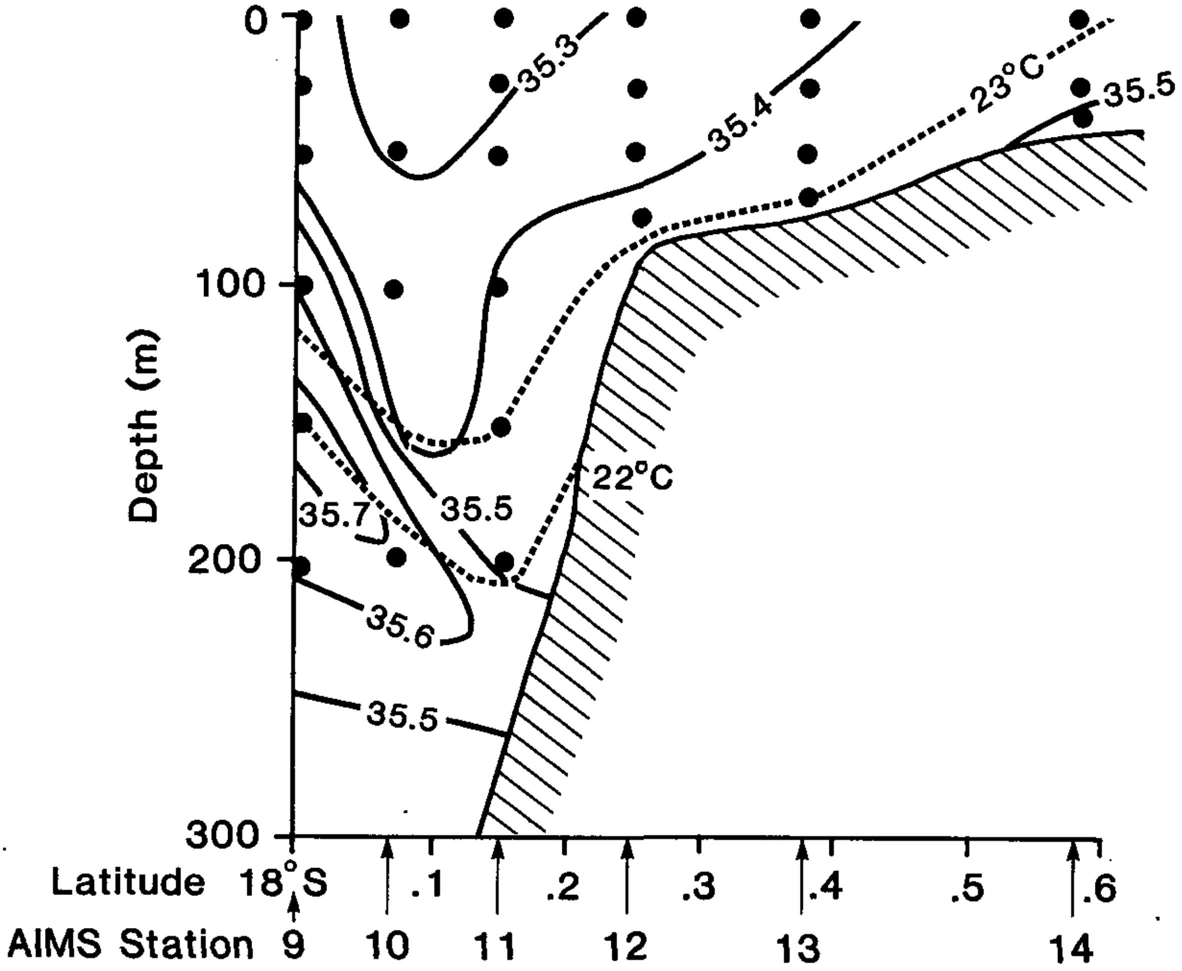

**Figure** 15 The vertical distribution of salinity and the 22°C and 23°C isotherms along the Palm Passage transect in August 1980

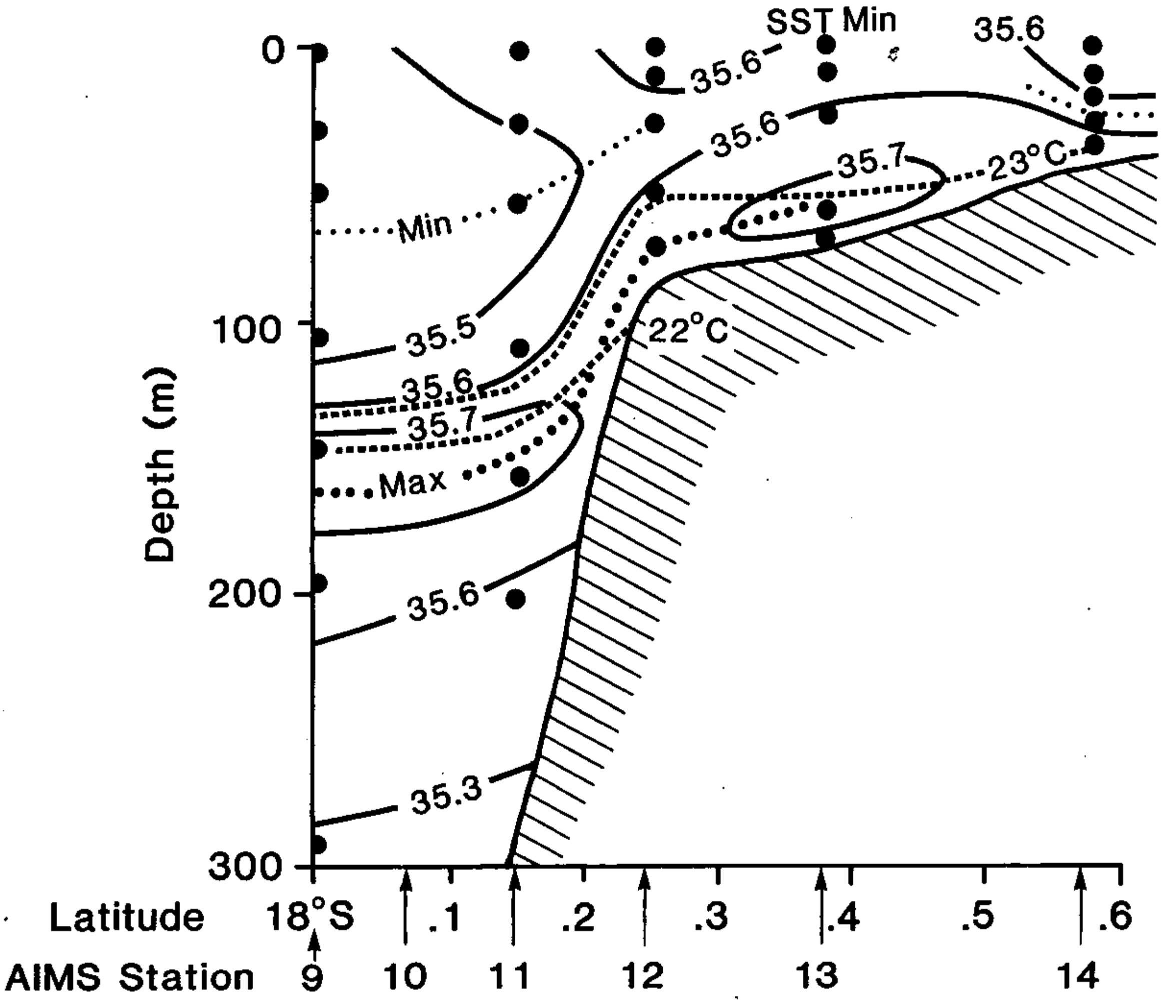

**Figure 16** The vertical distribution of salinity and the 22°C and 23°C isotherms along the Palm Passage transect in November 1980

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