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D. J. Staples

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ENVIRONMENTAL MONITORING: CLIMATE OF KARUMBA AND HYDROLOGY OF THE NORMAN RIVER ESTUARY, SOUTH-EAST GULF OF CARPENTARIA

D.J. Staples

Division of Fisheries Research
CSIRO Marine Laboratories
P.O. Box 120, Cleveland, Qld 4163

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ABSTRACT

An automatic event recorder was used to monitor six climatic variables (air temperature, relative humidity, wind speed and direction, barometric pressure, rainfall) and five hydrological variables (conductivity (salinity), water temperature, tide height, current speed and direction) at Karumba in northern Queensland and the adjacent Norman River estuary. Monitoring was carried out from December 1976 until August 1979. The data set was analysed at three different time scales ranging from hourly values, which were used to examine diel and tidal variation of parameters from a subset of the data, to monthly means, which were used to determine seasonality and year-to-year variation. Much of the small time scale variation could be accounted for by diel cycles in the case of climatic variables and tidal cycles for hydrological variables. Although Karumba lies well within the tropical equatorial zone (17° S) all variables showed marked seasonality. Winter was characterized by higher barometric pressures (1014-1016 mbar), cool south-east to east trade winds and virtually no rain. In summer, as the low pressure equatorial air masses moved south, (1002-1006 mbar), north-easterly to north-westerly monsoonal winds predominated, and a rainfall ranging from 441-1184 mm fell between December and March each year. Year-to-year differences in climate and associated physical and chemical (silicate silicon and nitrate nitrogen concentrations) environment are discussed.

INTRODUCTION

Although ecologists often stress the importance of measuring abiotic variables within an ecosystem, adequate data are seldom collected. In the estuarine environment, which is characterized by wide variation in many environmental parameters over a broad range of time scales, detailed knowledge of the processes which influence the estuarine environment are of special importance. As part of a study on the ecology of juvenile banana prawns, *Penaeus merguiensis* de Man, in the river estuaries of the south-eastern Gulf of Carpentaria, detailed climatic and hydrological data were collected from 1976 to 1979. The overall aim of the study was to examine the main factors influencing the year-to-year changes in adult prawn numbers in the Gulf of Carpentaria. Some environmental data for 1975-76 have been published by Staples (1980a) and the importance of seasonality in several environmental factors has been discussed (Staples, 1980a, 1980b). Year-to-year changes in some variables and associated changes in the commercial catch of *P. merguiensis* have also been described (Vance *et al.*, in press). This report presents a summary of the environmental data collected to examine in greater detail the factors affecting the population dynamics and production of juvenile *P. merguiensis* in the Norman River, south-eastern Gulf of Carpentaria.

Recent accounts of the climate and hydrology of the south-eastern Gulf have been given by Munro (1973, 1975) and Rhodes (1980). These descriptions, however, were based mainly on Meteorological Bureau observations and provide only a very broad picture of climatic patterns. Insufficient detail is available to examine enviromental processes on time scales similar to those used in ecological analyses. More detailed environmental data were therefore collected in the present study

Table 1. Climatic and hydrological variables used for monitoring of climate and hydrology of Karumba and Norman River 1976-79.

(a) Climate		(b) Hydrology	
Variable	***Event Step***	***Variable***	***Scale***
Air temperature	± 0.5° C	Conductivity	30 mS/cm
Relative humidity	± 2%	Water temperature	0.05° C
Wind speed	2 km wind run	Water level	3 mm
Wind direction	± 6°	Current speed	0.1 cm/s
Barometric pressure	± 1 mbar	Current direction	0.18°
Rainfall	0.25 mm		

using a data logging system capable of providing results on time scales varying from several minutes to several years. Because of the large size of the data base available, this report can give only examples of analyses made on several time scales. An attempt will be made to outline the important links between climate and the estuarine environment.

METHODS

Instrumentation

An automatic 14 channel RIMCO-CSIRO event recorder was set up at Karumba (17° 30'S, 140° 50'E), south-eastern Gulf of Carpentaria from December 1976 until August 1979 to monitor six climatic and five hydrological variables. Karumba is situated on the Norman River which extends approximately 375 km inland, perpendicular to the coast, and is the main river in a drainage basin of approximately 6,000 km^2 (Figure 1). Tidal influence extends approximately 100 km upstream. The river is a simple, one-channel system of fairly uniform depth ranging from 4 to 6 m at low water. A deeper channel of approximately 12 to 15 m depth exists at the mouth of the river.

Records of all variables were punched on paper tape, recording climatological variables in event mode and hydrological variables in analog mode through an interface with the event recorder. In event mode, a change in value of any variable over a predetermined step (as defined in Table 1(a)) was recorded as an event on the appropriate channel. For example, a punch was made on channel 2 of the event recorder after every 0.25 mm of rain had accumulated in the tipping bucket rain gauge. Bi-directional variables (both positive and negative changes possible) were recorded on two channels. The control for events was maintained by recording time pulses at 6 minute intervals. In the analog mode, variable values were recorded at regular 30 minute intervals. Scaling factors used to convert signal strengths to parameter values are given in Table 1(b).

Climatic transducers were situated in a meteorological enclosure built in accordance with Australian Meteorological Bureau specifications. Hydrological transducers were situated at the end of a 20 m wharf projecting into the Norman River (Figure 2) with current measurements being taken 1 m from the substrate, 10 m beyond the end of the wharf. The type and position of all transducers are given in Table 2.

Data Analysis and Processing

Ground truth readings of all transducers were made at weekly intervals for later checking and calibrations. The number of events punched for each channel was also noted from visual display counters mounted in the event recorder. Data processing was carried out through four stages using programs developed by the CSIRO Division of Land Use Research (Bellamy, 1980) or the author (Figure 3). The stages were:-

(i) Paper tapes from the event recorder were processed and translated to BCD card images. Number of punches counted for each channel was then checked against weekly counter records and edited to remove spurious data punched as a result of outside interference (e.g. lightning

Table 2. Type and position of transducers used for recording of climate and hydrology variables 1976-79.

Variable	*Transducer*	*Position*
Air temperature	Mercury temperature sensor in Stevenson type screen	1 m above ground Meteorological enclosure
Relative humidity	Twin permix hygrometer in Stevenson type screen	1 m above ground Meteorological enclosure
Wind speed	13 cm cup anemometer	10 m above ground Meteorological enclosure
Wind direction	Wind vane direction sensor	10 m above ground Meteorological enclosure
Wind Barometric pressure	Anaeroid barometer	5.8 m above sea level Meteorological enclosure
Rainfall	20 cm tipping bucket rain gauge	Ground level meteorological enclosure
Conductivity	Induction bridge	3 m above substrate; end of jetty
Water temperature	Mercury temperature sensor in Stevenson type screen	3 m above substrate; end of jetty
Water level	Still well float sensor	End of jetty
Current speed and direction	Lerici current meter	1 m above substrate; 10 m from jetty

strikes) or equipment malfunction. Because no absolute time values are recorded on the tape, start times, checking times and finish times were also entered at this stage.

(ii) Data were edited for instrument drift or recalibration using a comparison of calculated hourly values and weekly ground truth values. Changes in the rate of the time signal was also possible at this stage.

(iii) Files were sorted into yearly blocks and mean values calculated for hourly, daily and monthly intervals.

(iv) Special calculations were applied to certain variables requiring further analysis, including wind and current vectors and conductivity to salinity conversions. Northerly and easterly wind components and mean wind vectors were derived from hourly scalar wind speed and direction observations. Current data were decomposed into long-channel and cross-channel components calculated for hourly current speed and direction data. Salinity was calculated from conductivity and water temperature values. Results were then plotted using GPGS routines available on CSIRONET computer system.

No recordings were made during the winter of 1978 and during this and other periods when instrument failures occurred, daily climate records were taken from the meteorological station at Normanton. Regressions between Normanton and Karumba values during periods when concurrent readings were made showed that Normanton data, with appropriate scaling, provided a good estimate of Karumba daily means. No information on shorter time scales, however, could be gained. Water temperature and salinity data were also supplemented by regular manual recordings and tide height records were made using a Foxboro pressure gauge which recorded on conventional paper charts.

Chemical Characteristics

Water samples were taken monthly at 1 m depth intervals from surface to bottom at a station 400 m directly offshore from the Karumba laboratory. Nitrate-nitrogen concentrations were determined using the strychnidine method, and silicate-silicon concentrations were determined using reduced beta silicomolybdate as described by Major *et al.* (1972).

RESULTS

The Gulf of Carpentaria is influenced by warm moist north-west monsoonal circulation from December to March and a cooler drier south-east to east monsoon from May to October. Although Karumba lies well within the tropics the seasonal shift in air masses, coupled with the proximity to the inland of the Australian continent, results in a climate at Karumba which is markedly seasonal in many variables including both rainfall and temperature.

A. SHORT TERM VARIATIONS

Hourly mean values for all variables have been selected for two short periods in 1977 to demonstrate the nature of the short term variations at different times of the year. Climatic variables were selected for July (winter) and December (summer) while hydrological variables were analysed for March (wet season) and November (dry season). Much of the short term variation was periodic and could be described by diel cycles in the case of climatic variables, and tidal cycles in the case of hydrological variables. Daily means of the climatic variables were then calculated for 1978-79 to demonstrate the day-to-day variation and patterns in climate.

(i) Barometric Pressure

Some evidence of diel periodicity was apparent in the hourly barometric readings (Figure 4) especially in winter when higher pressures typically occurred during the day. Daily mean pressures for 1978-79 (Figure 5) showed periods of relatively high pressures followed by shorter periods of lower pressures resulting from migratory high and low pressure systems, mainly from the south. After the obvious seasonal fluctuation had been removed, autocorrelation analysis on the resulting residuals showed that a significant short-term correlation still existed with a periodicity of 8-12 days during the spring and summer period, and 18-25 days during the remainder of the year. The range in daily mean pressure was in the order of 7 mbar and remained fairly constant throughout the year.

(ii) Rainfall

The daily rainfall pattern, although variable in the different years studied, still showed the basic quasi-periodic pattern recorded for barometric pressure. In the wet season of 1978-79 (Figure 6) rainfall peaks occurred on the average every 8 to 12 days during periods of lower barometric pressure and lasted from 3 to 9 days.

(iii) Relative Humidity

Relative humidity exhibited fairly well defined diel periodicity, especially in winter (Figure 7) with higher humidities at night. During summer, humidity often reached 100% and the effect of rainfall on the diel pattern can be seen during the period of heavy rain of 19-21 December. Unlike pressure and temperature, the variance observed in daily mean relative humidity values depended on season (Figure 8). A much higher day-to-day variability occurred during winter than in summer when the relative humidity remained high and was positively correlated with rainfall.

(iv) Wind Speed and Direction

The diel periodicity in wind speed for selected periods in summer and winter is shown in Figure 9. The diel effect was much more consistent in winter during the dry season. Because Karumba is located on the coast a marked land and sea breeze effect exists (Figure 10), especially in spring and autumn. The sea breeze blows predominantly from the north-west and usually becomes established by noon and persists through into the evening. The land breeze tends to commence before midnight and blows until one or two hours after sunrise. Local squalls often associated with thunderstorms occur in the wet season, reaching gale force and lasting up to half an hour. From September to November a line of squalls known as the 'morning glory' pass across Karumba between 0300 and 0600 on about 40% of mornings. A sudden drop in pressure and temperature occurs and the squalls are accompanied by an arch of low black cloud and occasional light rain (Munro, 1975).

(v) Air Temperature

Diel periodicity in air temperature was most marked in winter when, as seen in the example (Figure 11), night temperatures dropped to 10-14° C and day temperatures reached 24-30° C. The diel cycle was not as consistent in summer, largely through the effects of increased cloud cover and rain. This occurred from 19 to 21 December. During this week of observations, temperature ranged from 22-26° C at night to 26-36° C by day. This decreased range in summer daily temperature was a general feature over all years of observations and the range between minimum and maximum temperatures was 14° C in winter and 9° C in summer. A comparison of the daily mean temperatures (Figure 12), however, showed that the range in the means remained relatively constant throughout the year. The daily pattern of air temperature followed changes in pressure, resulting in periods of relatively warmer weather, followed by shorter periods of cooler weather. Autocorrelations with increasing time lags revealed similar patterns to those described by barometric pressure changes.

(vi) Tides

During most of the year Karumba experiences diurnal tides reflecting the dominance of the diurnal harmonic constants, K_1 (Luni-solar diurnal of 23.93 hours) and O_1 (principal lunar diurnal of 25.82 hours). During some neap tides, semi-diurnal tides can occur for periods of one to three days. as seen during 21-25 March (wet season) (Figure 13). The mean tidal range during neap tides was 1.11 m and during springs was 3.05 m. During both this month and November, the tidal amplitudes differed from those predicted in the standard tide tables. Because of the dominance of the diurnal constituents two full tidal phase cycles occupied slightly less than a full lunar month (27.32 days compared with 29.53 days), and the tidal cycle, therefore, is out of phase with the moon's quarters, i.e. spring and neap tides can occur on any phase of the moon. For approximately one fortnight (one neap tide to the next), high water coincided approximately with the time of moon rise, while in the other fortnight in the month, high water coincided with the time of moon set. Times of high and low water therefore became progressively later each day by slightly less than one hour. At each neap tide the time of high water was delayed by 6-10 hours depending on season. As pointed out by Munro (1975), because each new fortnightly oscillation begins about an hour earlier than the preceding one, time of high water gradually changes throughout the year. High water typically occurs between midnight and noon from May to October and between noon and midnight from November to April.

(vii) Current Speed and Direction

The currents associated with the rise and fall of tide height showed some important differences during the year (Figure 14). During the dry season, the duration and speed of both flood and ebb tides showed a much more direct coupling between the water level changes and current. Current direction in both the ebb and flood direction changed 1-2 hours after high water and low water, respectively, resulting in an ebb tide of approximately 13 hours and a flood tide of 11 hours. During the wet season when freshwater discharge was large, both the duration and speed of the ebb tide were considerably greater than those of the incoming flood tide. Ebb tide started two to three hours before high water and continued for four to five hours after low water. Ebb tide, therefore, lasted approximately 20 hours while the flood tide lasted slightly less than four hours. During the smaller tidal height changes during the neaps, the outgoing ebbing tide was even more extended. At times of large freshwater runoff, although the normal pattern of tidal rise and fall persisted, the downstream flow continued for several weeks and no change in current direction occurred. As the time of high water changed throughout the year, flood tide predominated during the day in November, changing slowly to be night dominant in winter.

(viii) Salinity

Marked cycles of salinity changes were associated with the strong diurnal tide component (Figure 15). Salinity ranges exceeding 20×10^{-3} occurred during each tidal cycle in March, brought about by the alternating flood and ebb tides forcing salt and fresh water into the estuary mouth. Very steep peaks of high salinity water occurred during the short flood tide followed by longer periods of near 0×10^{-3} water occurring throughout the ebb tide. Salinity ranged approximately 10×10^{-3} around the semi-diurnal neap tides. The Norman River is one of the few rivers in the Gulf which maintains surficial flows during the dry season. In November, therefore, salinity changes in the order of $6\text{-}8 \times 10^{-3}$ over a tidal cycle were observed. The tidal cycles were not clear cut during this season, however, probably due to pockets of water of different salinities passing the sensor throughout the tidal cycle.

(ix) Water Temperature

Water temperature showed changes of up to 2.5° C over a 24 h period in both seasons (Figure 16). These temperature changes were influenced by both the tidal cycle current flow and the diel cycle of air temperature with the climatic effect tending to override the other, especially around the neap tide period. This was especially evident during the low current periods associated with neap tides (21-25 March).

B. SEASONAL VARIATION

(i) Barometric Pressure

With the movement of the air masses south and north with the seasons, a well defined seasonal cycle of pressure changes was obvious (Figure 17). The low pressures which developed during the north-west monsoon over the warm land mass of Australia in summer brought mean daily pressures between 1002 and 1006 mbar in Karumba. As the equatorial air mass moved north in winter, pressures rose to a mean range of 1014 to 1016 mbar.

(ii) Rainfall and Relative Humidity

Equatorial air masses which flow towards the semi-permanent low pressure area in summer brought heavy rain to Karumba from December to March (Figure 18). Over all years of study, 80% of the annual rainfall fell in those months and virtually no rain fell from April to November. As expected from this seasonal effect, relative humidity also showed a well defined seasonality. In the summer the air masses over the area were mainly of tropical maritime origin and the relative humidity remained high throughout this period reaching mean monthly values in excess of 85%. In the winter, when the tropical continental air moved north, dry air from the central land mass was brought in and mean monthly relative humidity during this period dropped to 60-65% (Figure 19).

(iii) Wind Speed and Direction

Mean progressive wind vectors for the three years of observation show the seasonal pattern of wind vectors (Figure 20) at Karumba. During winter and early spring (June to September), the wind flow was dominated by the south-east to east trade winds. A change to the north-west during September to October was then observed. During the following three months from November to January, winds were predominantly from the north-west as shown by the resultant wind vectors for these months. A return to the dominance of the east to south-east flow then occurred from February to March and the cycle was repeated. The net annual displacement was strongly eastwards.

(iv) Air Temperature

The seasonal movement of the air masses over Australia also brings large seasonal variation in air temperature at Karumba (Figure 21). The lowest mean monthly air temperature of approximately 19° C occurred either in June or July and following a rapid rise in temperatures in spring reached a peak of 29-30° C, usually in November. This summer temperature was then influenced by the duration and intensity of the wet season in any given year. In years of higher rainfall (for example 1976-77), summer temperatures were depressed and remained relatively constant for four to five months. In shorter wet seasons (for example 1977-78 and 1978-79), summer temperatures exhibited a second maximum in March. Seasons similar to those in more temperate climates can be defined as (i) a winter period of low temperatures from June to August; (ii) a spring period of rapidly increasing temperatures from September to November, (iii) a summer period of fluctuating high temperatures from December to February, and (iv) an autumn period of decreasing temperatures from March to May. Obviously, mean temperatures are higher than in temperate regions, but an annual mean range in excess of 10° C does not fit the commonly held concept of a stable temperature in the tropics.

(v) Mean Sea Level

Large seasonal variations also occurred in mean sea level (Figure 22) resulting from seasonal shifts in wind flow, annual variation in barometric pressure and density changes in the seawater as a result of heat gain or loss (Forbes and Church, 1983). The range in mean sea level from June to February was 1.01 m. The mean low water was 0.49 m and the mean high water was 2.78 m giving a mean tidal amplitude of 2.29 m. The maximum amplitude recorded during a spring tide was 3.80 m. The highest high water level was 4.06 m and the lowest low water level was -0.11 m.

(vi) Salinity

Along with the marked seasonality in rainfall, salinity was highest in November and lowest throughout December to March (Figure 23). With the onset of the wet season in December each year, salinity rapidly declined reaching 1.9×10^{-3} in 1976-77, 20.2×10^{-3} in 1977-78 and near zero in 1979-80. Very sudden changes in salinity at the mouth of the estuary occurred during the wet season in response to changes in local rainfall. After the wet season in March-April salinity then steadily increased reaching maximum values again in November.

(vii) Water Temperature

The seasonal water temperature cycle (Figure 24) closely followed that of air temperature. As in air temperature responses, the duration and intensity of the wet season had a marked effect on summer temperatures. In 1976-77 and 1978-79, a bimodal pattern occurred with maximum temperatures in November and again in March. Annual water temperature ranged from 15° C in winter to 32-33° C in summer (annual range 17-18° C).

C. YEAR-TO-YEAR VARIATIONS

(i) Climatic and Hydrological Variables

Year-to-year differences in climate and hydrology are described by the deviation of monthly values from the three-year mean calculated from the three years of observations (Figures 25 and 26). During 1976-77, barometric pressures were slightly lower than average during the dry season but remained average during the wet season. Rainfall, relative humidity and air temperature were also average for this season as were salinity and water temperature. In contrast, 1977-78 was characterized by a higher barometric pressure both before and during the wet season. This was associated with a below average rainfall and relative humidity. Summer air temperature and water temperature were correspondingly low; salinity for that time of year was exceptionally high. During the wet season of 1978-79, pressures were 2 to 3 mbar below normal and both rainfall and humidity were high. Both air and water temperatures were low and mean salinities approached zero during both February and March. Winter air and water temperatures also varied considerably among years, the coldest winter occurring in 1977 and the warmest in 1979.

Differences in monthly wind vectors were also related to these variations in barometric pressure and rainfall (Figure 20). The differences included both the duration and strength of the winter and autumn south-east trade winds as well as differences in the mean vector strength and direction of north-west monsoons. During the lower than average barometric pressures recorded during the spring of 1976-77, an early change from the south-east trade wind was observed. This was followed by a relatively strong west-north-west vector during the summer wet season, resulting in a net easterly drift of only 20×10^3 km for this year. In the following year, which was characterized by higher pressures during both the winter and spring periods, the east-south-east vector dominated and a much larger net easterly displacement resulted. In 1978-79, the onset of the wet season was delayed by at least one month compared with the previous two years, and the mean vector during this spring period was from the north-north-east. A relatively weak north-west monsoon compared with previous years again resulted in a larger net easterly drift for the whole year.

(ii) Chemical Characteristics

The seasonal cycles of dissolved oxygen, nitrate-nitrogen and silicate-silicon concentrations in the Norman River have been described by Staples (1980a) for the year 1975-76. In this study, the percentage saturation of dissolved oxygen remained relatively constant throughout the year, averaging 81.5% in the surface water and 76.8% near the bottom substrate. Increased oxygen concentrations occurred, therefore, during periods of lowered salinity during the wet season and during periods of lowered temperature during the winter.

A large input of silicate-silicon occurred during the wet season of 1975-76 reaching a maximum in March. Nitrate-nitrogen concentrations, on the other hand, peaked earlier in the wet season. Monthly nitrate-nitrogen concentrations for the

Table 3. Monthly nitrate-nitrogen concentration (μg atom/l) during the spring-summer period 1976-79.

Month	1976-77 Surface	1976-77 Bottom	1977-78 Surface	1977-78 Bottom	1978-79 Surface	1978-79 Bottom
September	0.5	0.6	0.8	0.1	0.4	0.9
October	1.7	1.3	Trace	0.2	1.6	0.6
November	6.5	6.6	5.1	3.8	3.9	2.3
December	10.5	10.3	21.6	21.1	12.5	10.9
January	1.2	2.3	11.2	9.0	5.2	5.5
February	2.7	6.0	5.5	7.8	0.9	2.4
March	2.4	2.8	3.6	3.2	0.6	0.4

three-year period 1976-79 showed similar seasonal changes to those observed in 1975-76, reaching a maximum in December each year (Table 3). Nitrate levels were considerably higher during the low rainfall year of 1977-78; maximum values during this year were double those of the other two years.

Silicate-silicon concentrations built up steadily during the wet season after reaching a minimum in November and December. Maximum values were recorded in February or March in all years of study (Table 4), and these were directly related to rainfall and salinity, lowest values being recorded during 1977-78.

D. LONG TERM INFLUENCES

Tropical cyclones form in latitudes between 5° S and 15° S throughout December to April. Cyclone Ted passed over the southern coast of the Gulf, 100 km west of Karumba, in December 1976. Barometric pressure decreased steadily from about midday on 18 December and reached a minimum value of 993 mbar around midnight on 19 December (Figure 27).

Table 4. Monthly silicate-silicon concentrations (μg atom/l) taken at two depths from the Norman River during spring and summer 1976-79.

Month	1976-77 Surface	1976-77 Bottom	1977-78 Surface	1977-78 Bottom	1978-79 Surface	1978-79 Bottom
September	32.6	32.1	82.6	51.4	22.2	72.4
October	38.1	37.0	26.5e	14.6	21.0	28.4
November	31.9	41.1	51.8	74.3	34.0	38.6
December	33.7	41.4	88.4	62.5	52.9	50.3
January	85.8	95.9	89.6	62.0	41.4	50.5
February	153.2	99.0	128.9	91.0	205.3	199.0
March	171.0	112.1	94.0	58.0	155.3	156.3

Mean wind velocity increased steadily, reaching 60 km/h with gusts to 110 km/h (Figure 28). Because the cyclone moved to the west of Karumba, winds blew from the east preceding the cyclone and then moved to the north and later to the north-west as the cyclone passed. One of the more destructive effects of the cyclone was the large storm surge which raised the sea level in the estuary 2 m above predicted high water on 19 December (Figure 29). Current velocities associated with this surge were in excess of 200 cm/s on the ebbing tide.

DISCUSSION AND CONCLUSIONS

Automatic recording of climatic and hydrological variables for long time periods generates extremely large data sets which require extensive editing and analysis. This type of data handling and analysis requires a considerable amount of computer time and can be expensive. Much of the editing was necessary because of instrument malfunctioning and interference from outside sources. One common source of false recording often occurred during electrical storms which triggered continuous time signals until discontinued by the operator. Of the tranducers used in this study, the wind direction sensor proved to be the most unreliable and required frequent maintenance and replacement of circuit boards. The largest gap in the recording occurred during the winter of 1977 when, due to manpower shortages, it was not possible to carry out the tape changes and regular checks necessary for maintaining the recording station. During this and other shorter periods, data collected from the Meteorological Station at Normanton proved to be adequate after suitable scaling had been carried out for calculating longer term averages such as weekly and monthly mean values.

The main advantage of the automatic recording station, apart from recording several variables not monitored by regular meteorological stations, lay in the detailed short term records of variables based on similar time scales to those recorded by ecological investigations. Because of the extensive nature of this data set, it was possible to give only examples in this report of the type of data available. Using hourly recordings, it was demonstrated that much of the short term variation seen in many variables could be accounted for by diel and tidal cycles. More in-depth time series analyses are possible on selected variables in conjunction with analyses of ecological data. During the study, Karumba came under the influence of Cyclone Ted and some of its effects on the climate at Karumba and the hydrology of the Norman River were monitored. The most significant changes occurred in water level and current speed of the tidal surge which swept up and down the estuary. Daily mean values of climatic variables for the year 1977-78 were used to show the changes which occurred on a day-to-day basis. Low pressure fronts moved across the area with an approximate frequency of 8-12 days in the spring and summer and were associated with periods of stronger winds from the south-east. During the wet season, the low pressure brought increased rainfall and correspondingly high relative humidity and lower air temperatures.

The tides at Karumba were dominated by a diurnal tide throughout much of the year, with semi-diurnal tides occurring only during the period of neap tides. Currents associated with the rise and fall of tides varied considerably throughout the year, varying from a unidirectional downstream current immediately following rain to a diurnal flood and ebb tidal current which followed the rise and fall of tide height with a time lag of 1-2 hours. These tidal flows resulted in marked changes in salinity and water temperature throughout a tidal cycle. During the wet season, salinity changes as large as 20×10^{-3} over a 12 hour period were recorded at the mouth of the river, and during the dry season salinity changes could be as large as $6\text{-}8 \times 10^{-3}$. Water temperature changes of up to 5° C were also recorded.

On a longer time scale, well defined seasonal changes occurred in all variables. Barometric pressure ranged from 1002-1006 mbar in winter to 1014-1016 mbar in summer. The winter period was characterized by cooler south-east to east trade winds and virtually no rain. During summer, winds were predominantly north-easterly to north-westerly and brought the total year's rainfall in a 4-5 month period from December to March or April. Annual air temperature ranged 20° C between summer and winter. Water temperature range was 15° C. Salinity also showed a marked seasonal change with an annual range from 36×10^{-3} recorded at the end of the dry season to near 0×10^{-3} during the wet season of years of abundant rainfall. During the first year of study (1976-77), barometric pressure, air and water temperature, rainfall, salinity and relative humidity all lay close to the three year mean calculated for 1976-79. Winter temperatures, however, were low. During the following year (1977-78), barometric pressures were high both before and during the wet season and this year was characterized by exceptionally low rainfall. Summer air and water temperatures and salinity were correspondingly higher than average. The last year was a year of much lower pressures and higher rainfall. This higher rainfall tended to depress both air and water temperatures, especially in January and February. The effects of these differences in climate and hydrology on the migrations, growth and survival of juvenile banana prawns are presently being examined and will be published elsewhere.

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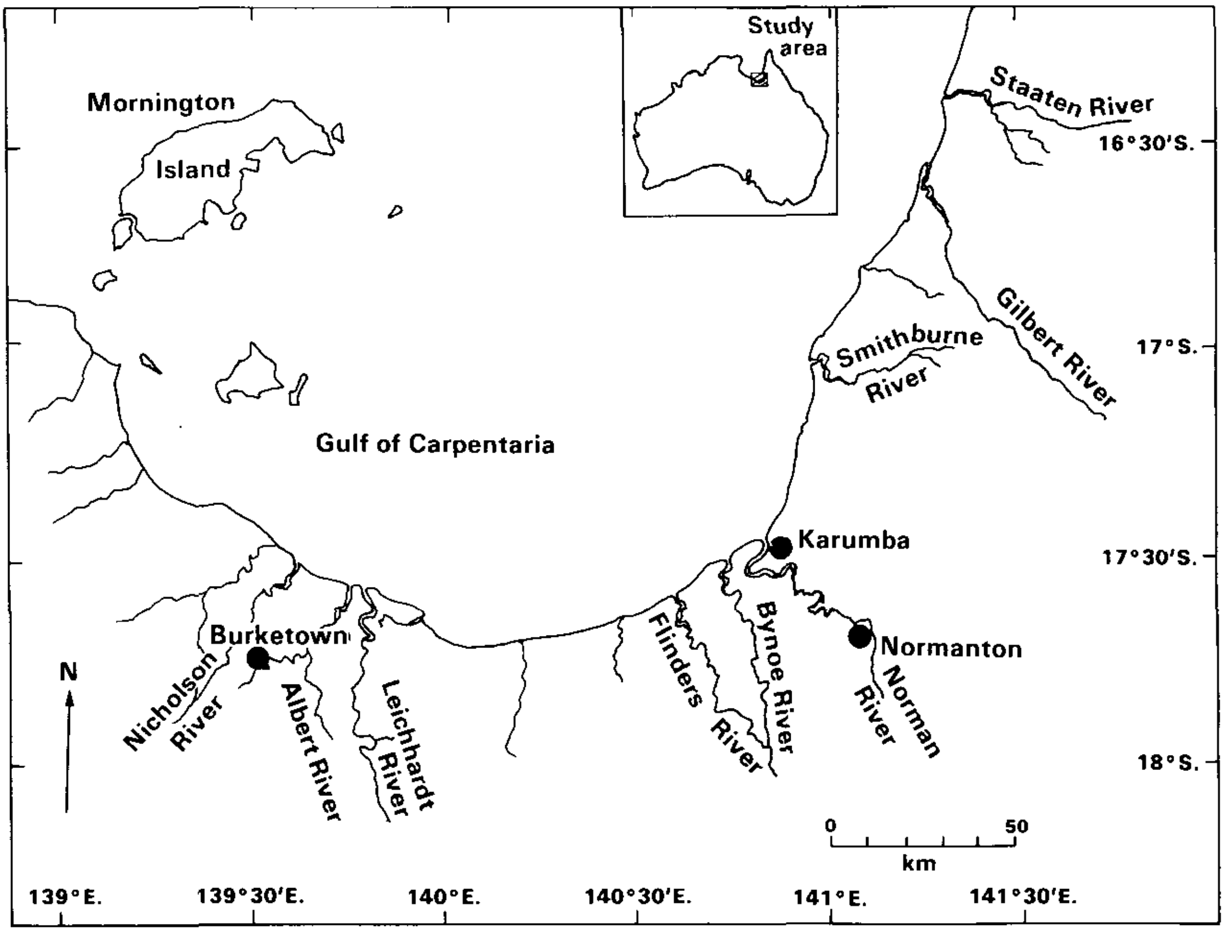


Figure 1. Map of south-eastern Gulf of Carpentaria showing location of meteorological and hydrological recordings at Karumba.

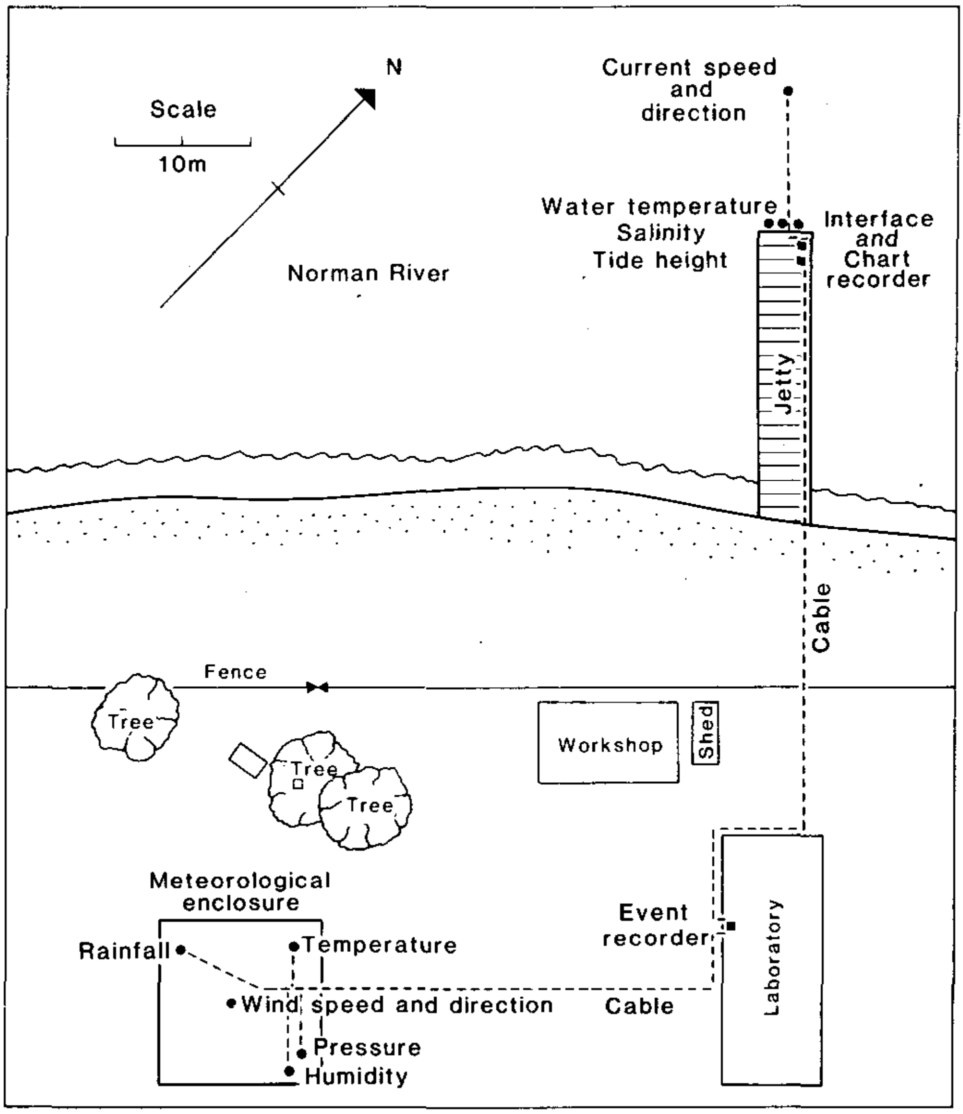


Figure 2. Site plan of meteorological recording station, data logger and hydrological recorders at Karumba.

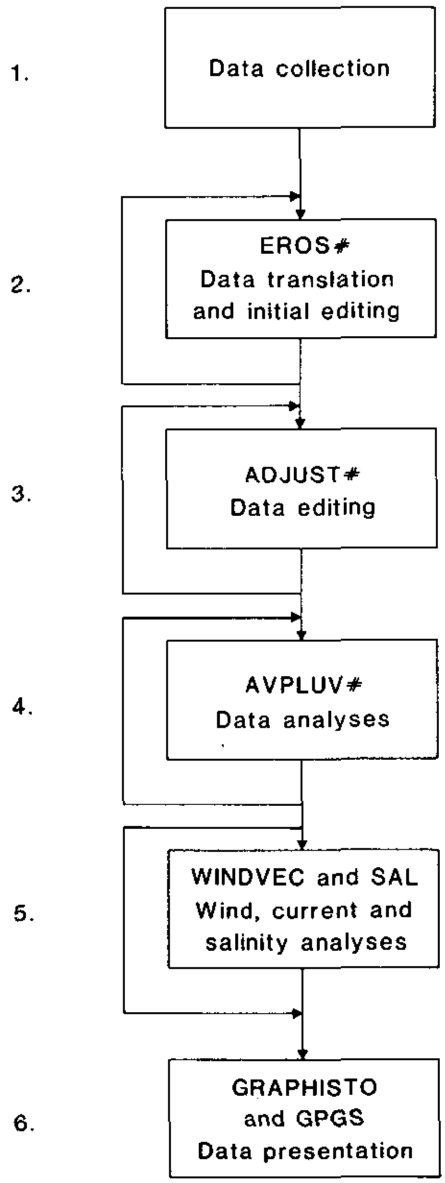


Figure 3. Flow chart of data analysis of meteorological and hydrological recordings (# indicates computer programs available from CSIRO Land Use Research.)

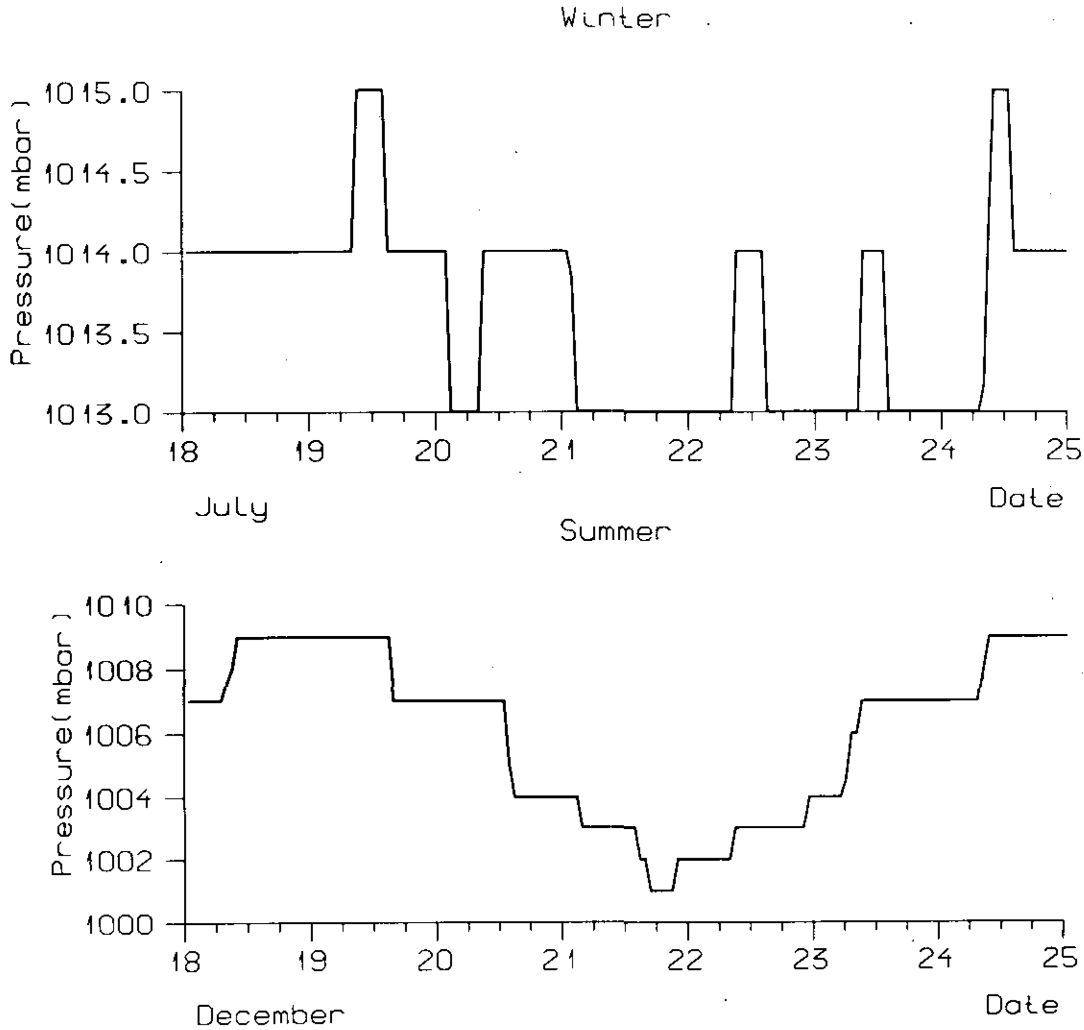


Figure 4. Hourly values of barometric pressure recorded during one week each in summer (December) and winter (July), 1977.

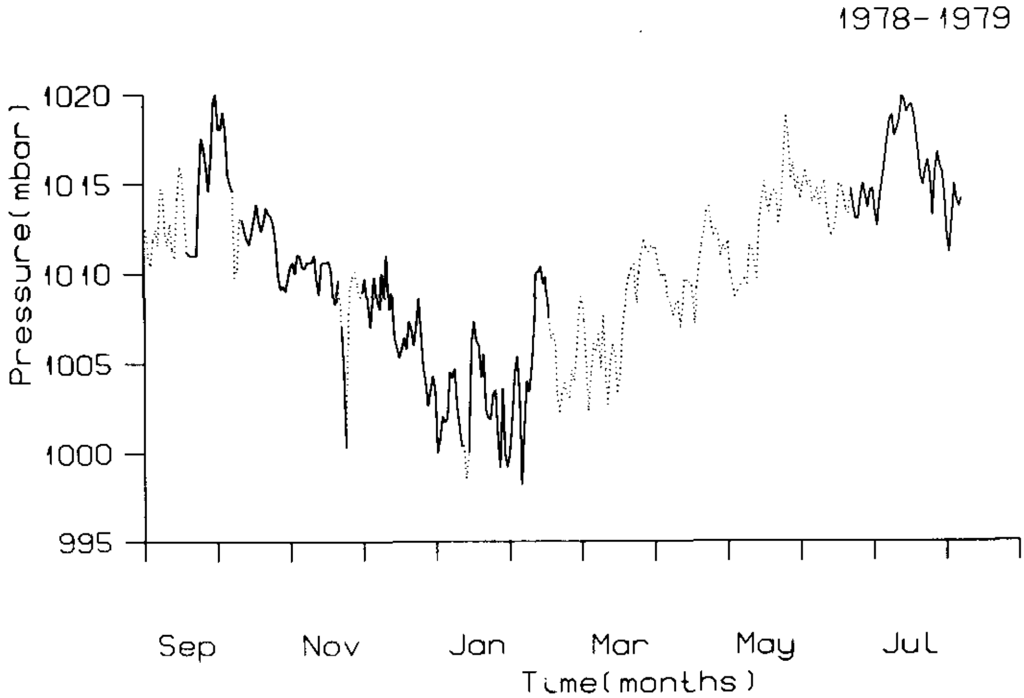


Figure 5. Daily variation in mean barometric pressure at Karumba from September 1978 to July 1979. Dotted line indicates data estimated from the Meteorological Bureau station at Normanton.

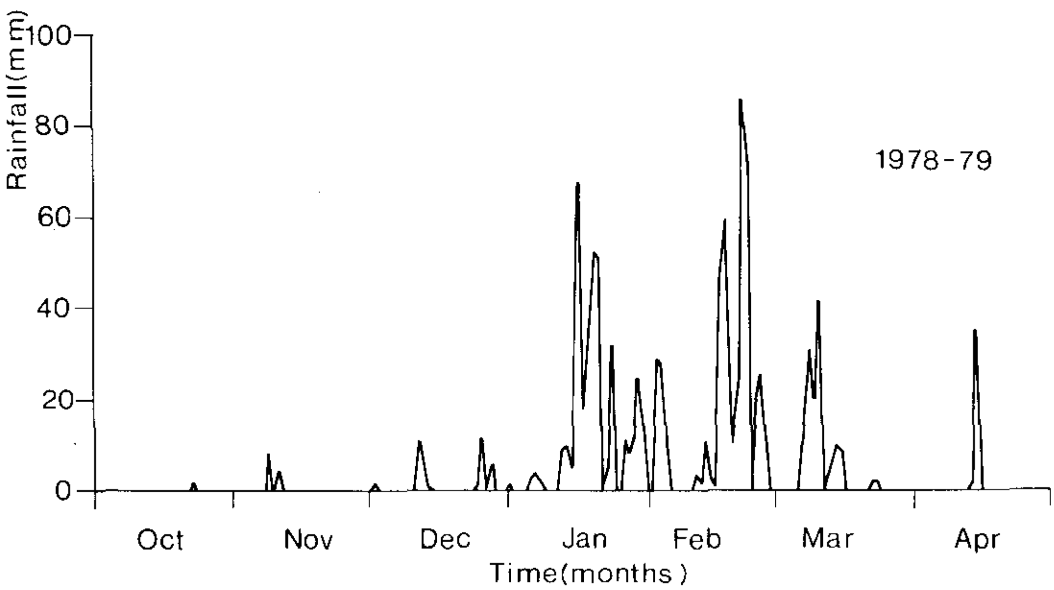


Figure 6. Daily rainfall for Karumba, October 1978 to April 1979.

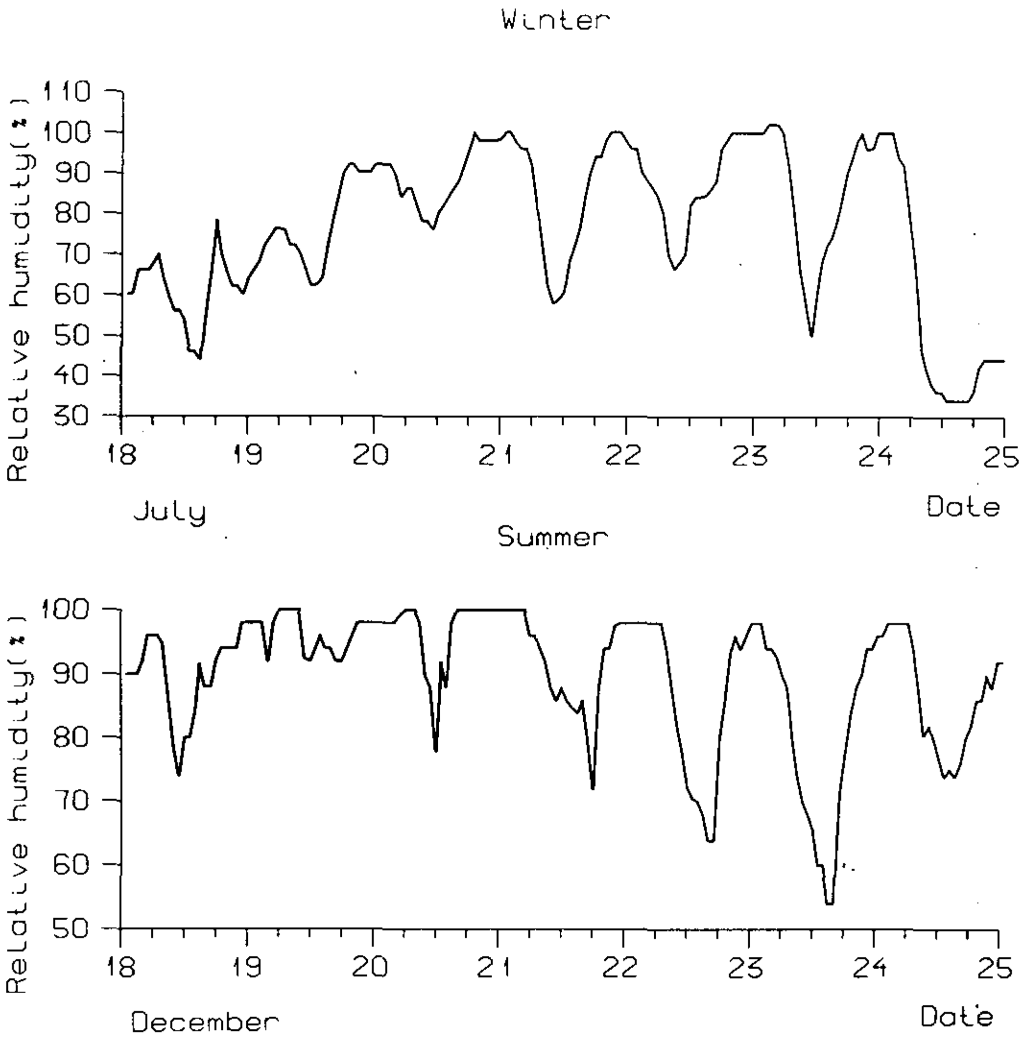


Figure 7. Hourly recordings of relative humidity at Karumba during one week in summer (December) and winter (July) 1977.

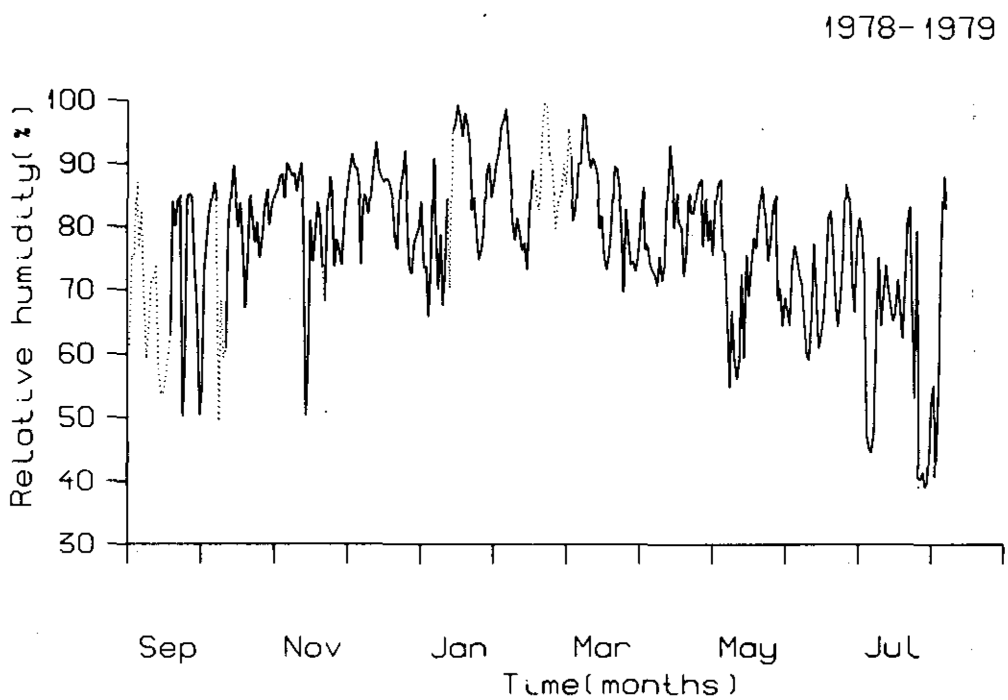


Figure 8. Daily mean relative humidity recorded at Karumba from September 1978 to July 1979. Dotted line represents scaled data taken from Normanton records.

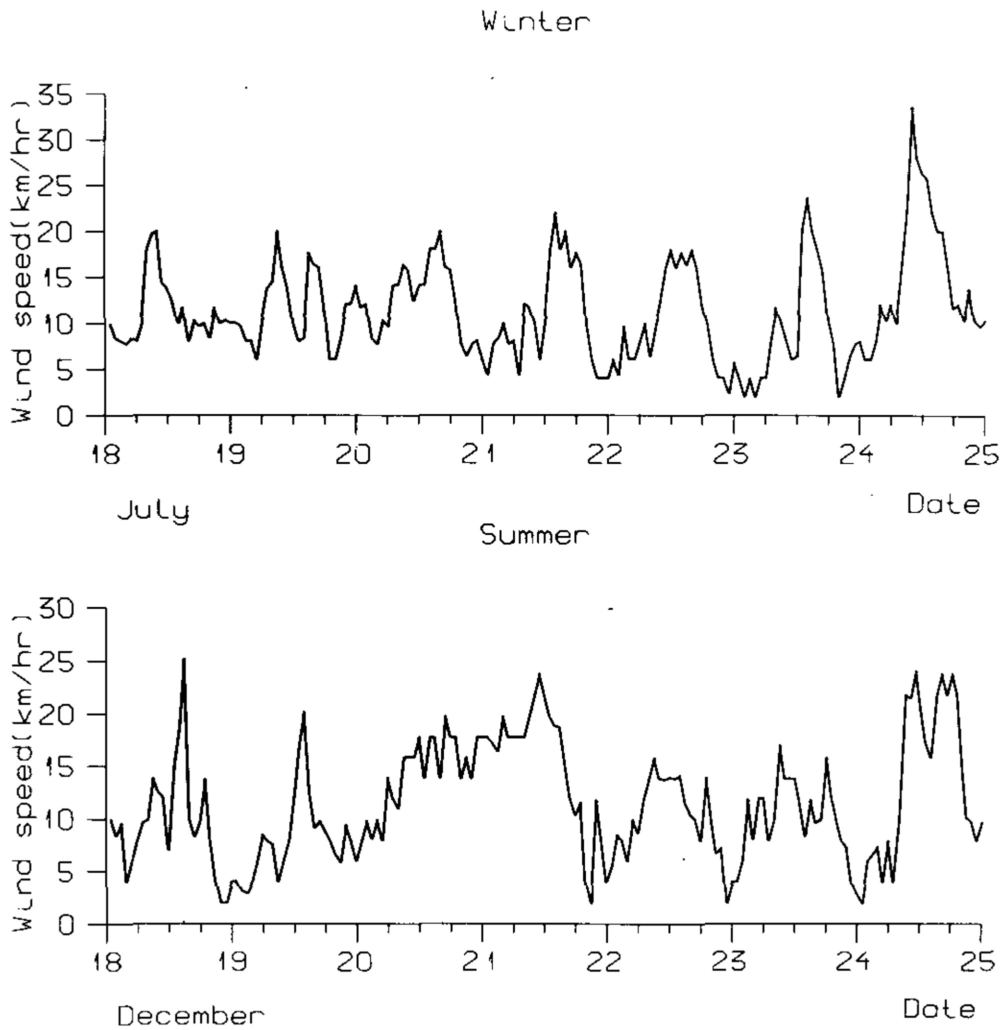


Figure 9. Hourly wind speed 10 m above ground at Karumba during one week each in summer (December) and winter (July), 1977.

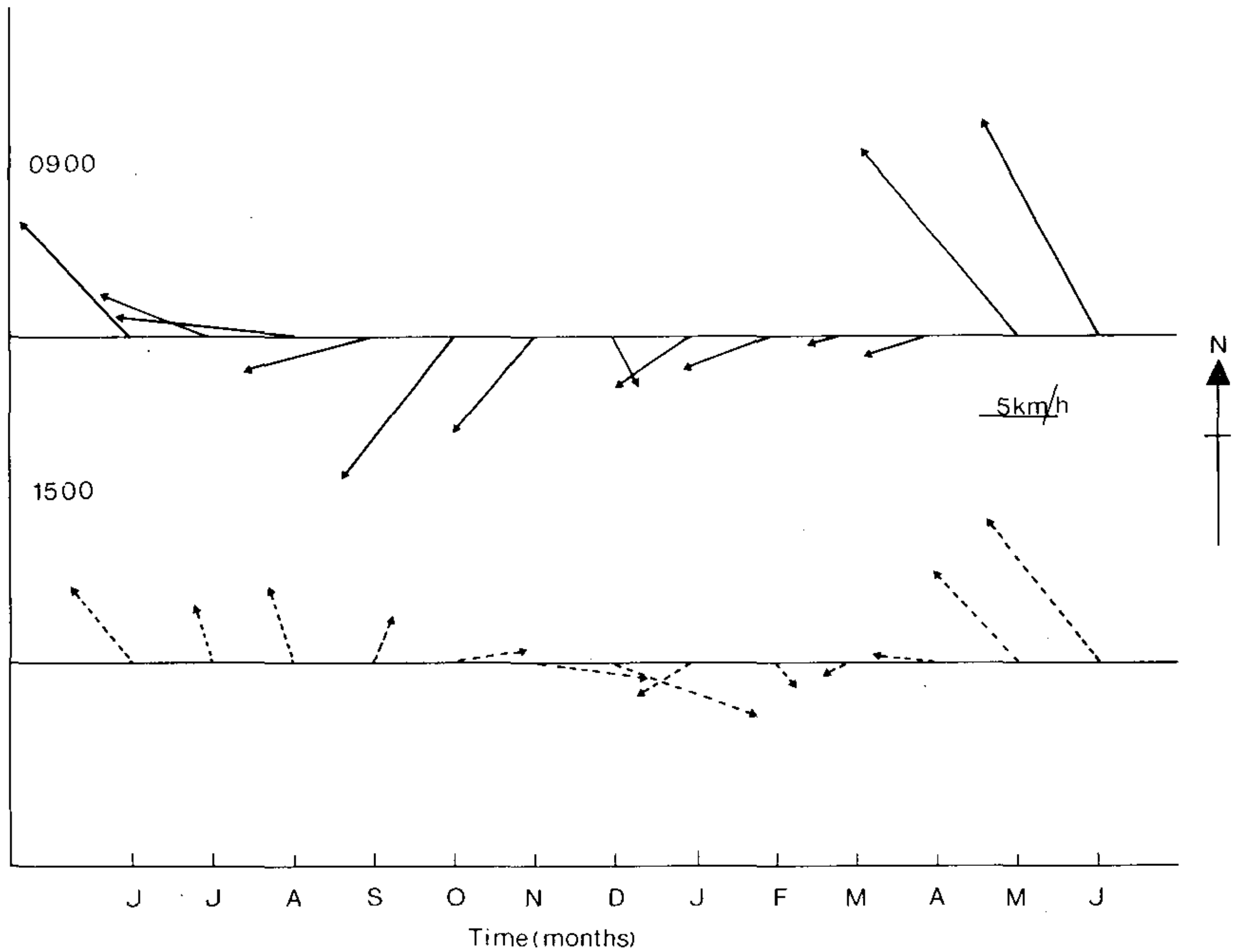


Figure 10. Mean monthly wind vector at 0900 h and 1500 h at Karumba, June 1978 to June 1979.

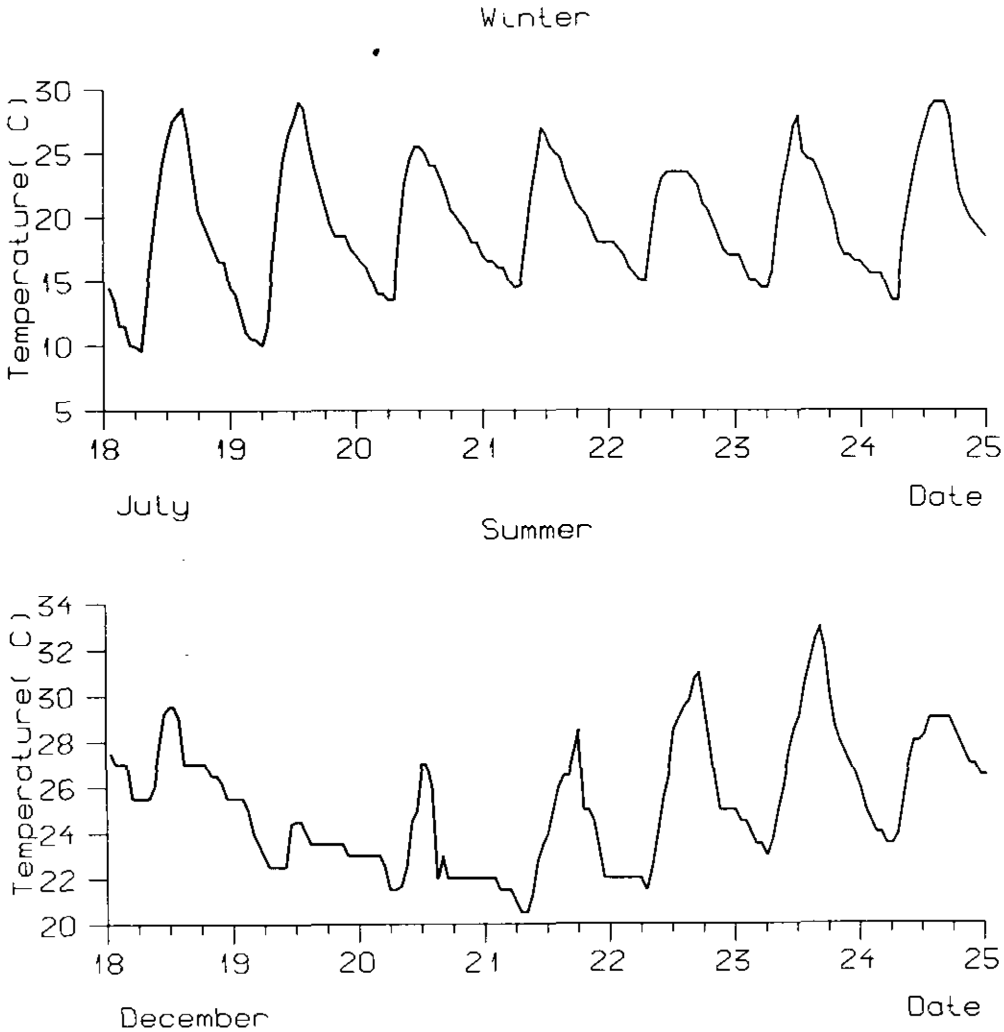


Figure 11. Hourly air temperature recordings at Karumba for one week in summer (December) and winter (July) 1977.

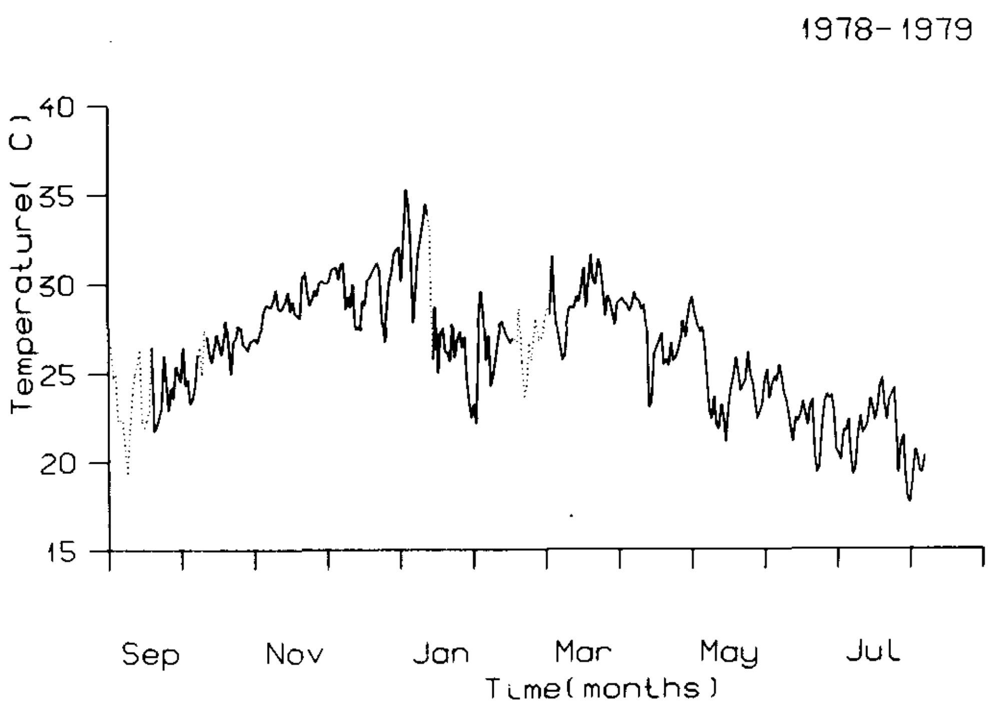
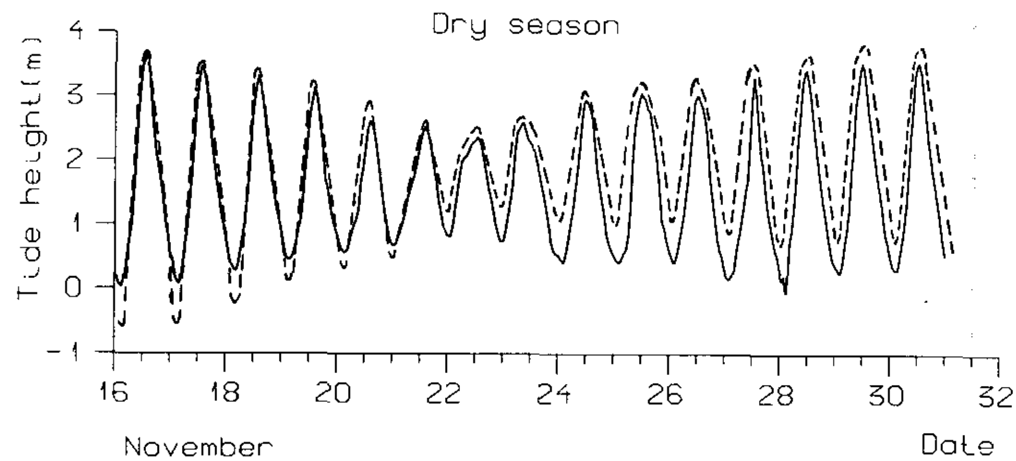


Figure 12. Daily mean air temperature at Karumba from September 1978 to July 1979. Dotted line represents data scaled from Normanton records.



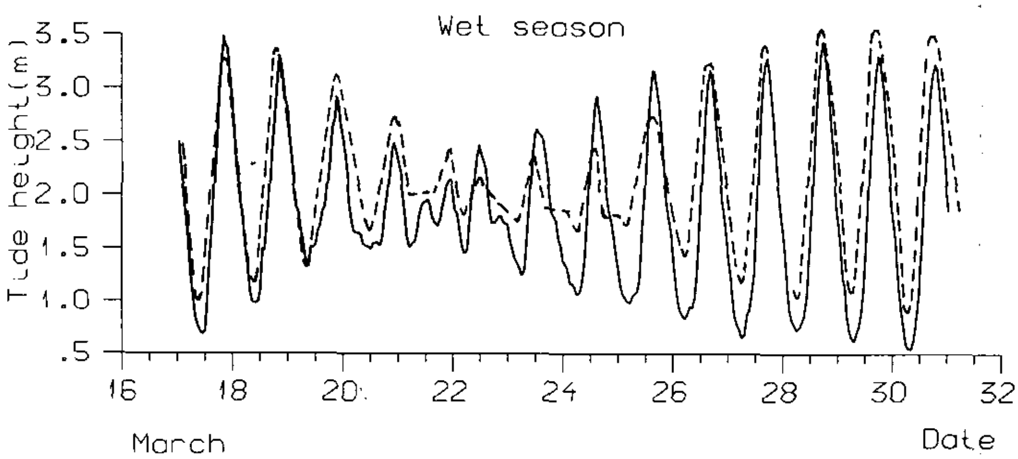


Figure 13. Hourly tide height of the Norman River during a fortnight in wet season (March) and dry season (November) 1977. Both observed (solid line) and predicted (dashed line) heights shown.

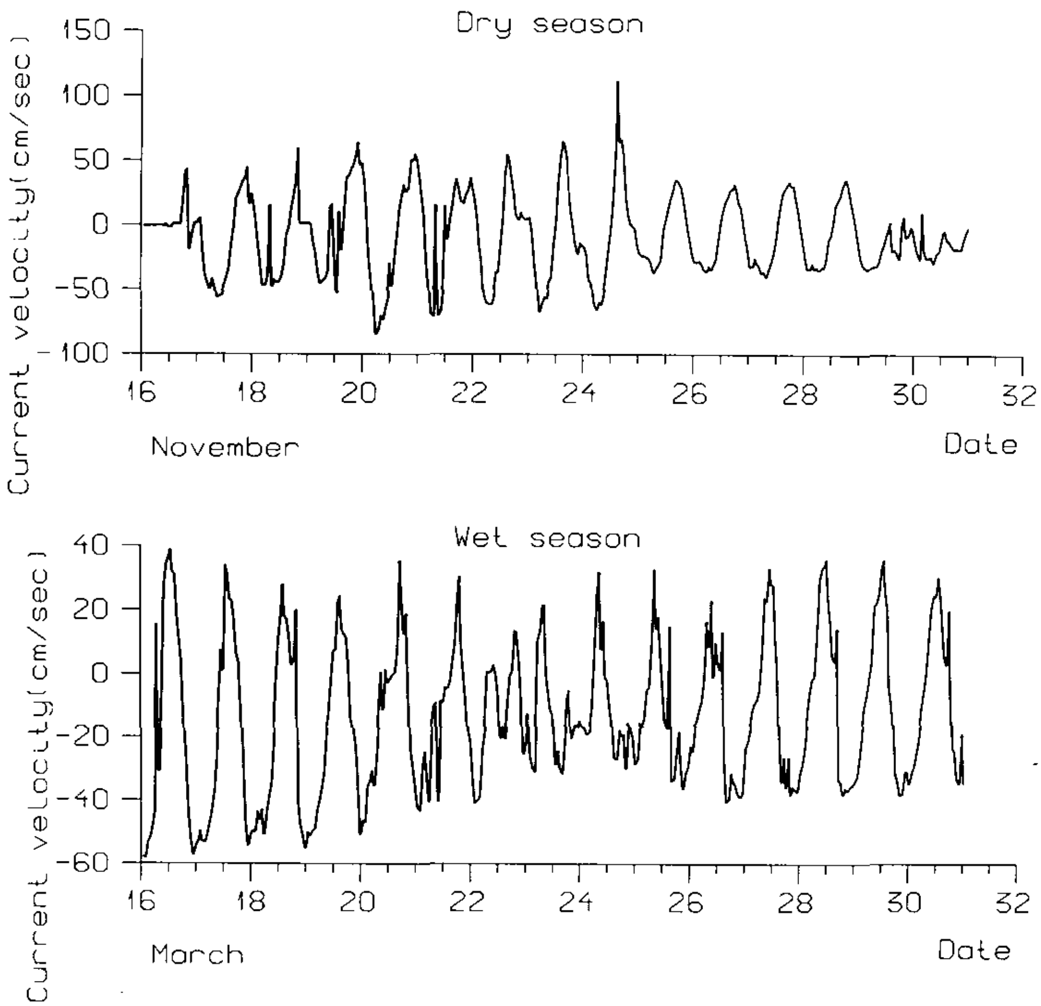


Figure 14. Hourly current velocity during the wet season (March) and dry season (November) 1977.

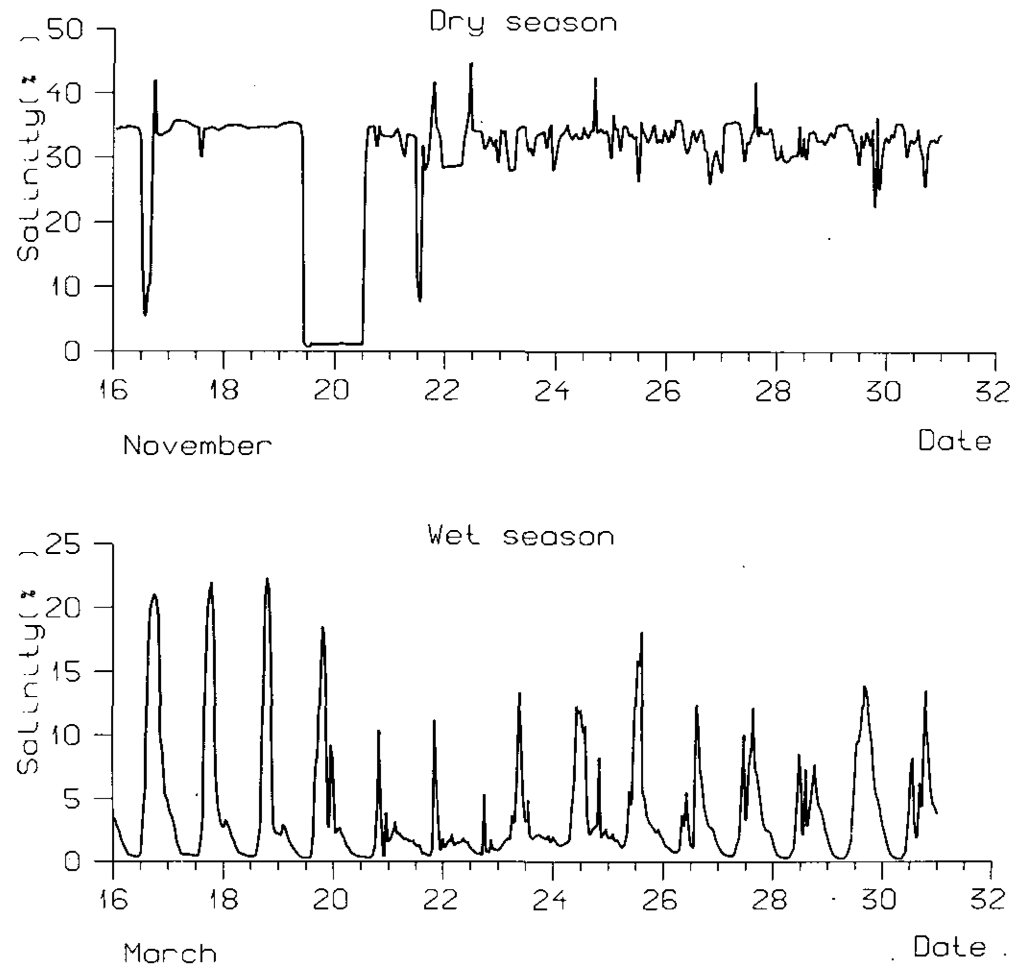


Figure 15. Hourly salinity values during wet season (March) and dry season (November) 1977.

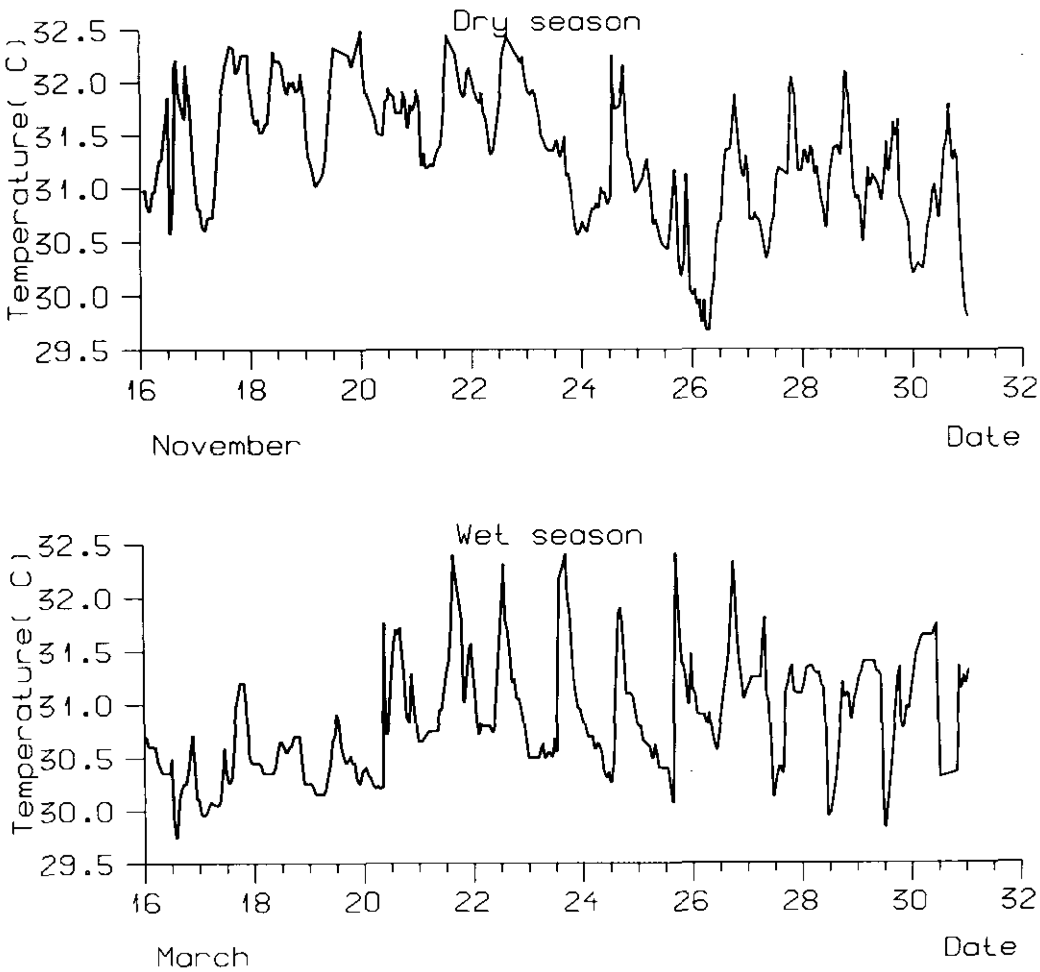


Figure 16. Hourly water temperature during wet season (March) and dry season (November) 1977.

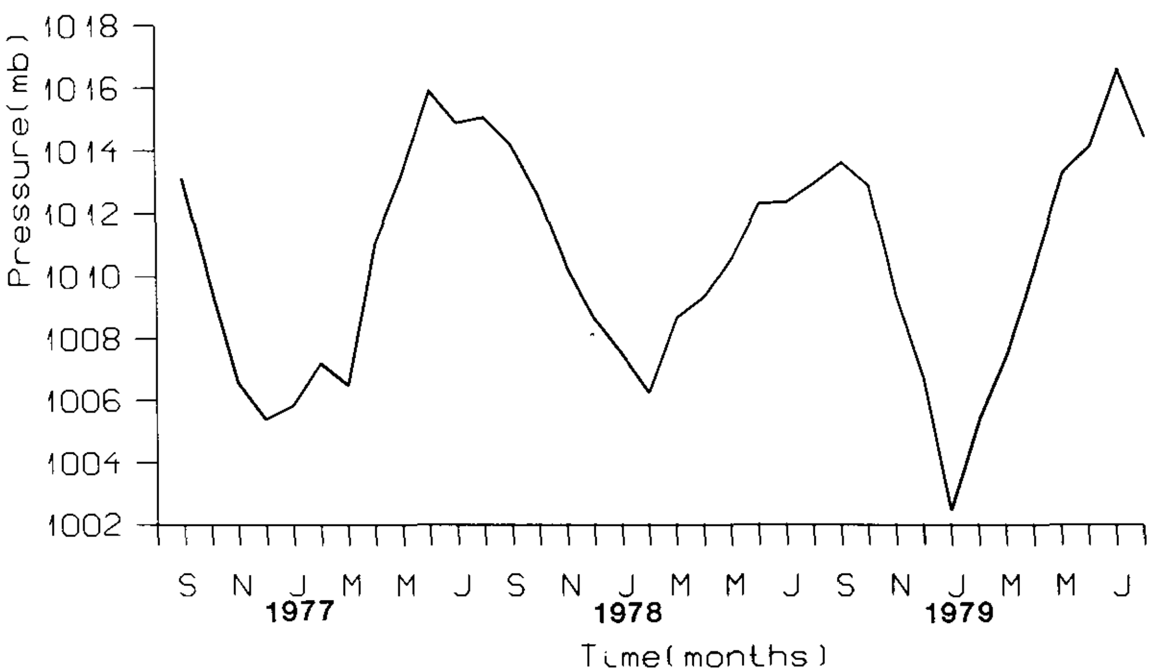


Figure 17. Mean monthly barometric pressures for the three-year period September 1976 - August 1979 at Karumba.

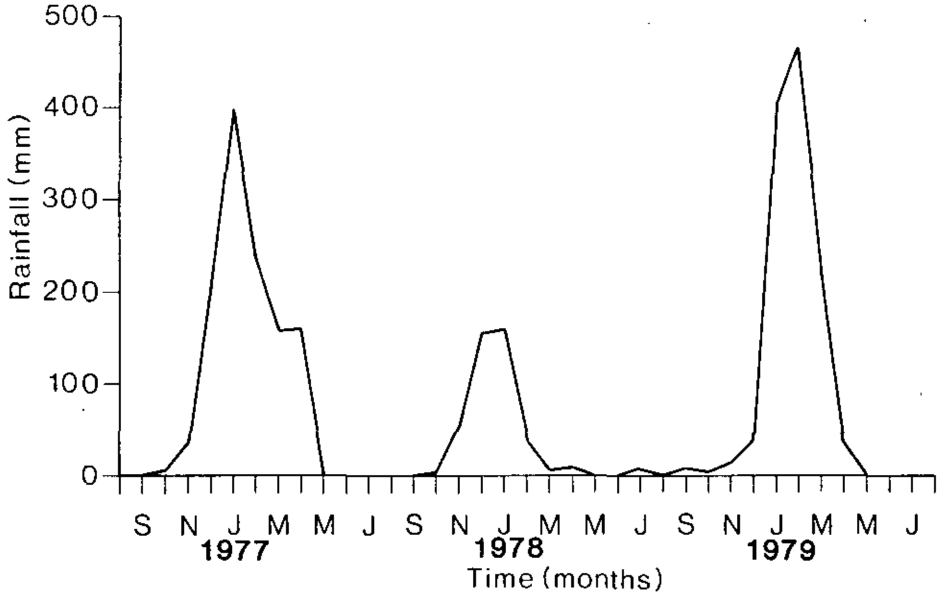


Figure 18. Monthly rainfall at Karumba for the three-year period September 1976 - August 1979.

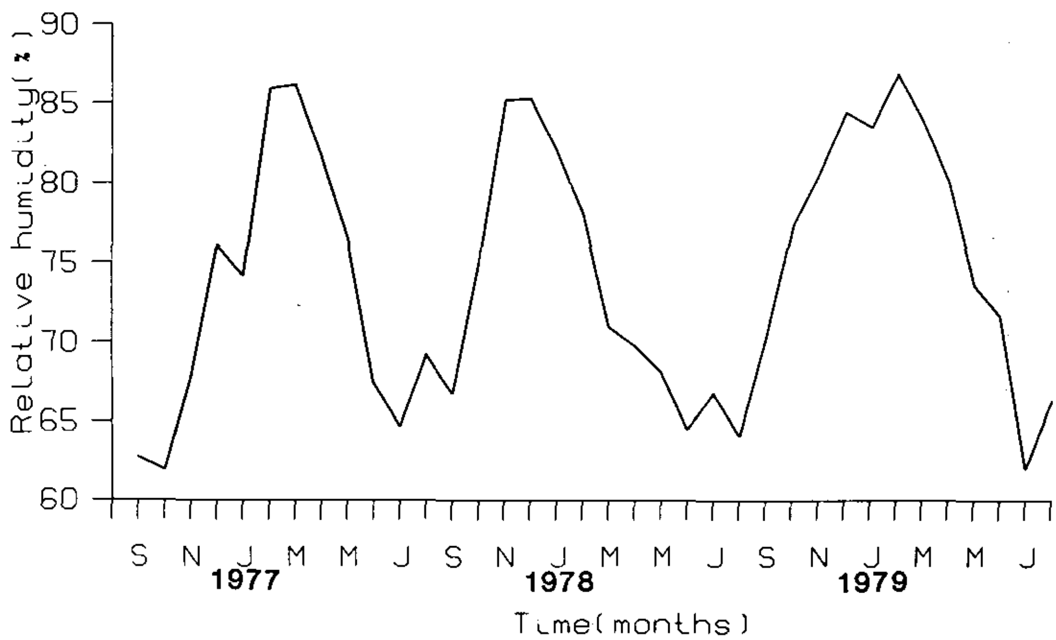


Figure 19. Mean monthly relative humidity at Karumba for the three-year period September 1976 - August 1979.

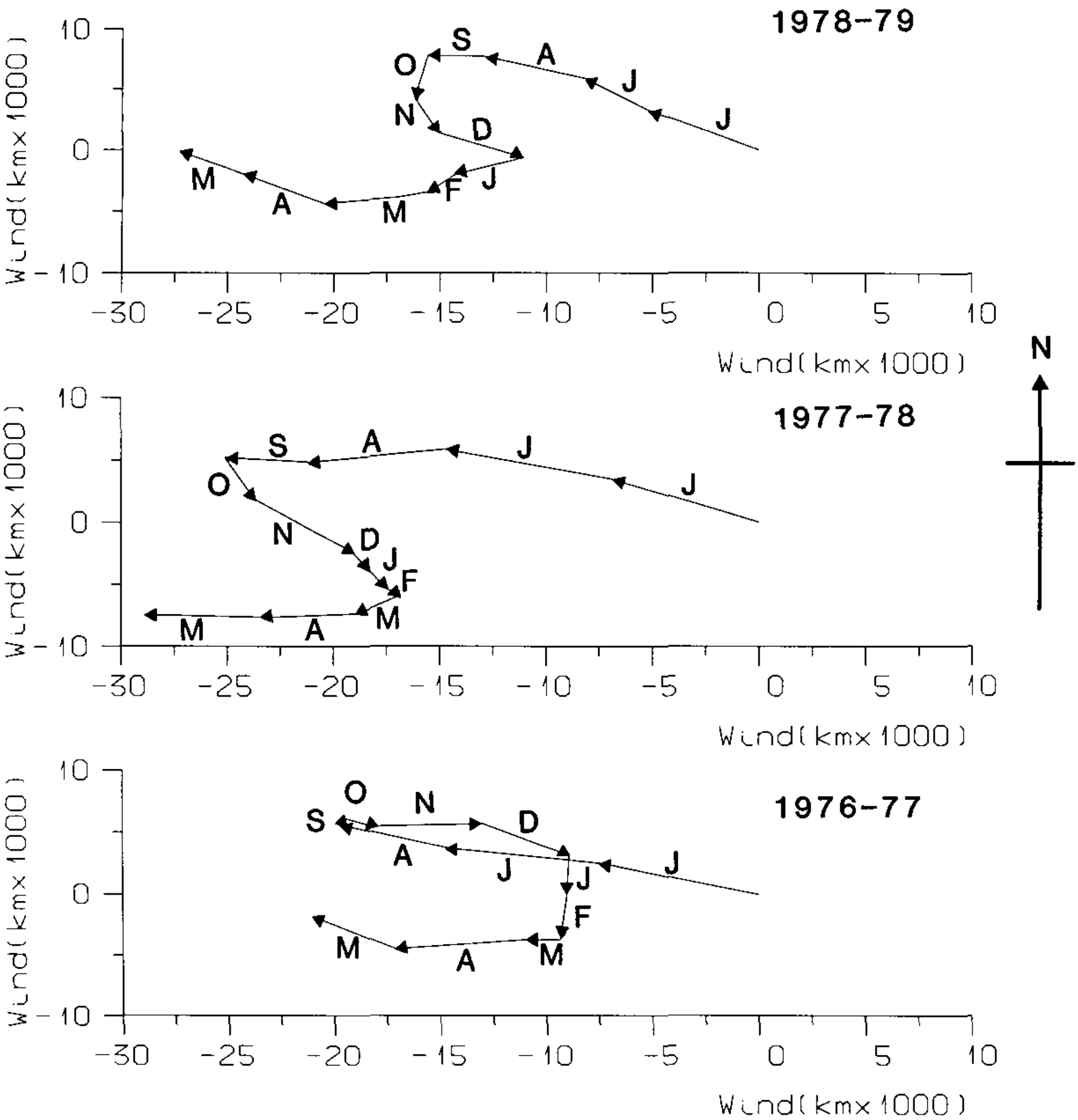


Figure 20. Progressive monthly wind vectors for Karumba for the three-year period September 1976 - August 1979. Arrow denotes strength and direction of the mean vector for each month.

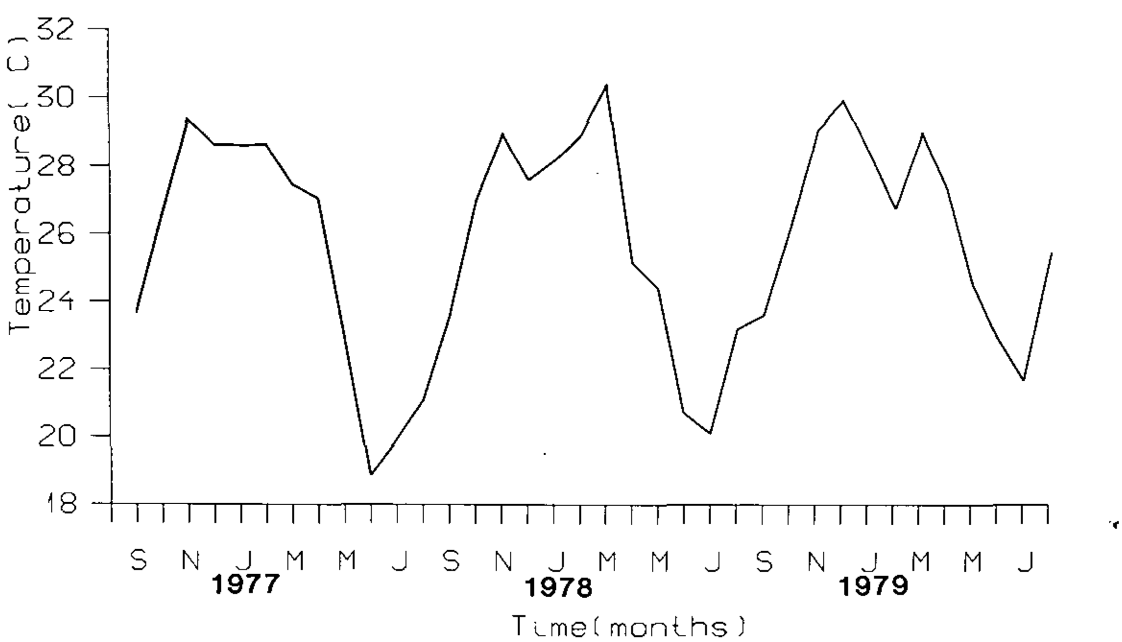


Figure 21. Monthly mean air temperature for Karumba for the three-year period September 1976 to August 1979.

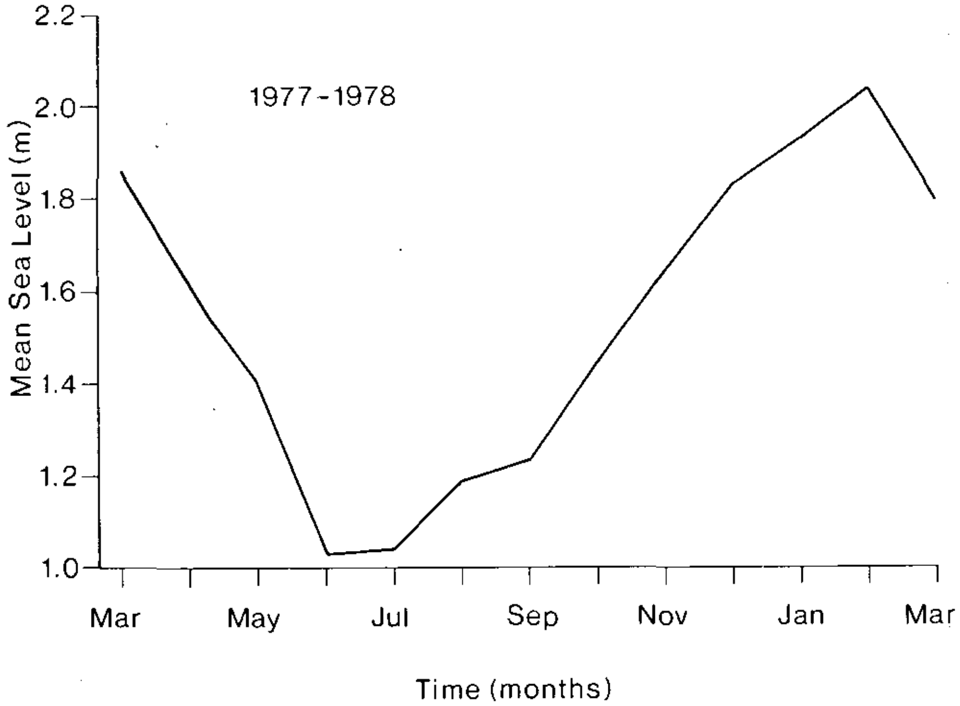


Figure 22. Mean monthly sea level at the mouth of the Norman River during 1977-78.

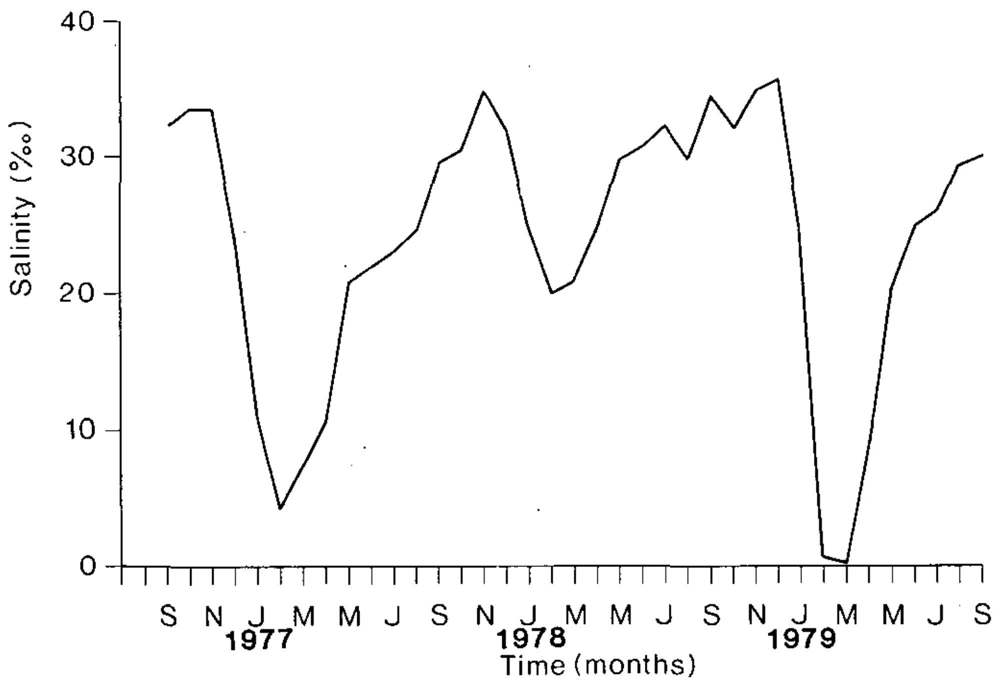


Figure 23. Mean monthly salinity values at the mouth of the Norman River for the three-year period September 1976-August 1979.

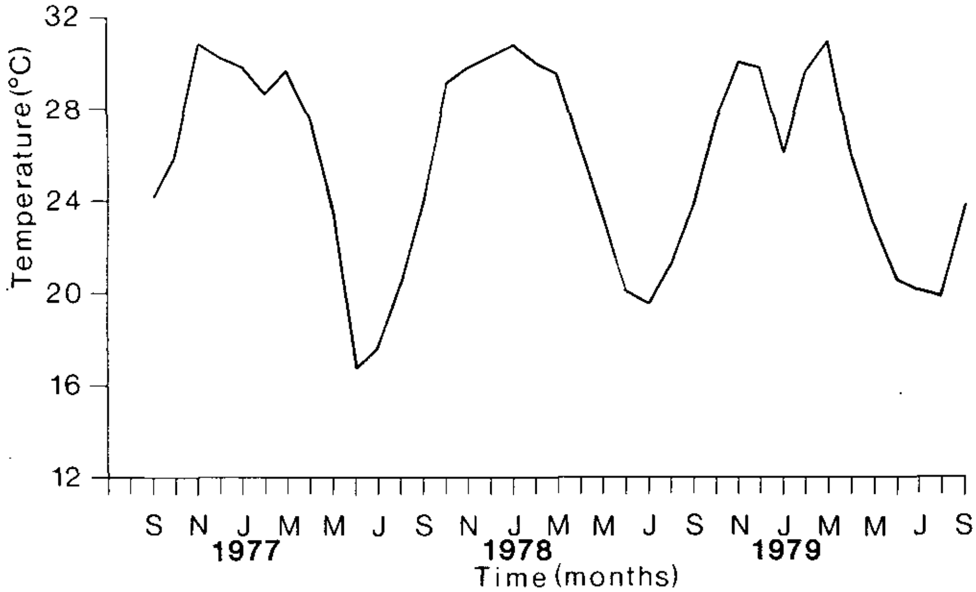


Figure 24. Mean monthly water temperature recordings for the Norman River for the three-year period September 1976 - August 1979.

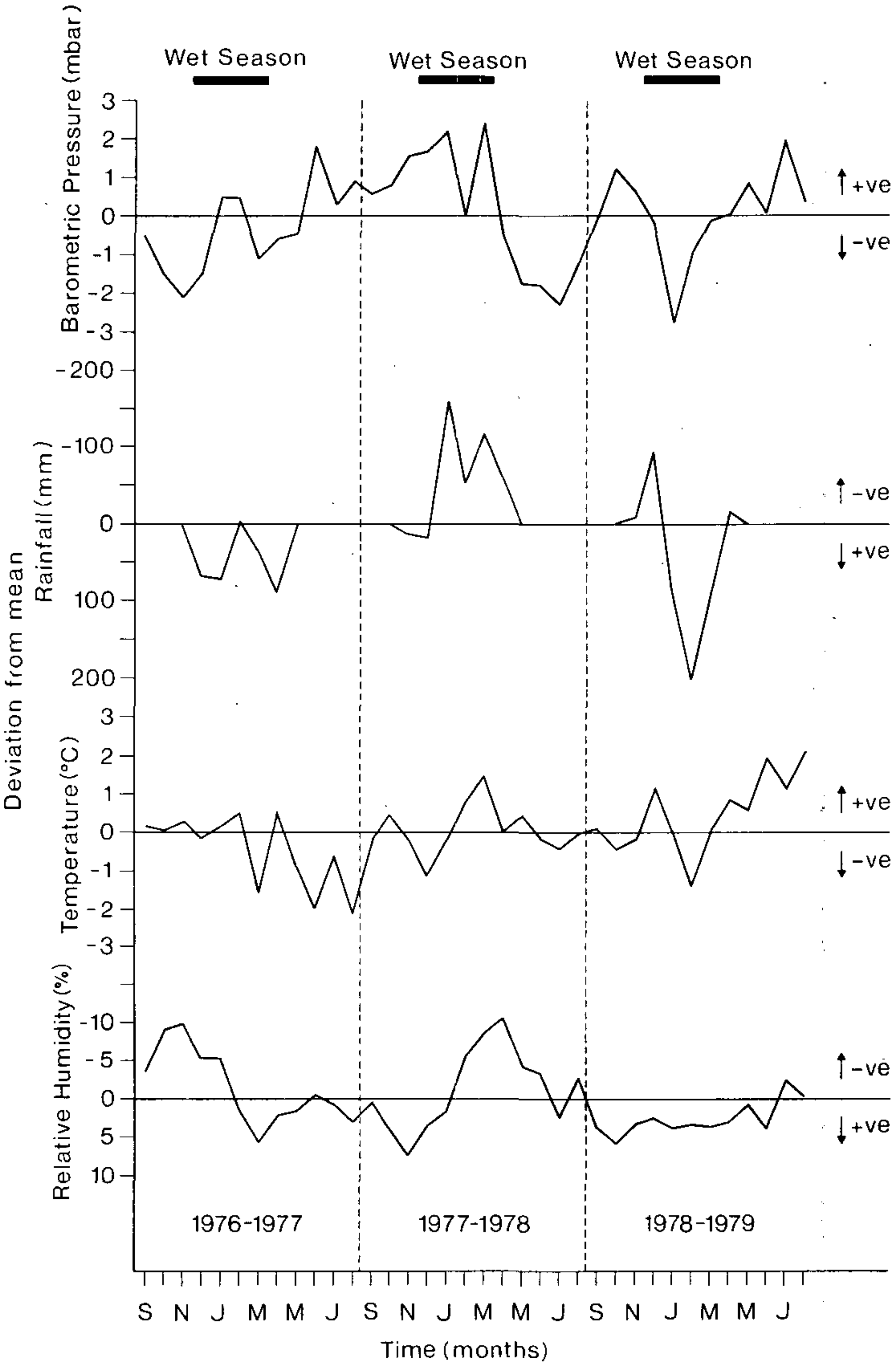


Figure 25. Year-to-year variation in barometric pressure, rainfall, air temperature and relative humidity recorded as monthly deviations from the three-year mean for each variable. Dotted line separates yearly recordings.

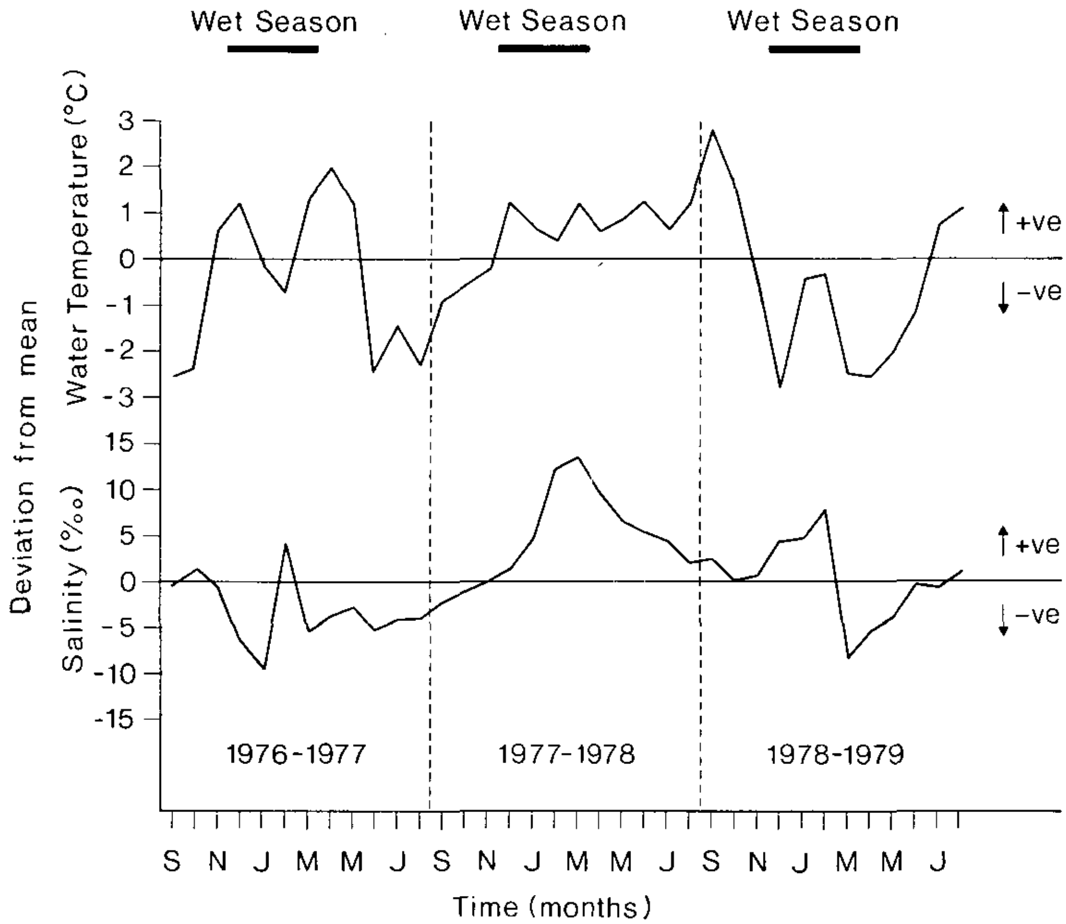


Figure 26. Year-to-year variation in water temperature and salinity recorded as the monthly deviation from the three-year mean calculated for each variable. Dotted line separates yearly recordings.

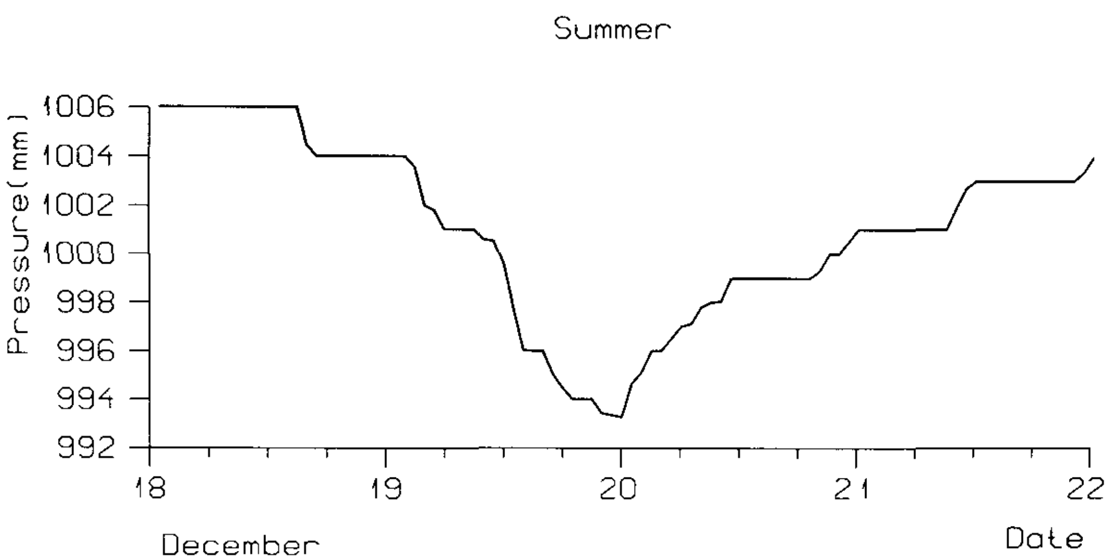


Figure 27. Barometric pressure at Karumba during Cyclone Ted, December 19 - 20, 1976.

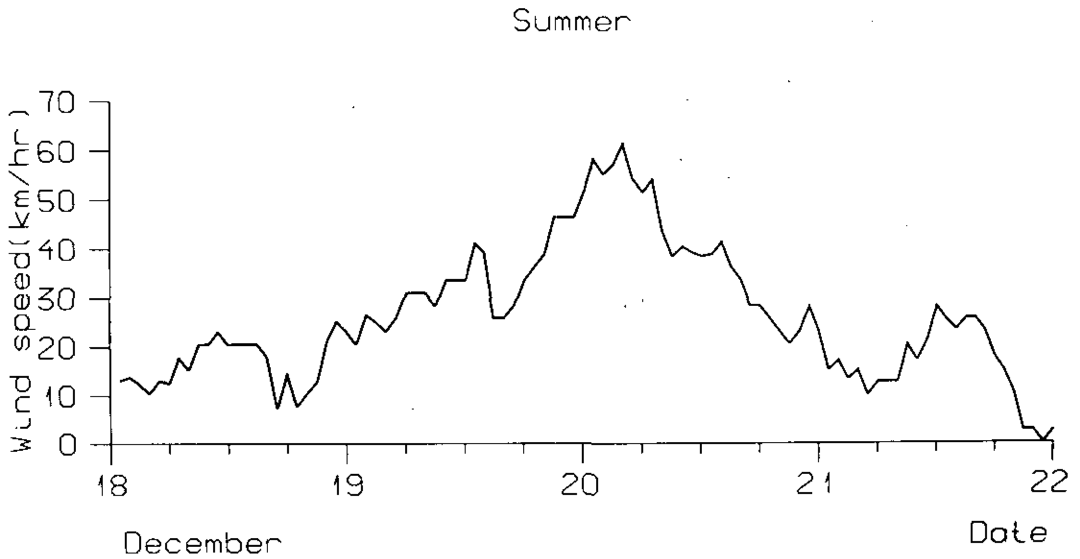


Figure 28. Wind velocity at Karumba during Cyclone Ted, December 19 - 20, 1976.

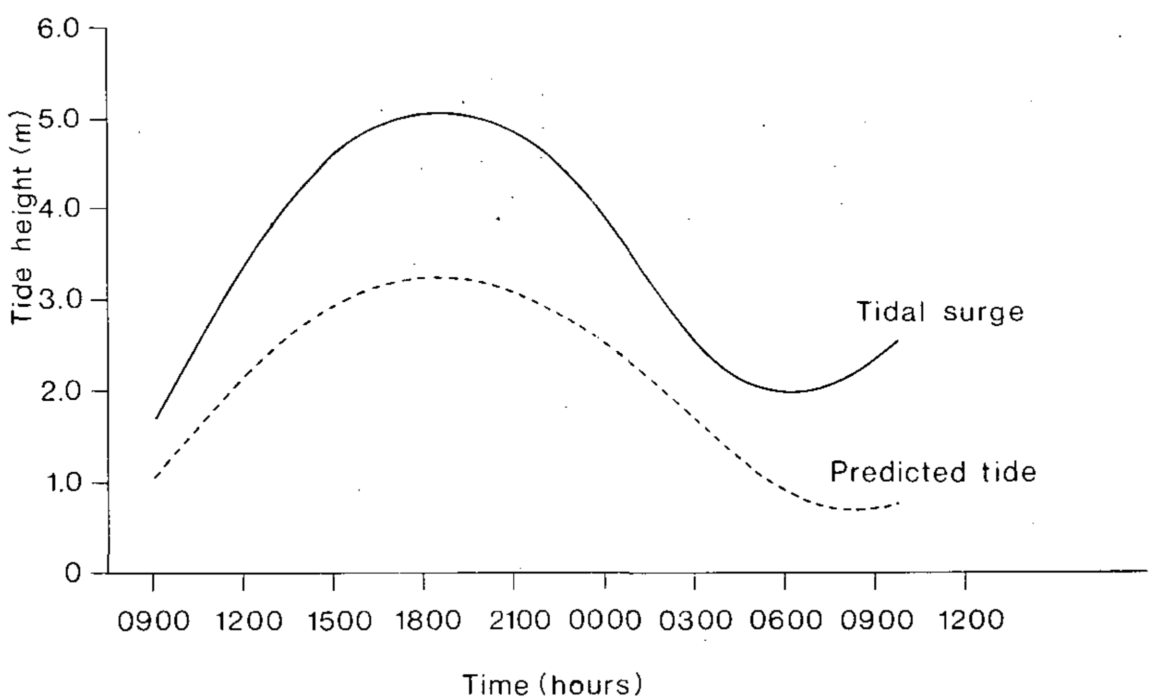


Figure 29. Tidal height in the Norman River during Cyclone Ted, December 19 - 20, 1976.

CSIRO
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Division of Fisheries Research
Division of Oceanography
Central Services Group

HEADQUARTERS
202 Nicholson Parade, Cronulla, NSW
P.O. Box 21, Cronulla, NSW 2230, 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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