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**HYDROGRAPHY OF A SEMI-ENCLOSED MANGROVE LAGOON,  
MANATEE CAY, BELIZE**

**BY**

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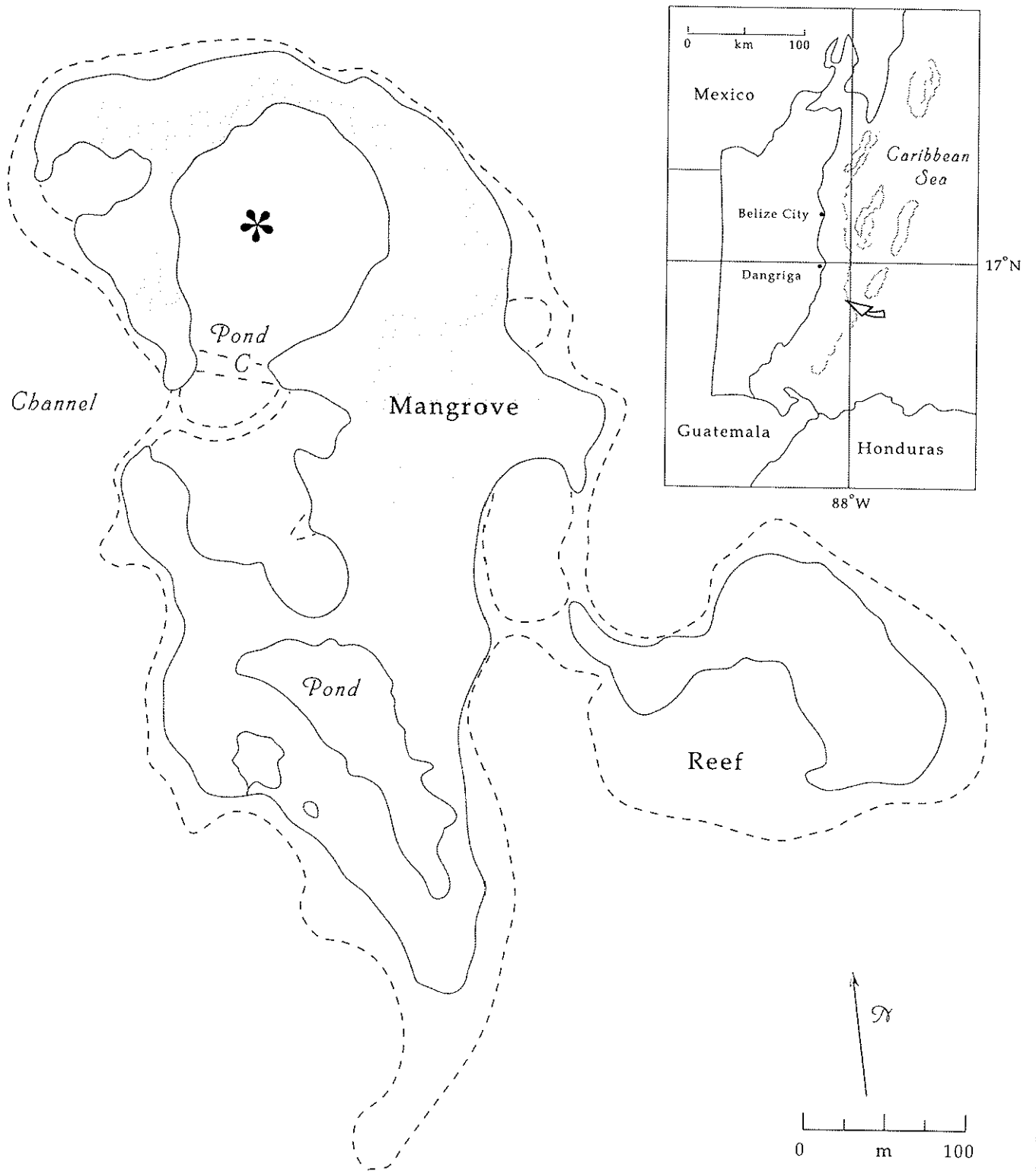


Figure 1. Manatee Cay Pond C sample site (asterisk).

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## ABSTRACT

Hydrographic surveys using a recording CTD system in 1995 and 1996 indicate that the semi-enclosed pond C in Manatee Cay has a distinct hydrographic, chemical, and biological signal. Pond water appears to be channel water advected into the pond surface and modified by local heating and evaporation. Temperature-salinity relationships suggest episodic formation of pond water and a long residence time, although the time scale for this is not known. Pond phytoplankton populations in these two years were dominated by migrating dinoflagellate populations (*Gymnodinium sanguinum*), although there is evidence that periodic diatom blooms created a midwater silicate minimum and near-bottom maximum as a result of midwater uptake and near-bottom remineralization.

## INTRODUCTION

The Belize Barrier Reef is the second largest reef system in the world, and the largest in the Western Hemisphere (Rützler and Macintyre, 1982). It extends approximately 250 km from the Yucatan Peninsula to the Gulf of Honduras (James and Ginsburg, 1979). North of Belize City, the shelf is shallow and has a series of islands with a discontinuous reef lacking a well-defined reef flat. South of Belize City, there is a well-developed barrier platform that averages 4 to 5 m deep (Stoddart et al., 1982). In the southern reaches of the platform near the latitude of Gladen Spit, the barrier reef is cut by deep channels that form a number of shelf atolls, or faros (James and Ginsburg, 1979). The Pelican Cays group is located near this region where shallow mangrove cays are immediately adjacent to deep channels on the order of 20 to 30 m in depth. Cay morphology is unusual in that several of the group have relatively deep central ponds separated by shallow sills from the adjacent channels. This honeycomb pattern originates in the topography of the underlying Pleistocene karst relief (Macintyre, this volume). The lagoon-like ponds may be 10 to 12 m deep and harbor rich tunicate and sponge populations on the fringing

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mangrove prop roots (Goodbody, this volume, Rützler et al., this volume). Within the ponds, the encrusting prop root fauna and the mangroves have complex interactions and nutrient exchanges (Ellison et al., 1996, Rützler and Feller, 1996). The importance of local processes is enhanced by the limited exchange with adjacent channel water resulting from only 30-cm tides and wind-driven circulation.

Little is known of the phytoplankton dynamics in these ponds. The composition of the pond phytoplankton species is distinct from that found in the deep channels only a few meters away and is undoubtedly a result of the shallow, fjord-like sill that isolates most of the pond. Shallow cays to the north have been reported to contain intense blooms of dinoflagellates that visibly discolor the water red (Morton and Villareal, in press). However, there are no quantitative surveys of the phytoplankton in the Pelican Cays ponds, and only limited hydrographic surveys (Urish, this volume). We report here on the general characteristics of one of these ponds (C) in Manatee Cay and briefly describe the phytoplankton community during late May for two years.

## METHODS

Surveys were conducted from small boats during May 1995 and 1996 in the north pond (C), Manatee Cay (16°40.07'N, 88°09.64'W). The general sample site and location are illustrated in Fig. 1. Time-series sampling was conducted in the center of the pond while the boat was anchored. For comparison, casts were also taken outside the pond in the channel and at an open ocean station approximately 1 km east of Carrie Bow Cay (16°48'N, 88°05'W). Hydrographic data (salinity, temperature, depth) were collected in 1996 using a Sea Bird Model 19 Seacat recording CTD equipped with a Sea Tech fluorometer. Data were logged internally at 0.5-sec intervals and downloaded at the field station at Carrie Bow Cay. Discrete chlorophyll, phytoplankton, and nutrient samples were collected in the pond at 1-m depth intervals using a hand pump in 1995 and a bottle sampler in 1996. Two discrete samples were collected by snorklers under the mangrove prop root fringe surrounding the pond at a depth of approximately 0.5 m. Secchi disk depth was determined immediately after the discrete water sample cast. Chlorophyll samples were returned to the lab (approximately 1 h) and filtered through Poretics GF-75 filters for total chlorophyll (both years) and on Poretics 5- $\mu$ m pore size polycarbonate filters for the > 5- $\mu$ m fraction (1995 only). Chlorophyll was extracted in methanol overnight and measured either on a Turner Model 10-AU fluorometer using a nonacidification technique in 1995 (Welschmeyer, 1994) or on Turner Model 111 fluorometer in 1996 using an acidification technique (Parsons et al., 1984). Both fluorometers were calibrated to pure chlorophyll *a*. The 1-L phytoplankton samples were concentrated using a 5- $\mu$ m mesh net and fixed with 1% glutaraldehyde. Phytoplankton populations were enumerated using a 1-ml Sedgwick Rafter counting chamber. Nutrient samples were immediately filtered and placed on ice packs until their return to Carrie Bow Cay (approximately 1 h) where 15-ml samples were frozen and returned to the University of Massachusetts for analysis on a TrAACs 800 automated nutrient analysis system (nitrate + nitrite, silicate, phosphate, and ammonium). A separate 30-ml aliquot was measured on site for phosphate using a 10-cm spectrophotometer cell (Parsons et al., 1984). For purposes of clarity, pond stations refer to Manatee Pond C, channel stations refer to locations near the cays but in deep water (> 15 m), and ocean stations refers to the stations east of Carrie Bow Cay.

## RESULTS

Discrete chlorophyll samples in 1995 (Fig. 2) indicated a midwater maximum ( $5.8 \mu\text{g L}^{-1}$ ) on 5/23/95 (Fig. 2b) and a surface maximum of  $5.0 \mu\text{g L}^{-1}$  on 5/25/95 (Fig. 2c). A midwater maximum is suggested in the 5/21/95 sample (Fig. 2a); however, our initial sampling at three depths was inadequate to capture the detail found at 1-m resolution. Significant variability was found in the size structure. The  $> 5.0\text{-}\mu\text{m}$  size fraction accounted for  $< 50\%$  of the total chlorophyll *a* on 5/21/95 (Fig. 2a), but greater than  $80\%$  at the surface on 5/25/95 (Fig. 2c). Regardless of the day, the  $> 5.0\text{-}\mu\text{m}$  fraction accounted for  $25\%$  of the total chlorophyll *a* and generally  $> 30\text{--}40\%$  of the total. A *Gymnodinium sanguinum* population corresponded to the  $> 5\text{-}\mu\text{m}$  chlorophyll *a* data for each date in 1995 (Fig. 3).

The hydrographic casts from Manatee Cay in 1996 revealed a complex vertical structure that varied on a diurnal basis. Three time series were collected: 5/20/96, 5/23/96, and 5/25/96 (Figs. 4, 5, and 6, respectively). Several generalities are evident. Highest temperatures were found at the surface later in the day. Significant heating occurred during the day, as much as  $0.45^\circ\text{C}$  on 5/23/96 (Fig. 5a). Both 5/20/96 (Fig. 4a) and 5/23/96 (Fig. 5a) showed a complex temperature curve with a subsurface minimum increasing to a maximum and then decreasing to the bottom. The 5/25/96 data did not show this as clearly, although there was a slight inflection at approximately 6 m (Fig. 6a). Salinity showed no consistent pattern between the days. On 5/20/96, there was a complex structure with midwater minimum and maximum (Fig. 4b), while on 5/23/96 salinity increased to a sharp inflection at 6 m (Fig. 5b) and gradually increased with depth. On 5/25/96, salinity was similar throughout the upper 5 m and was separated from the more saline bottom water by a very sharp halocline at 5 m (Fig. 6b).

The density structure on 5/20/96 was highly unusual (Fig. 4d). The observed T-S structure created a high density layer at 3.5 to 4.0 m that was 0.2 sigma-t units higher than the underlying layer. There was a small indication of a similar phenomenon on 5/23/96 (Fig. 5d), but no evidence of it on 5/25/96 (Fig. 6d).

Fluorescence patterns were very similar on all days. There was  $< 1$  fluorescent unit at the surface, which increased to a bottom or near-bottom maximum. The magnitude of the maximum varied from day-to-day, reaching a maximum of 12 units on 5/25/96 (Fig. 6c). The maximum on 5/23/96 (Fig. 5c) was clearly several meters above the bottom.

Discrete chlorophyll values from bottle measurements (Fig. 7a) corresponded well with the fluorescence data in 1996 ( $r^2 = 0.92$ ). On 5/23/96, values gradually increased from  $0.5 \mu\text{g L}^{-1}$  at the surface to  $1.0 \mu\text{g L}^{-1}$  at 7 m. Below that depth, they increased sharply to  $11.5 \mu\text{g chl L}^{-1}$  at the bottom, where *Gymnodinium sanguinum* was again the dominant phytoplankton. Discrete nutrient samples (Fig. 7b) consistently showed a pattern of elevated concentration at the surface, a midwater column minimum, and increased concentrations in the lower 3 m. Individual nutrients did not track each other but tended to have slightly different patterns. Nitrate values were maximal at the surface ( $0.35 \mu\text{M}$ ) and were elevated in the upper 3 m ( $0.20\text{--}0.28 \mu\text{M}$ ), decreased to  $< 0.03$  to  $0.08 \mu\text{M}$  from 4 to 8 m and then increased by  $> 0.30 \mu\text{M}$  from 8 to 9 m to a bottom maximum of  $0.35 \mu\text{M}$  from 9 to 11 m. Phosphate concentrations (0–1 m) were  $< 0.02 \mu\text{M}$  to  $0.06 \mu\text{M}$  in the upper 2 m, were undetectable at 4–5 m, and then steadily increased to  $0.10 \mu\text{M}$  below 6 m. This pattern was seen in both the manual (reported) and automated analyses. Ammonium was at detection limits in the upper 8 m, and then increased to a bottom maximum of

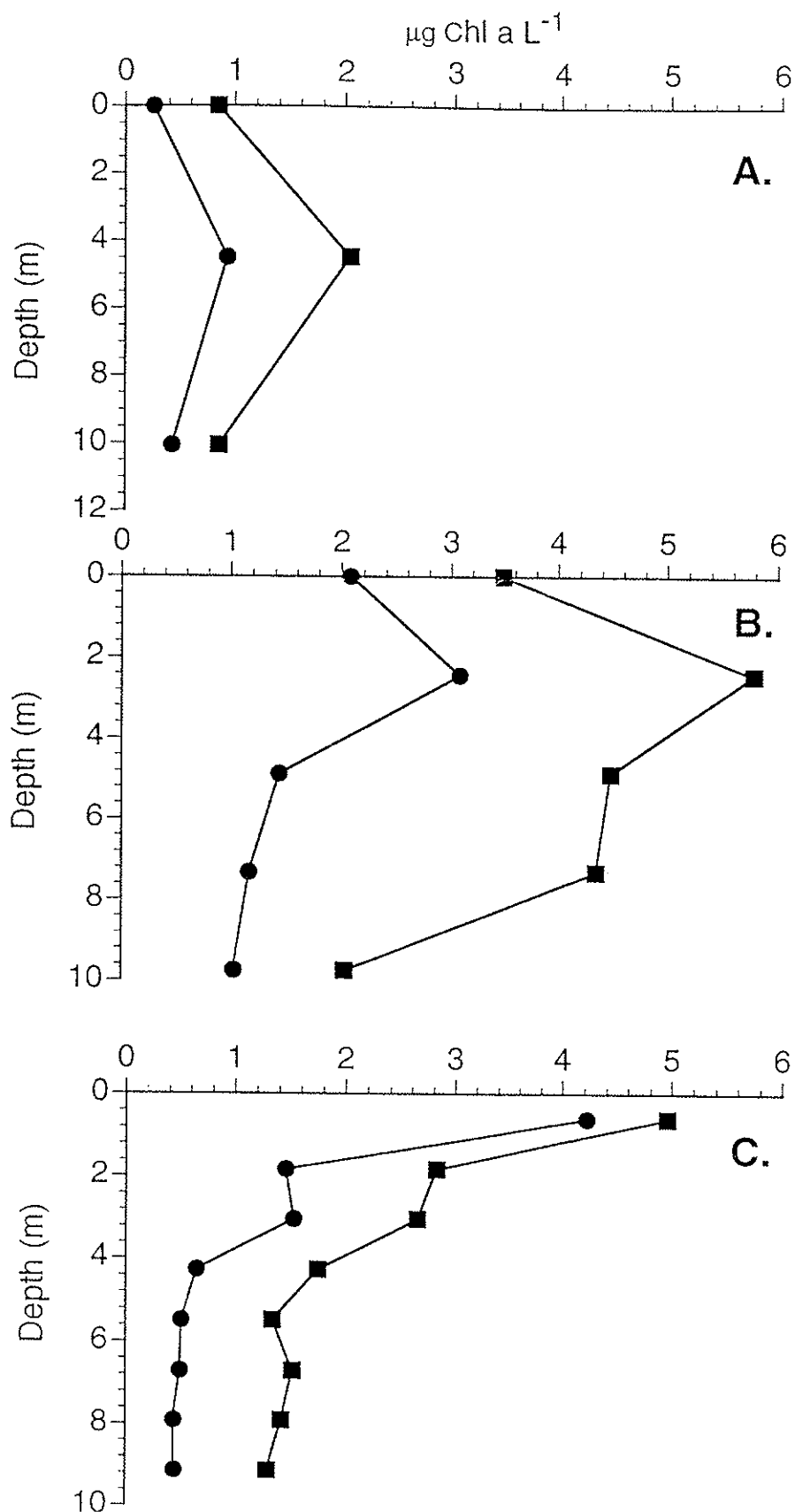


Fig. 2. Size-fractionated chlorophyll measurements in Pond C from 1995. A. 5/21/95 at 11:45 h, B. 5/23/95 at 12:49 h, C. 5/25/95 at 15:15 h.

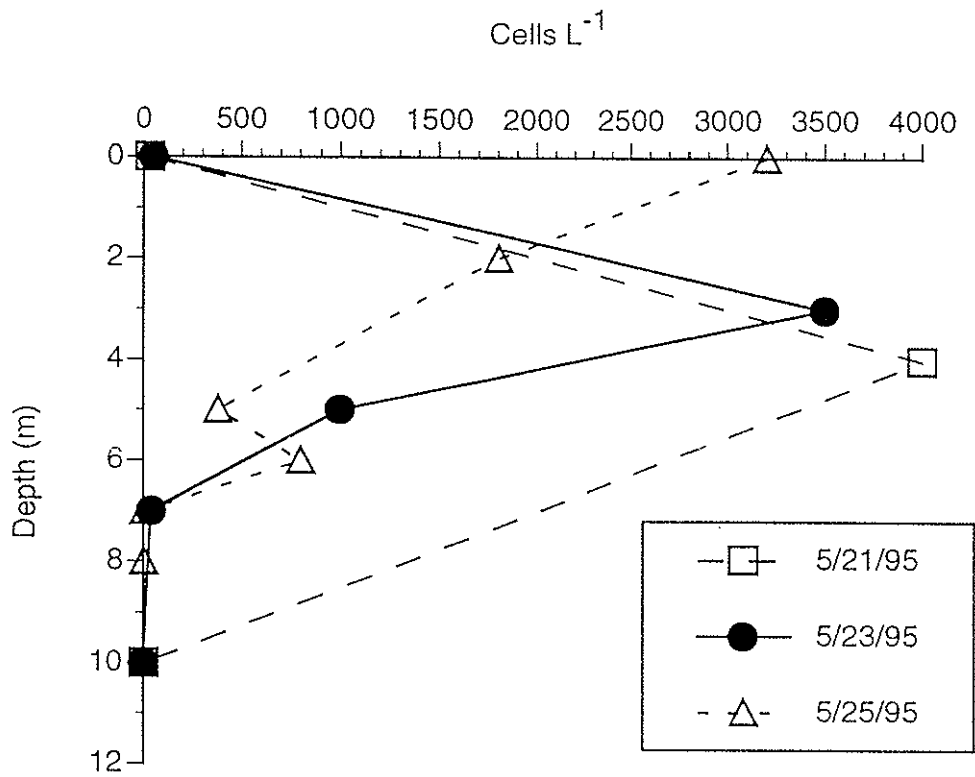


Fig. 3. *Gymnodinium sanguinium* cell abundance in Pond C in May 1995. Samples are from the same aliquots as the chlorophyll data in Fig. 2.

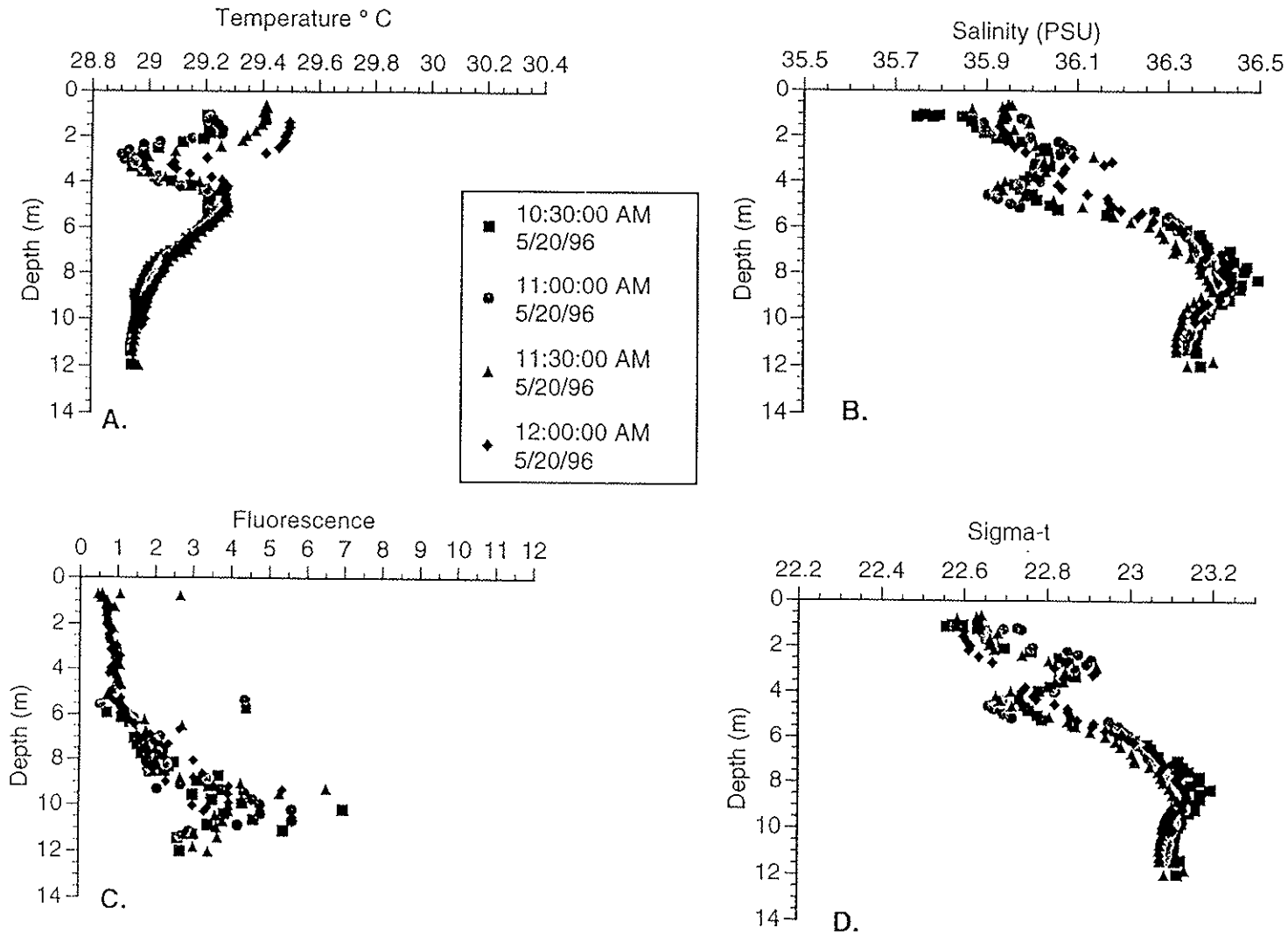


Fig. 4. Manatee Cay Pond C water column measurements from 5/20/96. A. Salinity, B. Temperature, C. Chlorophyll fluorescence, D. Density.



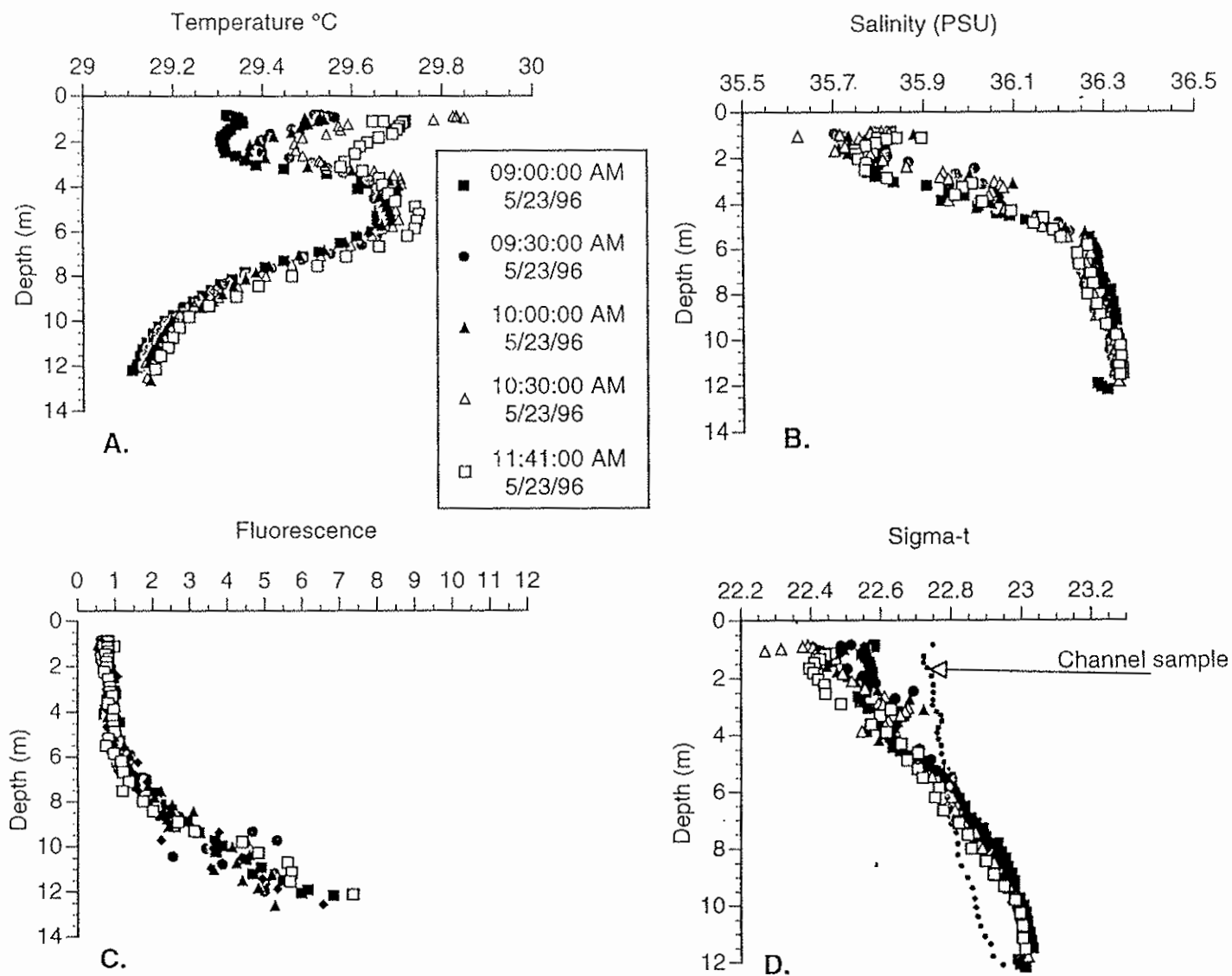


Fig. 5. Manatee Cay Pond C water column measurements from 5/23/96. A. Salinity, B. Temperature, C. Chlorophyll fluorescence, D. Density (sigma-t). Arrow indicates density of channel water at the same depth.

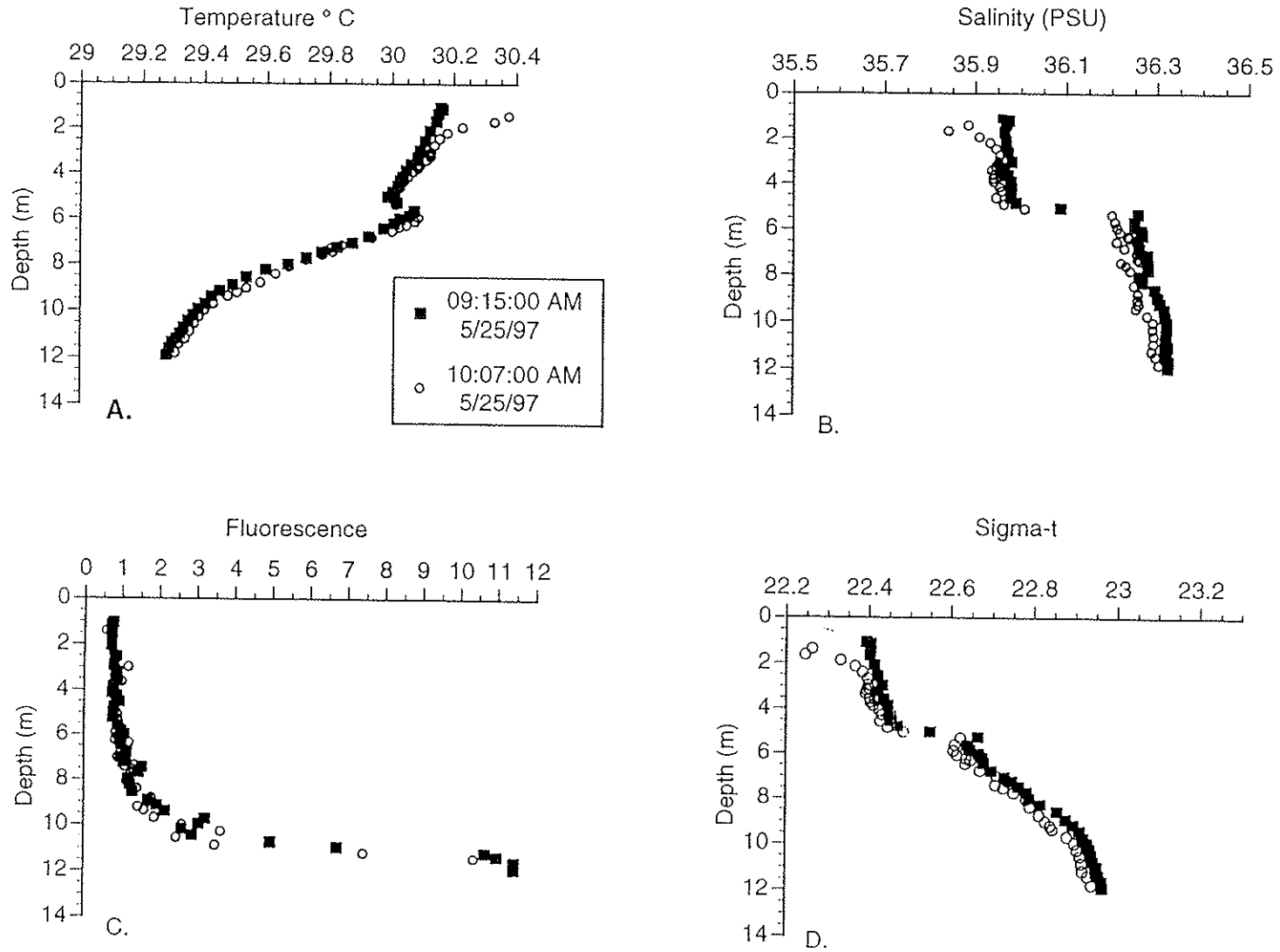


Fig. 6. Manatee Cay Pond C water column measurements from 5/25/95. A. Salinity, B. Temperature, C. Chlorophyll fluorescence, D. Density (sigma-t).

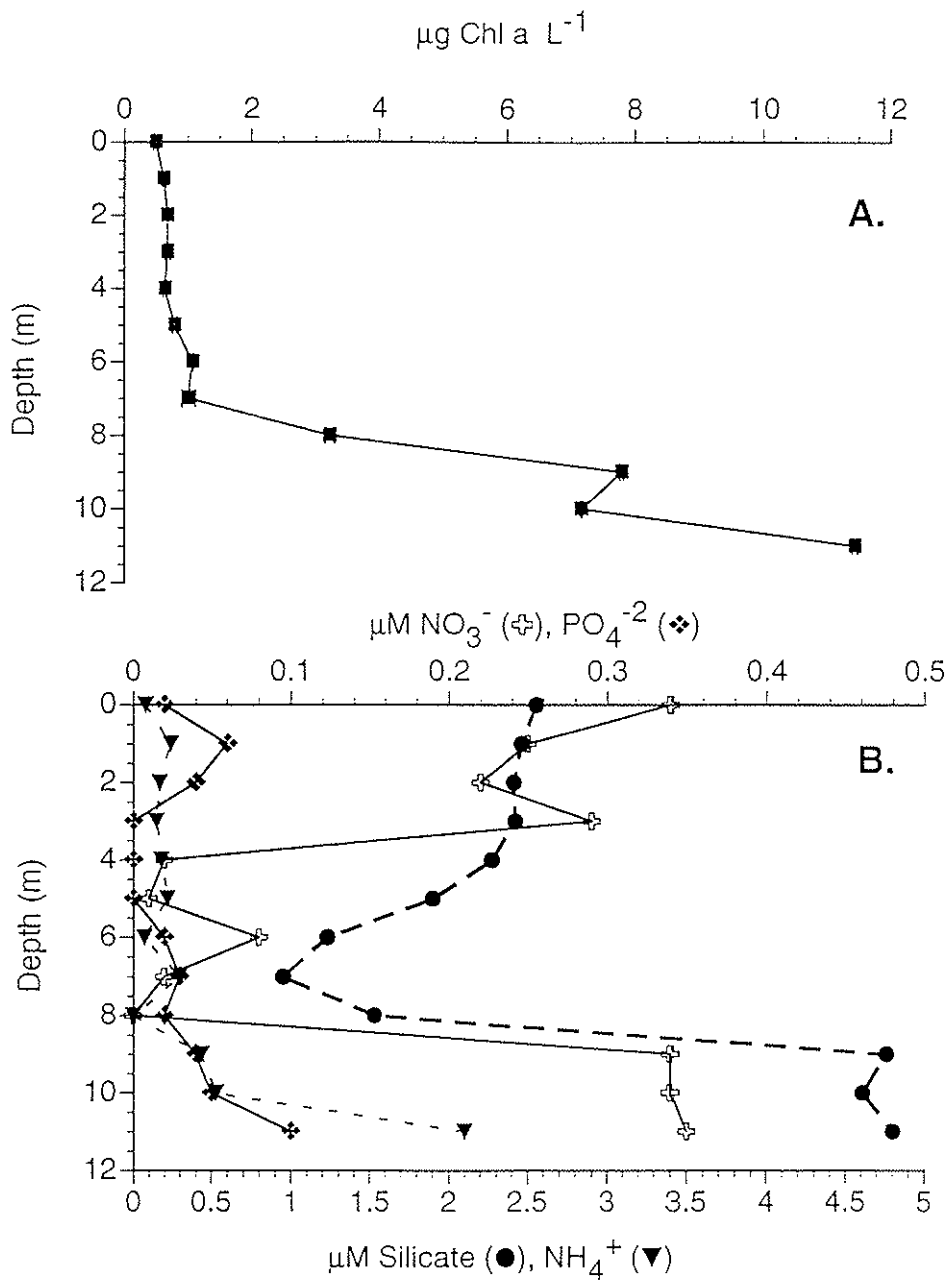


Fig. 7. Discrete bottle measurements from Manatee Cay Pond C on 5/23/96. A. Extracted chlorophyll *a*, B. Nutrients.

0.2  $\mu\text{M}$ . Silicate decreased gradually from 0 to 4 m, had a pronounced midwater minimum at 7 m (1.90  $\mu\text{M}$ ), and then increased to its maximum (4.75–5.00  $\mu\text{M}$ ) in the lower 3 m. The surface Si values are similar to values noted previously from surface water at the offshore station and the coastal pond (Villareal, unpublished observation).

Nitrate concentrations from under the prop root fringe were 0.7 and 1.1  $\mu\text{M}$  in samples collected 2 m apart. Si was elevated in one sample (5.5  $\mu\text{M}$ ) while similar to the station water at the other. P was not detectable using the automated analysis (< 0.1  $\mu\text{M}$ ).

The channel site (approximately 50 m outside the pond sill) had a surface temperature maximum (28.95° C) with a small subsurface temperature minimum at 5 m (Fig. 8). This was similar to that seen in the pond except that it was approximately 0.5 degrees colder and was 2 m deeper. Salinity increased uniformly with depth from 35.88 to 36.14 at 14.5 m, where it became nearly uniform from there to the bottom. Sigma-t increased from the surface to a sharp pycnocline at 14.5 m and was nearly uniform to the bottom. Fluorescence was low (< 0.2 units) and uniform throughout the water column and near the instrumental limit because of the scale setting (data not shown).

Temperature-salinity relationships for the pond, channel, and offshore regions (Fig. 9) suggest that Manatee pond C has extremely limited exchange with the deeper water outside the sill. Pond water was consistently warmer and saltier than water at equivalent depths in the channel. Considerable daily variation was noted, with a steady progression of increased salinity and warmer temperatures from May 19 to May 23 (Fig. 10). This was particularly evident in the water below 36.3 PSU, which increased in temperature from 29.0 to 29.6° C. The sharp discontinuities noted in the lower 4–5 m of the pond suggest that this water does not originate in channel water overwashing the sill and sinking. This can be seen in the boxed area in Fig. 10, which represents the water below 6 m. Although the density (sigma-t) values for the channel and pond water intersect at this point (Fig. 5d), the channel water is 0.4 PSU lower and > 0.9° C cooler than the pond water at this depth. Pond water at this depth must be heavily modified by local heating and evaporative processes. The rapid changes from 5/20/96 to 5/25/96 above 6 m suggest a time scale of a few days or less for replacement or modification.

## DISCUSSION

Hydrographic conditions in Manatee Pond are complex and appear to respond rapidly to local heating. The deep water of the pond appears to be hydrographically isolated from the surface, as is evident from both density profiles and nutrient distribution. The time scale for renewal is unclear. Limited fetch and intense heating create strong barriers to vertical mixing. The nutrient data suggest that the upper 3–4 m is modified channel water, as indicated by the Si concentrations (similar to surface channel water) and the salinity. The T-S profiles (Figs. 9, 10) also indicate that the pond water is not simply channel water but has been modified by local heating and evaporative process. We suggest that a thin layer of surface water advects into the pond, possibly by tidal or wind-driven circulation, and then is modified by local heating and evaporation to create the surface pond water. The rapid change in water above 6 m appears to occur within a few days.

It is likely, although unknown at this time, that cooling increases density sufficiently to

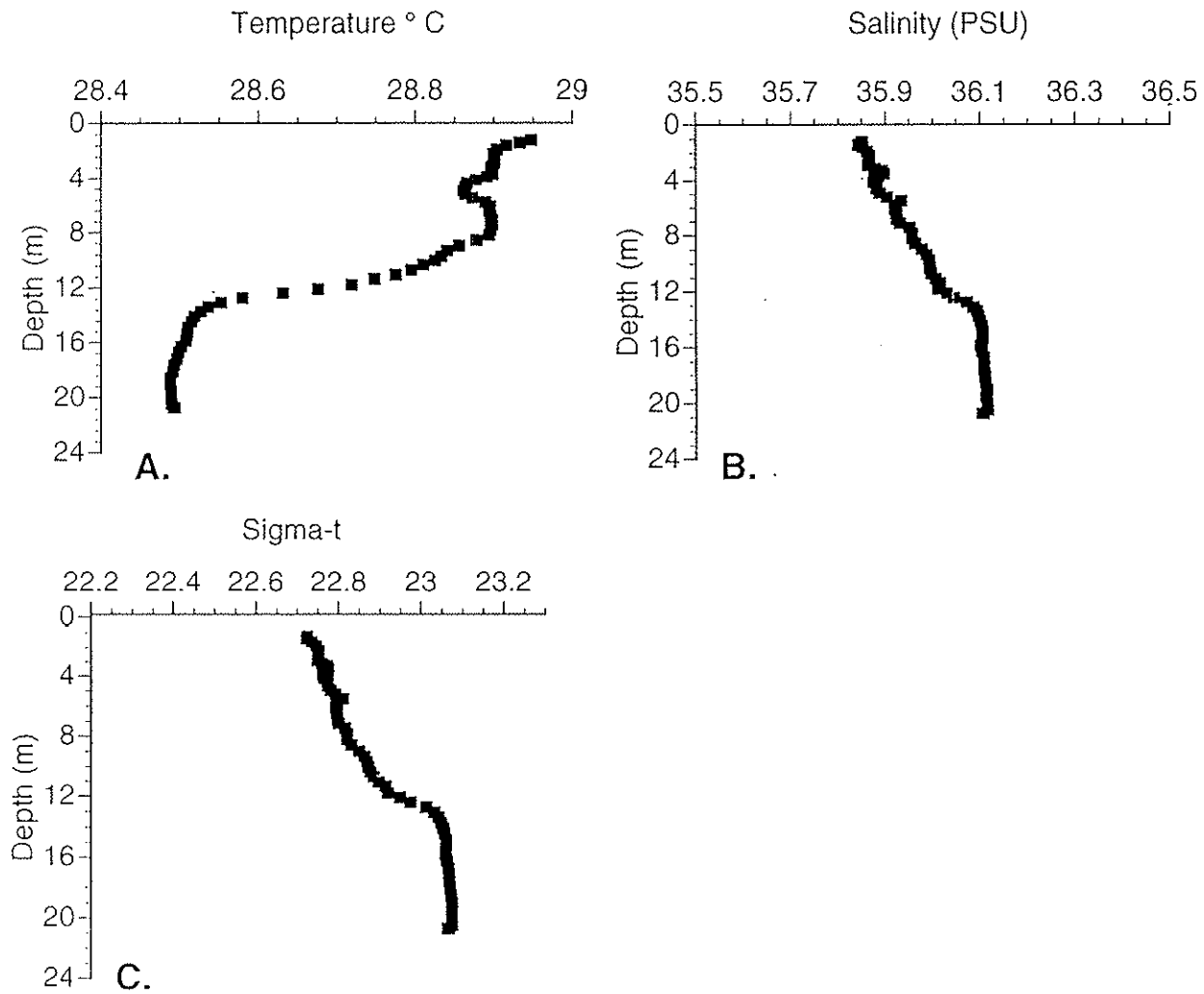


Figure. 8. Channel water column measurements from 5/23/96. A. Salinity, B. Temperature, C. Density (sigma-t). Fluorescence was below instrument settings.

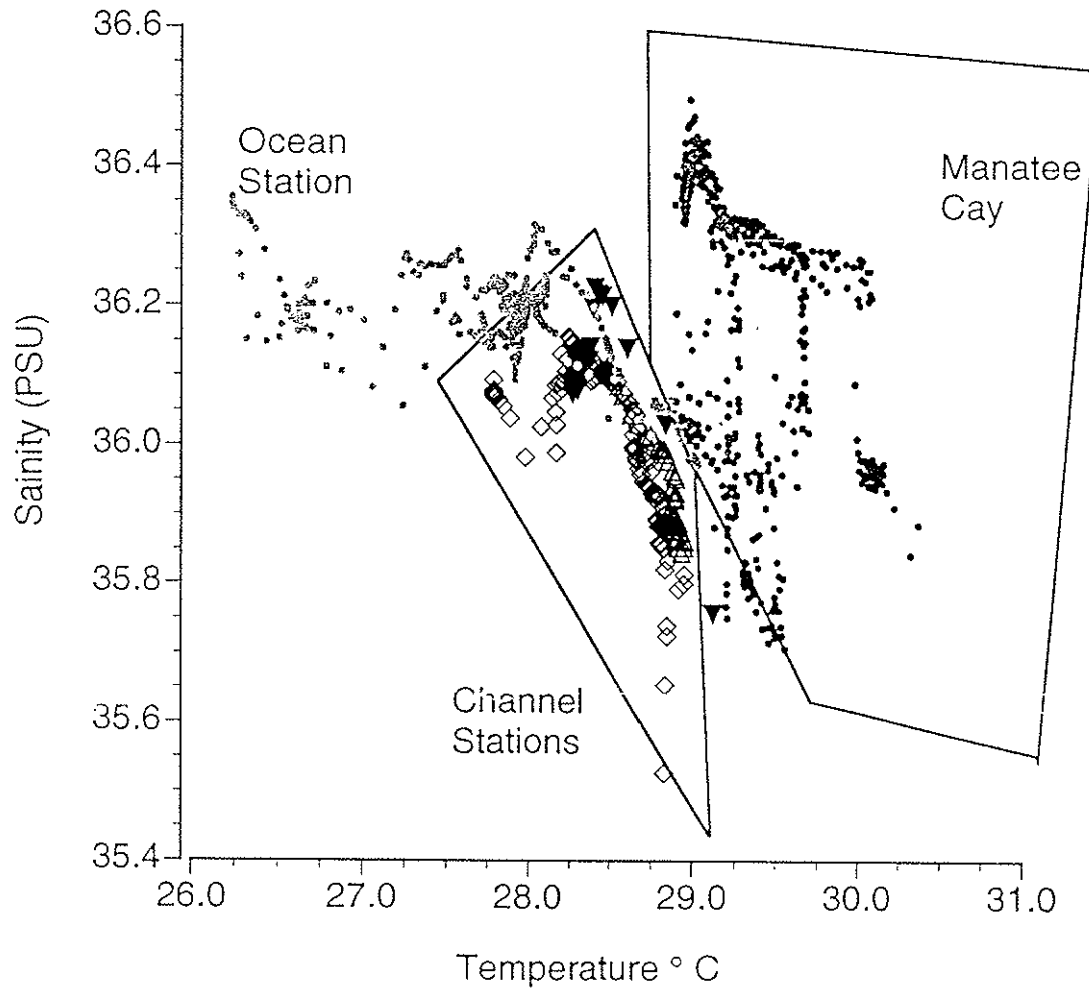


Fig. 9. Temperature-salinity plot including all 1996 ocean, channel and Manatee Cay Pond C stations. The boxes generally circumscribe the data points from a particular area, although a few outliers are evident.

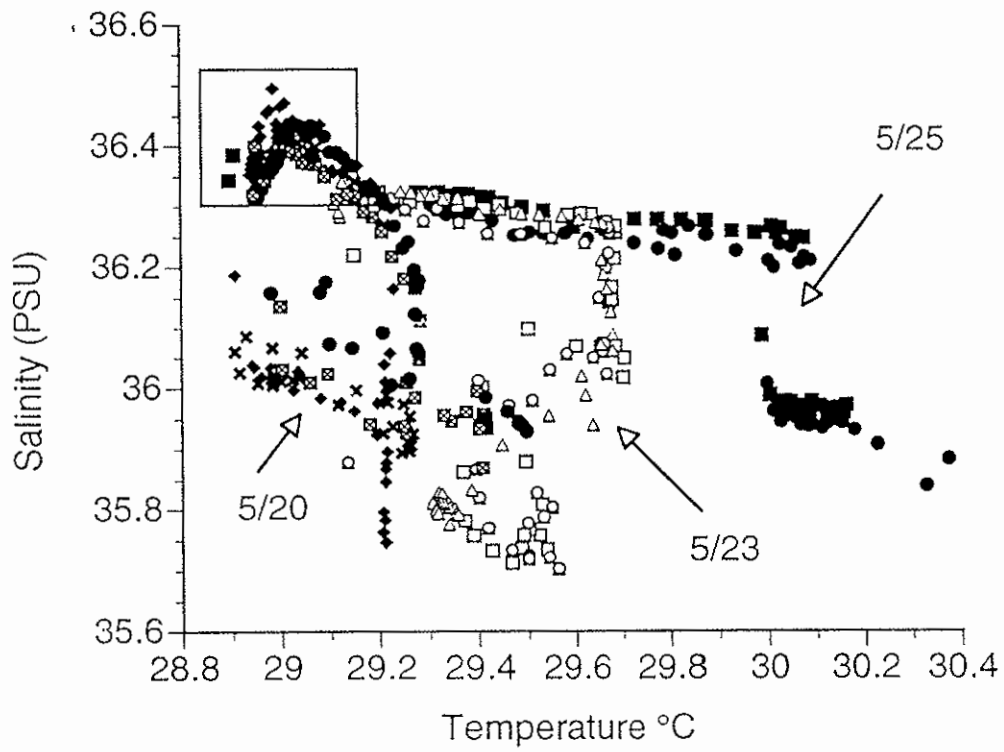


Fig. 10. Temperature-salinity plot of the 1996 Manatee Cay Pond C data. Boxed area indicates deep water pool below 6 m.

cause sinking of this saline surface water. This is the only plausible mechanism that can create the high-salinity bottom water noted in the pond; however, the time scale for this process is unclear. The T-S relationships with the channel (Fig. 8) indicate that the bottom water is modified only slightly by daily heating and cooling, with most of the changes occurring in the upper 6 m. Density data (Fig. 5d) indicate that surface channel water would sink only to mid-depth and lacks the requisite T-S structure. Water below 6-m depth appears stable and isolated from the surface. In the absence of tropical storms or hurricanes, and excluding the possibility of cross-platform water infiltration, the deeper water mass may remain isolated on a seasonal basis.

The most anomalous observation is the persistent density inversion seen clearly on 5/23/96. This distribution would have been unstable and not likely to persist for more than a few minutes. We have eliminated instrument error as a cause but are at a loss to explain the feature. Possibly, the complex organics released by the mangroves are modifying the equation of the state of the water or the relationship between conductivity and salinity. We are continuing to examine this anomaly.

The mid-depth nutrient depletion noted on May 23, 1996, is clearly the result of biological activity. The near-bottom chlorophyll increase occurs at the same depth as the near-bottom nutrient increase and suggests that the phytoplankton were responding to the low-light, high-nutrient conditions at the bottom. In contrast to all the 1996 data, the 1995 data note midwater chlorophyll maxima on successive days. Unfortunately, we have no nutrient data from that year, and we are unable to determine conditions at that time. In 1995 most of the chlorophyll was in the larger size fraction, an unusual occurrence for oligotrophic waters. The 1996 midwater minimum and bottom maximum suggest that at some time scale, phytoplankton production consumes the nutrients, sinks or migrates, and is remineralized at depth. Possibly, diatom growth in the midwater strips out the Si and deposits it at depth as diatoms are remineralized. Previous surveys have noted extensive diatom blooms within these ponds, although we did not note them in this study (Faust, personal communication).

The combined data from the two years suggest that phytoplankton populations are dynamic. Secchi disc depths indicate that the euphotic zone reaches the bottom and can support the 1996 bottom chlorophyll maximum. From the 1995 results, it appears that motile populations can create a midwater chlorophyll maximum. At some point, diatom growth stripped out the silicate in the mid-depth region and created an unusual bimodal nutrient distribution. Dinoflagellates are also dominant in the shallow pond of nearby Douglas Cay, the site of a red tide of *Gonyaulax polygramma* (Morton and Villareal, in press).

These data provide only a snapshot of conditions in Manatee Cay and no information about rates. The lack of a phytoplankton peak at the surface where nutrients are abundant may be the result of photoinhibition or intense grazing by the mangrove prop root fouling community. The CTD data suggest that distinctive water masses occur in the pond, but we cannot identify any time scale for either overturn or flushing in the pond. Although we cannot estimate rates, the elevated biomass in the pond does raise questions about nutrient supply required to sustain this biomass. Tidal exchange is extremely limited in the pond, and the shallow sill suggests wind-driven circulation will be restricted to a meter or two. The dense fouling community on the prop roots consists primarily of sponges and tunicates that may aid remineralization by grazing or symbiotic nitrogen fixation, but this input would be expected to occur as ammonium, not nitrate. The elevated nitrate concentration under the prop root fringe suggests another source, either



symbiotic nitrification (Corredor et al., 1988) or processes in the mangroves. Phosphate was extremely depleted in the water column, and was consistent with possible P limitation in the mangroves themselves (Feller, 1995). Future work must include water column rate measurements, time-series hydrography, and mangrove-pond interactions in order to interpret the phytoplankton dynamics in the pond.

### ACKNOWLEDGMENTS

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