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St. Anthony Falls Hydraulic Laboratory

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HEATING AND COOLING OF A  
SHALLOW BAY IN EAU GALLE RESERVOIR:  
FIELD MEASUREMENTS AND INTERPRETATION  
PART 2 (1989)

by

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## I. INTRODUCTION

The distributions of nutrients in lakes and reservoirs effect water quality. Movement of water within these water bodies is the main mechanism by which nutrient transport occurs. The process of water movement within a lake or reservoir is a consequence of natural forces. These forces depend on the effects of rain, wind, solar radiation, surface cooling, ground water intrusion, photosynthetic activity, gravity, tidal effects, and the Coriolis force. This study concentrates on the effects of the diurnal heating and cooling cycle as the primary factor which causes water movement between the littoral and profundal waters in lakes and reservoirs. It has been shown that heating and cooling of water on a littoral slope induces a horizontal temperature gradient and that the density of water associated with this temperature gradient induces horizontal and vertical exchange of water along the littoral slope and adjacent profundal waters (Stefan, Horsch, and Barko, 1989).

The dependence of water movement and consequent nutrient transport on the water temperature, during the diurnal heating and cooling cycle, is investigated through analysis of the time dependent temperature profiles within a shallow heavily vegetated bay and adjacent profundal waters. The effect of wind on these temperature profiles is also investigated. The data was collected in a protected bay of a flood detention basin in western Wisconsin. In this progress report some of the analyzed data is given a qualitative interpretation. The quantitative analysis, which is currently being performed, will be the subject of a future report.

This study is based on temperature measurements taken with 38 temperature probes, located at six stations, in the littoral and adjacent profundal waters of Eau Galle Reservoir at 30 minute intervals during the period of May 15 to October 13, 1989. Wind speed and direction, air temperature, solar radiation, and reservoir pool elevation were also measured. This data is presented in time series plots and the interrelationship of some parameters is explored. Contour plots of the spatial distribution of temperatures within the bay transect are also presented during episodes of heating and cooling, and during a windy period to illustrate the time and spatial dependence of the water temperatures during these events.

The data presented in this report were collected by Dr. William F. James and his auxiliary staff under direction by Dr. John W. Barko. The data were made available in diskettes, reviewed and plotted by the first author of this report with guidance provided by the second author. An earlier report (No. 286) dealt in a very similar fashion with the data collected in 1988 and has been back labeled Part 1 (1988). This report deals with data collected in 1989 and is, therefore, labelled Part 2 (1989).

## II. DATA COLLECTION

The Eau Galle Reservoir (Fig. II-1) is located in the western part of central Wisconsin and is used for flood control and recreation, with recreational uses limited to fishing and swimming. The reservoir is surrounded on all sides by significantly higher ground, thereby decreasing the effects of wind on the bay, while increasing the possibility of ground water intrusion. The bay used in this study (Fig. II-2) was filled with dense vegetation, mainly *Ceratophyllum demersum* or "coon tail," from the shore out to just beyond the 1 meter depth. The vegetation began to thin between the 1 and 2 meter depths, and it was virtually nonexistent beyond the 3 meter depth. A detailed investigation of vegetation was made by Filbin and Barko (1985). The Eau Galle River enters the bay a short distance to the south of the bay under study. However, a long spit separates the mouth of the river from the study area (Fig. II-2). This prevents the inflow from significantly affecting the water in the bay.

The data were collected by monitoring systems installed by Dr. William F. James of the Army Corps of Engineers, Waterways Experiment Station, as part of a long term project on reservoir ecology under the direction of Dr. John W. Barko. Six thermistor arrays were deployed along the transect of the bay (Fig. II-2). Individual thermistors, Model ES060-W manufactured by Omnidata International, Inc., in each array were located at various depths.

These depths were as follows:

Station 1: 0.05m, 0.25m, 0.50m, and 0.75m

Station 2: 0.05m, 0.25m, 0.50m, and 0.75m

Station 3: 0.05m, 0.25m, 0.50m, 0.75m, and 1.00m

Station 4: 0.05m, 0.25m, 0.50m, 0.75m, 1.00m, 1.25m, 1.50m,  
1.75m, and 2.00m

Station 5: 0.05m, 0.50m, 1.00m, 1.50m, 2.00m, 2.50m, 3.00m,  
3.50m, and 4.00m

Station 6: 0.05m, 1.00m, 2.00m, 3.00m, 4.00m, 5.00m, and 6.00m.

The position of each thermistor can be seen in Figure II-3.

The thermistors at stations 1 - 3 were mounted on vertical sections of PVC pipe, which were attached to stationary platforms, with the bottom ends firmly embedded in the sediment. The thermistors at stations 4 and 5 were also mounted on PVC pipe, but the pipes were attached to floating platforms. The thermistors at station 6 were mounted in a flexible hose which was attached to a floating platform. A weather station, equipped with a wind speed and direction sensor, Model ES-040 manufactured by R. M. Young Co., was deployed at station 3 to collect weather parameters: air temperature, wind speed and direction, and relative humidity. The wind speed and direction were measured at 2.6 meters above the water surface. The air temperature and relative humidity were measured at 0.3 meters above the water surface. The data were collected using Model EL824-GP Easy Logger Field Units, manufactured by Omnidata International, Inc., which were mounted on the platforms located at each station. The "Easy Loggers" recorded instantaneous water and air temperature measurements at

30 minute intervals. Wind speed and direction were recorded every 15 minutes. Incident solar radiation was recorded every hour. Due to a malfunction in the programming of the "Easy Logger," no time dependent relative humidity data were collected; only the daily minimum and maximum relative humidity were recorded.

The recording of water temperatures at stations 1 - 5 began on May 15, 1989, while the "Easy Logger" at station 6 started recording water temperatures on May 18, 1989. Temperatures from all stations were stored and recorded every 30 minutes until October 13, 1989, except for short periods while bringing the stations online, during downloading of the data, and during two storms. During the first of these storms, which occurred in early July, the rise in water level in the reservoir destroyed the "Easy Loggers" at stations 1 - 3 and lightning destroyed the wind vane at both the weather station at station 3 and the nearby experimental station. No wind direction data were available after this point in time. The "Easy Logger" from station 4 was used at station 3 for more than a week after the storm so that weather data could be collected during this period. Therefore, no data were available for station 4 until a replacement "Easy Logger" arrived. In anticipation of the second storm which occurred in early September the "Easy Loggers" at stations 1 - 3 were removed until the water level in the reservoir returned to normal. Station 4 became a roosting site for muskrats. Despite efforts to keep them out of the equipment their affinity for chewing through the cables supplying power to the "Easy Logger" brought an early end to data collection at the station in mid-September.

The weather data were used to select periods desirable for study, such as a period with calm cool nights and calm sunny days to study the effect of diurnal heating and cooling on water temperature in the bay, or a windy day to study the effect of wind on the water temperatures in the bay.

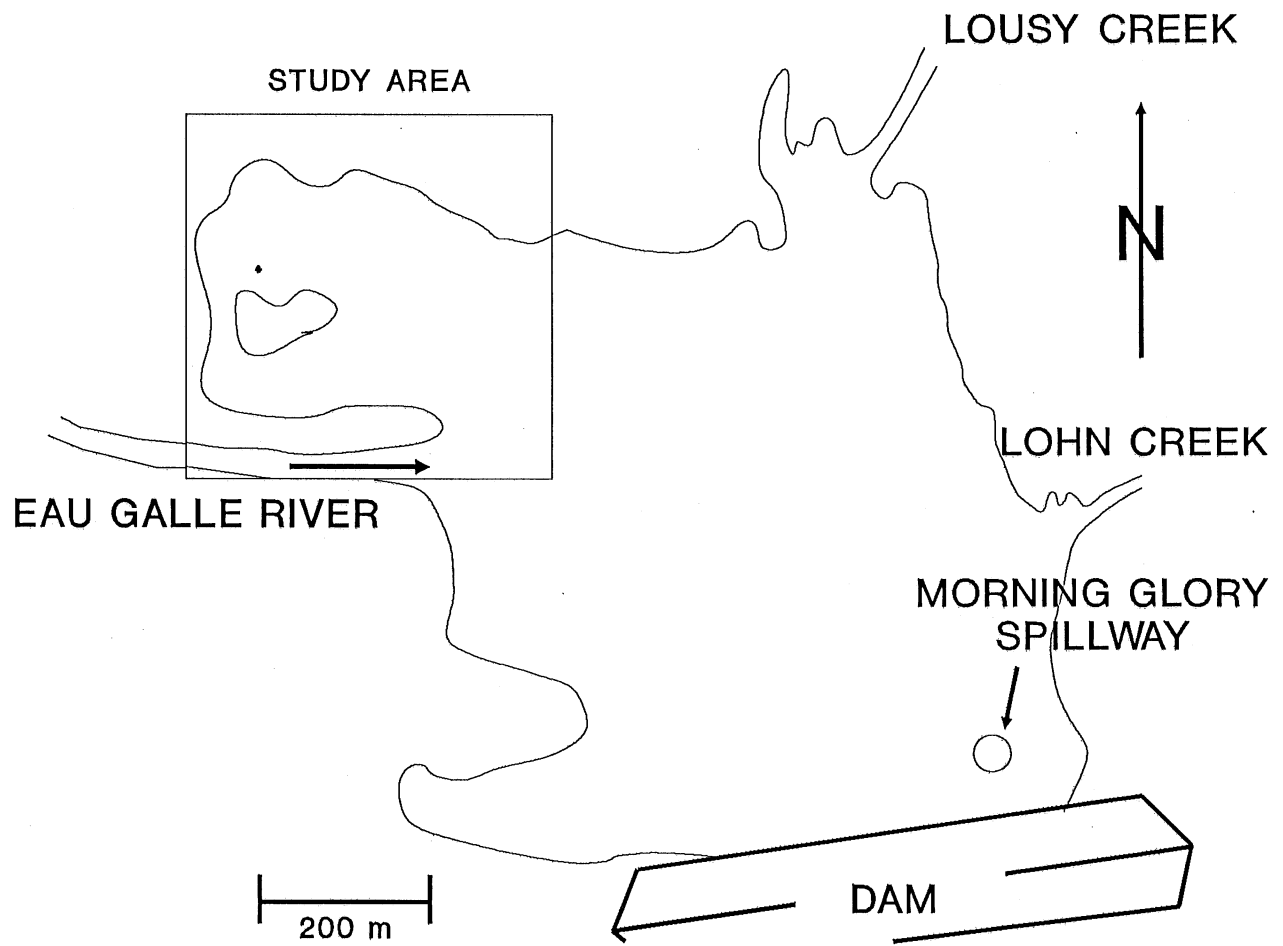


Fig. II-1. EAU GALLE RESERVOIR

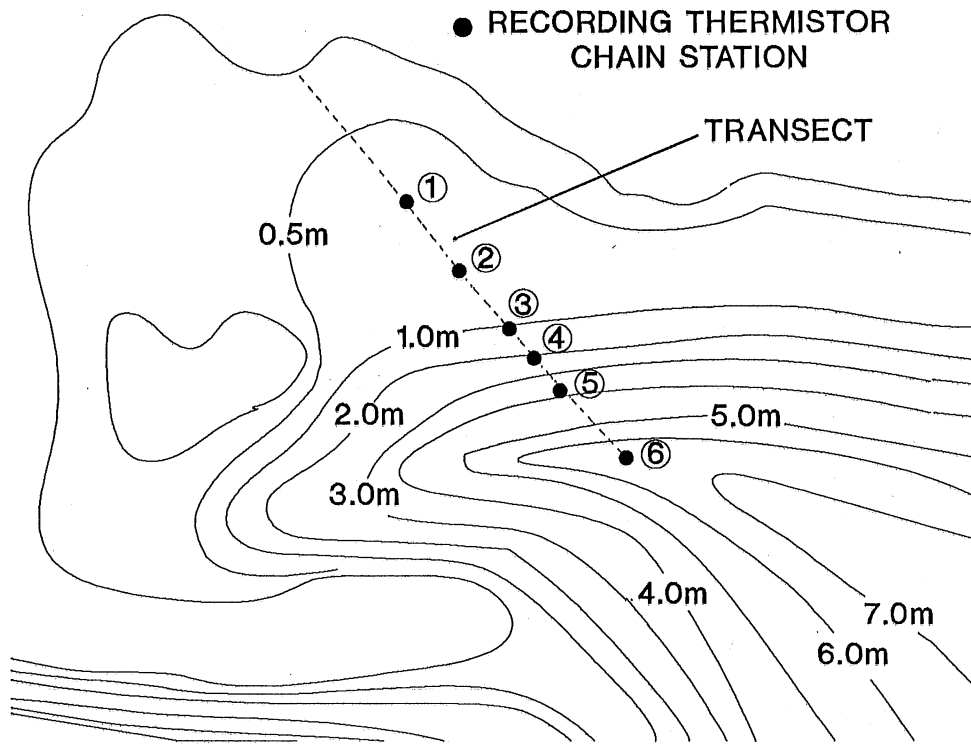


Fig. II-2. THERMISTOR CHAIN POSITIONS

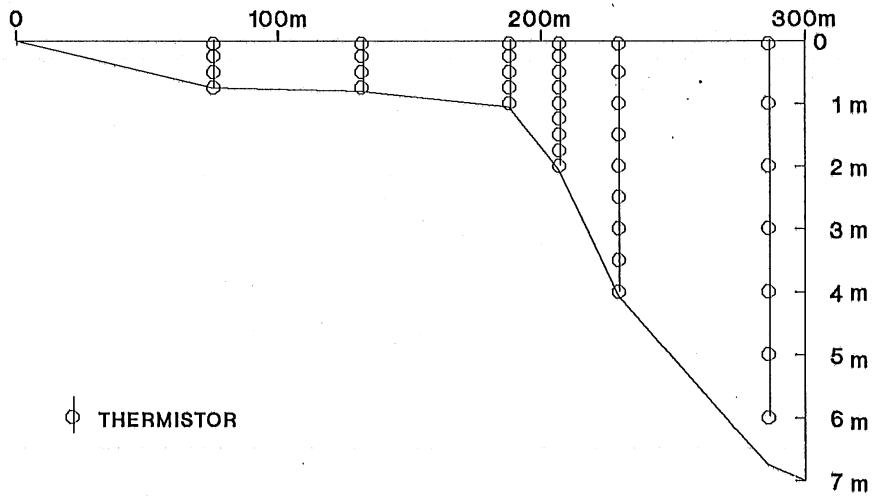


Fig. II-3. THERMISTOR POSITIONS IN TRANSECT

### III. DATA REDUCTION

The water temperature data from stations 1 - 6 and the weather data were received from William F. James in "Lotus" files contained on ten 1.2 MB floppy disks. Each file contained water temperature data for each month, taken at 30 minute intervals, from each station for the period between May 15 - October 13, 1989. Air temperature data were included in the station 3 files. Wind speed and direction data were contained in separate files and recorded every 15 minutes. The thermistors were calibrated at 10°, 14°, 18°, 22°, 26°, 30°C NBS temperatures on April 12, 1989, before field installation, and on November 10, 1989, after removal from the reservoir, and the calibration temperature readings for each thermistor were also provided.

The water and air temperature data files were combined into a matrix format, the columns consisting of each of the 38 thermistors and air temperature, and the rows consisting of each time increment. Each of the 153 matrices contained the data for an entire day. This matrix format facilitated the calibration of the recorded temperatures based on the April 12 and November 10 calibration data. This was achieved through a double linear interpolation. First, the "calibration temperatures," at a specific time, were found through linear interpolation between the April 12 and November 10 temperatures. "Calibration temperatures" are defined as the temperatures which would be measured (read) by a thermistor, at a specific time, at given NBS (true) temperatures of 10°, 14°, 18°, 22°, 26°, 30°C. Second, the actually measured temperature, at a specific time, was linearly related to the "calibration temperatures" and consequently the NBS (true) temperature. The calibration of data was performed on a personal computer using a Pascal program.

Pascal programs were written to interpolate solar radiation data points to convert the solar radiation data from an hourly format into a 30 minute format and to average wind speed data points to convert from a 15 minute format to a 30 minute format.

Calibrated water and air temperature, solar radiation, and wind speed data were combined into 14 "Lotus" files each consisting of approximately ten days of data. The files were in a matrix format with each row representing a 30 minute increment.

The "Lotus" files were used to create temperature vs. time plots of all data. Five day graphs were generated for each station and the weather data. Inspection of these graphs along with the calibration data revealed the locations of "errant probes," which were subsequently removed from the data record. A probe was considered "errant" if it showed unusual behavior when compared to surrounding probes, e.g. drift, lag, and unreasonable amplitudes or readings. Some of the errant probe readings were caused by the leakage of water into the probe tip containing the thermistor. Half of the probes at station 4 had been used in the previous year's study and were not designed for underwater use. Attempts were made to seal the vulnerable sections of the probes. These attempts were

not successful, and due to water leakage these probes failed early in the data record. Other probes began to drift or wander shortly after the July storm and were judged unsatisfactory by comparing their readings with the readings of other probes surrounding them. Therefore, this data was also removed from the record. The lower probes at stations 1 and 2 were found to be in the sediment when the probes were removed. The data from these probes appeared to be accurate so they were not removed from the record but were identified as sediment probes. The locations of all probes left in the data record are shown in Figure III-1.

Inspection of the graphs also provided the information necessary to determine periods for which all data were present and no gaps existed. Two major periods, May 30 - July 5, 1989 and July 18 - August 31, 1989, with no gaps in the water temperature data record, did exist. Although other shorter periods of complete data existed, these two periods were considered time windows during which events of interest could be studied.

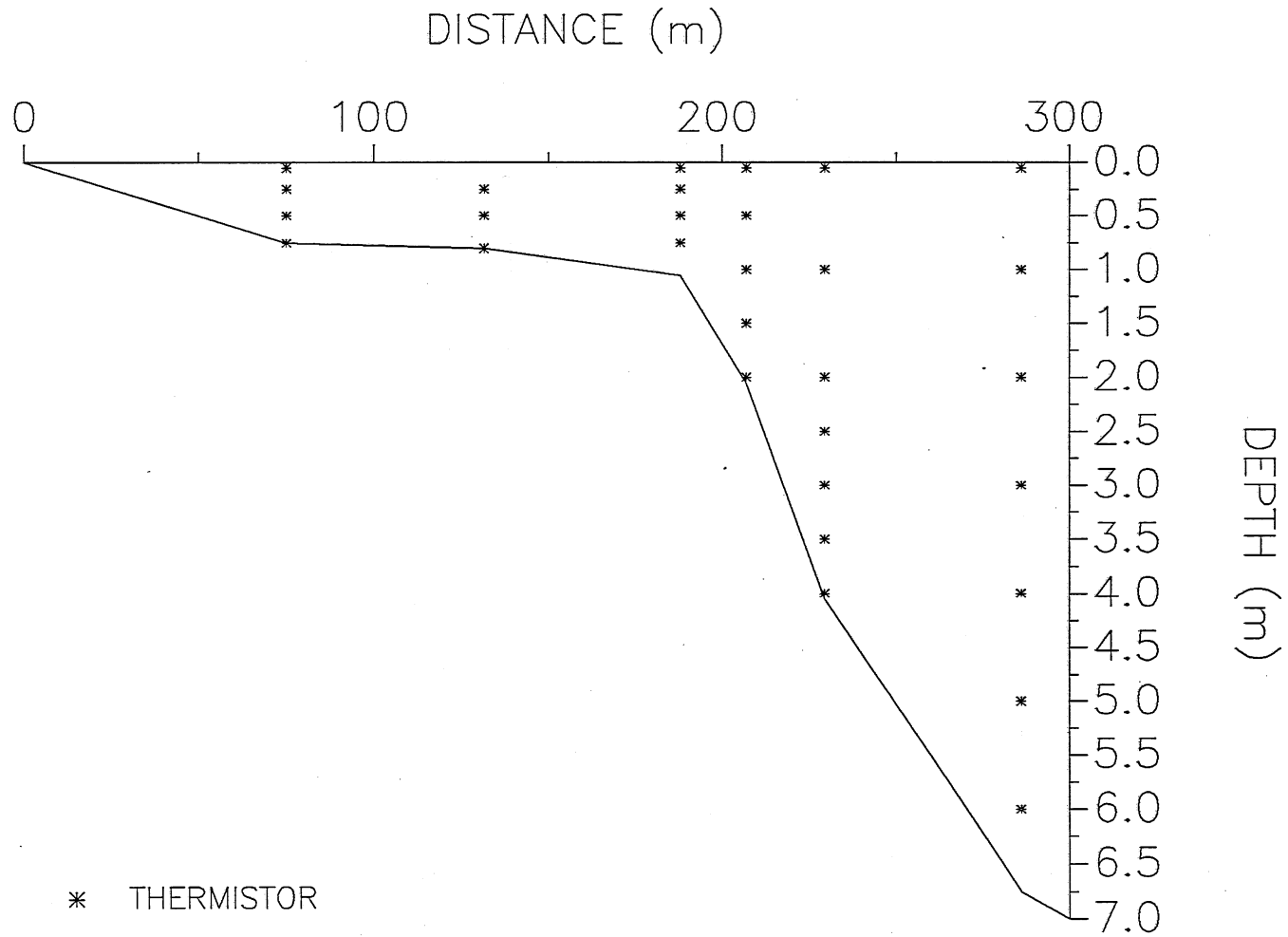


Fig. III-1. THERMISTORS USED IN WATER TEMPERATURE TIME SERIES



## IV. DATA PRESENTATION

The water temperature data is presented in two different ways for interpretation:

### (1) TIME SERIES PLOTS

The first graphical representation of the water temperature data was done in a time series (temperature vs. time) format, one graph representing a five-day period at one station along the transect of the bay. All time series plots are shown in Appendix A. Examples of these time series plots are shown in Figures IV-1 to IV-6. Weather parameters are also provided in the same format in Appendix A. Examples of these are found in Figure IV-7 (wind speed and air temperature), Figure IV-8 (solar radiation), and Figure IV-9 (pool elevation).

### (2) ISOTHERM PLOTS

Isotherm plots were generated on a personal computer using the temperature data at a specific time. These plots were only generated for periods of particular interest. All isotherm plots generated, are given in Appendix B. Examples are shown in Figure V-1. For further explanation of the interpolation techniques used to produce these plots see Appendix C.

INITIAL WATER COLUMN DEPTH 0.75m

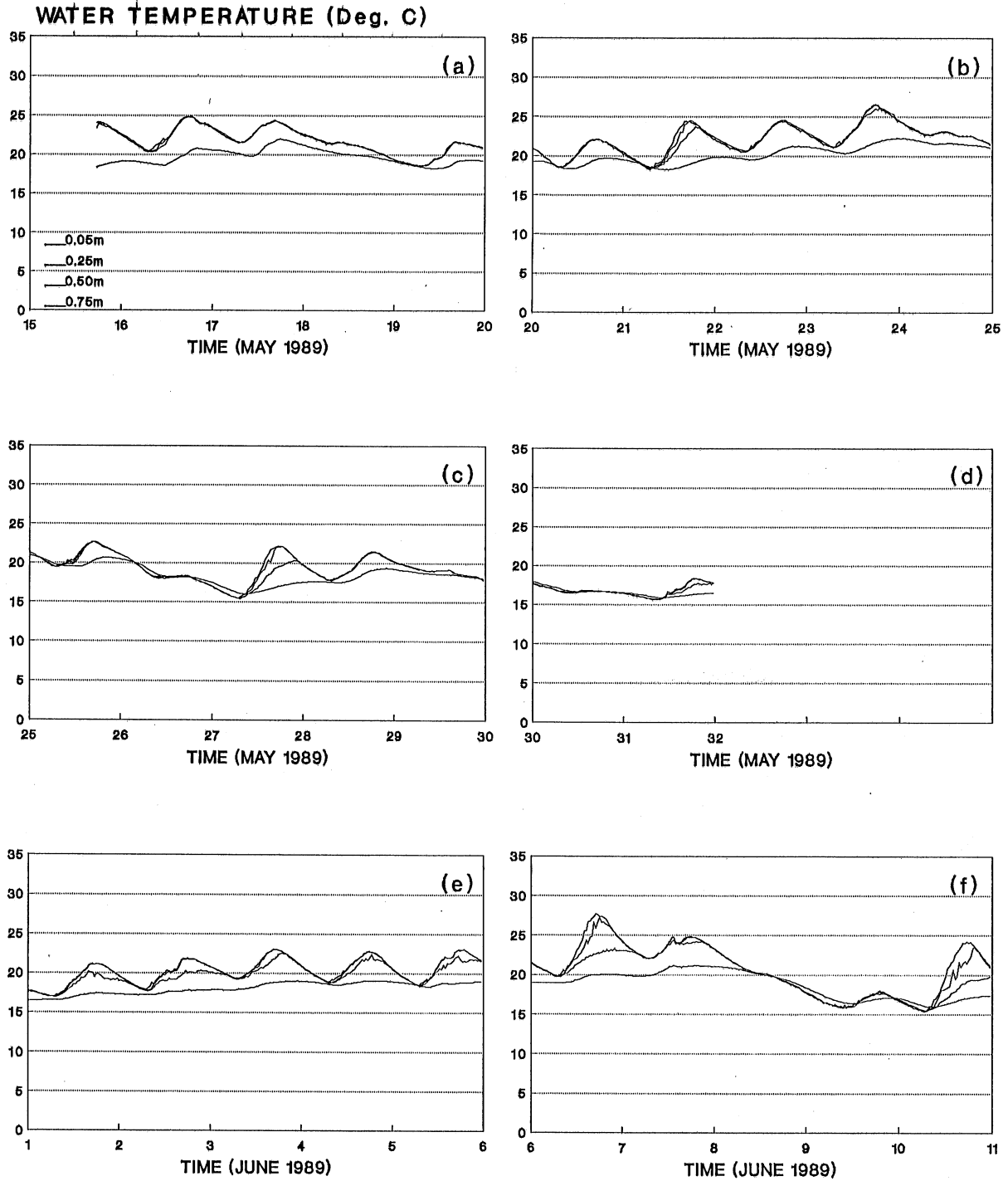


Fig. IV-1(a-f), WATER TEMPERATURE TIME SERIES - STATION #1

INITIAL WATER COLUMN DEPTH 0.80m

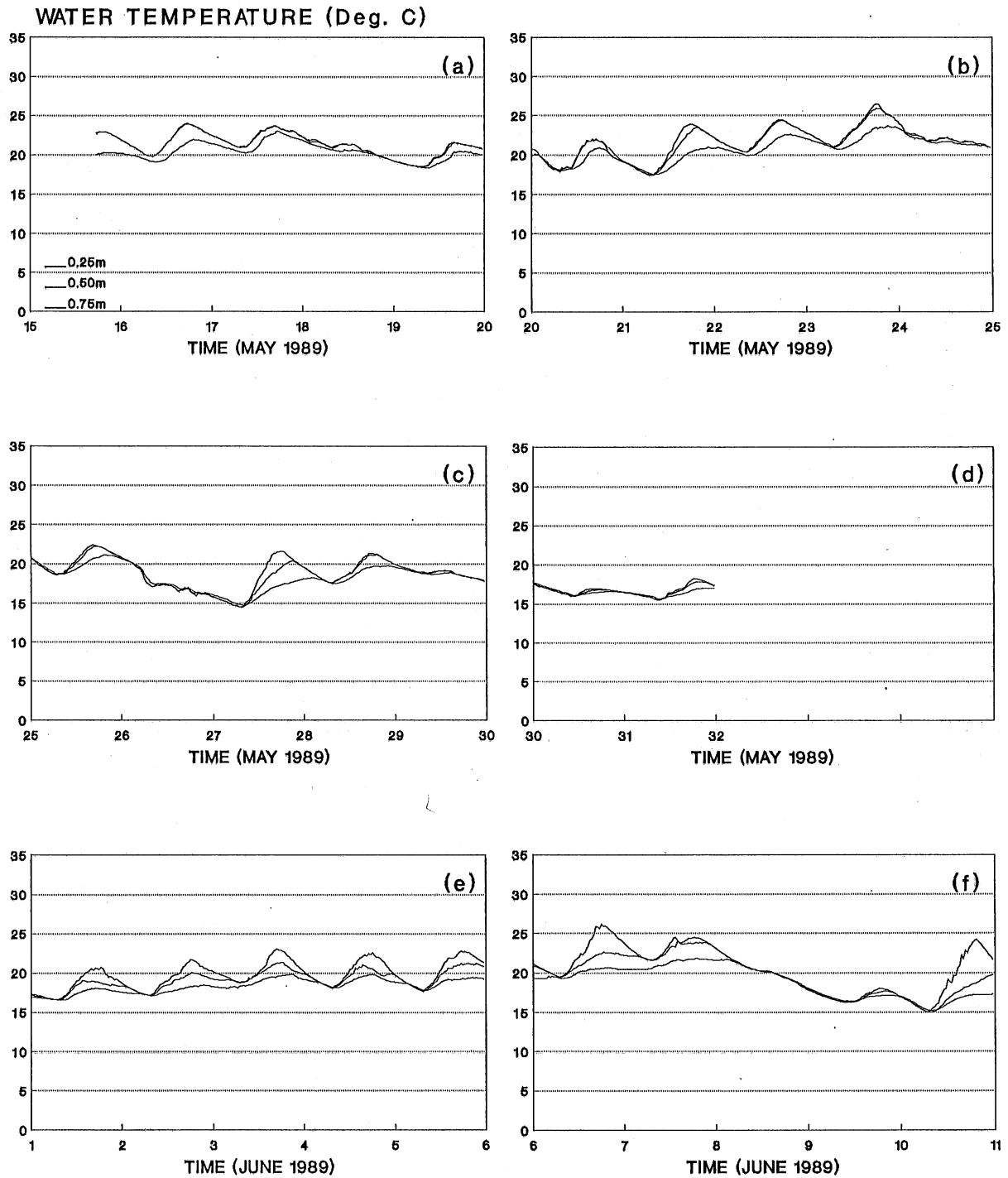


Fig. IV-2(a-f). WATER TEMPERATURE TIME SERIES - STATION #2

INITIAL WATER COLUMN DEPTH 1.05m

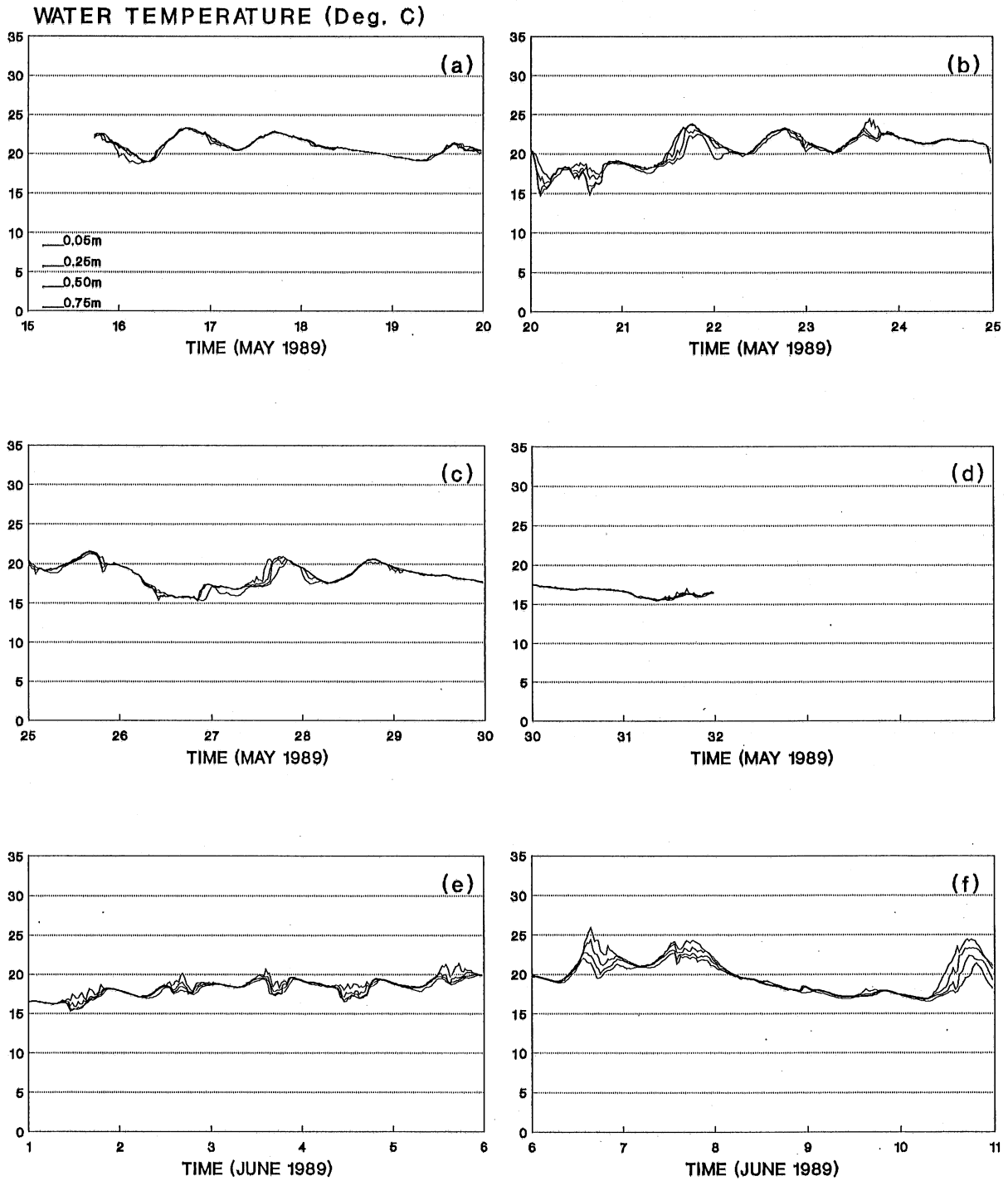


Fig. IV-3(a-f). WATER TEMPERATURE TIME SERIES - STATION #3

INITIAL WATER COLUMN DEPTH 2.05m

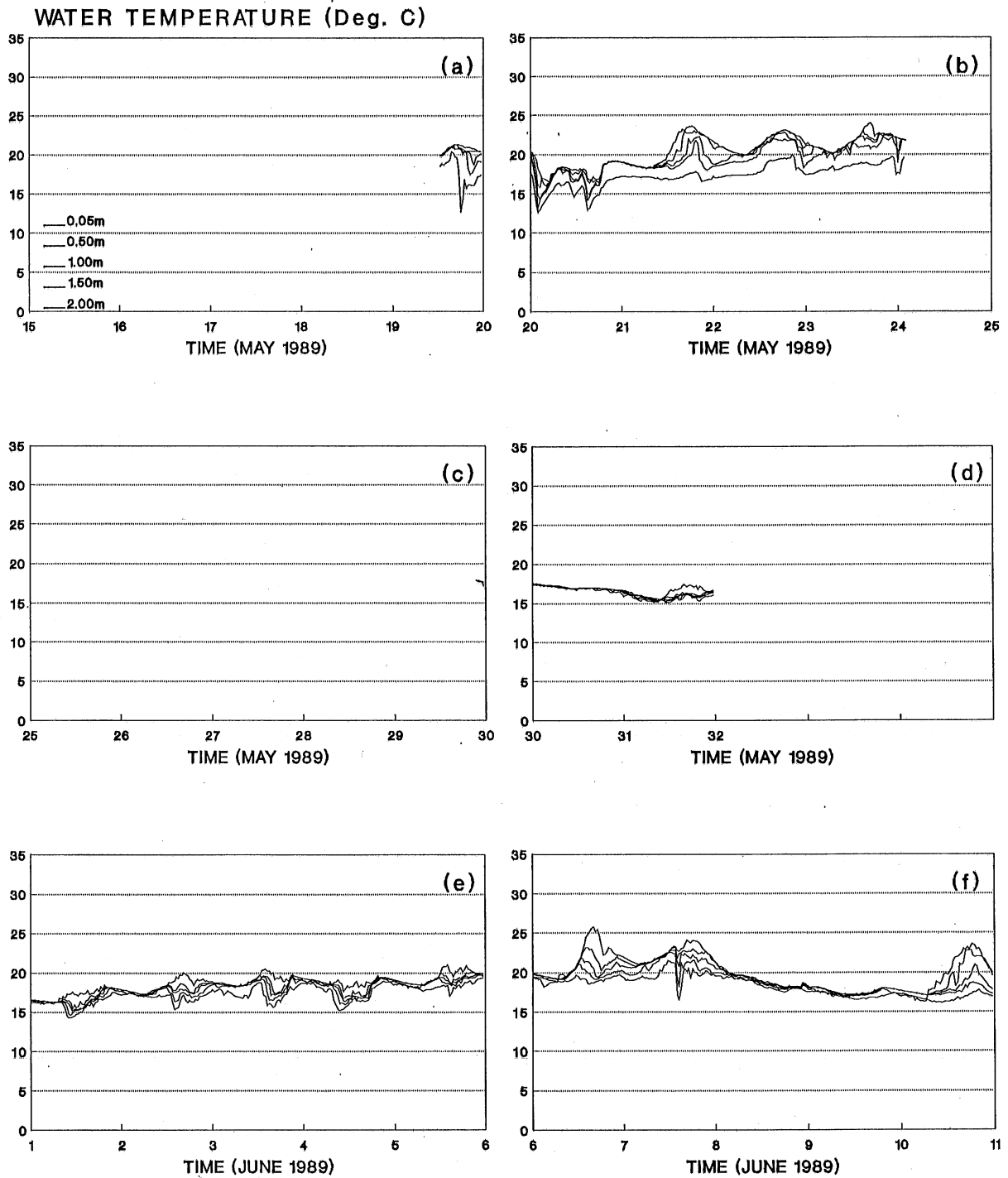


Fig. IV-4(a-f). WATER TEMPERATURE TIME SERIES - STATION #4

INITIAL WATER COLUMN DEPTH 4.05m

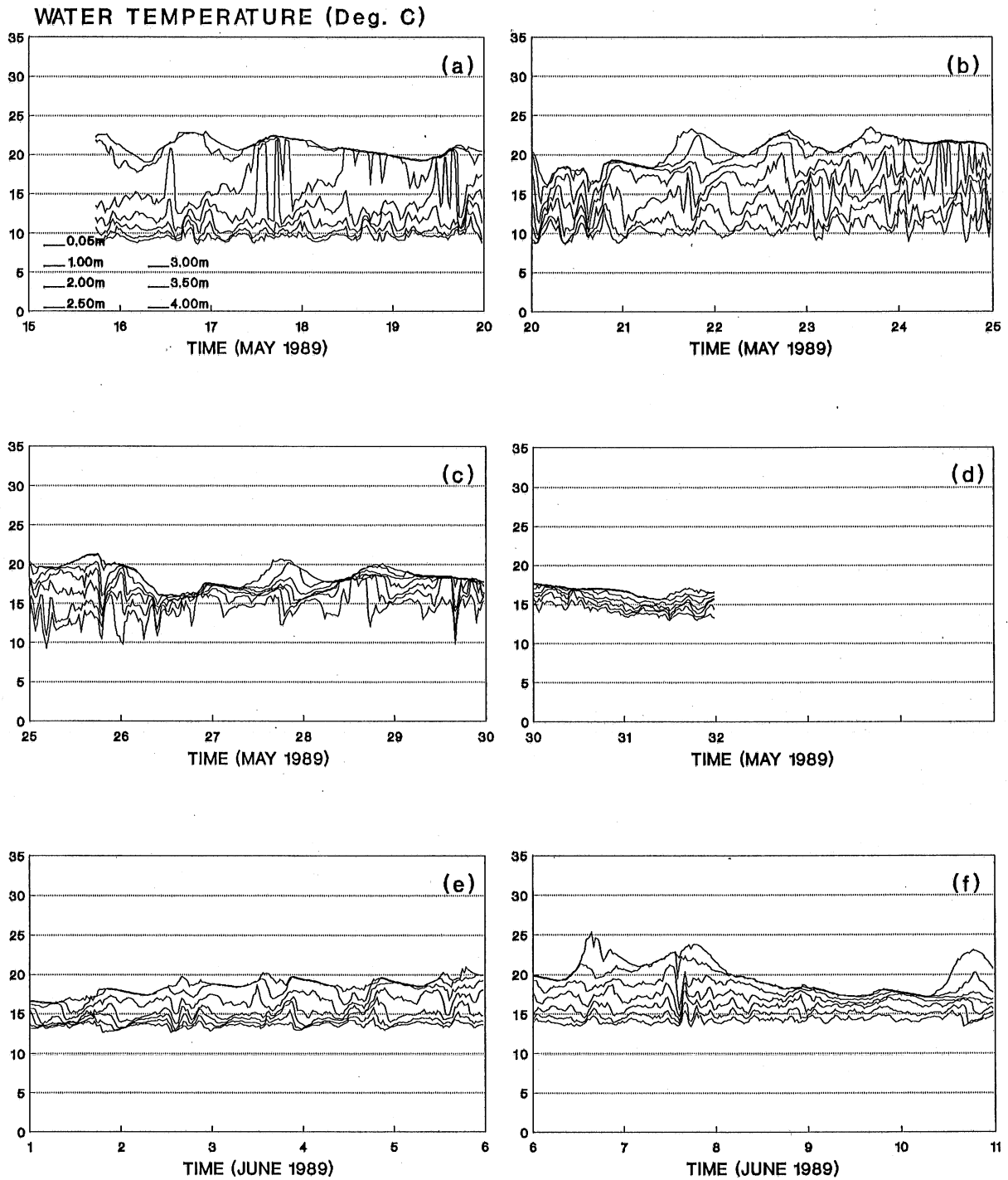


Fig. IV-5(a-f). WATER TEMPERATURE TIME SERIES - STATION #5

INITIAL WATER COLUMN DEPTH 6.75m

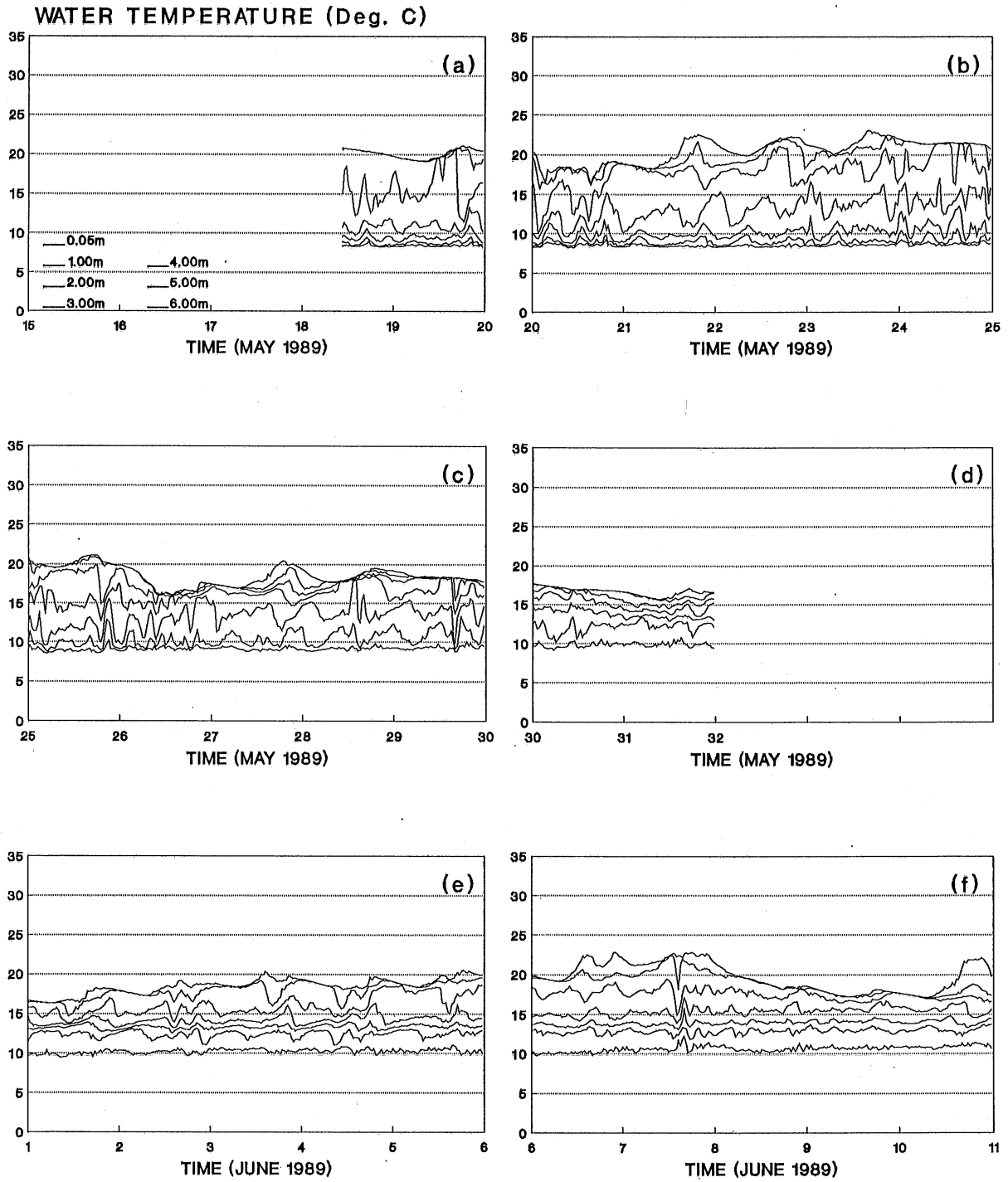


Fig. IV-6(a-f). WATER TEMPERATURE TIME SERIES - STATION #6

AIR TEMPERATURE (Deg. C)  
WIND SPEED (m/s)

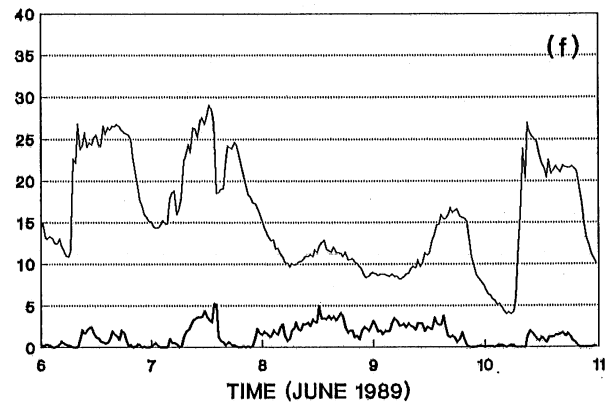
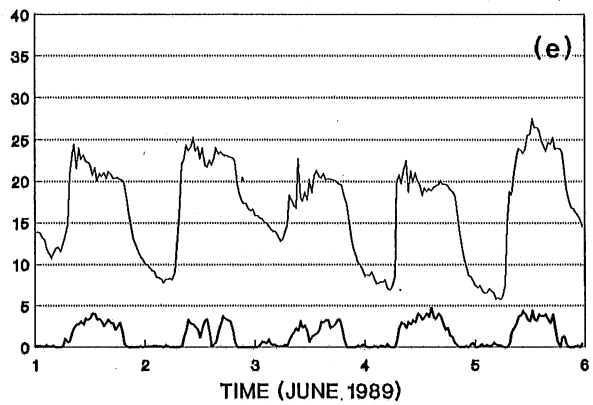
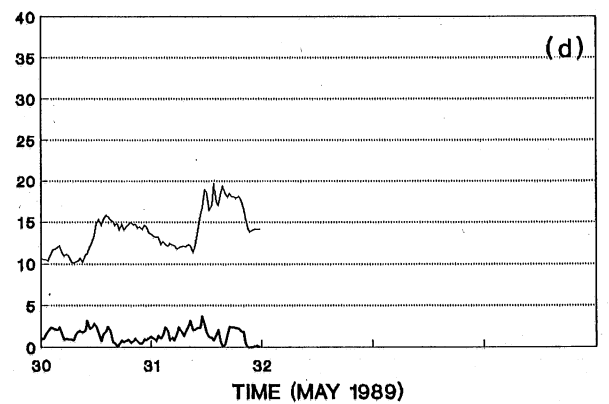
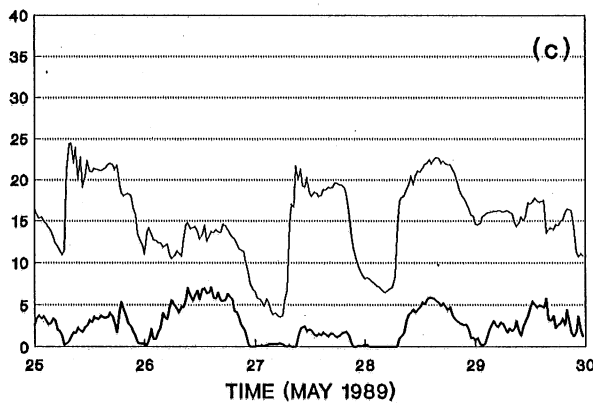
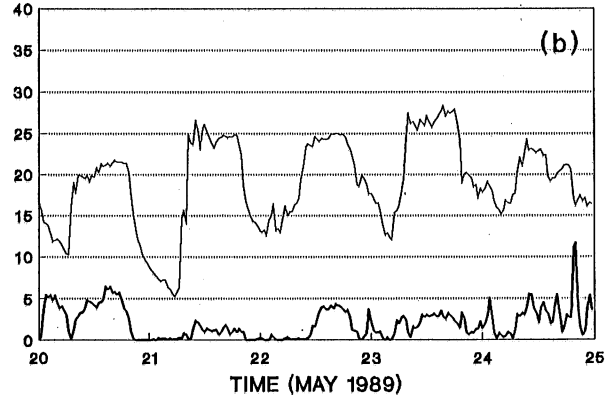
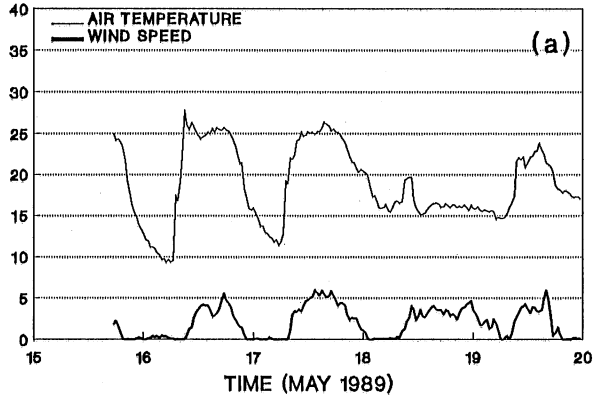


Fig. IV-7(a-f), WEATHER PARAMETERS TIME SERIES



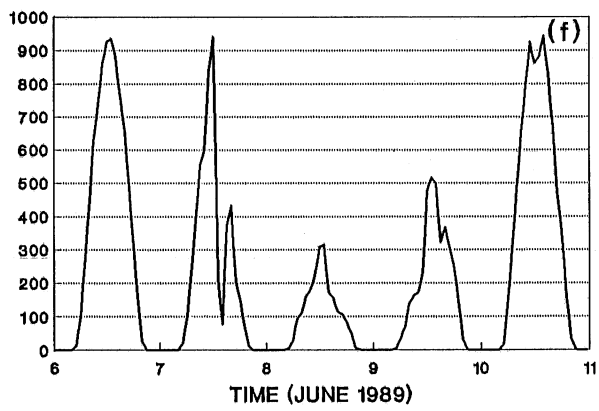
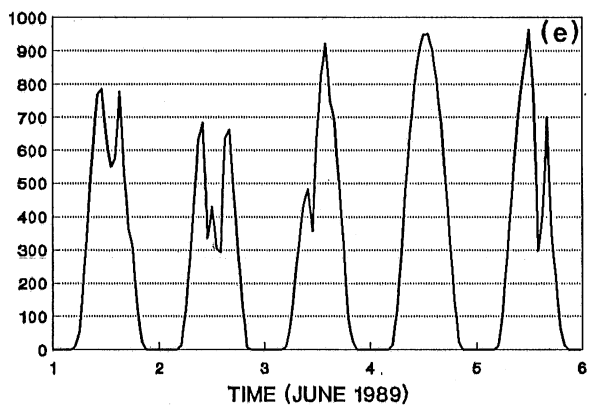
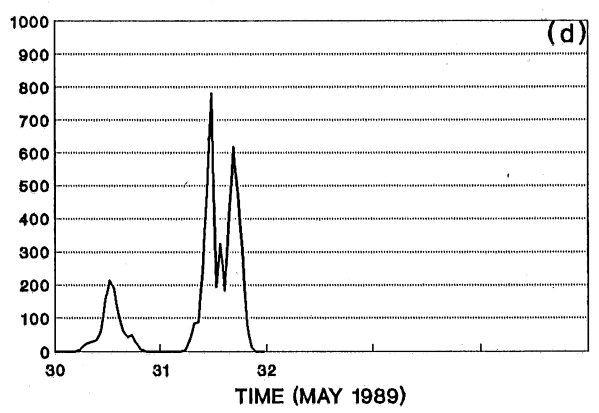
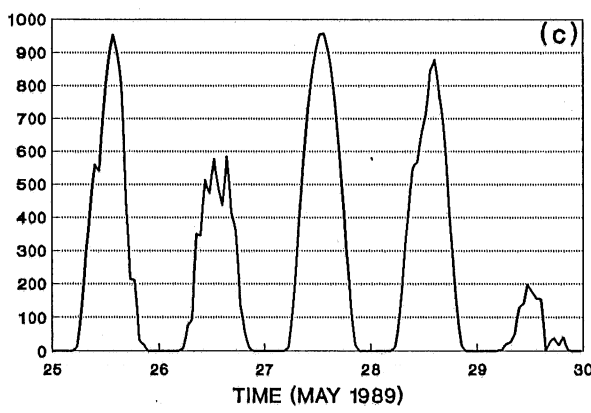
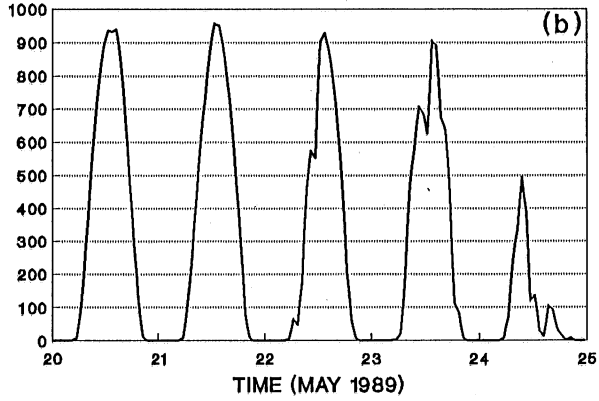
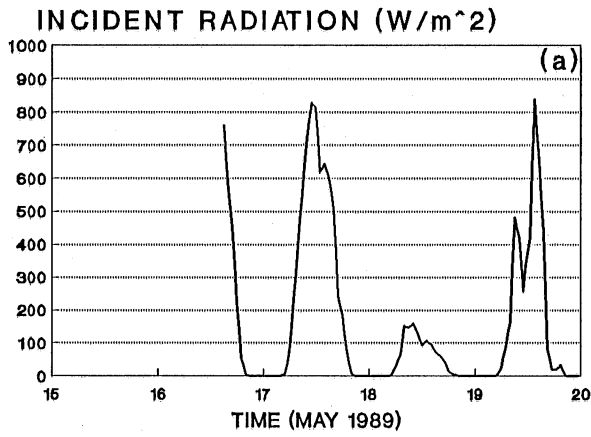


Fig. IV-8(a-f), INCIDENT RADIATION TIME SERIES

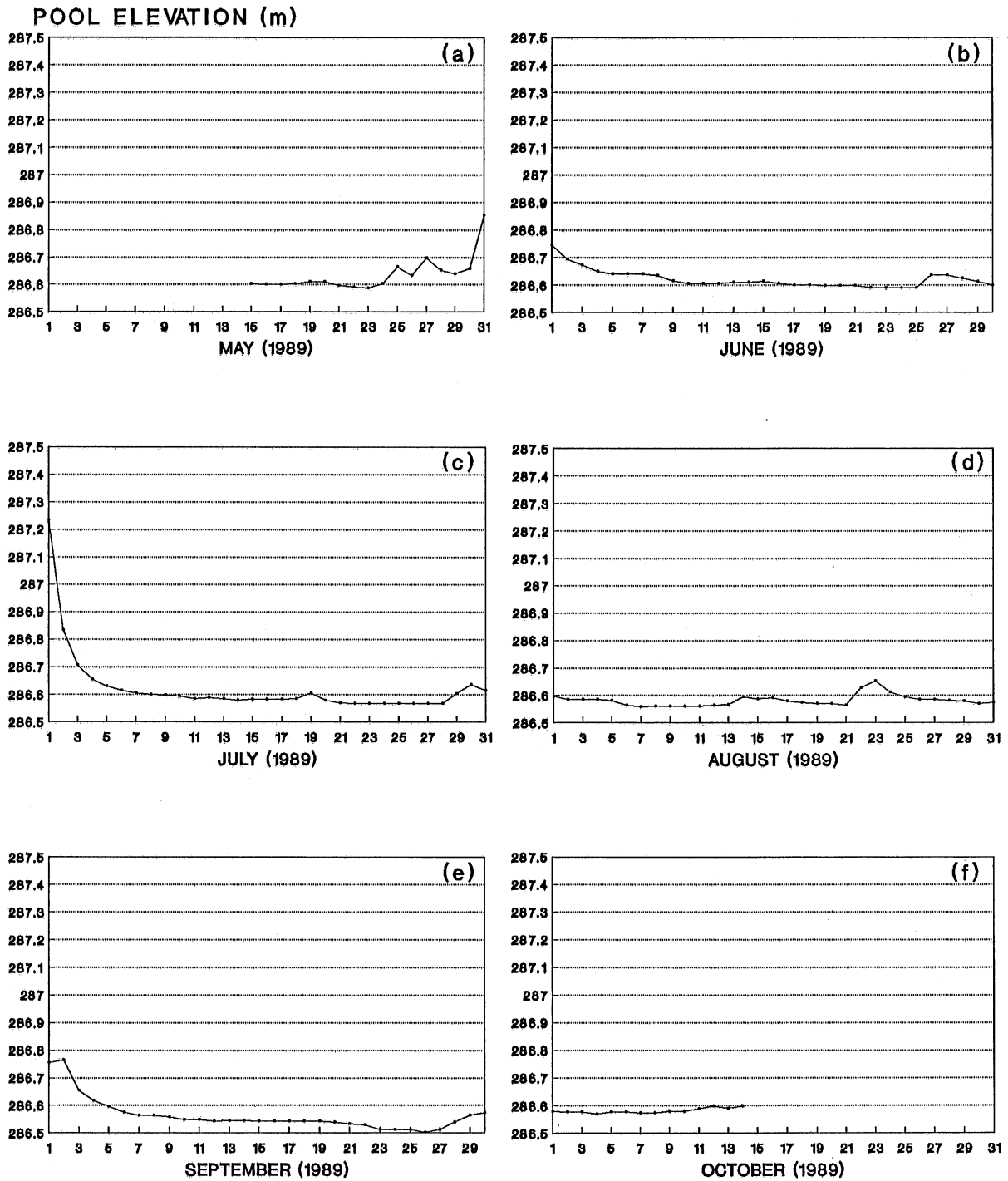


Fig. IV-9(a-f). POOL ELEVATION TIME SERIES

## V. DATA INTERPRETATION

### (1) GENERAL OBSERVATIONS

The volume of field measurements obtained in this study made it possible to investigate the time dependent temperature regimes of a shallow bay and adjacent profundal waters during seasonal and diurnal changes in weather conditions. The record provided data for the windy day of June 20, and the strong heating periods of July 19 - 21, and August 9 - 13; the latter two events occurred during periods with little wind (Fig. IV-7). However, other events of interest are contained in this record. One such event is the transitional cooling period of August 14 - 16, which followed the heating period of August 9 - 13, when lack of solar radiation and the 5° - 10° C drop in average air temperature combined to cool the average morning bay temperature by more than 3° C.

Solar heating and surface cooling are the natural heat transfer processes which directly affect the time dependent temperature distribution of the bay. Vegetation and wind effects are also significant and will be addressed in the following sections.

### (2) THE DIURNAL HEATING / COOLING CYCLE

The diurnal heating and cooling cycle consists of daytime heating and nighttime cooling. The duration and intensity of these periods varied greatly with the prevalence of and changes in existing weather conditions. Cloud cover greatly affects the amount of incident solar radiation available for heating of the bay. Changes in air temperature and humidity affect the cooling rate of the water surface. During the period of study the heating period generally began between 7:00 and 9:00 and ended between 17:00 and 19:00. The remaining period can be considered the cooling period of the diurnal cycle. Figure V-1 shows the computed bay isotherms, at three hour intervals, from 0:00 to 21:00 on July 20. These plots are interpolations of instantaneous measurements obtained in the study. The figures show convective cooling layers that reach below 0.5 meter depth in the littoral zone and the 2.0 meter depth in adjacent profundal waters and typical daytime stratification with top to bottom temperature differences of 7° - 10° C in the littoral zone.

## 2.1 SOLAR HEATING

Evidence of strong solar heating can be found throughout the data record. July 19 - 21 is an period of strong solar heating. During the period of solar heating the water temperature near the surface increases rapidly due to incident radiation (Fig. V-1, Appendix A, and Appendix B). The greater thermal inertia of the profundal water causes it to warm more slowly than the littoral water when subjected to an equal rate of surface heat transfer. This process causes a strong stratification in the littoral water which is indicative of solar heating throughout the data record. This stratification is evident in the 12:00 - 21:00, July 20 bay isotherms (Fig. V-1). These plots also show a strong horizontal temperature gradient between littoral and profundal waters. These temperature (density) gradients are the major cause of exchange flows (density currents) which affect transport processes in the bay.

## 2.2 CONVECTIVE SHORT TERM COOLING

Convective short term cooling is the term used to describe the process by which the littoral waters experience a drop in temperature. During this process thermal stratification is weakened through convective heat transfer (Appendixes A and B). The surface water in the littoral region of the bay is cooled more rapidly than the water beneath it. Consequently, the surface water attains a greater density and sinks until it reaches equilibrium with the surrounding water. This cooled water is usually more dense than any water in the littoral region. Therefore, the cooled water slowly sinks (flows) down the littoral slope. The movement of water caused by this process is called a density current or exchange flow between littoral and adjacent profundal waters. Evidence of the movement of a cold water lens near the bottom down the littoral slope during the cooling phase of the diurnal cycle is found in the isotherm plots of 0:00 - 9:00 June 20 (Fig V-1) and other isotherm plots (Appendix B).

## (3) SEASONAL HEATING AND COOLING

A seasonal increase in water temperature is apparent in the data record from May 15 to August 13 (Appendix A). The increase is more rapid during the period of May 15 to June 15, when average water temperature in the profundal region increased by about 5°C. During the remaining two months of seasonal heating the average water temperature increased by approximately the same amount.

Beginning with the sustained cooling of August 14 - 15, caused by lack of solar radiation and lower air temperatures for the two day period, the water temperature began to decline. The average water temperature dropped about 5°C from August 14 to October 1. During the following 11 days, i.e. October 1 - 11, the average water temperature dropped an additional 5°C and thermal stratification, due to daytime heating, became virtually non-existent (Appendix A).

#### (4) EXPOSED PROBES AND SEDIMENT PROBES

Evidence of the exposure of probes to the atmosphere, due to the change in pool elevation in the reservoir (Fig. IV-9), can be found in the data record for stations 1 and 3 during September. The pool elevation fell to a level which partially exposed the 0.05 meter probes at stations 1 and 3 from September 8 - 21. This is evident in the erratic 1°C oscillations in these probes during this period (Appendix A). This behavior is not found in the temperature profiles of the 0.05 meter probes at stations 4 - 6 because these stations were attached to floating platforms, so that the depth of probes at these stations were not affected by changes in pool elevation. The probes at the 0.05 meter depth at stations 1 and 3 were completely exposed from September 21 - 26 when pool elevation fell further. The temperatures measured by these probes match the air temperatures for the period (Appendix A). After September 26 the pool elevation returned to a level which resubmerged all probes at stations 1 and 3.

Evidence of the embedding of probes in the sediment are found in the time series plots for stations 1 and 2. The 0.75 meter probes exhibit dampened responses to temperature fluctuations throughout the data record. The temperatures recorded by these probes were generally lower than those of other probes at these stations during seasonal heating. During the period of seasonal cooling these probes exhibited higher temperatures than other probes at these stations (Appendix A). This is indicative of (a) the seasonal lag in mean sediment temperature and (b) the smaller diurnal temperature fluctuations in the sediment compared to the water temperatures.

#### (5) WIND EFFECTS

The effect of wind is exemplified in the isotherm plots of June 20 (Appendix B). Wind direction was from the southeast, approximately 150°, blowing across the reservoir and into the bay. The relatively strong wind velocity of about 7.5 m/s experienced in the bay (Appendix A) prevented the formation of thermal stratification in the littoral region. This was probably due to the mixing of the water column by wave action. Downwelling of littoral water is exhibited in the isothermal plots during this period. This downwelling could have been the consequence of movement of surface water in this region towards the shore. Wind activity is a major factor in the mixing of water within the bay because wind is present throughout most of the data record.

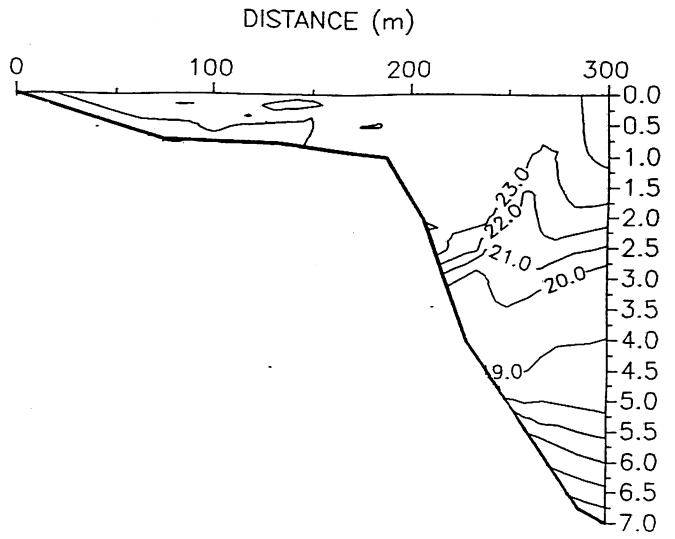
## (6) VEGETATION EFFECTS

The two major effects of plant growth within the bay with which this study is concerned are the attenuation of light in the water column and the resistance to water movement imposed by macrophytes. The rate of increase in temperature of water at different depths within the water column is indicative of the attenuation of solar radiation within the water column. The presence of dense vegetation does not prohibit the movement of water within the bay. However, the vegetation can exert substantial resistance to water movement.

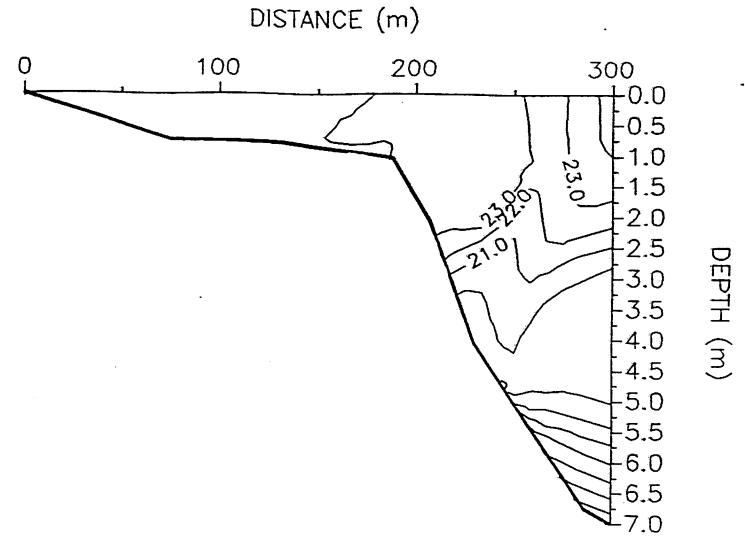
In the littoral region of the bay, solar radiation is completely attenuated within the upper 0.25 meters of the water column. This estimate is based on the plant distribution within the bay (Fig. V-2). Quantitative information on the vegetation density within Eau Galle Reservoir is available (Filbin and Barko, 1985). Dense vegetation existed out to the 1.0 meter depth. The vegetation was mainly *Ceratophyllum demersum* and blue-green algae. The proliferation of plants diminished from the 1.0 meter depth to the 3.0 meter depth and plants were virtually non-existent in water deeper than 3.0 meters. The effects of these plants on the temperature distribution within the bay were substantial. The strong thermal stratification and formation of local "hot spots" in the littoral region shown in the isotherm plots are taken as evidence of the effects of light attenuation and resistance to water movement exhibited by the plants (Appendix B). Temperature inversions in the littoral water were found in the data record in September during nighttime cooling (Appendix A). These inversions may be another indication of resistance to convective currents by the plants. However, these apparent inversions might also be the result of the partial exposure of the 0.05 meter probes to the air during this period.

## (7) GROUND WATER INTRUSION

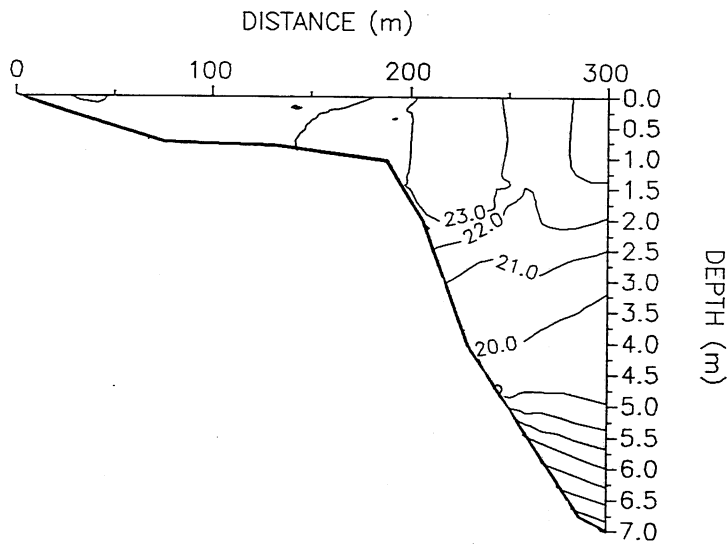
No evidence of significant ground water intrusion was found throughout the data record. The sediment probes at stations 1 and 2 registered temperatures significantly higher than the 10° - 15°C temperatures that would have been expected if significant ground water intrusion was present. Even after seasonal cooling had lowered the water temperatures to a temperature equal to that of ground water, the sediment probes maintained a notably higher temperature (Appendix A). No unusual temperature profiles for the adjacent profundal waters, which would suggest the intrusion of a significant amount of ground water, were exhibited either. This evidence supports the assumption that ground water intrusion was not significant in the bay.



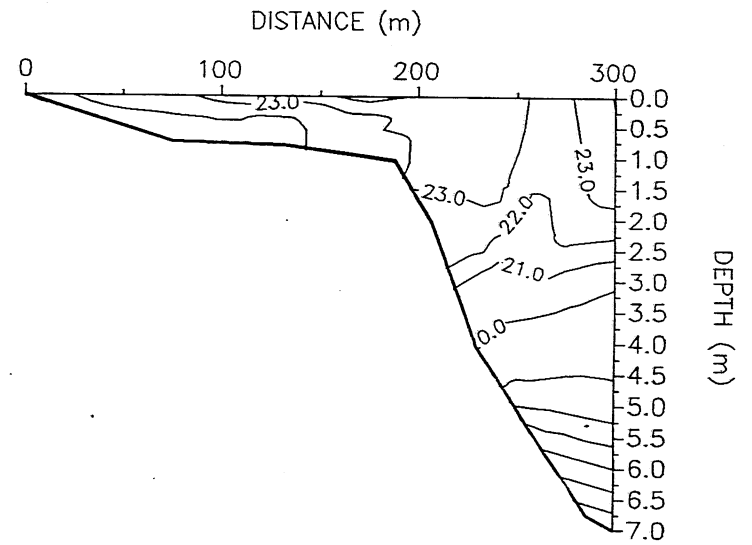
JULY 20 1989 0:00



JULY 20 1989 3:00

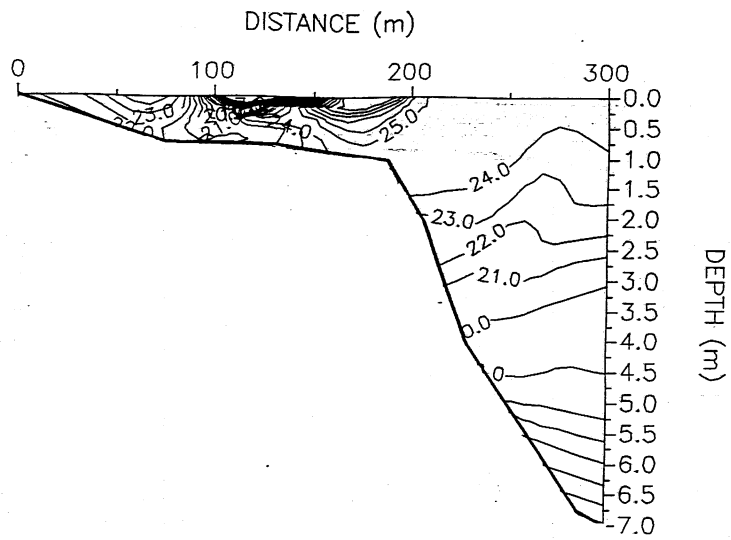


JULY 20 1989 6:00

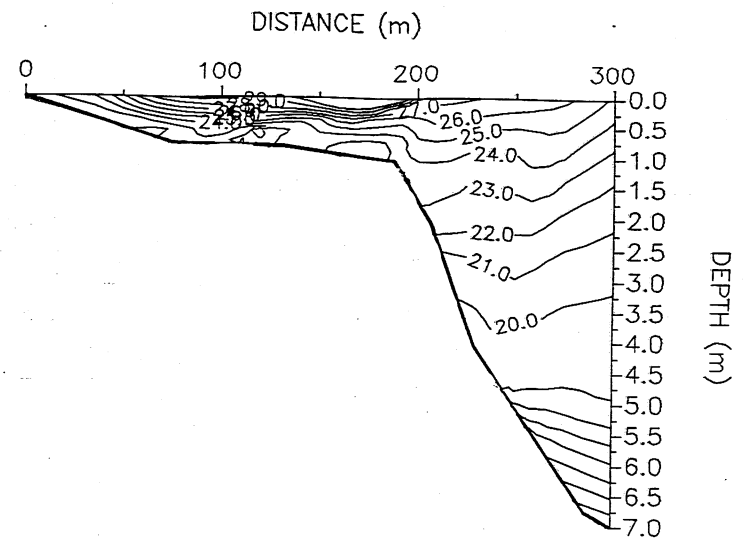


JULY 20 1989 9:00

Fig. V-1. ISOTHERM PLOTS OF THE BAY TRANSECT (JULY 20, 1989)

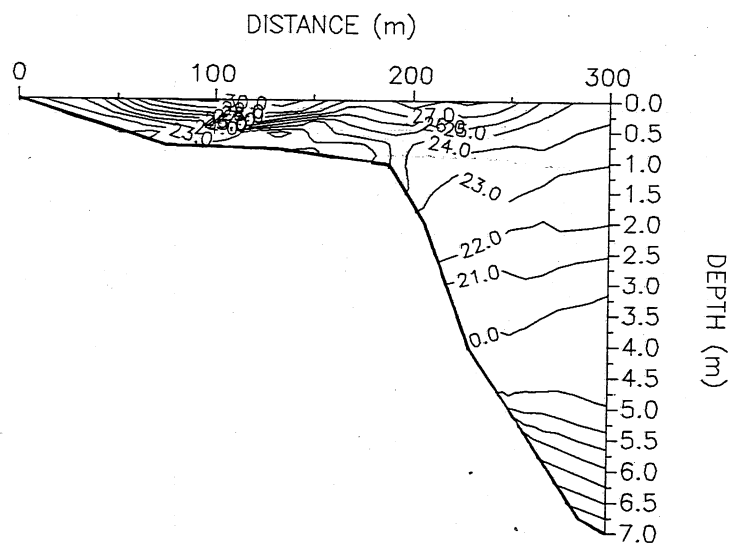


JULY 20 1989 12:00

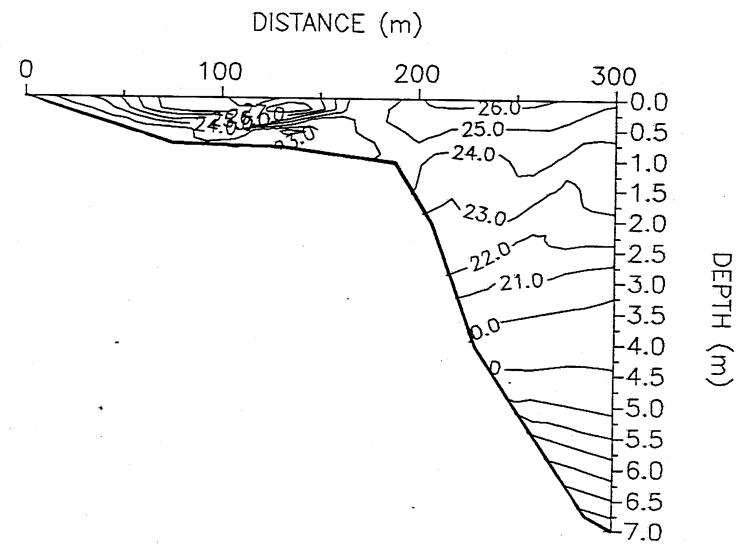


JULY 20 1989 15:00

24



JULY 20 1989 18:00



JULY 20 1989 21:00

Fig. V-1. ISOTHERM PLOTS OF THE BAY TRANSECT (JULY 20, 1989)



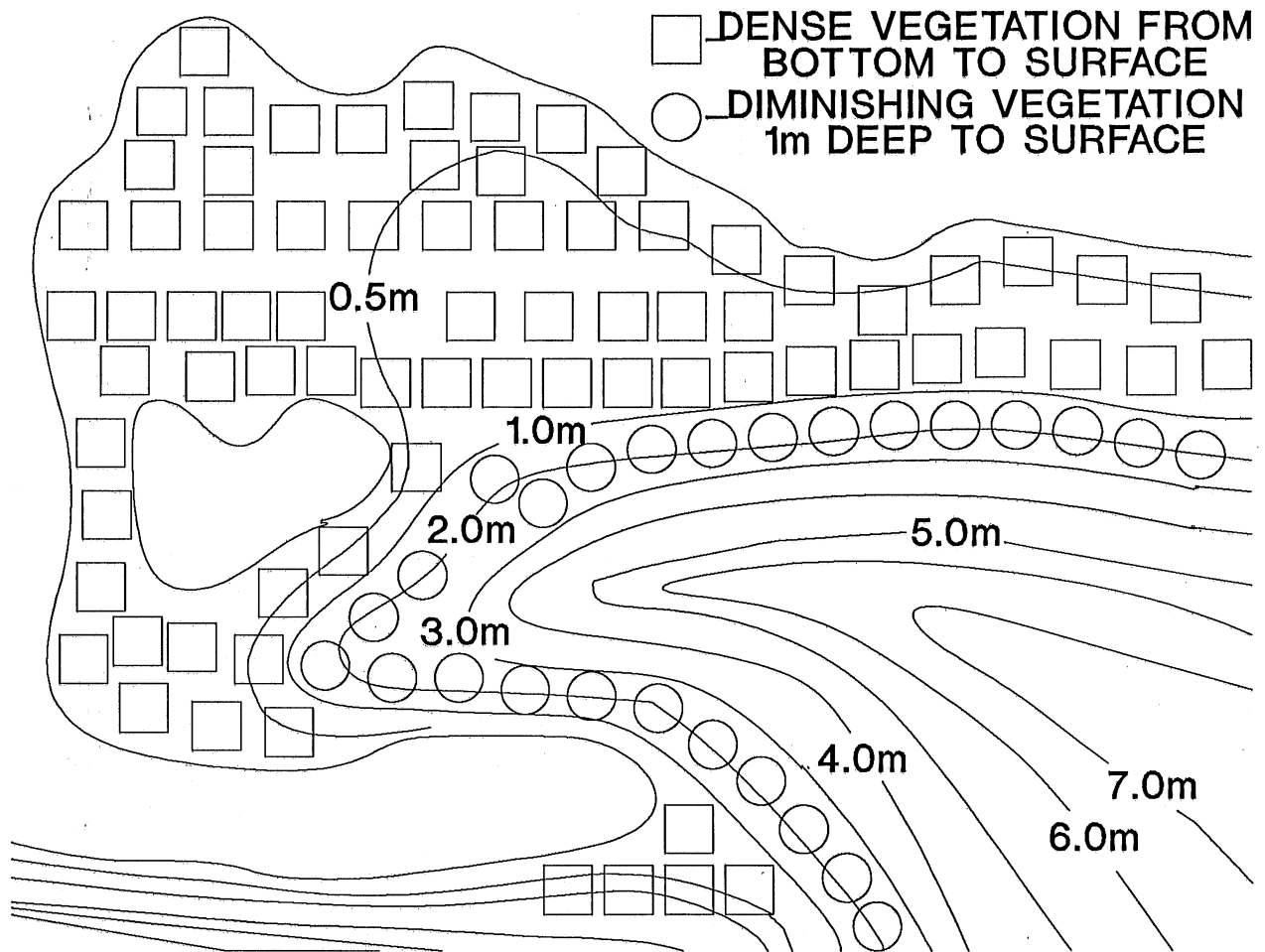


Fig. V-2. APPROXIMATE VEGETATION DENSITY

## VI. REFERENCES

1. Stefan, H. G., G. M. Horsch, and J. W. Barko, 1989. A model for the estimation of convective exchange in the littoral region of a shallow lake during cooling, Hydrobiologia 174: 225-234.
2. Filbin, G. J. and J. W. Barko, 1985. Growth and nutrition of submersed macrophytes in a eutrophic Wisconsin impoundment, Journal of Freshwater Ecology 3: 275-288.
3. Silver, C. A., C. R. Ellis, and H. G. Stefan. Heating and cooling of a shallow bay in Eau Galle Reservoir: field measurements and interpretation, Part 1 (1988), St. Anthony Falls Hydraulic Laboratory: Project Report #298.

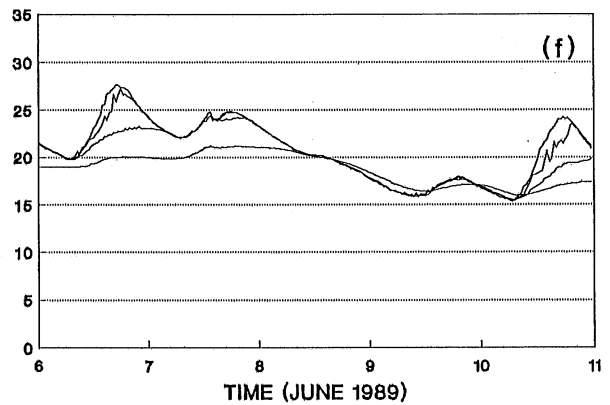
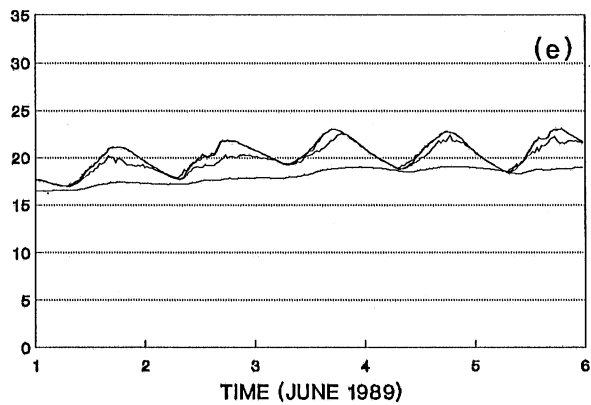
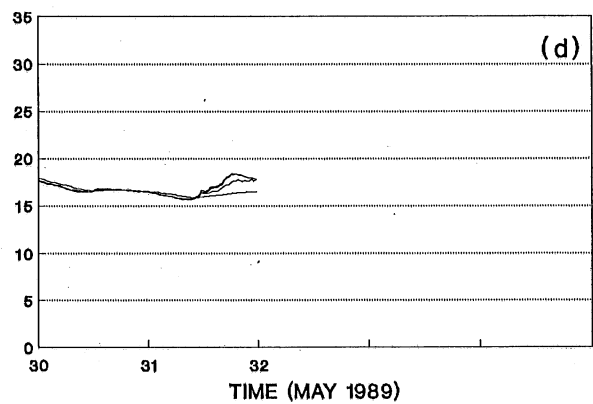
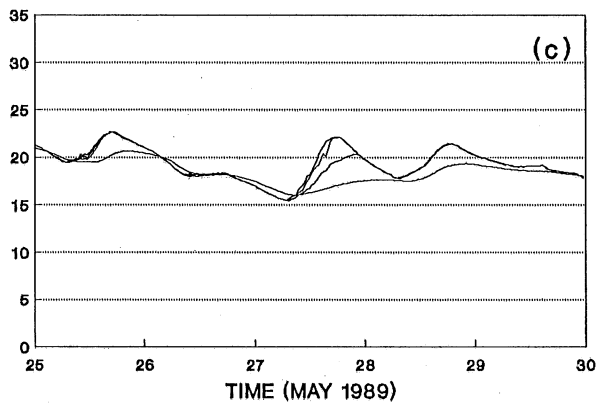
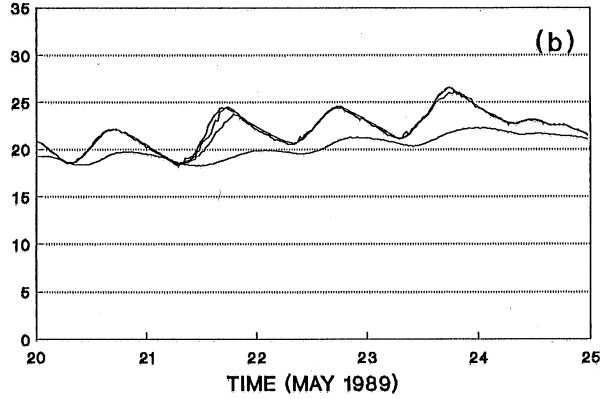
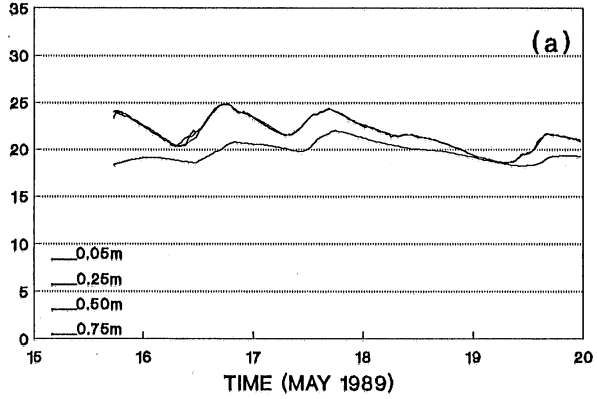
# APPENDIX A

## TIME SERIES PLOTS

WATER TEMPERATURES  
WEATHER PARAMETERS  
AND POOL ELEVATION

INITIAL WATER COLUMN DEPTH 0.75m

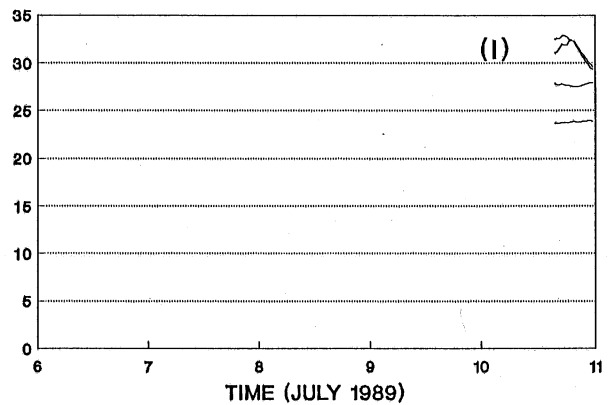
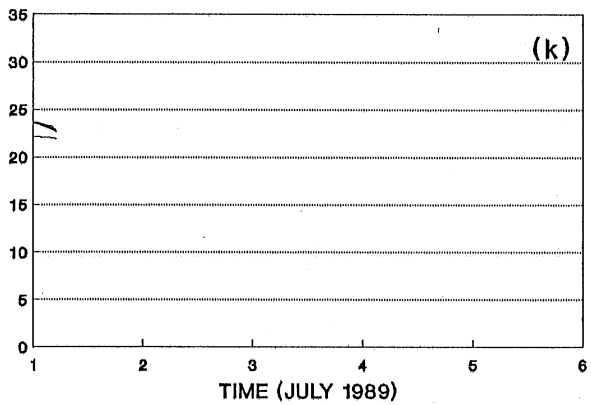
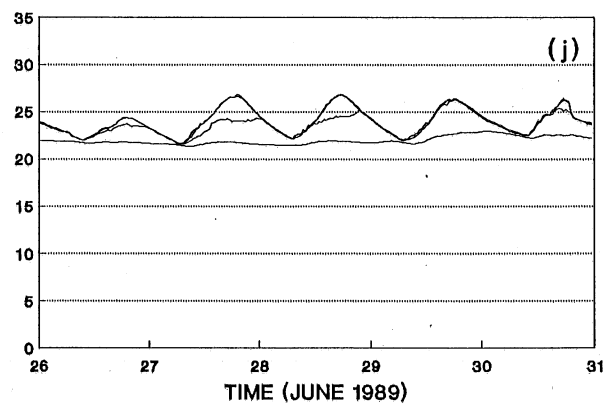
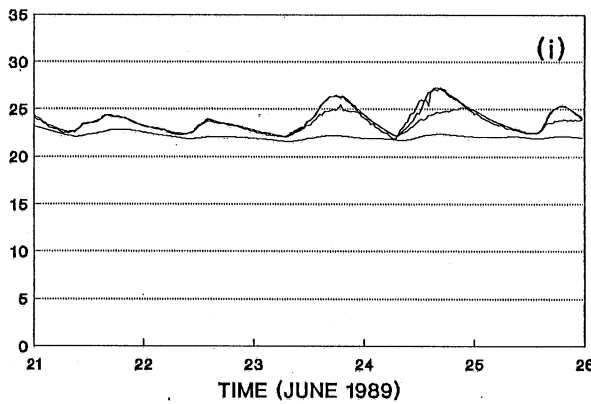
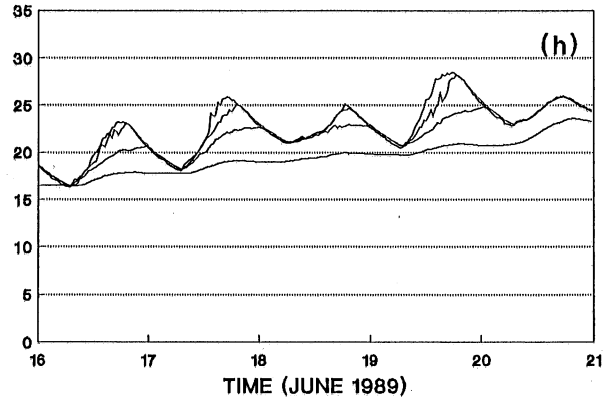
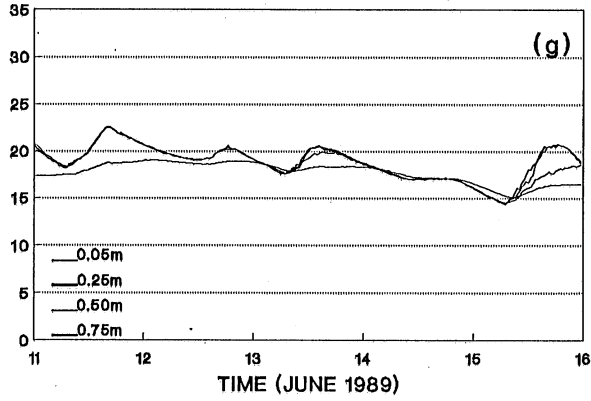
WATER TEMPERATURE (Deg. C)



WATER TEMPERATURE TIME SERIES - STATION #1 (a-f)

INITIAL WATER COLUMN DEPTH 0.75m

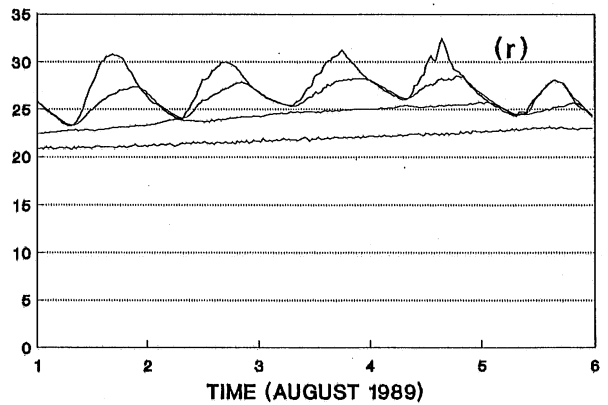
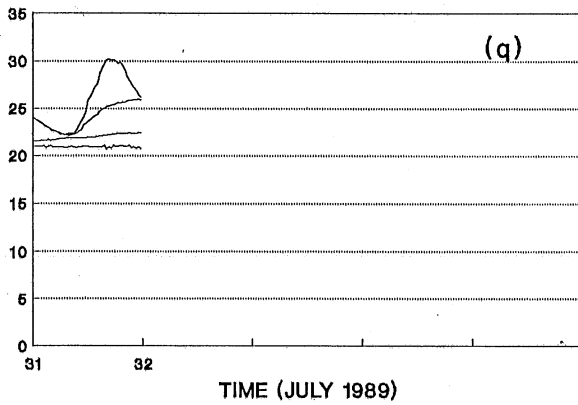
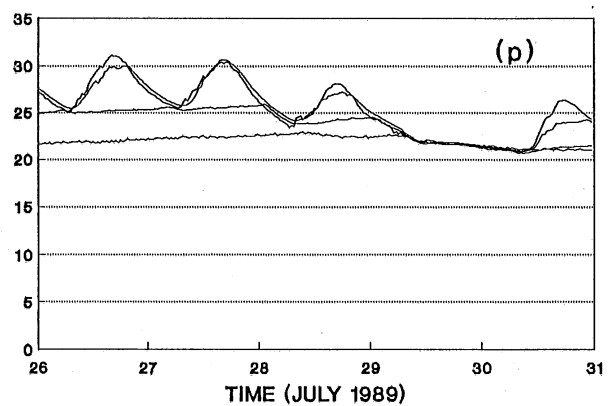
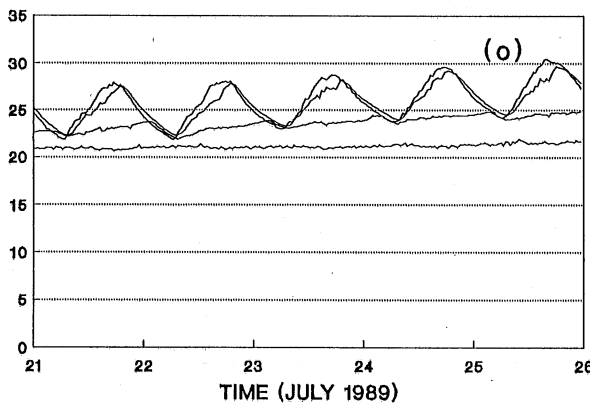
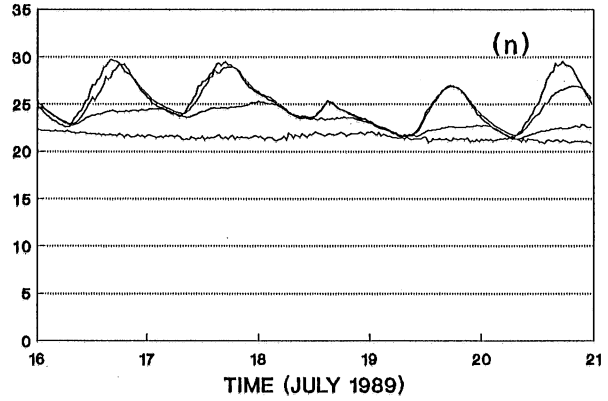
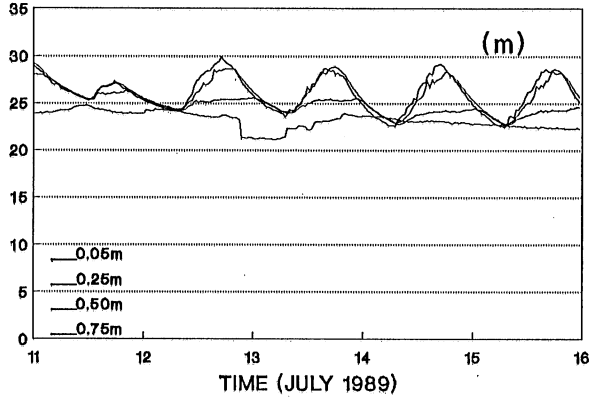
WATER TEMPERATURE (Deg. C)



WATER TEMPERATURE TIME SERIES - STATION #1 (g-l)

INITIAL WATER COLUMN DEPTH 0.75m

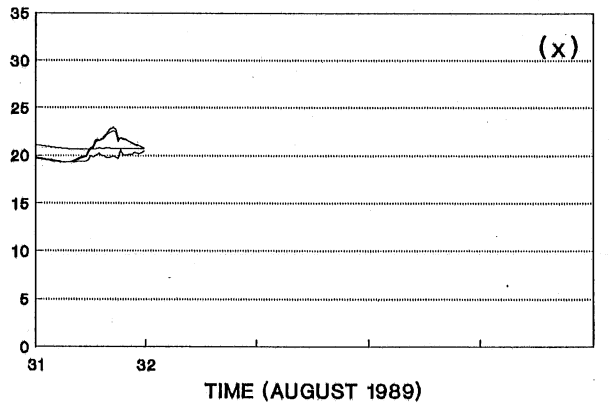
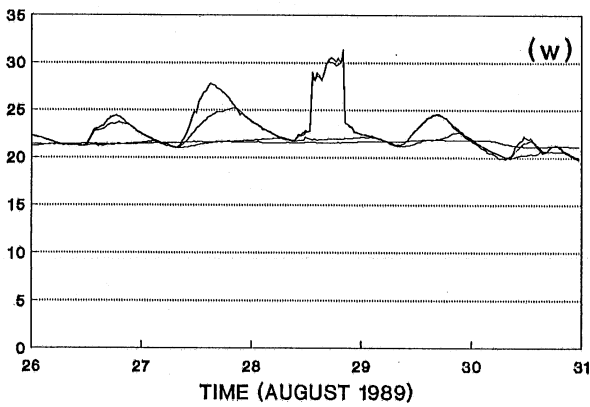
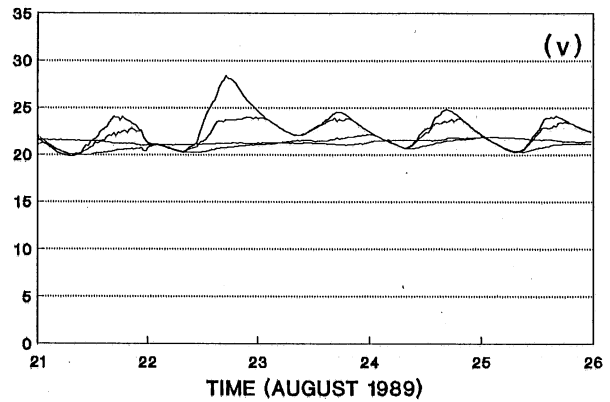
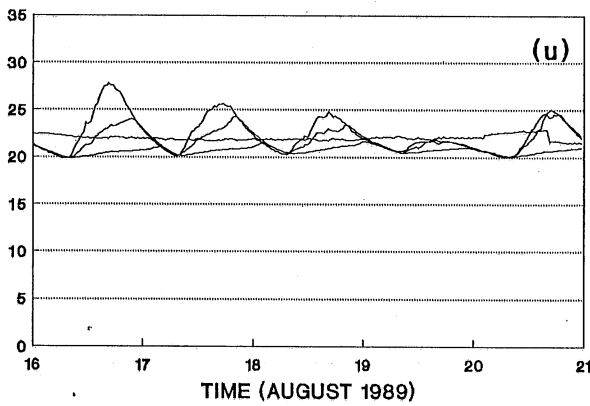
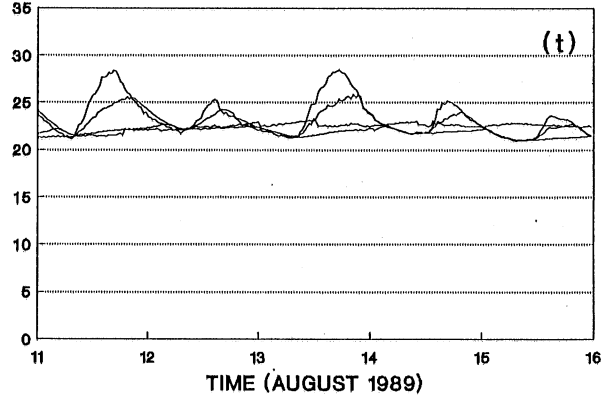
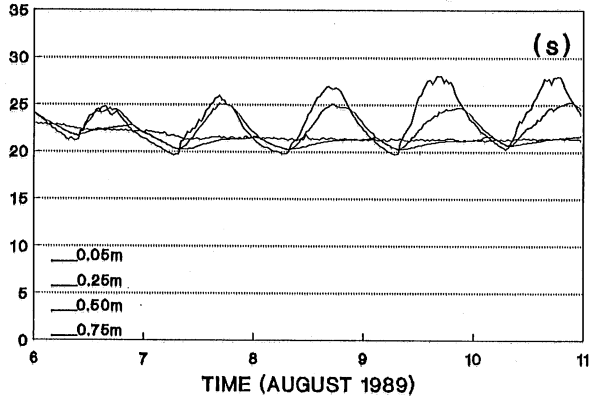
WATER TEMPERATURE (Deg. C)



WATER TEMPERATURE TIME SERIES - STATION #1 (m-r)

INITIAL WATER COLUMN DEPTH 0.75m

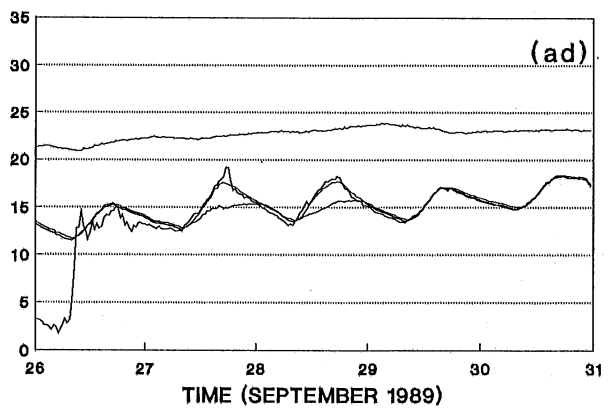
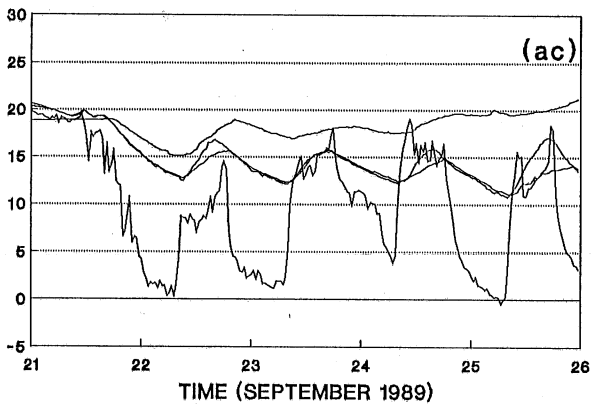
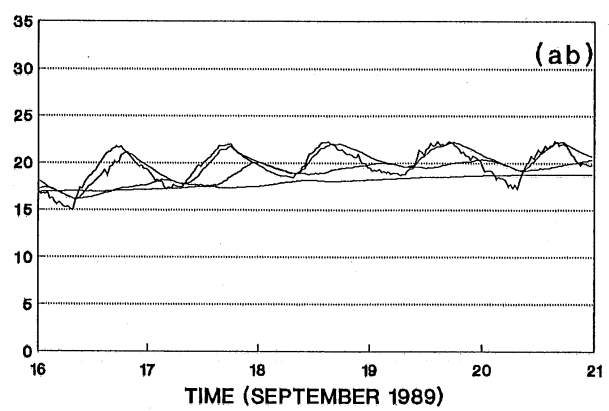
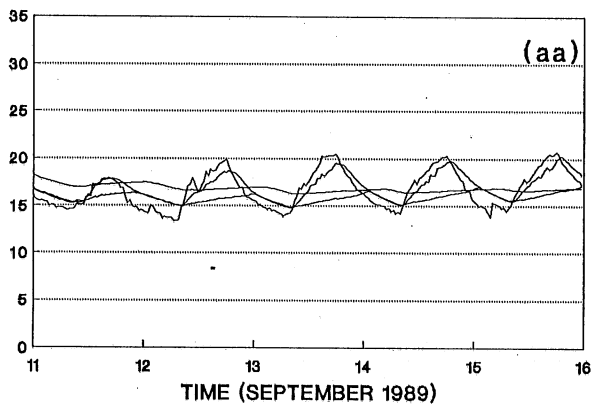
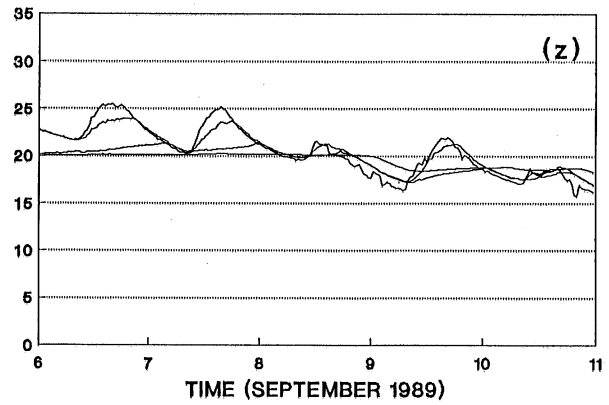
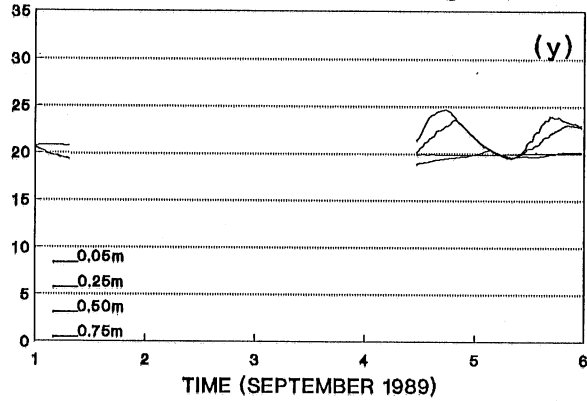
WATER TEMPERATURE (Deg. C)



WATER TEMPERATURE TIME SERIES - STATION #1 (s-x)

INITIAL WATER COLUMN DEPTH 0.75m

WATER TEMPERATURE (Deg. C)

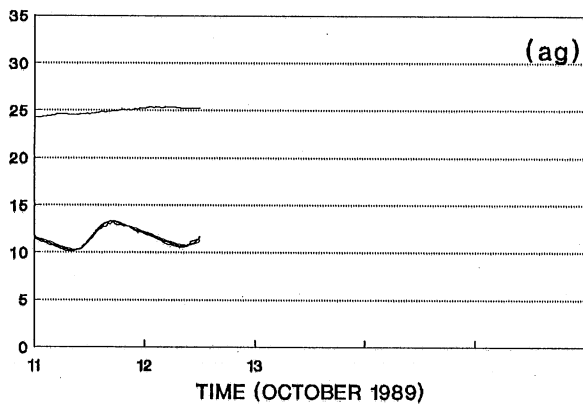
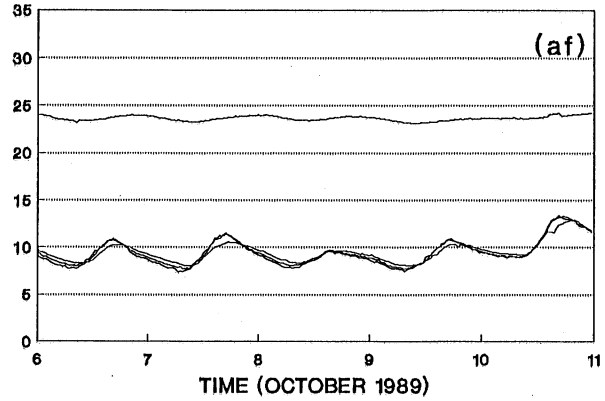
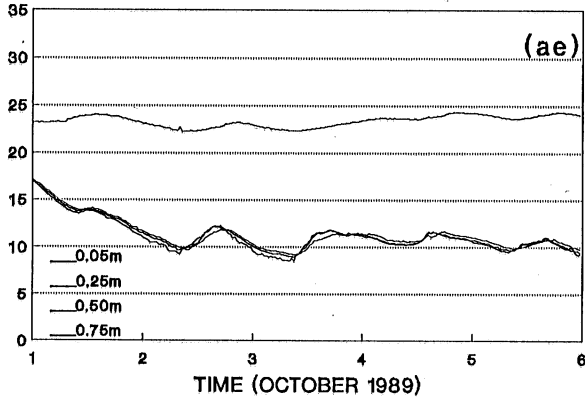


WATER TEMPERATURE TIME SERIES - STATION #1 (y-ad)



INITIAL WATER COLUMN DEPTH 0.75m

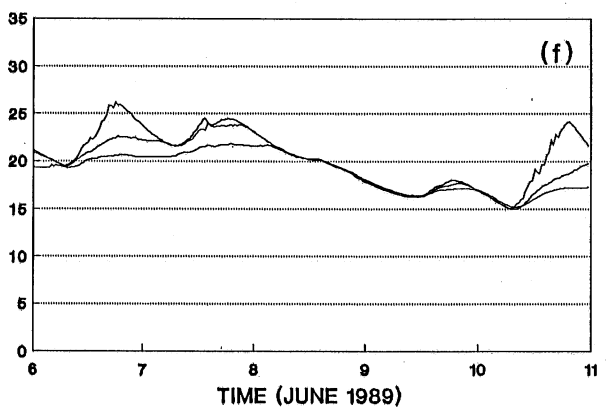
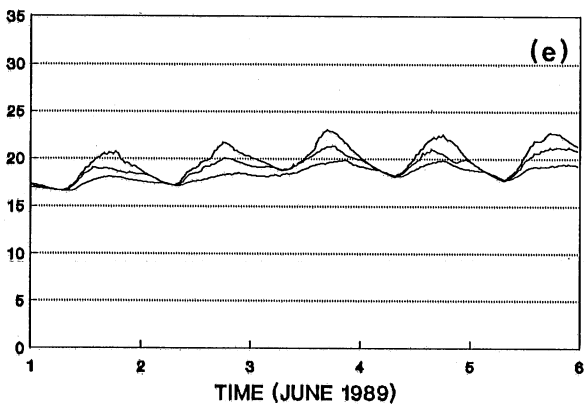
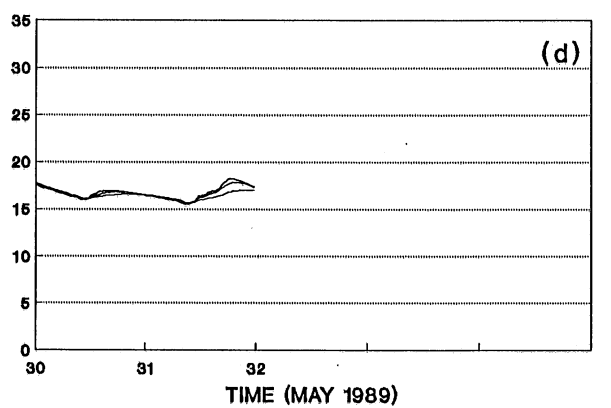
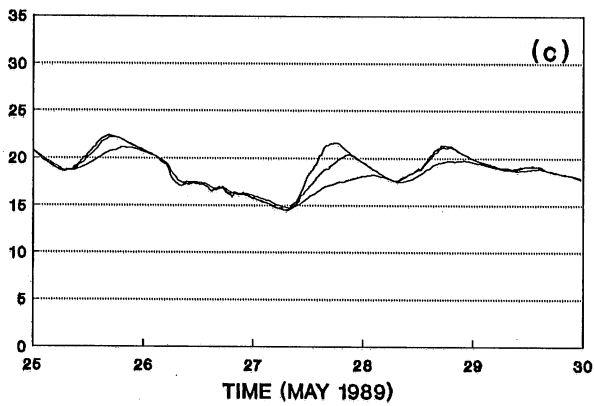
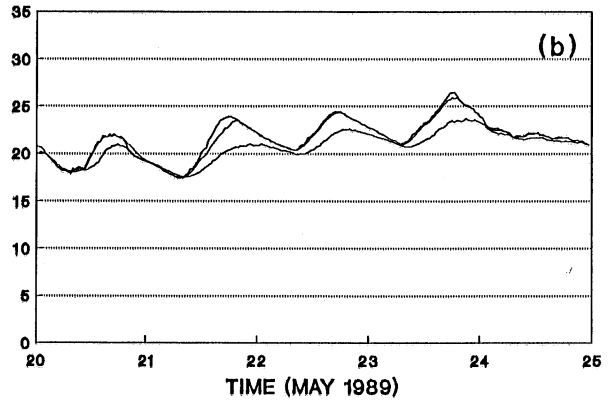
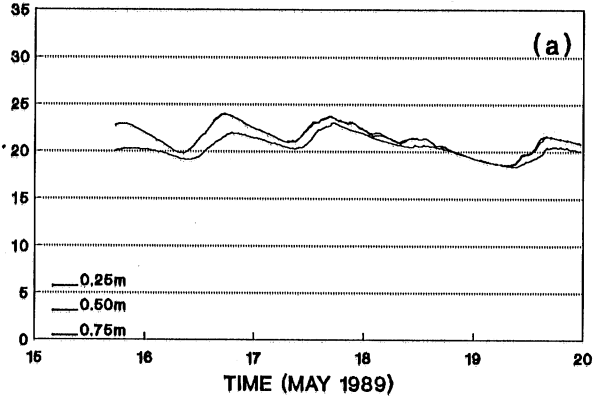
WATER TEMPERATURE (Deg. C)



WATER TEMPERATURE TIME SERIES - STATION #1 (ae-ag)

INITIAL WATER COLUMN DEPTH 0.80m

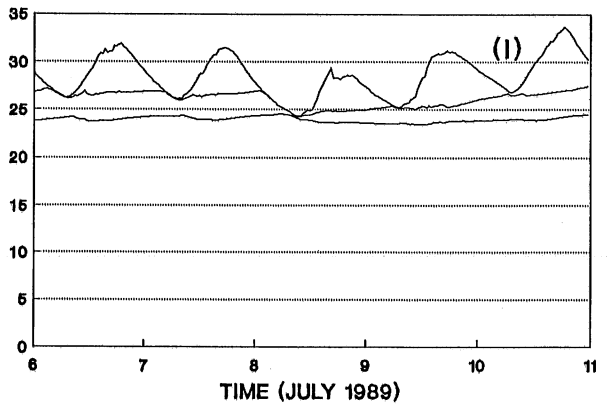
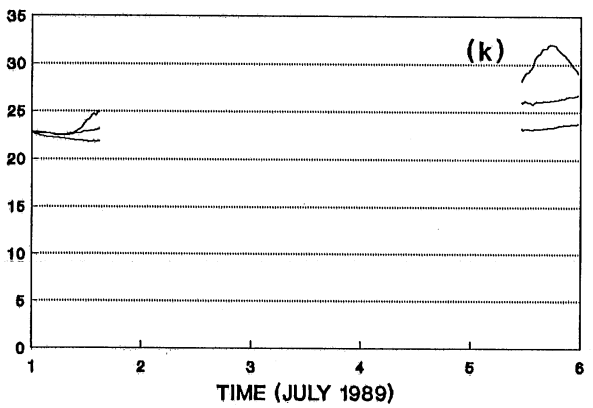
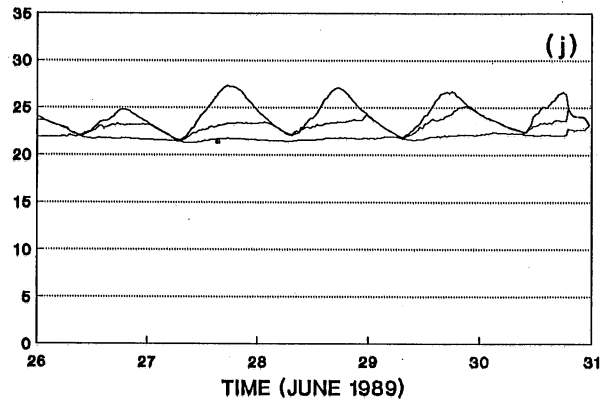
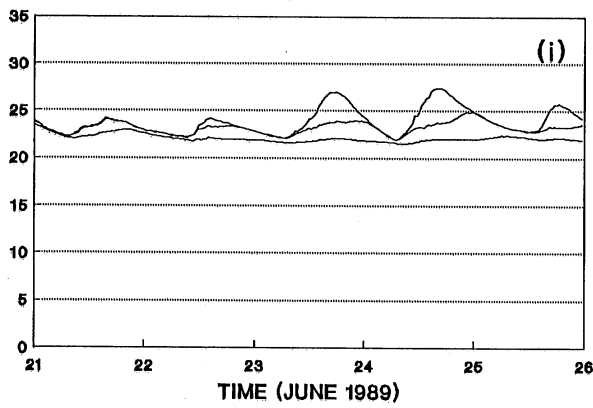
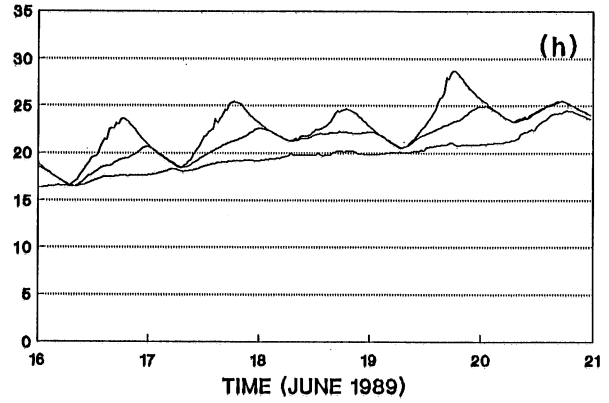
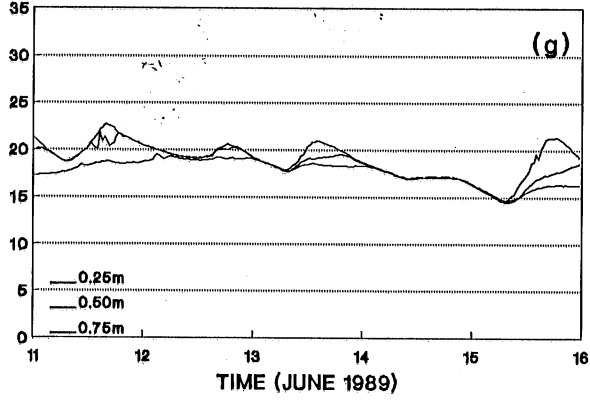
WATER TEMPERATURE (Deg. C)



WATER TEMPERATURE TIME SERIES - STATION #2 (a-f)

INITIAL WATER COLUMN DEPTH 0.80m

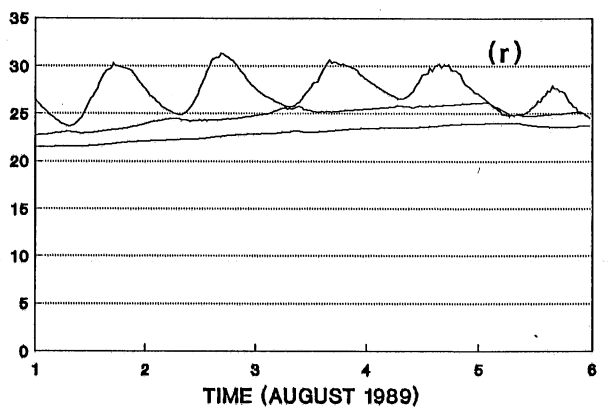
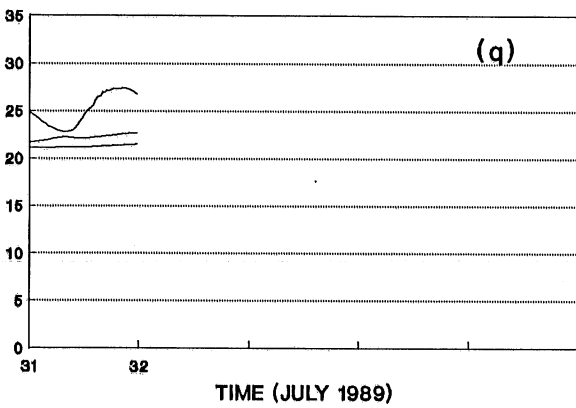
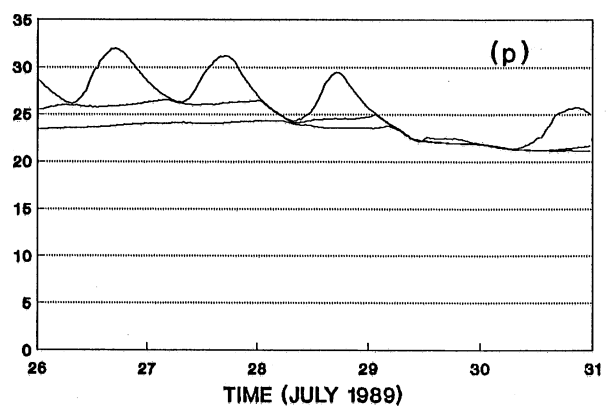
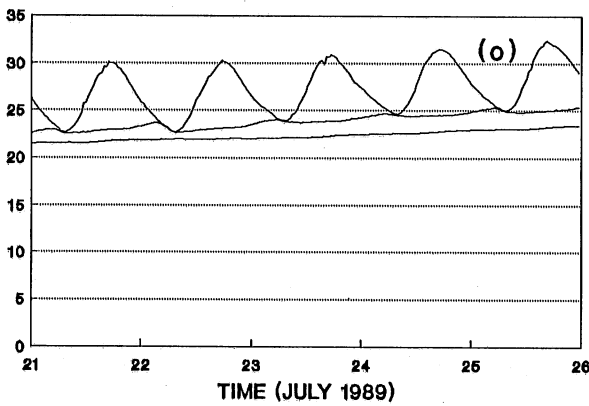
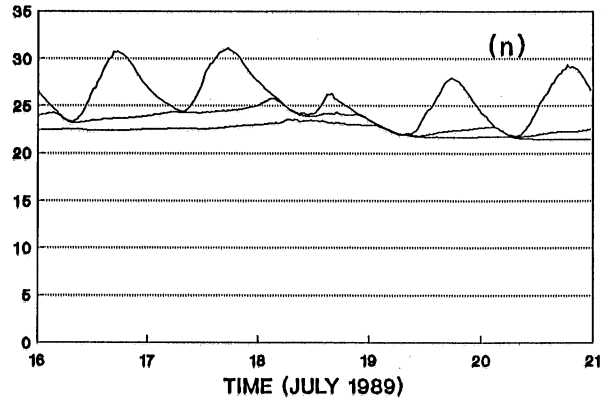
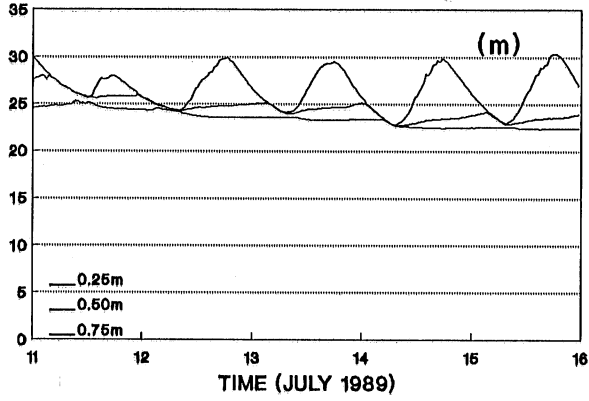
WATER TEMPERATURE (Deg. C)



WATER TEMPERATURE TIME SERIES - STATION #2 (g-l)

INITIAL WATER COLUMN DEPTH 0.80m

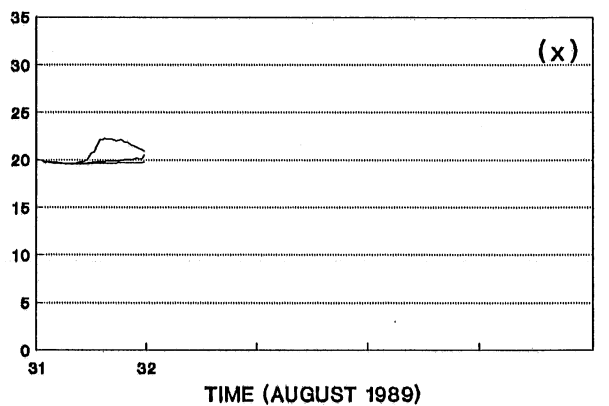
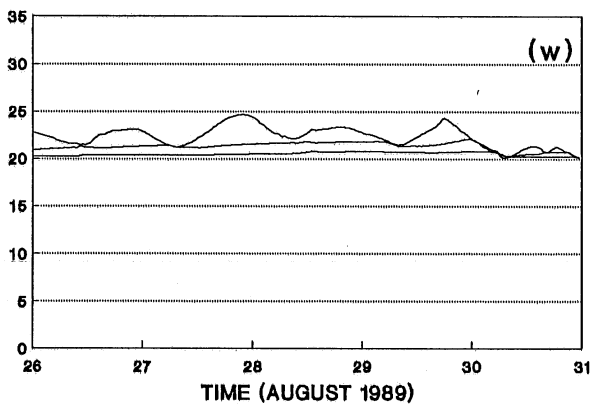
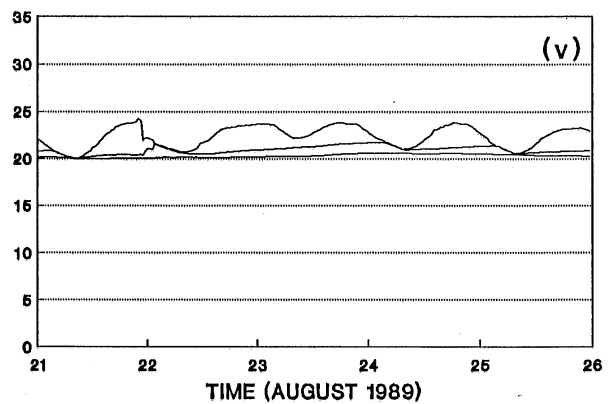
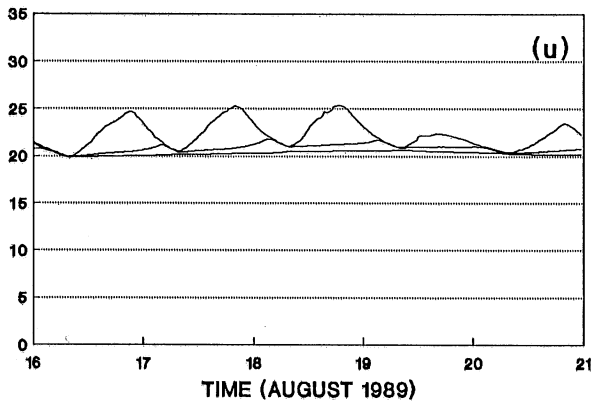
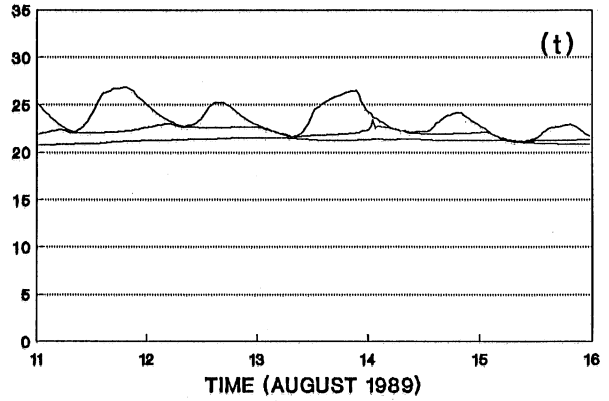
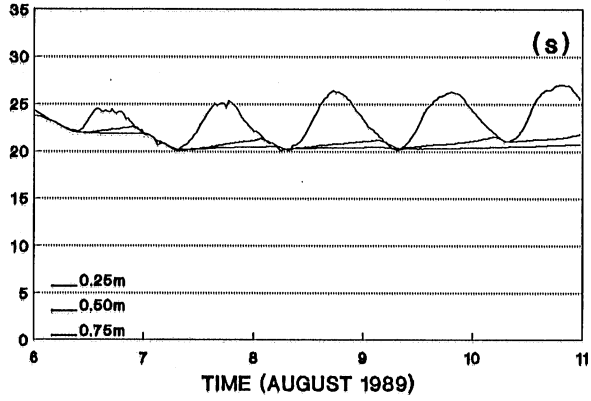
WATER TEMPERATURE (Deg. C)



WATER TEMPERATURE TIME SERIES - STATION #2 (m-r)

INITIAL WATER COLUMN DEPTH 0.80m

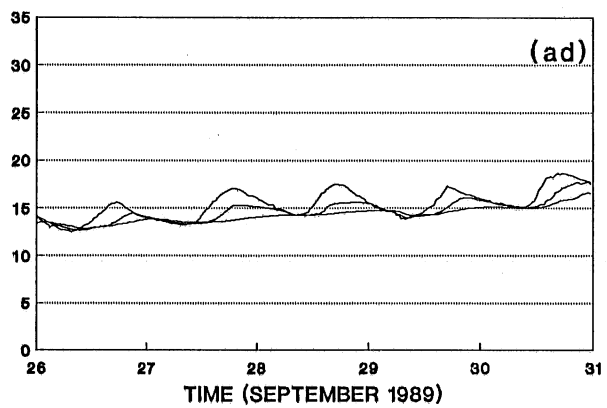
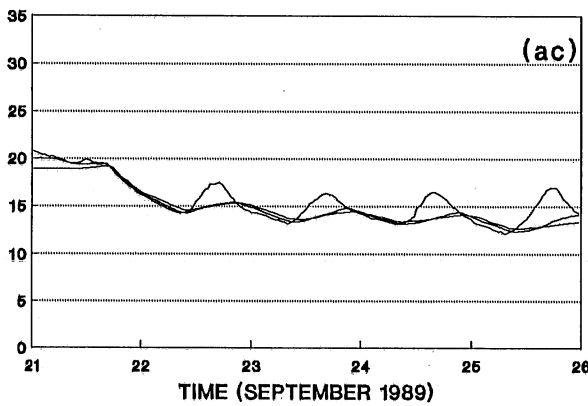
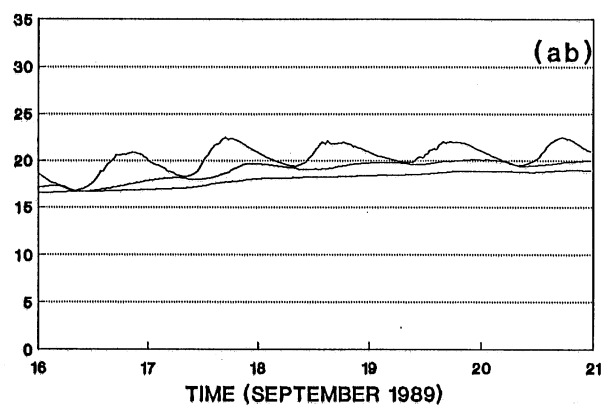
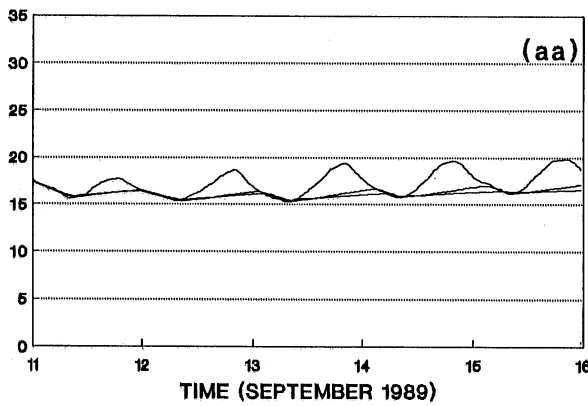
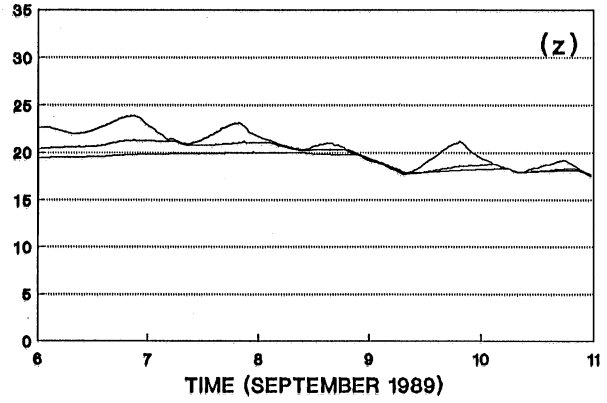
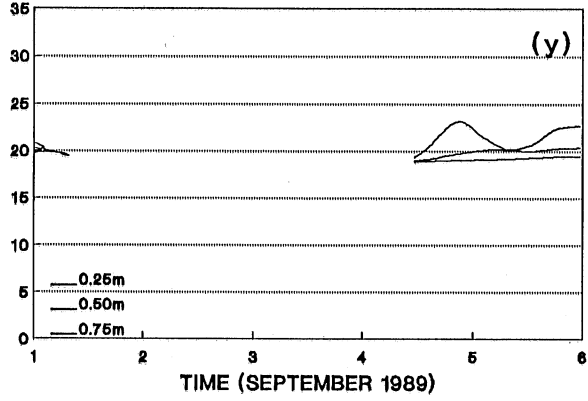
WATER TEMPERATURE (Deg. C)



WATER TEMPERATURE TIME SERIES - STATION #2 (s-x)

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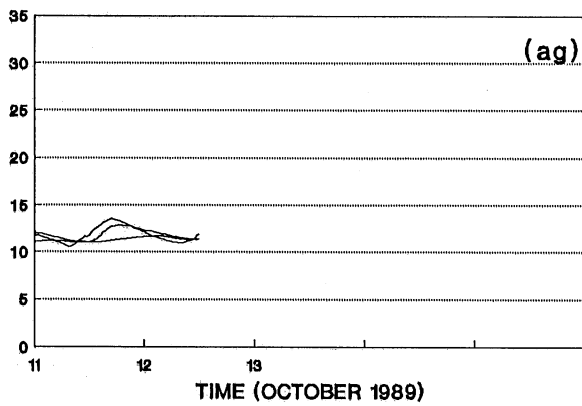
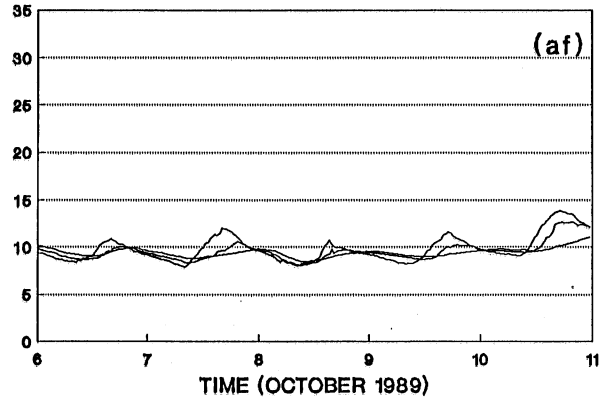
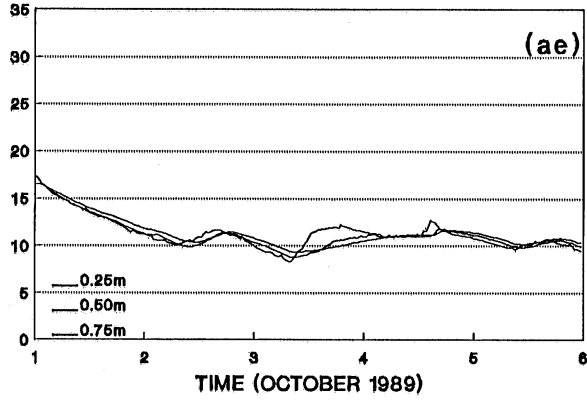
WATER TEMPERATURE (Deg. C)



WATER TEMPERATURE TIME SERIES - STATION #2 (y-ad)

INITIAL WATER COLUMN DEPTH 0.80m

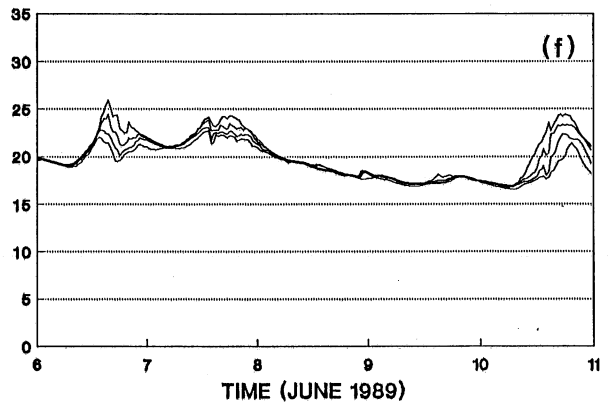
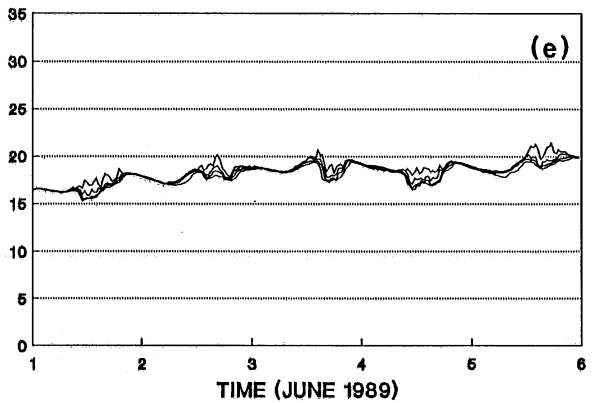
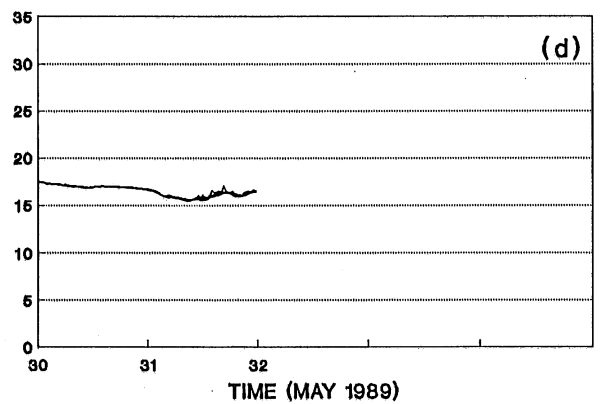
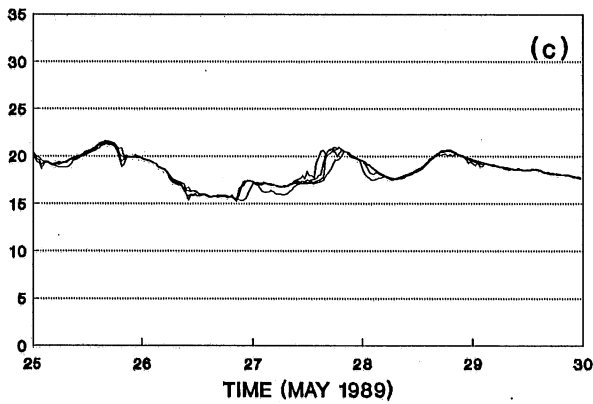
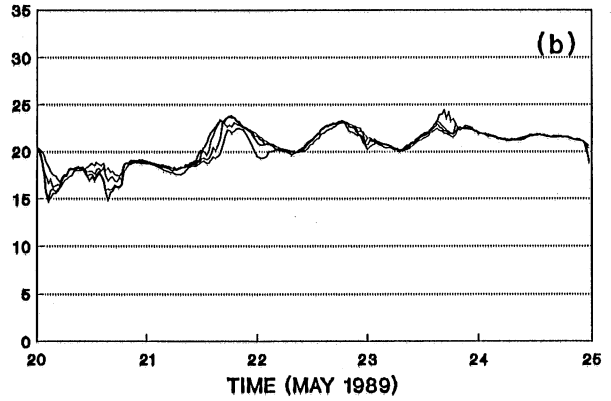
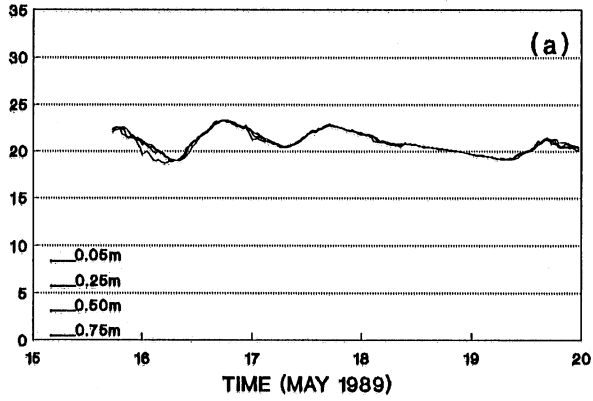
WATER TEMPERATURE (Deg. C)



WATER TEMPERATURE TIME SERIES - STATION #2 (ae-ag)

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WATER TEMPERATURE (Deg. C)

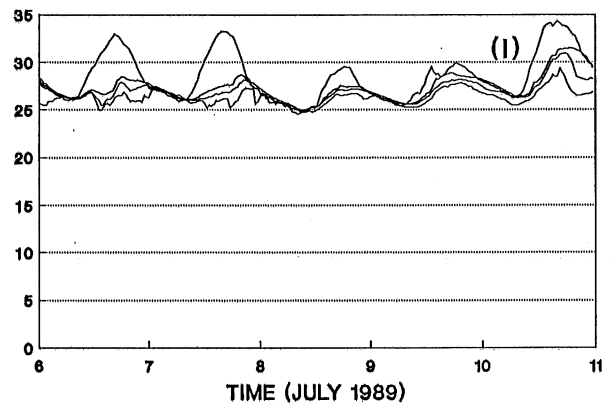
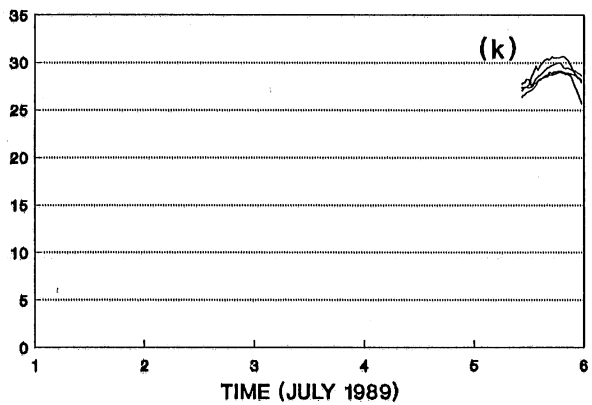
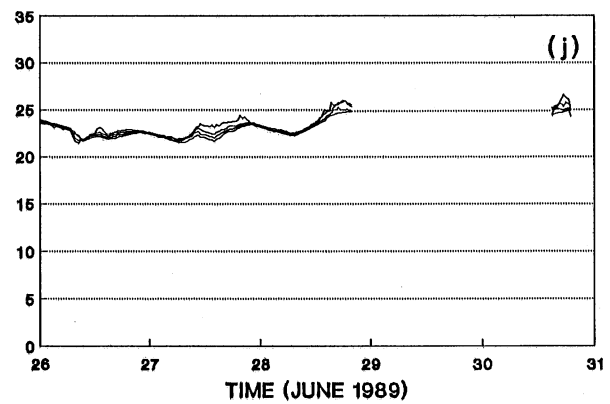
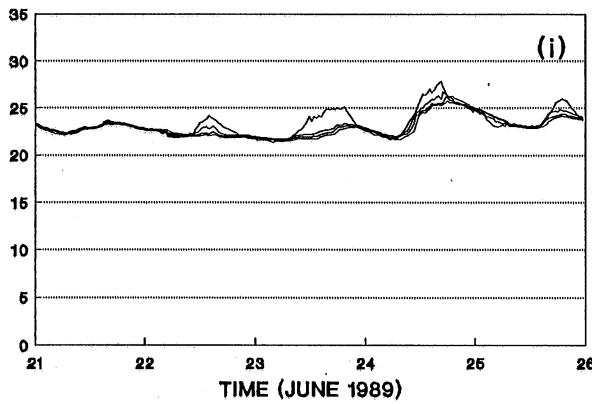
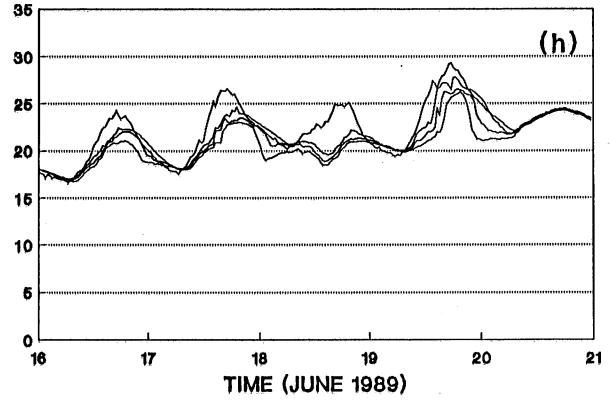
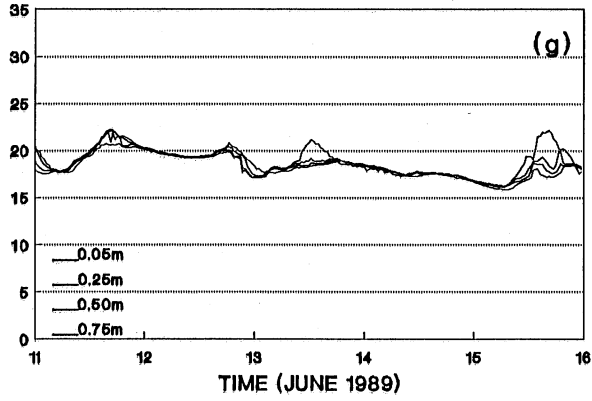


WATER TEMPERATURE TIME SERIES - STATION #3 (a-f)



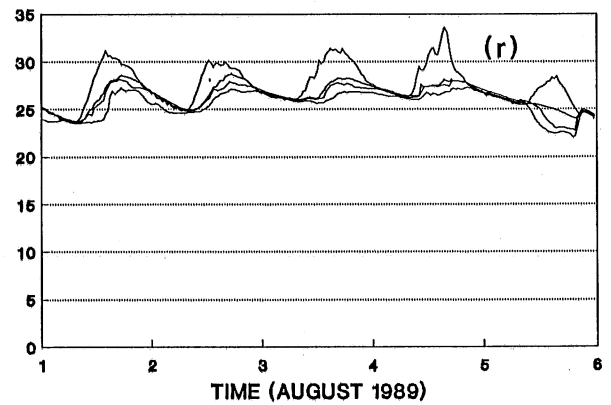
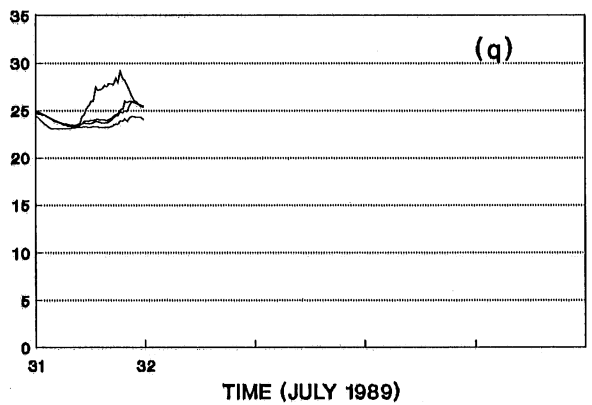
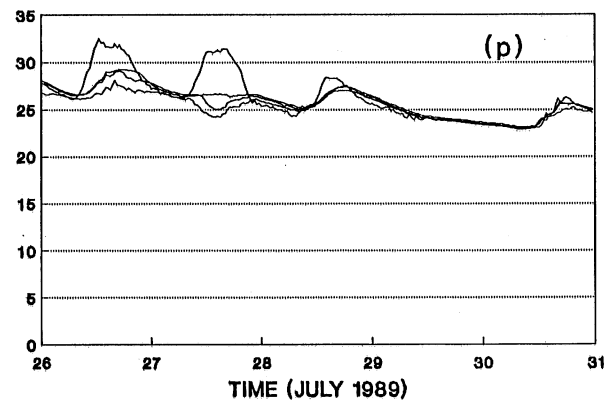
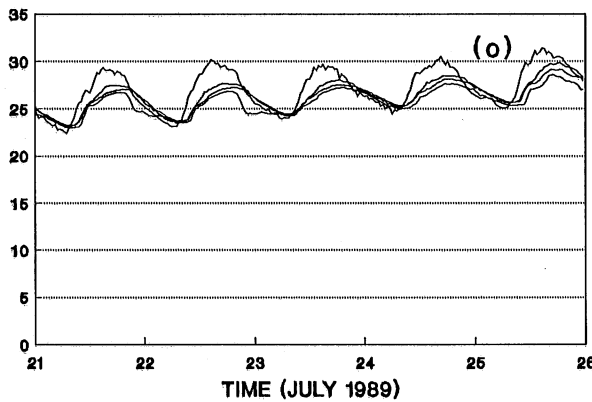
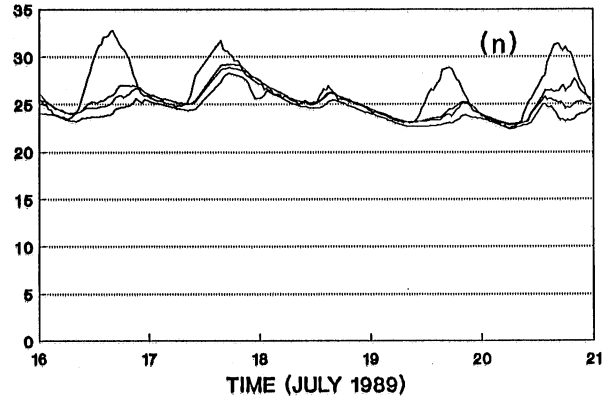
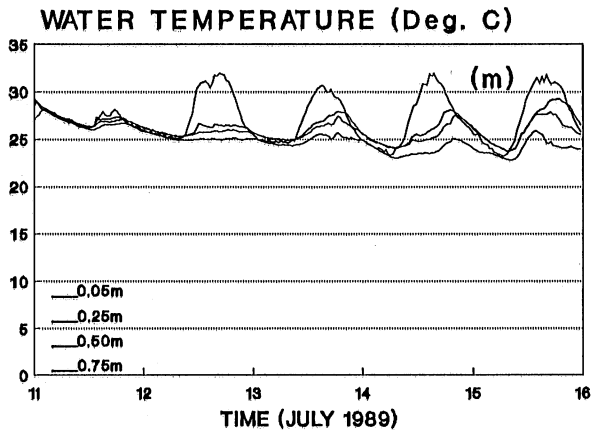
INITIAL WATER COLUMN DEPTH 1.05m

WATER TEMPERATURE (Deg. C)



WATER TEMPERATURE TIME SERIES - STATION #3 (g-l)

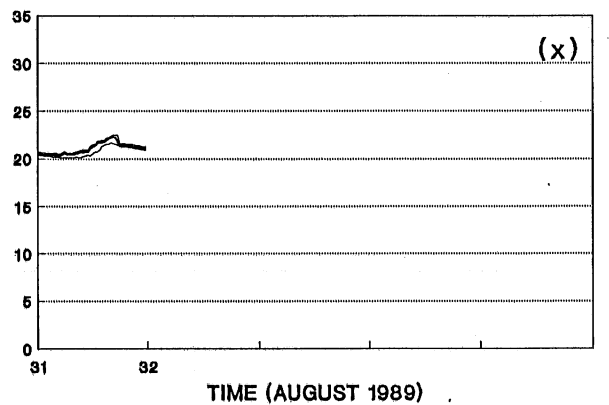
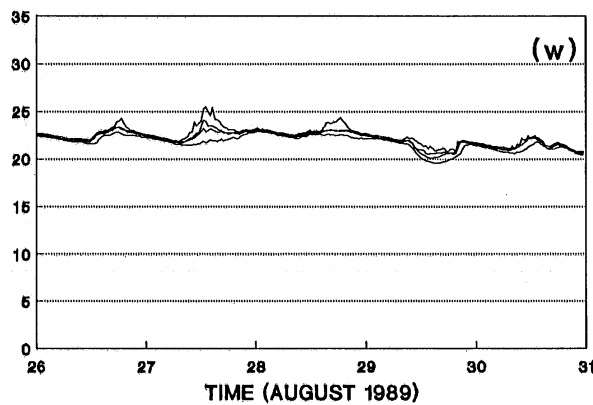
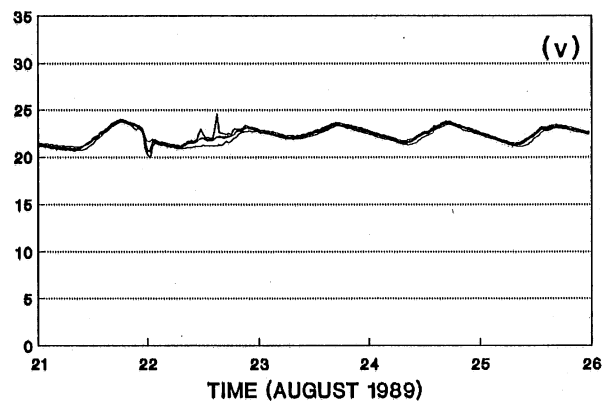
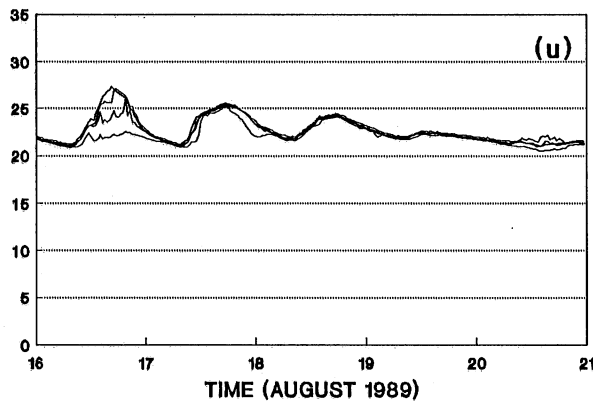
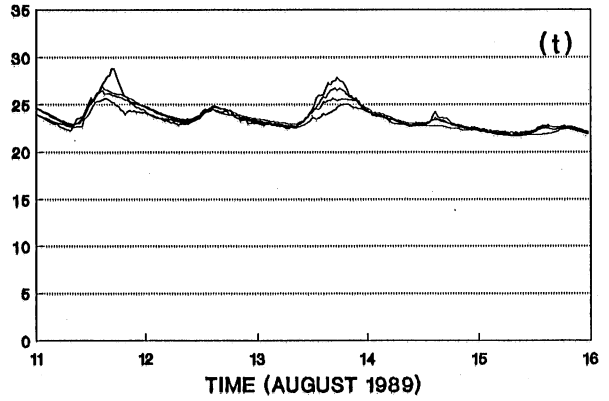
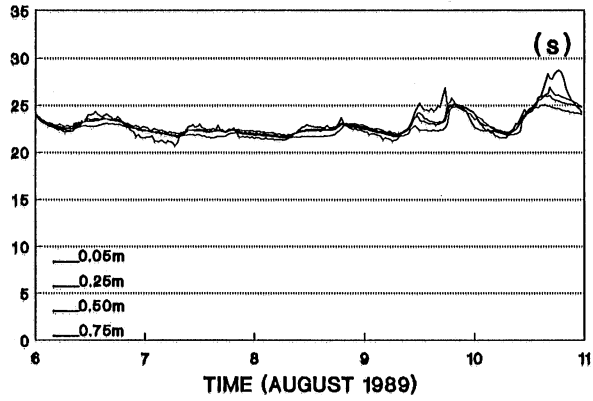
INITIAL WATER COLUMN DEPTH 1.05m



WATER TEMPERATURE TIME SERIES - STATION #3 (m-r)

INITIAL WATER COLUMN DEPTH 1.05m

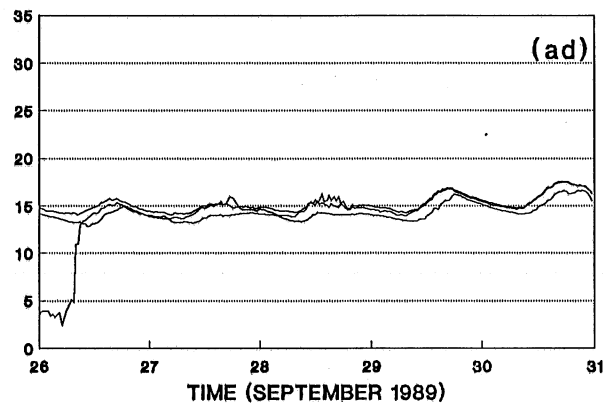
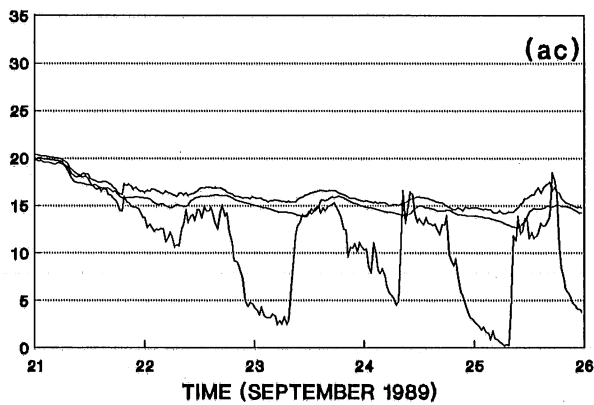
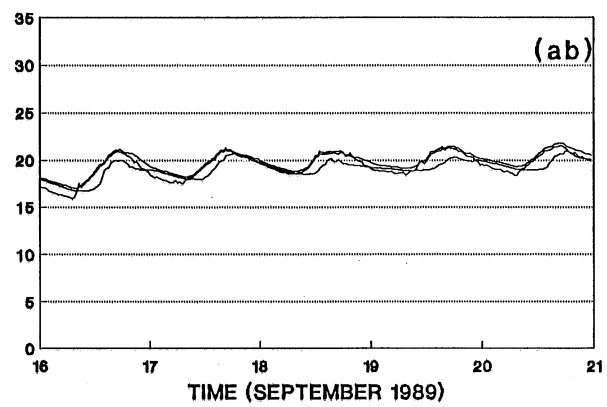
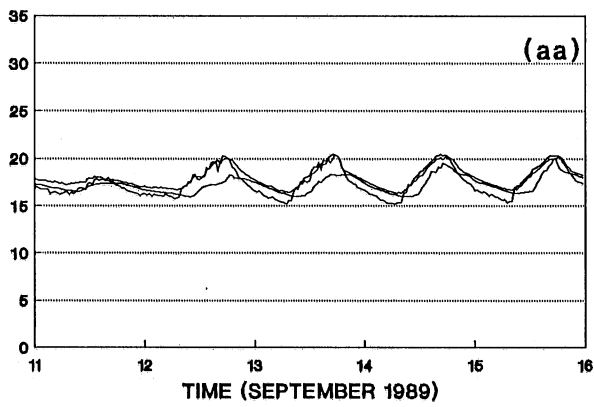
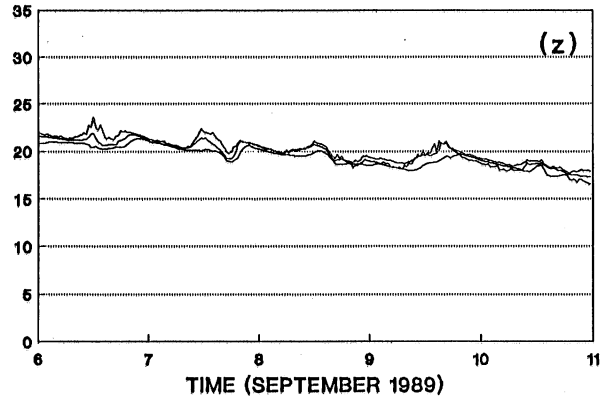
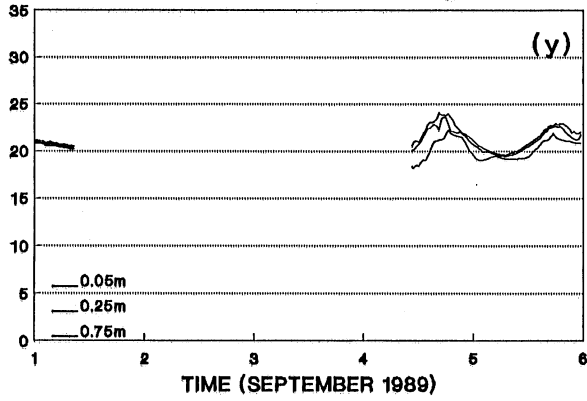
WATER TEMPERATURE (Deg. C)



WATER TEMPERATURE TIME SERIES - STATION #3 (s-x)

INITIAL WATER COLUMN DEPTH 1.05m

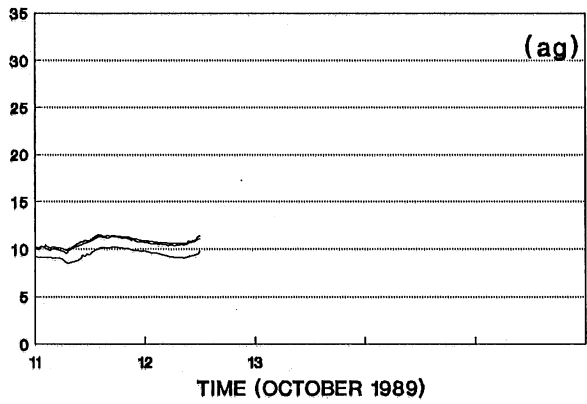
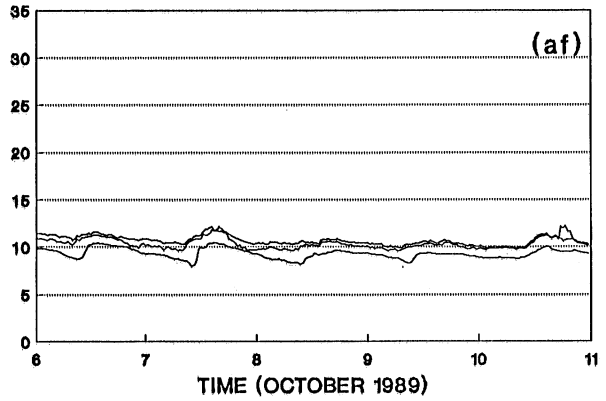
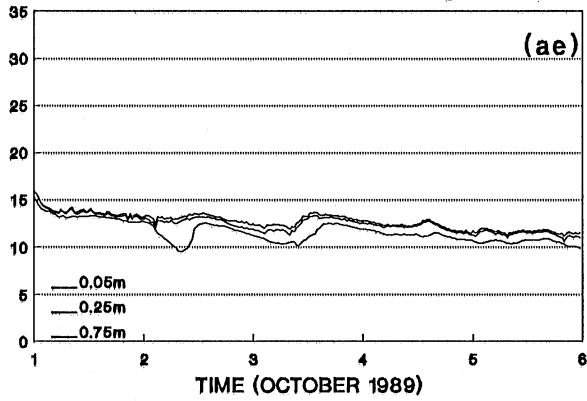
WATER TEMPERATURE (Deg. C)



WATER TEMPERATURE TIME SERIES - STATION #3 (y-ad)

INITIAL WATER COLUMN DEPTH 1.05m

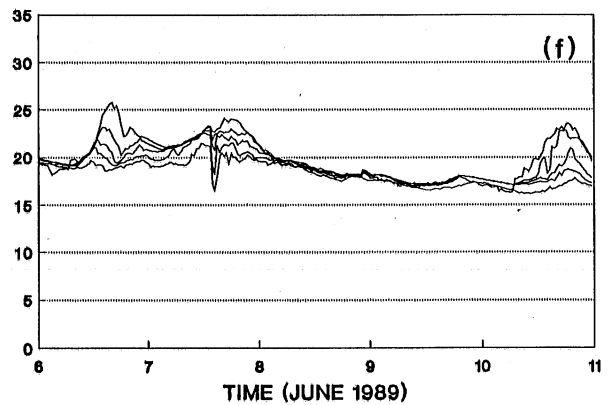
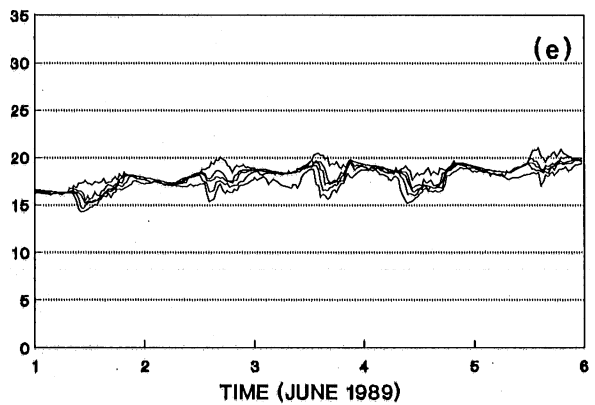
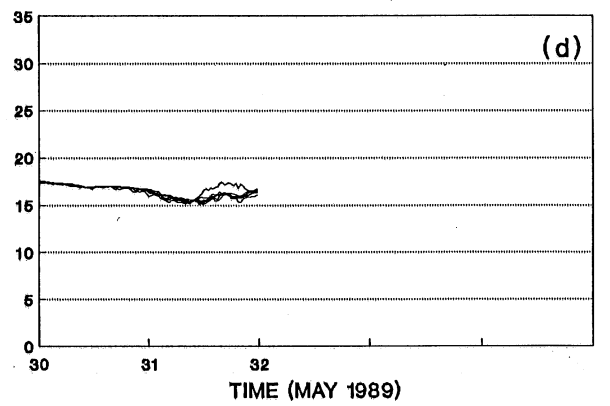
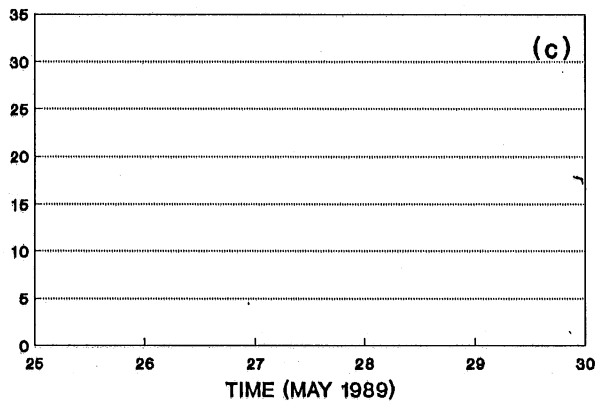
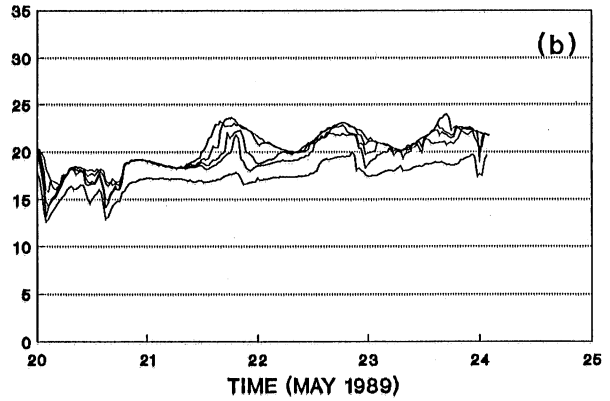
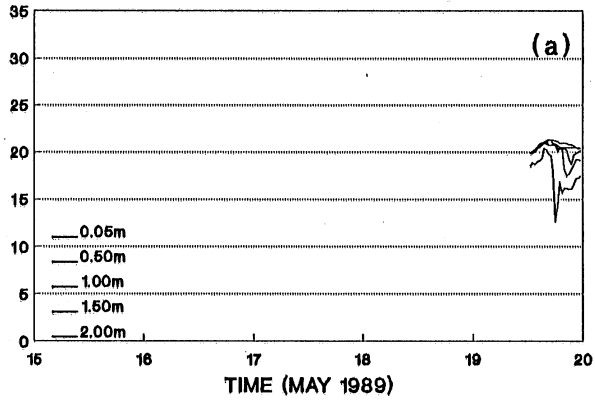
WATER TEMPERATURE (Deg. C)



WATER TEMPERATURE TIME SERIES - STATION #3 (ae-ag)

INITIAL WATER COLUMN DEPTH 2.05m

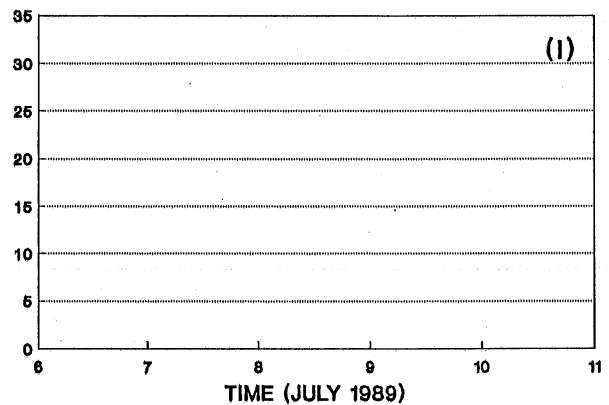
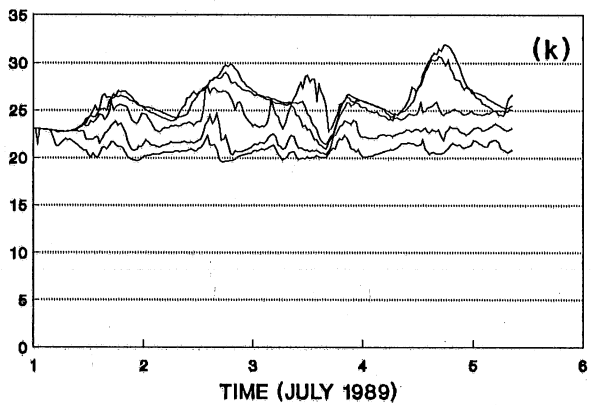
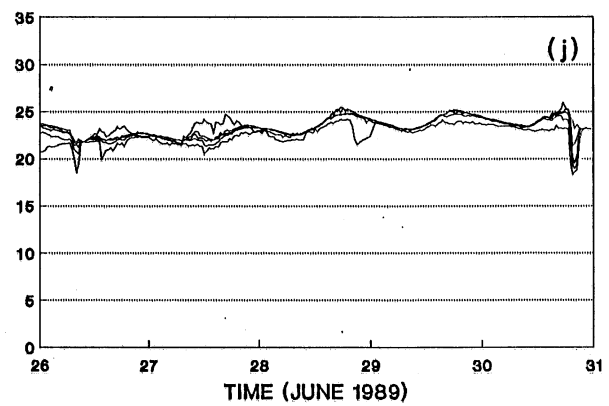
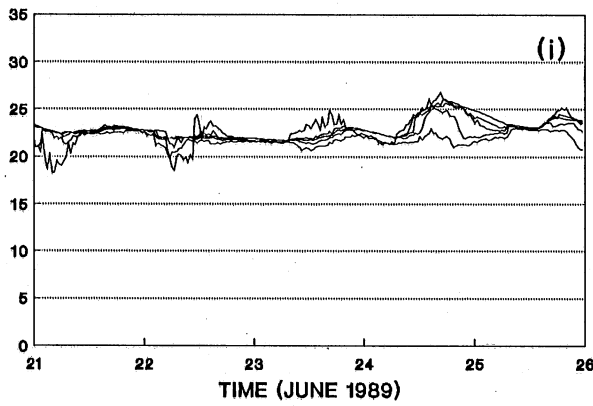
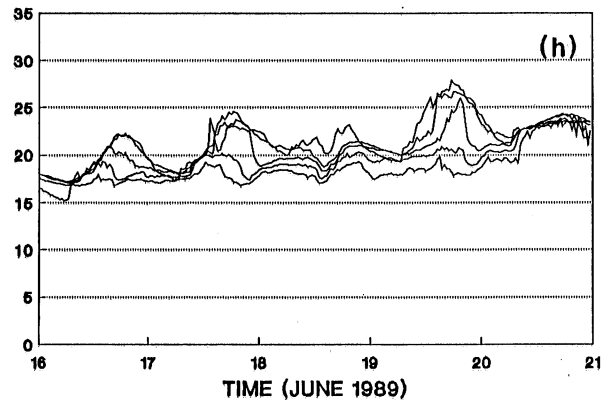
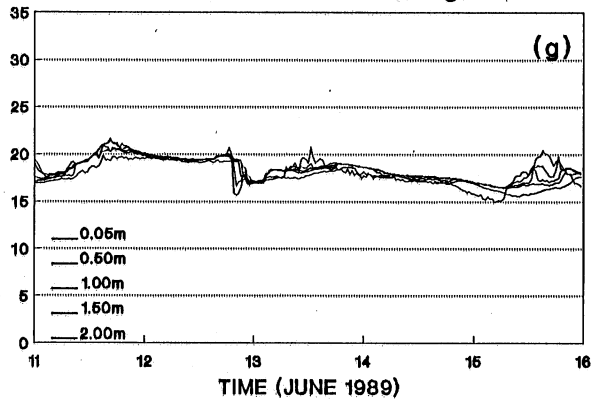
WATER TEMPERATURE (Deg. C)



WATER TEMPERATURE TIME SERIES - STATION #4 (a-f)

INITIAL WATER COLUMN DEPTH 2.05m

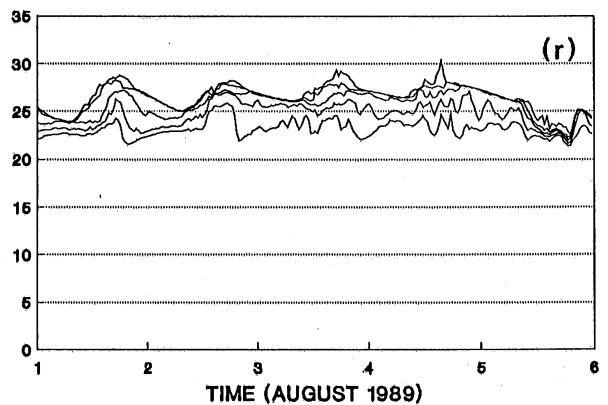
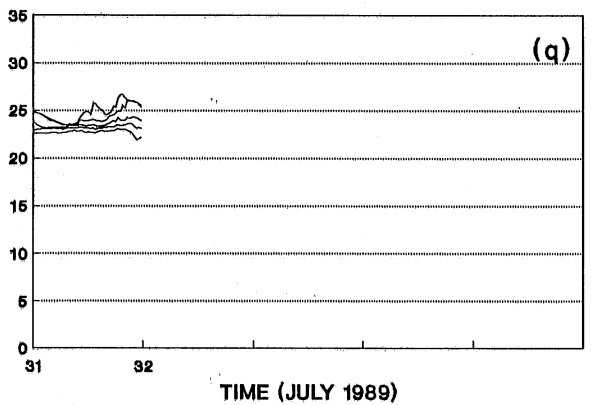
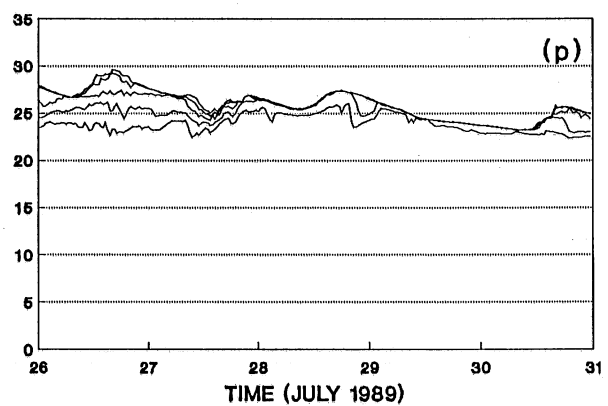
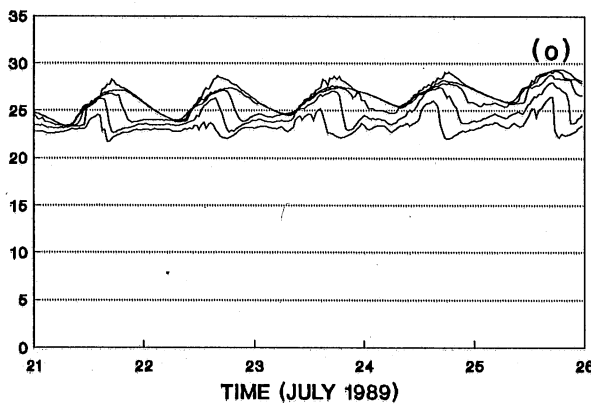
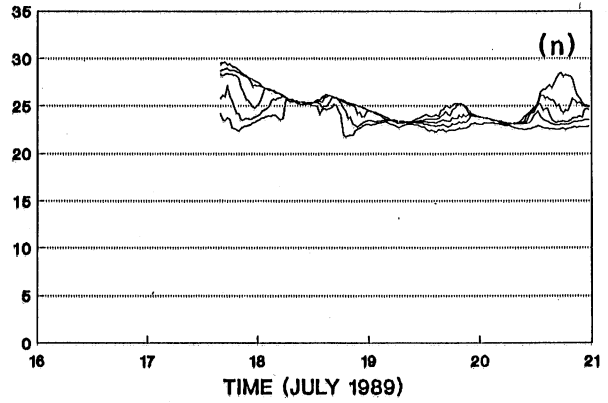
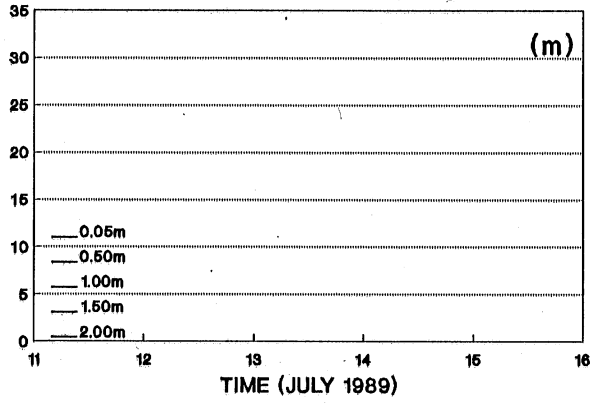
WATER TEMPERATURE (Deg. C)



WATER TEMPERATURE TIME SERIES - STATION #4 (g-l)

INITIAL WATER COLUMN DEPTH 2.05m

WATER TEMPERATURE (Deg. C)

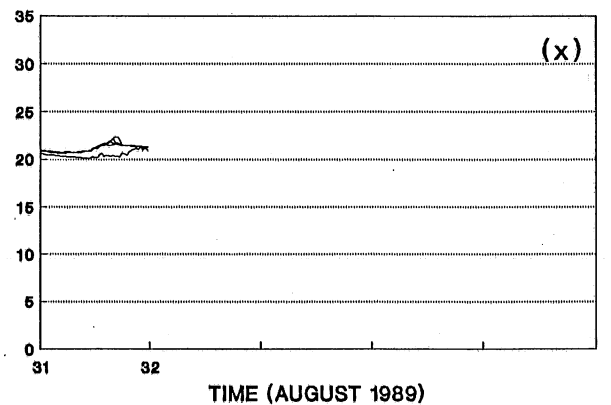
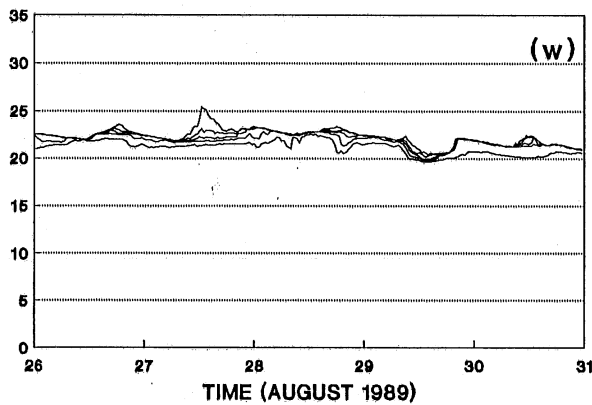
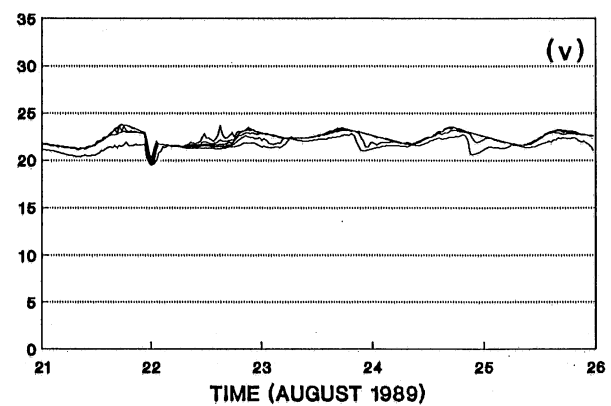
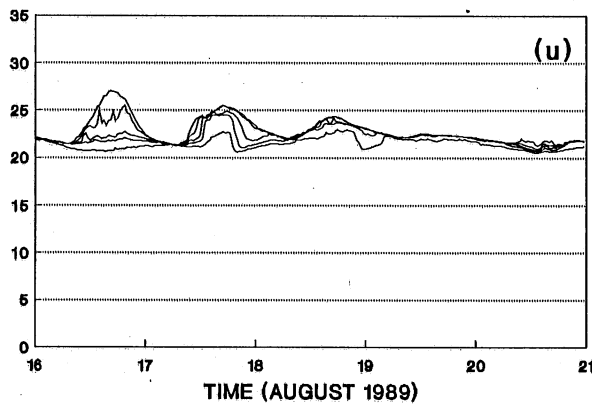
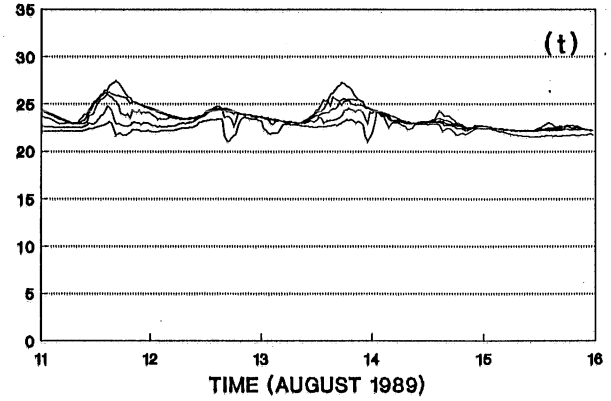
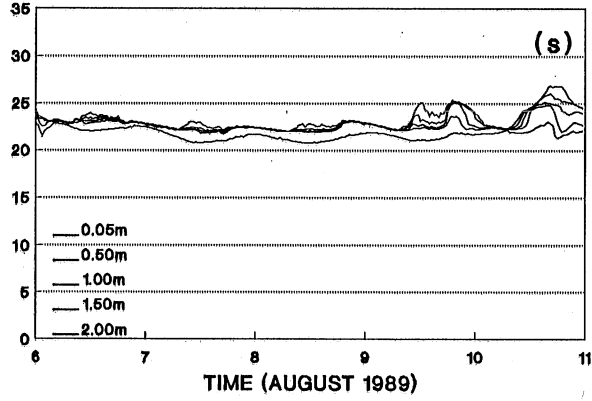


WATER TEMPERATURE TIME SERIES - STATION #4 (m-r)



INITIAL WATER COLUMN DEPTH 2.05m

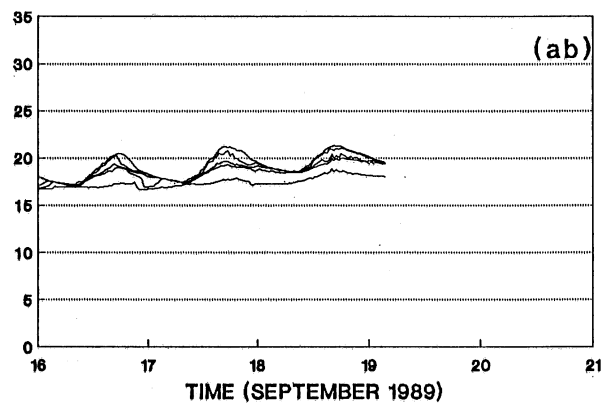
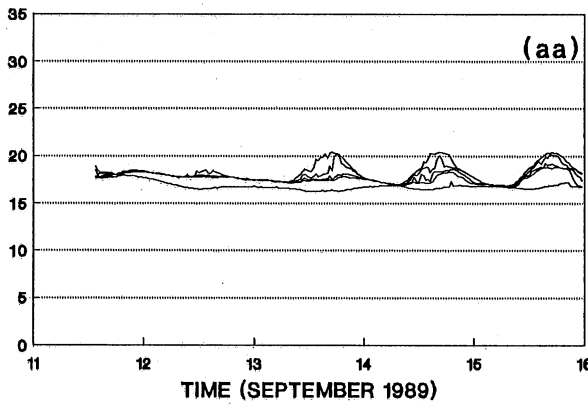
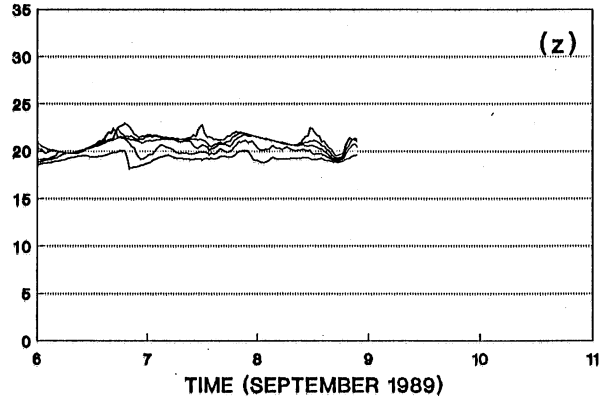
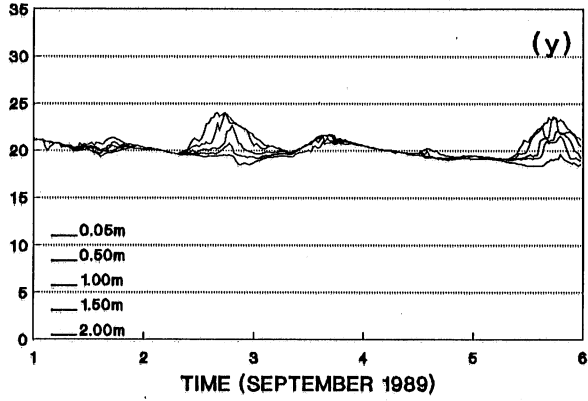
WATER TEMPERATURE (Deg. C)



WATER TEMPERATURE TIME SERIES - STATION #4 (s-x)

INITIAL WATER COLUMN DEPTH 2.05m

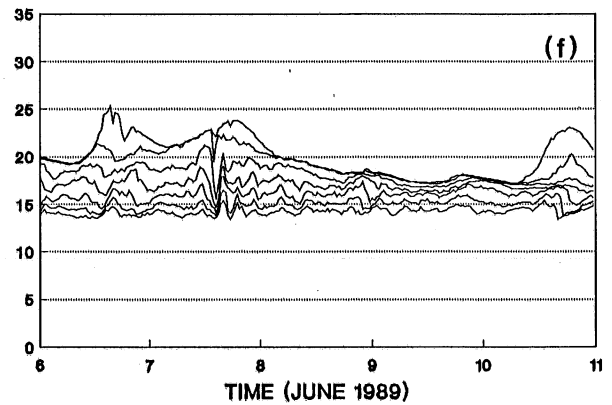
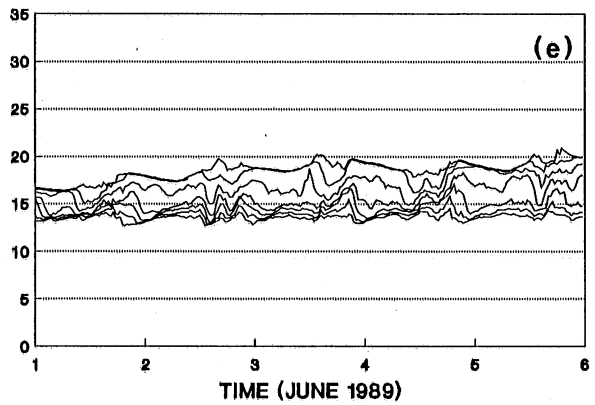
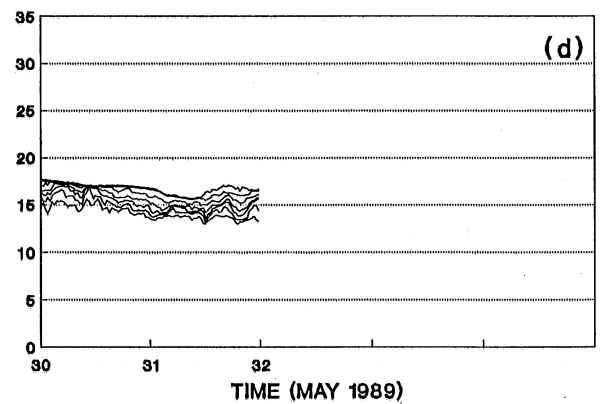
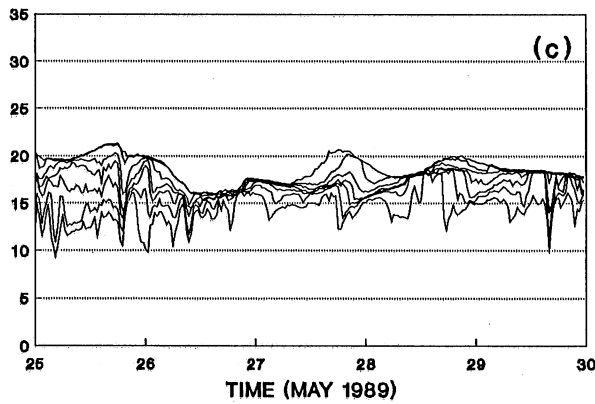
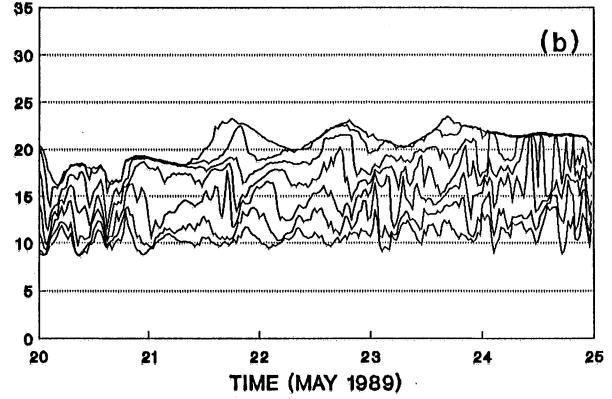
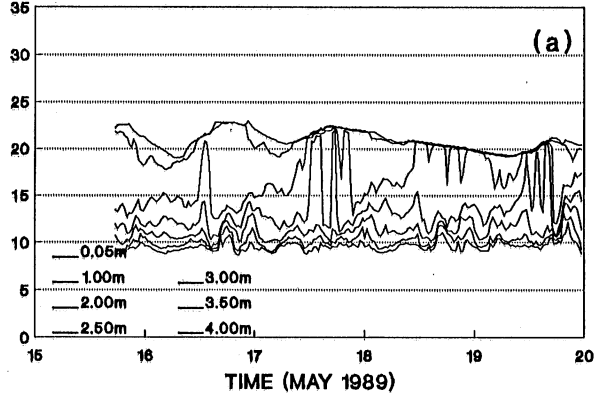
WATER TEMPERATURE (Deg. C)



WATER TEMPERATURE TIME SERIES - STATION #4 (y-ab)

INITIAL WATER COLUMN DEPTH 4.05m

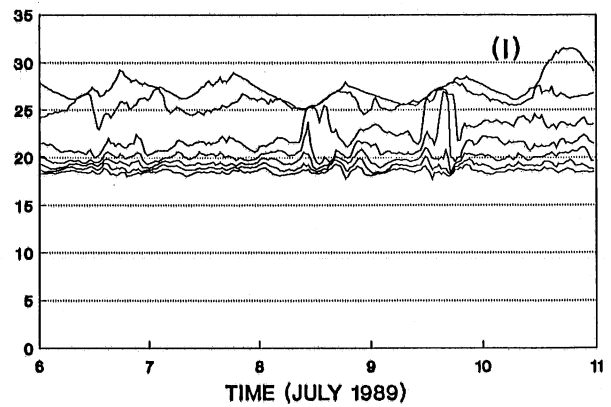
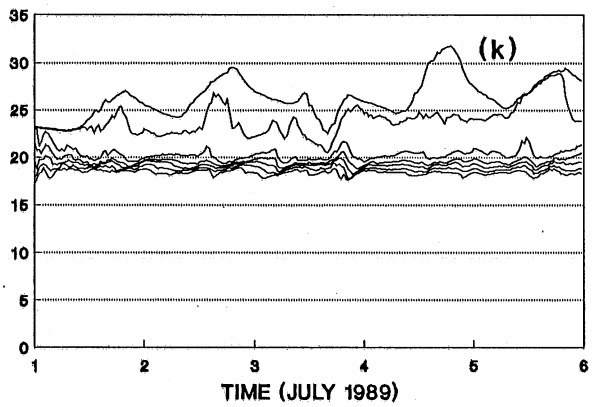
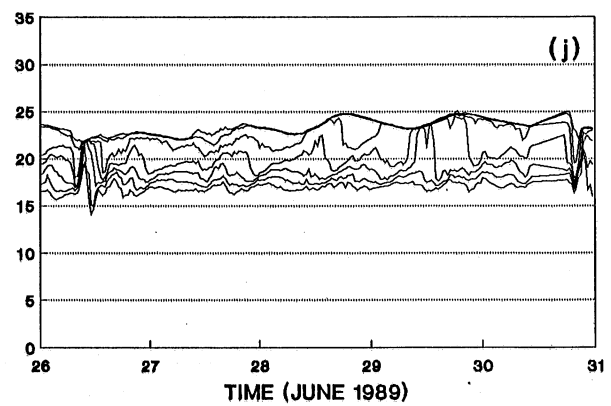
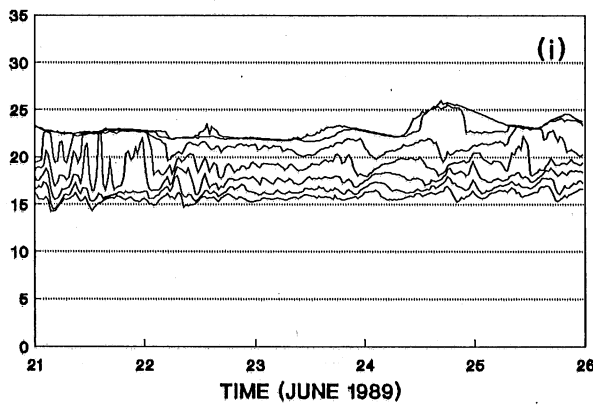
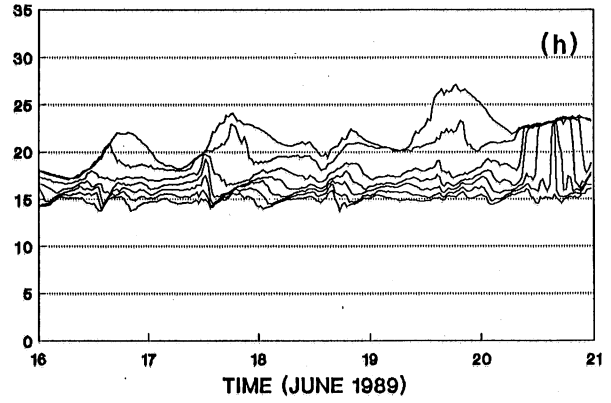
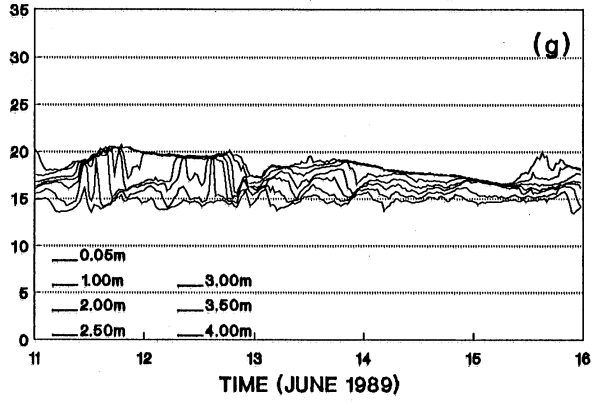
WATER TEMPERATURE (Deg. C)



WATER TEMPERATURE TIME SERIES - STATION #5 (a-f)

INITIAL WATER COLUMN DEPTH 4.05m

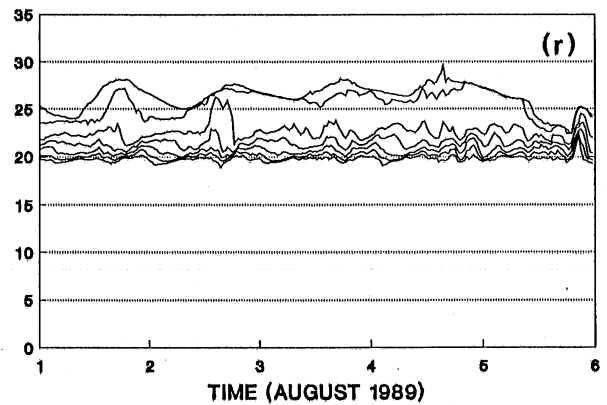
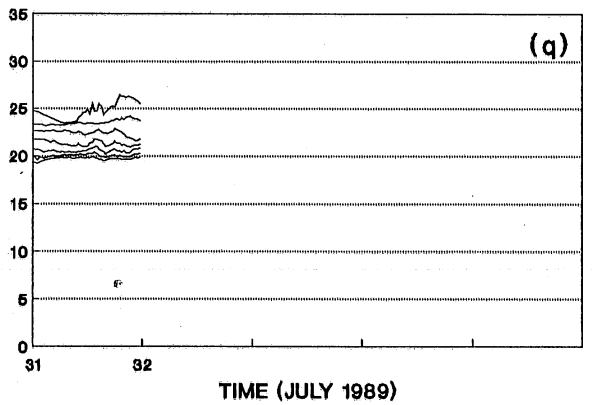
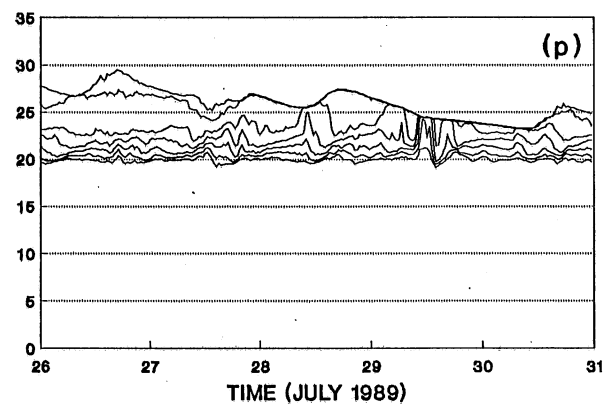
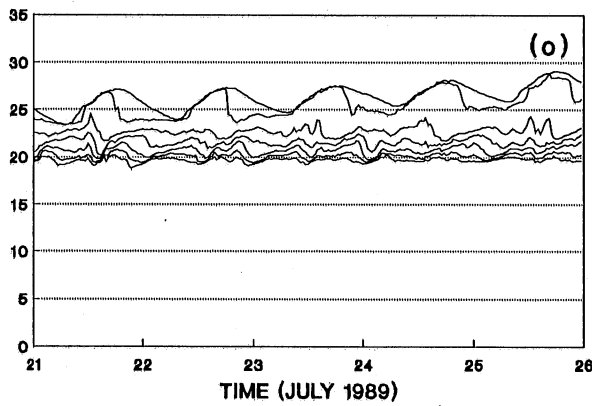
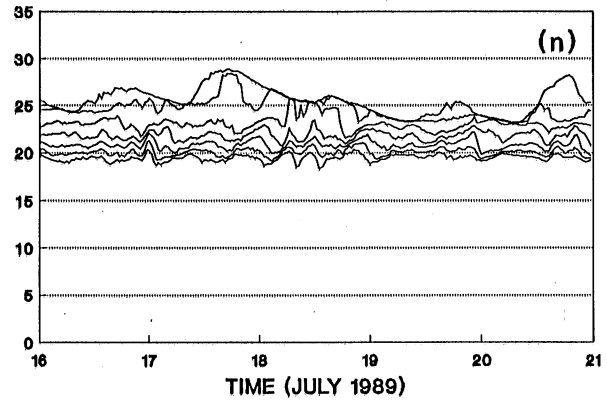
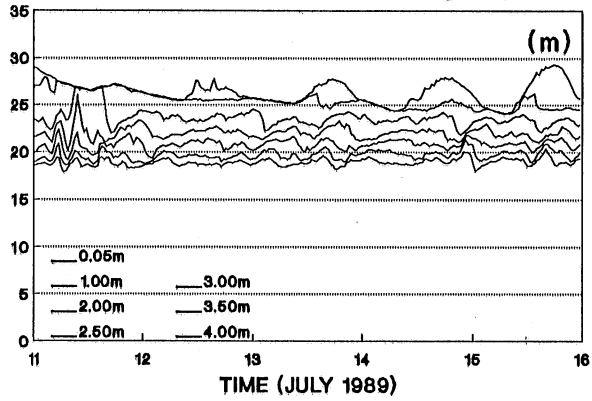
WATER TEMPERATURE (Deg. C)



WATER TEMPERATURE TIME SERIES - STATION #5 (g-l)

INITIAL WATER COLUMN DEPTH 4.05m

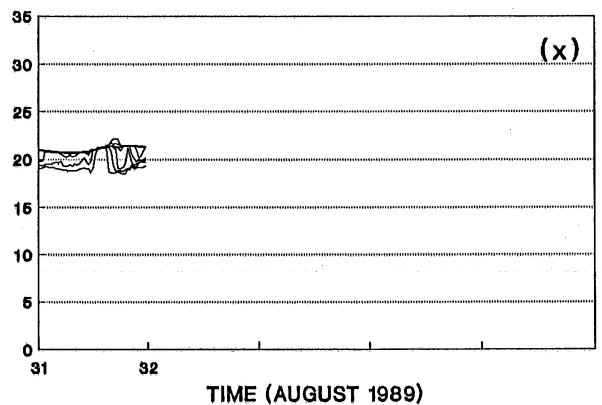
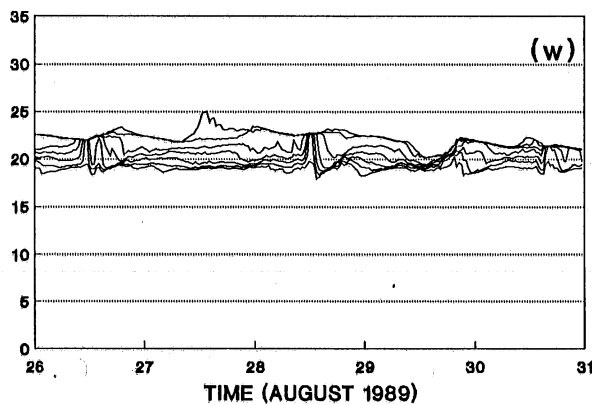
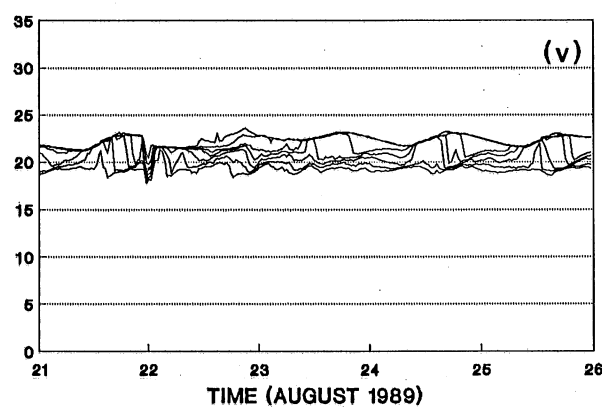
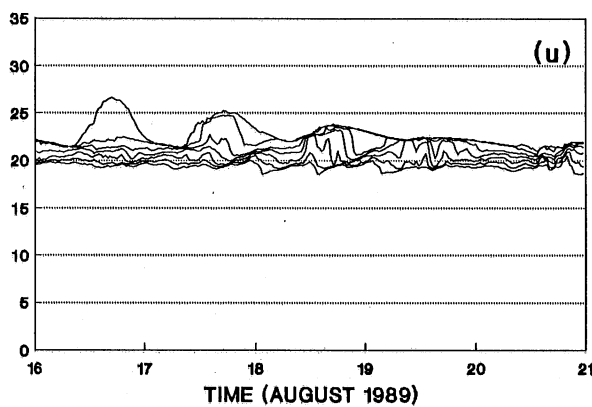
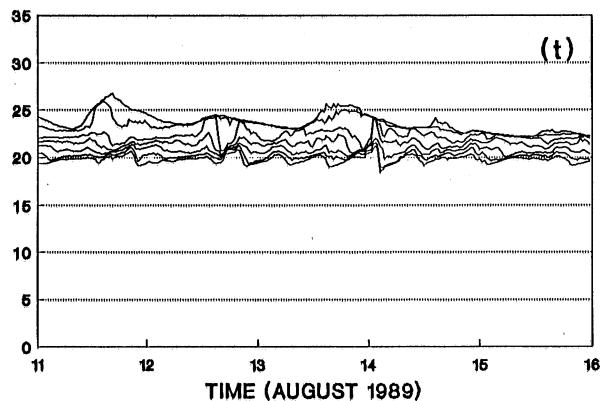
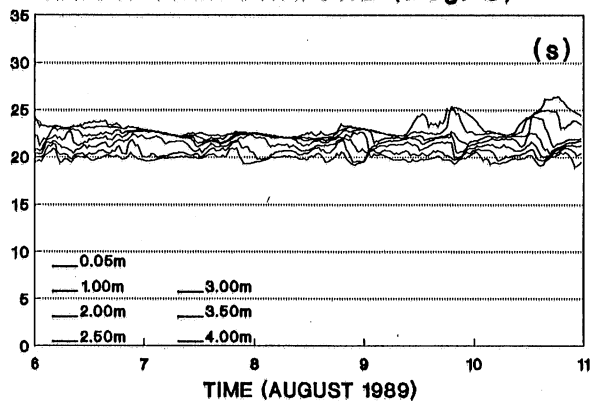
WATER TEMPERATURE (Deg. C)



WATER TEMPERATURE TIME SERIES - STATION #5 (m-r)

INITIAL WATER COLUMN DEPTH 4.05m

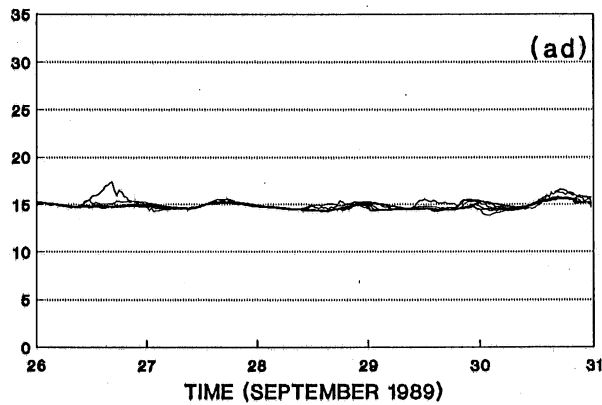
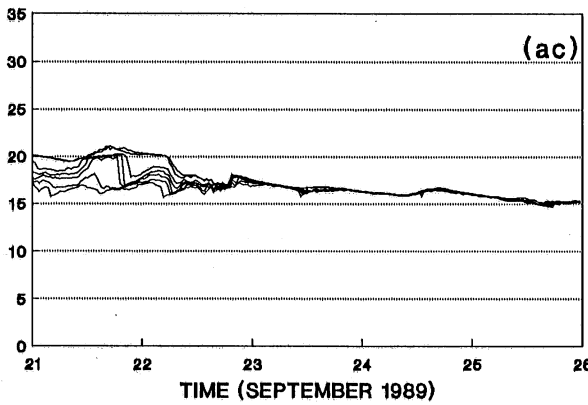
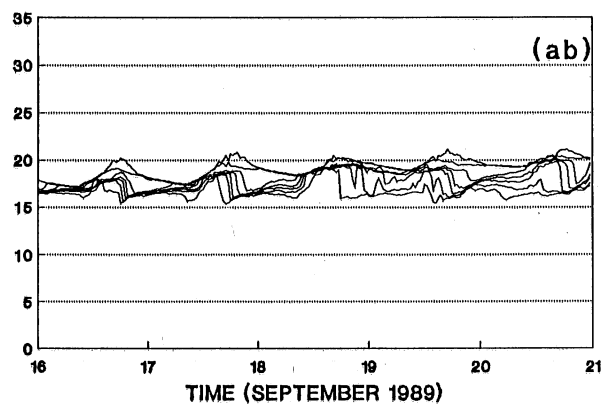
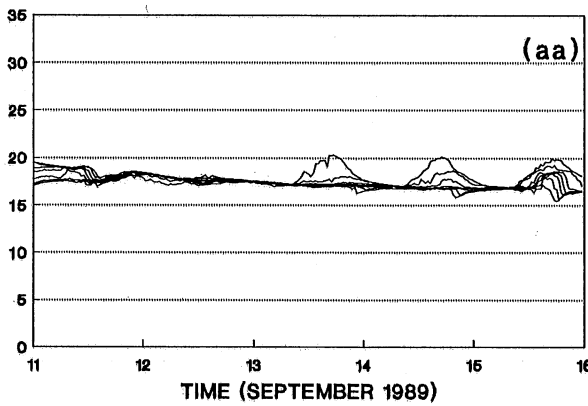
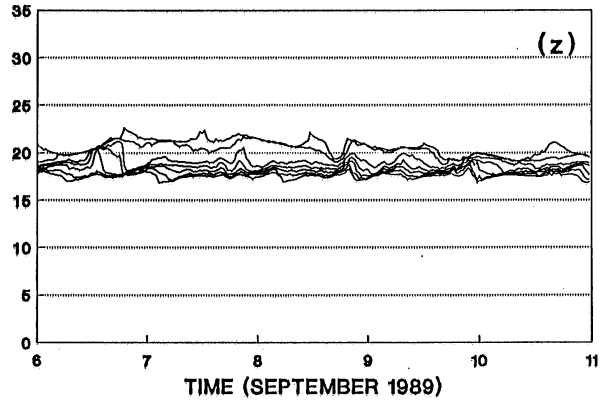
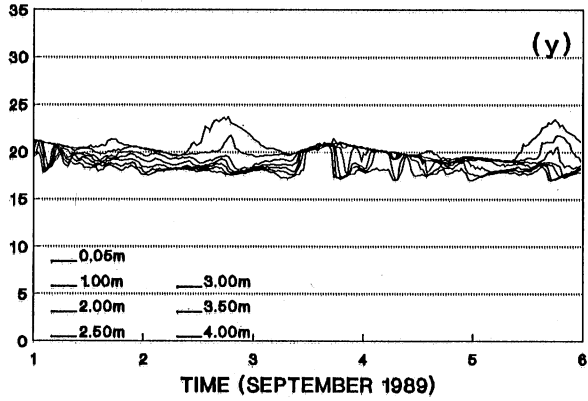
WATER TEMPERATURE (Deg. C)



WATER TEMPERATURE TIME SERIES - STATION #5 (s-x)

INITIAL WATER COLUMN DEPTH 4.05m

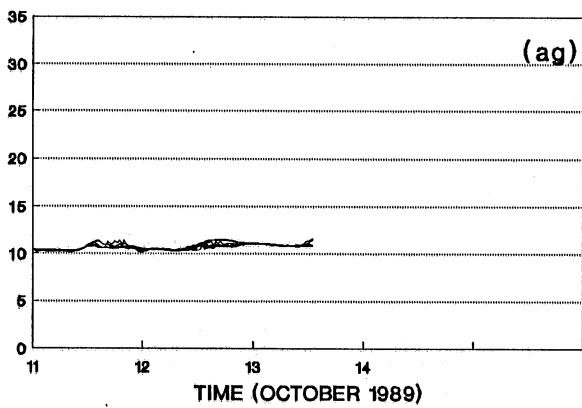
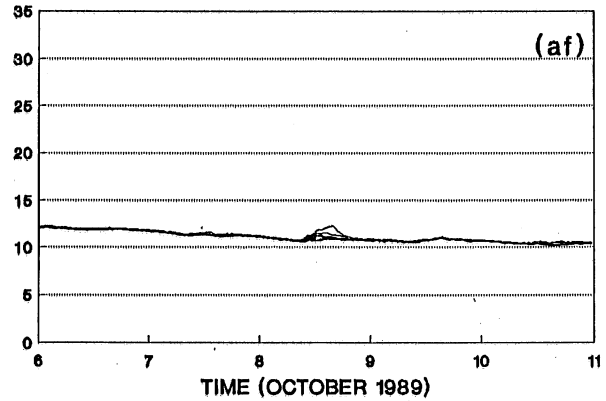
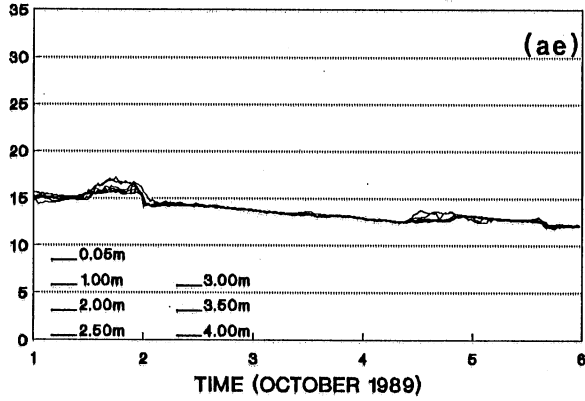
WATER TEMPERATURE (Deg. C)



WATER TEMPERATURE TIME SERIES - STATION #5 (y-ad)

INITIAL WATER COLUMN DEPTH 4.05m

WATER TEMPERATURE (Deg. C)

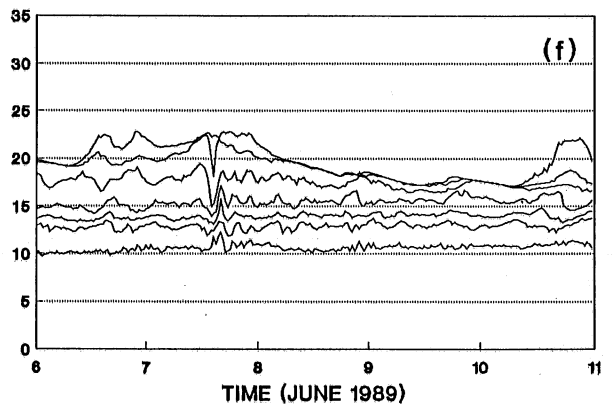
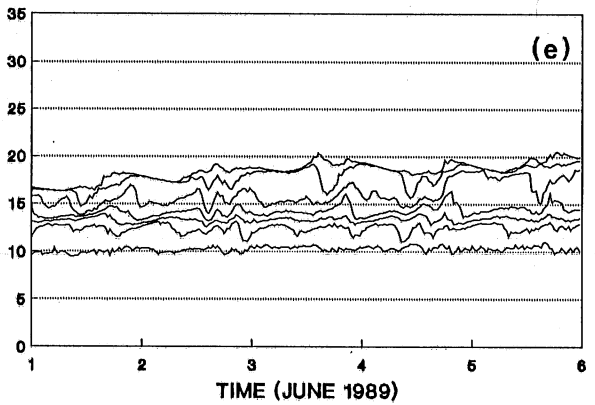
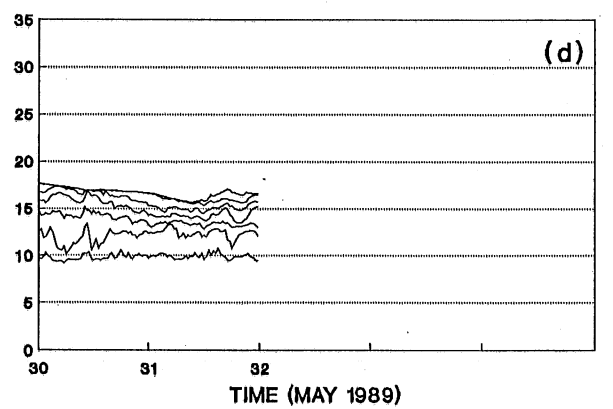
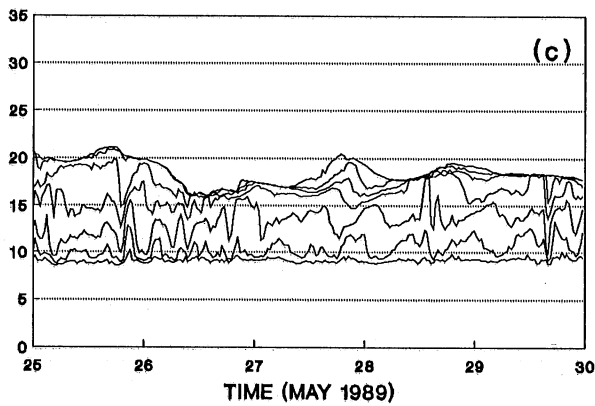
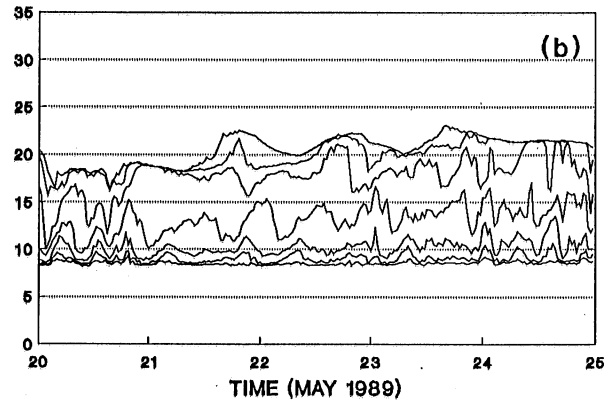
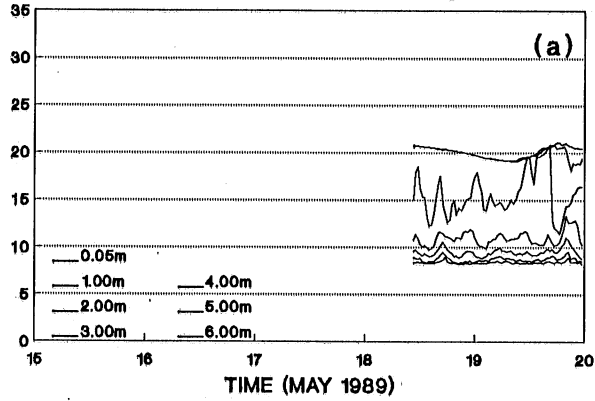


WATER TEMPERATURE TIME SERIES - STATION #5 (ae-ag)



INITIAL WATER COLUMN DEPTH 6.75m

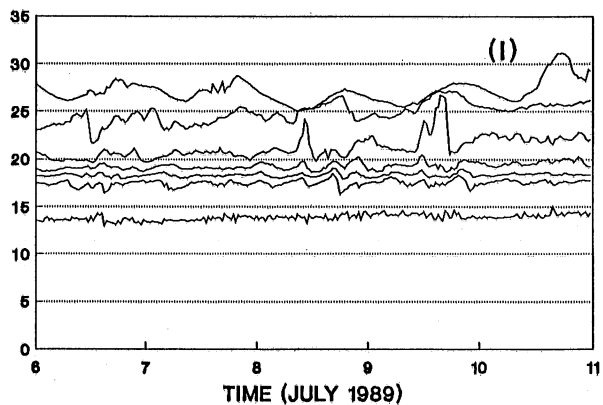
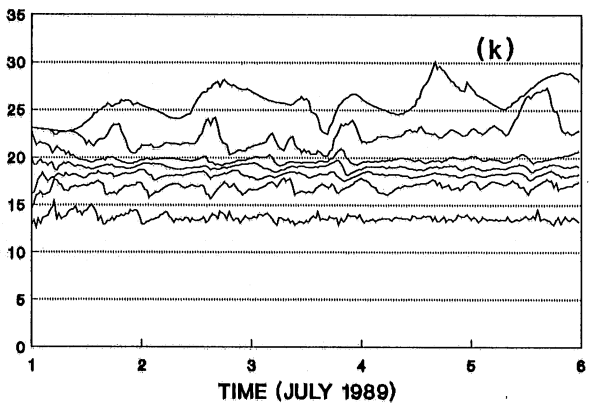
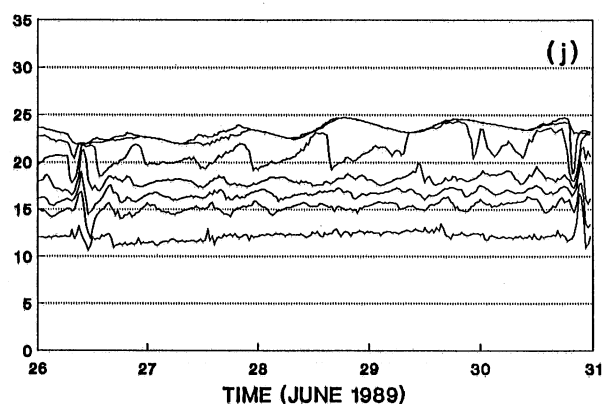
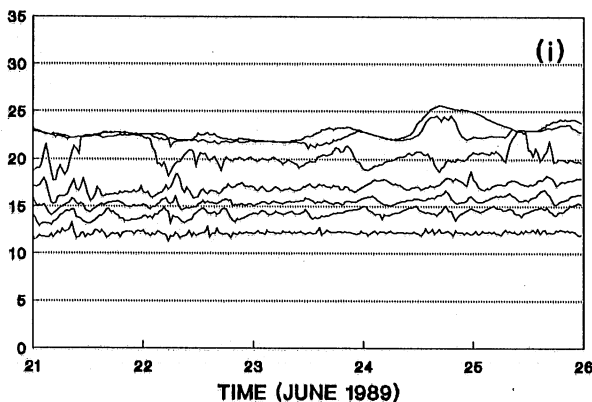
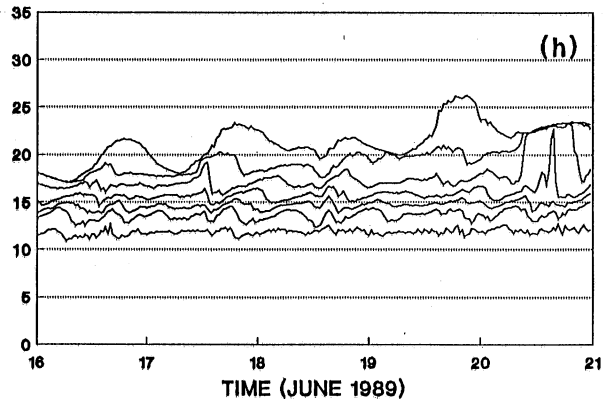
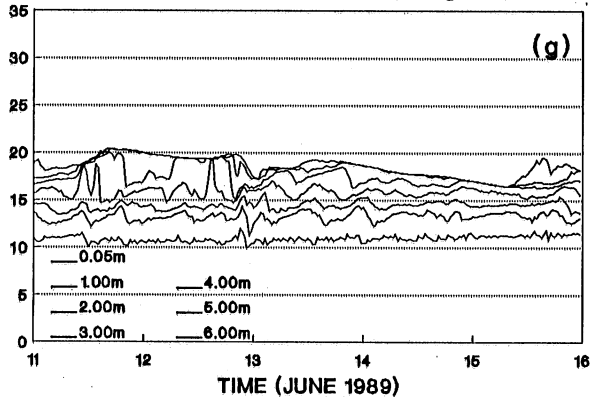
WATER TEMPERATURE (Deg. C)



WATER TEMPERATURE TIME SERIES - STATION #6 (a-f)

INITIAL WATER COLUMN DEPTH 6.75m

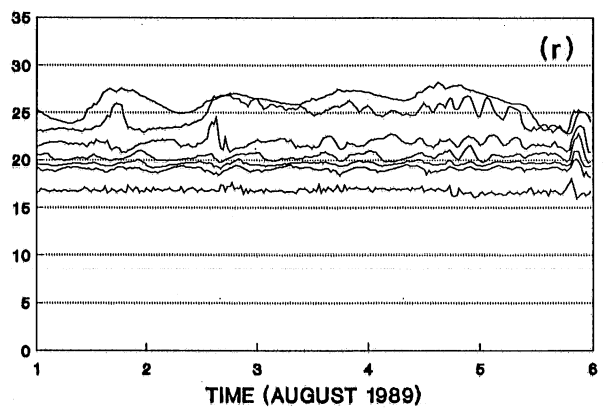
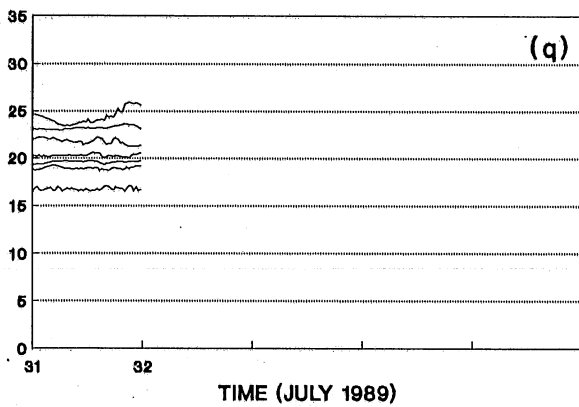
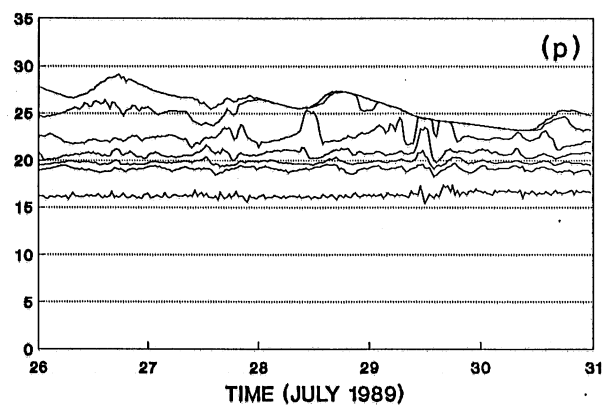
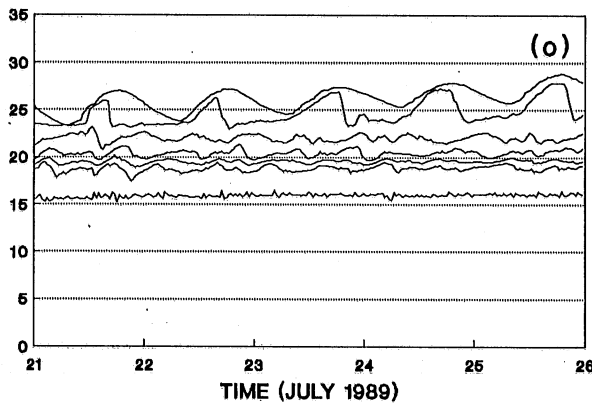
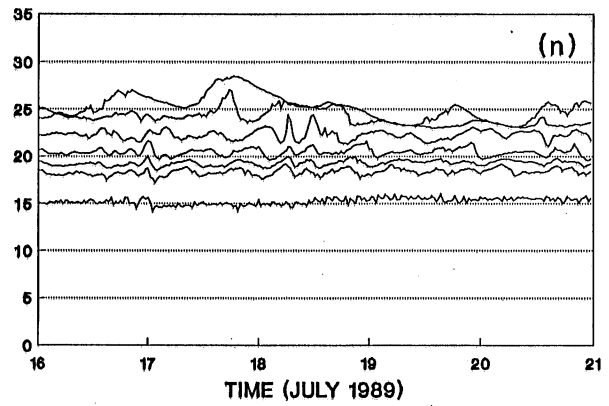
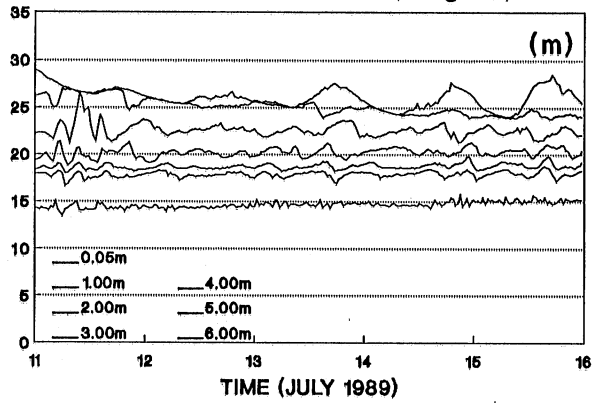
WATER TEMPERATURE (Deg. C)



WATER TEMPERATURE TIME SERIES - STATION #6 (g-l)

INITIAL WATER COLUMN DEPTH 6.75m

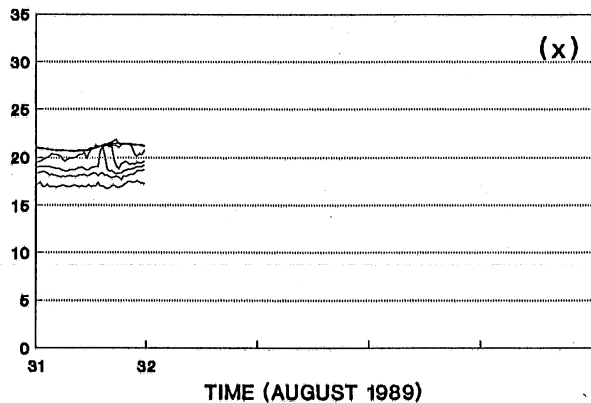
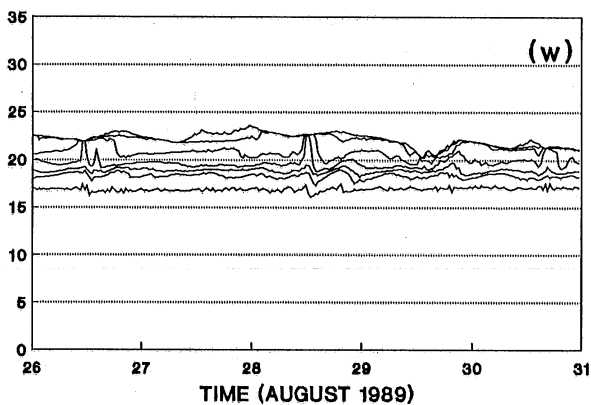
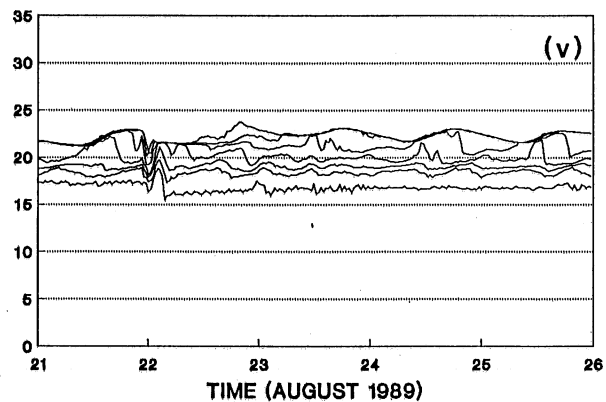
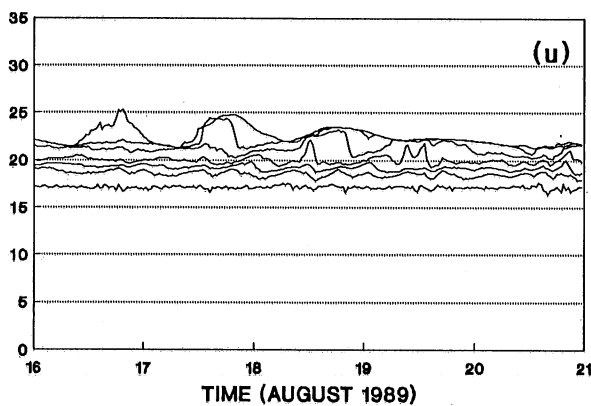
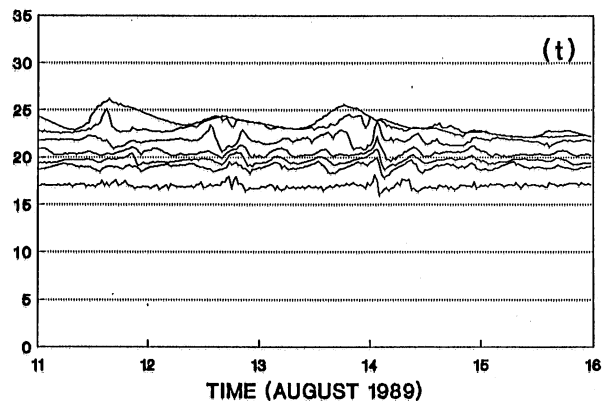
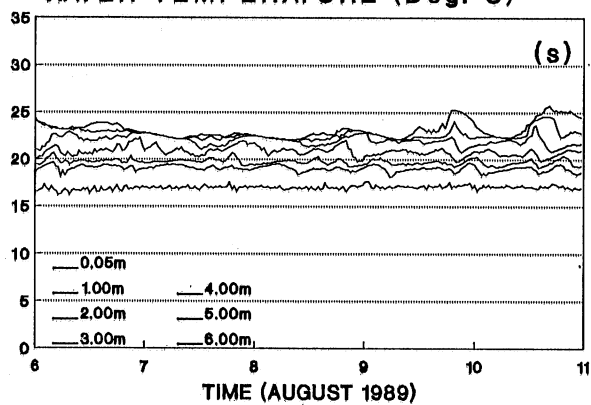
WATER TEMPERATURE (Deg. C)



WATER TEMPERATURE TIME SERIES - STATION #6 (m-r)

INITIAL WATER COLUMN DEPTH 6.75m

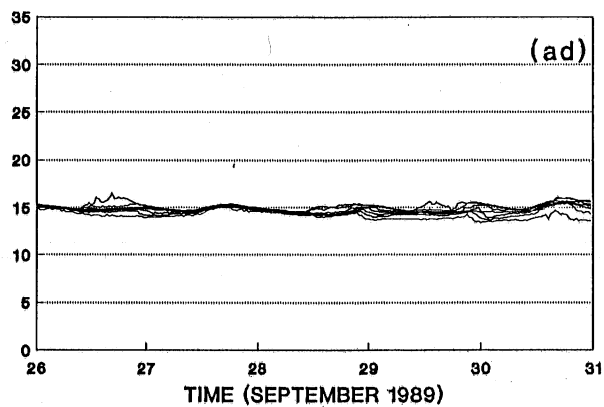
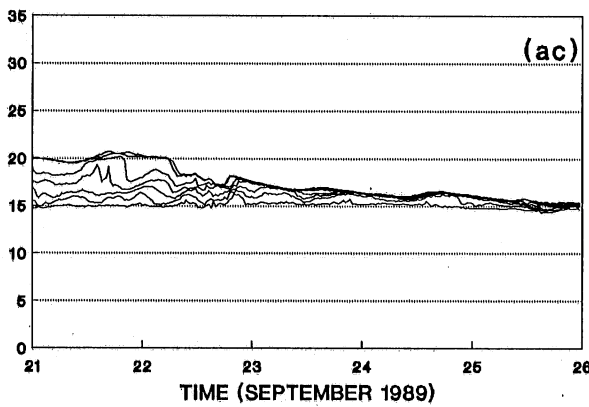
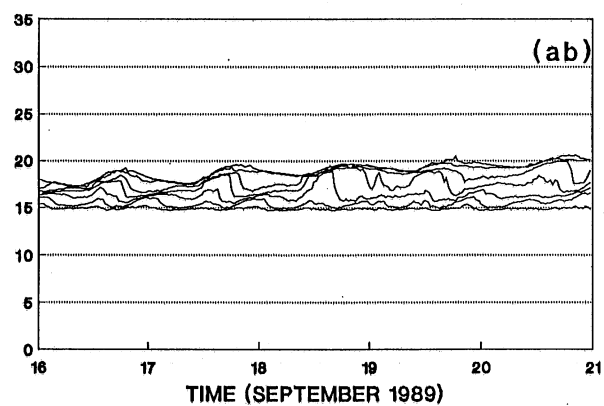
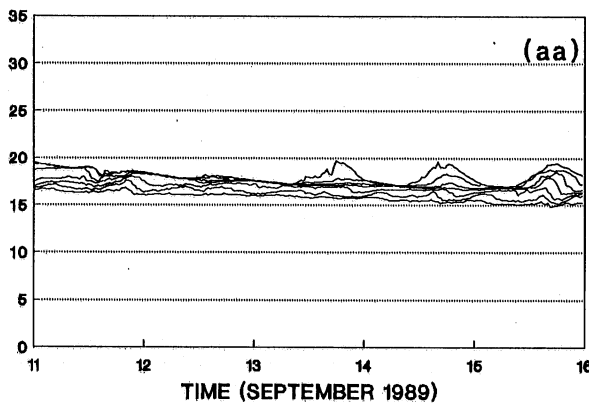
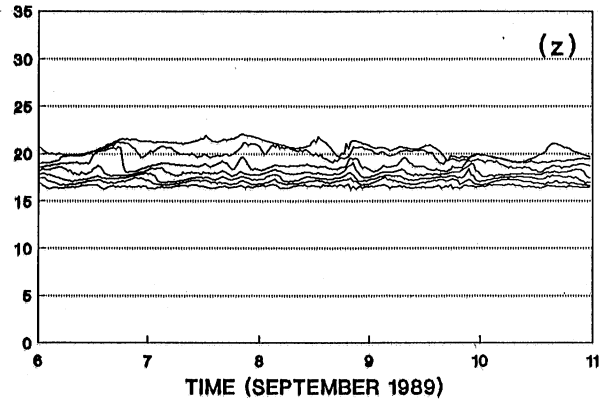
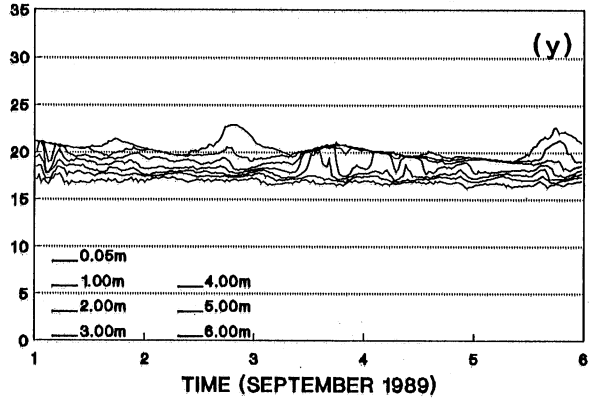
WATER TEMPERATURE (Deg. C)



WATER TEMPERATURE TIME SERIES - STATION #6 (s-x)

INITIAL WATER COLUMN DEPTH 6.75m

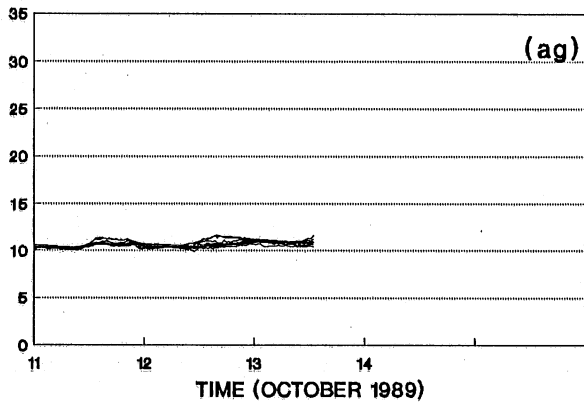
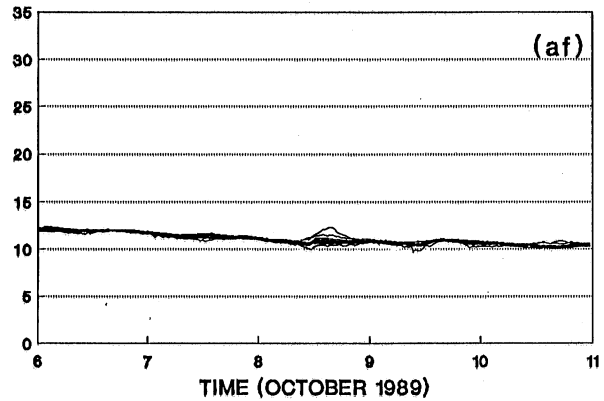
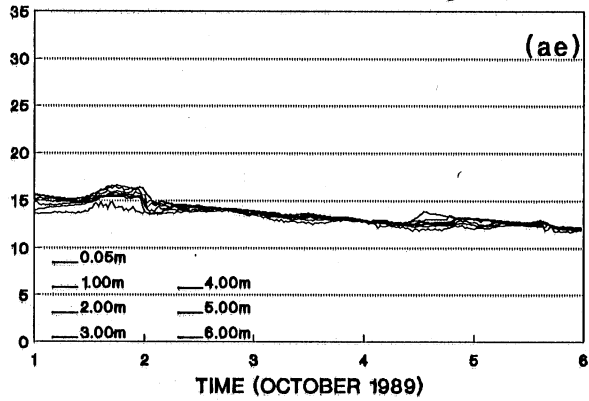
WATER TEMPERATURE (Deg. C)



WATER TEMPERATURE TIME SERIES - STATION #6 (y-ad)

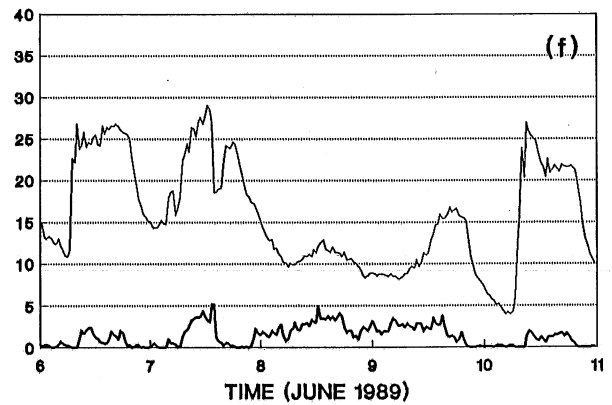
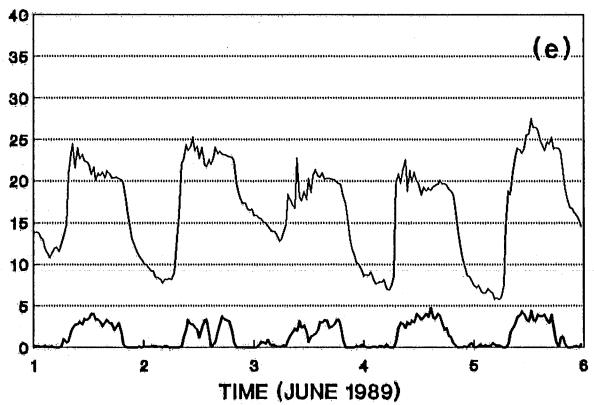
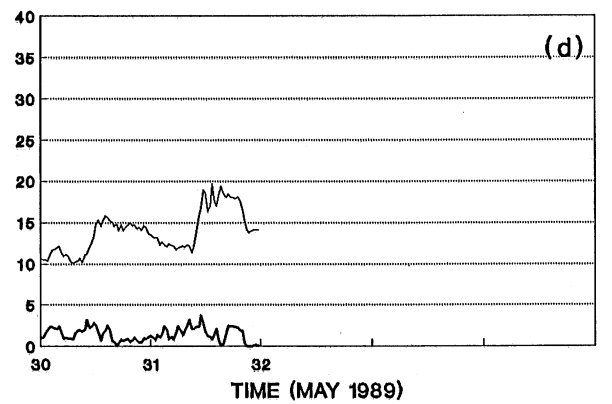
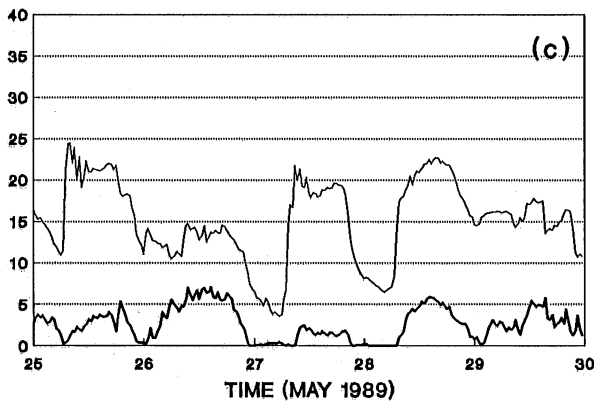
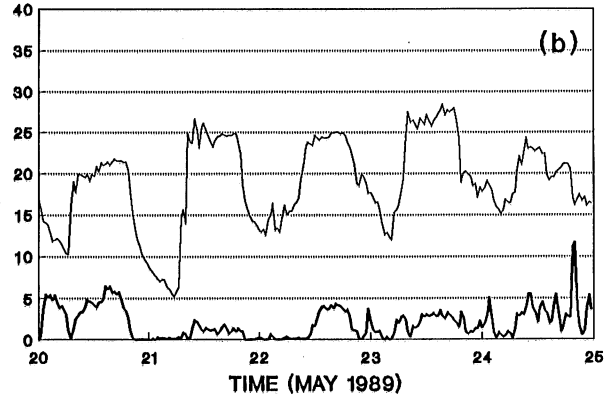
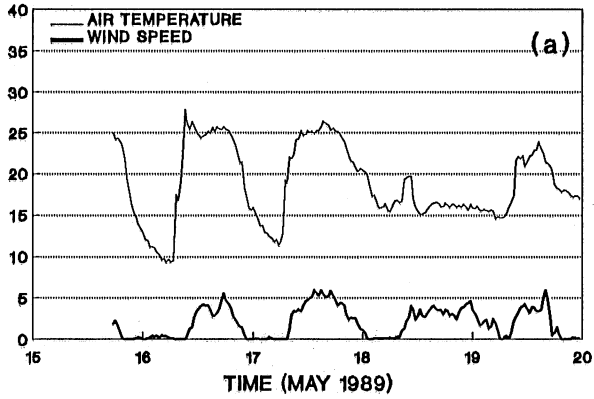
INITIAL WATER COLUMN DEPTH 6.75m

WATER TEMPERATURE (Deg. C)



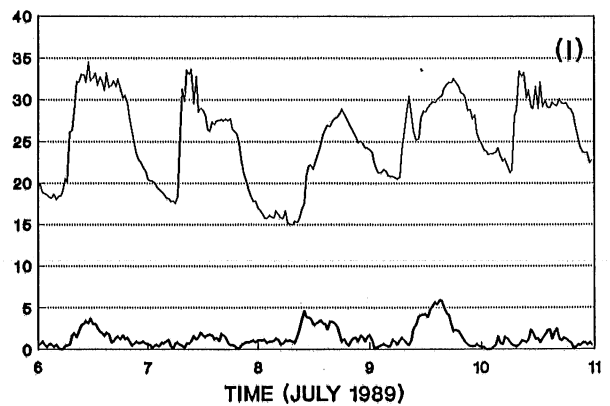
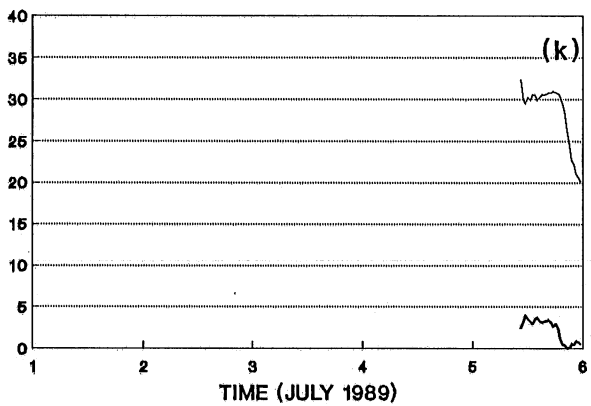
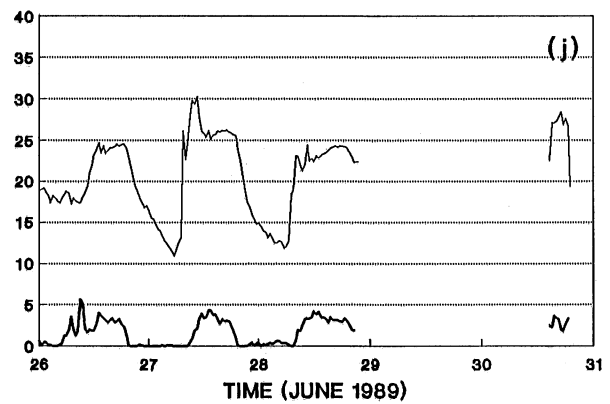
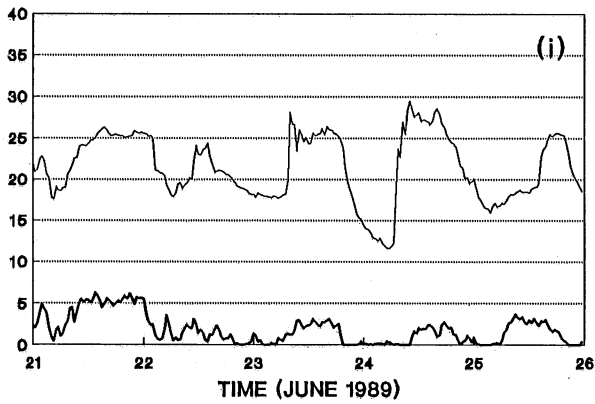
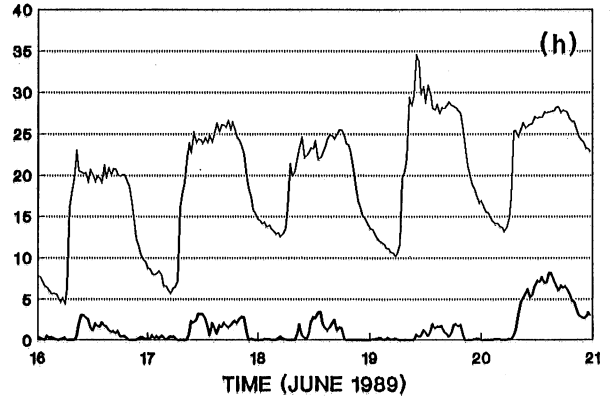
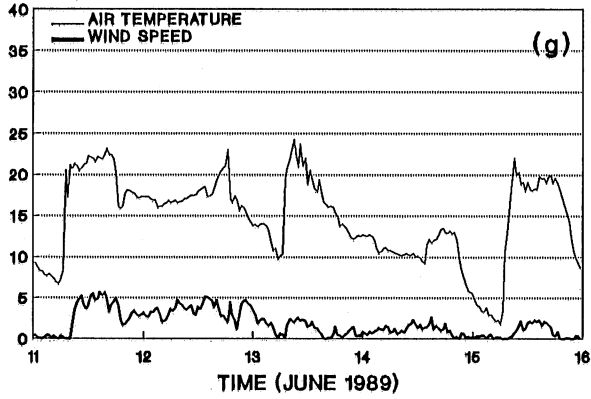
WATER TEMPERATURE TIME SERIES - STATION #6 (ae-ag)

AIR TEMPERATURE (Deg. C)  
WIND SPEED (m/s)



WEATHER PARAMETERS TIME SERIES (a-f)

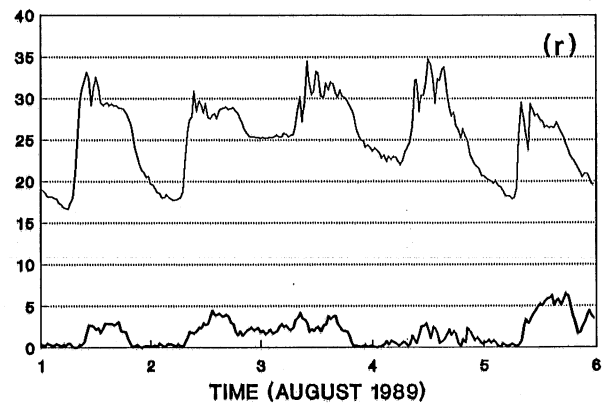
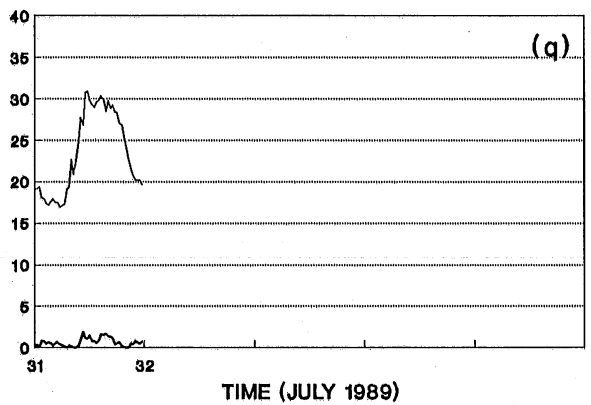
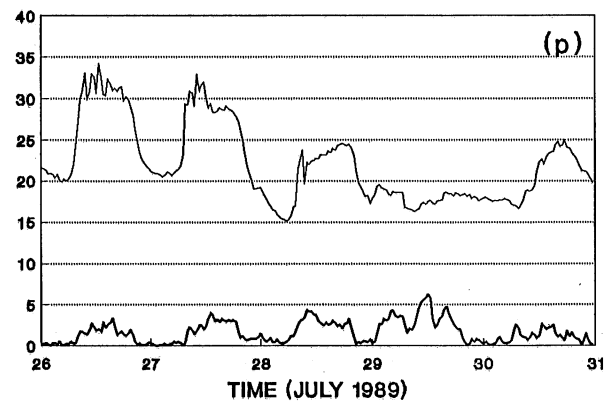
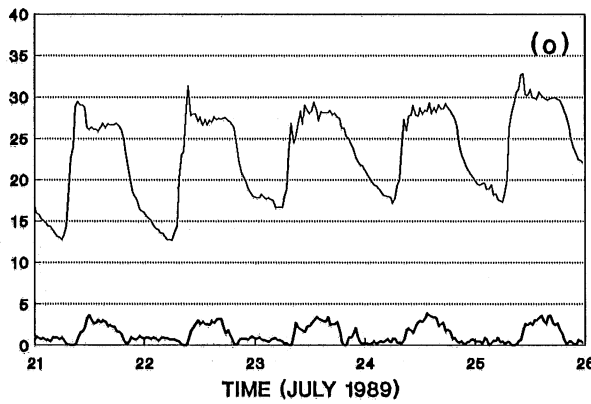
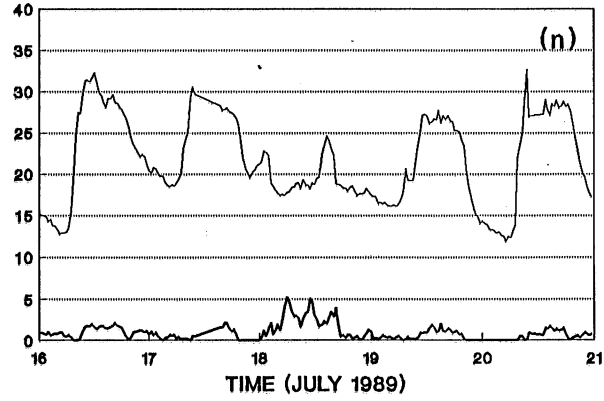
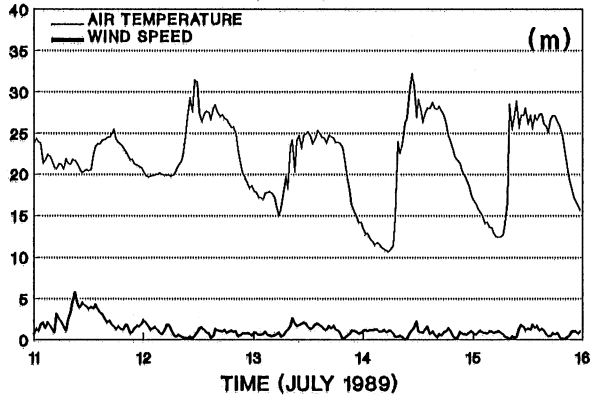
AIR TEMPERATURE (Deg. C)  
WIND SPEED (m/s)



WEATHER PARAMETERS TIME SERIES (g-l)

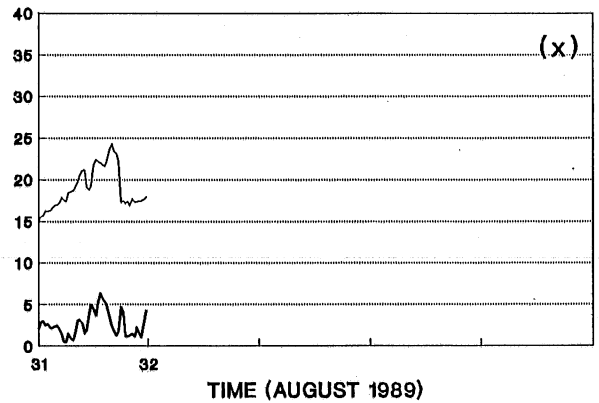
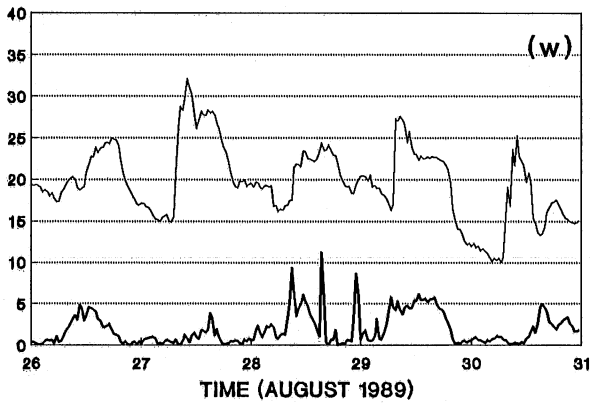
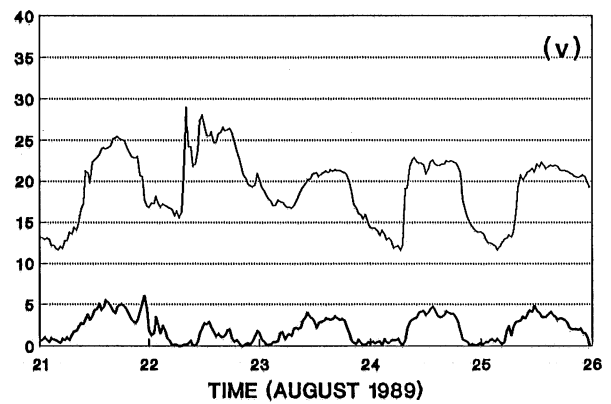
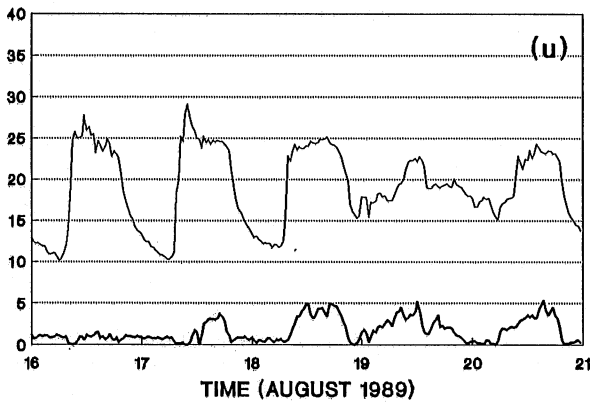
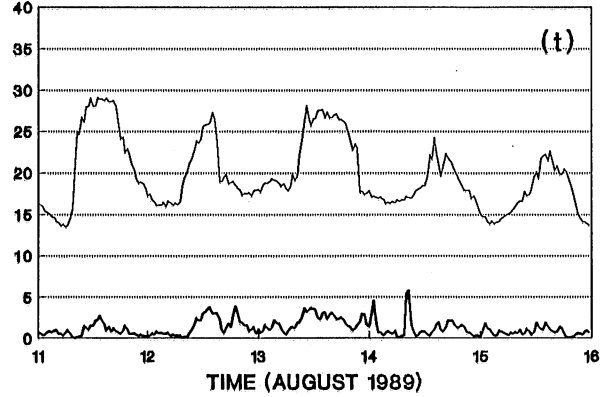
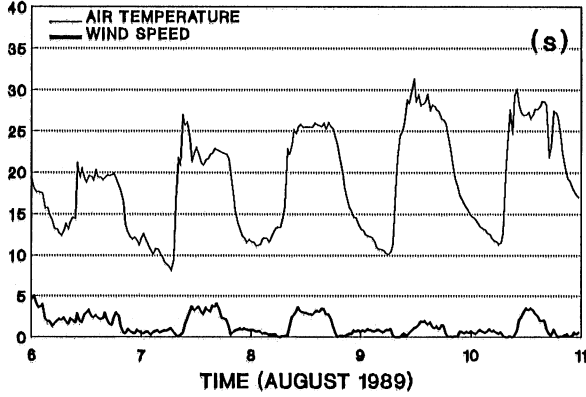


AIR TEMPERATURE (Deg. C)  
WIND SPEED (m/s)



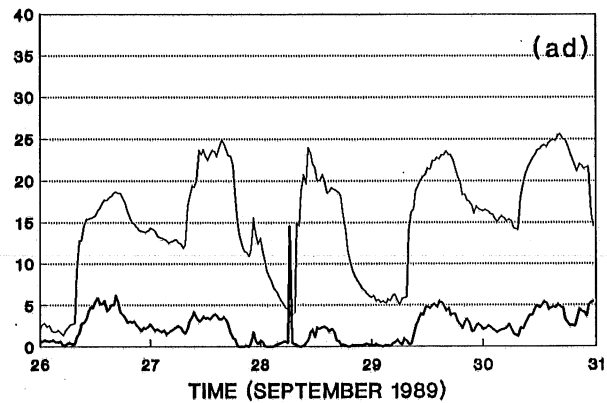
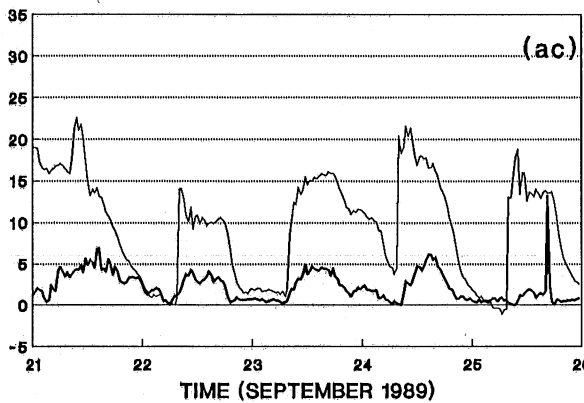
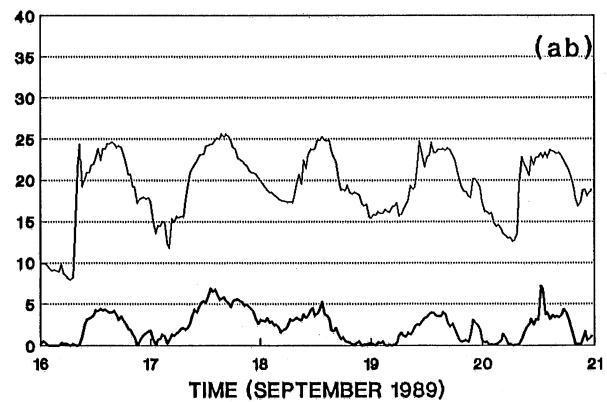
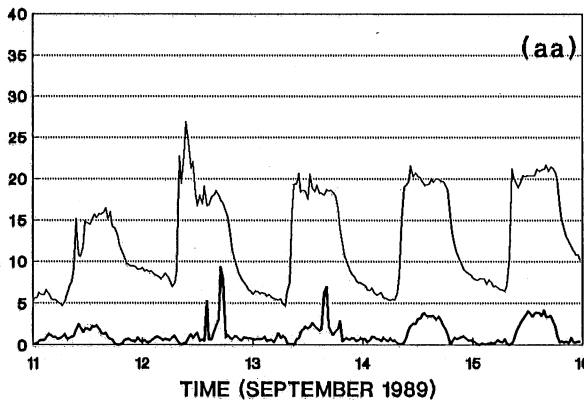
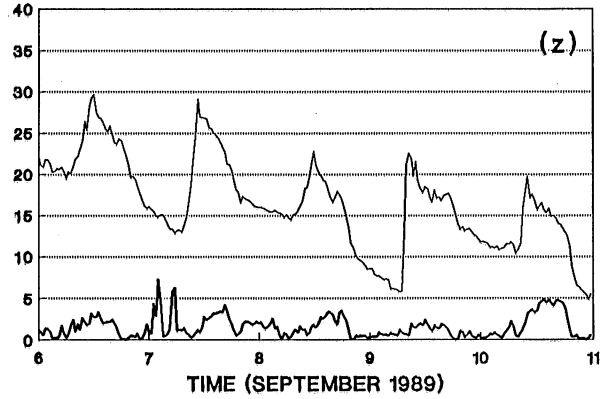
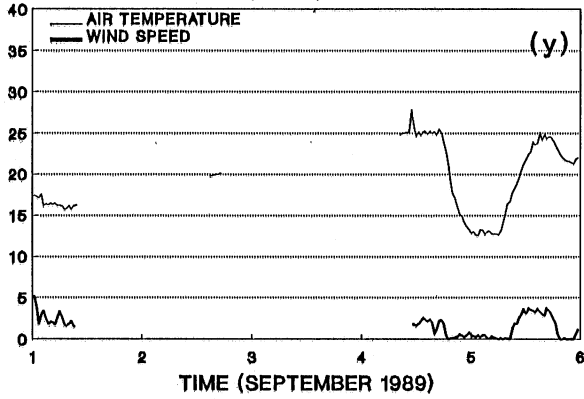
WEATHER PARAMETERS TIME SERIES (m-r)

**AIR TEMPERATURE (Deg. C)  
WIND SPEED (m/s)**



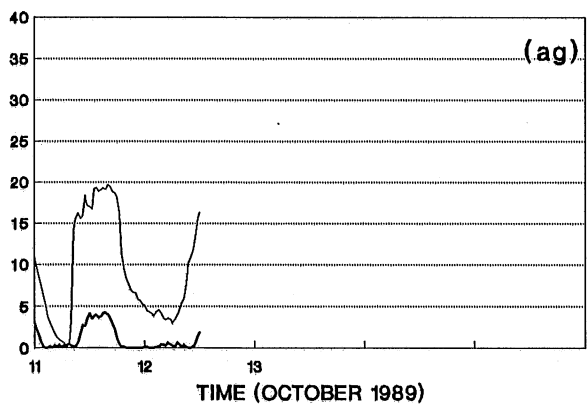
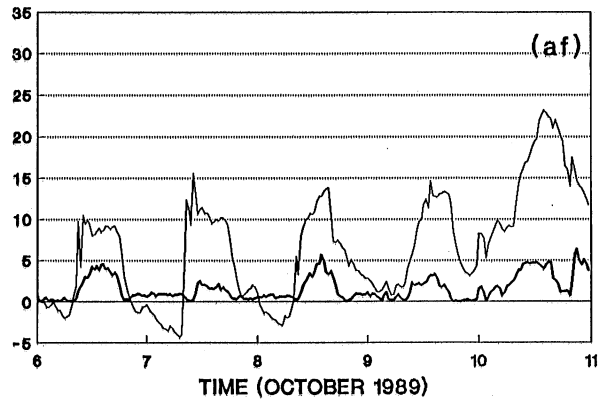
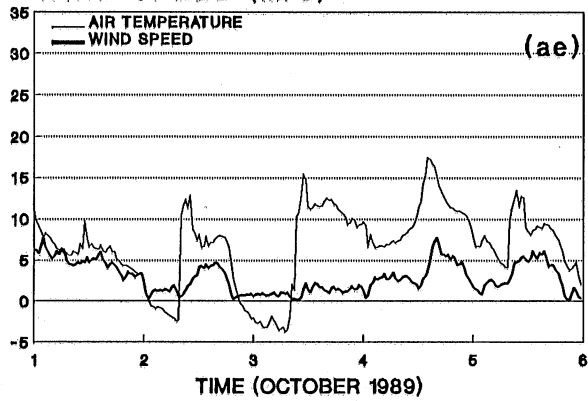
**WEATHER PARAMETERS TIME SERIES (s-x)**

AIR TEMPERATURE (Deg. C)  
WIND SPEED (m/s)

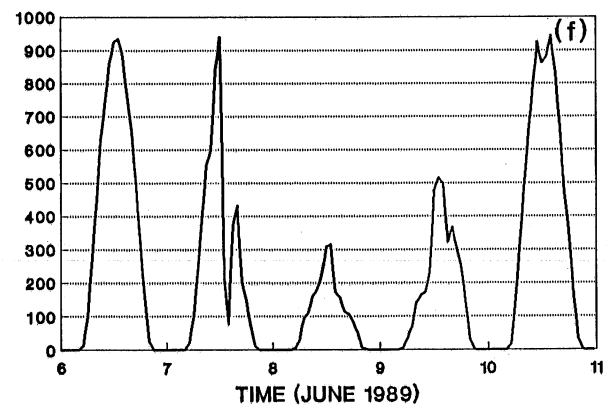
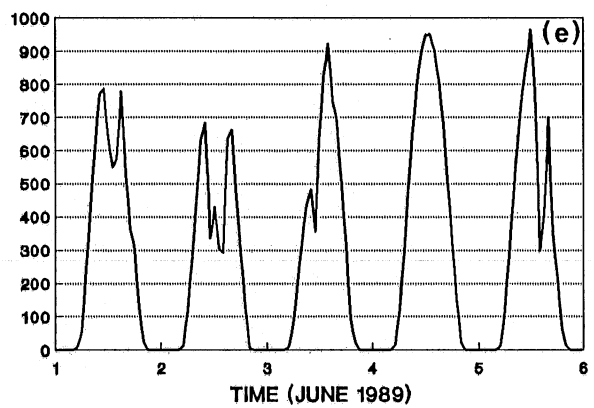
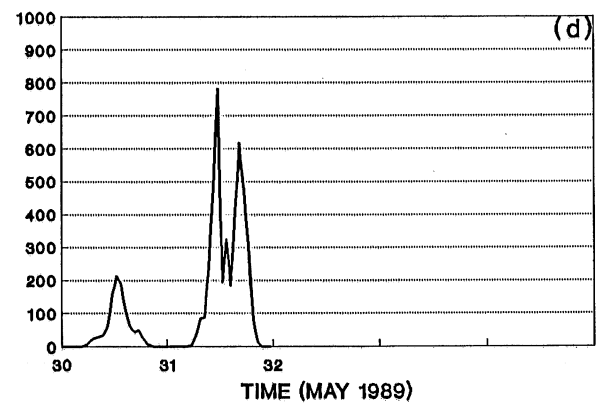
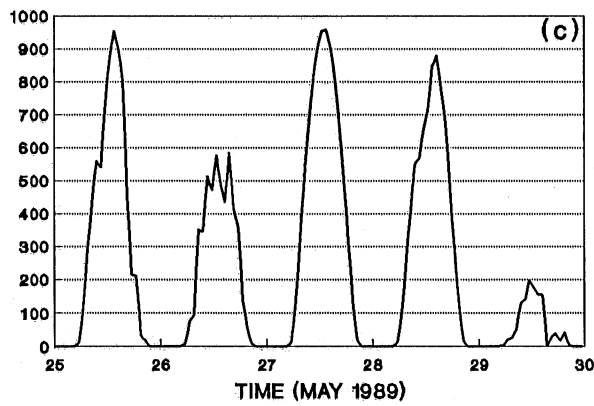
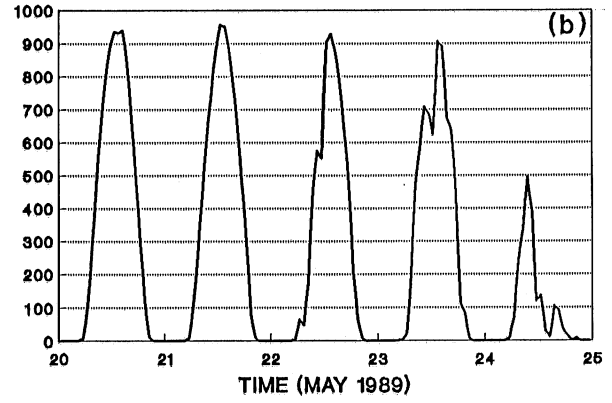
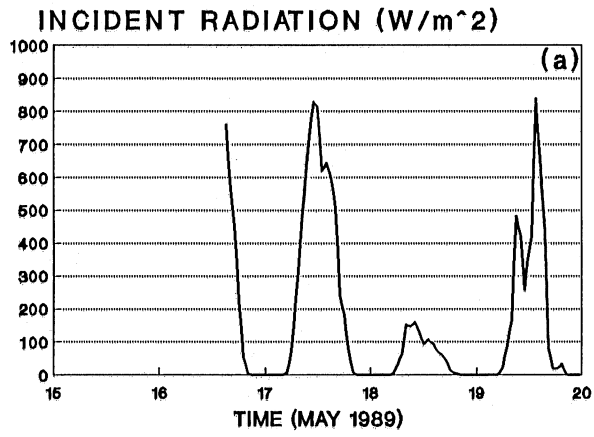


WEATHER PARAMETERS TIME SERIES (y-ad)

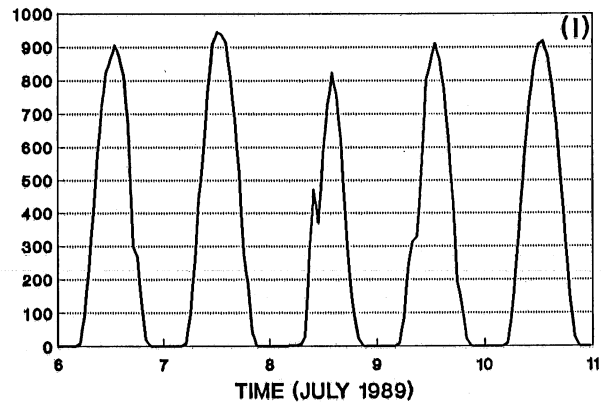
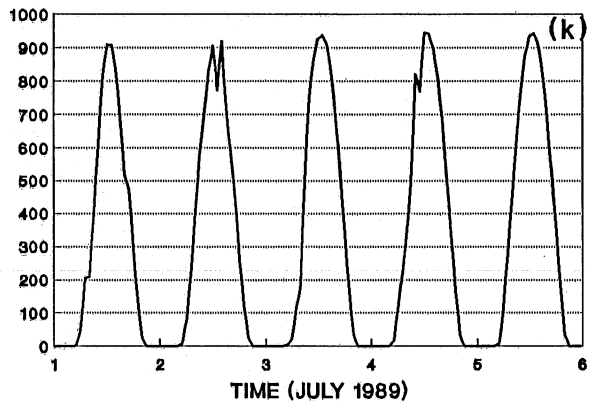
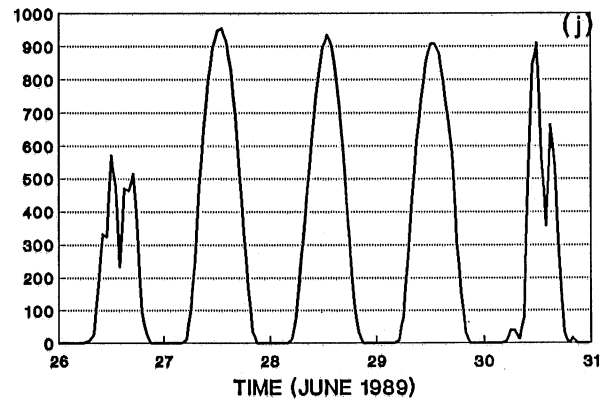
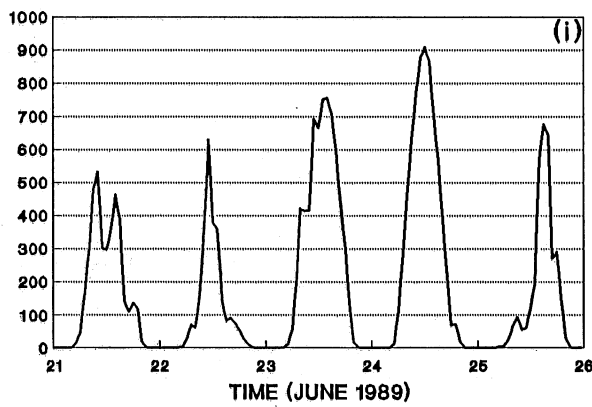
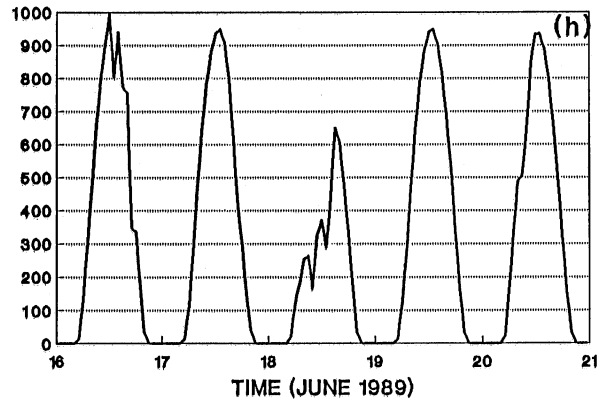
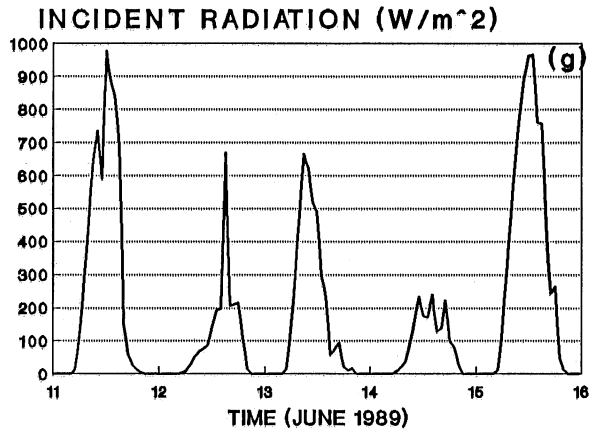
AIR TEMPERATURE (Deg. C)  
WIND SPEED (m/s)



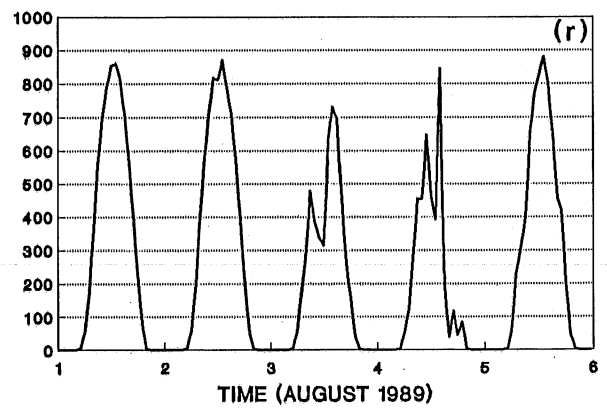
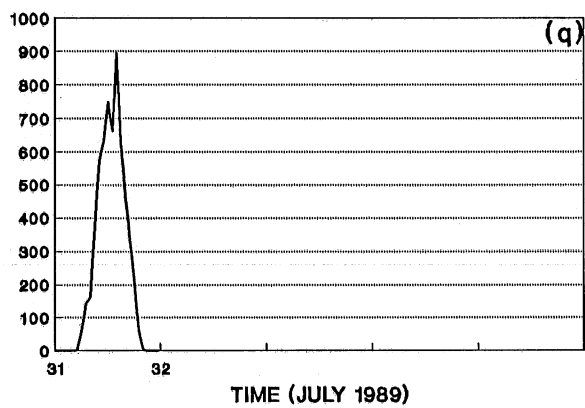
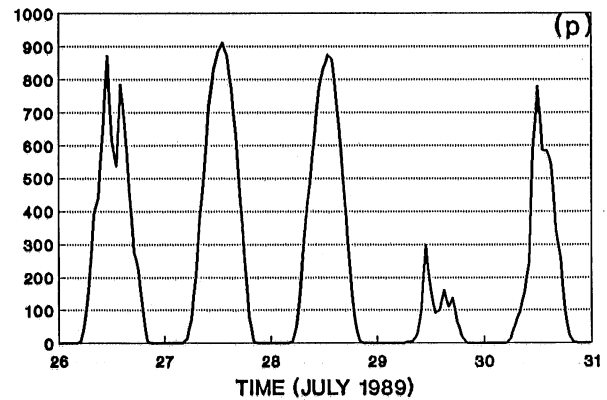
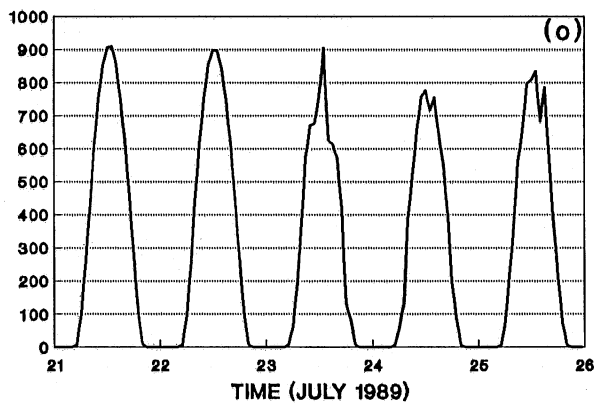
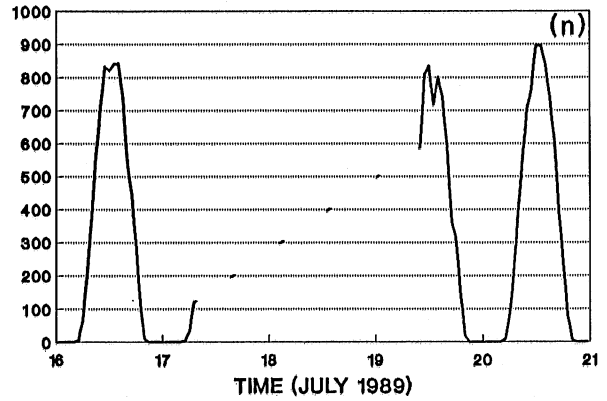
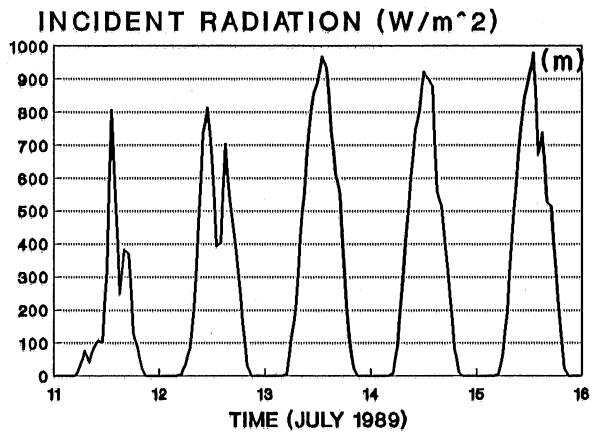
WEATHER PARAMETERS TIME SERIES (ae-ag)



**INCIDENT RADIATION TIME SERIES (a-f)**

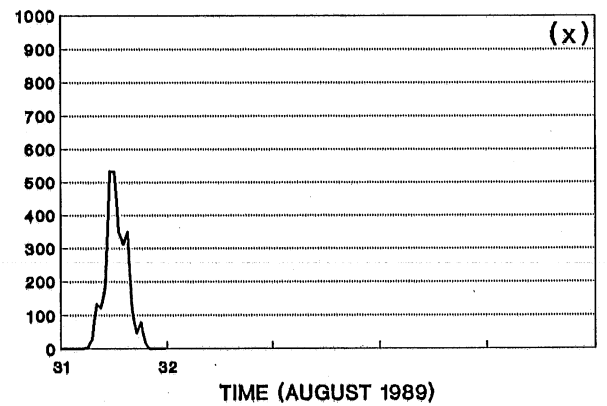
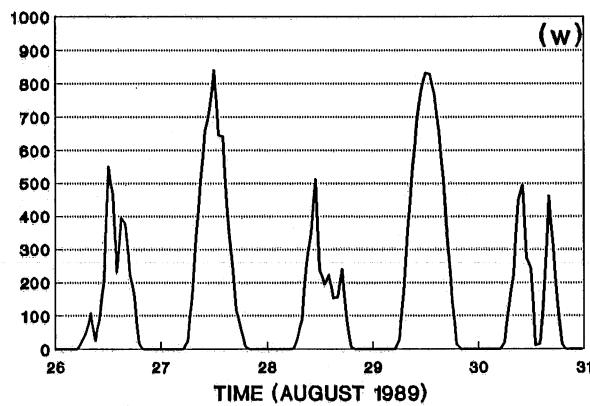
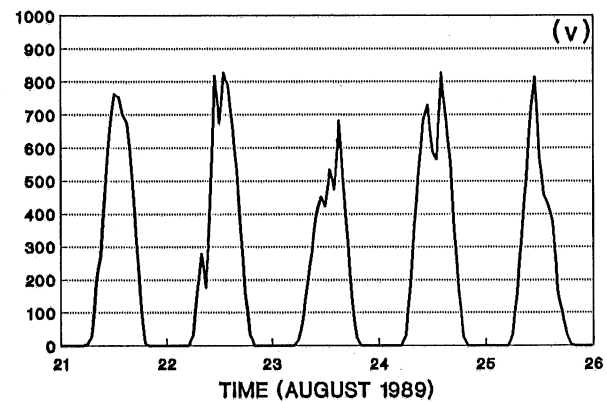
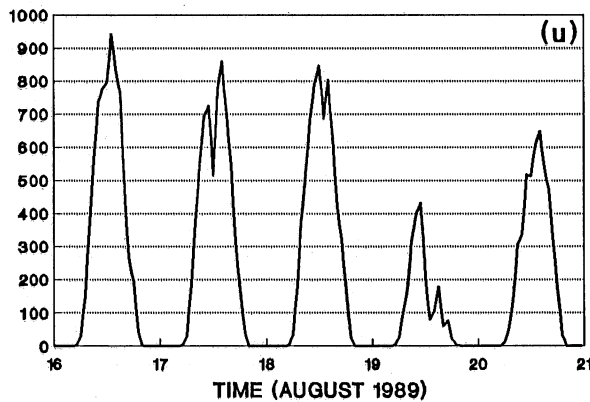
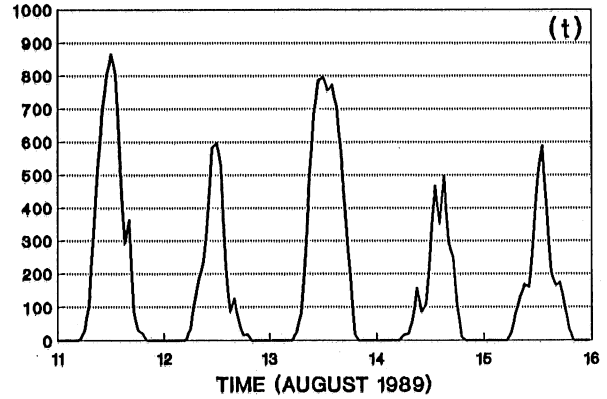
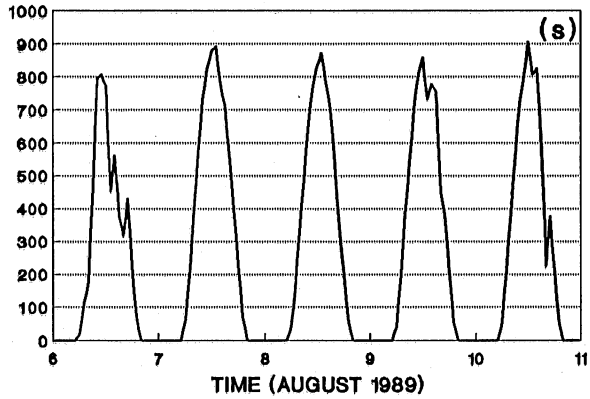


**INCIDENT RADIATION TIME SERIES (g-l)**



**INCIDENT RADIATION TIME SERIES (m-r)**

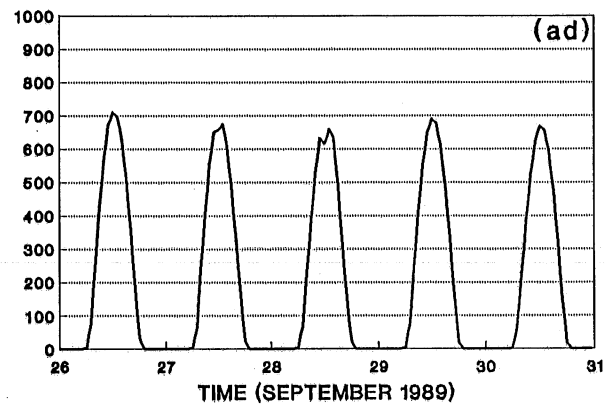
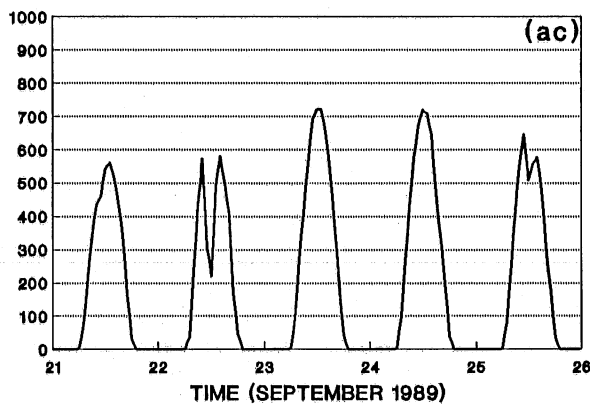
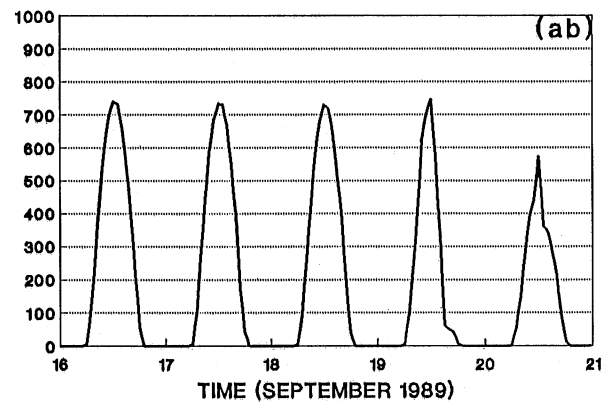
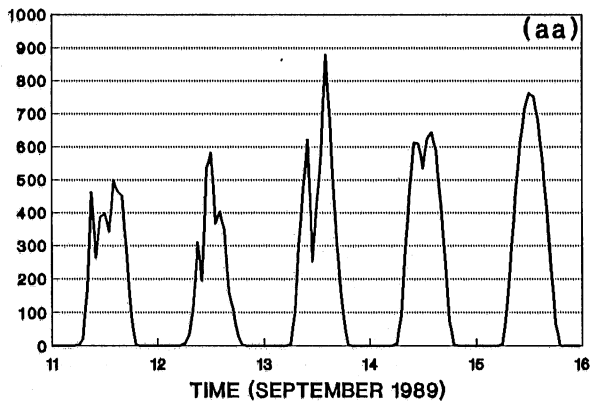
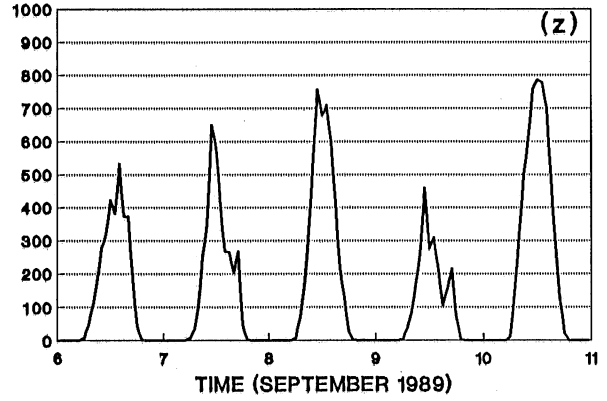
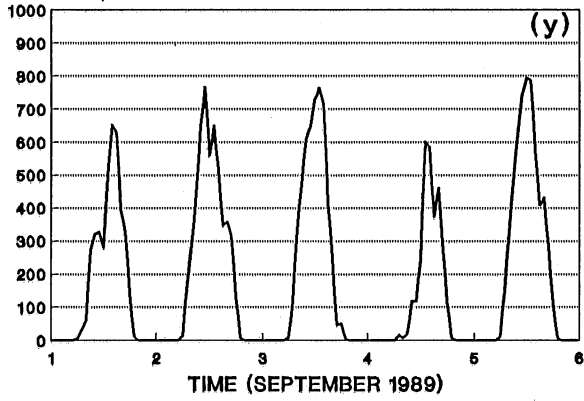
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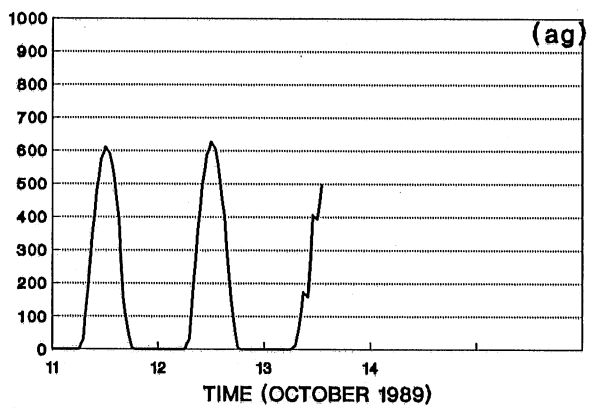
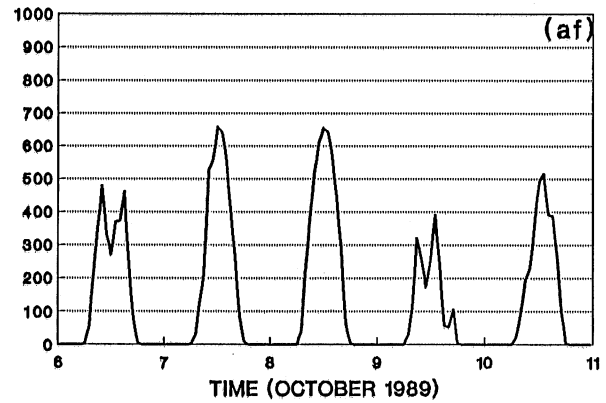
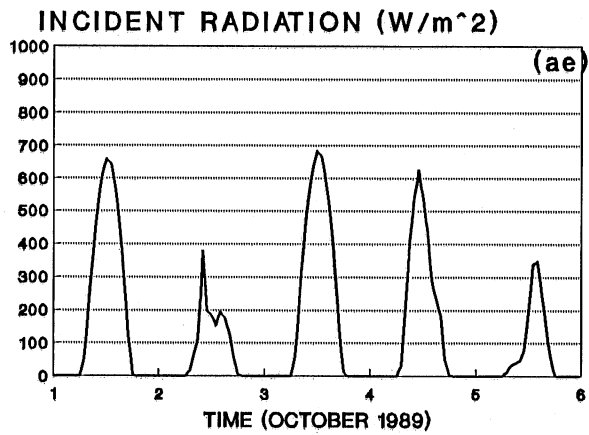
INCIDENT RADIATION TIME SERIES (s-x)



INCIDENT RADIATION (W/m<sup>2</sup>)

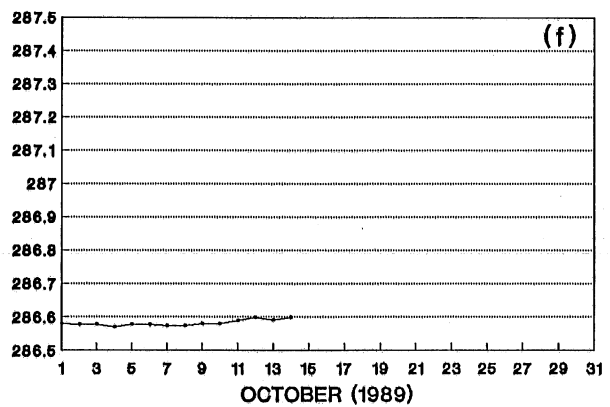
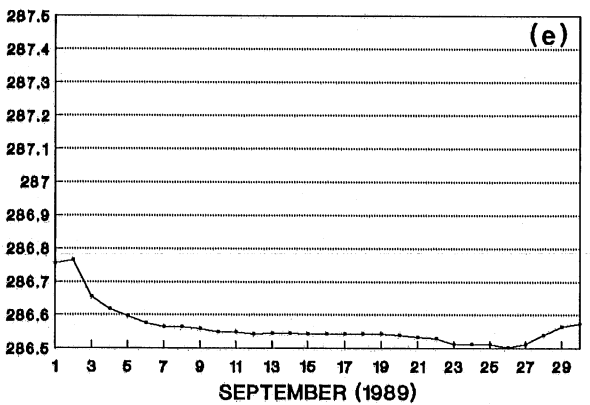
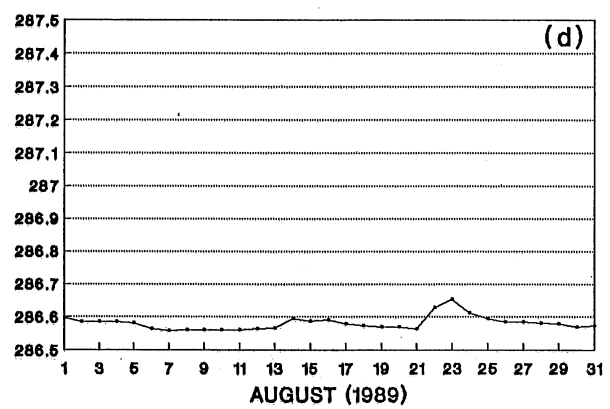
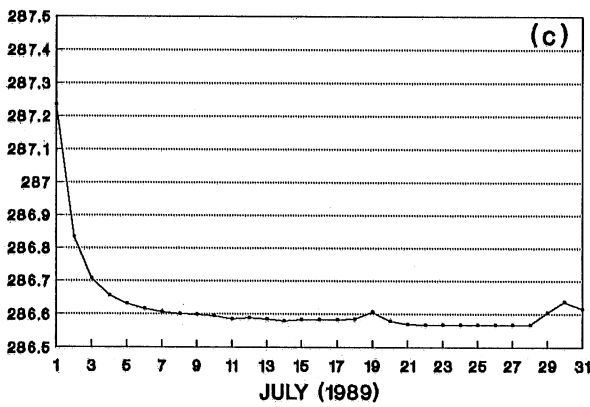
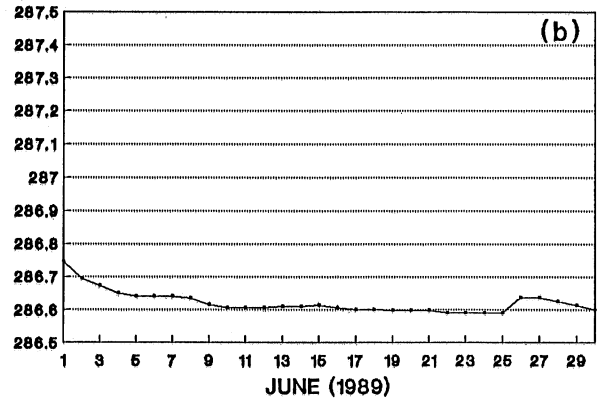
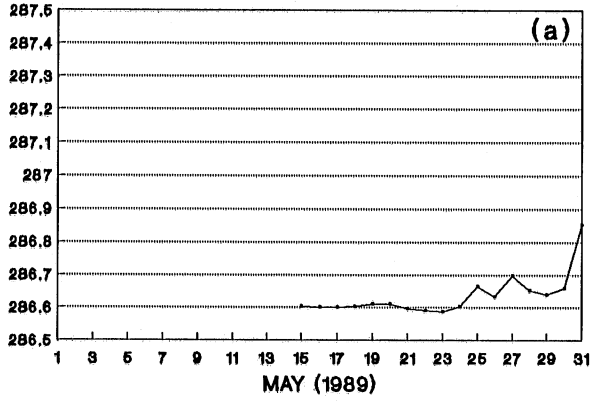


INCIDENT RADIATION TIME SERIES (y-ad)



**INCIDENT RADIATION TIME SERIES (ae-ag)**

POOL ELEVATION (m)



POOL ELEVATION TIME SERIES (a-f)

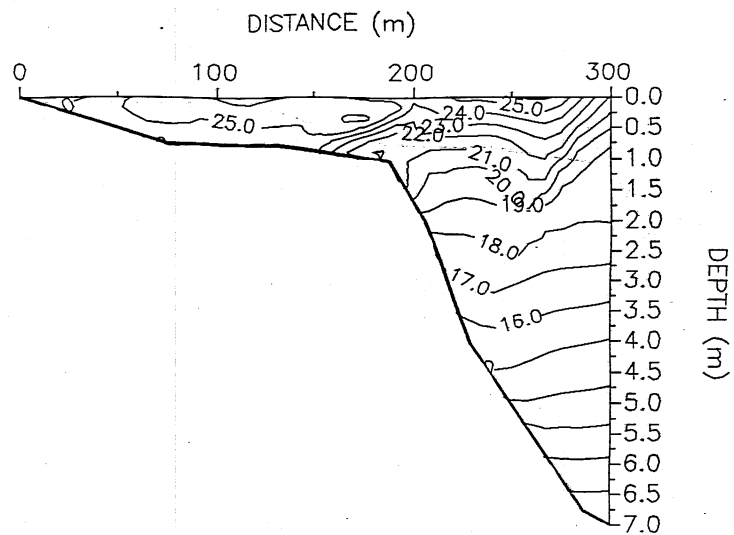
APPENDIX B

ISOTHERM PLOTS OF THE BAY TRANSECT

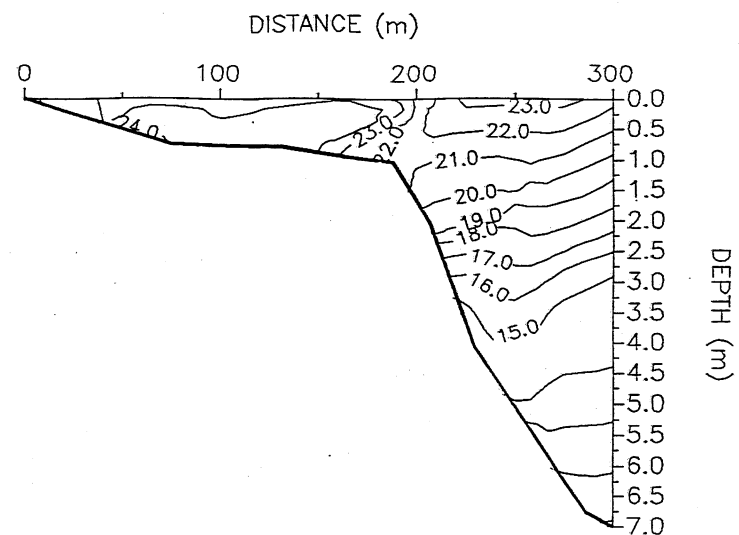
JUNE 20

JULY 19 - 21

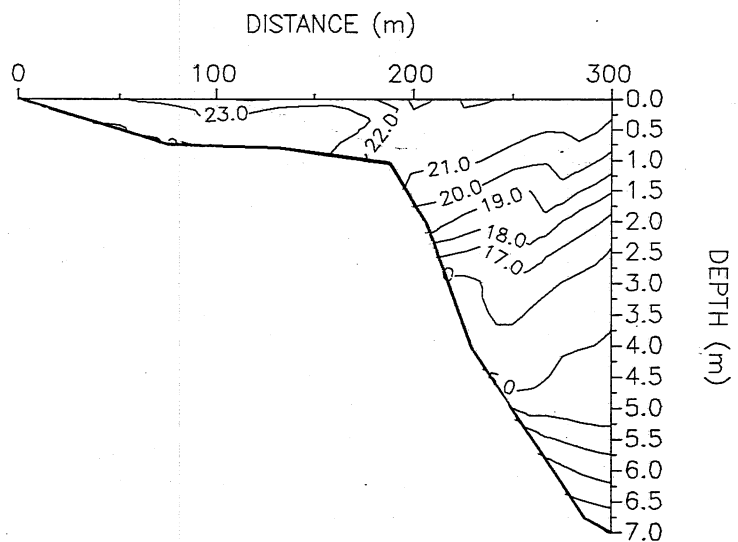
AUGUST 9 - 16



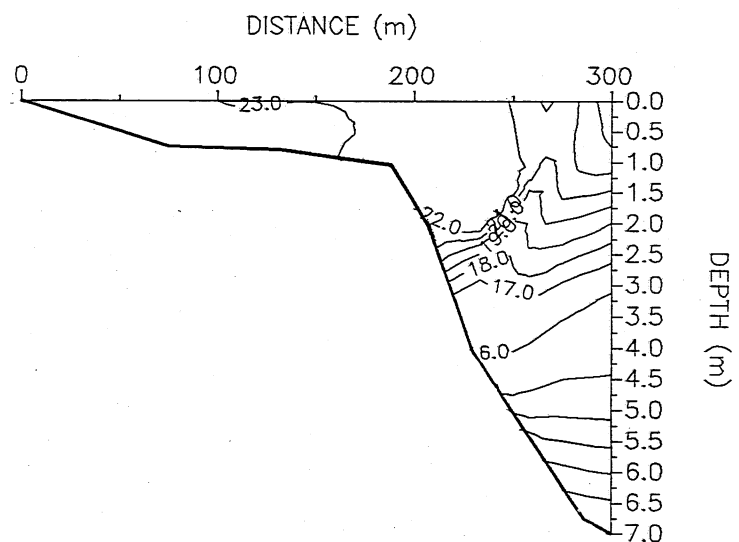
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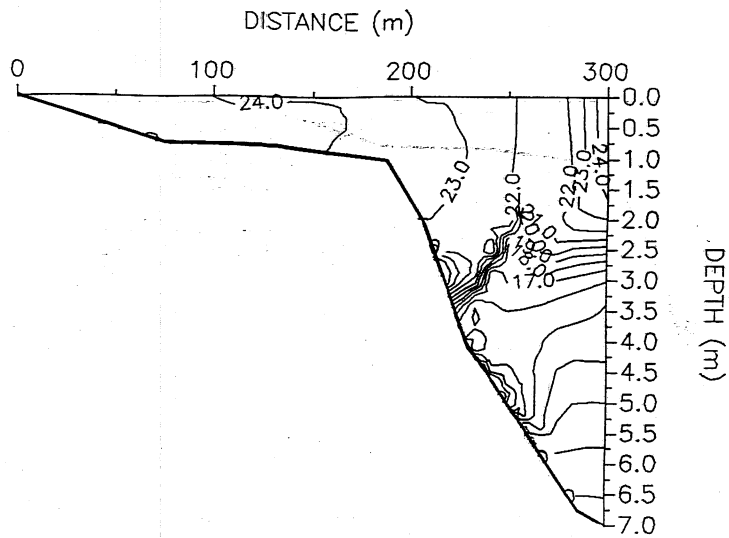
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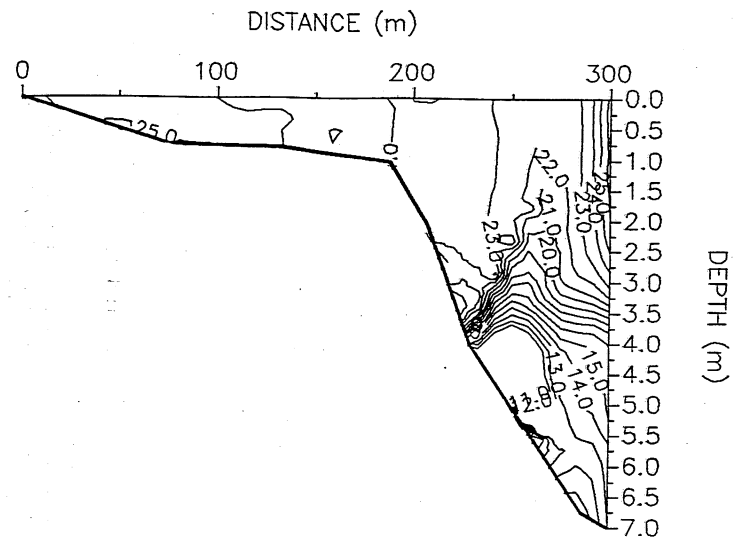
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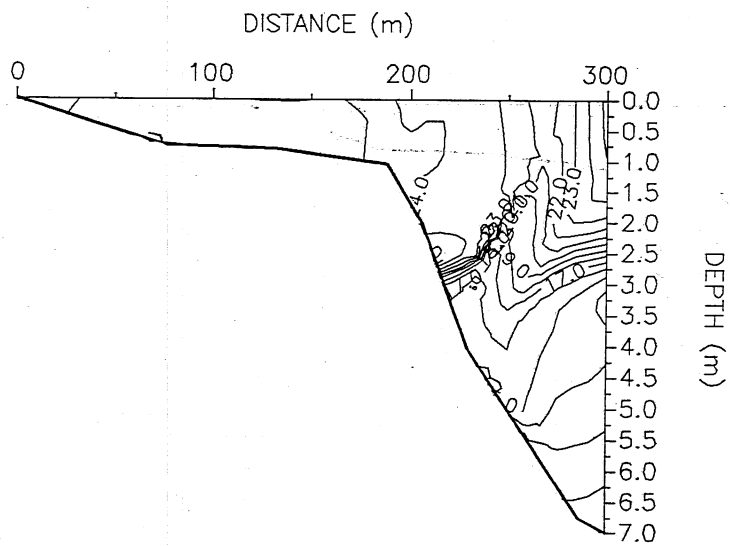
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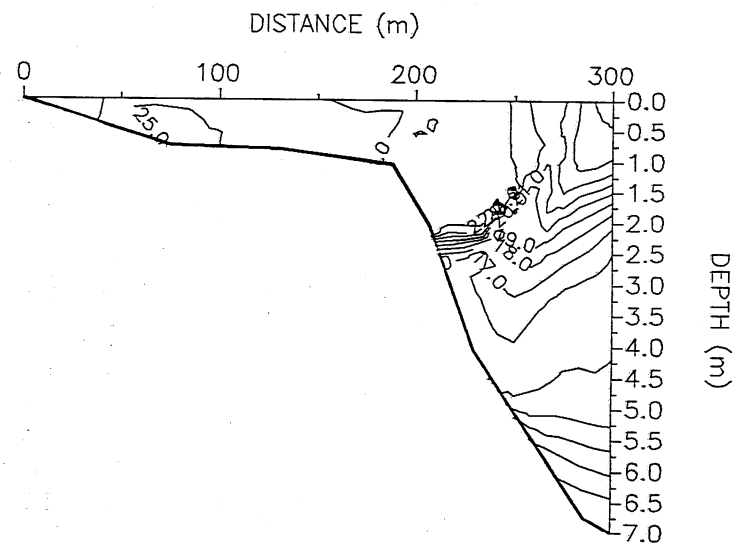
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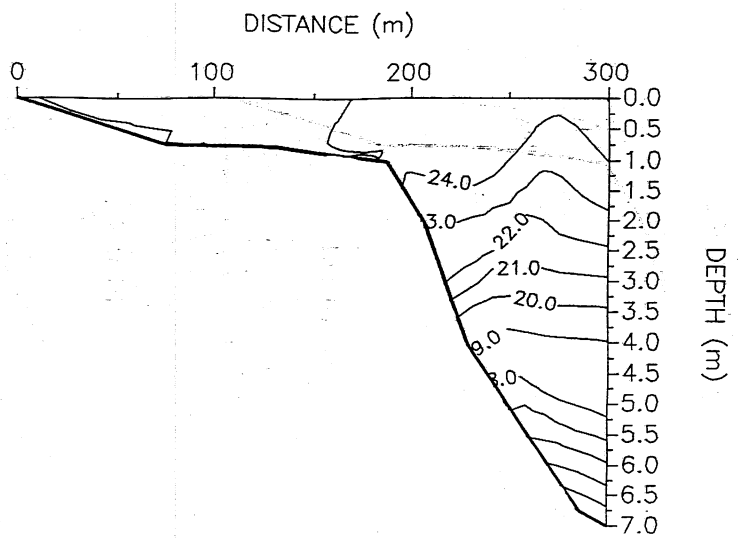
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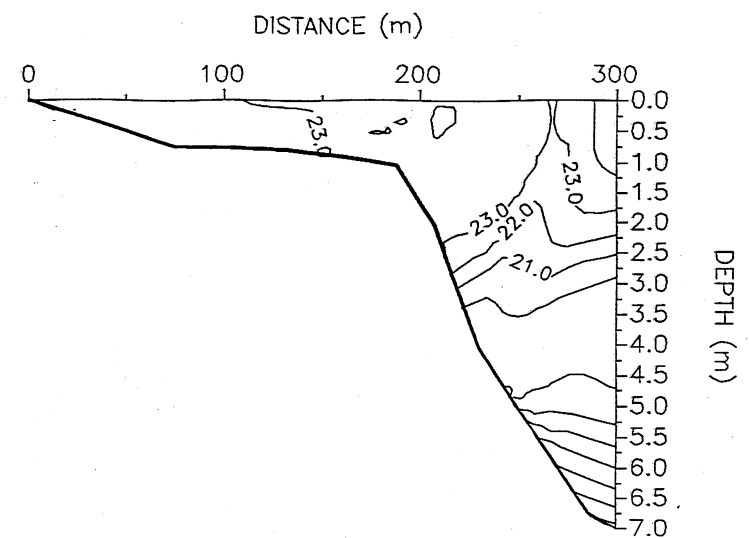
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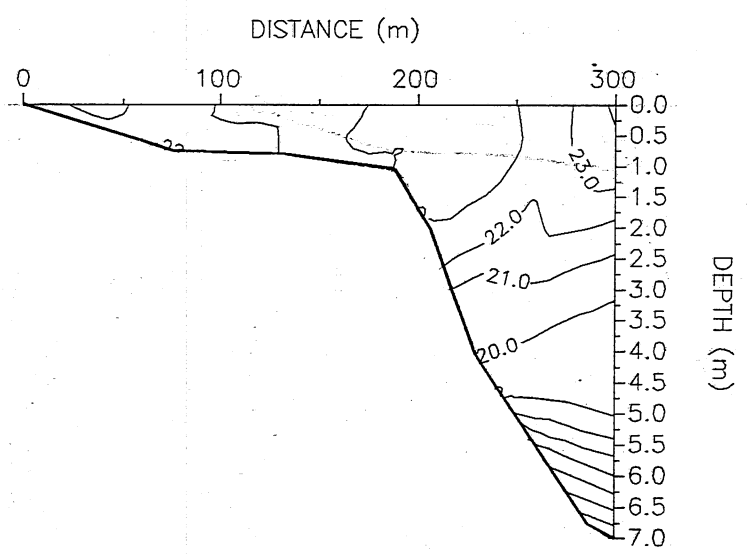
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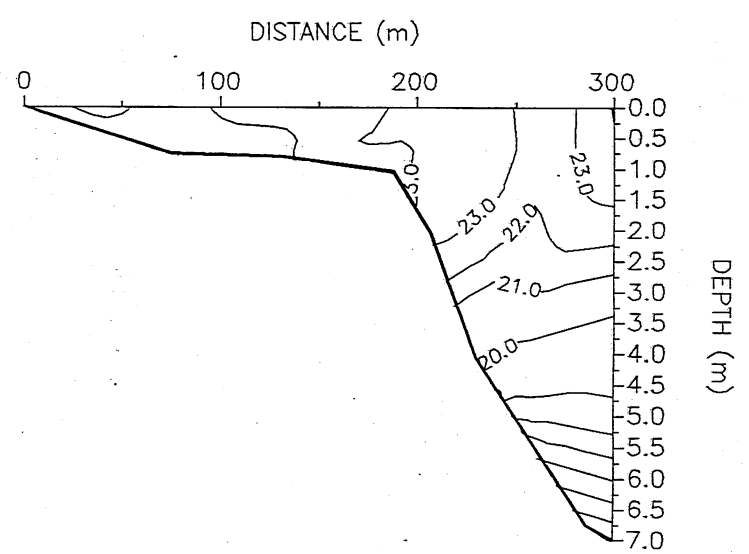
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JULY 19 1989 3:00

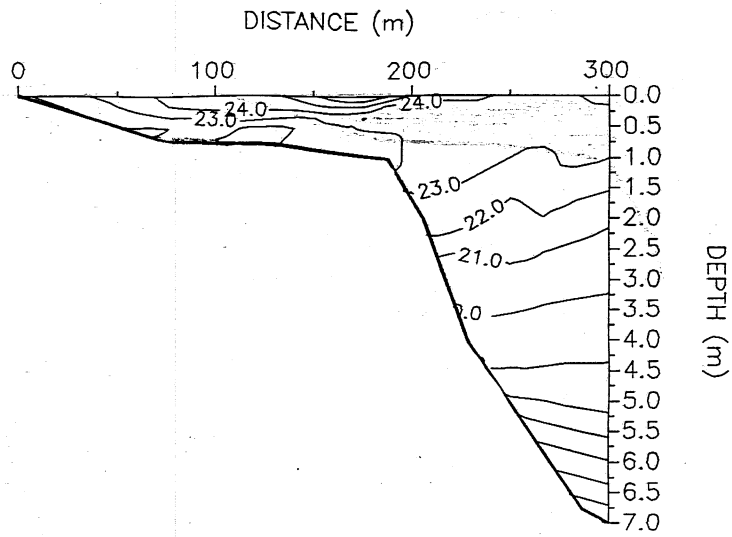


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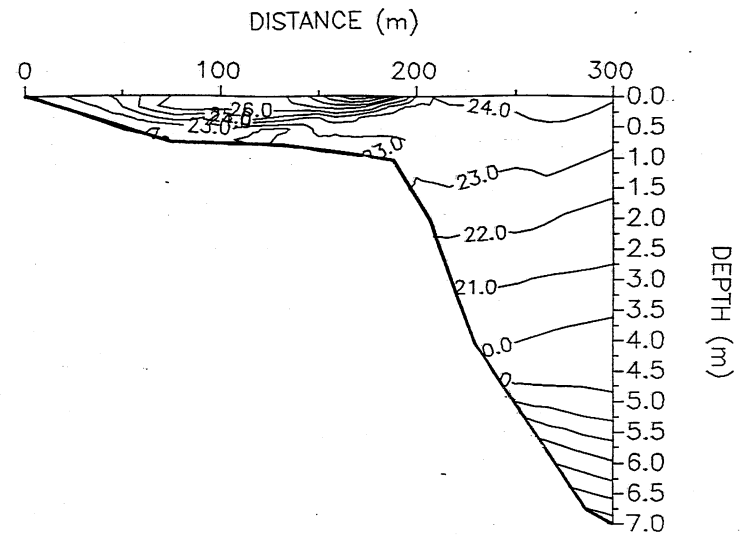


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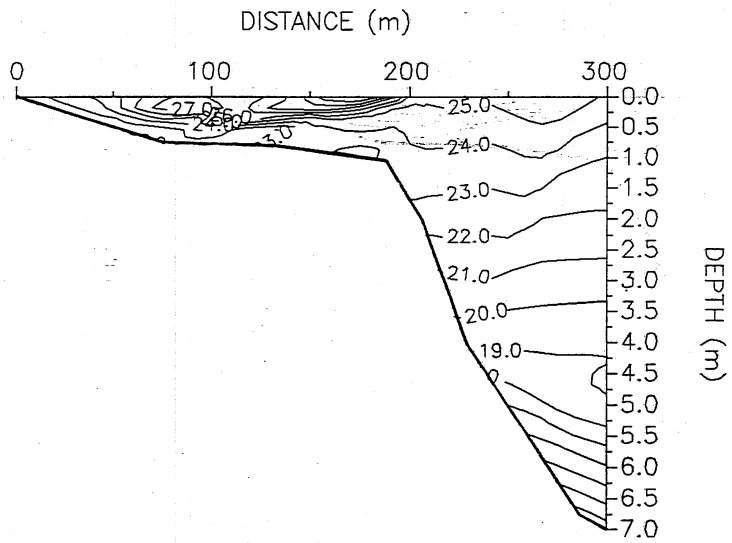
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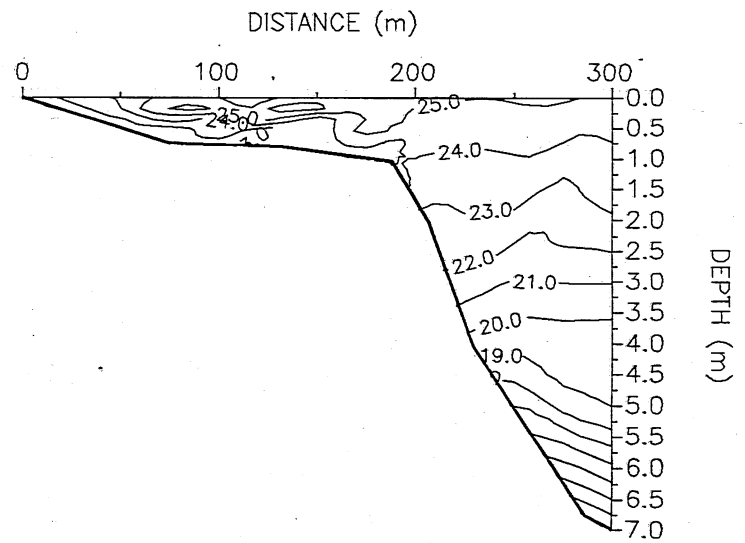
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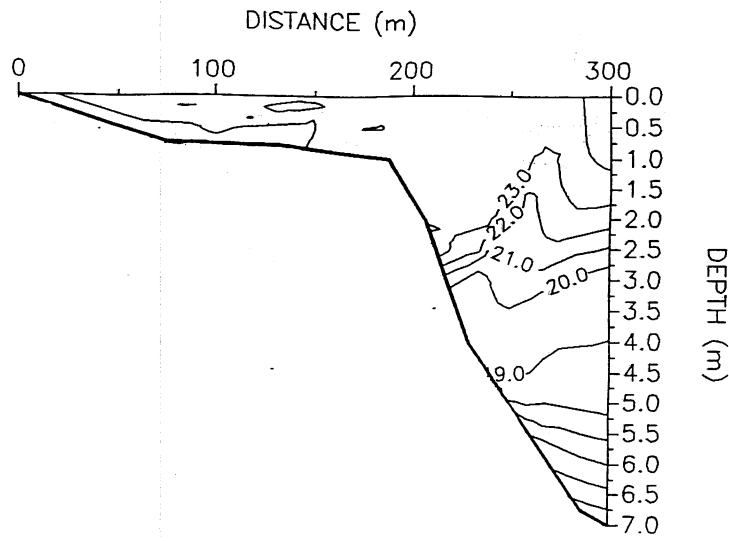


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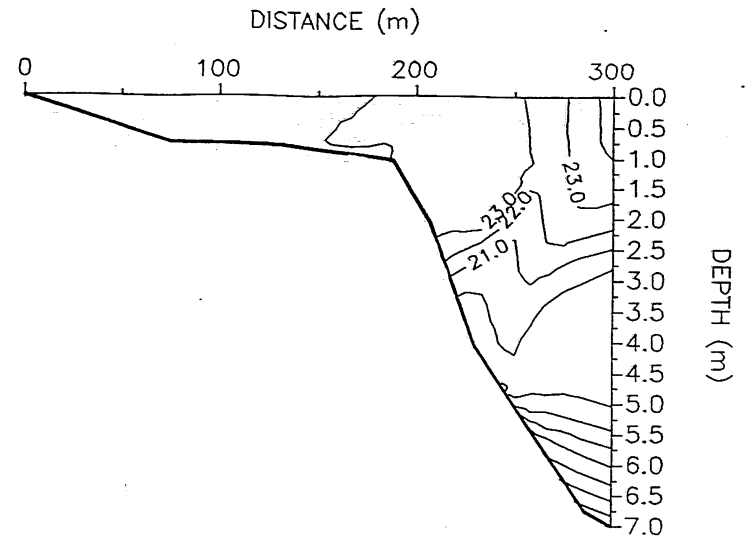


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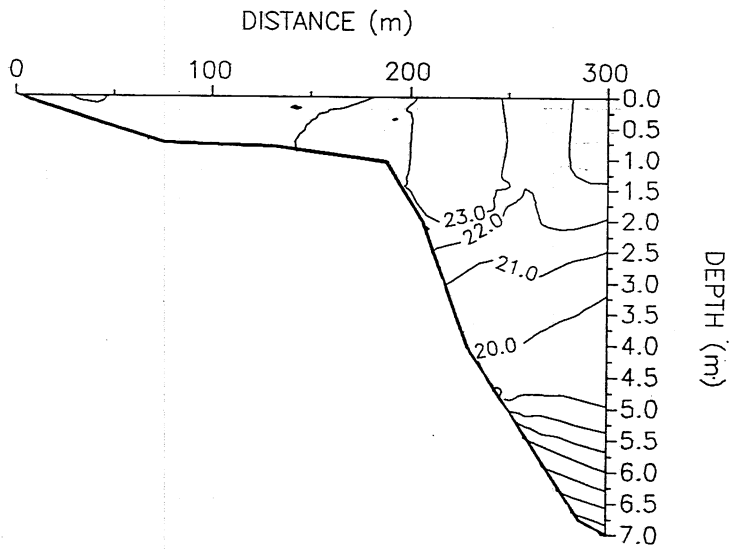




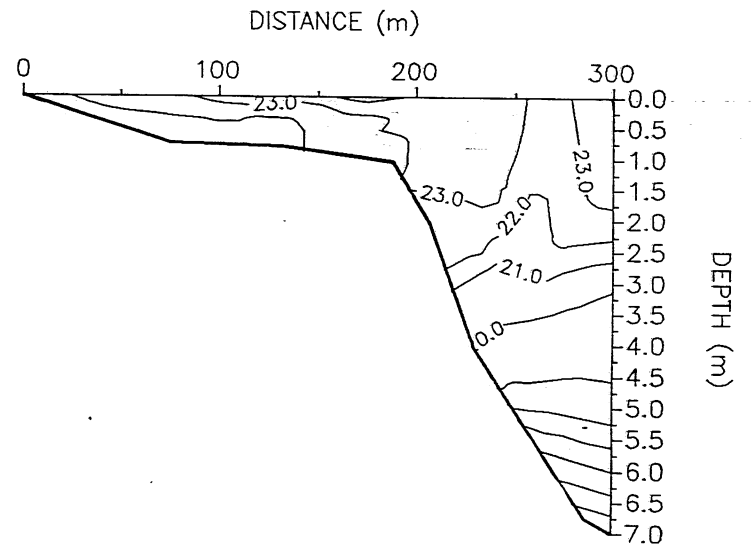
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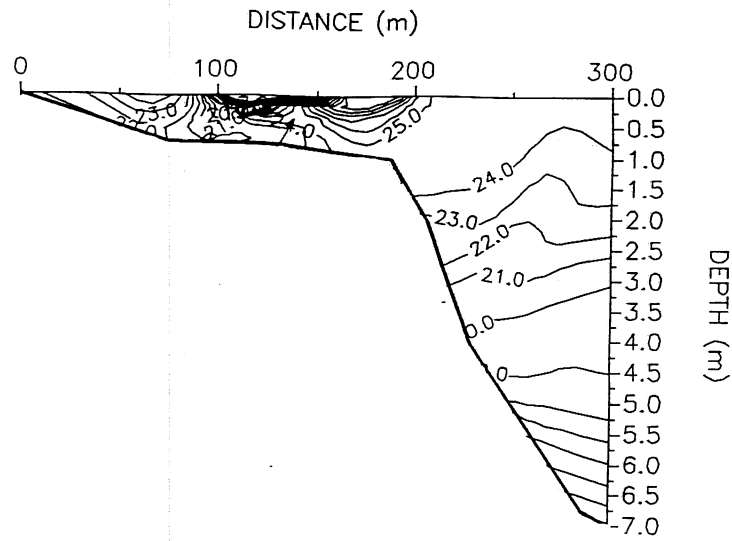
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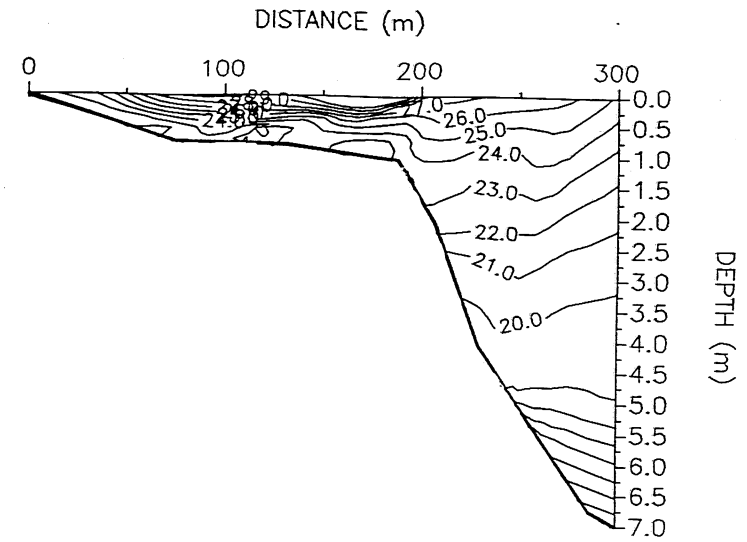
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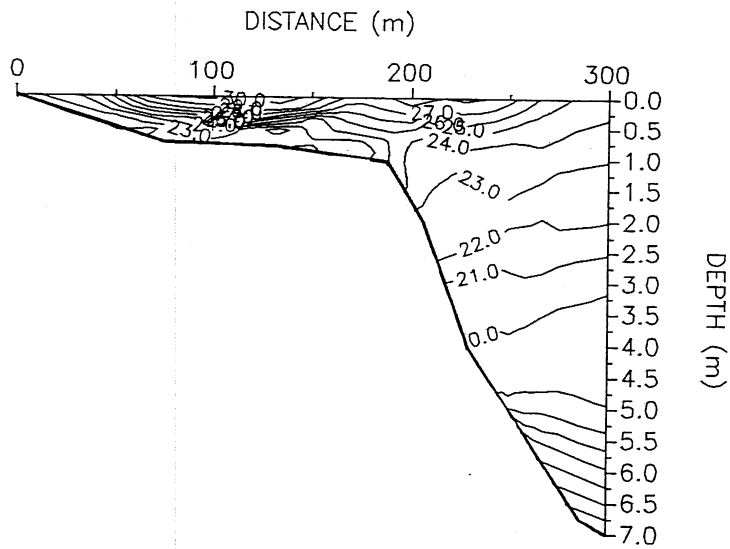
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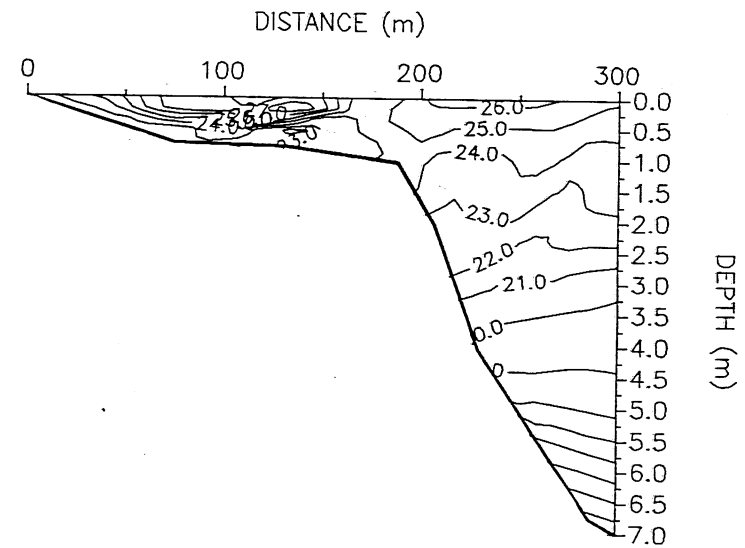
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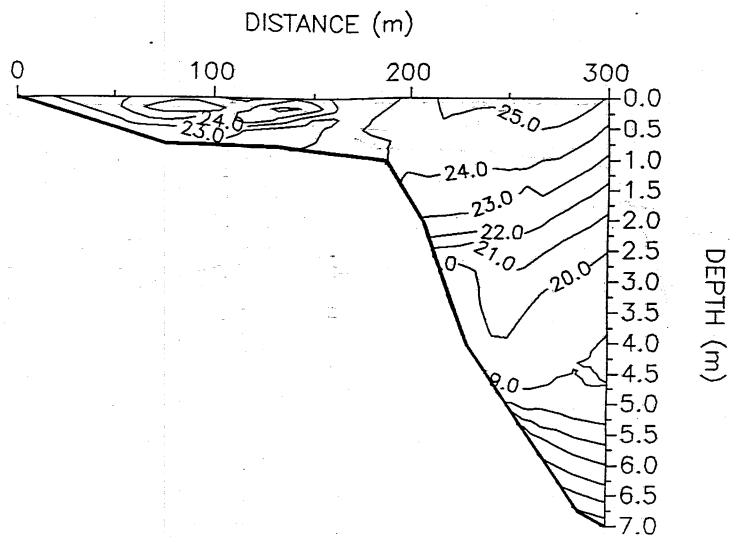
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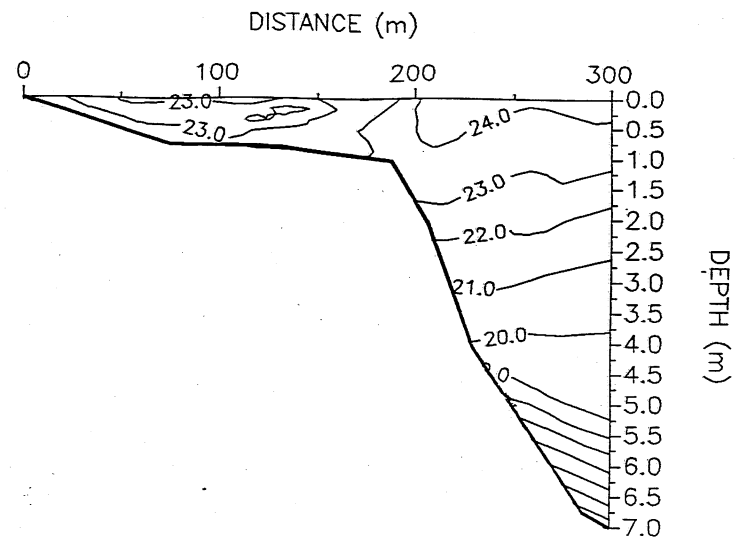
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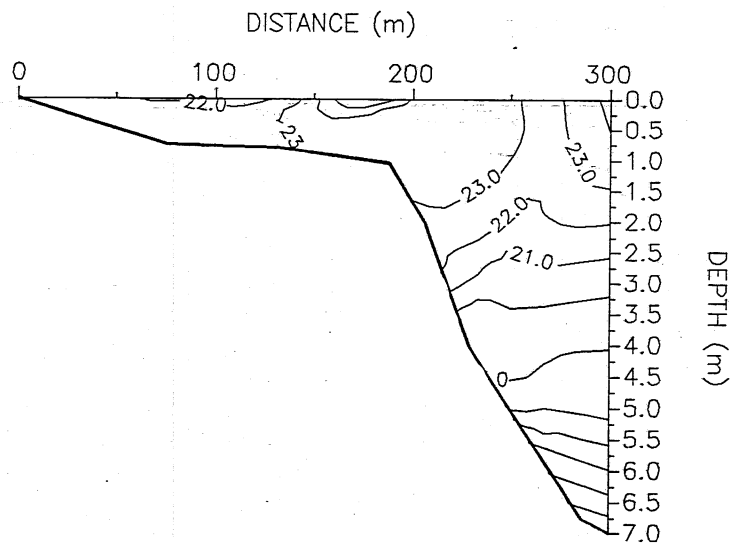
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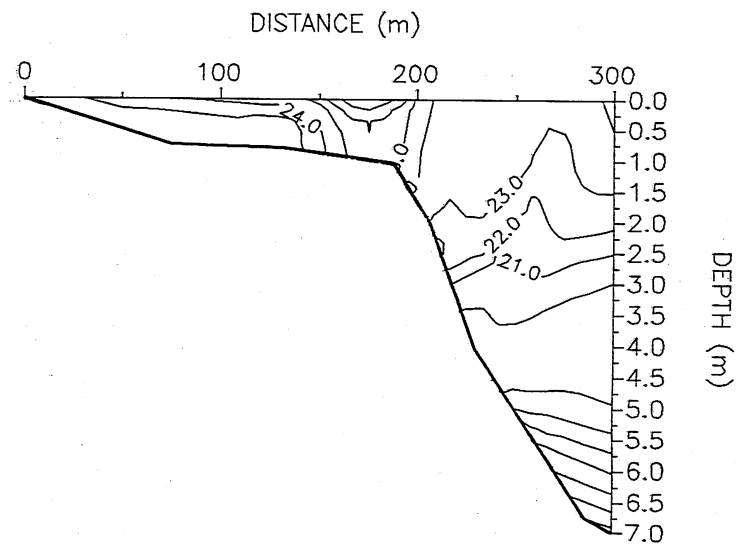
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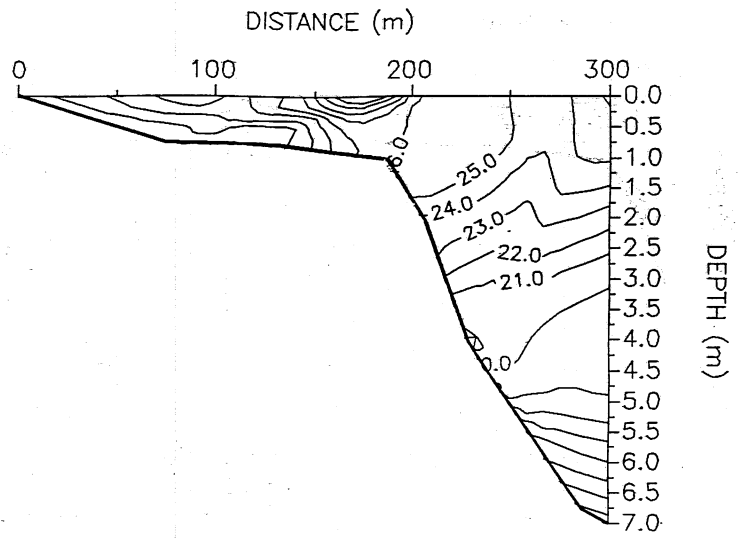
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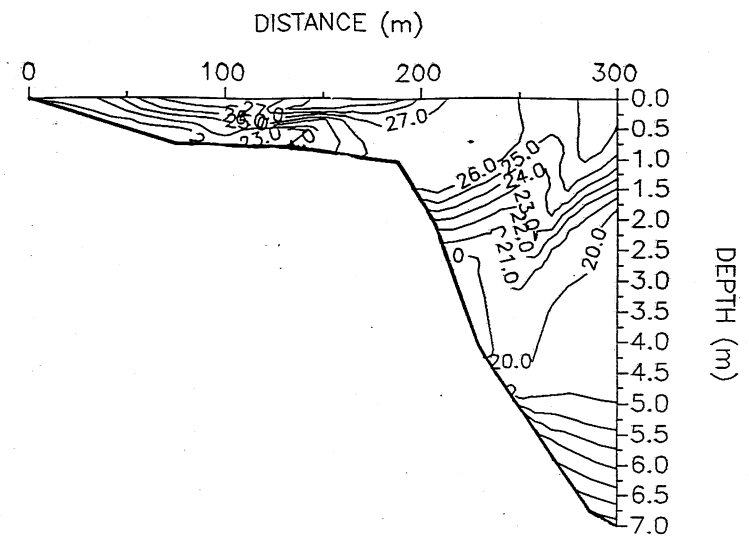
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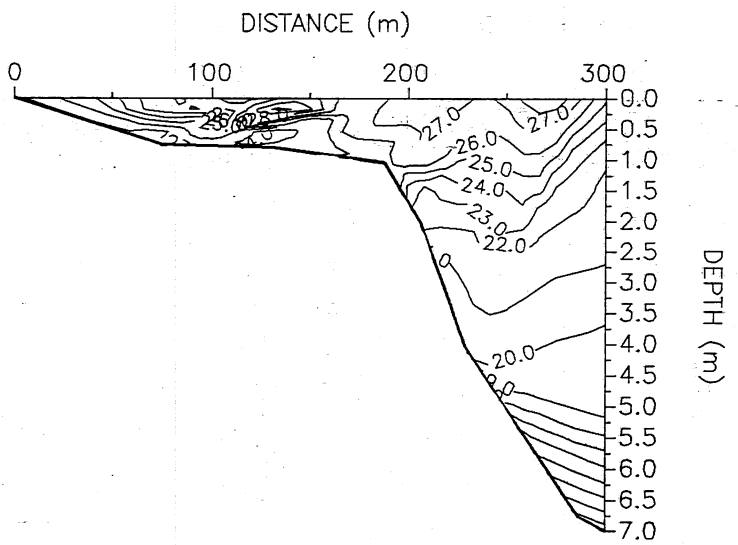
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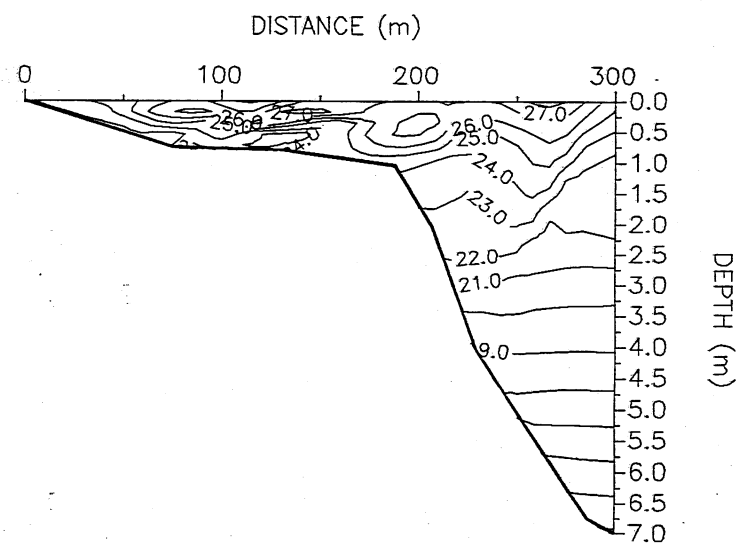
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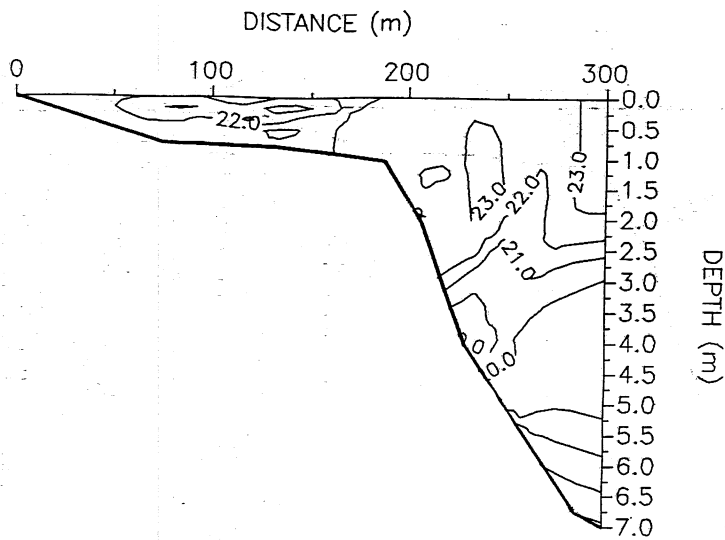
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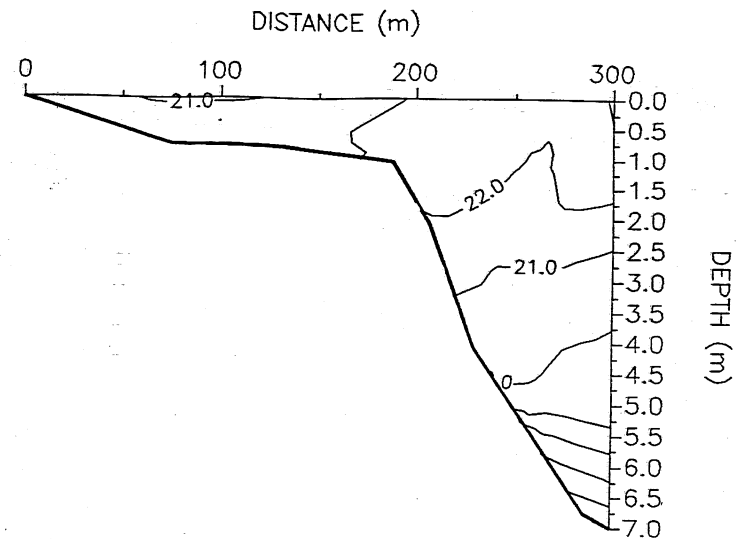
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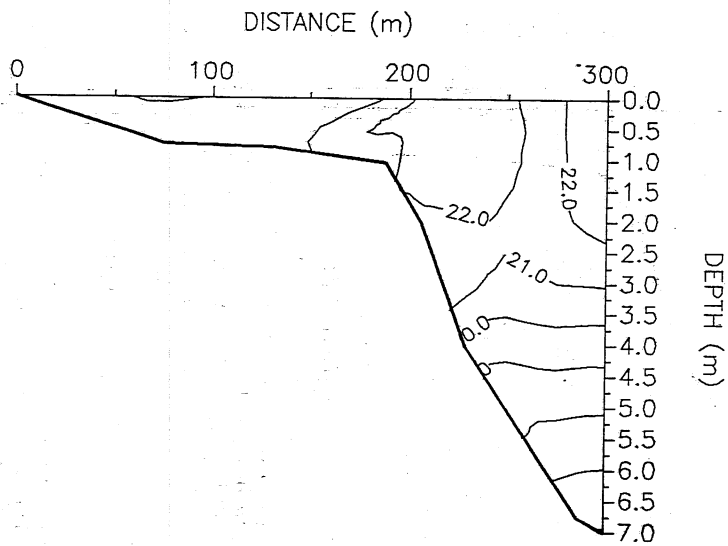
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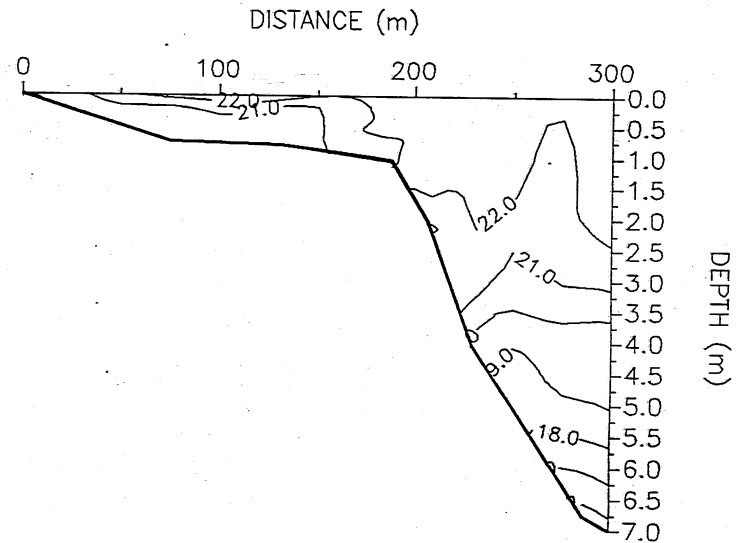
AUGUST 9 1989 0:00



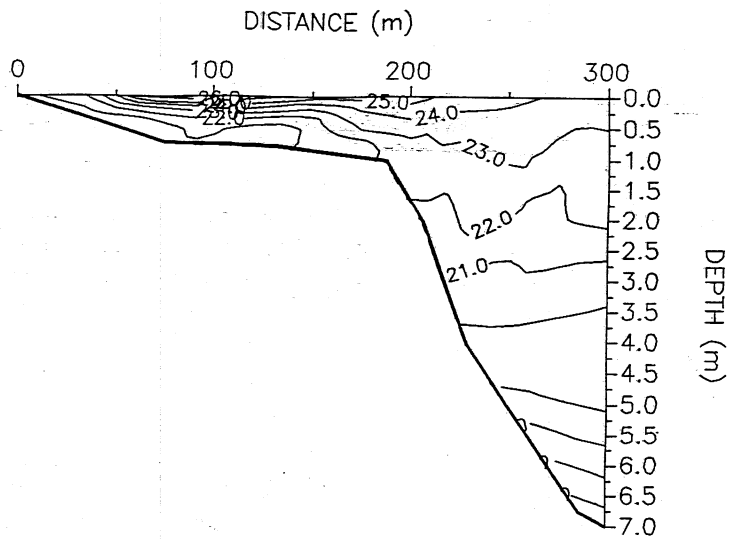
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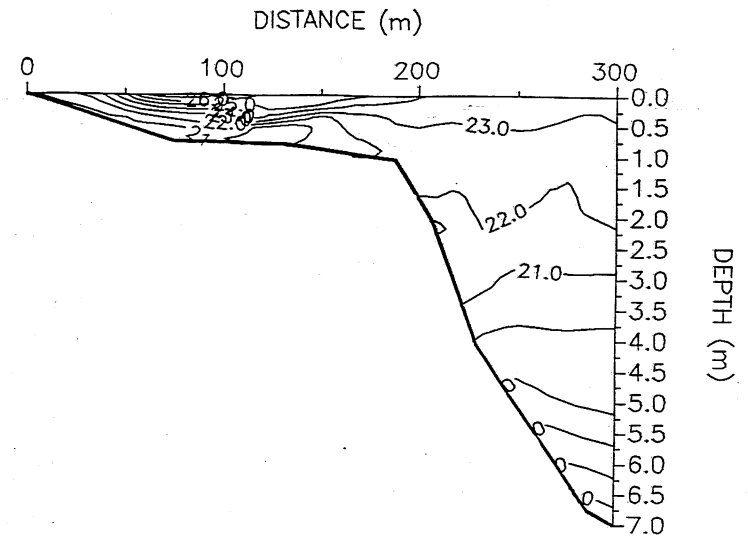
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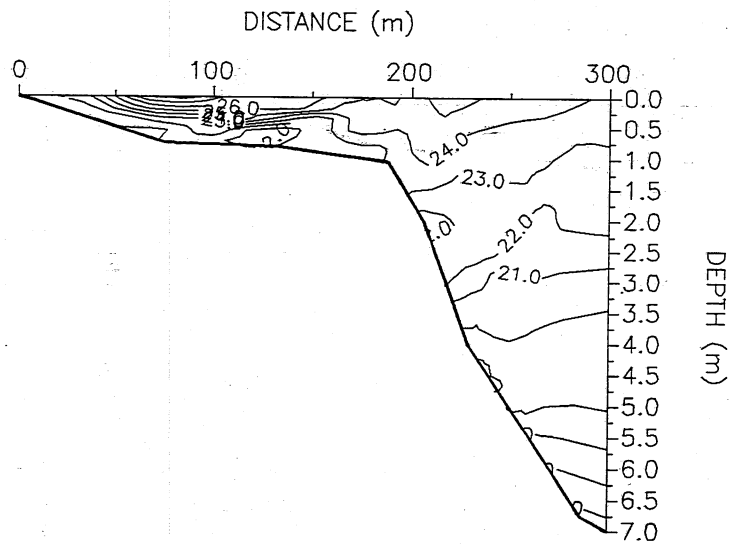
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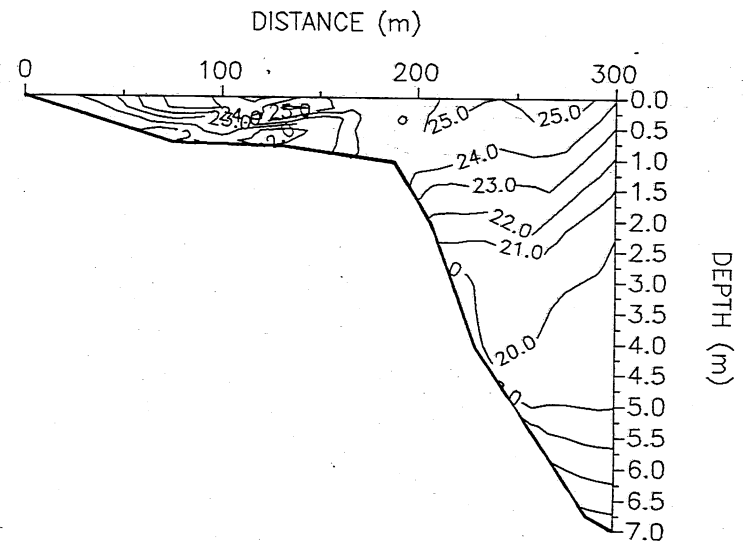
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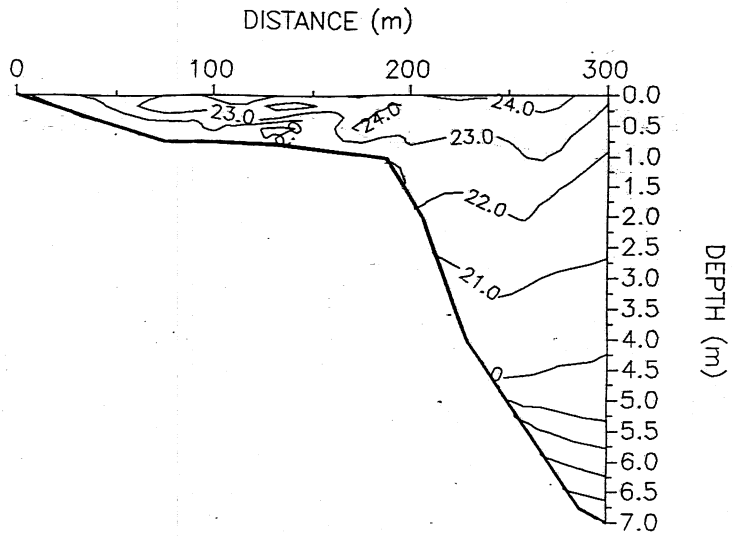
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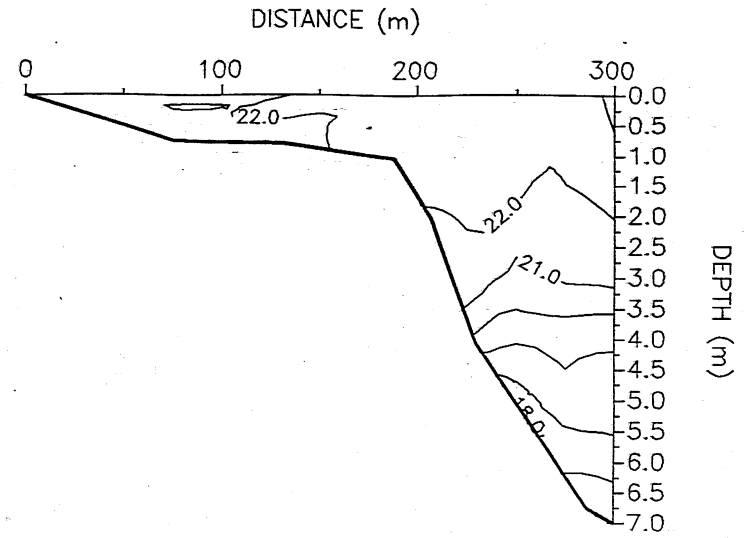
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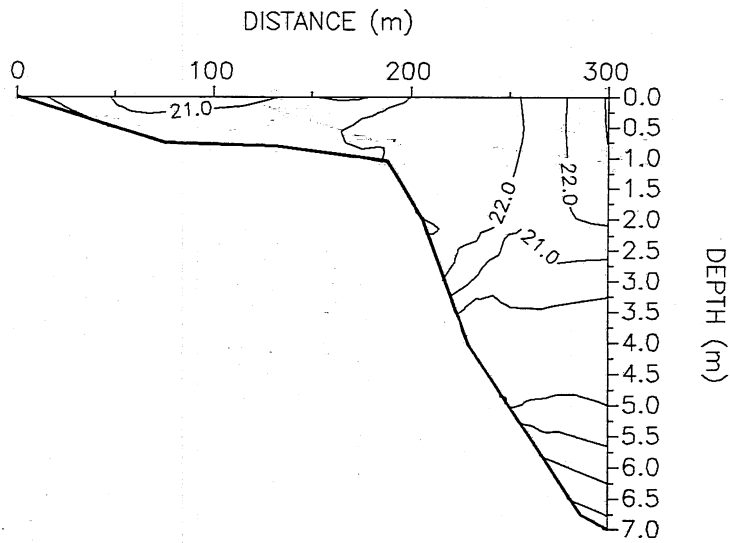
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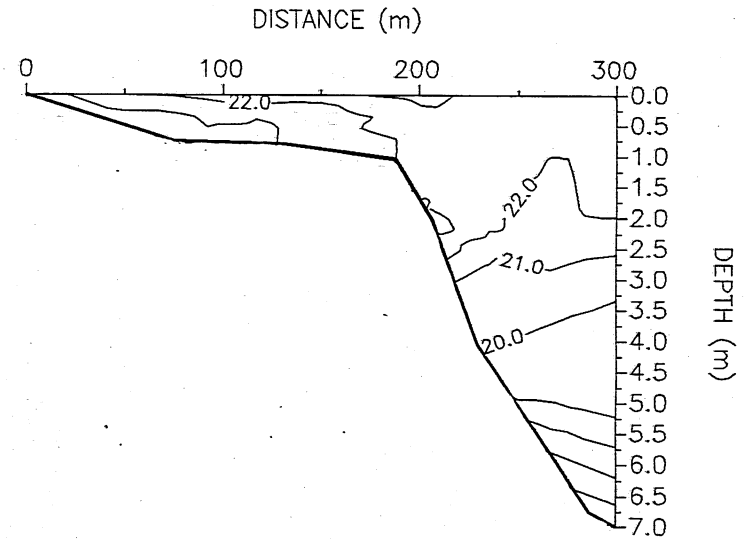
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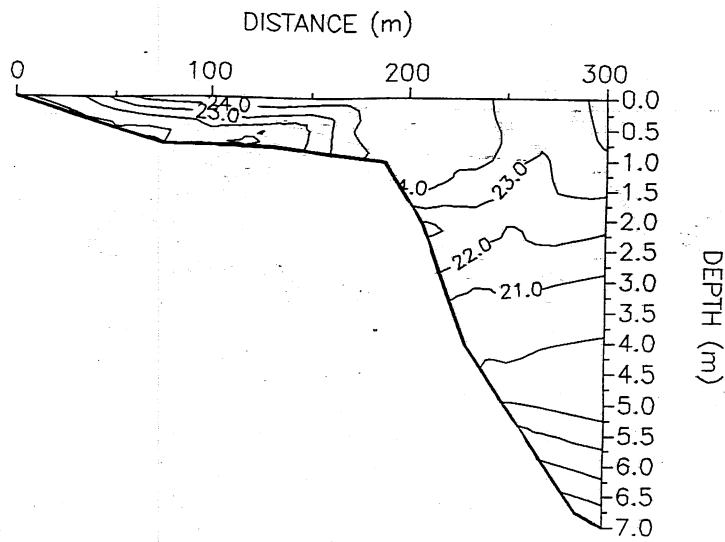
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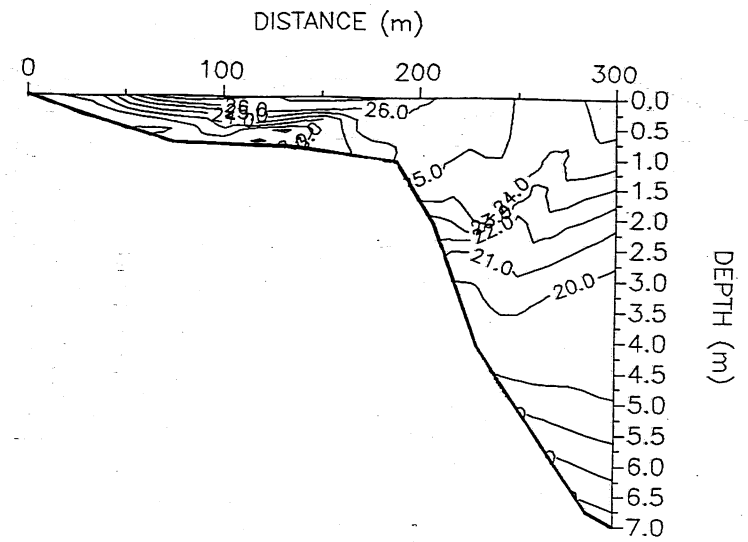
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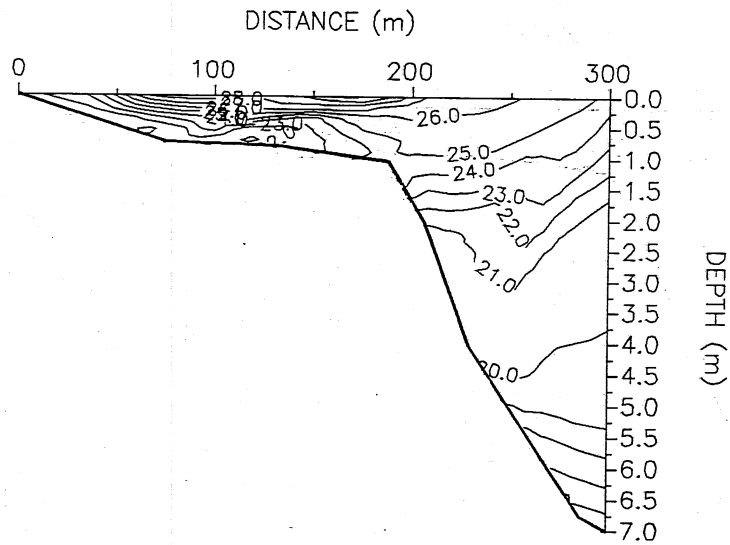
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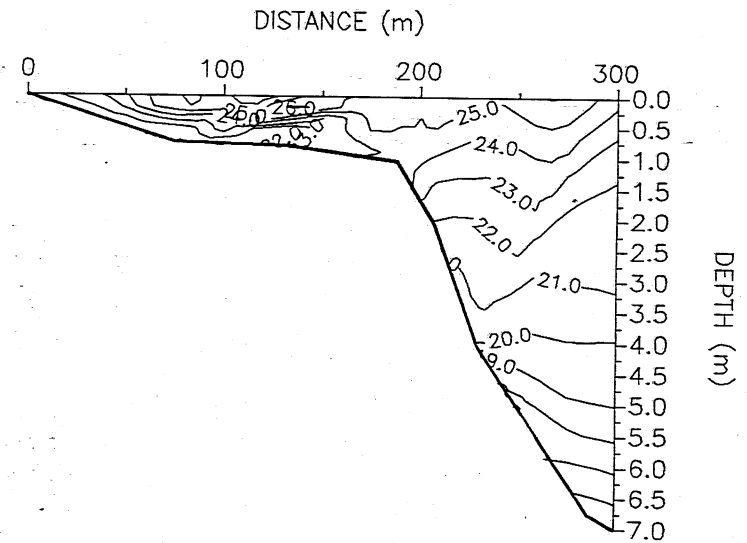
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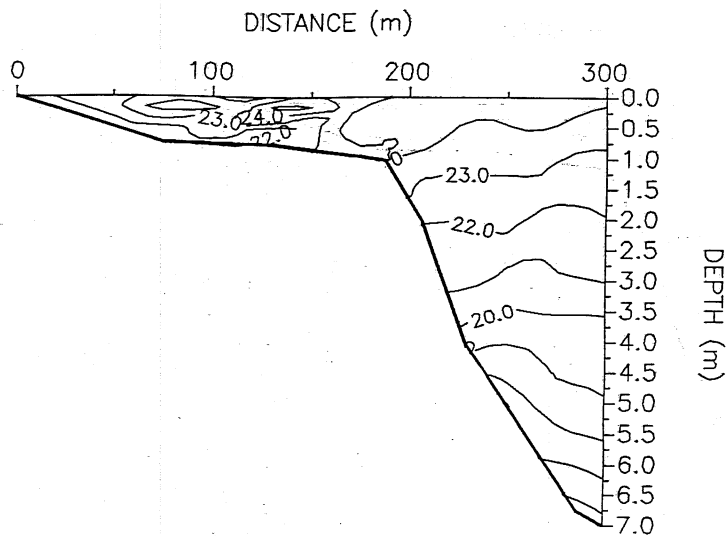


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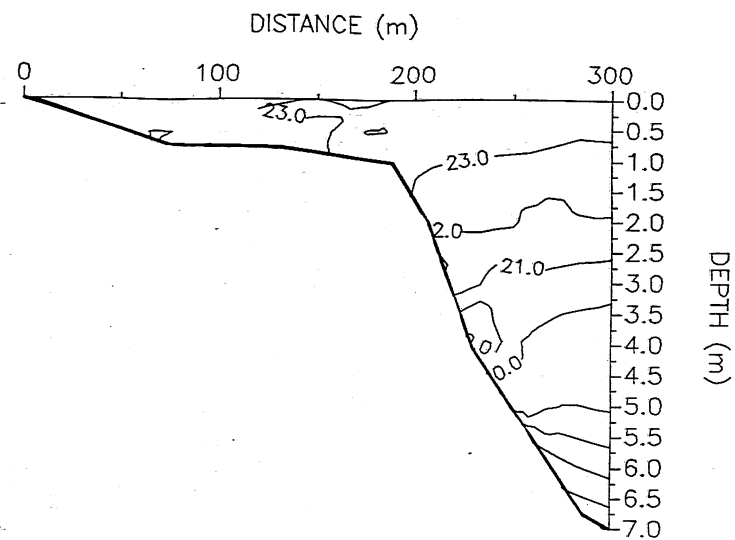


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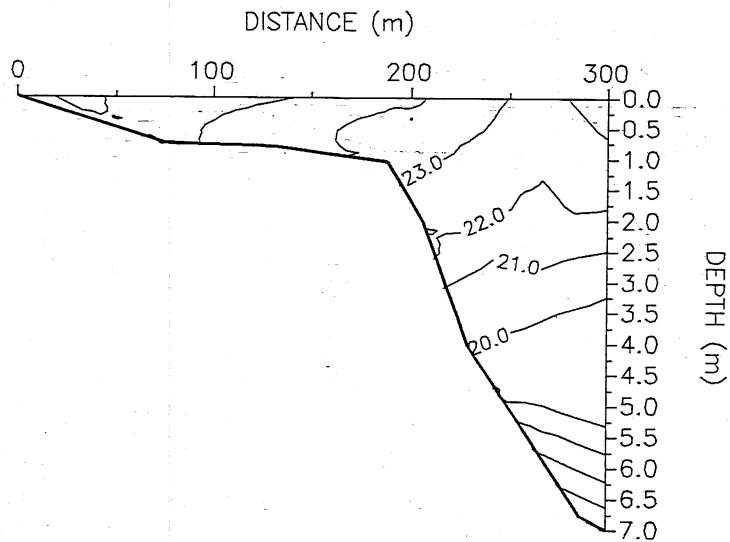




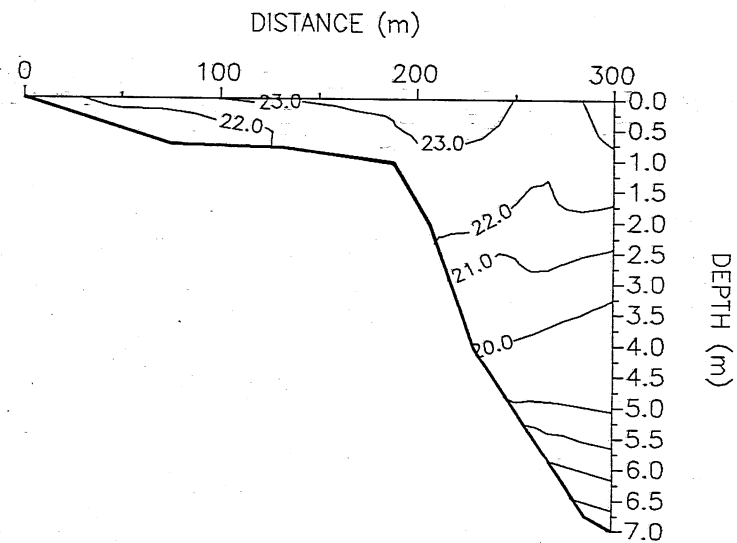
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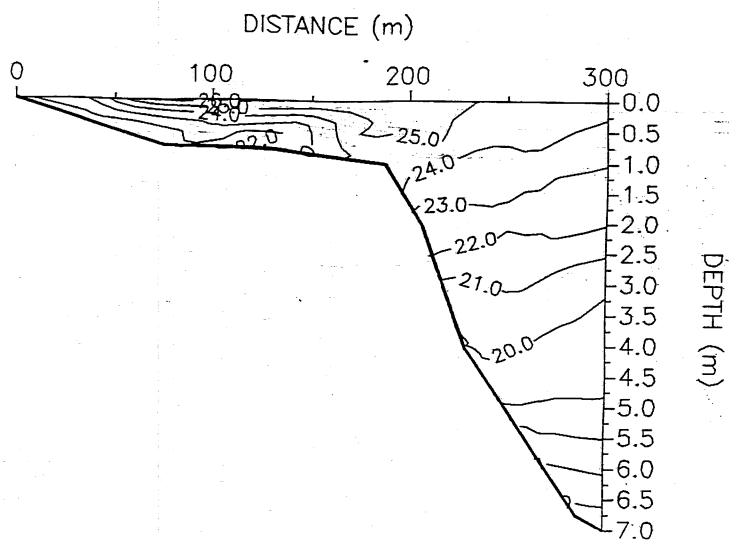
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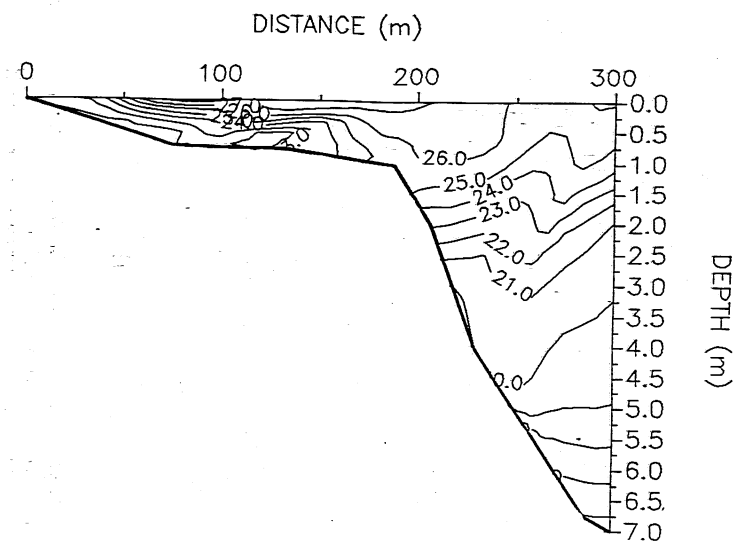
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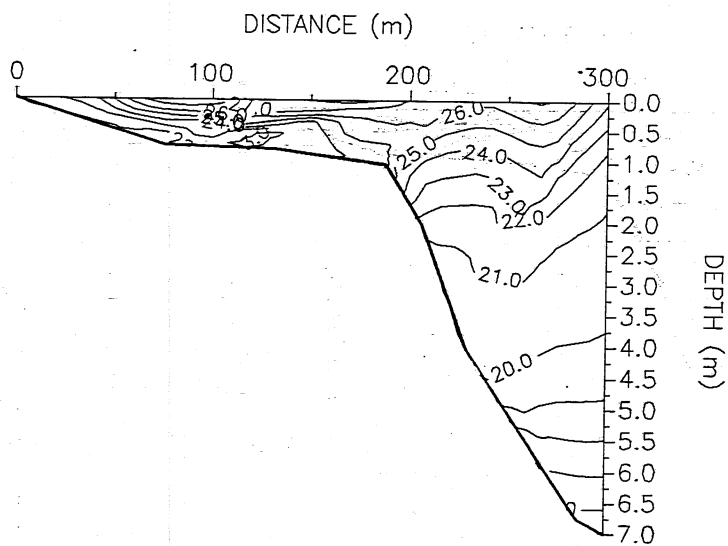
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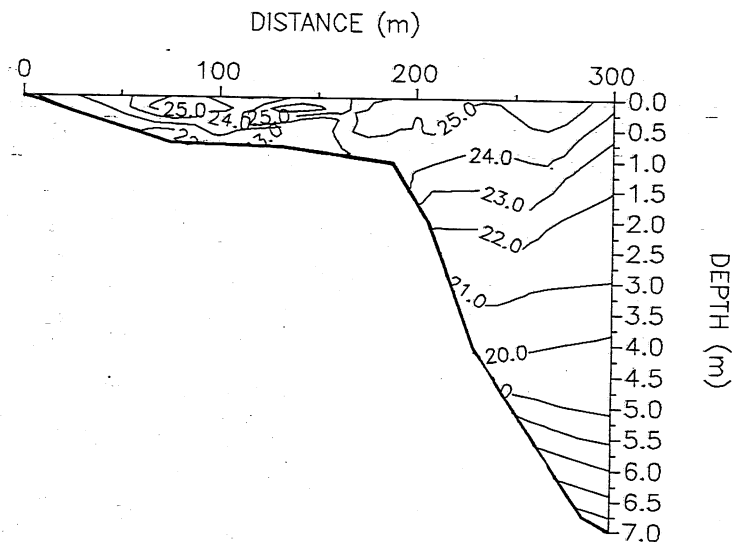
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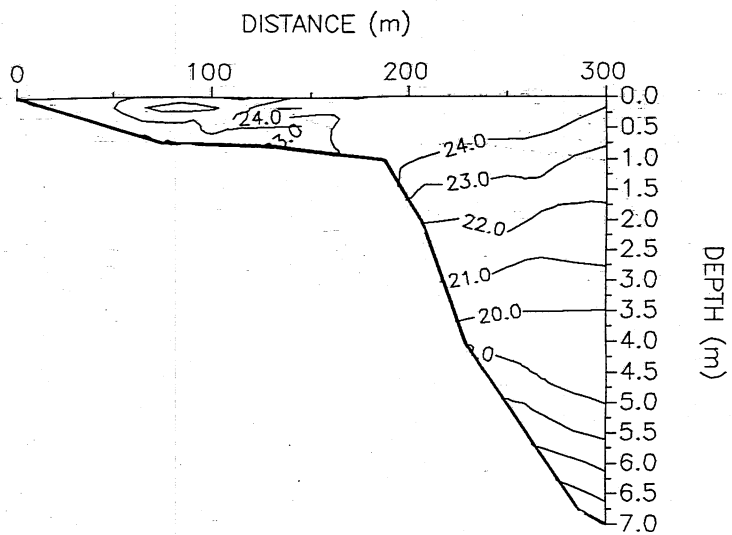
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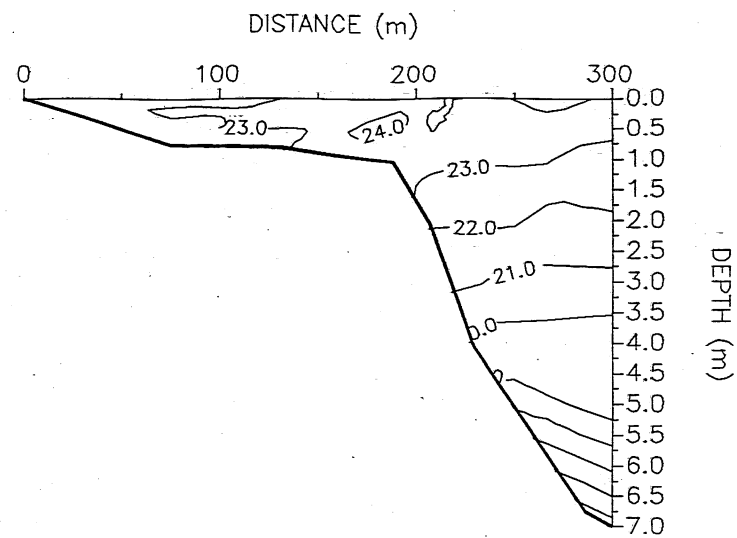
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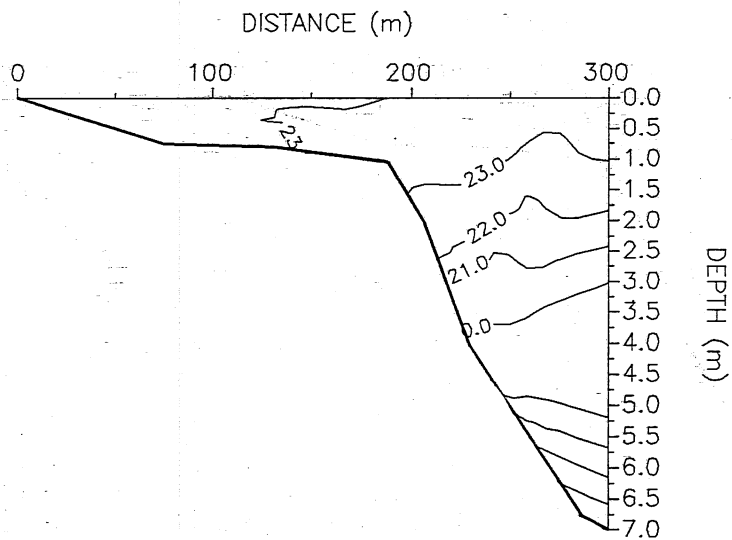
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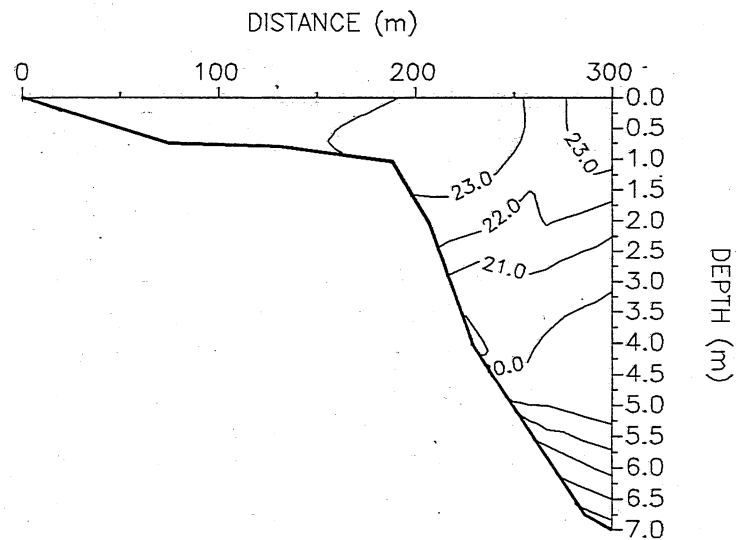
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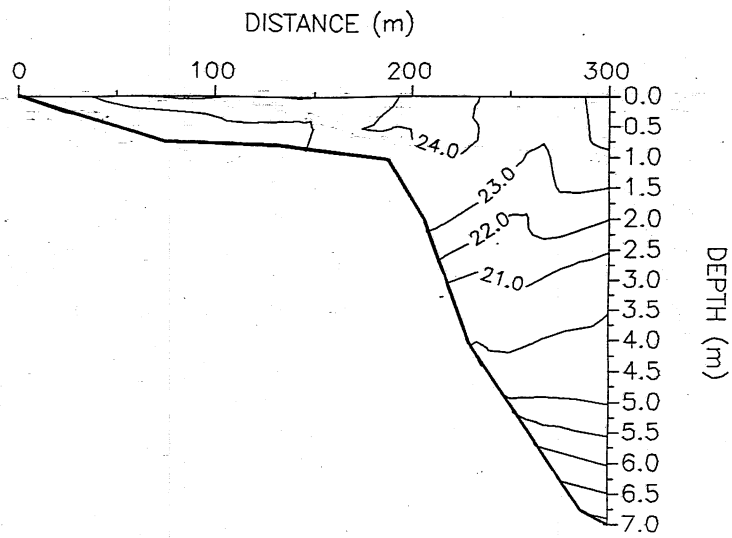
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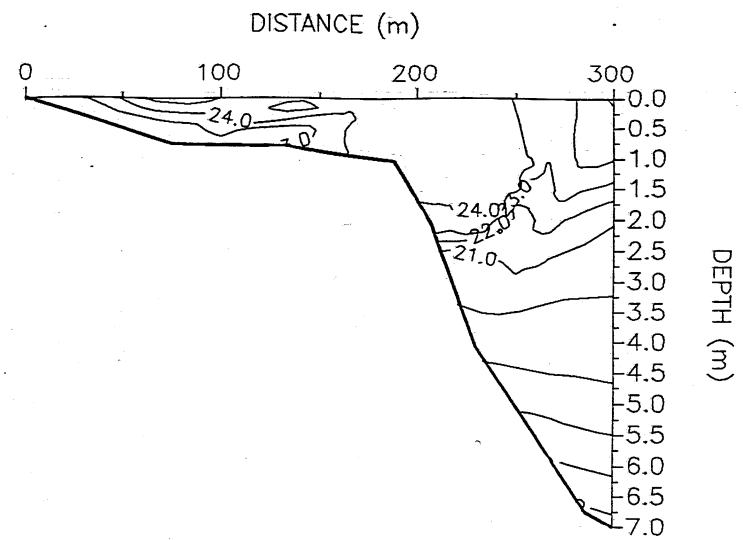
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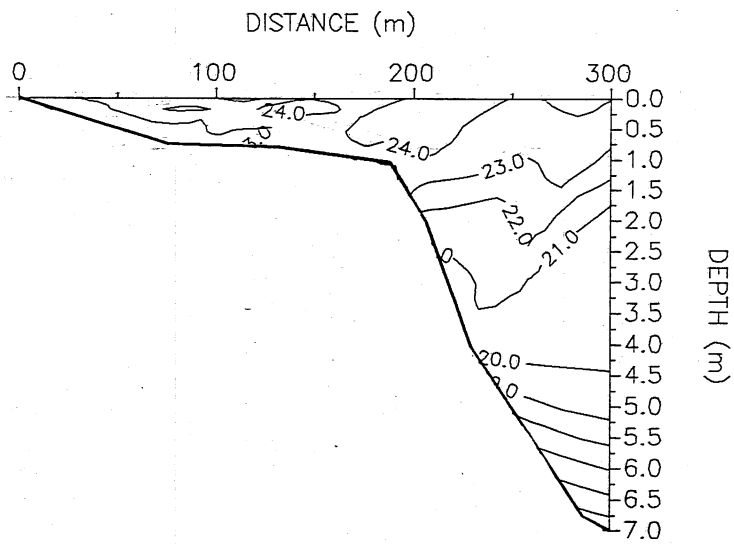
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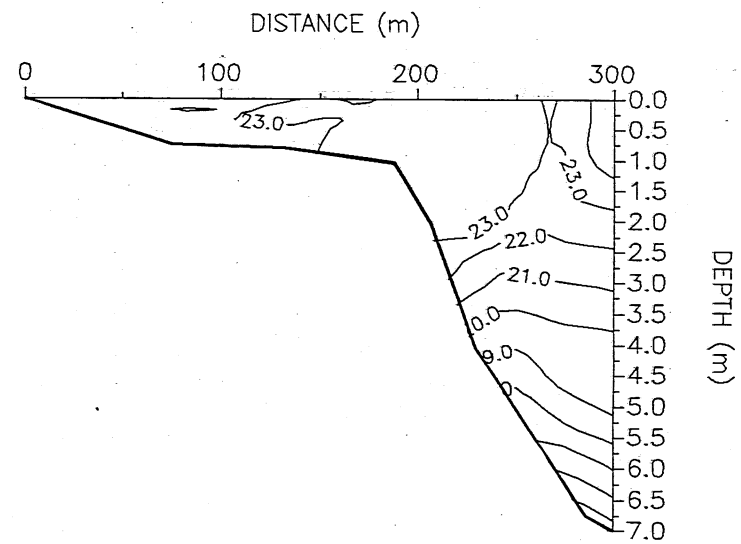
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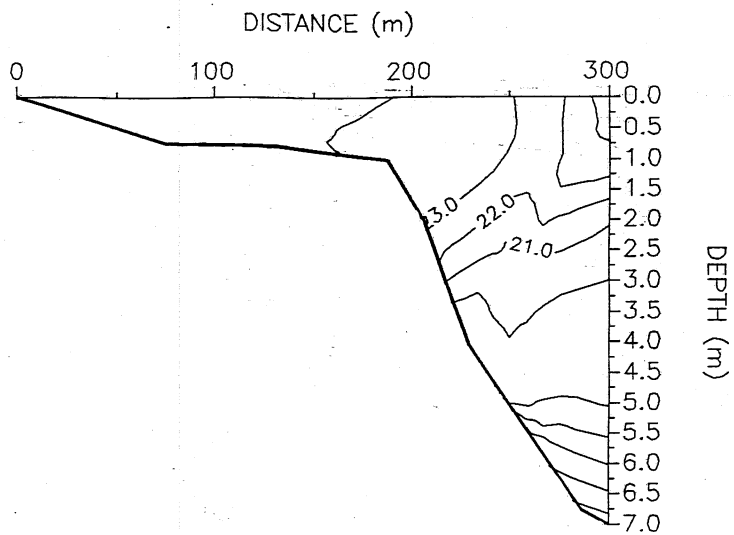
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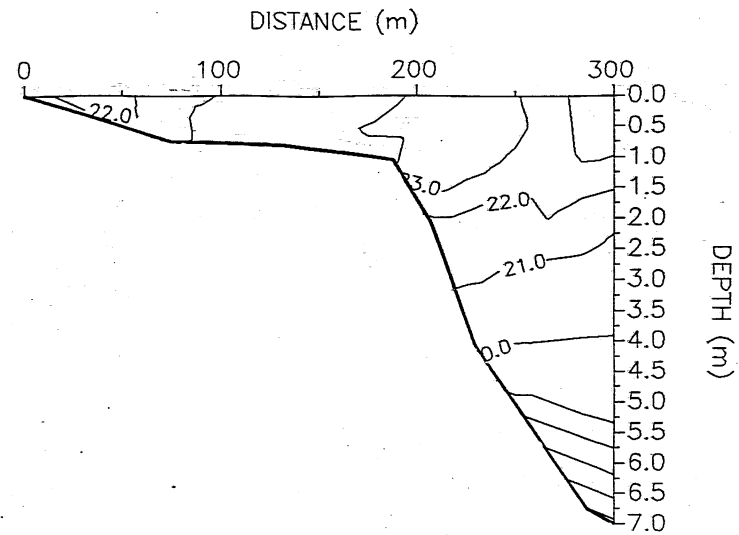
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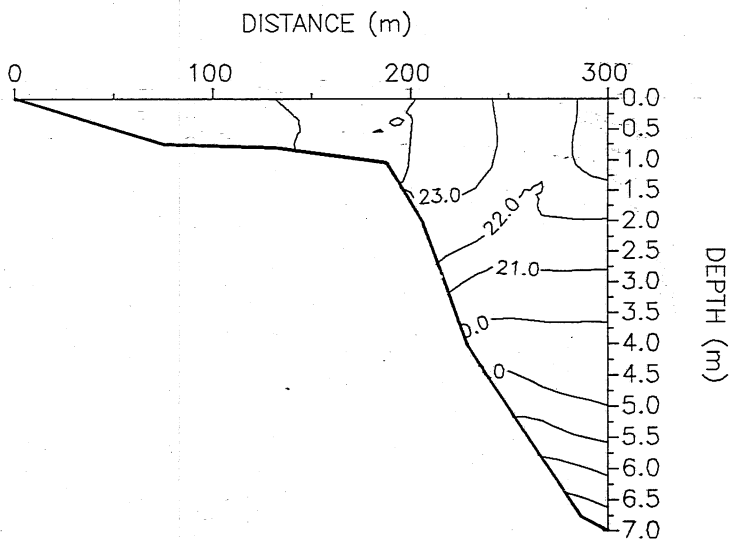
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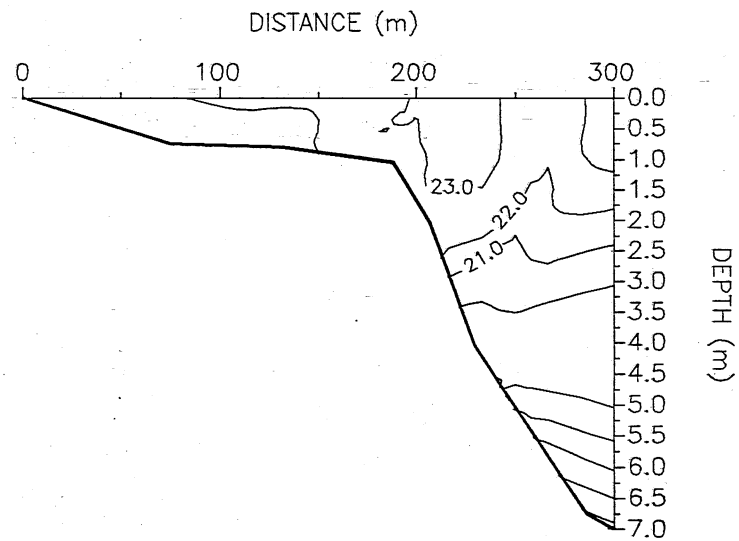
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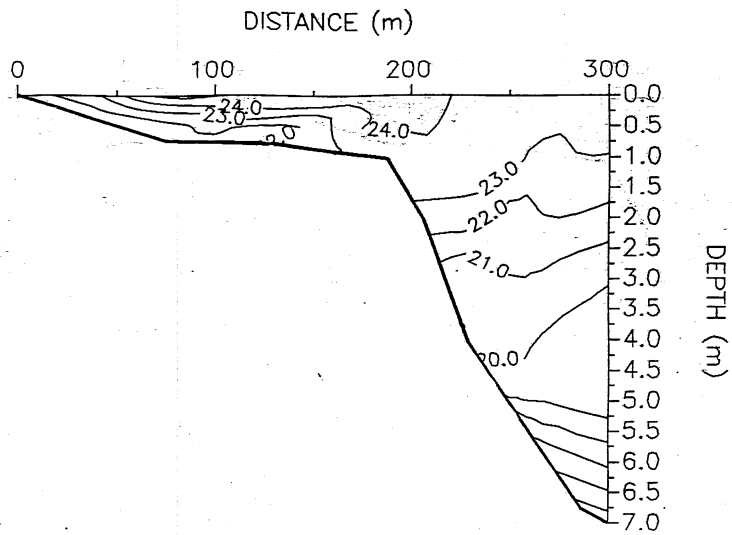
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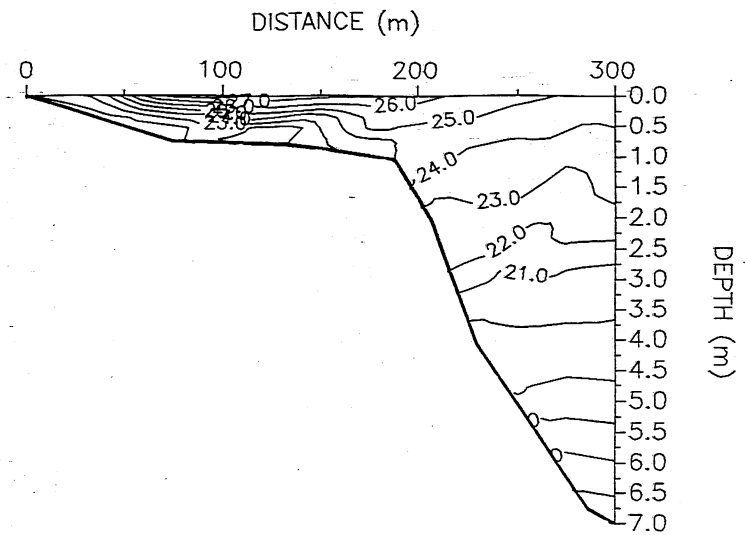
AUGUST 13 1989 6:00



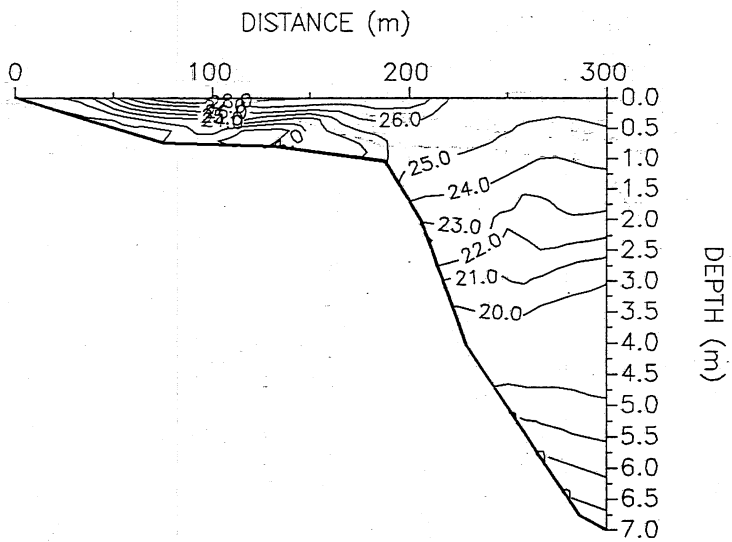
AUGUST 13 1989 9:00



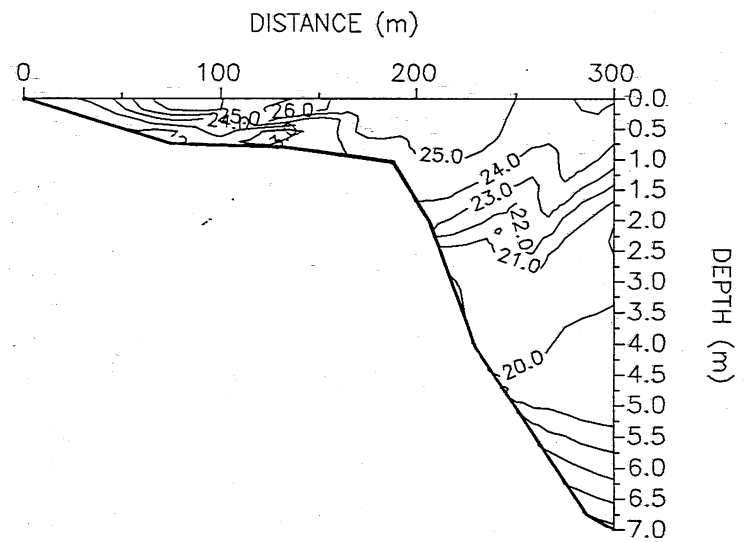
AUGUST 13 1989 12:00



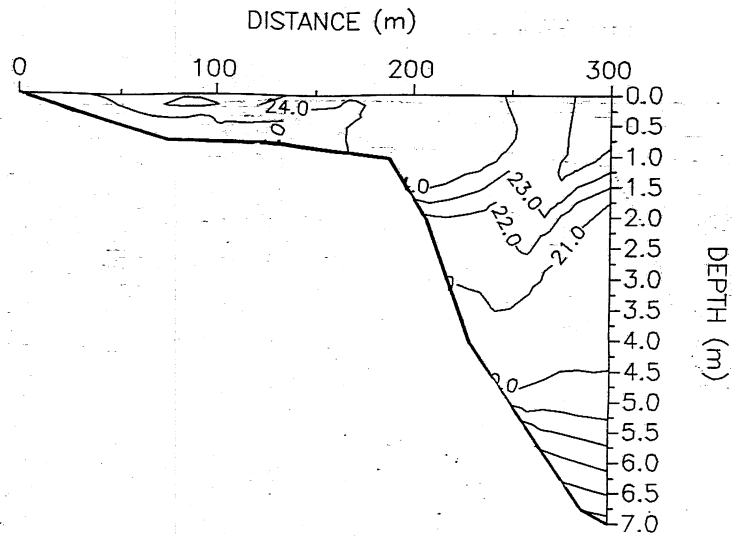
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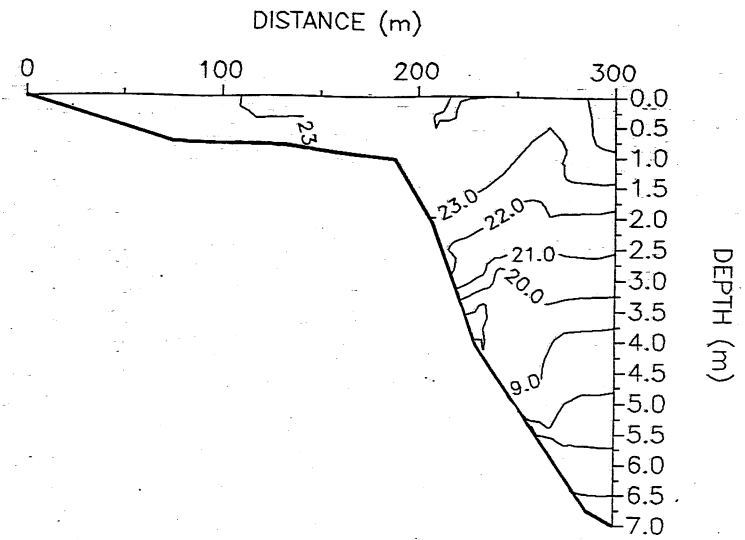
AUGUST 13 1989 18:00



AUGUST 13 1989 21:00

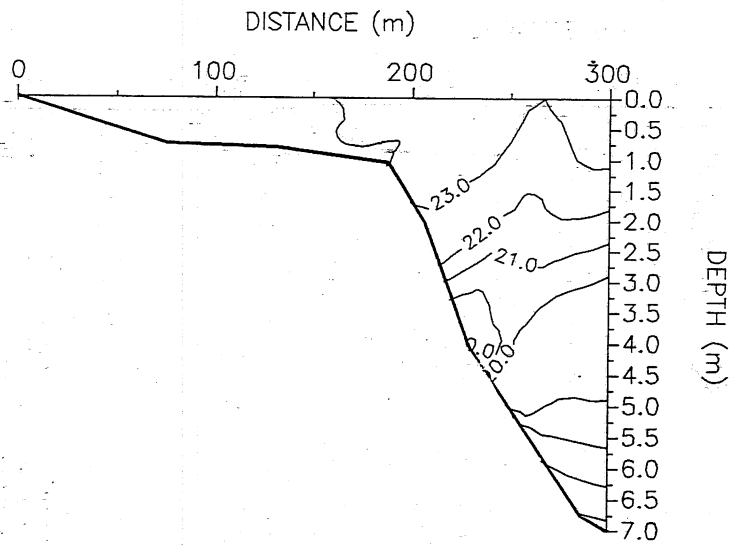


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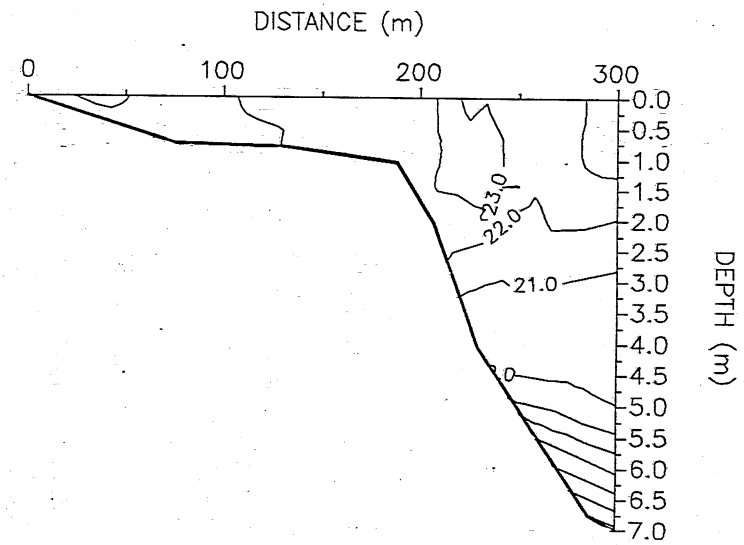


AUGUST 14 1989 3:00

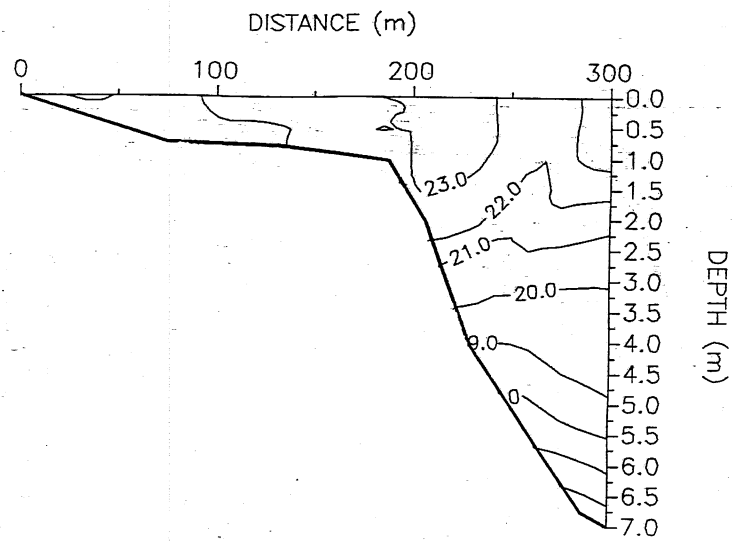
A-69



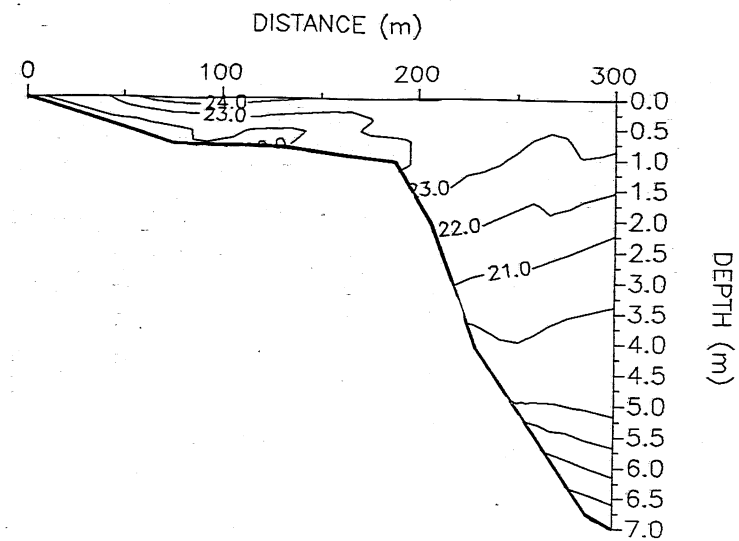
AUGUST 14 1989 6:00



AUGUST 14 1989 9:00

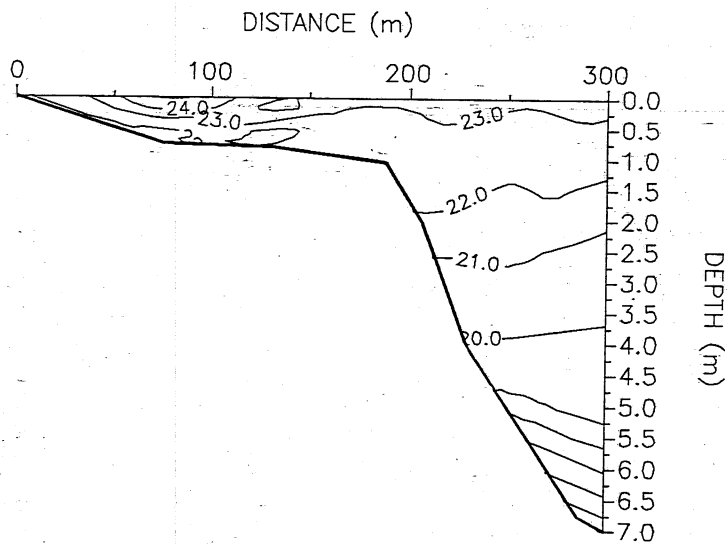


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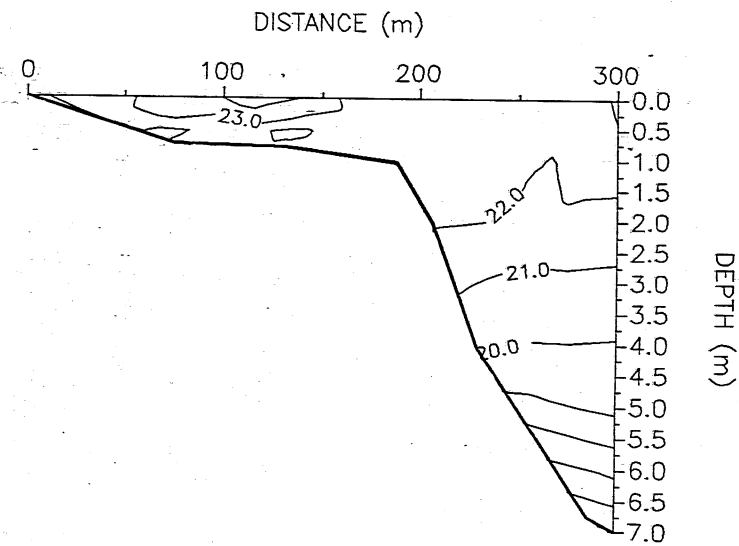


AUGUST 14 1989 15:00

A-70

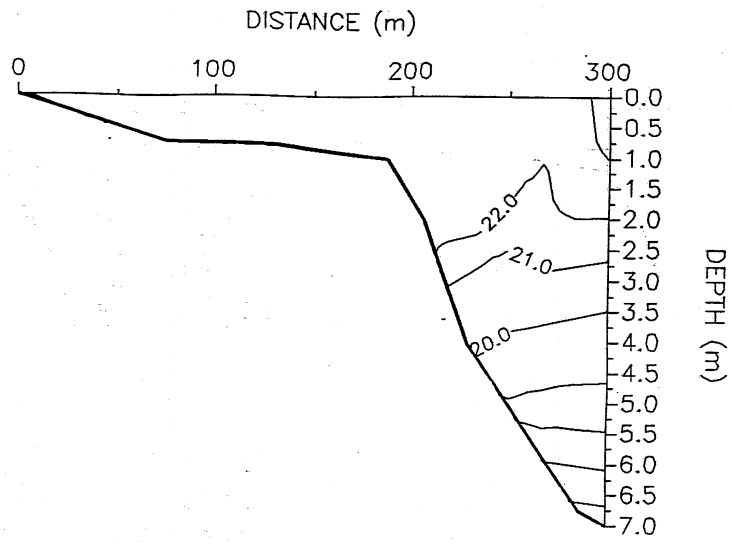


AUGUST 14 1989 18:00

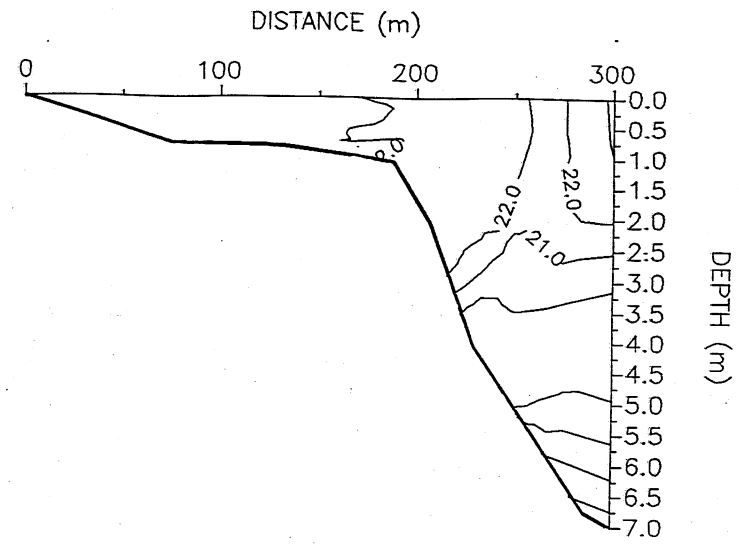


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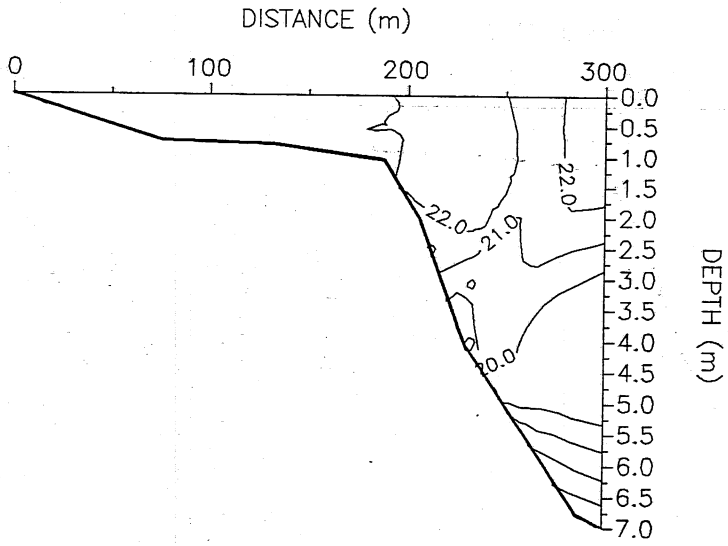




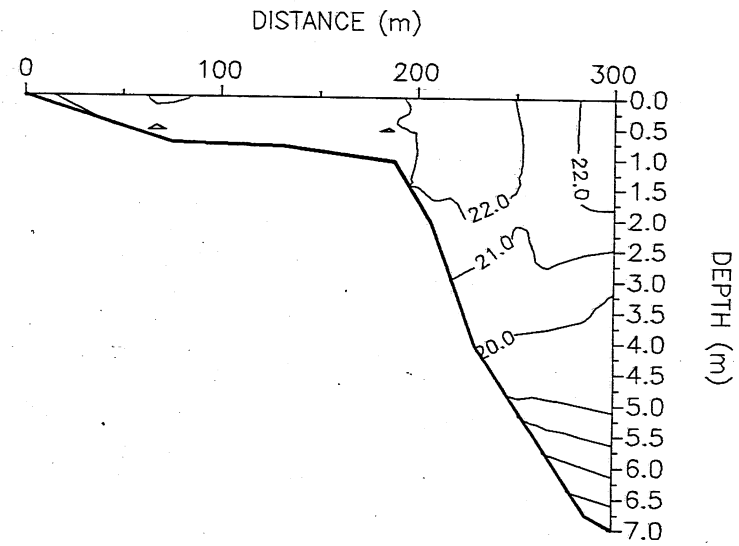
AUGUST 15 1989 0:00



AUGUST 15 1989 3:00

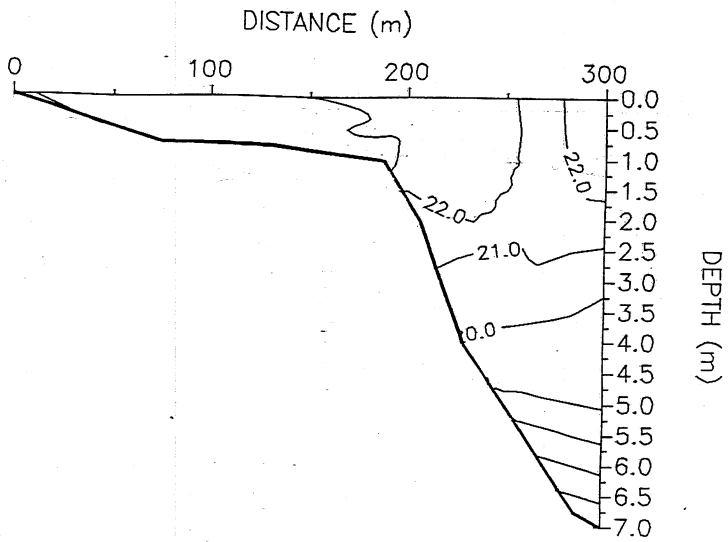


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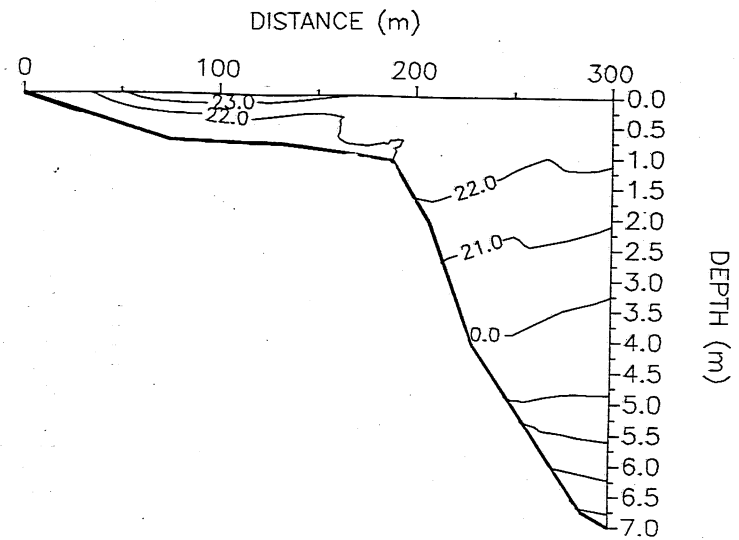


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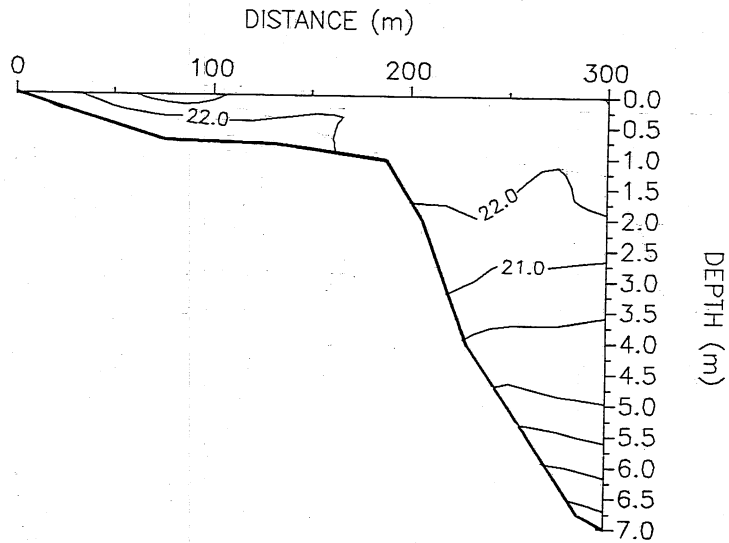
A-71



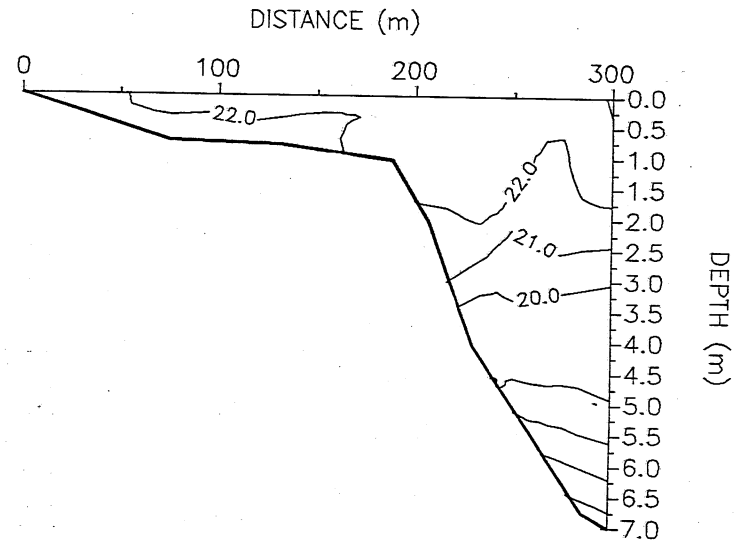
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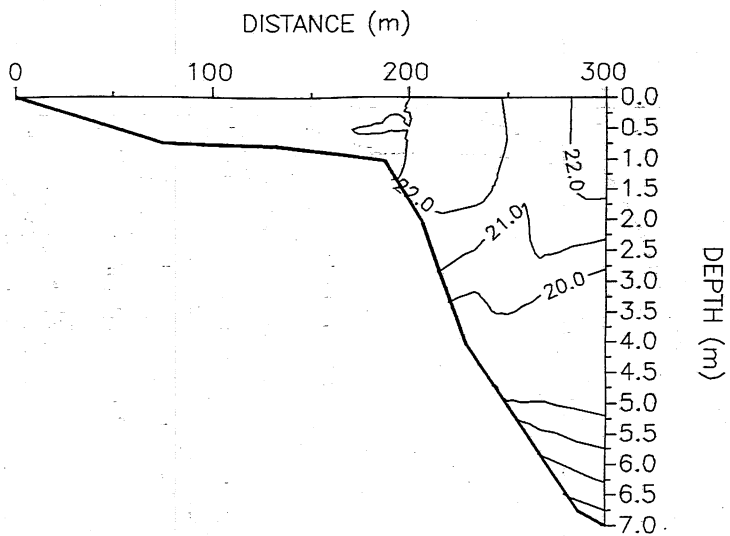
AUGUST 15 1989 15:00



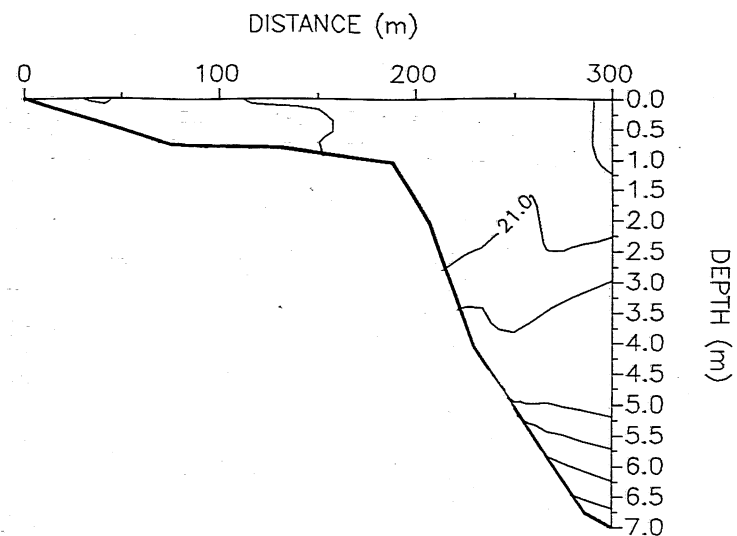
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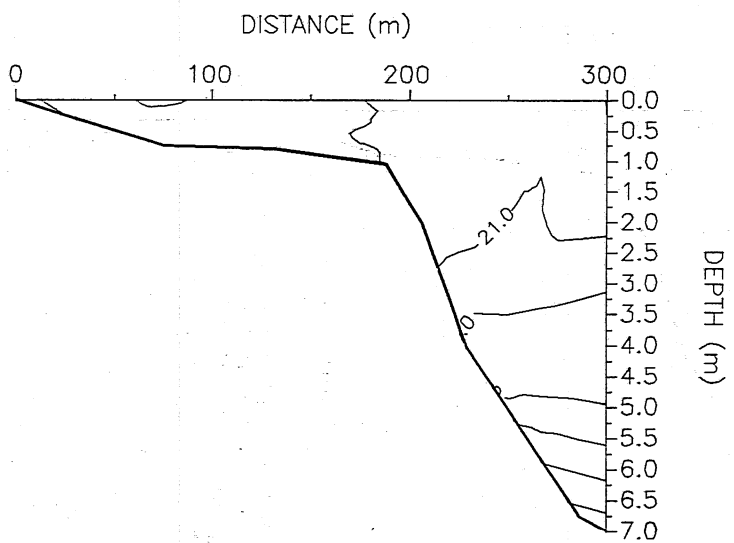
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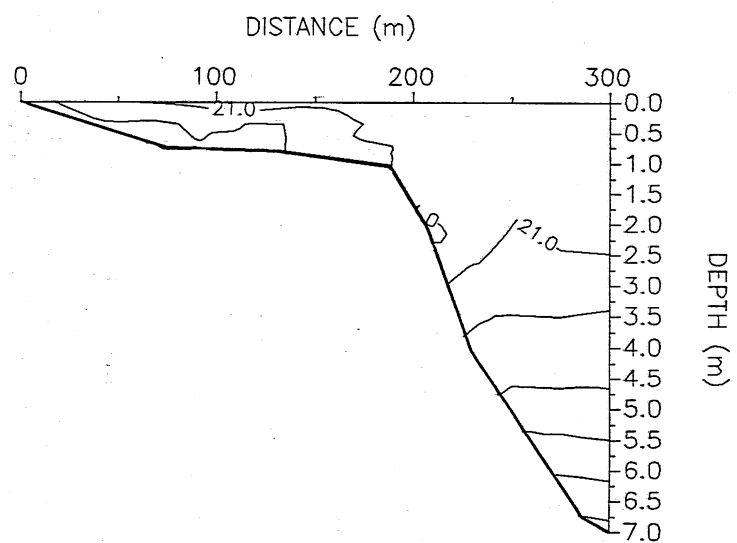
AUGUST 16 1989 0:00



AUGUST 16 1989 3:00



AUGUST 16 1989 6:00



AUGUST 16 1989 9:00

## APPENDIX C

### SELECTION OF DATA POINTS FOR INTERPOLATION TO PRODUCE ISOTHERMS IN BAY TRANSECT

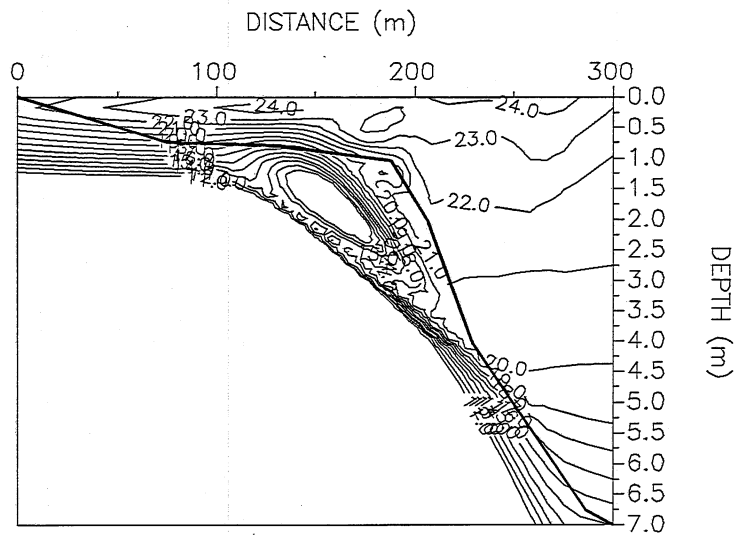
The temperature contours shown in the isotherm plots of the bay transect were found by using a bivariate interpolation over a rectangular grid based on the temperatures recorded by the thermistors and selectively added data points. The computer program, "Plotit," was used to produce the contours. Because the probe at 0.05 meter depth at station 2 was "errant" and had been removed from the data, the temperature at this point was taken as the average of the temperatures at the same depth at stations 1 and 3.

Interpolation and extrapolation based on the data from stations 1 - 6 and the interpolated data point yielded contours which were not consistent with the data. For example, the strong temperature gradient between the lower two probes in littoral thermistor chains produces water temperatures of 19°C at the sediment surface (Fig C-1(a)). This is inconsistent with the actual data since probes, which were in the sediments, recorded temperatures no lower than 20°C. Also, contouring between station 1 and the shore is subject to extrapolation based on temperature gradients between data points at stations 1 and 2. There are no data points between station 1 and the shore (Fig C-2(a)). These extrapolations were very unacceptable. Therefore, additional "data points" had to be added to the measured data points to provide contouring which is more consistent with the measured data and less dependent on unacceptable extrapolation.

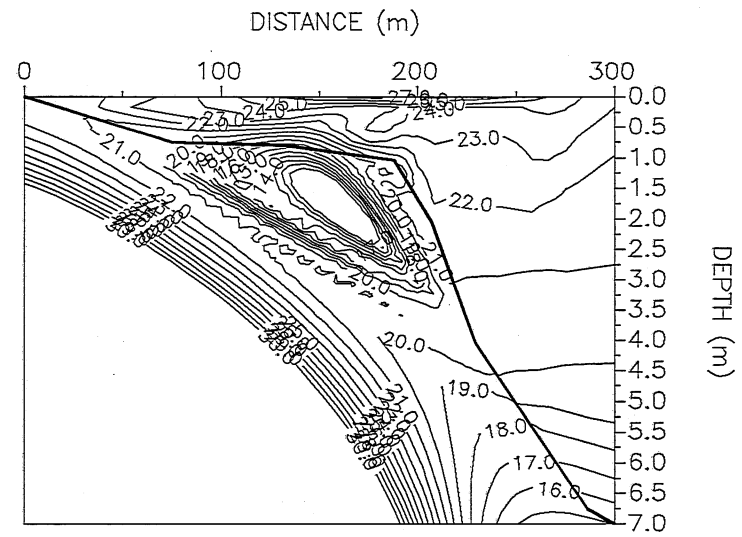
On a tentative basis an additional data point was added at zero depth at the shore line using either the upper thermistor temperature (Fig. C-2(b)) or the lower thermistor temperature (Fig. C-2(c)) from station 1. Addition of this point reduced the area of the cold water contours near the bottom in the littoral zone and improved the contouring between station 1 and the shore. However, these schemes produced a surface temperature contour of 27°C (Fig. (C-1(b-c))) which was much higher than the measured surface temperature anywhere. The measured surface temperature did not exceed 25° at this time.

These results made it apparent that the strong temperature gradient in the littoral region was a major factor in the extrapolation of surface and bottom temperatures. To reduce the effect of this gradient, data points were added at stations 1 through 3 at the bottom of the water column with a temperature equal to the lower thermistor temperature of each station, respectively (Fig. C-2(d)). The addition of a data point at zero depth at the shore was replaced with a point at 0.25 meter depth 30 meters from the shore with a temperature equal to the lower thermistor temperature at station 1 (Fig C-2(d)) because this was a more representative location than one at the edge of the contour grid. Isotherms in the littoral region (0 - 75 meters from shore) will be affected by this

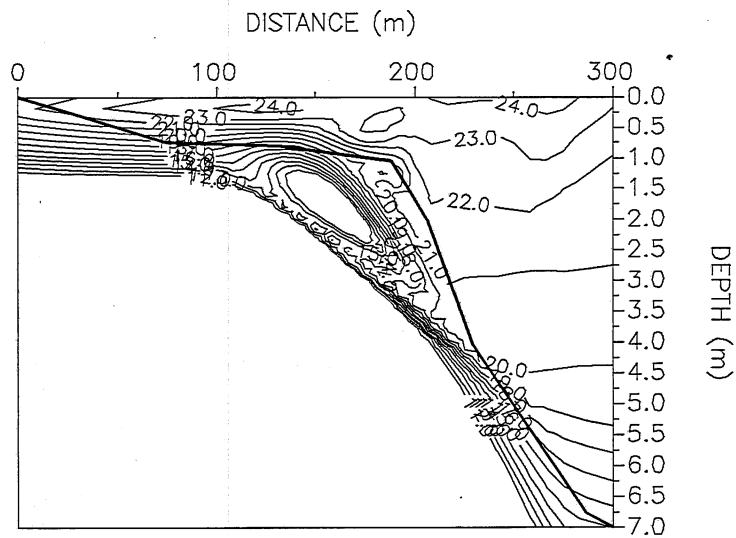
procedure and this must be kept in mind when isotherms are interpreted. This scheme provided temperature contours which were consistent with the measured data (Fig C-1(d)). Therefore, this pattern of additional data points and assignment of temperatures to the additional points was used for all isotherm plots of the bay transect.



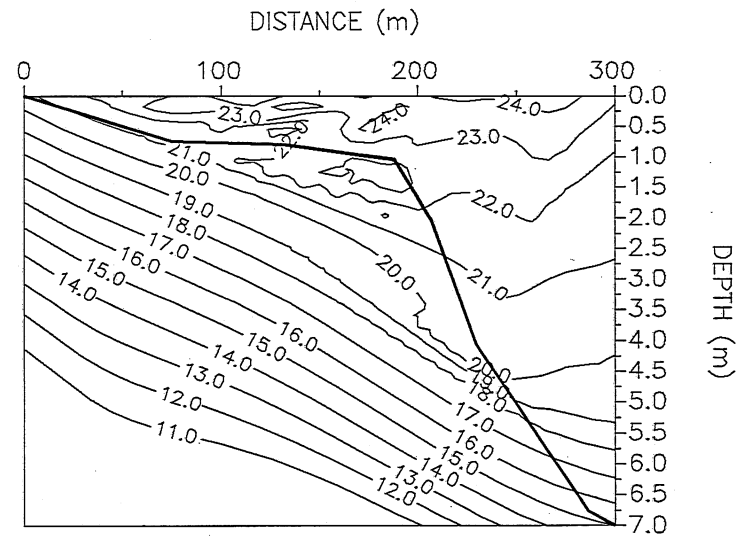
AUGUST 10 1989 0:00 NO ADDED DATA POINTS (a)



AUGUST 10 1989 0:00 T-TOP at (0,0) (b)



AUGUST 10 1989 0:00 T-BOTTOM at (0,0) (c)



AUGUST 10 1989 0:00 INTERPOLATION SCHEME USED (d)

Fig. C-1(a-d). INTERPOLATION SCHEMES FOR BAY ISOTHERMS

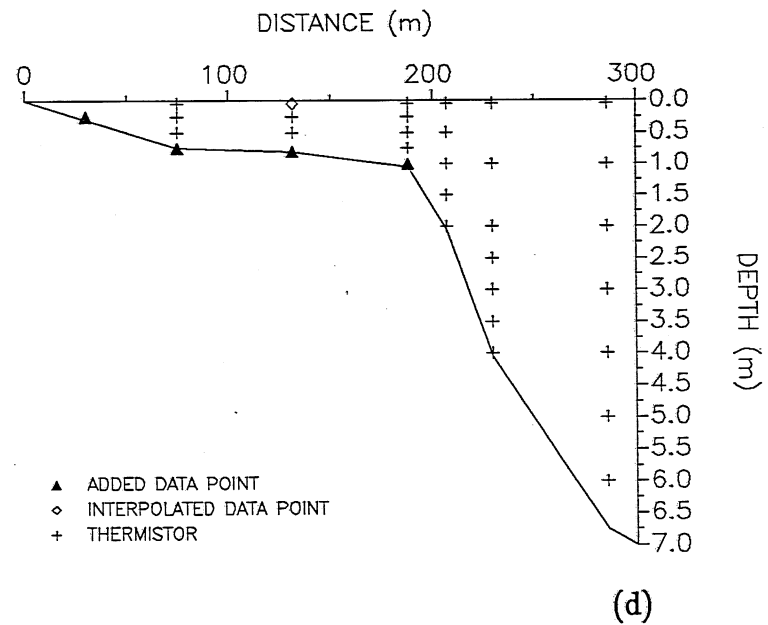
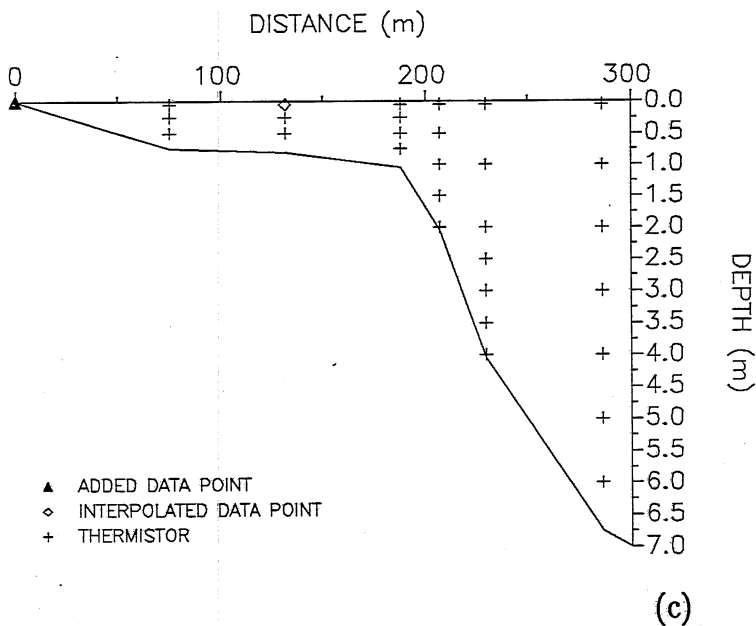
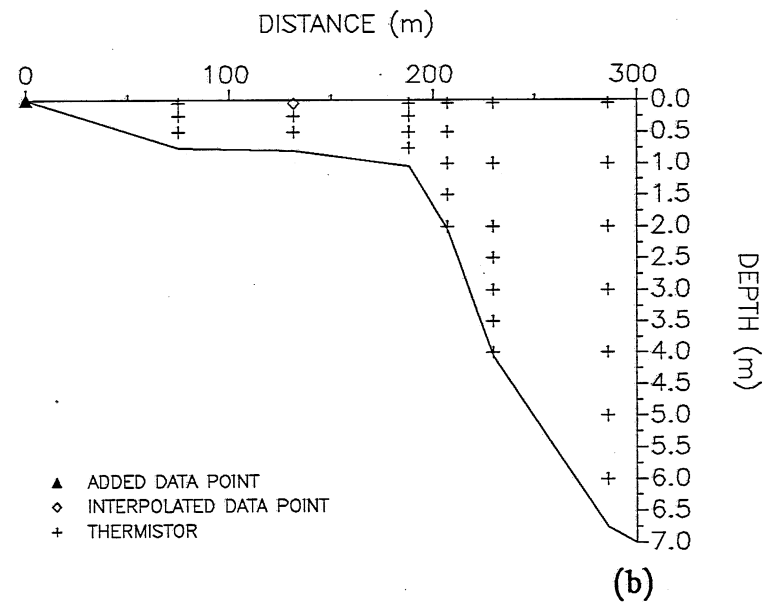
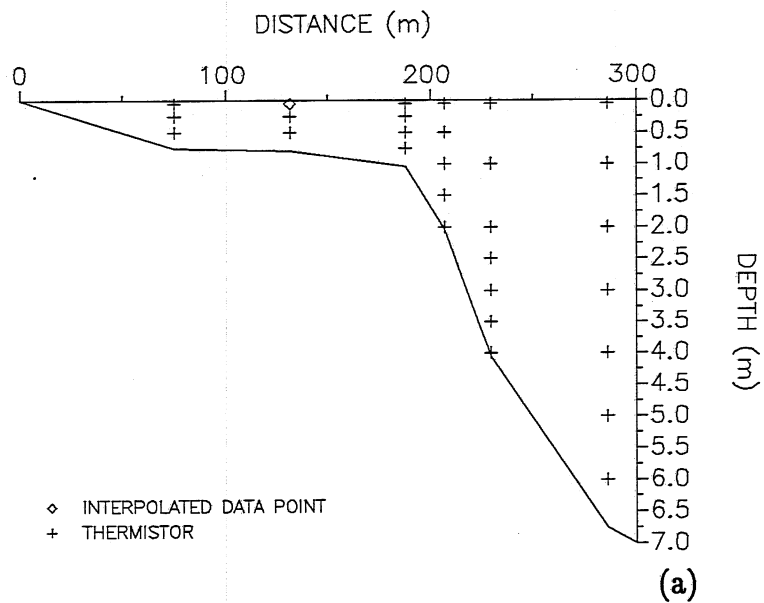


Fig. C-2(a-d). INTERPOLATION SCHEMES FOR BAY ISOTHERMS