NOAA Technical Memorandum ERL GLERL-91

PHYSICAL AND CHEMICAL VARIABLES OF SAGINAW BAY, LAKE HURON IN 1991-93

Thomas F. Nalepa[1]
Gary L. Fahnenstiel[1]
Michael J. McCormick[1]
Thomas H. Johengen[2]
Gregory A. Lang[1]
Joann F. Cavaletto[1]
Gregory Goudy[3]

[1]NOAA, Great Lakes Environmental Research Laboratory, Ann Arbor, Michigan
[2]Cooperative Insfitute for Limnology and Ecosystems Research, University of Michigan, Ann Arbor, Michigan
[3]Michigan Department of Natural Resources, Surface Water Quality Division, Lansing, Michigan

Great Lakes Environmental Research Laboratory
Ann Arbor, Michigan
May 1996

UNITED STATES
DEPARTMENT OF COMMERCE

Mickey Kantor
Secretary

NATIONAL OCEANIC AND
ATMOSPHERIC ADMINISTRATION

D. James Baker
Under Secretary for Oceans
and Atmosphere/Administrator

NOTICE

Mention of a commercial company or product does not constitute an endorsement by the NOAA Environmental Research Laboratories. Use of information from this publication concerning proprietary products or the tests of such products for publicity or advertising purposes is not authorized.

ACKNOWLEDGEMENTS

We thank A. Beeton and D. Reid for their support and encouragment of this project, particularly during the early planning and implementation period. We also thank W. Burns for his help and cooperation during field operations; the crew of the R/V *Shenehon* also for assistance during field operations; J. DeKam of the Bay City Water Plant for providing laboratory space; the City of East Tawas and the Michigan Department of Natural Resources for providing an area for our mobile laboratory and dockage of our vessels; R. Kreis of the Environmental Protection Agency (EPA) for his support of the project and role in obtaining funds for nutrient analysis in 1991 and 1992; F. Boettcher of EPA for sampling support with the R/V *Bluewater* in 1991; and D. Jude, J. Barres and D. Francis of the University of Michigan for sample collection, sample processing, and nutrient analysis in 1991 and 1992. We especially thank the following personnel of NOAA's Great Lakes Environmental Research Laboratory and the Cooperative Institute of Limnology and Ecosystems Research (CILER) for their dedication in sample collection, sample analysis, and data tabulation: T. Bridgeman, D. Fanslow, M. Ford, W. Gordon, G. Gostenik, A. Krausse, B. Wagner, M. Wimmer, and J. Wojcik. This is GLERL Contribution No. 998.

Printed copies of this publication can be ordered from: Publications Office, NOAA, Great Lakes Environmental Research Lab, 2205 Commonwealth Blvd., Ann Arbor, MI 48105, pubs.glerl@noaa.gov

CONTENTS

PAGE

ABSTRACT 1

1. INTRODUCTION 1

2. JUSTIFICATION OF STUDY SITE 1

3. DESCRIPTION OF STUDY SITE 2

4. SAMPLING SITES AND DATES 3

5. FIELD PROCEDURES 4

6. LABORATORY PROCEDURES 6

6.1 Chlorophyll 6

6.2 Nutrients 6

6.3 Alkalinity 6

6.4 Carbon 6

6.5 Total Suspended Solids 7

7. RESULTS 7

7.1 Data 7

7.2 Vertical Profiles 11

7.3 Inner Bay Means 11

8. REFERENCES 11

TABLES

Table 1.-- Mean depth, surface area, and water volume of the inner bay, the outer bay, and the bay as a whole. Values were computed from digitized NOAA chart No. 14863. A 0.66-m offset was used to account for low water datum 3

Table 2.-- Location and water depth of sampling sites in Saginaw Bay in 1991-93. The sites were designated as Stations 1 through 26. Thirteen of the sites were established by the Environmental Protection Agency (EPA) in 1974-75 while the other 13 sites were established by NOAA 4

PAGE

Table 3.-- Stations sampled during each sampling period in 1991-93. The number in parentheses after the sampling period indicates the cruise number for that year 5

Table 4.-- A list of outliers for water temperature as determined from the functional relationship between shipboard temperature and CTD temperature for all values in 1991-1993. Outliers were corrected as defined in the text and included in Appendix I. The case number corresponds to numbers given in Figure 2 9

Table 5.-- A list of outliers for chlorophyll as determined from the functional relationship between chlorophyll and CTD fluorescence for all values in 1991-1993. Chl_1 is the value derived from this relationship. Outliers were corrected as given in the text and included in Appendix I. The case number corresponds to numbers given in Figure 3 9

Table 6.-- List of outliers for total suspended solids (TSS) as determined from the functional relationship between TSS and CTD transmissivity (cases 1-8). Other values of TSS (cases 9-14) were considered analytically incorrect or inconsistent compared to values in surrounding areas. TSS_1 is the value derived from the functional relationship between TSS and CTD transmissivity, and TSS_2 is the value derived from the relationship between TSS and Secchi-depth transparency. Values were corrected as defined in the text and included in Appendix I. Case numbers 1-8 correspond to numbers given in Figure 4 10

Table 7.-- Mean coefficients of variation for each of the listed variables. Each individual coefficient of variation (each n) was derived from a duplicate water sample collected at each sampling depth at Stations 2, 5, 20, 21, and 25 on each sampling depth in 1991 and 1992, and at each sampling depth at Stations 5 and 20 on each sampling date in 1993 10

FIGURES

Figure 1.-- Location of sampling sites in Saginaw Bay, 1991-93. Circled sites were sites sampled only in 1991 and 1992, while uncircled sites were sampled all 3 years. Dashed lines differentiate the inner bay from the outer bay and the outer bay from Lake Huron 2

Figure 2.-- Relationship between temperatures taken shipboard on water collected with a Niskin bottle and temperatures from similar depths taken *in situ* with a CTD. Each point represents a sampling date, site, and depth where temperature was taken by both methods. Circled points are considered outliers at $P < 0.01$. Individual outliers are numbered and can be identified by the corresponding case number in Table 4 8

Figure 3.-- Relationship between chlorophyll (ug/L) and fluorescense as measured *in situ* with the CTD. Each point represents a sampling date, site, and depth where the two variables were measured. Circled points are considered outliers at $P < 0.01$. Individual outliers are numbered and can be identified by the corresponding case number in Table 5 8

Figure 4.-- Relationship between total suspended solids (mg/L) and transmissivity as measured *in situ* with the CTD. Each point represents a sampling date, site, and depth where the two variables were measured. Circled points are considered outliers at $P < 0.01$. Individual outliers are numbered and can be identified by the corresponding case number in Table 6 11

PAGE

Figure 5.-- Relationship between total suspended solids (mg/L) and Secchi-disk transparency (m). Values natural-log transformed. Each point represents a sampling date, site, and depth where the two variables were measured 12

Figure 6.-- Vertical profiles of temperature (C), transmissivity (%), and algal fluorescense (ug/L) at each of the sites on each sampling date as measured by the CTD 14

Figure 7.-- Mean (± SE) values of the following select variables on each sampling date in 1991-93 for the inner and outer bay: temperature, secchi-disk, transparency, chlorophyll, kPar, particulate organic carbon, dissolved organic carbon, total suspended solids, total phosphorus, total dissolved phosphorus, soluble reactive phosphorus, ammonium, nitrate, particulate silica, dissolved silica, and chloride 39

Legend: ●——● = 1991; ■— — —■ = 1992; ▲— — —▲ = 1993

Appendix I.--Values of all physical and chemical variables collected in Saginaw Bay in 1991-1993 54
All data from this appendix are available in a simple ASCII format. The data files are available from GLERL's WWW site or from the anonymous FTP site. From the GLERL home page (www.glerl.noaa.gov), select FTP server, **or** point your browser to: ftp://ftp.glerl.noaa.gov/publications/tech_reports/glerl-091.

PHYSICAL AND CHEMICAL VARIABLES OF SAGINAW BAY, LAKE HURON IN 1991-93

Thomas F. Nalepa
Gary L. Fahnenstiel
Michael J. McCormick
Thomas H. Johengen
Gregory A. Lang
Joann F. Cavaletto
Gregory Goudy

ABSTRACT. Physical and chemical data were collected in Saginaw Bay, Lake Huron over the period 1991-1993 to determine impacts of the zebra mussel, *Dreissena polymorpha*, on the Saginaw Bay ecosystem. This report gives values of data collected during that time period along with a detailed account of all sampling methods and analytical procedures.

1.0 INTRODUCTION

This report presents physical and chemical data collected in Saginaw Bay from 1991 to 1993. These data were collected as part of a larger effort to monitor and assess impacts of the zebra mussel, *Dreissena polymorpha*, on the Saginaw Bay ecosystem. Although mussels were found in the bay in 1990, the first large recruitment did not occur until summer 1991. Thus, the data presented herein reflect physical and chemical conditions, and subsequent changes, during the initial years of the mussel's invasion into the bay. Also included in this report is a detailed account of sampling sites and dates, and of collection methods and analytical procedures.

While all physical and chemical data collected over the 3-year period is presented, no attempt is made at interpretation. Data summaries and interpretations are contained in a series of papers published in a special issue of the *Journal of Great Lakes Research* (Volume 21, Number 4). The following papers specifically summarize and interpret these physical and chemical data: Fahnenstiel et al. (199Sa, 1995b) and Johengen et al. (1995).

2.0 JUSTIFICATION OF STUDY SITE

Soon after the zebra mussel was discovered in the Great Lakes in 1988, we identified Saginaw Bay as an ideal location to assess ecological changes that might result from the filtering activities of this organism. Specific considerations that led to the decision to initiate a monitoring program in the bay were: (1) at the time, the zebra mussel was not yet established in the bay, thus baseline conditions immediately prior to the mussel's invasion could be documented; further, previous surveys of water quality parameters in 1974-80 (Smith et al., 1977; Bierman et al., 1984) could provide a longer term perspective to assess potential changes; (2) the bay had extensive areas of hard bottom, along with ideal temperature and food regimes, and, thus, large populations of mussels were expected to develop; (3) there existed an important commercial and sport fishery that may be affected; (4) a natural gradient occurs between the eutrophic inner bay and the more oligotrophic outer bay, providing an opportunity to assess impacts over a wide range of trophic conditions, and; (5) the bay is an Area of Concern as designated by the International Joint Commission and the subject of remedial action by the State of Michigan. After a decade of little or no monitoring in the bay, surveys of selected physical and chemical variables not only provide information to assess changes induced by the zebra mussel, but also provide information to assess the bay's response to continued efforts to improve water quality.

3.0 DESCRIPTION OF STUDY SITE

Saginaw Bay is a shallow, well-mixed extension of the western shoreline of Lake Huron (Figure 1). The bay is 21-42 km wide, about 82 km long, and has a drainage basin of about 21,000 km2. Total area of the bay is 2.77 x 109 m2, and total water volume is 24.54 x 109 m3 (Table 1). The bay can be functionally divided into an inner and outer region by a line extending along its narrowest width (21 km) from Sand Point to Point Lookout (Figure 1). A broad shoal and several islands (Charity Islands) along this line provide a natural demarcation between the two regions. The outer bay can be defined from Lake Huron by a line from Pte. aux Barques to Au Sable point. Differences in physical and chemical features of the inner and outer bay regions are distinct (Beeton et al., 1967; Smith et al., 1977). The inner bay has a mean depth of 5.1 m, is nutrient-rich,

and is heavily influenced by input from the Saginaw River, which accounts for over 70% of the total tributary flow into the bay. The outer bay has a mean depth of 13.7 m and is more influenced by the colder, nutrient-poor waters of Lake Huron.

Circulation within the inner and outer bay is generally weak; currents average about 7 cm s~~ in the inner bay and about 11 cm s~i in the outer bay (Danek and Saylor, 1977). Exchange and flushing of water in the inner bay occurs when winds blow along the long axis of the bay (southwestlnortheast). Dominant winds in the summer are from the southwest. Little exchange occurs when winds are perpendicular to the long axis (west/east). Most water exchange/flushing between the inner and outer bay occurs on the northem side of the bay within the deep channel between Point Lookout and Charity Island. Although some water may exit the inner bay along the southern shoreline, it is of minor significance because of the shallowness of the region (Danek and Saylor, 1977). Furthermore, preliminary results of Lagrangian current measurements in the outer bay during the summers of 1992 and 1993 suggest that the flushing of inner bay waters into Lake Huron is episodic in nature (McCormick unpublished).

Bottom substrates in Saginaw Bay range from silt to mostly cobble and rock. The inner bay has a wide sand-gravel bar that extends along the eastern side of the bay from the Saginaw River to the Charity Islands. Another sand-gravel bar extends along the western shoreline to Point Au Gres. Both sand bars have irregular areas of cobble along with patches of sand,

Table 1.--Mean depth, surface area, and water volume of the inner bay, the outer bay, and the bay as a whole. Values were computed from digitized NOAA chart No.14863. A 0.66-m offset was used to account for low water datum.

	Mean Depth (m)	Surface Area (m^2)	Volume (m^3)
Inner Bay	5.09	1.55×10^9	7.91×10^9
Outer Bay	13.66	1.22×10^9	16.63×10^9
Whole Bay	8.86	2.77×10^9	24.54×10^9

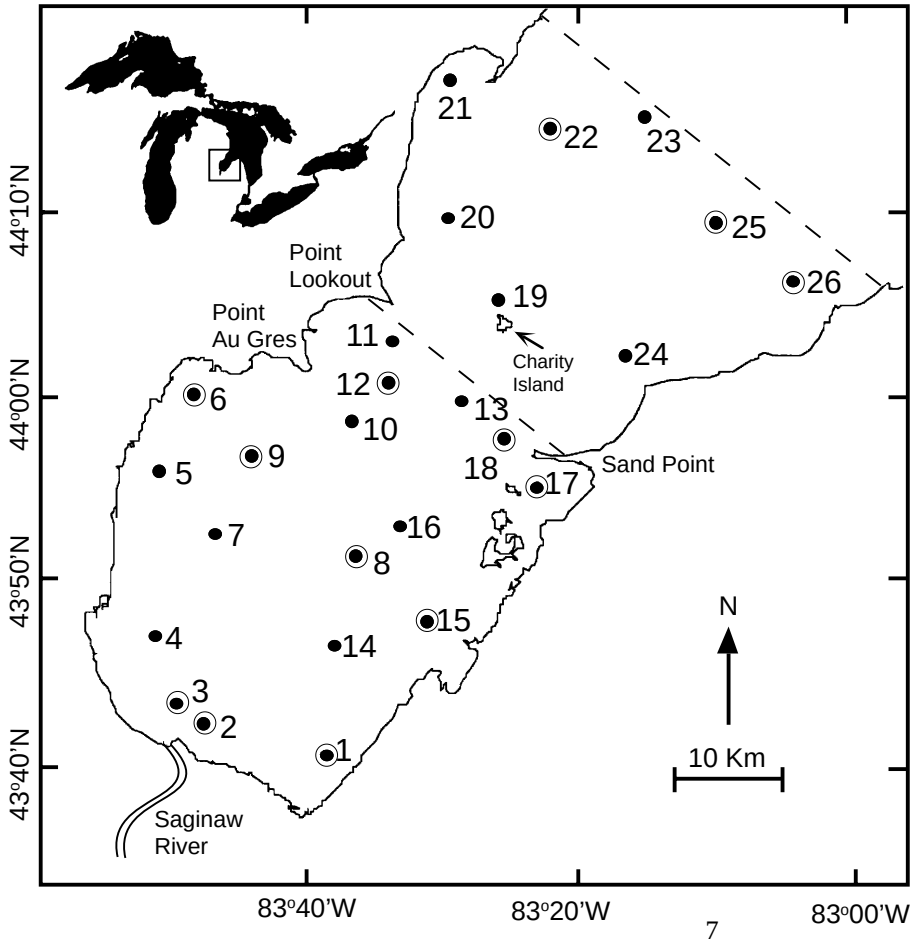


Figure 1.--Location of sampling sites in Saginaw Bay, 1991-93. Circled sites were sites sampled only in 1991 and 1992, while uncircled sites were sampled all 3 years. Dashed lines differentiate the inner bay from the outer bay and the outer bay from Lake Huron.

gravel, and pebbles. The bars extend into the shorelines as extensive flats grade into marshes. Between the two sand bars is an area of maximum depth where the substrate consists of fine-grruned sediments (silt/mud). Based on areal estimates of substrate type by Wood (1964) and extensive benthic sampling in the late 1980s (Nalepa unpublished), we estimated that 70% of the bottom in the inner bay consists of sand, gravel, and cobble, and 30% consists of silt/mud. In the outer bay, the east shore is rocky, as is the area around the Charity Islands. The western shore has extensive sandy areas, with rock and clay found near Point Lookout. Most of the offshore region of the outer bay has a bottom consisting of silty sand (Nalepa unpublished).

4.0 SAMPLING SITES AND DATES

The exact location and water depth of the 26 sampling sites are given in Table 2. These sites, designated as Stations 1 though 26, were selected to provide thorough coverage of both the inner and outer bay (Figure 1). Thirteen of the sites (Stations 1, 2, 3, 6, 8, 9, 12, 15, 17, 18, 22, 25, 26) were the same sites sampled by the Environmental Protection Agency (EPA) in 1974-75 (Smith et al., 1977), while the other 13 sites (Stations 4, 5, 7, 10, 11, 13, 14, 16, 19, 20, 21, 23, 24) were designated as sites by this laboratory (NOAA) . The EPA sites were sampled only in 1991 and 1992, while the NOAA sites were sampled all 3 years. Samples were generally collected once a month from April to October. The exception was in May when two sampling periods occurred, one in early May and one in late May (Table 3). The first sampling occurred in the middle of April, except in 1993 when it was delayed until late April because of the presence of ice. Consequently, there was no early May sampling date in 1993. Because of poor weather conditions or technical problems, not all sampling sites were visited on all sampling dates (Table 3). All sites were located using Loran-C.

5.0 FIELD PROCEDURES

Water samples for nutrients, carbon, chlorophyll, and total suspended solids were collected with a 5-L Niskin bottle at a depth of 1 m at every site and at the mid-water column depth for sites deeper than 10 m. Samples were placed into acid-rinsed 4-L polyethylene containers and immediately stored in coolers. Water temperature was obtained by placing a

Table 2.--Location and water depth of sampling sites in Saginaw Bay in 1991-93. The sites were designated as Stations 1 through 26. Thirteen of the sites were established by the Environmental Protection Agency (EPA) in 1974-75 while the other 13 sites were established by NOAA.

Station	Latitude	Longitude	Water Depth (m)
SB1 (EPA-12)	43 38' 25"	83 39' 40"	4.0
SB2 (EPA-8)	43 40' 00"	83 48' 25"	4.0
SB3 (EPA-7)	43 41' 05"	83 50' 35"	3.0
SB4 (NOAA)	43 44' 39"	83 52' 04"	7.0
SB5 (NOAA)	43 53' 43"	83 51' 38"	3.0
SB6 (EPA-30)	43 58' 05"	83 49' 15"	4.0
SB7 (NOAA)	43 50' 17"	83 47' 34'	7.0
SB8 (EPA-27)	43 49' 10"	83 37' 10"	5.0
SB9 ((EPA-29)	43 54' 50"	83 44' 50"	7.0
SB10(NOAA)	43 56' 30"	83 37' 26"	11.0
SBll (NOAA)	44 01' 14"	83 34' 25"	9.0
SB12(EPA-35)	43 58' 45"	83 34' 40"	13.0
SB13 (NOAA)	43 57' 34"	83 29' 19"	3.0
SB14 (NOAA)	43 44' 18"	83 38' 27"	3.0
SB15 (EPA-26)	43 45' 40"	83 31' 35"	5.0
SB16(NOAA)	43 50' 49"	83 33' 45"	3.0
SB17(EPA-34)	43 53' 00"	83 23' 35"	3.0
SB18(EPA-61)	43 55' 40"	83 26' 25"	2.0
SBl9(NOAA)	44 03' 10"	83 26' 31"	4.0
SB20 (NOAA)	44 07' 34"	83 30' 00"	16.0
SB21 (NOAA)	44 15' 10"	83 30' 23"	4.0
SB22 (EPA-49)	44 12' 40"	83 22' 40"	20.5
SB23 (NOAA)	44 13' 15"	83 15' 45"	28.5
SB24 (NOAA)	44 00' 05"	83 17' 00"	12.5
SB25 (EPA-51)	44 07' 25"	83 10' 15"	28.5
SB26 (EPA-52)	44 04' 10"	83 04' 50"	13.5

Sampling Date	Station																								
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
1991																										
Apr 11-18 (1)	x	x	x			x			x	x	x					x	x	x		x	x		x	x	x	x
Apr 29- May 3 (2)	x	x	x	x	x	x	x	x		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
May 20-22 (3)	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Jun 17-18 (4)	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Jul 22-26 (5)	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Aug 19-22 (6)	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Sep 9-12 (7)		x	x	x	x		x			x	x		x	x		x			x	x	x	x		x		x
Oct 7-18 (8)	x	x	x	x	x	x	x	x	x	x	x	x	x		x		x	x	x	x	x	x		x		x
Nov 8-12 (9)	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
1992																										
Apr 13-15 (1)	x	x	x	x	x	x		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
May 4-7 (2)	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
May 27-Jun 3 (3)	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Jun 15-23 (4)	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Jul 20-22 (5)	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Aug 10-12 (6)	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Sep 9-15 (7)	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Oct 4-7 (8)	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
1993																										
Apr 29-30 (1)			x		x		x			x	x	x			x		x	x	x	x	x		x	x		
May 17 (2)				x	x		x			x	x		x	x		x			x	x	x		x	x		
Jun 21 (3)				x			x			x	x		x	x		x			x	x	x		x	x		
Jul 12 (4)				x	x		x			x	x		x	x					x	x	x		x	x		
Aug 10 (5)				x	x		x			x	x		x	x		x			x	x	x		x	x		
Sep 8 (6)				x	x		x			x	x		x	x		x			x	x	x		x	x		
Oct 5 & 14 (7)				x	x		x			x	x		x	x		x			x	x	x		x	x		

Table 3.--Stations sampled during each sampling period in 1991-93. The number in parentheses after the sampling period indicates the cruise number for that year.

thermometer in a portion of water collected in the Niskin bottle immediately after it was brought to the surface. At each of the NOAA sites, a Sea-Bird CTD with fluorometer and transmissometer (25-cm beam path) was slowly lowered from the surface to 1 m above the bottom. All data points were logged twice each second. Secchi-disk transparency was measured by lowering a white disk that was 25 cm in diameter. At the NOAA sites, photosynthetically active irradiation (PAR) was measured at a number of depths in the water column with a LI-COR 193SB spherical (4 p) light sensor and LI-COR 1000 data logger, from which the underwater light extinction coefficient (kPAR) was calculated.

For quality control, duplicate water samples were collected at each sampling depth at Stations 2, 5, 15, 20, 21, and 25 on each sampling date in 1991 and 1992, and at each sampling depth at Stations 5 and 20 on each sampling date in 1993. Nutrient analysis was performed separately on the two samples.

6.0 LABORATORY PROCEDURES

All water samples were processed within 24 h of collection. The following are detailed analytical procedures for each of the variables measured.

6.1 Chlorophyll

Chlorophyll (Chl) was measured in triplicate using the method of Strickland and Parsons (1972). Fifty or 100 mL of water was filtered through a 47-mm GF/F Whatman Glass Fiber filter. The filters were placed individually into amber vials containing 5 mL of cold acetone (90 %) and then stored in the freezer. W~thin 30 days, the filters were ground in cold acetone and then steeped for 24 h in the freezer. Samples were centrifuged, the extract poured into a 1-cm curvette, and readings taken with a Turner Design Fluorometer. After an initial reading, 2 drops of 1N HCL were added to the curvette and another reading taken.

6.2 Nutrients

Nutrient concentrations were determined using standard automated colorimetric techniques (APHA, 1990) on a Technicon Auto Analyzer II, as detailed in Davis and Simmons (1979). Dissolved nutrients were determined on sample aliquots that were filtered through a pre-rinsed 0.2-um HA Millipore filter or a 0.2-um Nucleopore filter. Nitrate + nitrite was determined using the cadmium reduction method and hereafter is simply referred to as nitrate (NO3). Ammonia concentrations (NH4) were determined by the Bertholet reaction. Phosphorus concentrations were determined by the molybdate/ascorbic acid method. Soluble reactive phosphorus (SRP) was determined on a filtered portion of the water sample (100 mL), while total phosphorus (TP) and total dissolved phosphorus (TDP) were determined after digesting 50 mL of unfiltered and filtered sample, respectively, with potassium persulfate in an autoclave for 30 min (Menzel and Corwin, 1965). Values of nitrate and soluble reactive phosphorus were occasionally below detection. For these occasions, concentrations were reported to be at our operationally defined detection limit of 0.01 mg/L for nitrate and 0.1 mg/L for soluble reactive phosphorus. Particulate silica (PSI) was determined on 100 mL aliquots of water filtered through a 0.45-mm Nucleopore filter and then extracted with 0.2N NaOH at 95•C for 30 minutes (Krausse et al., 1983). The extract was neutralized with 1N H2SO4 and silica (SiO2) concentrations determined by the heteropoly blue method. Chloride (C1) concentrations were determined by the mercuric thiocyanide/ferric ammonium sulfate method.

6.3 Alkalinity

Alkalinity (Ark) was determined from the milk-equivalents of acid needed to bring the pH of the water sample below 4.0 (Davis and Simmons, 1979). Twenty mL of sample was pipetted with a volumetric buret into a chemically clean polyethylene bottle that contained 5 mL of 0.01 N HCL. Additional 1 mL aliquots of acid were added if the pH was above 4.0.

6.4 Carbon

Samples for particulate organic carbon (POC) and dissolved organic carbon (DOC) were processed in triplicate by filtering 50 or 100 mL of sample through pre-combusted GFF filters. For POC, filters were frozen until analysis, then thawed, acid)fied with 10 % v/v HCL, and dried at 70•C for 24 h. POC measurements were made with a Perkin Elmer (model 2400) CHN elemental analyzer. The filtrate was frozen for later determination of DOC. Prior to analysis, the filtrate was acid)fied with HCL and sparged with air for 6 min to remove CO2. DOC was determined using a Shimadzu total organic carbon analyzer (model TOC-5000) fitted with an auto sampler.

6.5 Total Suspended Solids

Total suspended solids (TSS) were determined by filtering between 500-2,000 mL of sample through a pre-dried, pre-weighed Whatman GFC 47-mm filter. The filters were then dried at 60•C for at least 48 h and then reweighed.

7.0 RESULTS

7.1 Data

Values of all measured physical and chemical variables on each sampling date in 1991-93 are given in Appendix I. As noted, kPAR was calculated from light sensor readings when available. On dates when light sensor readings were not available, kPAR values were derived from the relationship between kPAR and CTD transmissivity or Secchi-disk transparency (Fahnenstiel et al., 1995a). Before temperature, chlorophyll, and total suspended solids were included in the appendix, values were compared to values for same/similar variables derived from the CTD. That is, water temperature measured shipboard was compared to CTD temperature, chlorophyll was compared to CTD fluorescence, and TSS was compared to CTD transmissivity for all sampling dates, stations, and depths for which a comparison was possible. Statistical models describing the relationship between the three variables and their CTD counterparts were all sign)ficant, indicating good agreement between the two independent measures for each of the three variables. Outliers were identified as values where the studentized residual was greater than a l-value corresponding to P = 0.01. Before inclusion in Appendix I, the outliers were examined and corrections made if deemed necessary. Several factors were considered in deciding whether or not to correct an outlier, including values at nearby sites and the value derived from the model.

For temperature, the relationship fit a linear model ($P < 0.001$; $r2 = 0.978$; $n = 427$), with seven outliers identified (1.6 %) (Figure 2). Outliers were corrected by taking the average temperature of the two methods (Table 4). The relationship between chlorophyll and CTD fluorescence also fit a linear model ($P < 0.001$; $r2=0.663$; $n=393$), with 11 outliers identified (2.8 %) (Figure 3). For these outliers, a chlorophyll value was derived from the model (Chl~). Depending on chlorophyll values at nearby sites, values of these outliers were either left uncorrected, were corrected by averaging the value and Chl~, or were corrected by changing the value to Chl~ before being included in Appendix I (Table 5).

The relationship between TSS and CTD transmissivity fit a linear model after transmissivity was log transformed ($P < 0.001$, $r2 = 0.840$, $n=381$). Eight outliers were identified (2.1%) (Figure 4). Besides these eight outliers, six other TSS values were considered analytically in error or inconsistent with values in nearby areas. As another independent estimate of TSS, the relationship between TSS and Secchi-disk transparency was also examined (Figure 5). Using only those values of TSS from the 1-m depth, the relationship between TSS and Secchi-disk transparency was described by a power function ($P < 0.001$, $r2 = 0.856$, $n = 456$). For each of the 14 values identified as being either an outlier or incorrect, a derived value for TSS was determined from each of the two relationships (TSS~ = derived from CTD transmissivity, and TSS2 = derived from Secchi-disk transparency) (Table 6). In correcting the outliers, if the two derived values were in agreement, then TSS~ was used in Appendix I. If TSS~ and TSS2 did not agree, then TSS was not changed. If either TSS~ or TSS2 was not available, then the mean of TSS, and whichever derived value was available, was used in Appendix I. If the TSS value was considered in error, the derived value was used in Appendix I.

As noted, water samples were collected in duplicate at six sites (eight total duplicate samples since two sites were sampled at two depths) on each date in 1991 and 1992, and at two sites (three total duplicate samples) on each date in 1993. The coefficient of variation was determined for each duplicate for the following variables: alkalinity, total suspended solids, soluble reactive phosphorus, nitrate, ammonia, silica, particulate silica, particulate organic carbon, dissolved organic carbon, and chlorophyll. The yearly mean coefficient of variation for each of these variables is given in Table 7.

7.2 Vertical Profiles

Figure 6 gives vertical profiles of temperature (C), fluorescence (ug/L), and transmissivity (percent) for all CTD casts. The profiles are arranged by cruise date and station number.

7.3 Inner Bay Means

Figure 7 gives mean values of selected variables for all sites in the inner bay and outer bay on each cruise in 1991-93.

Figure 2.--Relationship between temperatures taken shipboard on water collected with a Niskin bottle and temperatures from similar depths taken *in situ* with a CTD. Each point represents a sampling date, site, and depth where temperature was taken by both methods. Circled points are considered outliers at P < 0.01. Individual outliers are numbered and can be identified by the corresponding case number in Table 4.

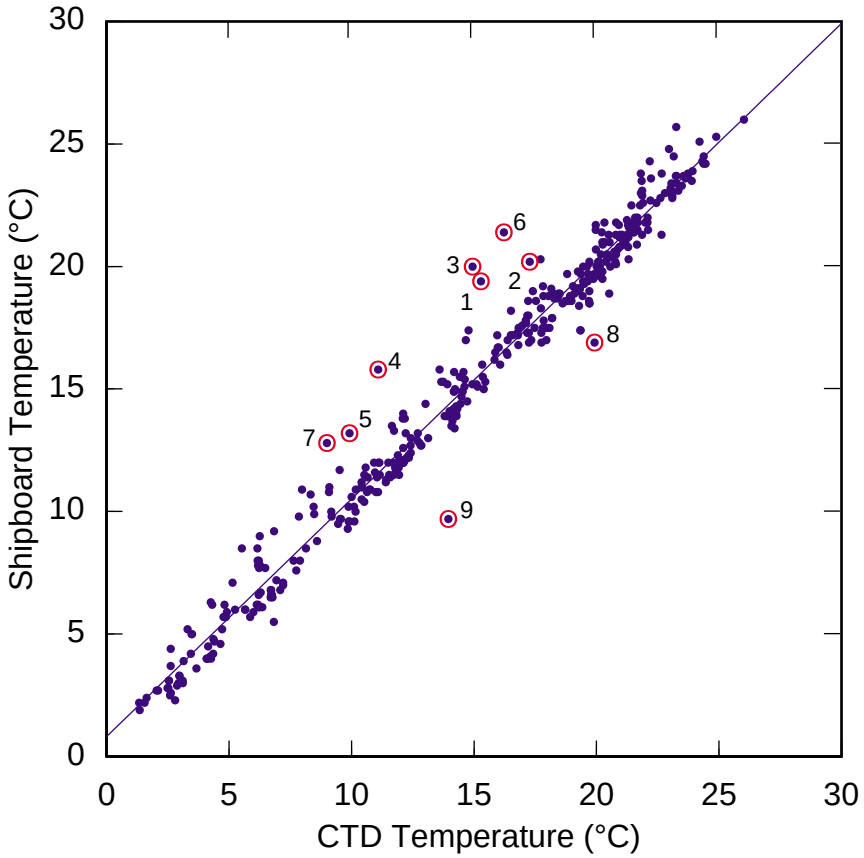
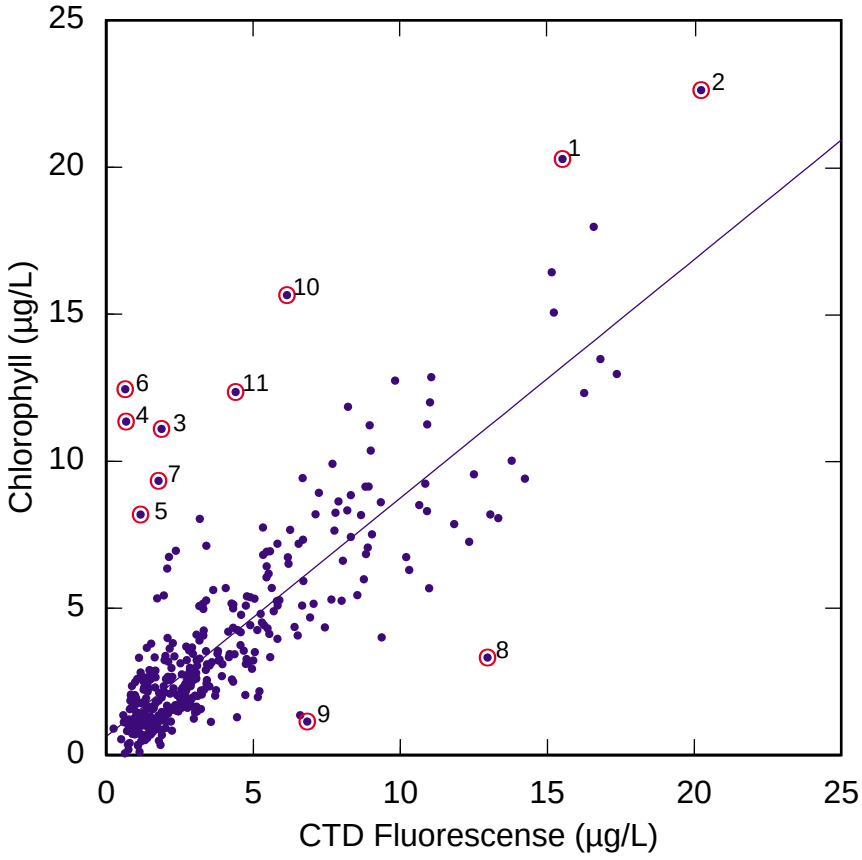


Figure 3.--Relationship between chlorophyll (ug/L) and fluorescense as measured *in situ* with the CTD. Each point represents a sampling date, site, and depth where the two variables were measured. Circled points are considered outliers at P < 0.01. Individual outliers are numbered and can be identified by the corresponding case number in Table 5.



Flgure 4.--Relationship between total suspended solids (mg/L) and transmissivity as measured *in sim* with the CTD. Each point represents a sampling date, site, and depth where the two variables were measured. Circled points are considered outliers at P < 0.01. Individual outliers are numbered and can be identified by the corresponding case number in Table 6.

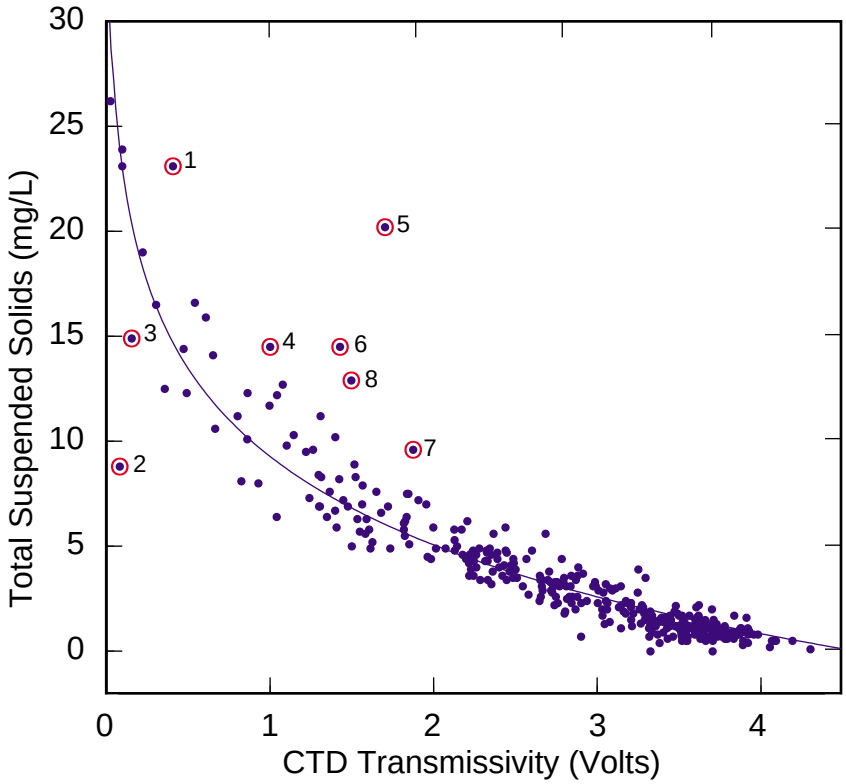


Figure 5.--Relationship between total suspended solids (mg/L) and Secchi-disk transparency (m). Values natural-log transformed. Each point represents a sampling date, site, and depth where the two variables were measured.

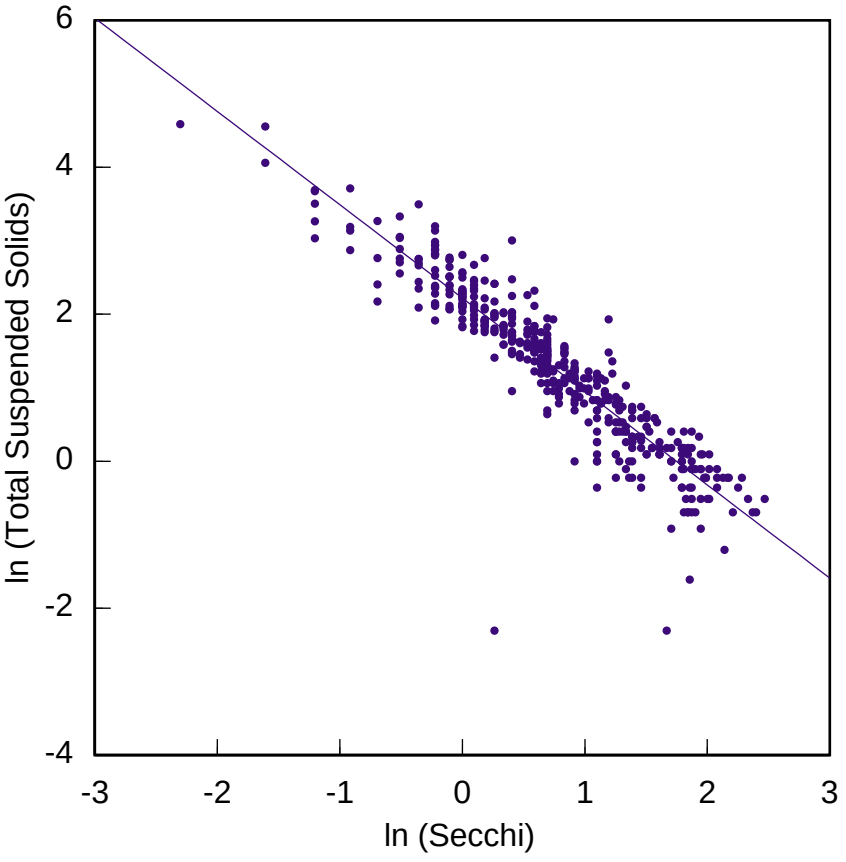


Table 4.--A list of outliers for water temperature as determined from the functional relationship between shipboard temperature and CTD temperature for all values in 1991-1993. Outliers were corrected as defined in the text and included in Appendix I. The case number corresponds to numbers given in Figure 2.

Case	Year	Cruise	Station	Sampling Depth (m)	Shipboard Temp. (C)	CTD Temp. (C)	Appendix I Temp. (C)
1	1991	3	4	1	19.4	15.3	17.4
2	1991	3	5	1	20.2	17.3	18.8
3	1991	3	7	1	20.0	14.9	17.5
4	1991	4	23	14	15.8	11.1	13.5
5	1991	4	25	15	13.2	9.9	11.6
6	1991	5	23	14	21.4	16.2	18.8
7	1992	4	25	15	12.8	9.0	10.9
8	1992	6	21	1	16.9	19.9	18.4
9	1993	4	10	6	9.7	14.0	11.9

Table 5.--A list of outliers for chlorophyll as determined from the functional relationship between chlorophyll and CTD fluorescence for all values in 1991-1993. Chl_1 is the value derived from this relationship. Outliers were corrected as given in the text and included in Appendix I. The case number corresponds to numbers given in Figure 3.

Case	Year	Cruise	Station	Sampling Depth (m)	Chl (µg/L)	Chl_1 (µg/L)	Appendix Chl (µg/L)
1	1991	3	10	1	20.3	13.8	20.3
2	1991	3	10	6	22.6	15.5	22.6
3	1991	3	21	1	11.1	1.9	1.9
4	1991	3	22	1	11.4	1.0	1.0
5	1991	3	22	9	8.2	1.6	1.6
6	1991	3	23	1	12.4	1.0	1.0
7	1991	3	23	14	9.3	2.0	2.0
8	1991	6	4	1	3.3	9.6	6.5
9	1991	7	16	1	1.2	6.5	3.8
10	1992	7	7	1	15.7	6.4	6.4
11	1993	5	13	1	12.4	6.3	6.3

Table 6.--List of outliers for total suspended solids (TSS) as determined from the functional relationship between TSS and CTD transmissivity (cases 1-8). Other values of TSS (cases 9-14) were considered analytically incorrect or inconsistent compared to values in surrounding areas. TSS_1 is the value derived from the functional relationship between TSS and CTD transmissivity, and TSS_2 is the value derived from the relationship between TSS and Secchi-depth transparency. Values were corrected as defined in the text and included in Appendix I. Case numbers 1-8 correspond to numbers given in Figure 4.

Case	Year	Cruise	Station	Sampling Depth (m)	TSS (mg/L)	TSS_1 (mg/L)	TSS_2 (mg/L)	Appendix I TSS (mg/L)
1	1991	2	5	1	23.1	14.7	12.2	14.7
2	1991	2	7	1	8.8	23.9	22.2	23.9
3	1991	3	7	1	14.9	20.4	14.5	14.9
4	1991	7	16	1	14.5	9.3	8.1	9.3
5	1992	7	7	1	20.2	6.0	5.5	6.0
6	1992	7	16	1	14.5	7.1	—	10.8
7	1993	7	14	1	9.6	5.5	4.7	5.5
8	1993	7	16	1	12.9	6.8	9.2	6.8
9	1991	8	26	1	1.0	1.6	2.9	1.6
10	1992	3	12	1	0.1	-	6.6	6.6
11	1992	3	14	1	0.0	1.3	1.6	1.3
12	1992	7	24	6	0.0	2.0	—	2.0
13	1993	3	19	1	0.2	0.8	0.9	0.8
14	1993	4	10	1	0.7	2.8	2.3	2.8

Table 7.--Mean coefficients of variation for each of the listed variables. Each individual coefficient of variation (each n) was derived from a duplicate water sample collected at each sampling depth at Stations 2, 5, 20, 21, and 25 on each sampling depth in 1991 and 1992, and at each sampling depth at Stations 5 and 20 on each sampling date in 1993.

Year	n	Alk	TSS	SRP	TP	TDP	NO_3	NH_4	SiO_2	PSi	Cl	POC	DOC	Chl
1991	38	2.8	12.9	18.3	17.8	—	3.9	18.3	7.8	11.8	2.9	17.5	8.5	13.5
1992	40	1.9	15.5	21.1	10.9	—	5.3	21.8	6.4	7.0	3.7	8.6	7.2	9.0
1993	21	2.0	19.5	6.9	14.9	18.6	6.4	11.5	2.9	5.5	1.6	6.7	2.0	19.5
1991-93	99	2.3	15.4	17.0	14.3	18.6	5.0	18.3	6.2	8.5	3.0	11.5	6.7	12.9

8.0 REFERENCES

APHA. *Standard methodsfor the examination of water and wastewater.* 17th edition. American Public Health Association. Washington, DC, 1268 pp. (1990).

Bierman, V.J. Jr., D.M. Dolan, and R. Kasprzyk. Retrospective analysis of the response of Saginaw Bay, Lake Huron to reductions in phosphorus loadings. *Environmental Science and Technology* 18:23-21 (1984).

Beeton, A.M., S.H. Smith, and F.H. Hooper. Physical limnology of Saginaw Bay, Lake Huron. Great Lakes Fishery Commission, Technical Report Number 12, 56 pp. (1967).

Danek, L.J., and J.H. Saylor. Measurements of the summer currents in Saginaw Bay, Michigan. *Journal of Great Lakes Research* 3:65-71(1977).

Davis, C.O. and M.S. Simmons. Water chemistry and phytoplankton field and laboratory procedures. Special Report No. 70, Great Lakes Research Div., Univ. of Michigan, Ann Arbor, MI (1979).

Fahnenstiel, G.L., G.A. Lang, T.F. Nalepa, and T.H. Johengen. Effects of zebra mussel *(Dreissena polymorpha)* colonization on water quality parameters in Saginaw Bay, Lake Huron. *Journal of Great Lakes Research* 21: 435-448 (1995a).

Fahnenstiel, G.L., T.B. Bridgeman, G.A. Lang, M.J. McCormick, and T.F. Nalepa. Phytoplankton productivity in Saginaw Bay, Lake Huron: effects of zebra mussel *(Dreissena polymorpha)* colonization. *Journal of Great Lakes Research* 21:465-475 (1995b).

Johengen, T. H., T.F. Nalepa, G.L. Fahnenstiel, and G. Goudy. Nutrient changes in Saginaw Bay, Lake Huron after the establishment of the zebra mussel *Dreissena polymorpha. Journal of Great Lakes Research* 21: 449-464 (1995).

Krausse, G.L., C.L. Schelske, and C.O. Davis. Comparison of three wet-alkaline methods of digestion of biogenicsilicain wafer. *FreshwaterBiologyl3:73-81(1983).*

Menzel, D.W., and N. Corwin. The measurement of total phosphorus in seawater based on the liberation of organically bound fractions by persulfate oxidation. *Limnology Oceanography* 10:280-281 (1965).

Smith, V.E., K.W. Lee, J.S. Filkins, K.W. Hartwell, K.R. Rygwelski, and J.M. Townsend. Survey of chemical factors in Saginaw Bay (Lake Huron). EPA-600/3-77-125, U.S. Environmental Protection Agency, Duluth, Minnesota, 142 pp. (1977).

Strickland, J.D.H., and T.R. Parsons. *A Practical Handbook of SeawaterAnalysis,* 2nd ed. Bulletin Fisheries Research Board Canada No.167 (1972).

Wood, L.E. Bottom sediments of Saginaw Bay, Michigan. *Journal of Sediment Petrol.* 34: 173-184 (1964).

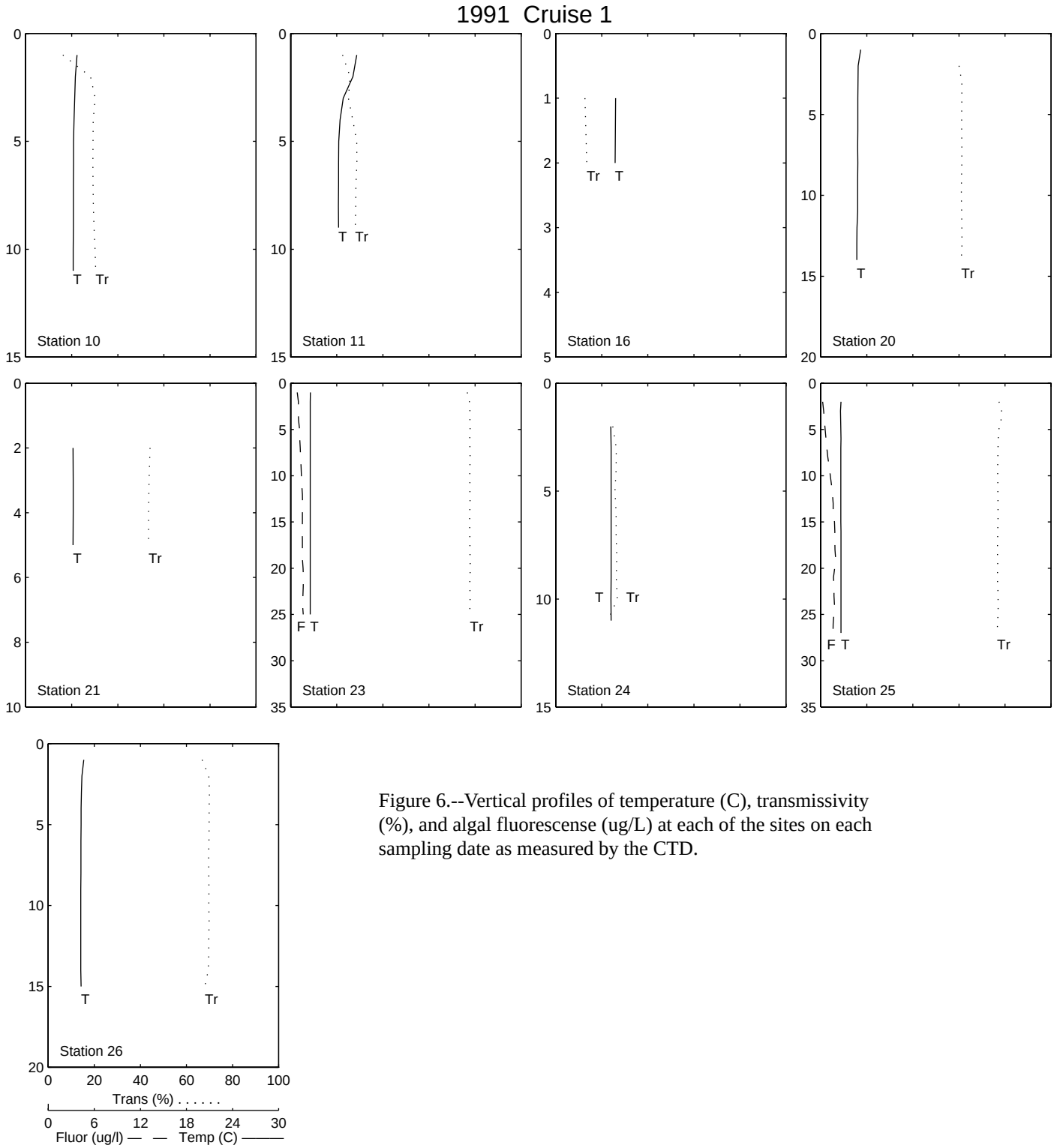


Figure 6.--Vertical profiles of temperature (C), transmissivity (%), and algal fluorescense (ug/L) at each of the sites on each sampling date as measured by the CTD.

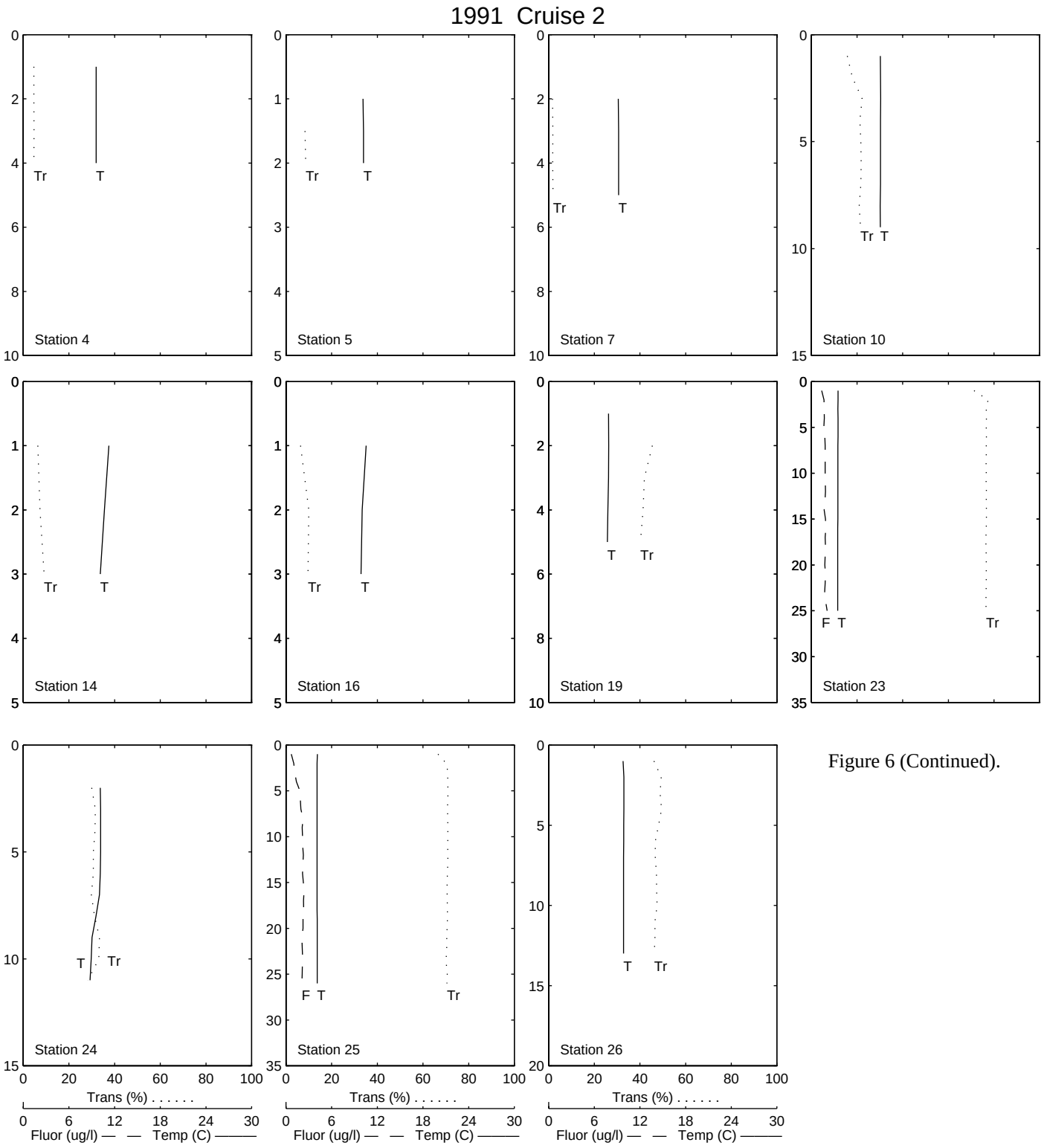


Figure 6 (Continued).

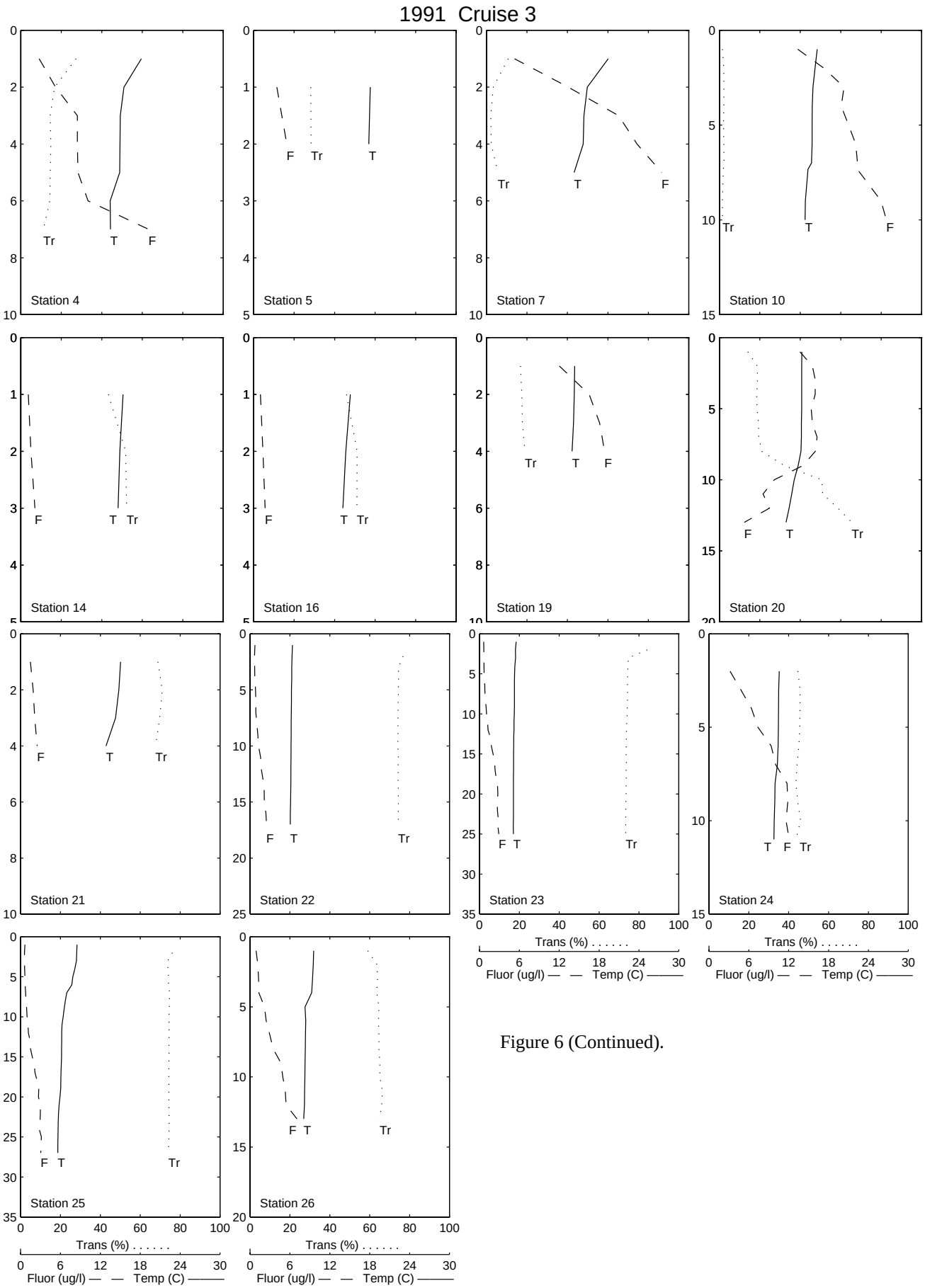


Figure 6 (Continued).

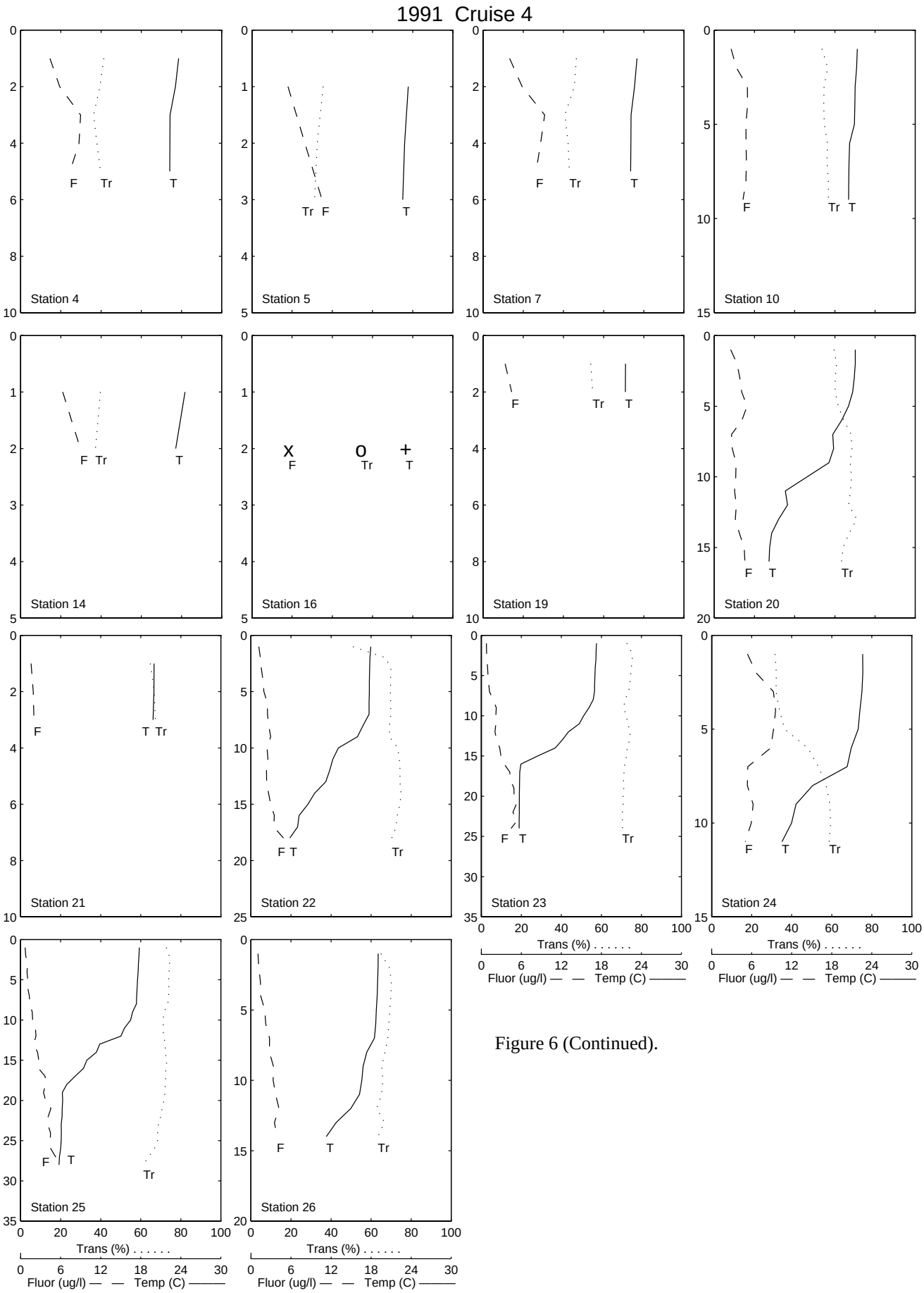


Figure 6 (Continued).

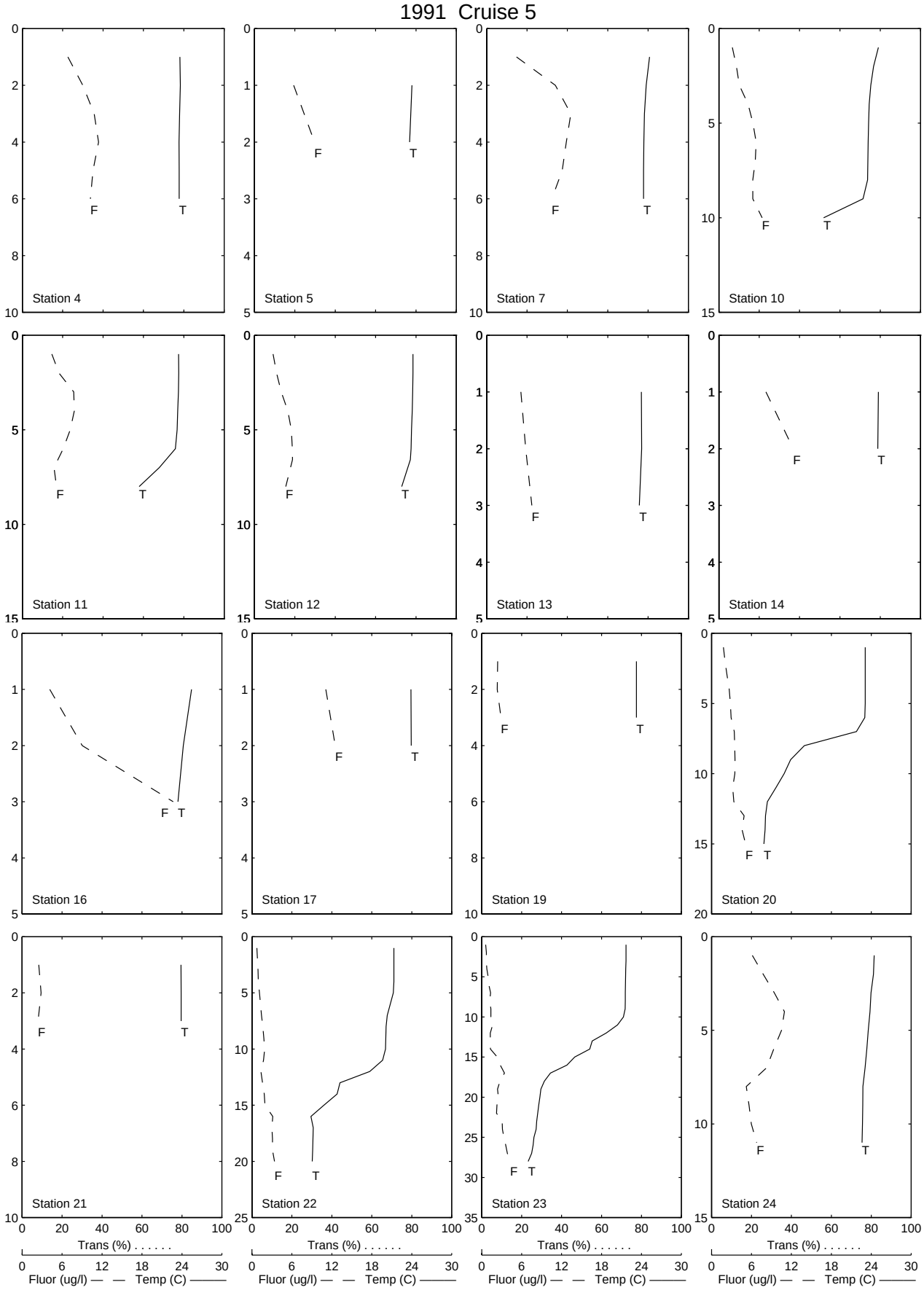


Figure 6 (Continued).

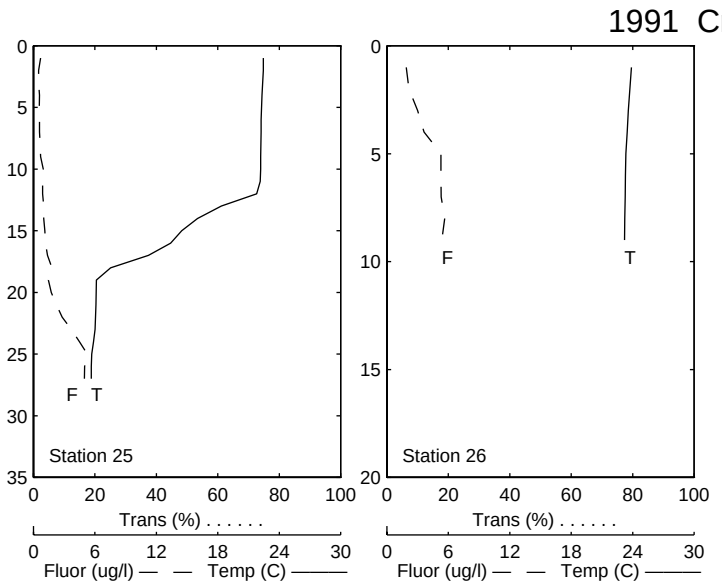


Figure 6 (Continued).

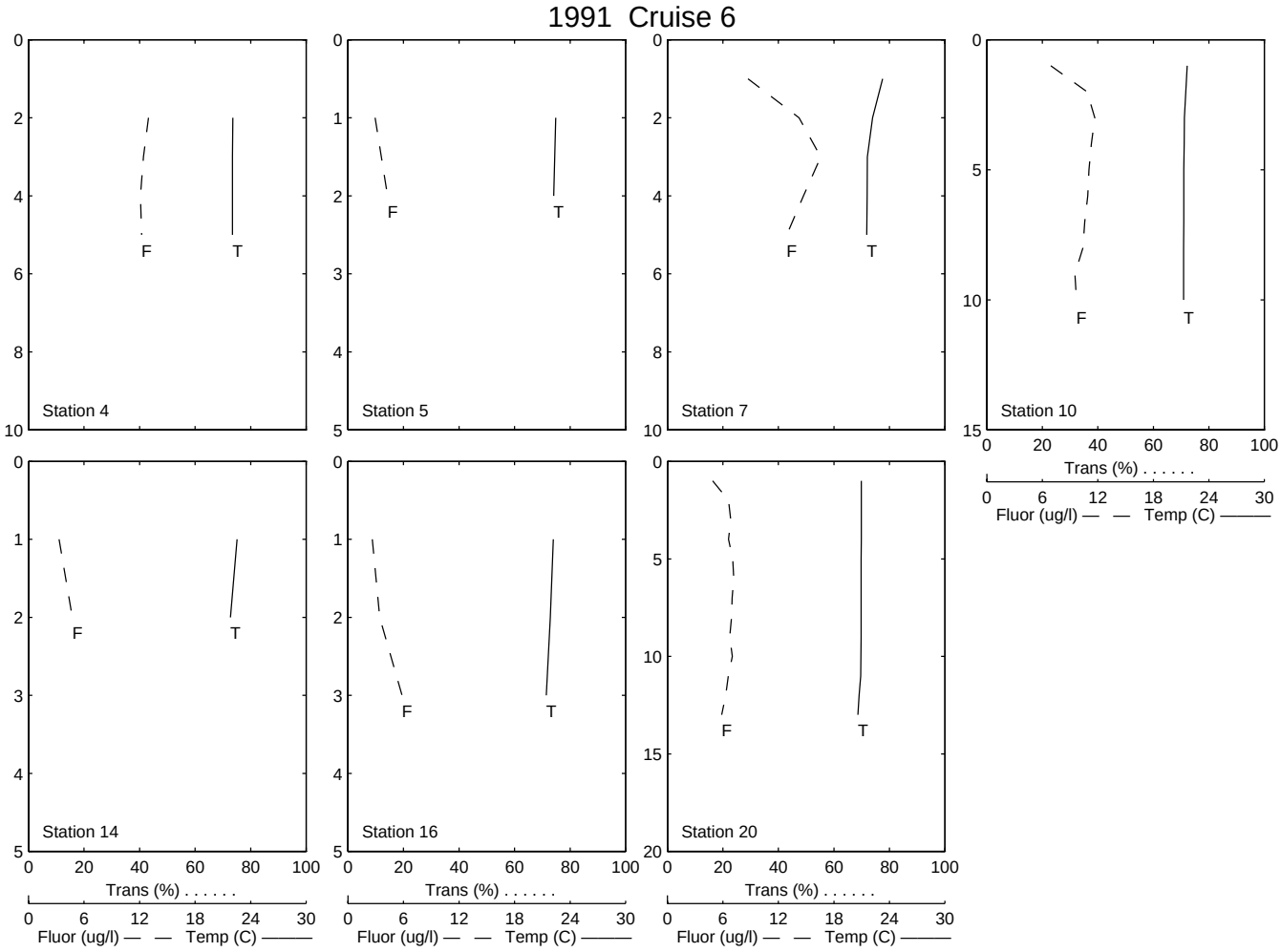


Figure 6 (Continued).

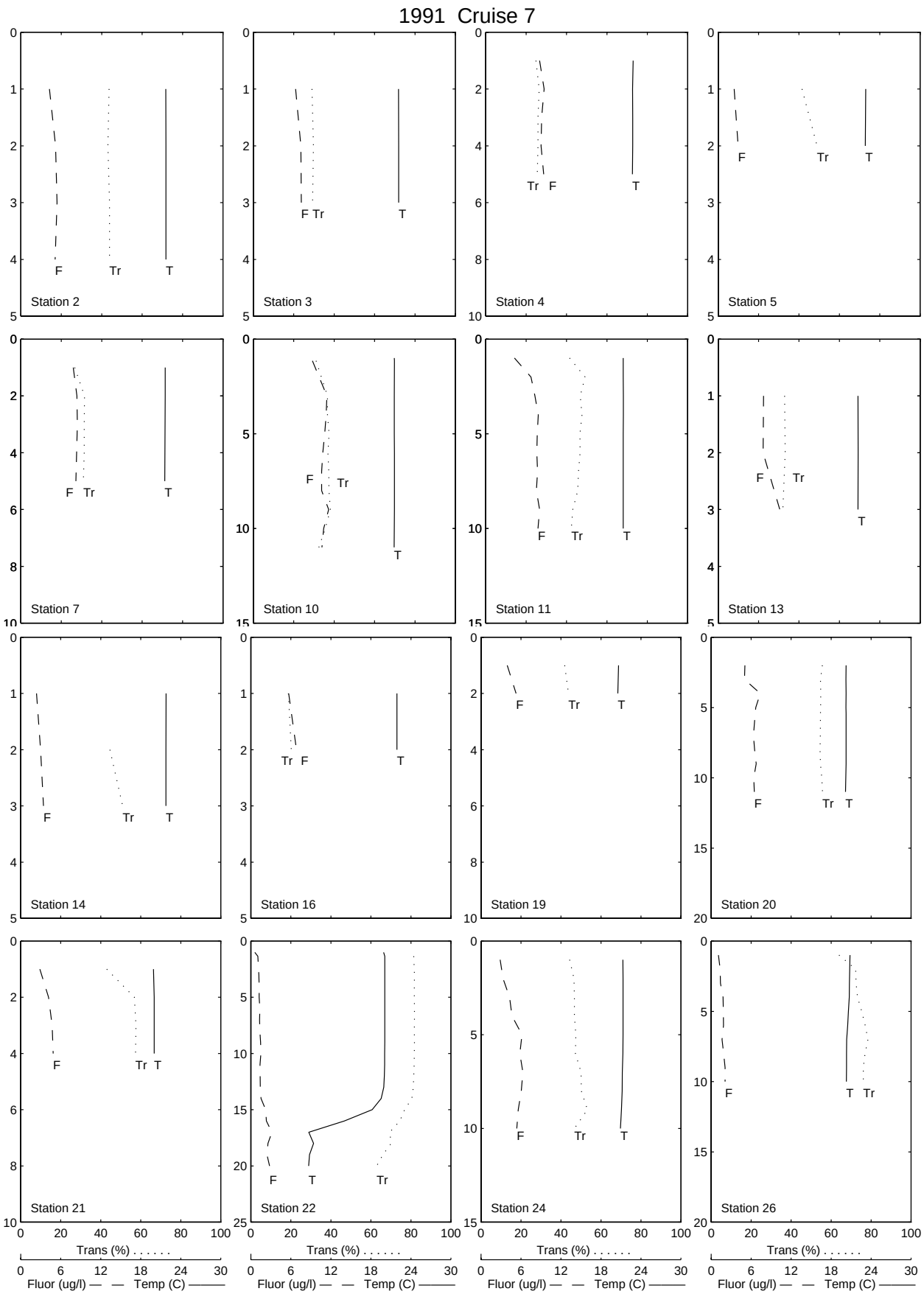


Figure 6 (Continued).

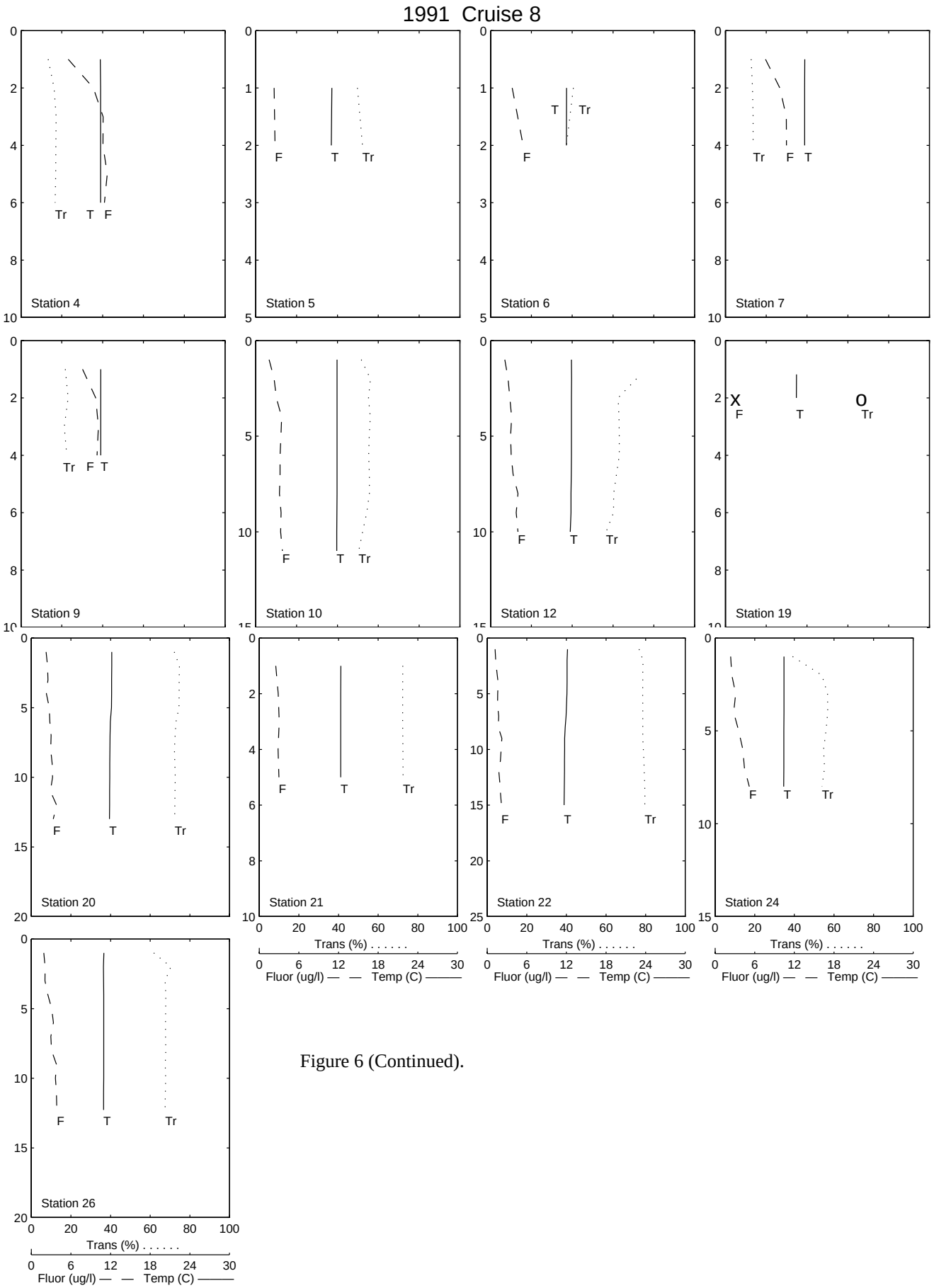


Figure 6 (Continued).

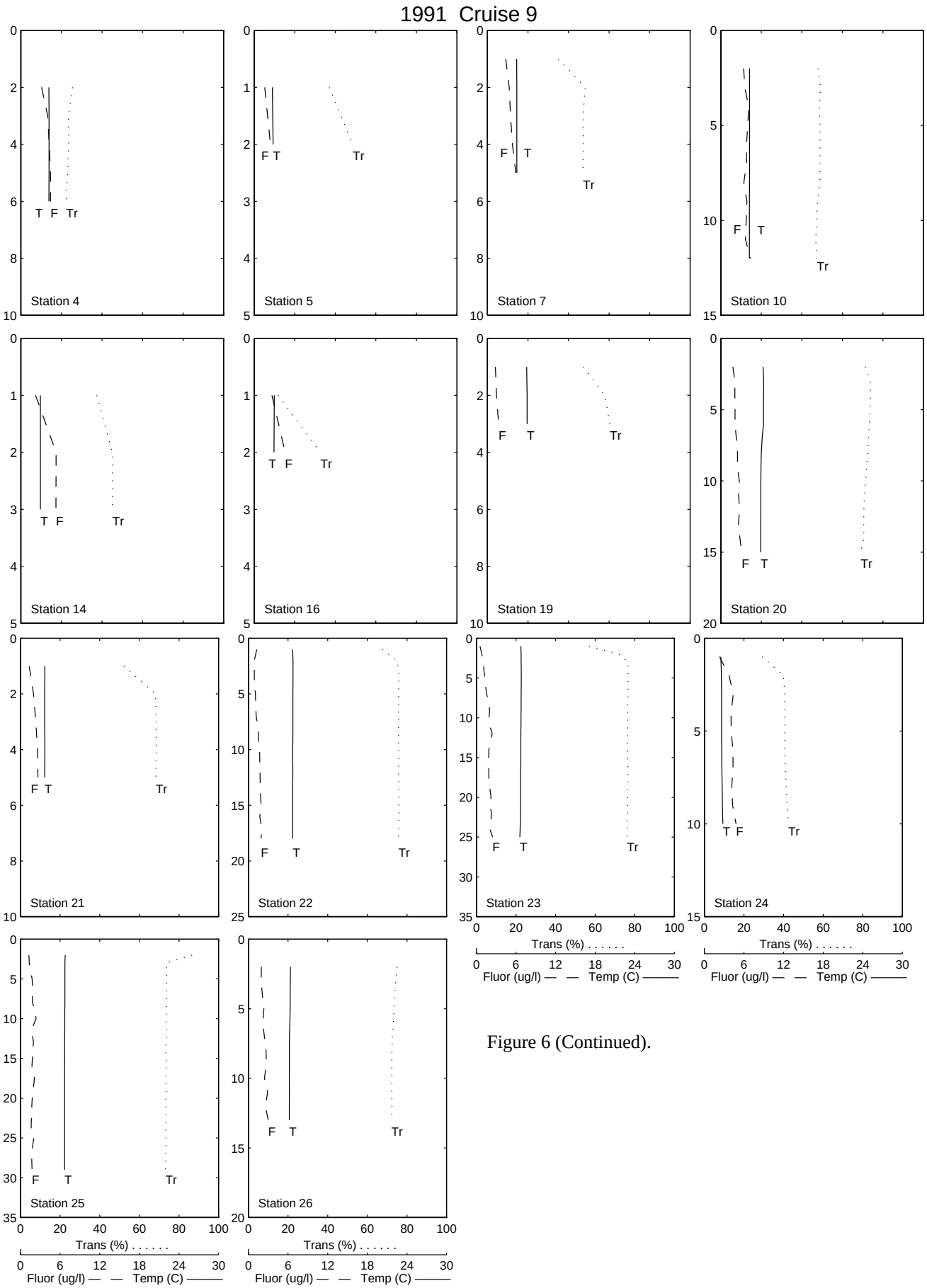


Figure 6 (Continued).

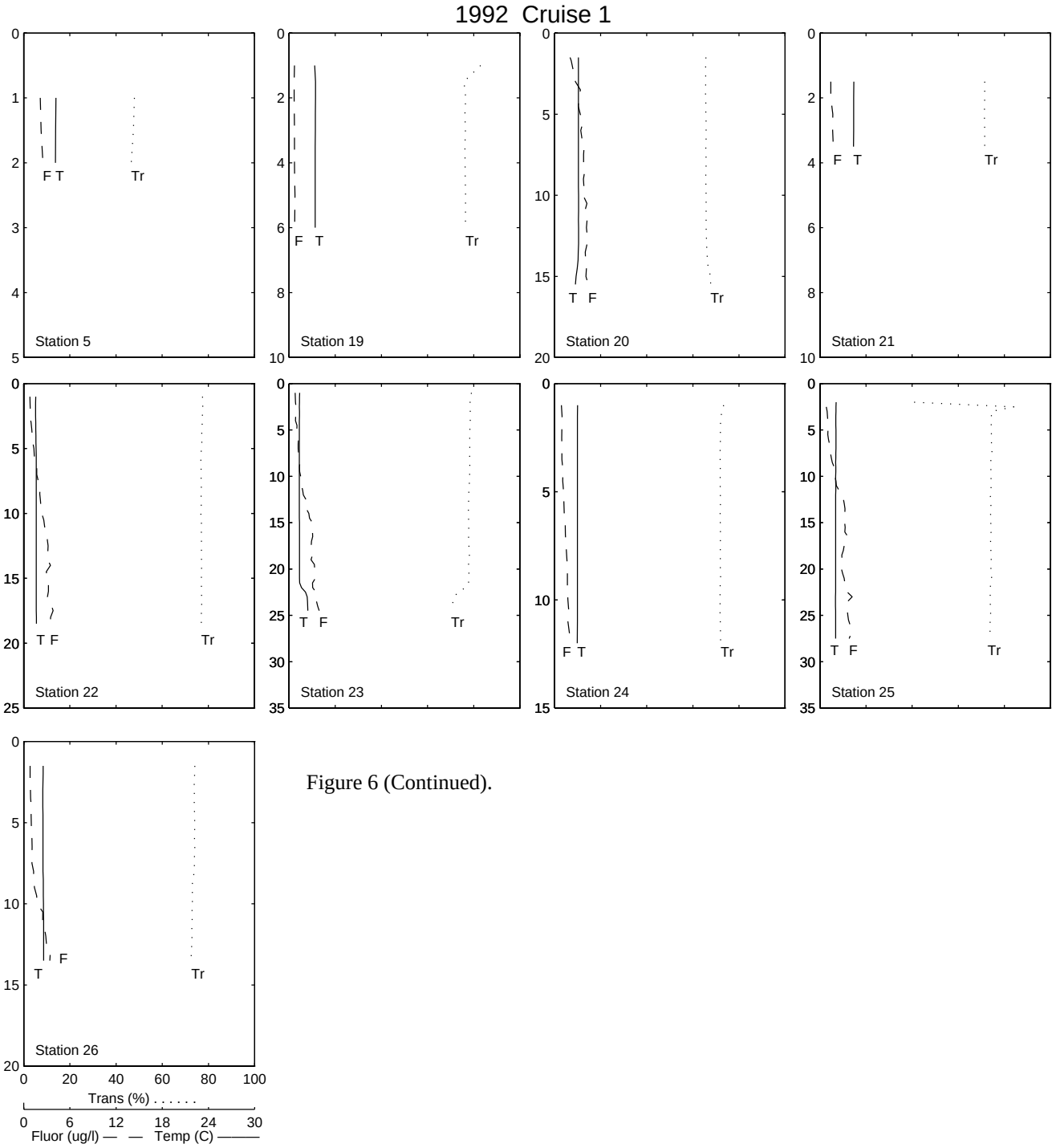


Figure 6 (Continued).

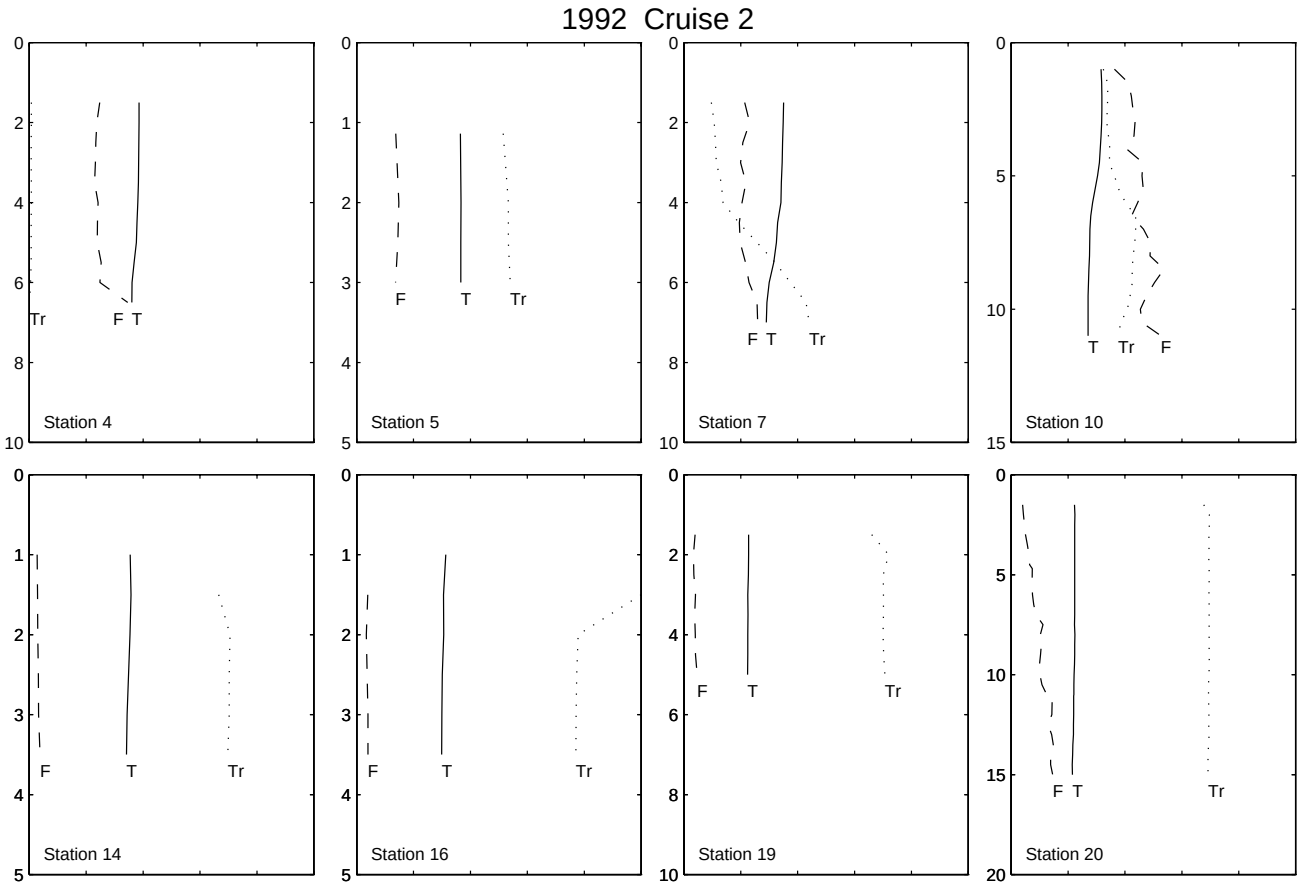


Figure 6 (Continued).

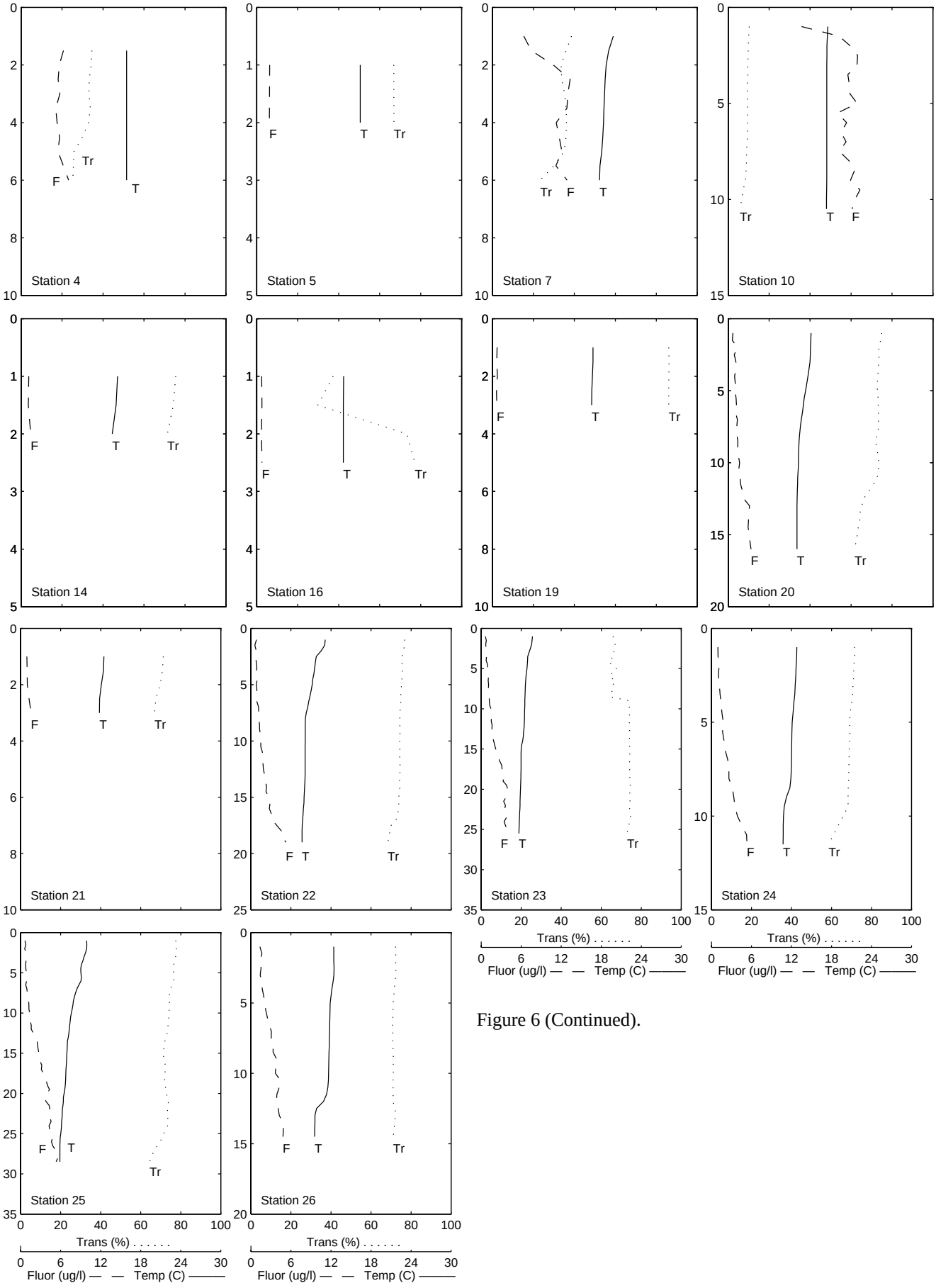


Figure 6 (Continued).

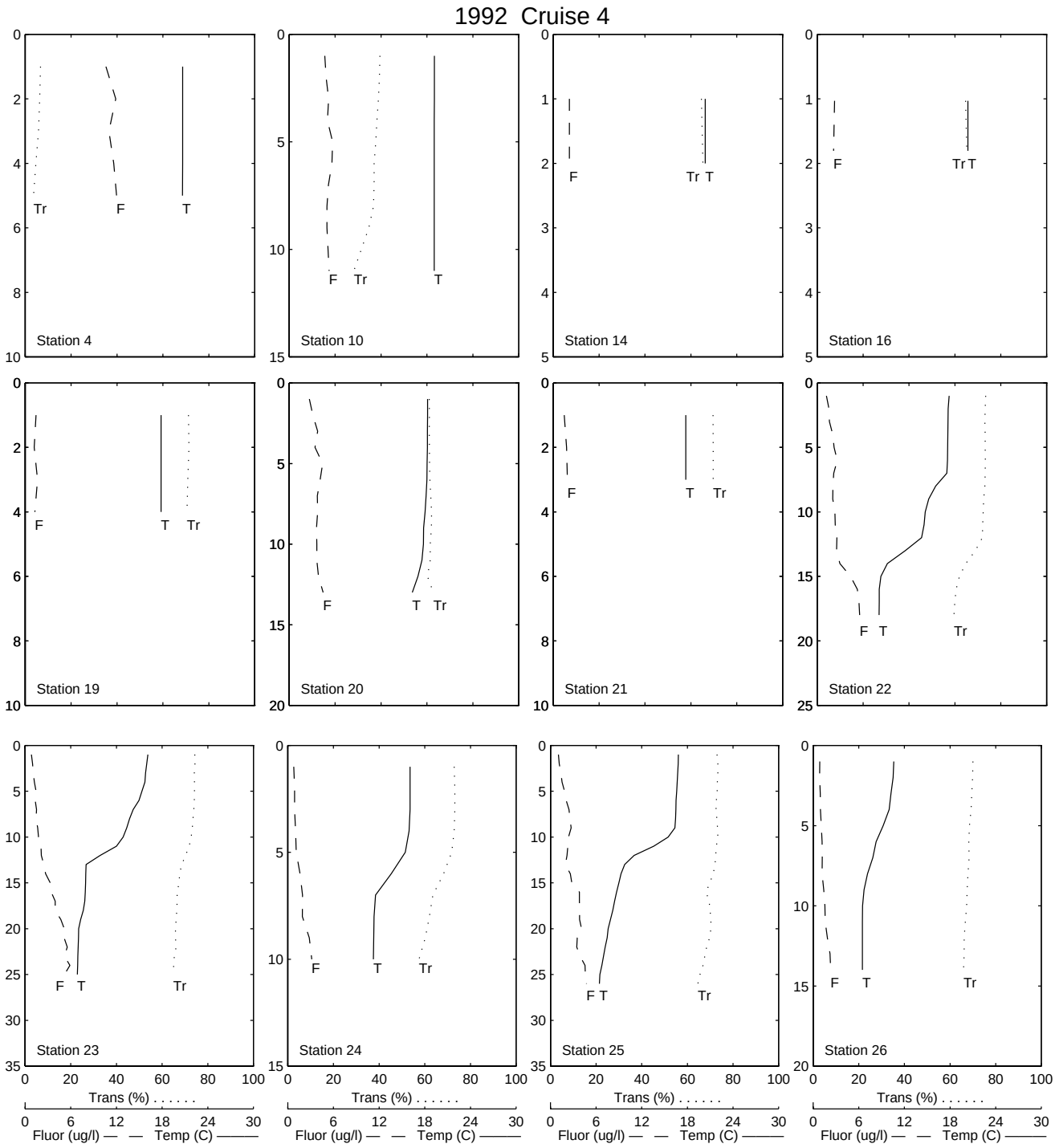


Figure 6 (Continued).

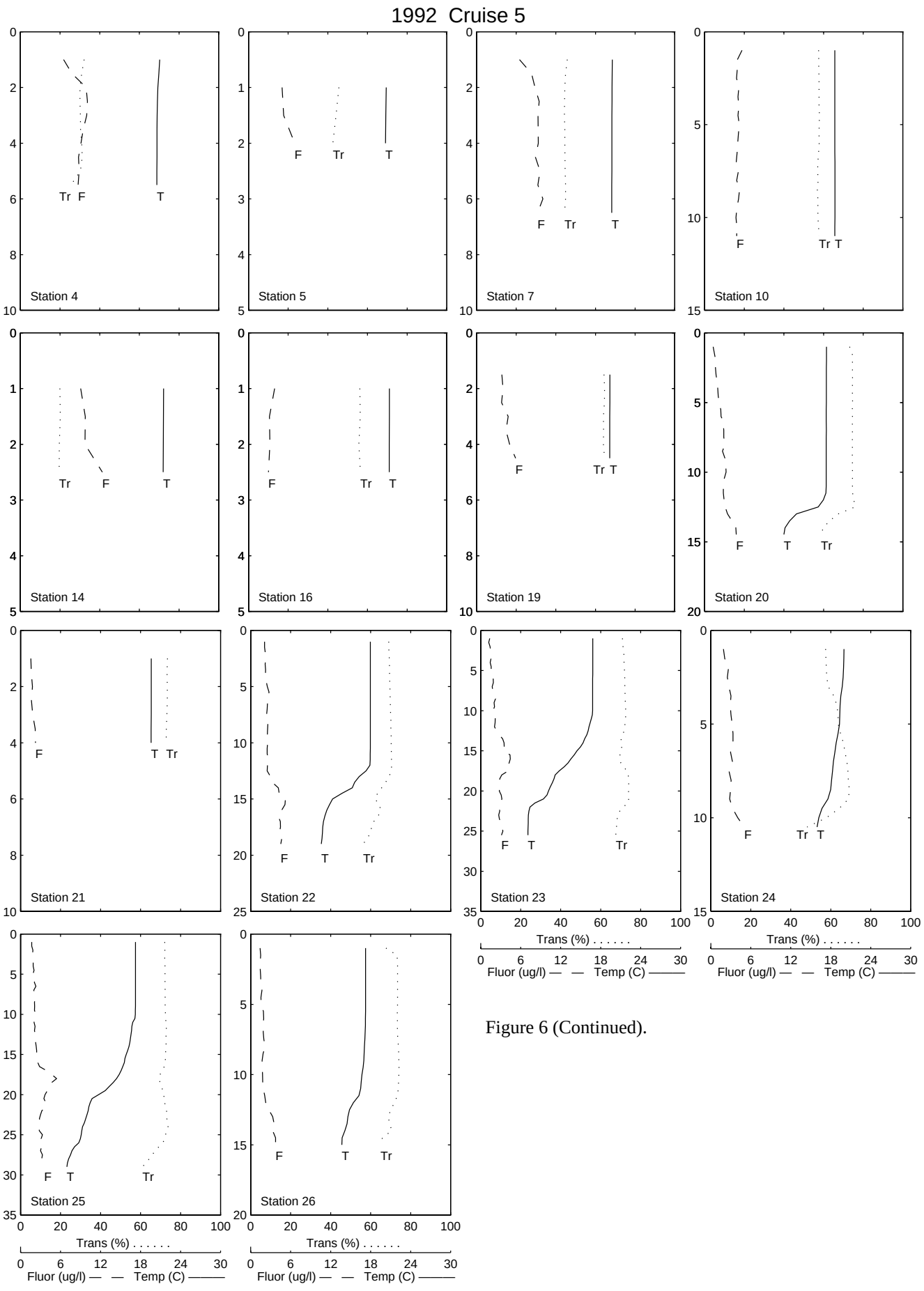


Figure 6 (Continued).

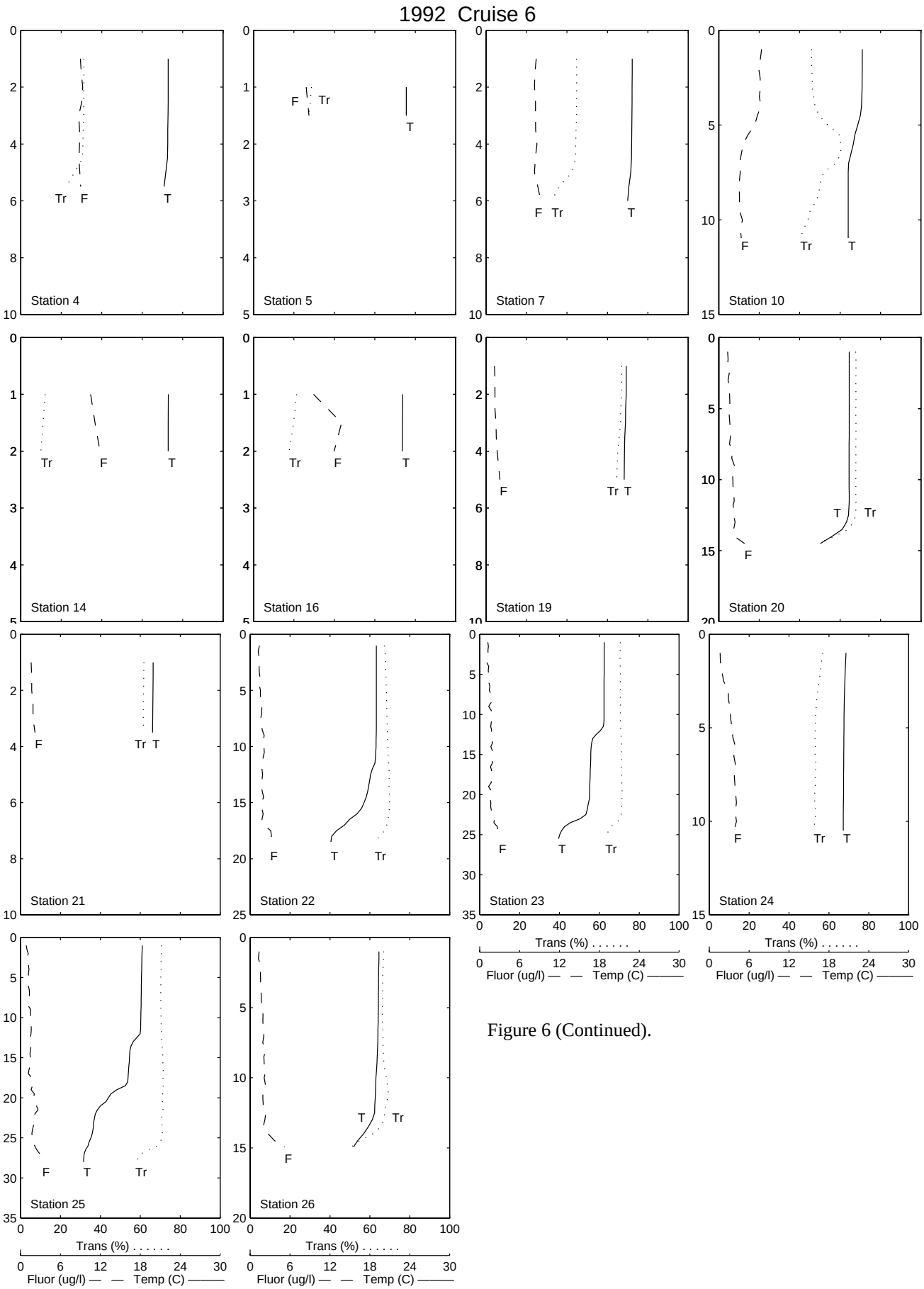


Figure 6 (Continued).

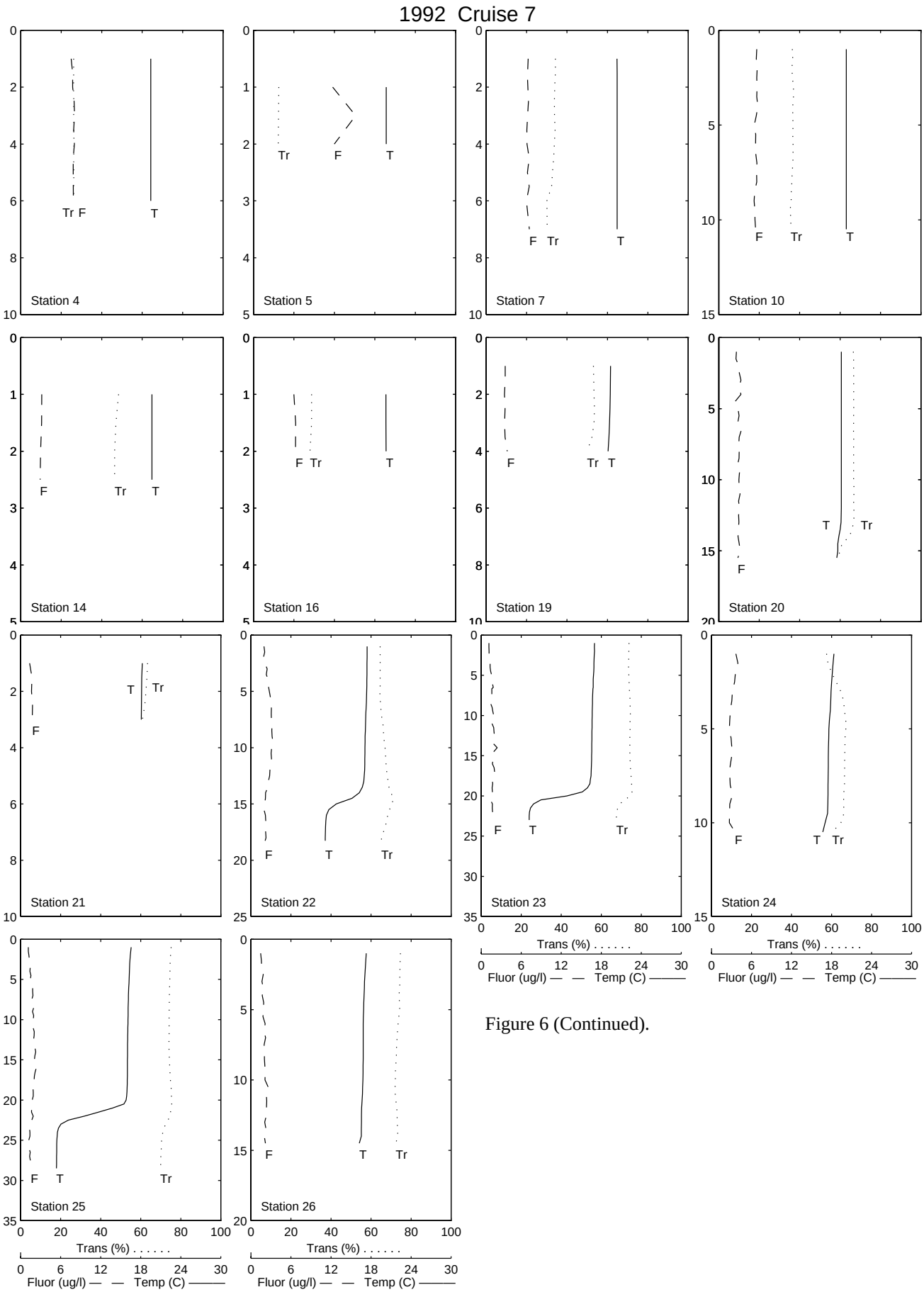


Figure 6 (Continued).

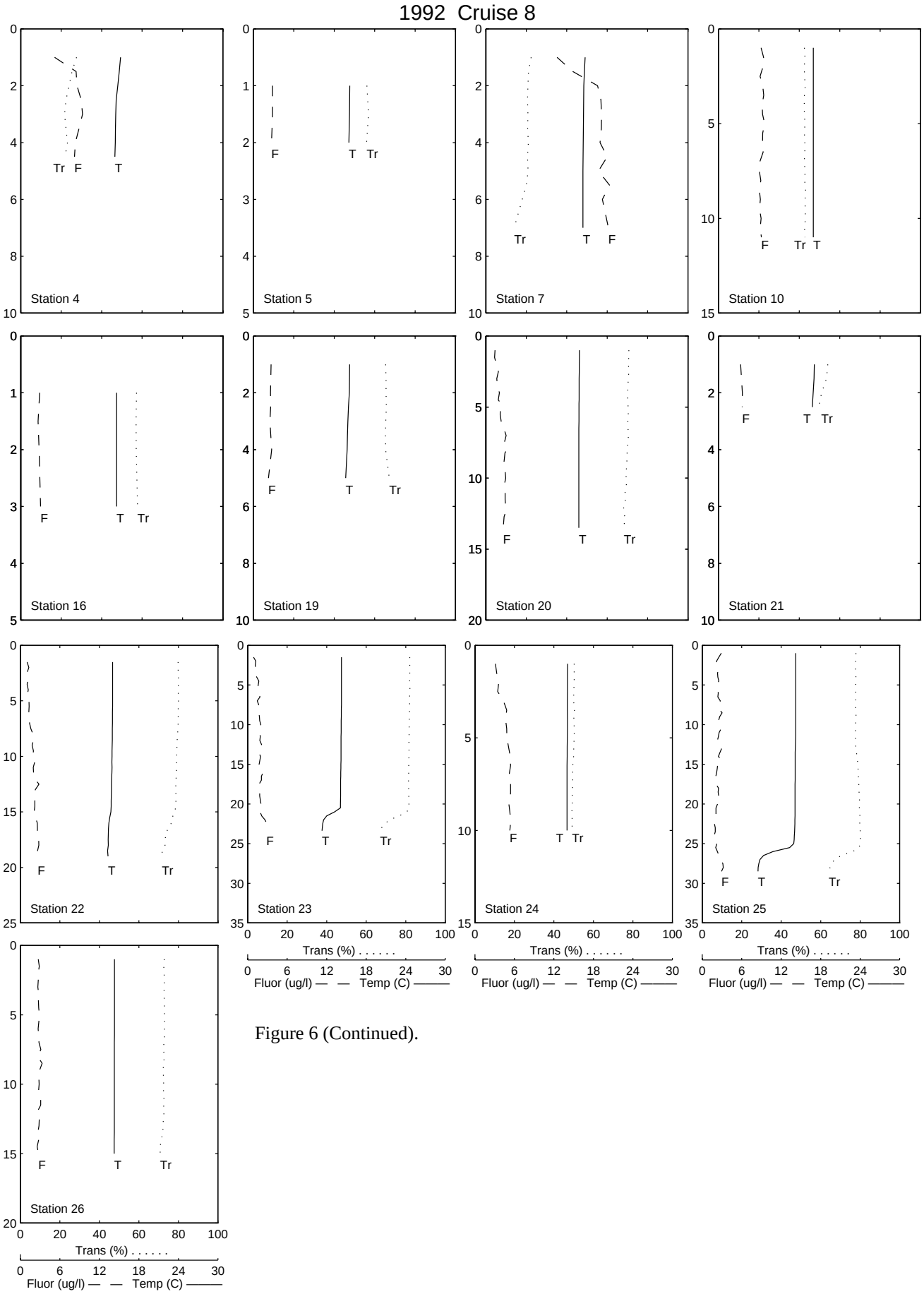


Figure 6 (Continued).

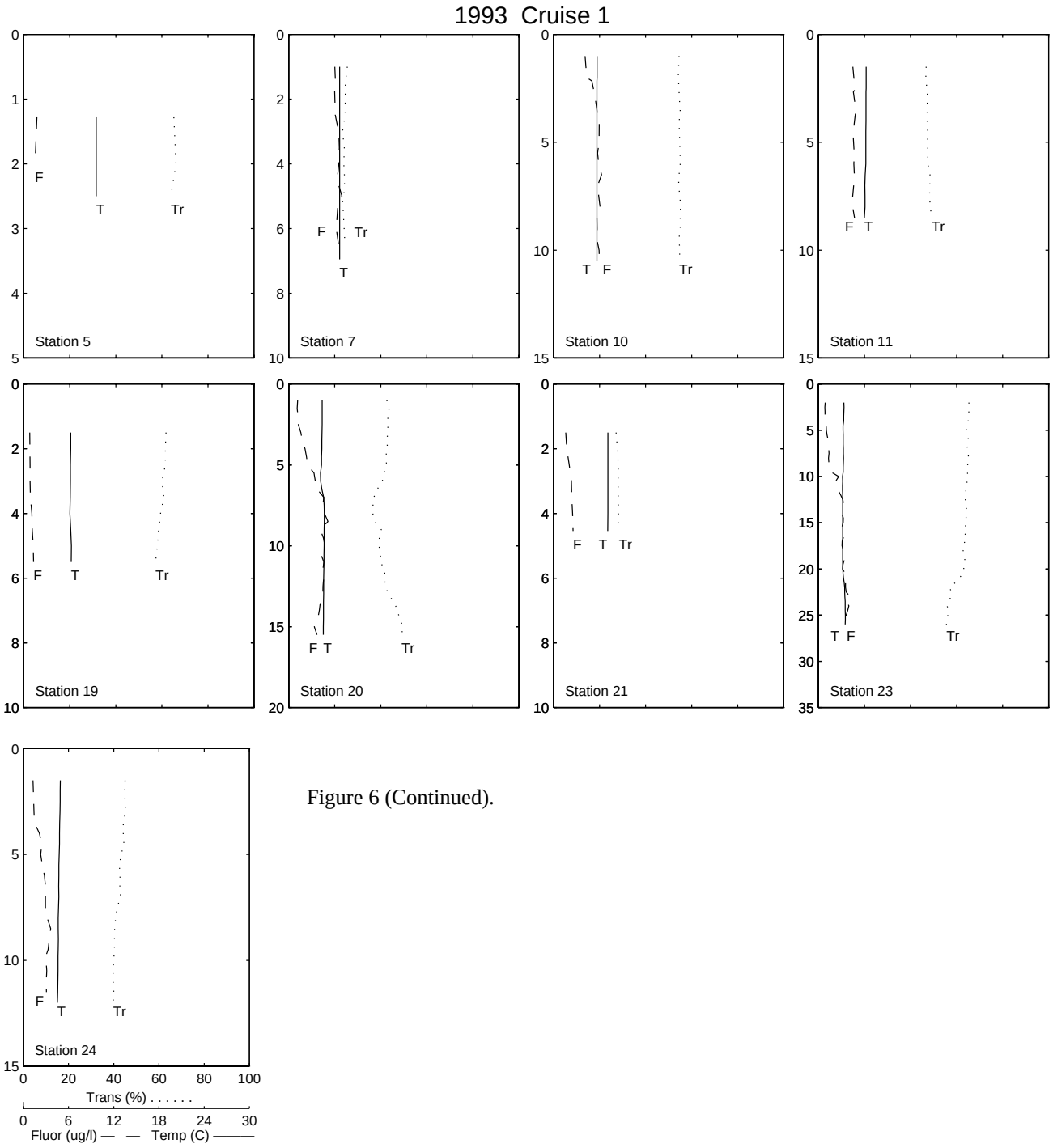


Figure 6 (Continued).

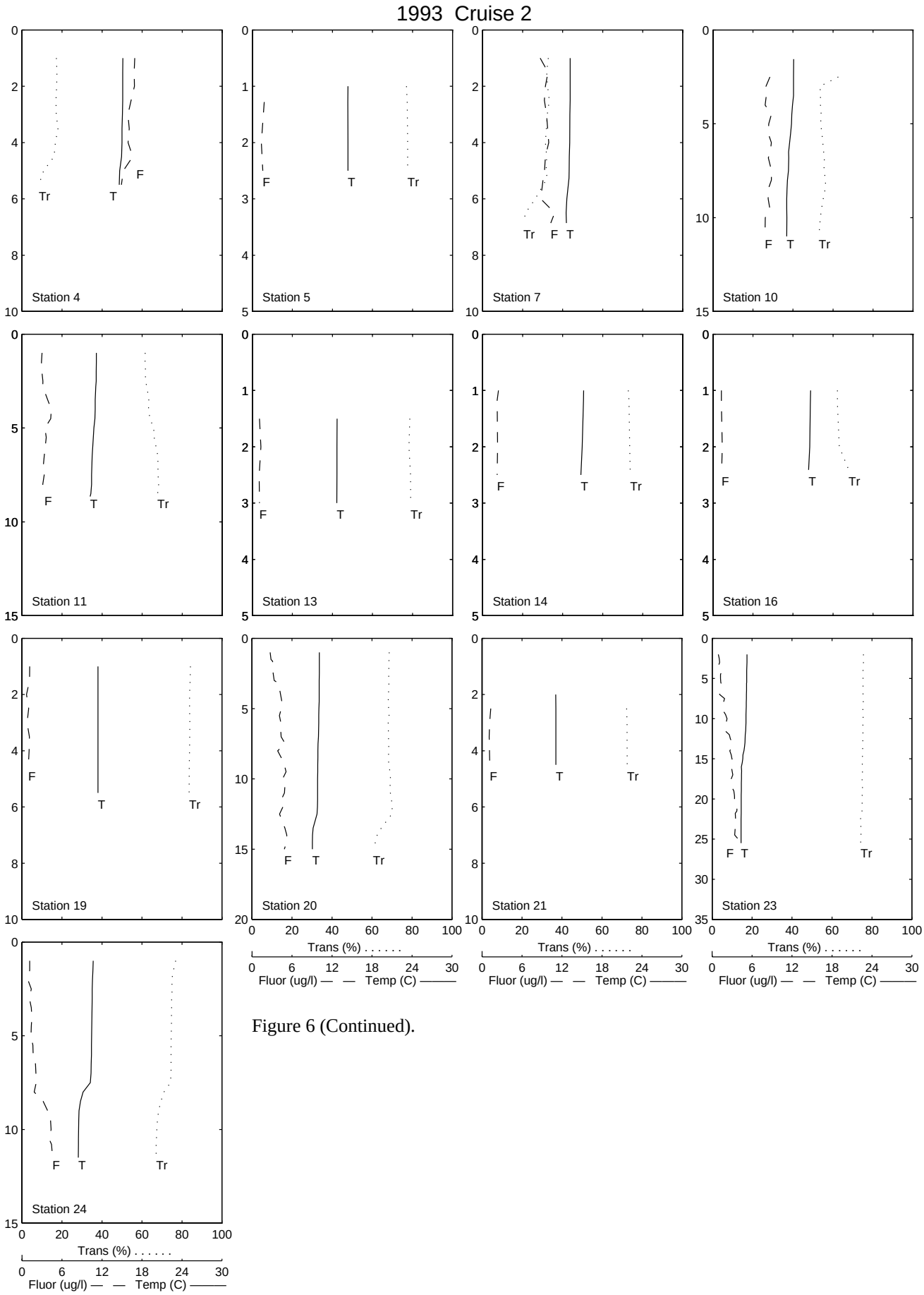


Figure 6 (Continued).

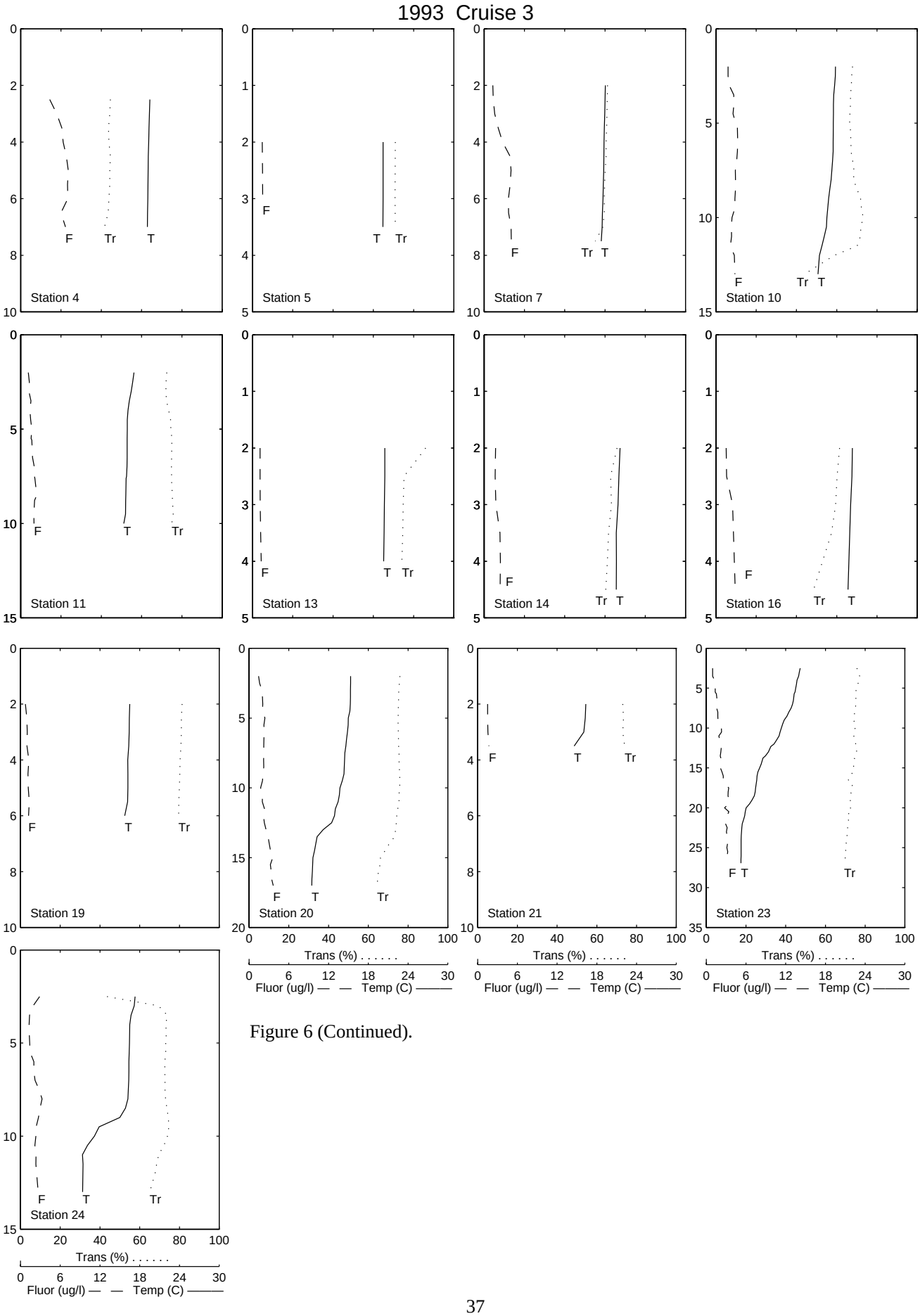


Figure 6 (Continued).

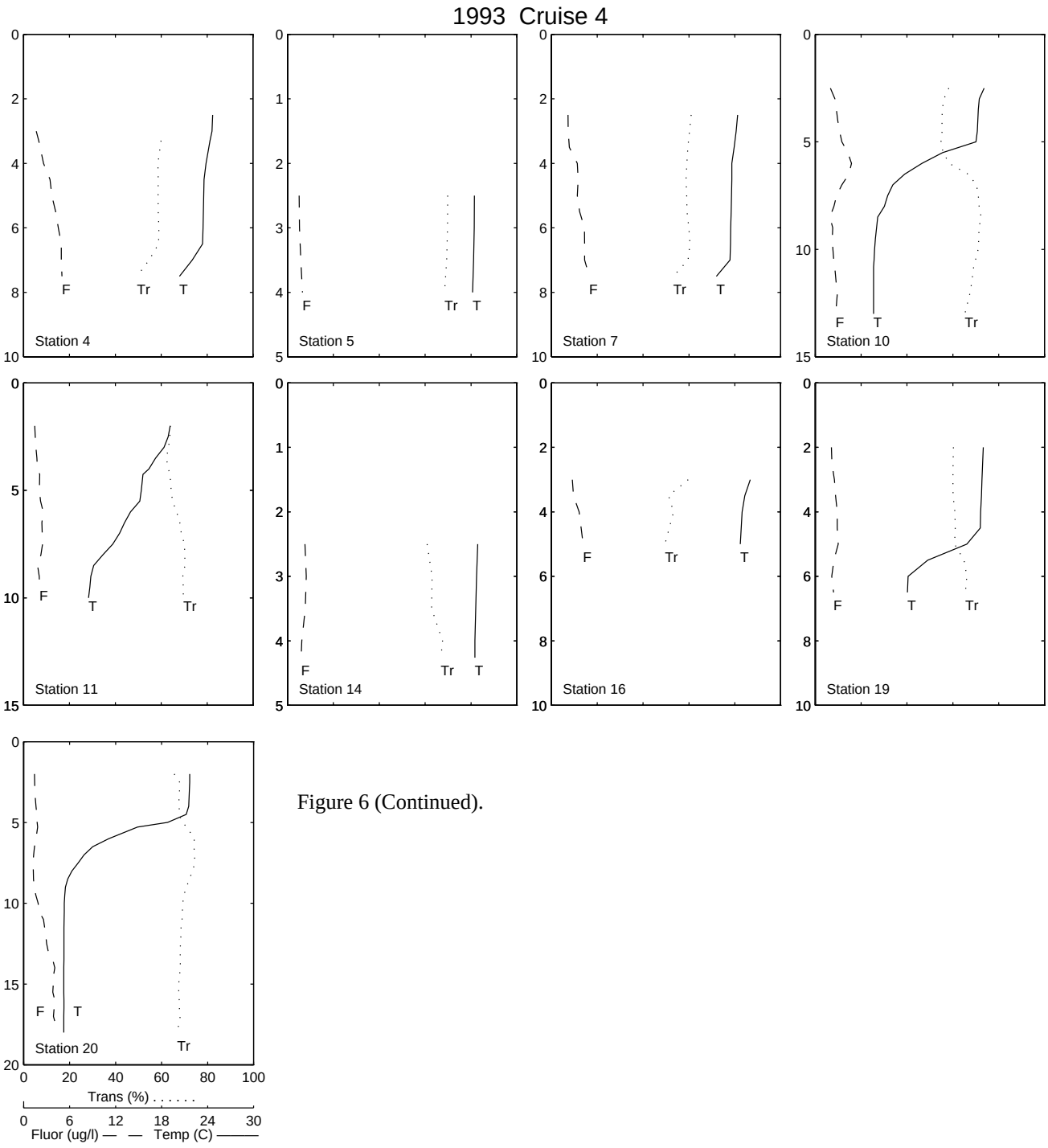


Figure 6 (Continued).

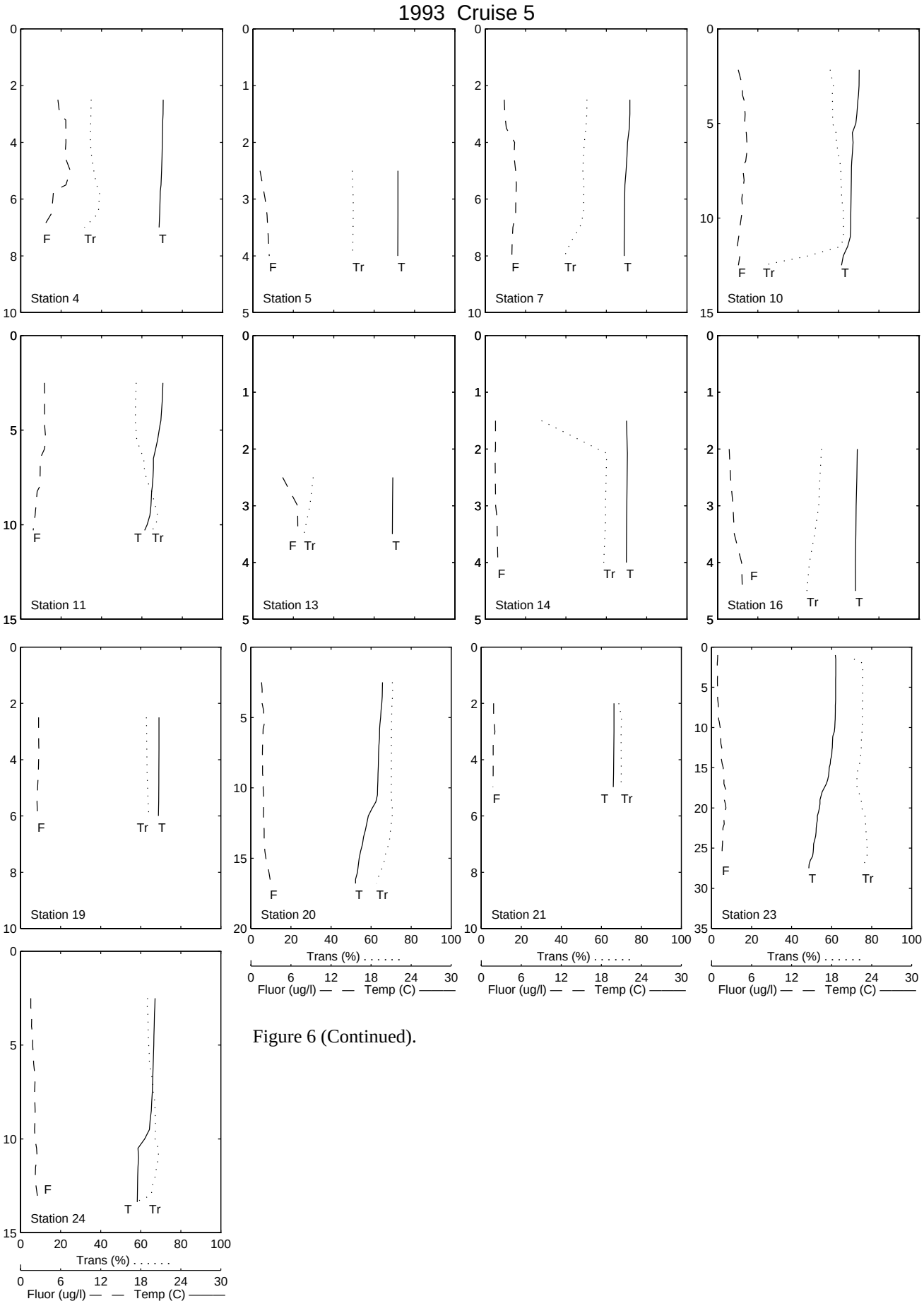


Figure 6 (Continued).

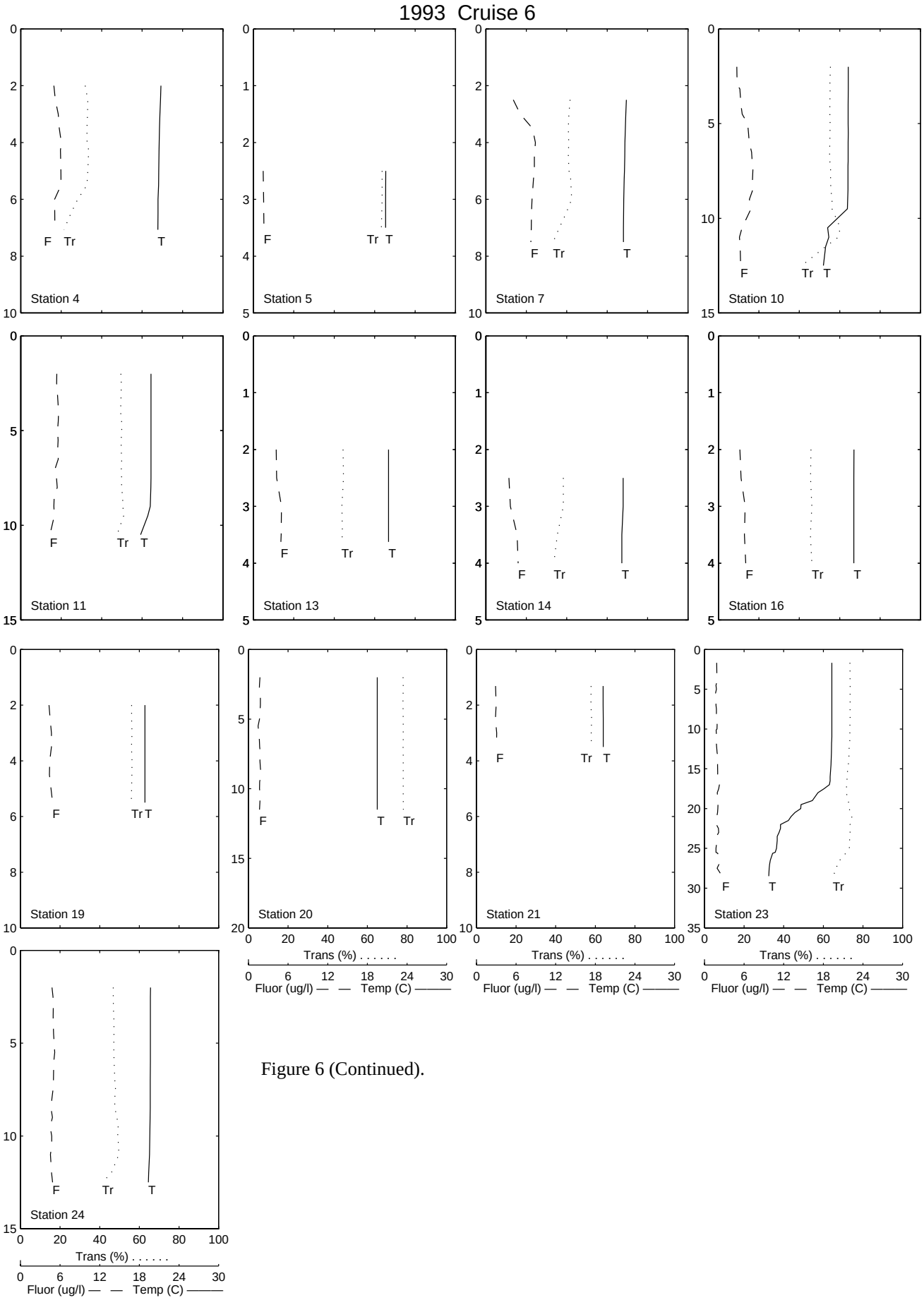


Figure 6 (Continued).

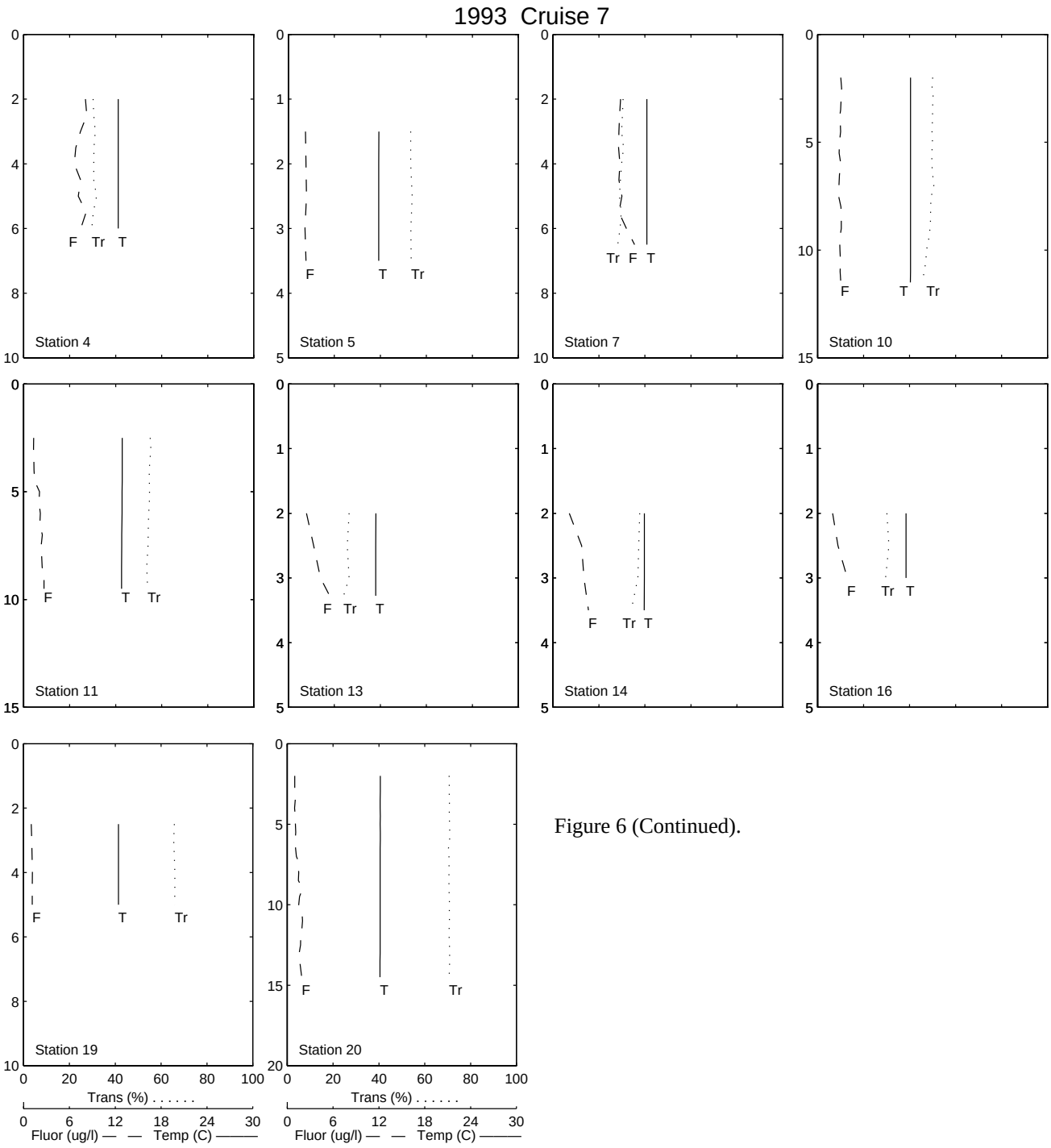


Figure 6 (Continued).

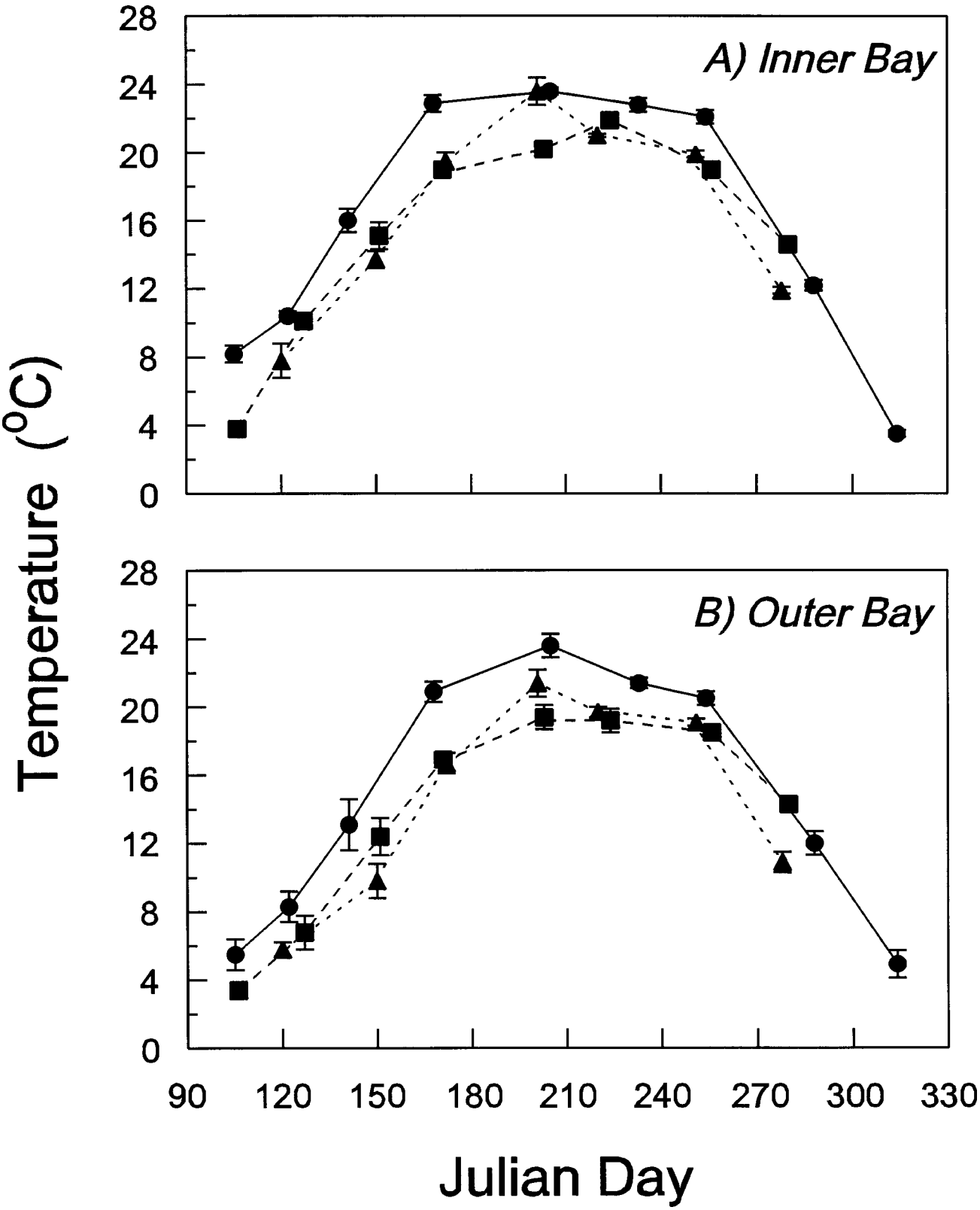


Figure 7.--Mean (± SE) values of the following select variables on each sampling date in 1991-93 for the inner and outer bay: temperature, secchi-disk, transparency, chlorophyll, kPar, particulate organic carbon, dissolved organic carbon, total suspended solids, total phosphorus, total dissolved phosphorus, soluble reactive phosphorus, ammonium, nitrate, particulate silica, dissolved silica, and chloride.

Legend: ●——● = 1991; ■— —■ = 1992; ▲— —▲ = 1993

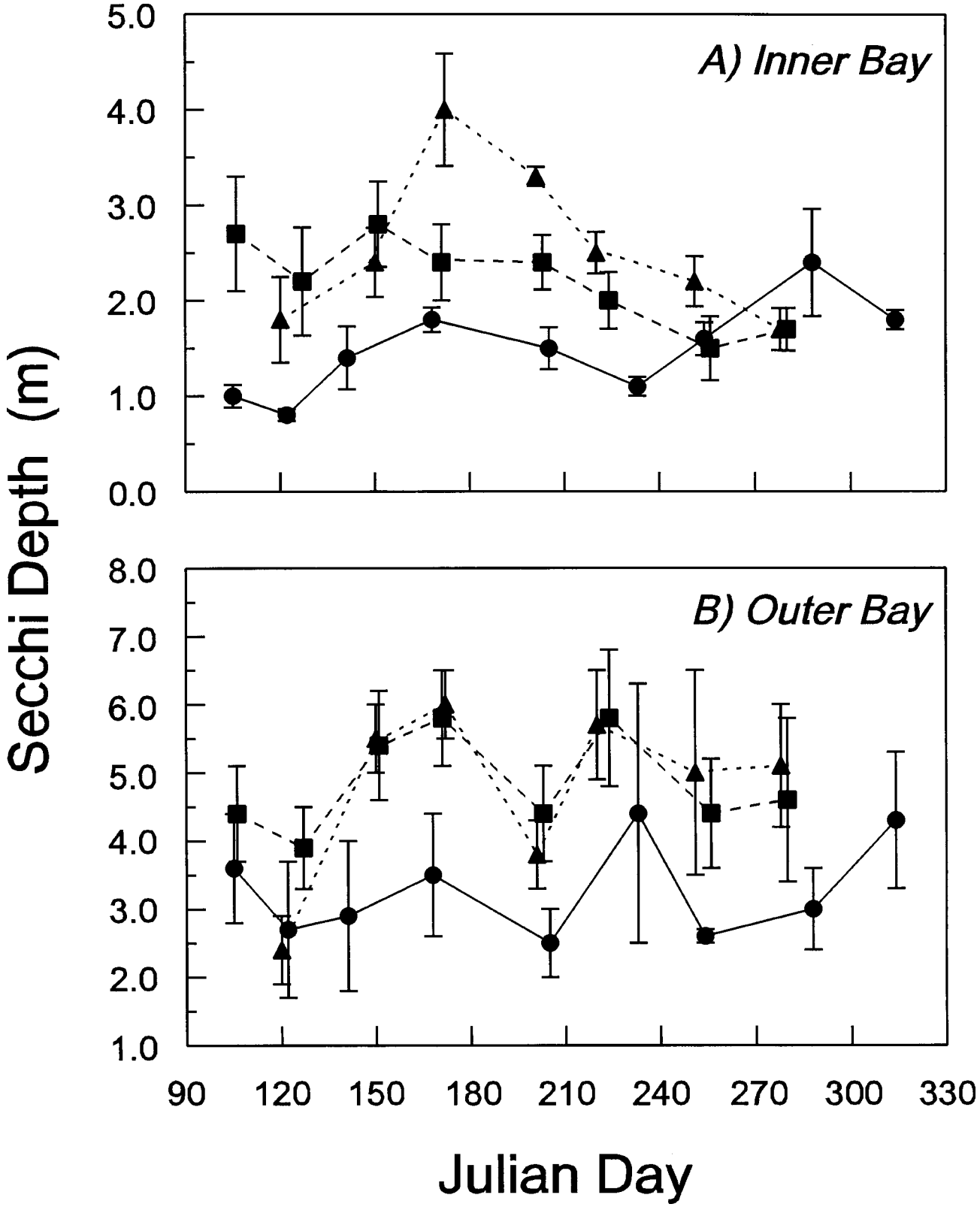


Figure 7 (Continued).

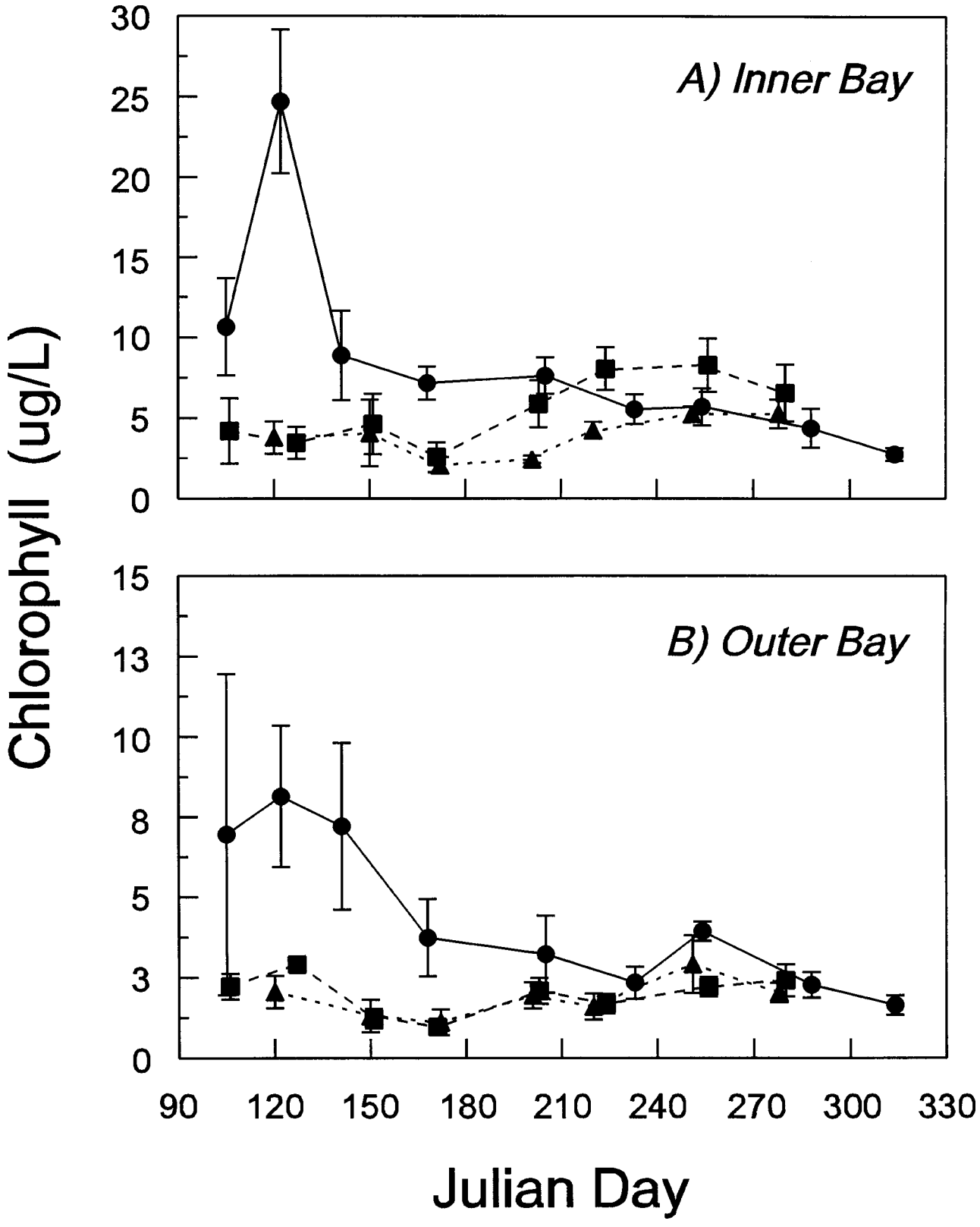


Figure 7 (Continued).

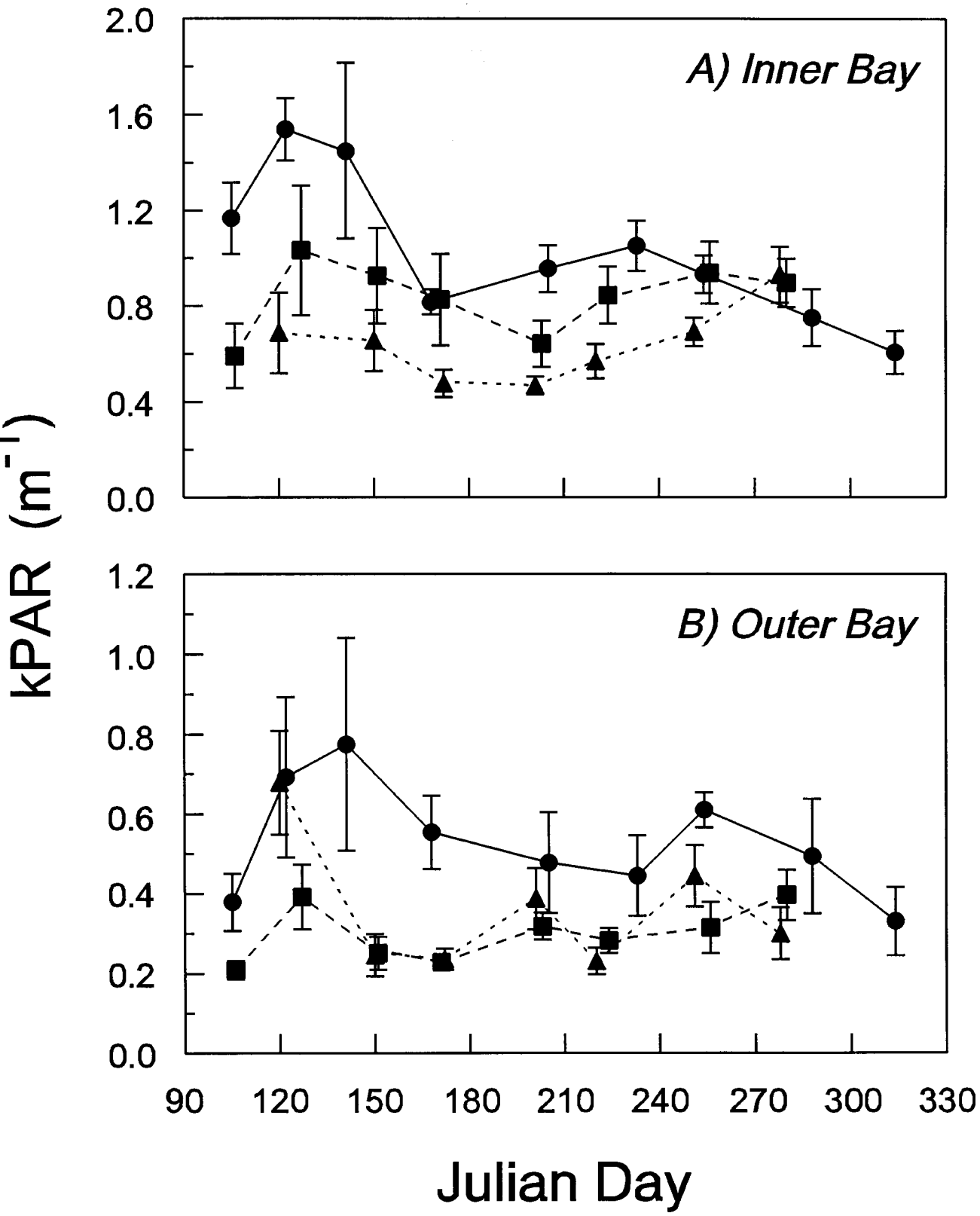


Figure 7 (Continued).

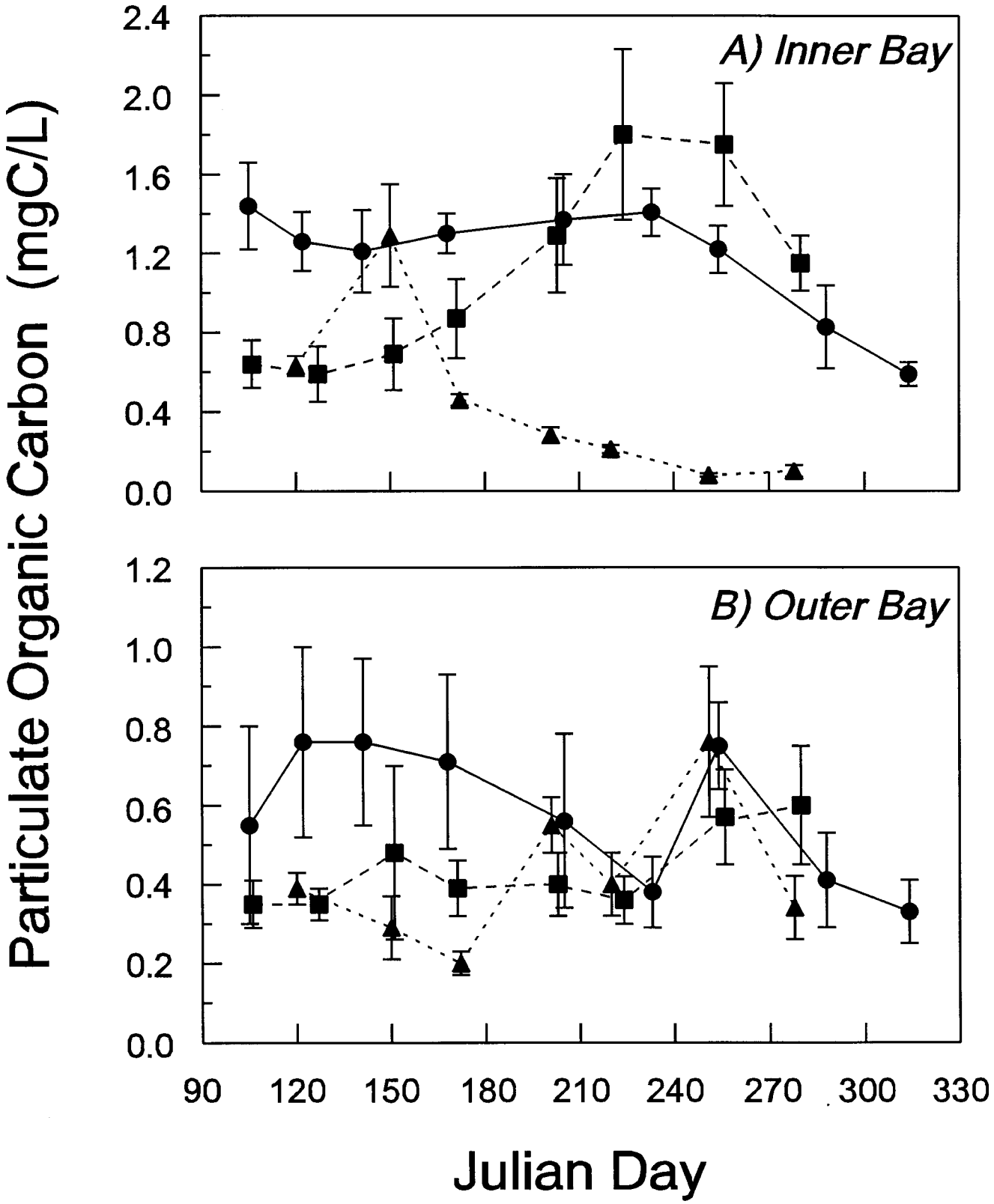


Figure 7 (Continued).

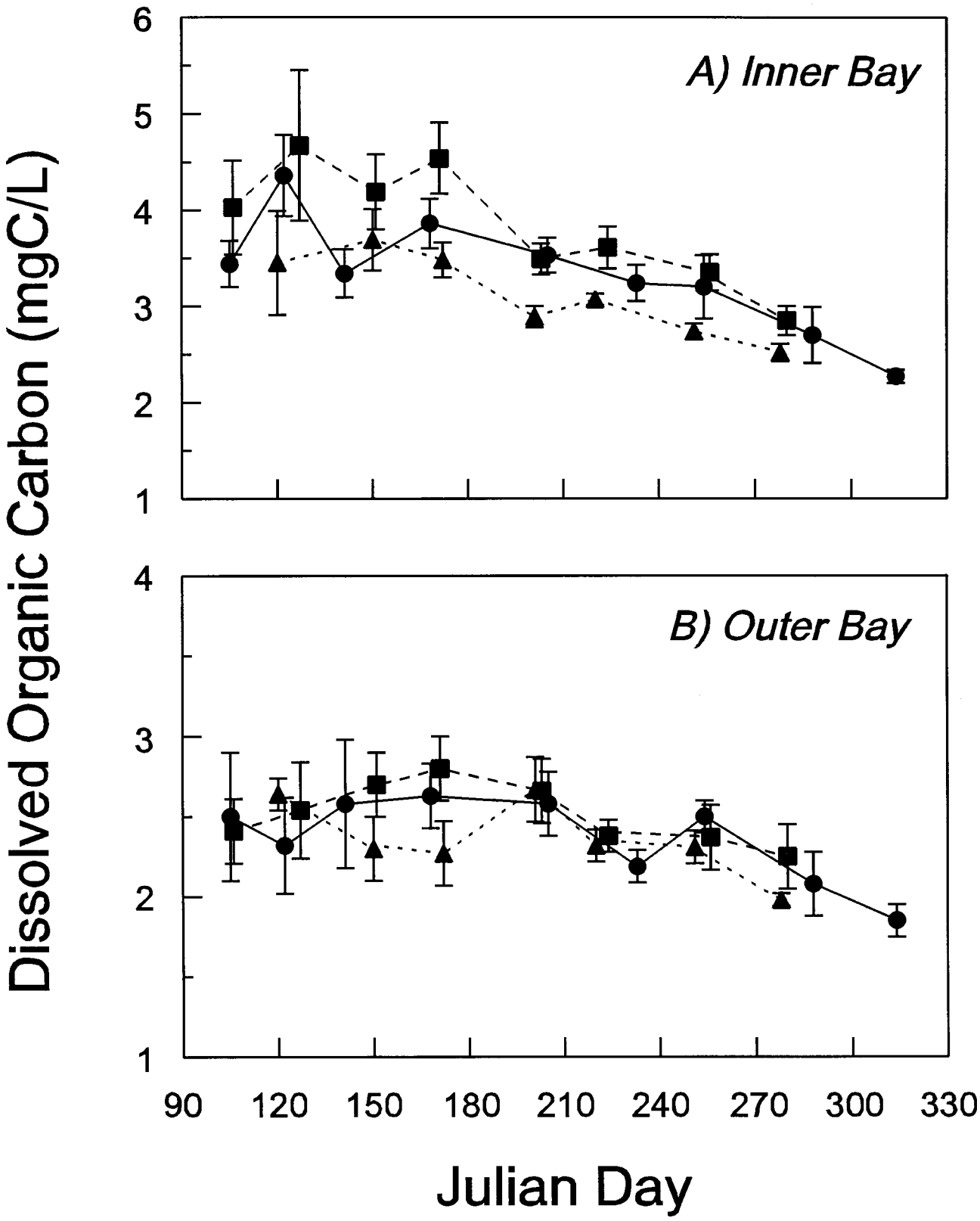


Figure 7 (Continued).

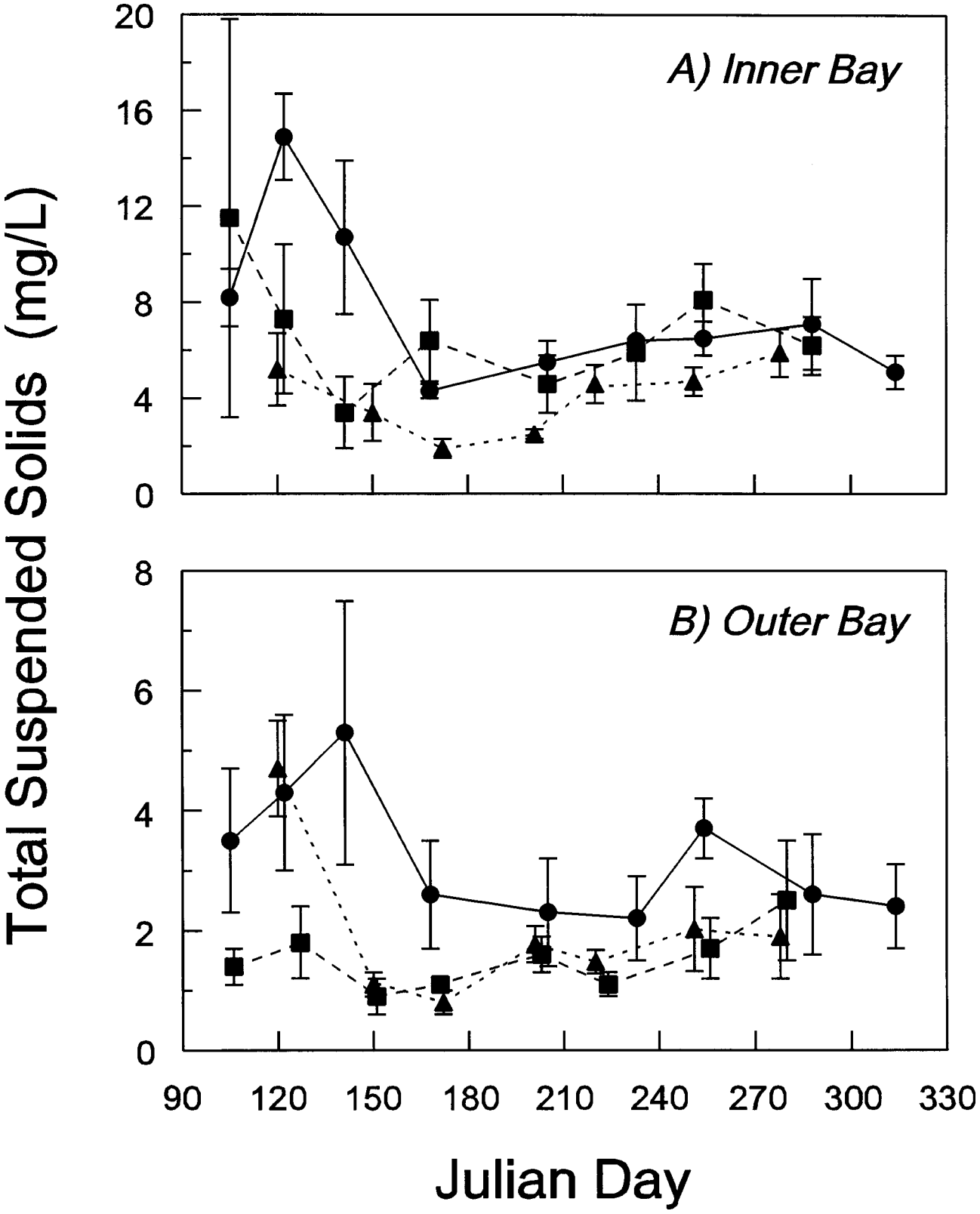


Figure 7 (Continued).

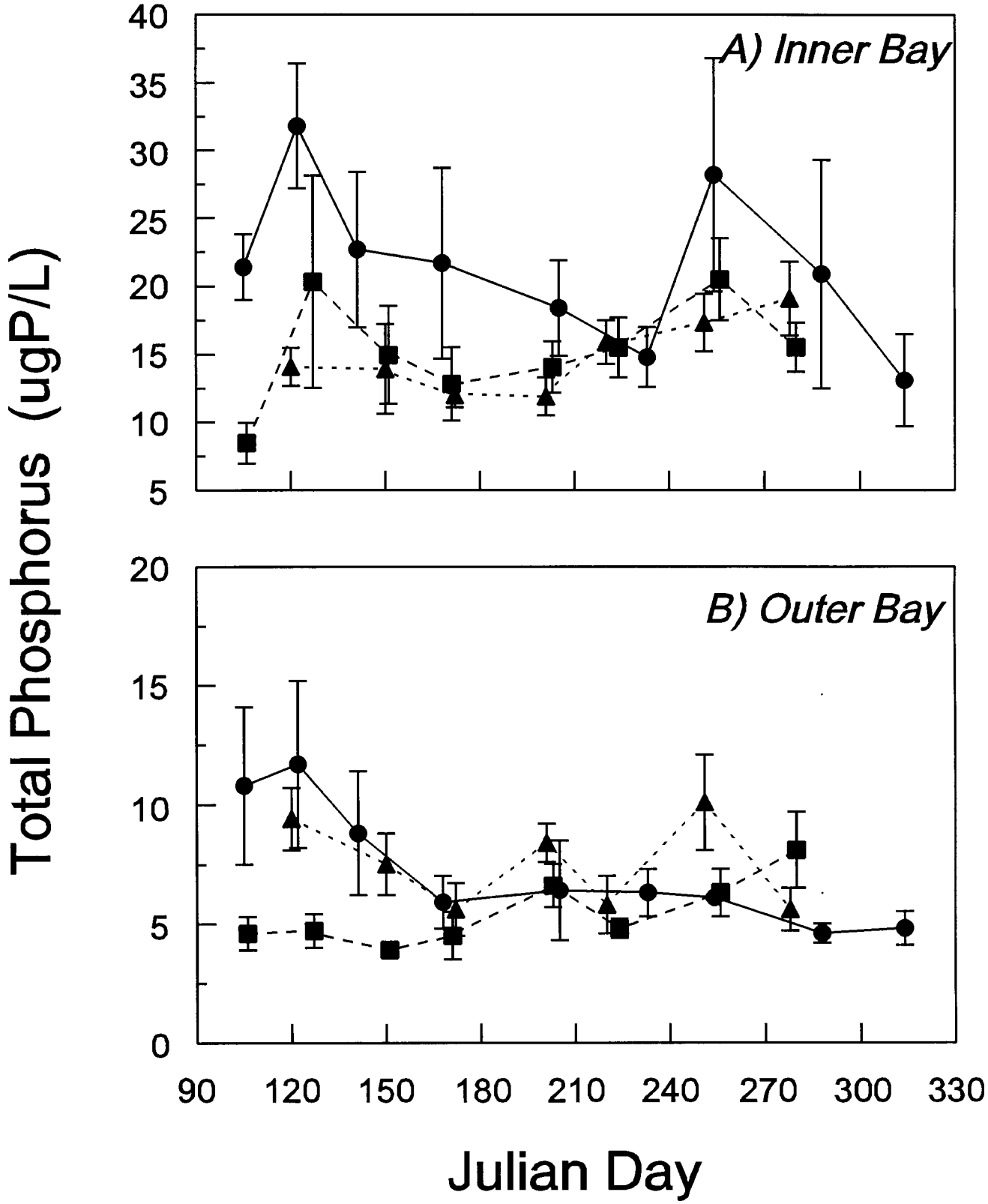


Figure 7 (Continued).

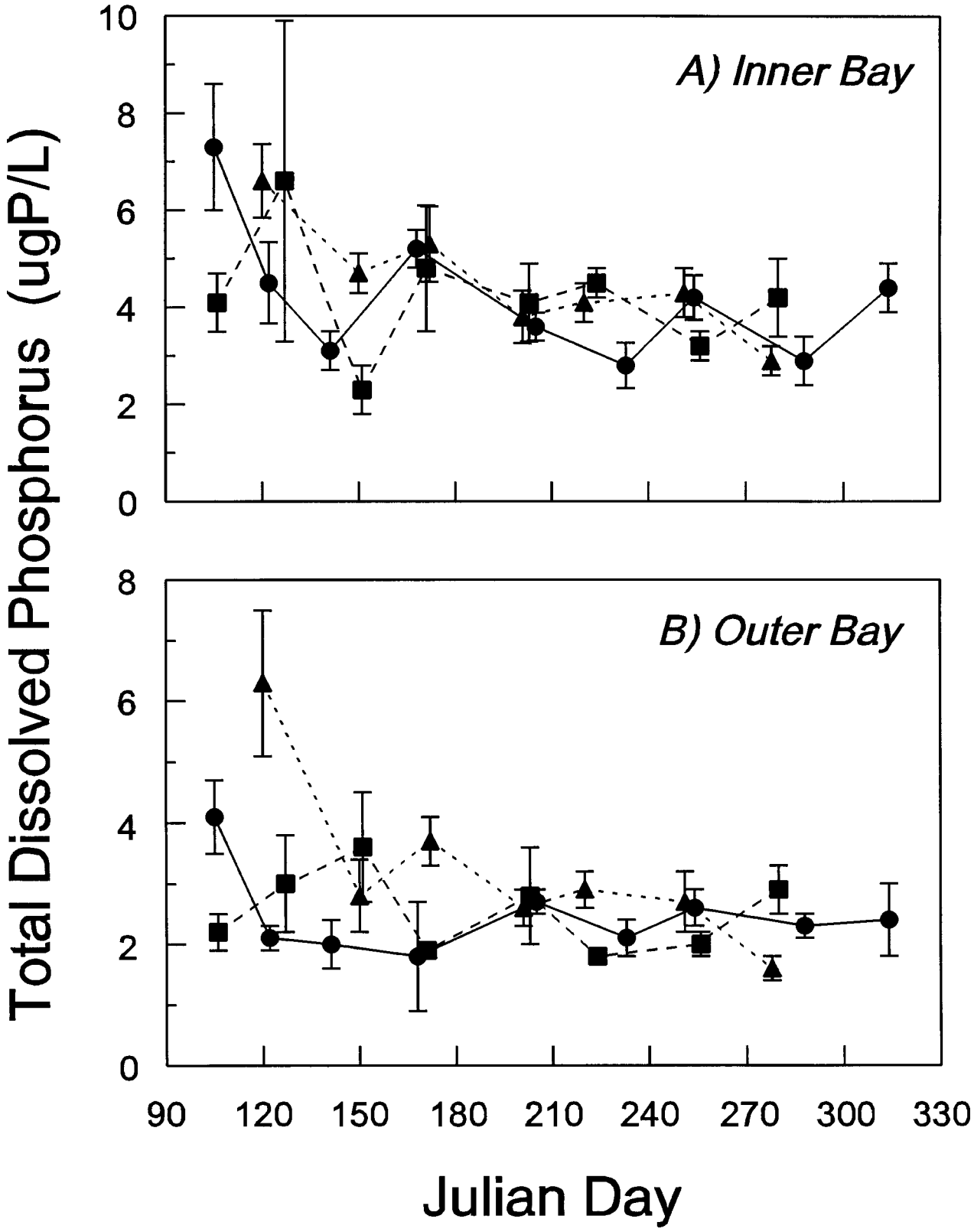


Figure 7 (Continued).

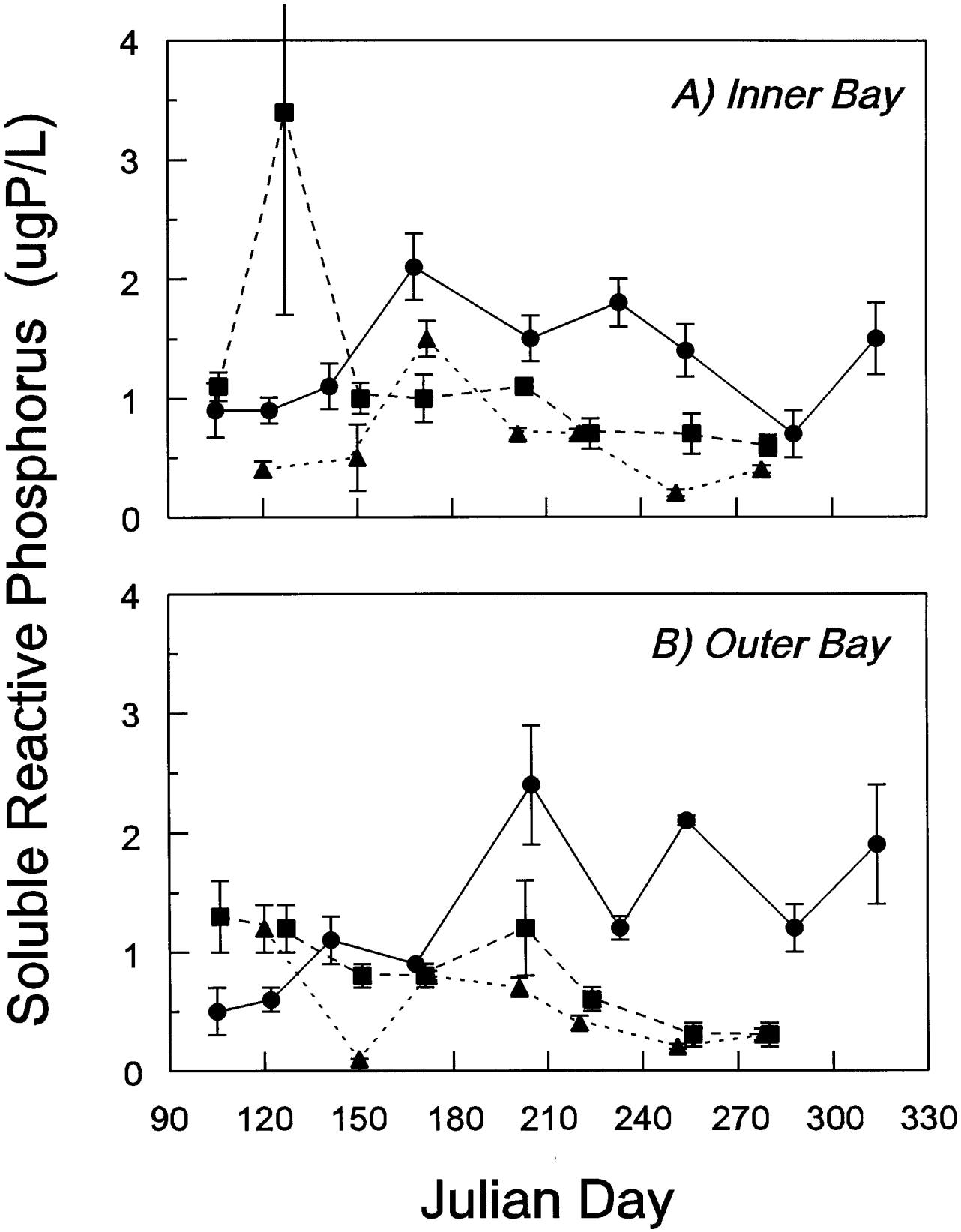


Figure 7 (Continued).

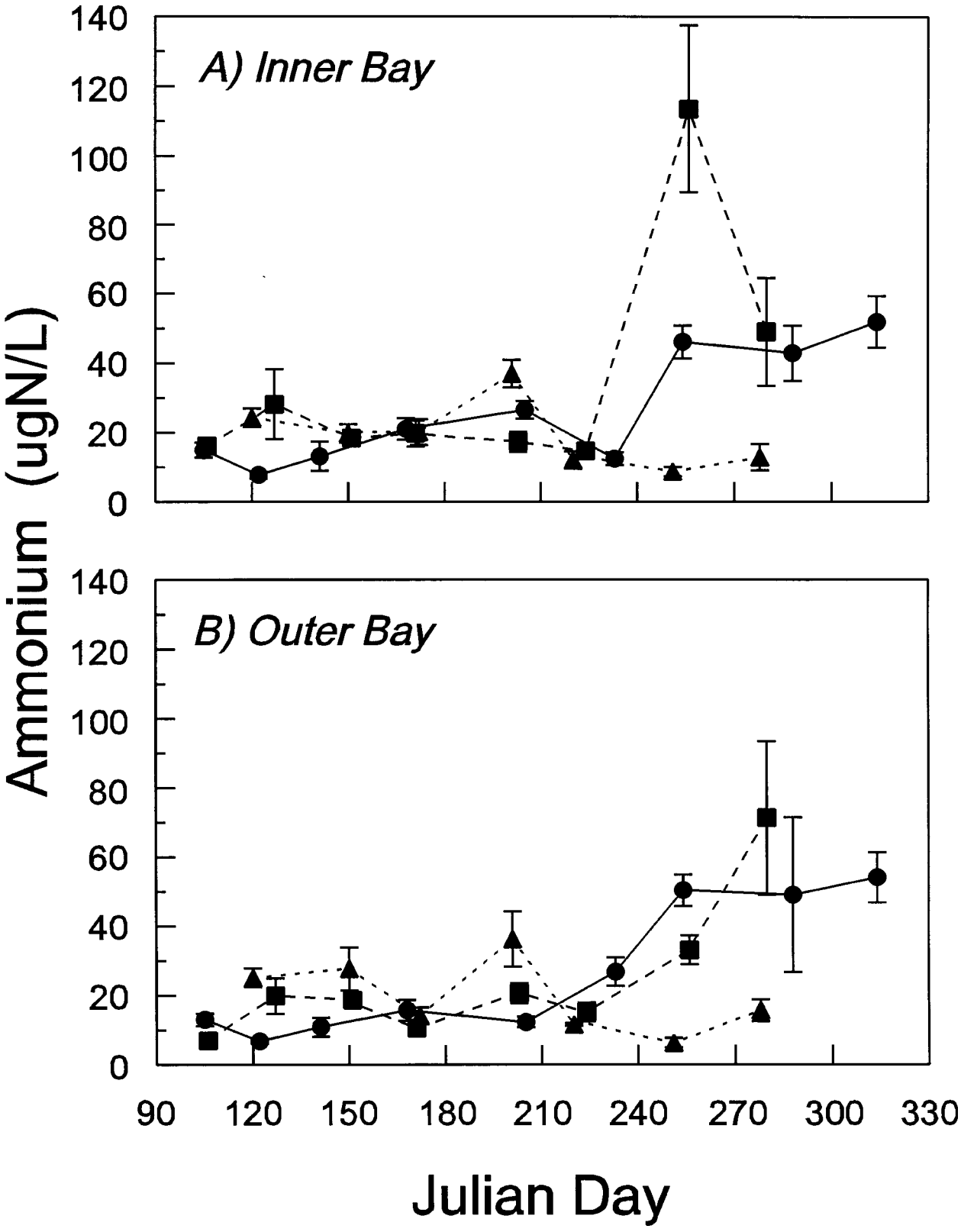


Figure 7 (Continued).

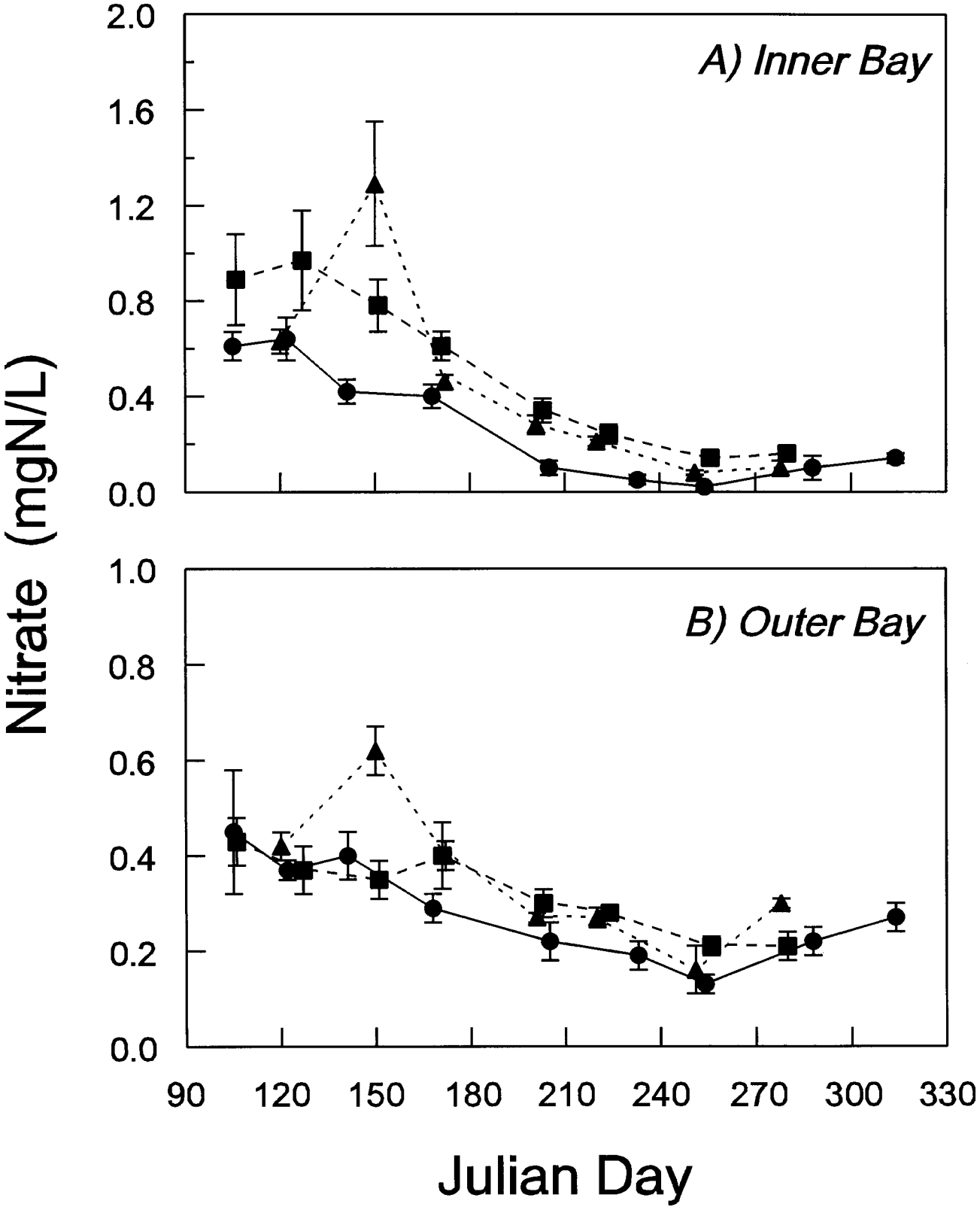


Figure 7 (Continued).

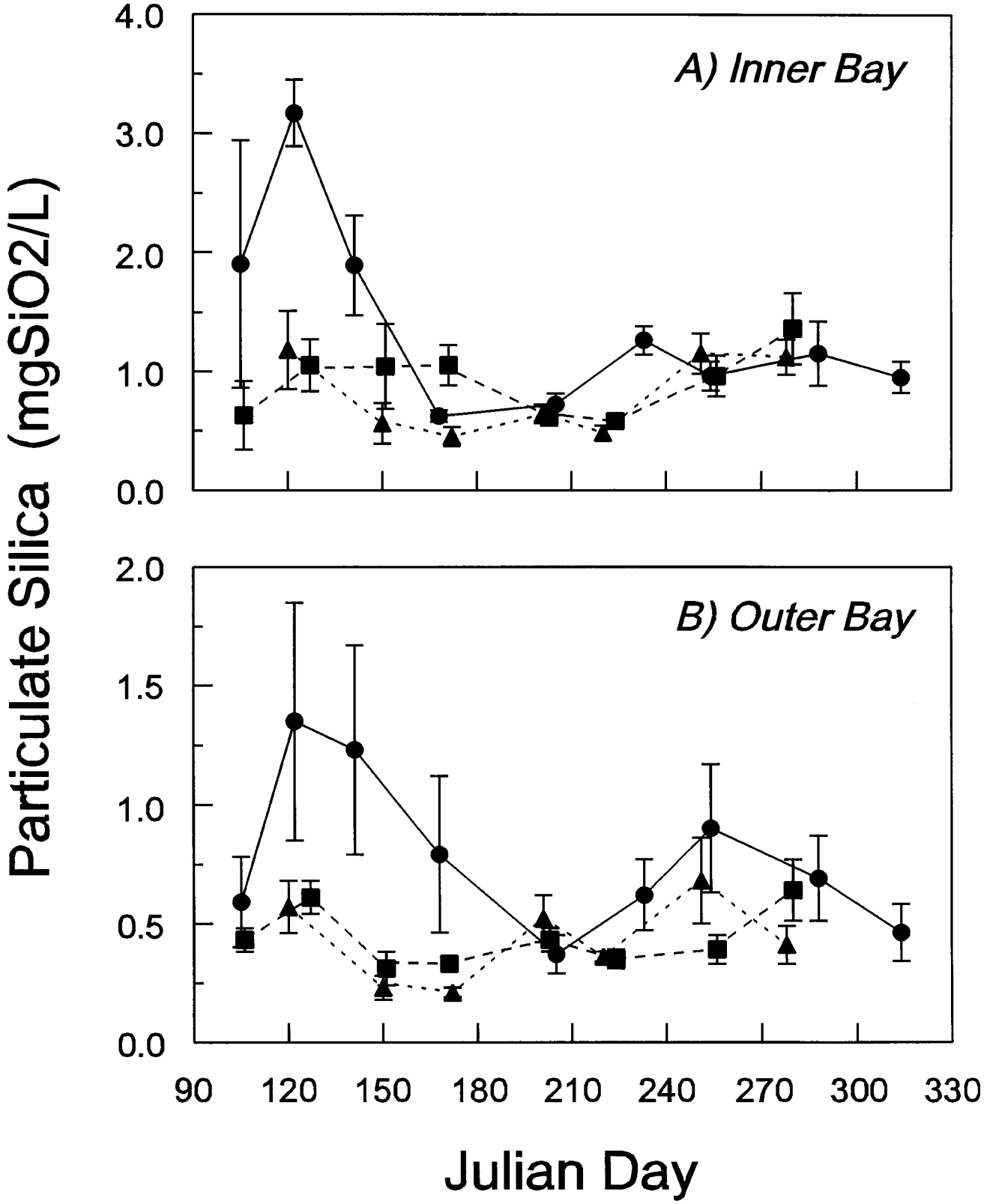


Figure 7 (Continued).

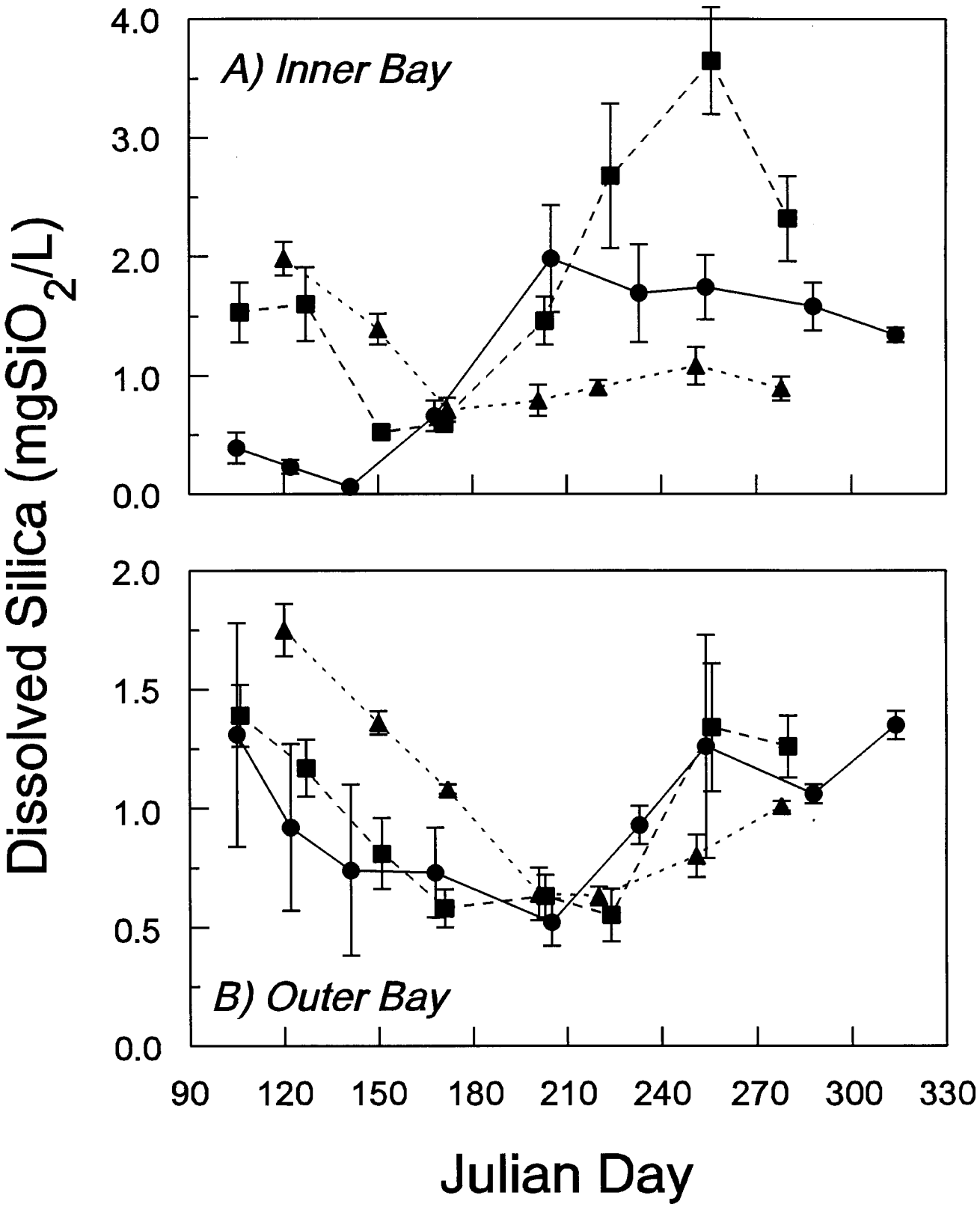
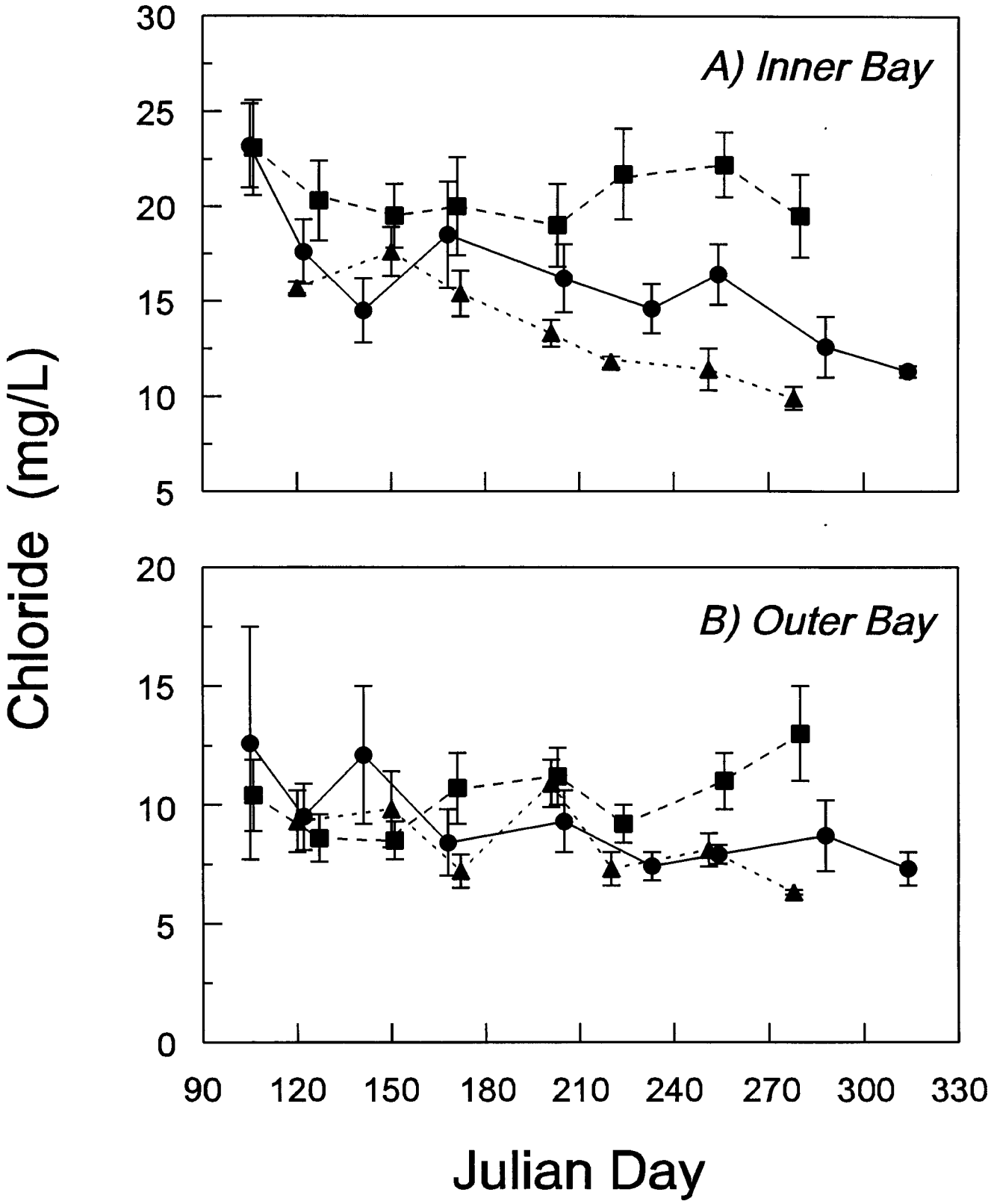


Figure 7 (Continued).


A) Inner Bay
B) Outer Bay
Chloride (mg/L)
Julian Day
30
25
20
15
10
5
20
15
10
5
0
90
120
150
180
210
240
270
300
330

Appendix I.--Values of all physical and chemical variables collected in Saginaw Bay in 1991-1993.

All data from this appendix are available in a simple ASCII format. The data files are available from GLERL's WWW site or from the anonymous FTP site. From the GLERL home page (www.glerl.noaa.gov), select FTP server, **or** point your browser to: ftp://ftp.glerl.noaa.gov/publications/tech_reports/glerl-091.