Monitoring of oceanographic properties of Glacier Bay, Alaska

2003 Annual Report

Photo by Bill Eichenlaub

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Prepared for Glacier Bay National Park (Gustavus, AK)

November 2004

Introduction

Glacier Bay is a recently (300 years ago) deglaciated fjord estuarine system that has multiple sills, very deep basins, tidewater glaciers, and many streams. Glacier Bay experiences a large amount of runoff, high sedimentation, and large tidal variations. High freshwater discharge due to snow and ice melt and the presence of the tidewater glaciers makes the bay extremely cold. There are many small- and large-scale mixing and upwelling zones at sills, glacial faces, and streams. The complex topography and strong currents lead to highly variable salinity, temperature, sediment, primary productivity, light penetration, stratification levels, and current patterns within a small area.

The oceanographic patterns within Glacier Bay drive a large portion of the spatial and temporal variability of the ecosystem. It has been widely recognized by scientists and resource managers in Glacier Bay that a program to monitor oceanographic patterns is essential for understanding the marine ecosystem and to differentiate between anthropogenic disturbance and natural variation.

This year's sampling marks the 11th continuous year of monitoring the oceanographic conditions at 23 stations along the primary axes within Glacier Bay, AK, making this a very unique and valuable data set in terms of its spatial and temporal coverage. In addition to the sampling of the monitoring stations throughout the seasons of 2003, we capitalized on the availability of the NOAA ship Miller Freeman in the area of Glacier Bay to opportunistically sample along a spatially-continuous transect along the axis of Glacier Bay using equipment not available to the USGS oceanographic monitoring program. These observations made by NOAA not only provided new types of measurements than those collected as part of the current monitoring program (e.g., nutrient levels and current velocity and direction), but also added a finer spatial resolution to the parameters that are currently measured with the monitoring program (e.g., temperature, salinity, chlorophyll-a). Additionally, the full length of the NOAA cruise allows comparisons of how oceanographic parameters in Cross Sound, Icy Strait, and Glacier Bay compare with other regions such as the Gulf of Alaska.

Therefore, this report is broken into two sections: 1) 2003 oceanographic patterns from data collected as part of the USGS oceanographic monitoring program, and 2) Spatially-continuous oceanographic observations made along the axis of Glacier Bay in August 2003 by NOAA oceanographic collaborators.

2003 Glacier Bay oceanographic patterns as observed by USGS monitoring program

Methods

The Glacier Bay oceanographic monitoring project was designed for the acquisition, analysis, and modeling of fjord-estuarine oceanographic data in Glacier Bay, Alaska. In 2003, sampling of Glacier Bay's oceanographic conditions was conducted seven times, including the months of February, April, June, July, August, October, and December (Table 1). Due to mechanical problems, we were only able to sample a small subset of the oceanographic stations during the month of July (Table 1). Repeated sampling of the lower Bay stations during both peak flood and slack high conditions was conducted in the months of July, August, and October (Table 1). Recent compilation and analysis of Glacier Bay's oceanographic data set led to suggestions for sampling consistency among years, by concentrating the core sampling on March, July, October and either December/January (time period of low variability), with June and/or August noted as additional beneficial time periods (Etherington et al. 2004).

Oceanographic sampling was conducted using the standard protocol for the Glacier Bay oceanographic monitoring program (Hooge et al. 2004). Sampling consisted of taking a single CTD (conductivity, temperature, depth) cast at each station. Data were collected for each 1 m depth bin of the water column from the surface to within 10 m of the bottom, to a maximum depth of 300 m (some stations are located at depths greater than 300 m). From each depth bin, the following parameters were measured: 1) salinity (psu) –calculated from conductivity; 2) temperature (ºC); 3) irradiance (microEinsteins

m^{-2}) – measure of photosynthetically active radiation (PAR); 4) optical backscatterance (OBS) (mg L^{-1}) – measure of turbidity; 5) fluorescence (mg m^{-3}) – a proxy for chlorophyll-a concentration; 6) density of water (σ_t) – derived from salinity and temperature.

Euphotic depth was defined as the depth at which the amount of PAR equals 1% of that measured at the surface (thus, euphotic depth measures the depth at which light availability becomes minimal). An index of stratification was calculated to describe the stability of the water column. Differences in the density of the water column between consecutive 1 m depth bins were calculated so that an overall mean of density change could be determined ($\Delta\sigma_t$ m^{-1}) for a specified stratum of the water column. Similar stratification indices have been used in other studies to quantify water column stability (e.g., Bowman and Esaias 1981, Sime-Ngando et al. 1995).

Oceanographic characteristics were defined for the top 15 m of the water column. Means of temperature, salinity, stratification, OBS, and chlorophyll-a were calculated over the surface stratum of 0-15 m for each cast. This depth stratum was chosen because it is the most dynamic region of the water column within Pacific fjords (the density typically reaches 90% of the deep water value by 10-15 m; Pickard and Stanton 1980), including Glacier Bay (Hooge and Hooge 2002). Additionally, the depth stratum of 0-15 m is a zone of high biological production in southeast Alaska estuarine systems (Ziemann et al. 1991, Hooge and Hooge 2002). For example, temporal patterns of chlorophyll-a concentrations within Auke Bay, AK varied only slightly when depth-integrated values for 0-15 m were compared to those for 0-35 m (Ziemann et al. 1991), suggesting that almost all of the phytoplankton occurred in the top 15 m. Further, Robards et al. (2003)

demonstrated that the most forage fish biomass within Glacier Bay was found within the shallowest water layer (<25 m), irrespective of bottom depth.

Results and Discussion

Salinity

Regional and seasonal patterns of surface water salinity in 2003 generally followed the average spatial and temporal salinity patterns over the years 1993-2002 presented in Etherington et al. (2004) (Fig. 2). There was a general decline in salinity of the surface waters as you move from the mouth to the head of the Bay, with more differences between stations apparent in summer months compared with winter (Fig. 2). Of interest is the size of the standard errors, with greater standard errors in July and August compared with the spring, fall and winter months. Since the average value is over the top 15 m of the water column, the larger standard errors represent a large variation in salinity between depth layers during the summer months. This variation within the surface layers suggests high freshwater input causing large differences in the surface water layers with depth. Since water density is mainly a reflection of salinity (as opposed to the contribution of temperature to water density) in Glacier Bay (Hooge and Hooge 2002, Etherington et al. 204) and other high latitude systems, these large variations in salinity suggest highly stratified waters. It is also apparent that the standard errors of salinity, and thus greater freshwater and stratification, are higher as you move towards the head of the Bay and the main sources of freshwater. In October, high variation in salinity within the surface layers is apparent at the upper portions of the East Arm (e.g., stations 18, 19, 20) as well as Geikie Inlet (stations 22 and 23), but is not apparent at the head of the West Arm (e.g., stations 11, 12, 21). These spatially-explicit patterns of salinity variation (and thus stratification) in the fall versus the summer support the concept that rainfall in the fall may be larger in the East Arm than the West Arm (Etherington et al. 2004). Also of interest are the very low salinity levels in August within Geikie Inlet (station 23) and the East Arm (station 20).

Temperature

Surface water temperatures in 2003 generally followed the average spatial and temporal temperature patterns over the years 1993-2002 presented in Etherington et al. (2004) (Fig. 3). Similar to salinity patterns, temperature generally decreased as you move from the mouth of the Bay to the head of the Bay, with more variation among stations in the summer compared with the fall, winter and spring months (Fig. 3). Unlike the surface water salinity patterns, water temperatures did not show much variation with depth as indicated by the relatively small standard errors. Therefore, the freshwater input to the surface layers within the upper portions of Glacier Bay (evident from salinity variation within casts; Fig. 2) is of similar temperature to those waters below. In addition, there was not a large difference in the degree of variation within the surface waters across seasons or stations.

Stratification

Regional and seasonal patterns of surface water stratification in 2003 generally follow the average spatial and temporal stratification patterns from the years 1993-2002 presented in Etherington et al. (2004) (Fig. 4). Stratification increased in the summer months compared with spring, fall, and winter, and generally increased as you move from the mouth to the head of the Bay (except for lower stratification levels at stations 13 and 14, which are located within shallower, more mixed areas). In July, August, and just within the upper portions of the Bay in October, there was a large variation in stratification levels across the surface waters within each cast. Most likely the highest degree of difference in adjoining depth bins is occurring at the uppermost surface layers. As suggested previously, time periods and stations with highest stratification corresponded to the highest variance in surface water salinity (compare Figs. 2 & 4).

Chlorophyll-a

Regional and seasonal patterns of surface water chlorophyll-a levels in 2003 generally follow the average spatial and temporal chlorophyll-a patterns found from the years 1993-2002 presented in Etherington et al. (2004) (Fig. 5). Of the months sampled, June, July and August had the highest concentrations of chlorophyll-a, and the stations within the central Bay and the lower reaches of the East and West Arms generally had the highest levels. In contrast, during the spring sampling in April, the highest chlorophyll-a level was found in the upper reaches of the East Arm followed by stations within the lower reaches of the East Arm, with these values much higher than locations within the West Arm and central Bay (Fig. 5b). The highest reading of chlorophyll-a in 2003 was at station 4 in June; this month generally contains the highest levels of chlorophyll-a (Fig. 5c). It is unfortunate that we do not have data on the rest of the stations in June to examine spatial patterns of abundance during this time period of highest abundance.

The plot of average chlorophyll-a from 1993-2002 by station indicates that the highest levels of chlorophyll-a in surface waters was found at stations 22 and 23 (Fig. 5h). Results from 2003 demonstrate that chlorophyll-a levels at station 22 and 23 were not exceptionally high compared to other stations during the months sampled (Fig. 5a-g). One thing to note is that stations 22 and 23 were only recently added to the sampling program in 1999, and that it is possible that conditions may have been different in the most recent years (1999-2002), compared with average patterns over ten years (1993-2002). Therefore, the higher abundance of chlorophyll-a in Geikie compared to the other stations that have been sampled consistently since 1993 could be an artifact of our sampling frequency (Etherington et al. 2004). The moderate to high chlorophyll-a concentrations within Geikie Inlet in 2003, as opposed to the exceptionally high levels demonstrated from the averaged 1993-2002 plots, support this notion of a sampling artifact.

Optical backscatterance

Patterns of optical backscatterance for each station and each month highlight the extreme concentrations at particular times and locations compared with values averaged over month or station (compare Figs. 6a-g with 6h-i, and notice differences in scale and magnitude). The highest turbidity levels are found nearest to tidewater glacial sources of high sediment loads, specifically stations 18, 19, 20, 12 and 21. Of the months sampled in 2003, July, August and October had the highest turbidity levels. Specifically, highest OBS in 2003 was detected at station 20 in August; however, it should be noted that stations 12 and 21 were not sampled in July, a time period and location of generally very high turbidity.

Euphotic depth

Regional and seasonal patterns of euphotic depth in 2003 generally follow the average spatial and temporal euphotic depth patterns found from the years 1993-2002 presented in Etherington et al. (2004) (Fig. 7). Unfortunately, sensor malfunction prevented us from obtaining data during August, October, and December 2003. As expected, euphotic depth in 2003 decreased in July and was lowest at stations nearest to glacial inputs (Fig. 7d).

2003 Products (papers and presentations) related to oceanographic monitoring program

Etherington, L.L., P.N. Hooge, E.R. Hooge. 2004. Factors affecting seasonal and regional patterns of surface water oceanographic properties within a fjord estuarine system: Glacier Bay, AK. U.S. Geological Survey, Anchorage, AK. A final report submitted to National Park Service. 79pp.

Etherington, L.L., P.N. Hooge, E.R. Hooge. 2004. Oceanographic patterns in a glacially-fed fjord estuary: Implications for biological productivity and hotspots. American Society of Limnology and Oceanography Annual Meeting, Honolulu, HI. Poster presentation.

Etherington, L.L. 2003. The role of oceanography in the marine ecosystem near Point Adolphus. SEAWEAD Pt. Adolphus Science Symposium. Gustavus, AK. Invited Presentation.

Etherington, L.L. 2003. Factors affecting the dynamics of surface water oceanographic properties within Glacier Bay. USGS-NPS May 2003 meeting. Gustavus, AK.

2003 other products:

- Major changes were made to the oceanographic monitoring protocol handbook to make it more user-friendly as well as to reflect recent updates to the program. The updated version has not been linked to the USGS oceanographic website, but is available in printed format.
- In addition to our own analyses of the data, we continue to provide these oceanographic data to the interested public and fellow researchers who use these data in interpreting their own data and formulating new research questions and programs. Glacier Bay oceanographic data was delivered to the following colleagues during 2003: Dr. Lisa Eisner (NOAA-Auke Bay), Chris Gabriele (NPS-GLBA), Jennifer Fisher (Moss Landing Marine Laboratory/NPS-GLBA)

Acknowledgements

We especially appreciate the assistance of Hope Rieden and Jim de La Bruere in field sampling and data processing. Additional sampling help was provided by Yumi Arimitsu, Lia Herron, Julie Nielsen, Phoebe Vanselow, Kevin Clement, Bob Vathke, Bruce McDonough, and Chiska Derr. Funding for this work was provided by Glacier Bay National Park and the United States Geological Survey.

Table 1. 2003 Glacier Bay oceanographic sampling schedule. Shaded areas represent months in which oceanographic sampling was conducted. Asterisks denote where repeat sampling was conducted to obtain data on both the slack high and peak flooding conditions within the lower Bay stations. It should be noted that station 15 has been removed from the sampling protocol.

Stations	Jan.	Feb.	Mar.	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
0				■		■	■ *	■ *		■		
1		■		■		■	■ *	■ *		■ *		■
2		■		■		■	■	■ *		■ *		■
3		■		■		■	■	■ *		■ *		■
4		■		■		■	■ *	■		■		■
5				■			■	■		■		■
6				■			■	■		■		■
7				■				■		■		■
8				■			■	■		■		■
9				■			■	■		■		■
10				■				■		■		■
11				■				■		■		■
12				■				■		■		■
13		■		■			■	■		■		■
14				■			■	■		■		■
16		■		■			■	■		■		■
17		■		■			■	■		■		■
18		■		■			■	■		■		■
19							■			■		■
20							■	■		■		■
21				■				■		■		
22				■			■	■		■		■
23				■			■	■		■		■

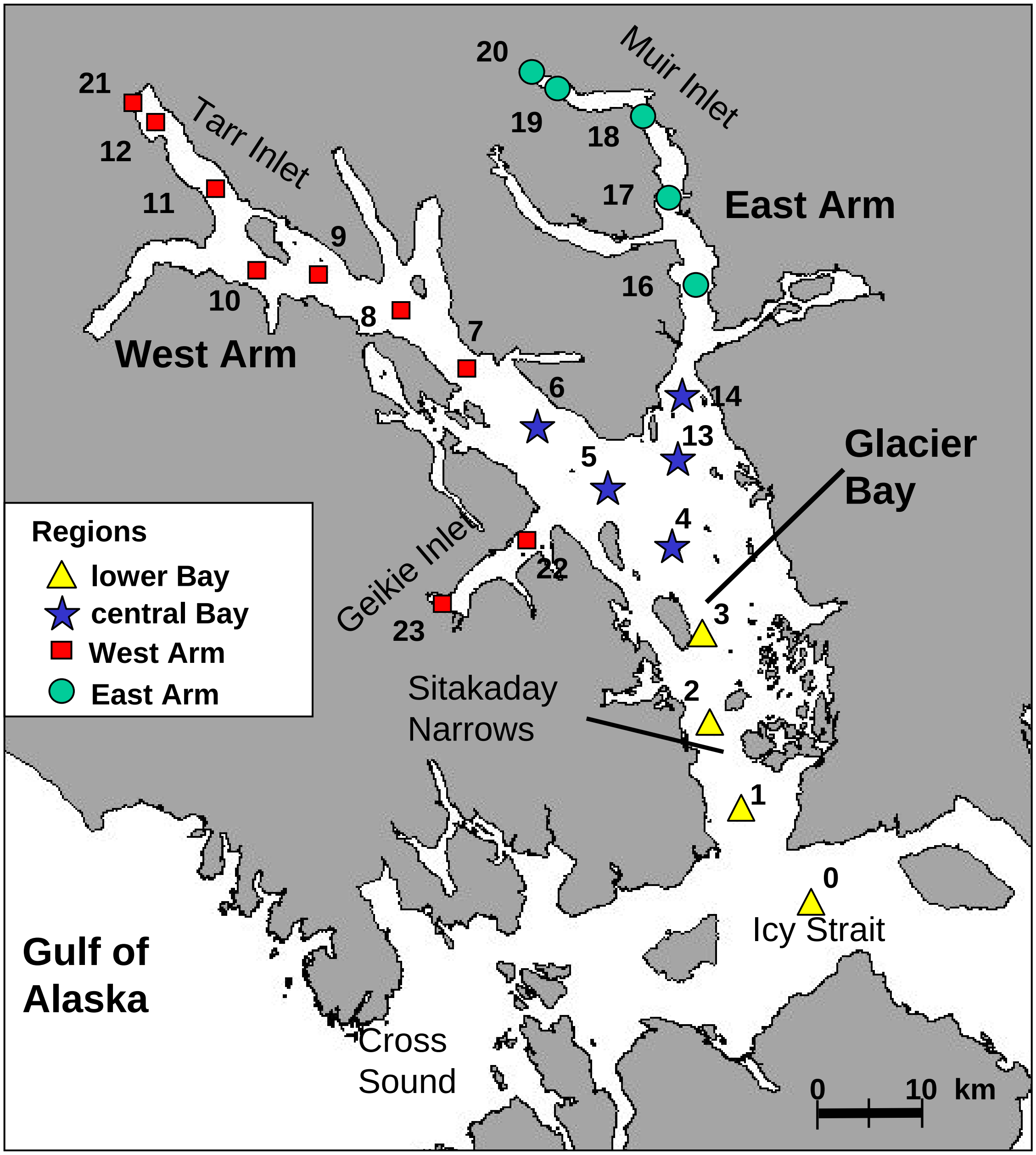

Figure 1. Glacier Bay, Alaska, and the oceanographic sampling stations. The regions indicated here were used to describe spatial variability in the oceanographic patterns within Etherington et al. (2004). Stations were grouped into regions based on similarities in bathymetry, relative position to glaciers and source of oceanic waters, and general examination of oceanographic patterns. It should be noted that station 15 is no longer sampled, due to redundancy with data from station 14.

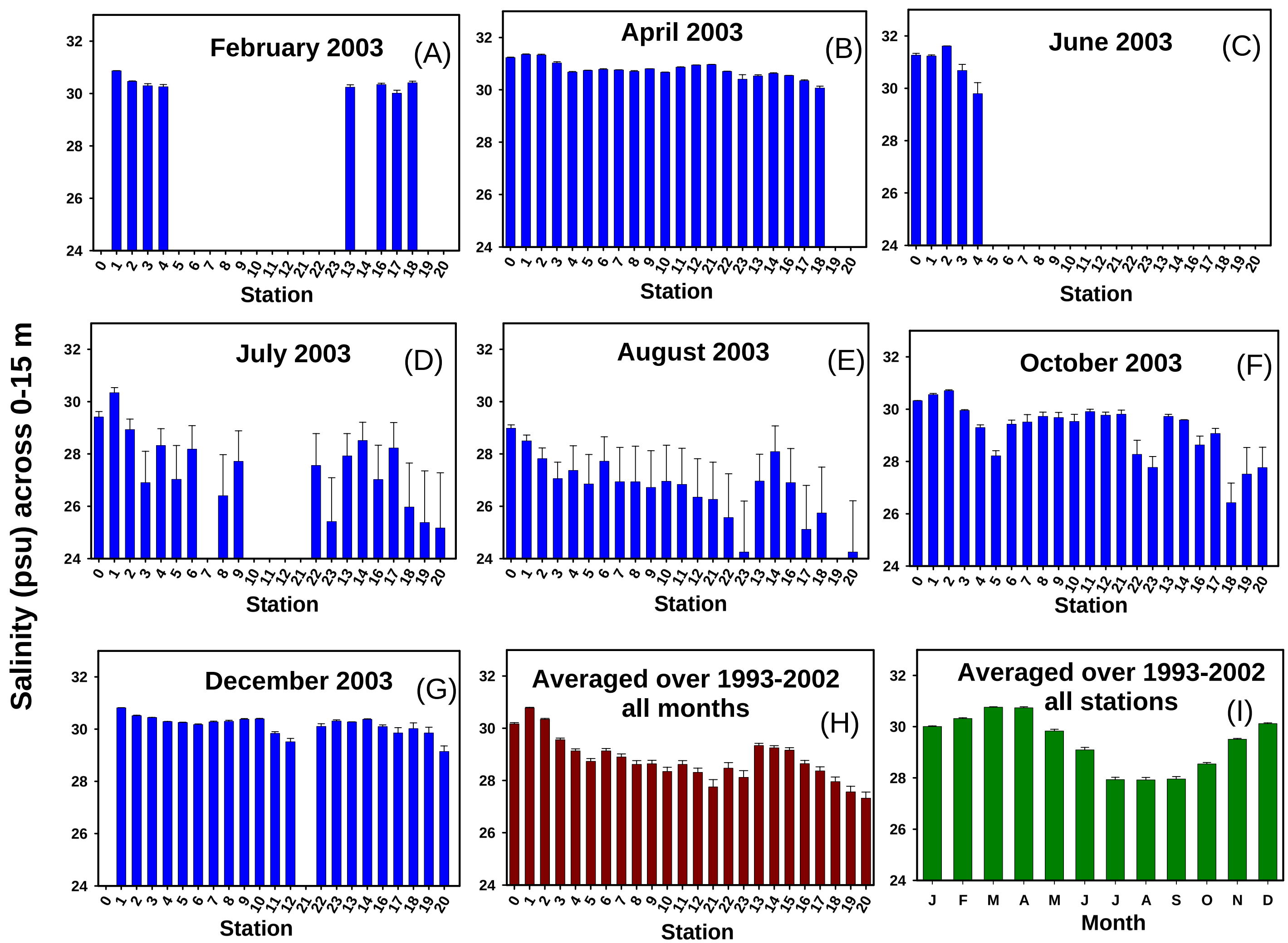

Fig. 2. Salinity patterns observed at Glacier Bay oceanographic monitoring stations. Values represent means (+ standard error) of salinity averaged over the top 15 m of the water column. Panels A-G represent 2003 values by month and station with each data point representing one cast. Zero data is presented where sampling was not conducted during that month (see Table 1 for stations sampled each month during 2003). Panel H represents salinity patterns for each station averaged over all months during the years 1993-2002. Panel I represents salinity patterns for each month averaged over all stations during the years 1993-2002. See Fig. 1 for station locations. Stations are oriented from the mouth to the head of the Bay, with stations 0-12, 21 representing the axis of the Bay from Icy Strait to the head of Tarr Inlet (West Arm), stations 22 and 23 characterizing Geikie Inlet, and stations 13-20 representing the Muir Inlet (East Arm) axis.

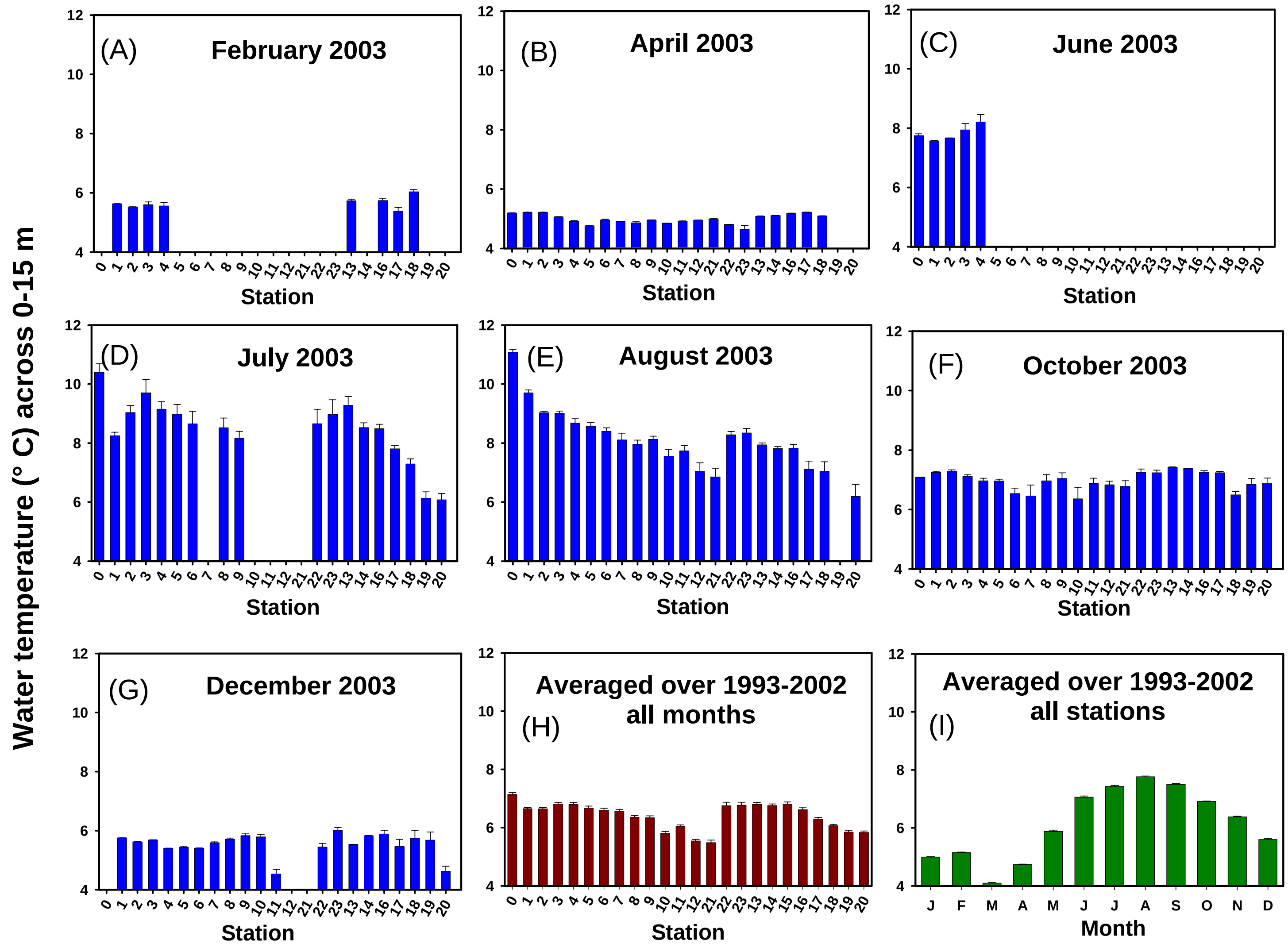

Fig. 3. Water temperature patterns observed at Glacier Bay oceanographic monitoring stations. Values represent means (+ standard error) of water temperature averaged over the top 15 m of the water column. Panels A-G represent 2003 values by month and station with each data point representing one cast. Zero data is presented where sampling was not conducted during that month (see Table 1 for stations sampled each month during 2003). Panel H represents water temperature patterns for each station averaged over all months during the years 1993-2002. Panel I represents water temperature patterns for each month averaged over all stations during the years 1993-2002. See Fig. 1 for station locations. Stations are oriented from the mouth to the head of the Bay, with stations 0-12, 21 representing the axis of the Bay from Icy Strait to the head of Tarr Inlet (West Arm), stations 22 and 23 characterizing Geikie Inlet, and stations 13-20 representing the Muir Inlet (East Arm) axis.

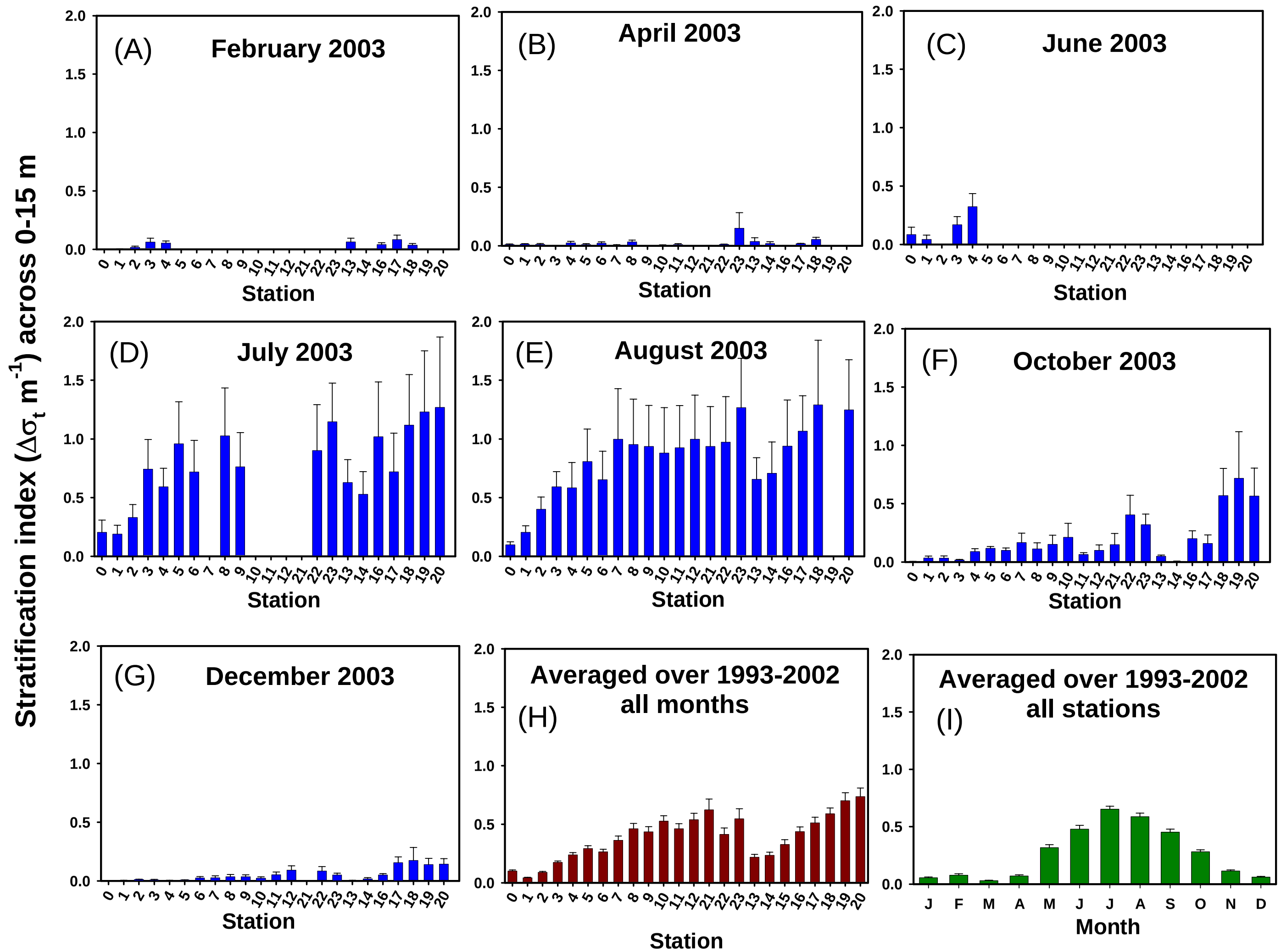

Fig. 4. Stratification patterns observed at Glacier Bay oceanographic monitoring stations. Values represent means (+ standard error) of stratification index. The stratification index for each cast represents the mean of the density differences from adjoining 1-m depth bins for the top 15 m of the water column. Panels A-G represent 2003 values by month and station with each data point representing one cast. Zero data is presented where sampling was not conducted during that month (see Table 1 for stations sampled each month during 2003). Panel H represents water temperature patterns for each station averaged over all months during the years 1993-2002. Panel I represents water temperature patterns for each month averaged over all stations during the years 1993-2002. See Fig. 1 for station locations. Stations are oriented from the mouth to the head of the Bay, with stations 0-12, 21 representing the axis of the Bay from Icy Strait to the head of Tarr Inlet (West Arm), stations 22 and 23 characterizing Geikie Inlet, and stations 13-20 representing the Muir Inlet (East Arm) axis.

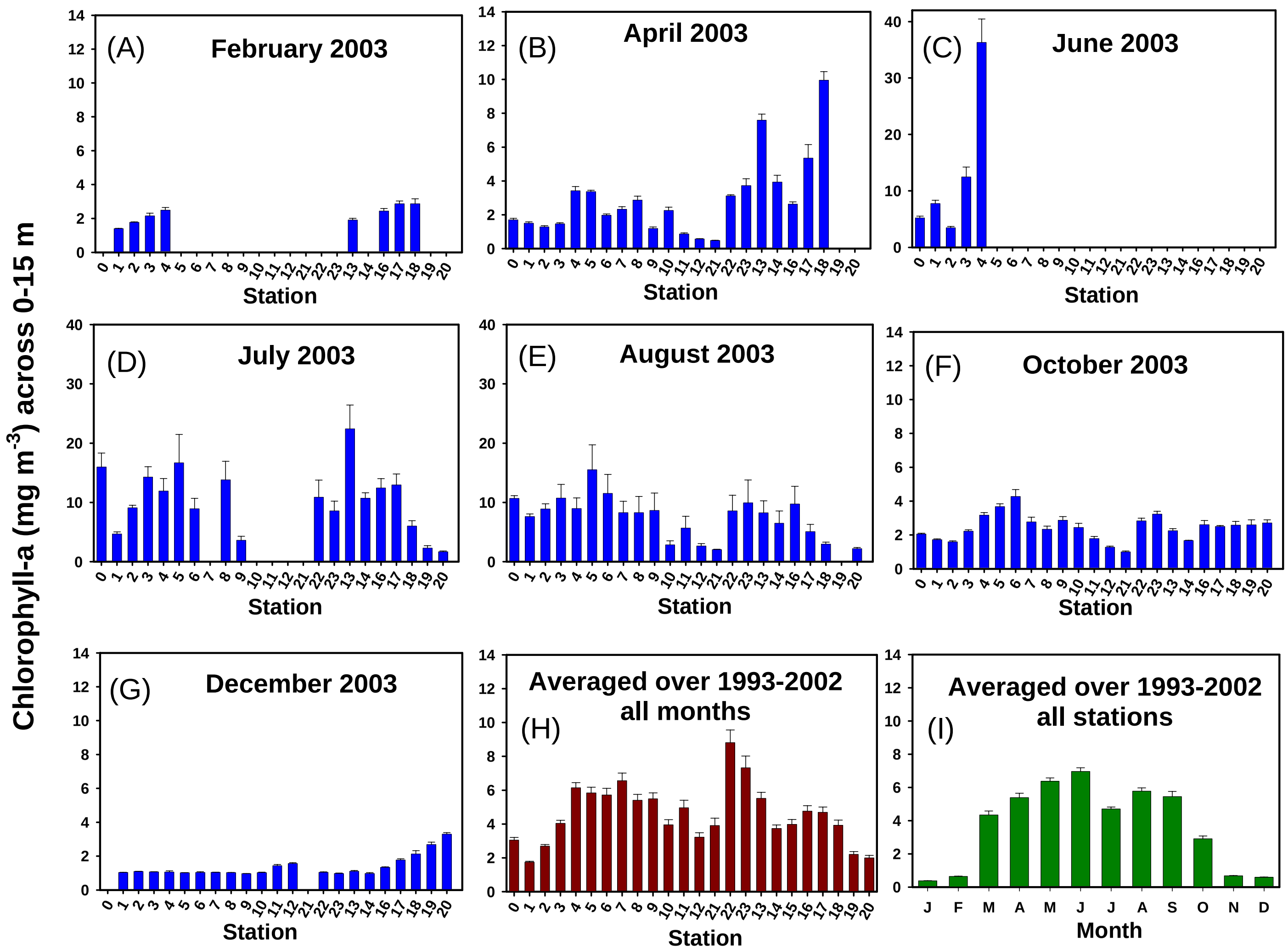

Fig. 5. Chlorophyll-a patterns observed at Glacier Bay oceanographic monitoring stations. Values represent means (+ standard error) of chlorophyll-a averaged over the top 15 m of the water column. Panels A-G represent 2003 values by month and station with each data point representing one cast. Zero data is presented where sampling was not conducted during that month (see Table 1 for stations sampled each month during 2003). Panel H represents chlorophyll-a patterns for each station averaged over all months during the years 1993-2002. Panel I represents chlorophyll-a patterns for each month averaged over all stations during the years 1993-2002. Note the change in y-axis scale for June, July, and August, when chlorophyll-a levels are much higher. See Fig. 1 for station locations. Stations are oriented from the mouth to the head of the Bay, with stations 0-12, 21 representing the axis of the Bay from Icy Strait to the head of Tarr Inlet (West Arm), stations 22 and 23 characterizing Geikie Inlet, and stations 13-20 representing the Muir Inlet (East Arm) axis.

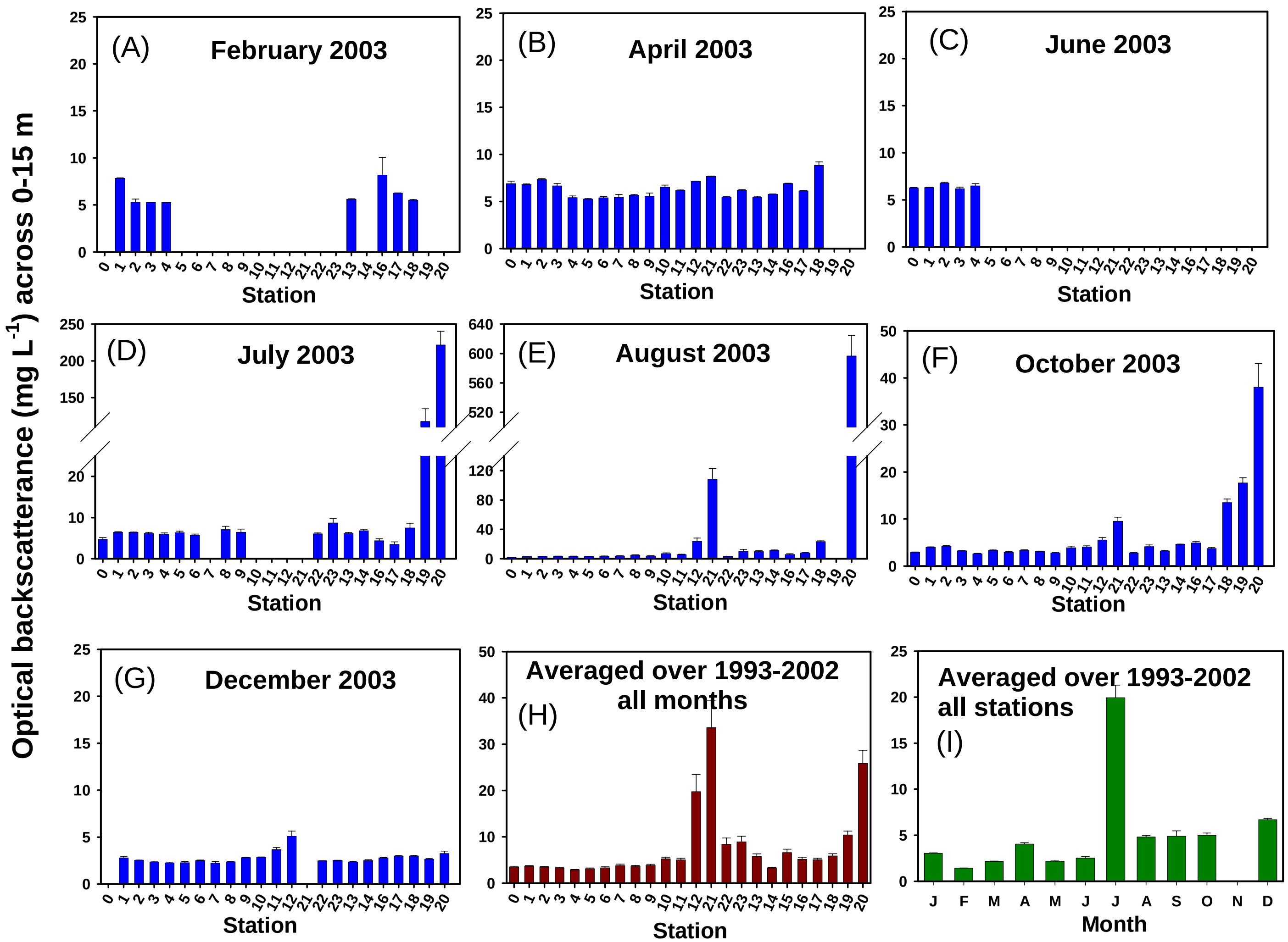

Fig. 6. Optical backscatterance patterns observed at Glacier Bay oceanographic monitoring stations. Values represent means (+ standard error) of optical backscatterance averaged over the top 15 m of the water column. Panels A-G represent 2003 values by month and station with each data point representing one cast. Zero data is presented where sampling was not conducted during that month (see Table 1 for stations sampled each month during 2003). Panel H represents optical backscatterance patterns for each station averaged over all months during the years 1993-2002. Panel I represents optical backscatterance patterns for each month averaged over all stations during the years 1993-2002. Note the change in y-axis scale for July, August, October, and the averages by station (H) when OBS levels are higher. See Fig. 1 for station locations. Stations are oriented from the mouth to the head of the Bay, with stations 0-12, 21 representing the axis of the Bay from Icy Strait to the head of Tarr Inlet (West Arm), stations 22 and 23 characterizing Geikie Inlet, and stations 13-20 representing the Muir Inlet (East Arm) axis.

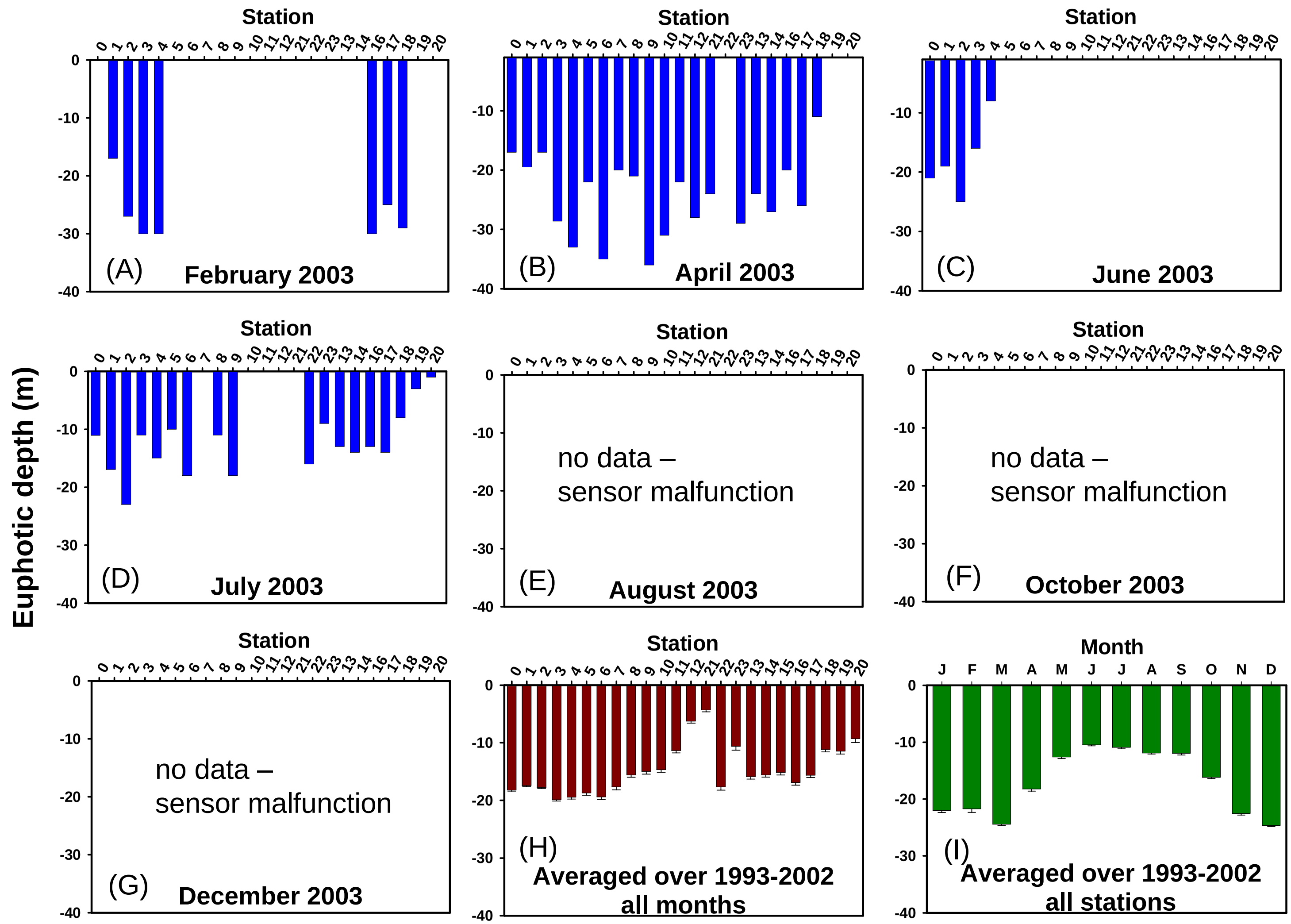

Fig. 7. Euphotic depth patterns observed at Glacier Bay oceanographic monitoring stations. Zero data is presented where sampling was not conducted during that month (see Table 1 for stations sampled each month during 2003). Panels A-G represent 2003 values by month and station with values representing the euphotic depth for one cast. Panel H represents PAR patterns (means plus standard error) for each station averaged over all months during the years 1993-2002. Panel I represents euphotic depth patterns (means plus standard error) for each month averaged over all stations during the years 1993-2002. Data are not available for the August, October, and December sampling periods due to sensor malfunction. See Fig. 1 for station locations. Stations are oriented from the mouth to the head of the Bay, with stations 0-12, 21 representing the axis of the Bay from Icy Strait to the head of Tarr Inlet (West Arm), stations 22 and 23 characterizing Geikie Inlet, and stations 13-20 representing the Muir Inlet (East Arm) axis.

***Miller Freeman* Cruise MF-03-10 Oceanographic Observations in Glacier Bay, AK, 8 Aug 2003 AKDT**

E. D. Cokelet

NOAA/PMEL, Seattle, WA

Introduction

NOAA Ship *Miller Freeman* conducted fisheries-oceanography studies in the Gulf of Alaska, 18 July to 9 August 2003, sailing from Kodiak to Juneau. The purpose of the cruise, MF-03-10, was to investigate relationships between physical and biological oceanographic processes that affect the distribution of zooplankton and salmon (*Oncorhynchus* spp) along 10 transects covering the continental shelf and slope. The research was sponsored by the Ocean Carrying Capacity (OCC) and Global Ocean Ecosystem Dynamics (GLOBEC) programs affiliated with NOAA's Pacific Marine Environmental Laboratory (PMEL) and the Alaska Fisheries Science Center's (AFSC) Auke Bay Laboratory (ABL).

Owing to good weather and the efficiency of *Freeman*'s crew, it became apparent that an extra day of ship time would be available at cruise end. Since the ship would pass the entrance to Glacier Bay enroute to Juneau, it seemed an opportune time to make some oceanographic measurements in the bay. We contacted Dr. Lisa L. Etherington of the U.S. Geological Survey, Alaska Science Center, Glacier Bay Field Station via e-mail, about the possibility of doing some work there. Following submittal of a research plan, she readily agreed to ask to incorporate our research under her permit in Glacier Bay National Park. After reviewing the research plan, Mary Kralovec, Assistant Chief of Resource Management, Glacier Bay National Park and Reserve, granted permission for us to work there for our one day of spare ship time.

With the limited time available to work in Glacier Bay, our modest research goals were as follows:

1. to traverse the West and East Arms as far as possible,
2. to measure temperature, salinity, nitrate + nitrite concentration and chlorophyll fluorescence underway from water pumped from the ship's sea chest at nominally 5 m depth, and
3. to measure ocean currents beneath the ship's hull with a 150-kHz acoustic Doppler current profiler (ADCP) down to ~400 m depth.

Methods

Temperature and salinity were measured electronically with a Sea Bird thermosalinograph (TSG). During the cruise in the Gulf of Alaska, 98 CTD casts were taken. The accurate CTD temperature was subsampled at 5 m and compared to the TSG temperature at the same times. A post-cruise linear regression (r^2=0.98) of the two temperature time series gave a correction to the TSG temperature that took into account sensor differences between the two instruments and warming of the water between the sea chest and the TSG. TSG temperature accuracy was estimated to be about 0.1 ^{o}C. The ship's CTD salinity was corrected to water bottle samples analyzed with a salinometer.

The CTD salinity at 5 m was then compared to the TSG salinity for all CTD casts. Linear regression (r^2=0.98) between the two salinity time series gave a correction to the TSG salinity. Its accuracy was about 0.2 psu. The TSG measurements were recorded every 30 s on the shipboard Scientific Computer System (SCS).

Underway nitrate + nitrite was measured with an EnviroTech NAS-2E automated shipboard nitrate measurement package. This research was courtesy of Dr. Calvin Mordy of the University of Washington's Joint Institute for the Study of the Atmosphere and Ocean (JISAO). Measurements were taken every 15 minutes, and a chemical standard was analyzed once per hour to maintain an accuracy of about 1.0 μM. Water samples were also gathered, frozen and analyzed later for calibration.

Underway chlorophyll fluorescence was measured with a Turner benchtop fluorometer plumbed to the ship's sea chest. Water samples were extracted from the underway flow-through system a few times each day, filtered and frozen for laboratory chlorophyll analysis. The analyses were performed in Dr. Jeffrey Napp's laboratory at AFSC, Seattle. The individual chlorophyll concentrations were fit with a linear least squares regression against the underway fluorescence values to compute chlorophyll from fluorescence. The fit's correlation coefficient was r^2=0.60.

The ADCP was an RD Instruments, 150-kHz, narrowband unit running Data Acquisition System (DAS) version 2.48 software. The ship's heading was provided by a Sperry Mk 37 gyrocompass, and its position by a Northstar differential GPS receiver. DAS 2.48 also used the University of Hawaii's CODAS User Exit 4 (UE4) to correct the computer's clock to GPS time. Accurate heading data is vital to measuring currents with the ADCP because at typical research vessel speeds (10-12 kt), each 1^{o} error in ship's heading leads to a 10 cm/s false across-ship current. Therefore the goal is to reduce heading inaccuracy to 0.1^{o} or less thus giving 1 cm/s accuracy in ADCP currents. *Miller Freeman* carried a TSS POS/MV GPS-aided inertial navigation system for this purpose. It provided a heading accuracy of 0.02^{o} throughout most of the cruise. Owing to other factors the current accuracy was probably 1-2 cm/s. The ADCP was set up with an 8-m pulse length and depth-bin thickness. The instrument remained in water track mode. ADCP eastward and northward velocity components were stored as 5-minute-averaged ensembles. The ADCP transducer was mounted on the ship's centerboard at a nominal depth of 10 m below the waterline. With 4-m specified as blanking distance after ping transmission, the center depth of the first ADCP depth bin was 22 m. The depth range of the ADCP was about 350 m.

Results

Figure 8a shows the ship's track on the approach to Glacier Bay and the incoming transect up West Arm. *Miller Freeman* approached Glacier Bay National Park from the Gulf of Alaska. She passed Icy Point (58.35 N, 137.1 W) on the west coast at about 10:00 GMT on 8 Aug 2003 heading southeast (Fig. 8a). (Unless otherwise noted, all times will be referred to Greenwich Mean Time, GMT. AKDT = GMT – 8 hours where AKDT is Alaska Daylight Time.) Table 2 shows the predicted tidal stage and height at Bartlett Cove in Glacier Bay.

Table 2. Predicted tidal height at Bartlett Cove, Glacier Bay, based on Juneau, AK

Date & Time (GMT)	Tidal Stage	Predicted Tide Height (ft)
8 Aug 2003 12:58	Low	-0.2
8 Aug 2003 19:35	High	11.1
9 Aug 2003 00:59	Low	4.8
9 Aug 2003 07:06	High	14.7

The tide was ebbing as the ship entered Cross Sound. *Miller Freeman* hove to in dense fog on the east side of Lemesurier Island in Icy Strait at about 14:00 as evidenced by the hook in the ship's track (58.3 N, 136.0 W) of Figure 8a. As the fog cleared later that morning she traversed to Bartlett Cove and sent a party ashore for the Park Service's vessel orientation. The ship departed about 18:00 on a flood tide and began the incoming transect at 10 kt up the West Arm. She reached Tarr Inlet at 23:21 (Fig. 8a) about 1.5 hours before low tide at Bartlett Cove. *Freeman* came about and began the outgoing transect, detouring up the East Arm past the mouth of Adams Inlet before returning southward (Fig. 8b). She broke off investigations in Icy Strait at 08:00 on 9 August 2003 just after high tide. The incoming and outgoing transects were conducted beneath clear, sunny skies with little wind.

Figure 8a shows the ADCP vectors at the shallowest depth measured (22 m), averaged along the ship's track every 4 km. These are among the first shipboard ADCP measurements made in Glacier Bay (Hooge & Hooge, 2002). The ship was bucking ~60 cm/s currents in Cross Sound, but these changed to flood in North Passage corresponding to the low tide at Bartlett Cove at 12:58 (Table 2). During the incoming transect over the shallow entrance sill to West Arm the tide was flooding, and the ADCP vectors show strong inflow at 22 m (Fig. 8a). The largest observed current was about 160 cm/s just south of Bartlett Cove. The tidal flow accelerates over the shallow entrance sill and then slows to a few cm/s in the deeper basin beyond. According to the predicted tidal heights (Table 2), the tide should have ebbed over the remaining up-bay transect, and the observed, weak outflowing currents agree (Fig. 8a).

The tide was in flood during the outgoing transect and the detour up East Arm. The current measurements confirm that. A maximum flood current velocity of about 140 cm/s was observed in Sitakaday Narrows where the channel narrows and the bottom shoals (Fig. 8b). This was near the end of a 10-foot tidal rise. Doubtless stronger currents can be expected at mid-flood with a larger tidal range.

ADCP currents were measured every 8 m from 22 m to near bottom. These merit further investigation especially as regards their interaction with the bottom topography, but that is beyond the scope of this report.

Figures 8a and 8b show the sea surface temperature along the incoming and outgoing transects. Beginning in the Gulf of Alaska, the ship encountered 11.5 ^{o}C water typical of the continental shelf in summer. Cooler water (~8 ^{o}C) was mixed up by strong tidal currents in Cross Sound. Cool temperatures persisted over the Glacier Bay entrance sill with an increase at the junction of West and East Arm to over 11.5 ^{o}C on the up-bay transect (Fig 8a). With further solar insolation, this temperature increased to over 12.0 ^{o}C on the down-bay leg (Fig. 8b). Tarr Inlet at the upper end of West Arm gave the coldest temperatures of 5.5-6.0 ^{o}C near where Margerie and Grand Pacific Glaciers enter salt water. The warmest water (14.0-14.5 ^{o}C) was encountered in Icy Strait outside Glacier Bay. This is an area of weaker tidal mixing and stronger stratification that allows solar radiation to heat the surface layer.

Salinity governs density stratification in Alaskan waters. Figures 9a and 9b show the near-surface salinity transects. 31-32 psu water was observed off shore. The salinity remained elevated in Cross Sound and over the entrance sill due to tidal currents that mix up salty, cold water from below. Mid bay, near the main junction, had some of the freshest, warmest water owing to reduced currents and mixing. The freshest water (19.6-20.0 ^{o}C) did not correspond to the coldest water near the faces of tidewater glaciers in Tarr Inlet, but rather it occurred in patches along the West Arm, presumably as lenses of river runoff from glaciers in Geikie, Johns Hopkins, Queen and Rendu Inlets. On the outgoing transect, fresher water was seen in Icy Strait than in nearby Cross Sound owing to a reduction of tidal mixing.

In the Gulf of Alaska, near-surface nitrate plus nitrite values were enriched from 4-5 μM to 19-20 μM by tidal mixing as one approached the entrance to Cross Sound (Fig. 10a). As with salinity, high values persisted over the highly mixed entrance sill, before falling off to very low (0-2 μM) values in mid bay (Figs. 10a and 10b). Apparently phytoplankton bloomed to a sufficient degree to draw down the nutrients. Chlorophyll concentrations were relatively low (1-2 μg/L) throughout the Cross Sound-Glacier Bay-Icy Strait system (Figs. 11a and 11b). This may be due to light limitation in areas where nitrate was sufficient (>1 μM) to support growth, but mixing kept the phytoplankton below the photic depth too long to reach their full photosynthetic potential. Higher levels of chlorophyll occurred near the main junction where temperature and salinity indicated a return to density stratification and potential confinement to illumined water.   High (8-9 μg/L) inferred chlorophyll levels were measured in Tarr Inlet, but these may be due to the effect of rock flour's blue color on fluorescence sensors.

Conclusion

Glacier Bay contains a unique environment and ecosystem in the United States. There is a competition between density stratification due to glacial melt water and vertical mixing due to strong tidal currents over a shallow sill. They compete to give areas of deep-water nutrient renewal and shallow stratified layers that can support primary production. It merits further study as Hooge and Hooge (2002) have recommended. We were pleased to be allowed to make some of the first ADCP measurements in Glacier Bay. We look forward to returning sometime for more than just one day.

Acknowledgements

We gratefully acknowledge the assistance of Lisa Etherington for inviting us into Glacier Bay on her research permit, to Mary Kralovec for granting us permission, to Jennifer Mondragon for providing bathymetric data, to the Captain and crew of NOAA Ship *Miller Freeman*, to Calvin Mordy for his nutrient measurements, to Jeff Napp and Colleen Harpold for their chlorophyll analyses, to Bill Floering for his hard work and oceanographic expertise on the cruise, to Antonio Jenkins for analyzing the ADCP data, and to Gary Stauffer for helping us obtain ship time on *Miller Freeman*.

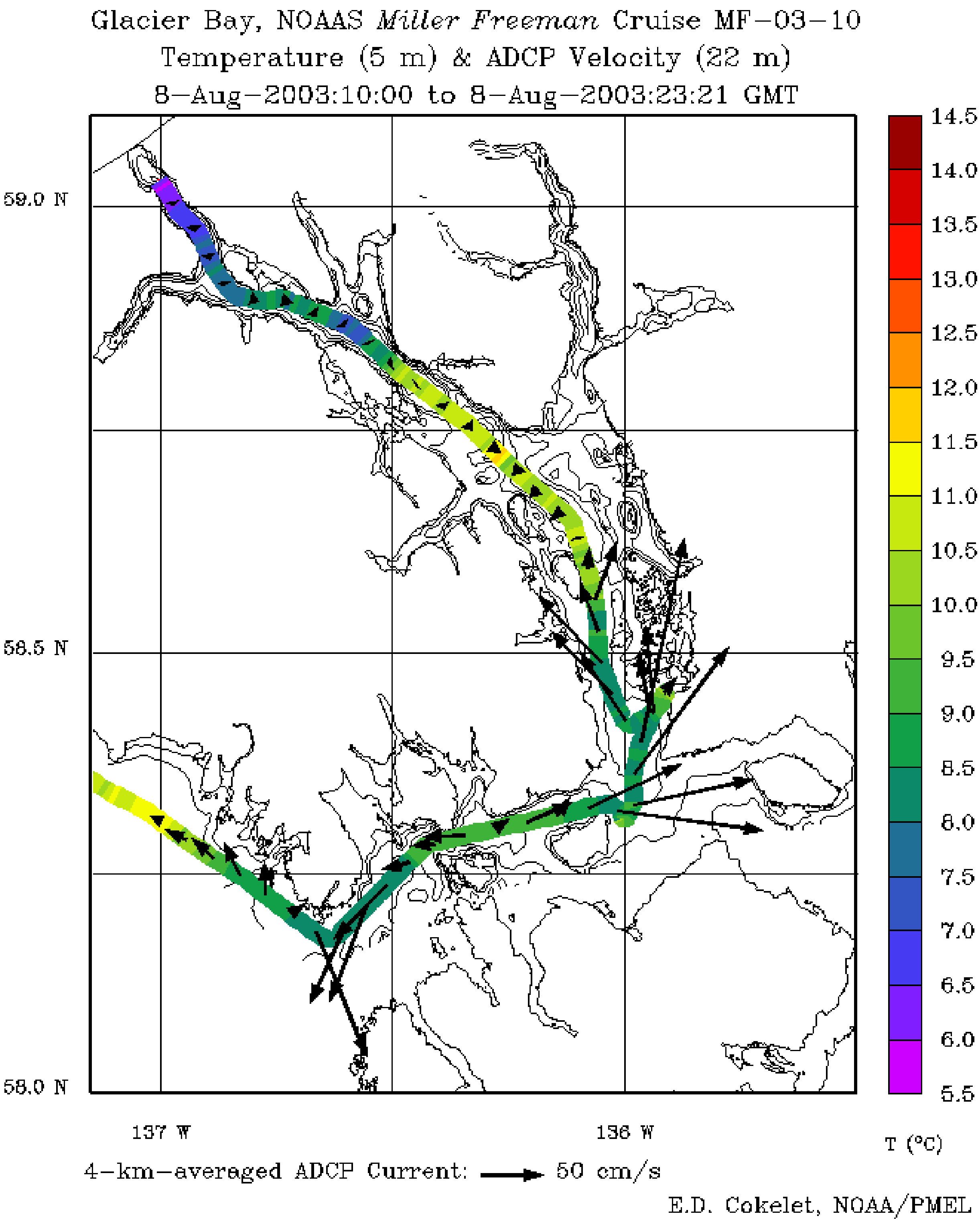

Figure 8(a). Temperature at 5 m and ADCP velocity vectors at 22 m during the incoming Glacier Bay transect. Depth is contoured at 0, 50, 100, 200, 300 and 400 m.

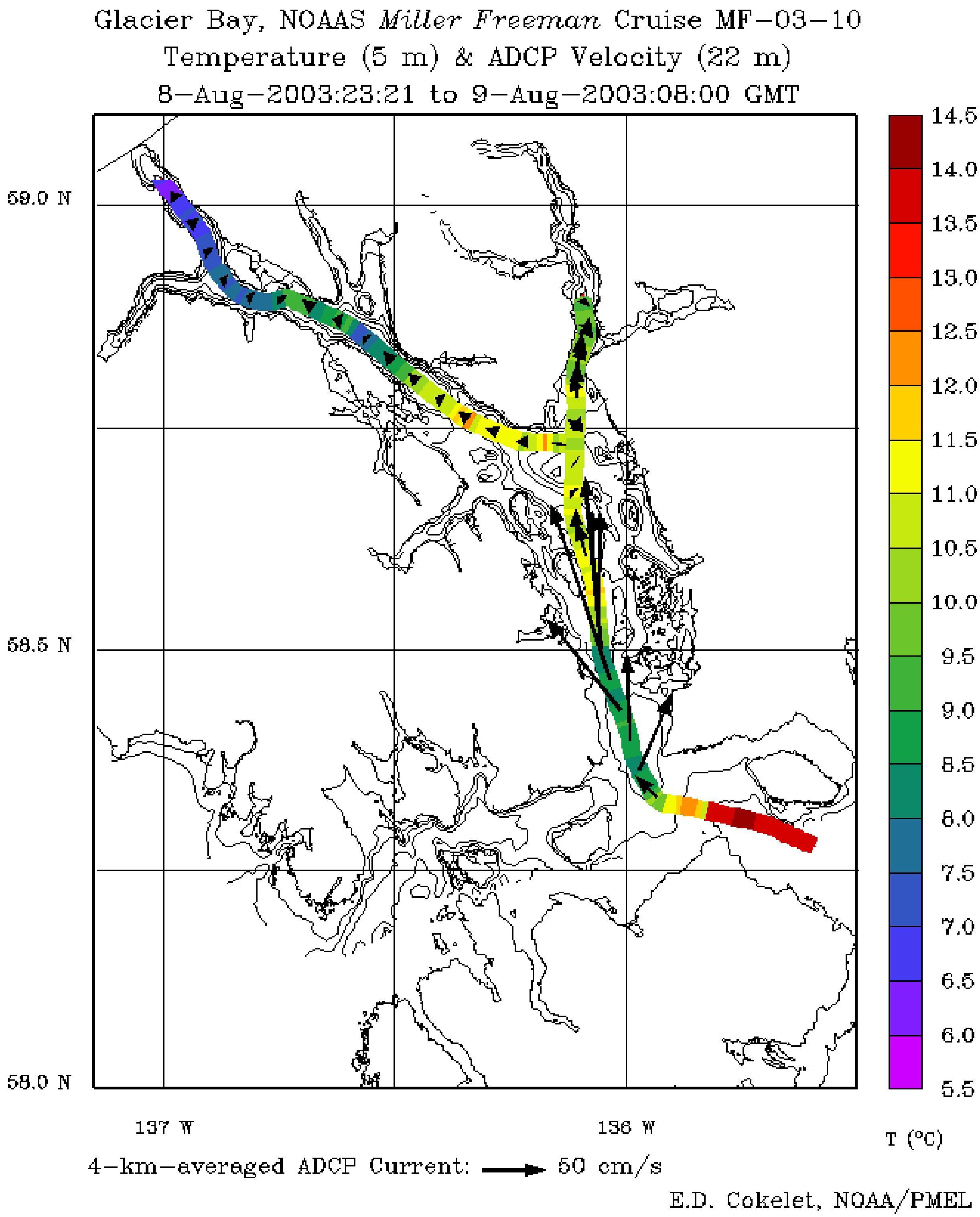

Figure 8(b). Temperature at 5 m and ADCP velocity vectors at 22 m during the outgoing Glacier Bay transect. Depth is contoured at 0, 50, 100, 200, 300 and 400 m.

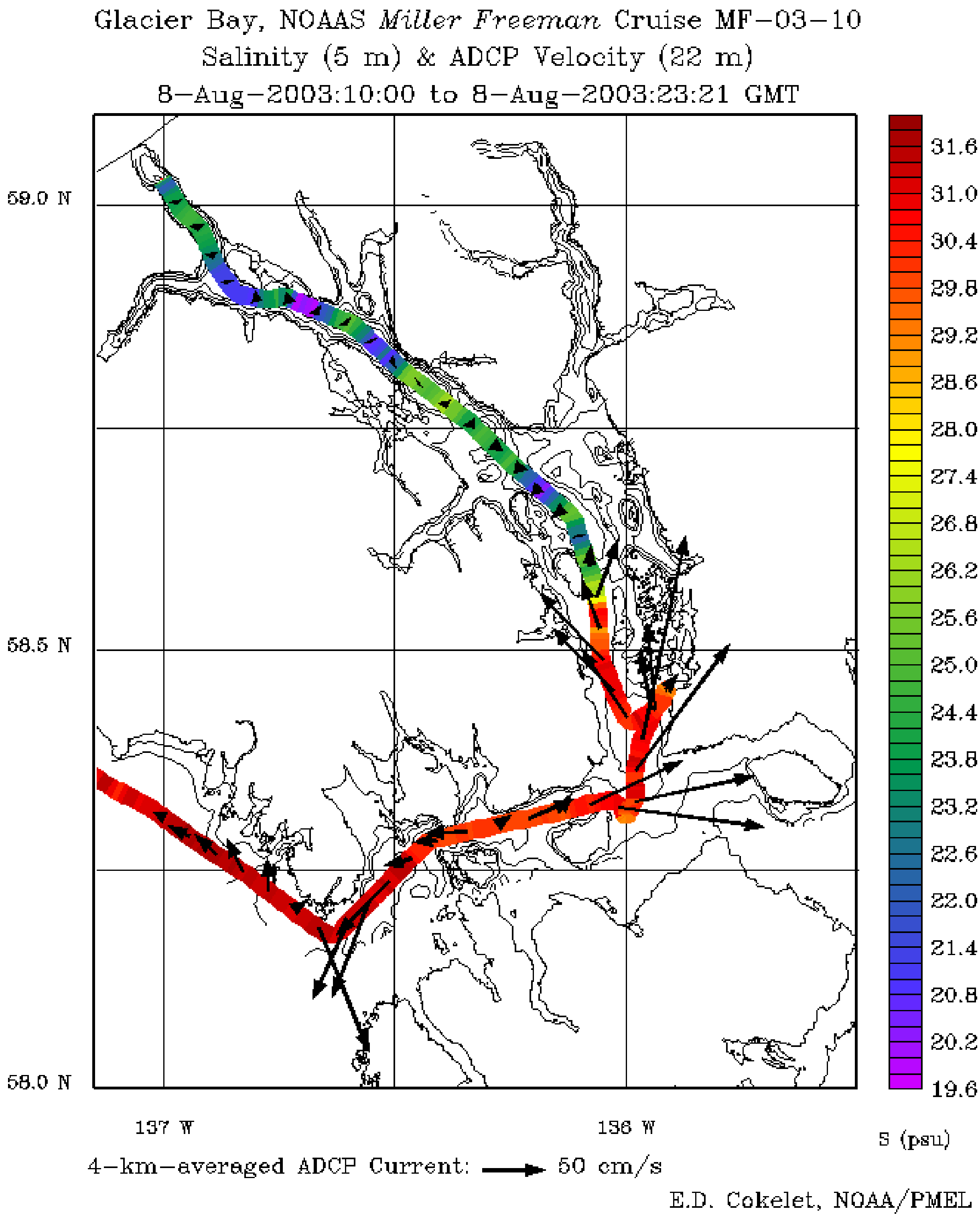

Figure 9(a). Salinity at 5 m and ADCP velocity vectors at 22 m during the incoming Glacier Bay transect. Depth is contoured at 0, 50, 100, 200, 300 and 400 m.

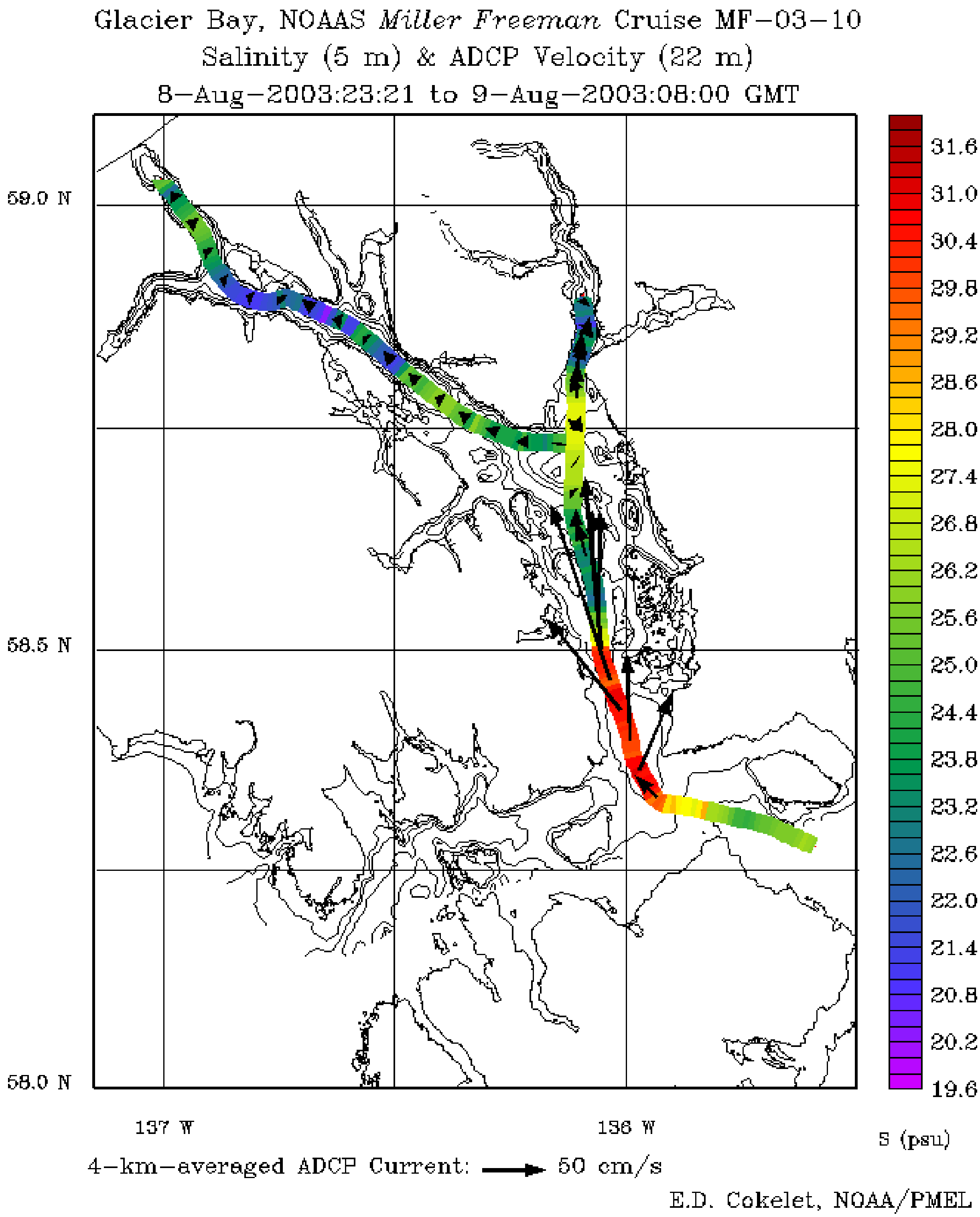

Figure 9(b). Salinity at 5 m and ADCP velocity vectors at 22 m during the outgoing Glacier Bay transect. Depth is contoured at 0, 50, 100, 200, 300 and 400 m.

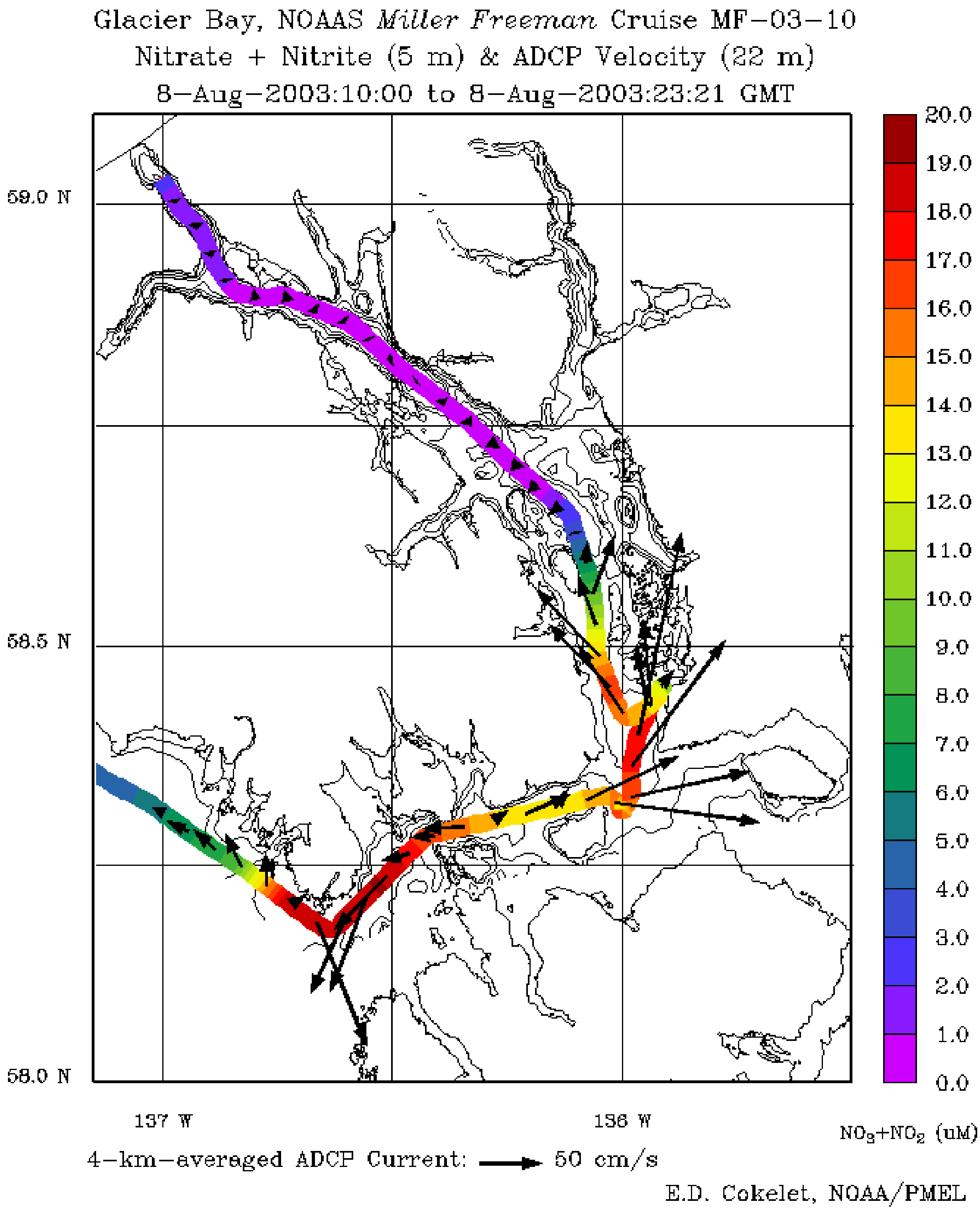

Figure 10(a). Nitrate + Nitrite at 5 m and ADCP velocity vectors at 22 m during the incoming Glacier Bay transect. Depth is contoured at 0, 50, 100, 200, 300 and 400 m.

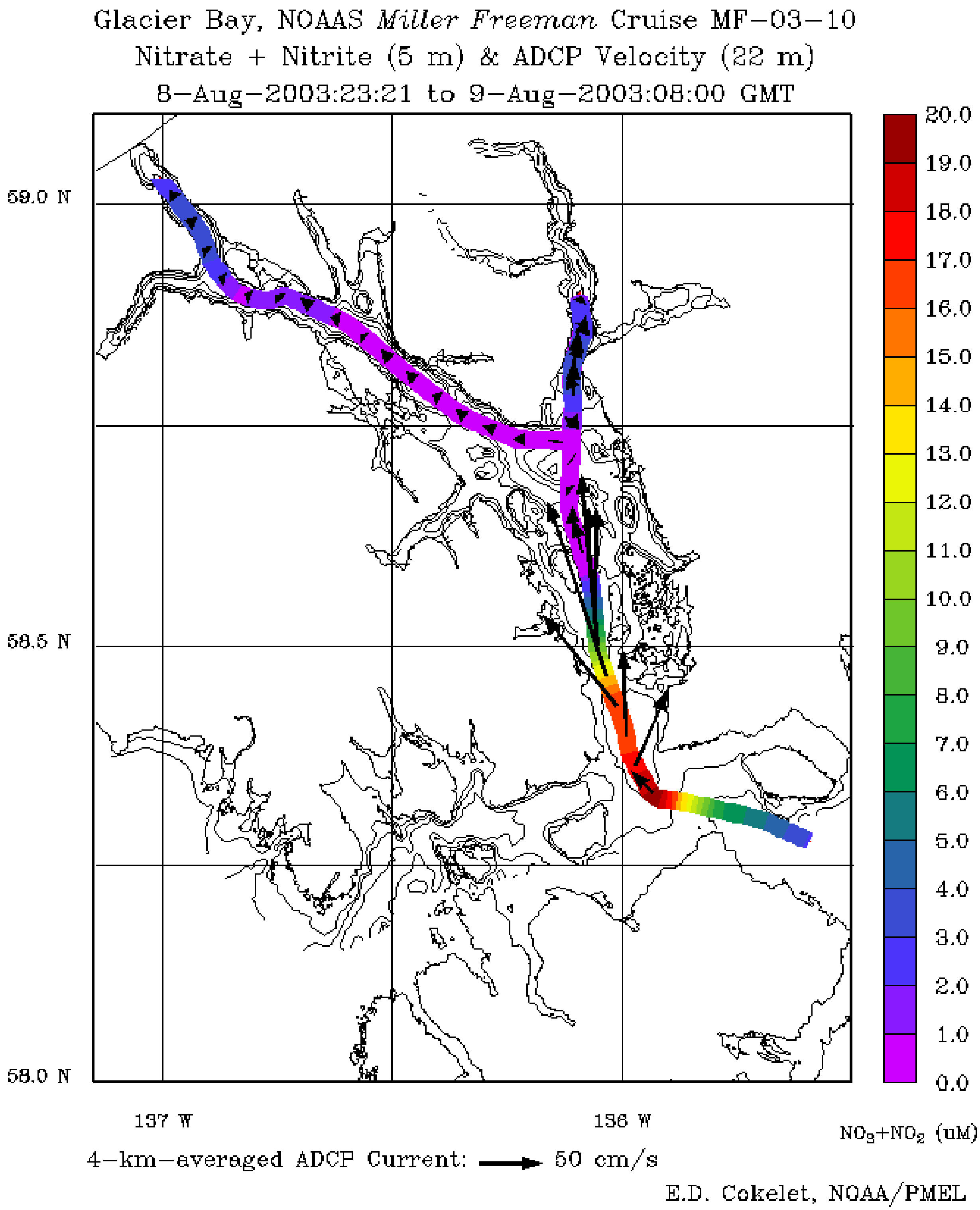

Figure 10(b). Nitrate + Nitrite at 5 m and ADCP velocity vectors at 22 m during the outgoing Glacier Bay transect. Depth is contoured at 0, 50, 100, 200, 300 and 400 m.

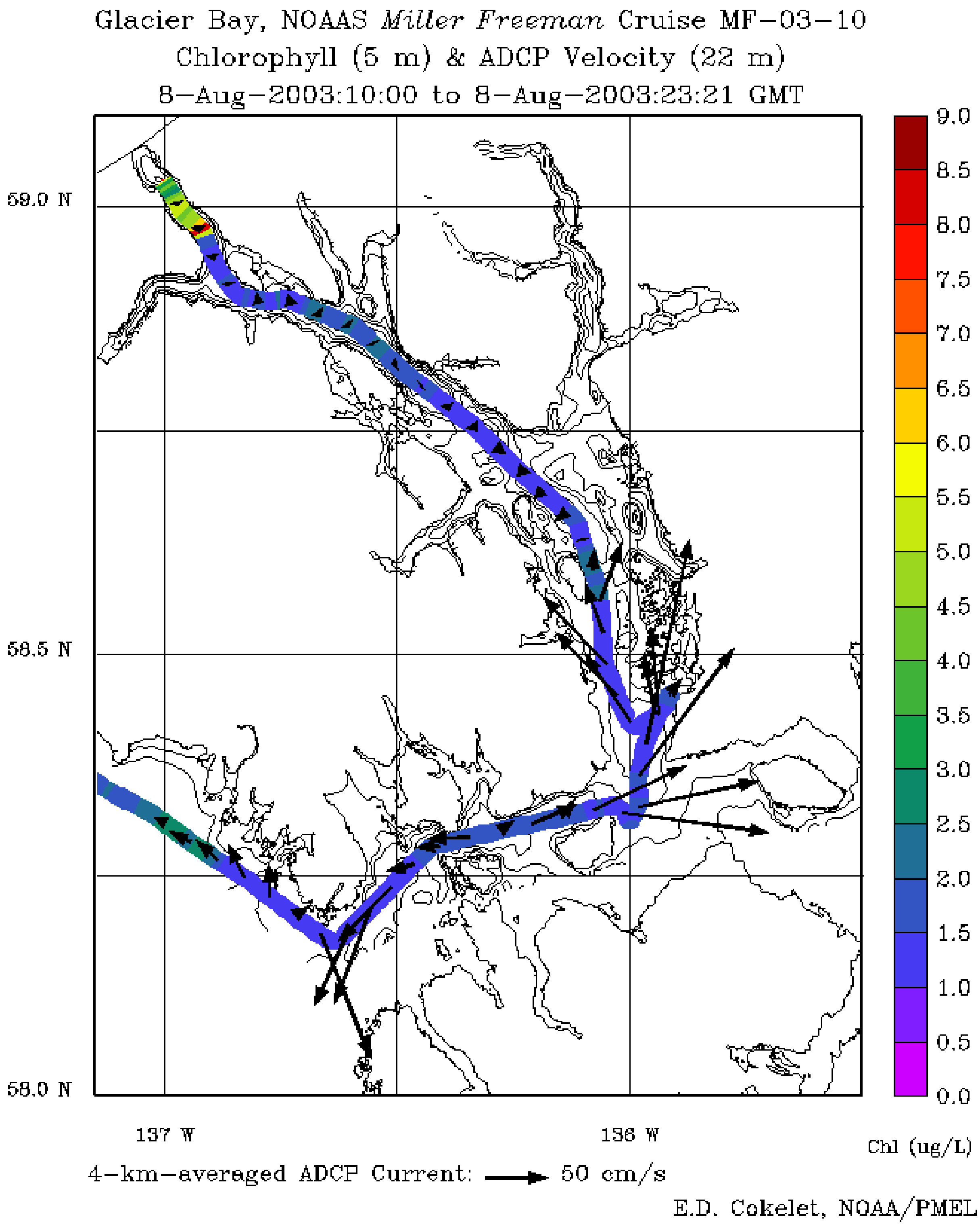

Figure 11(a). Chlorophyll at 5 m and ADCP velocity vectors at 22 m during the incoming Glacier Bay transect. Depth is contoured at 0, 50, 100, 200, 300 and 400 m.

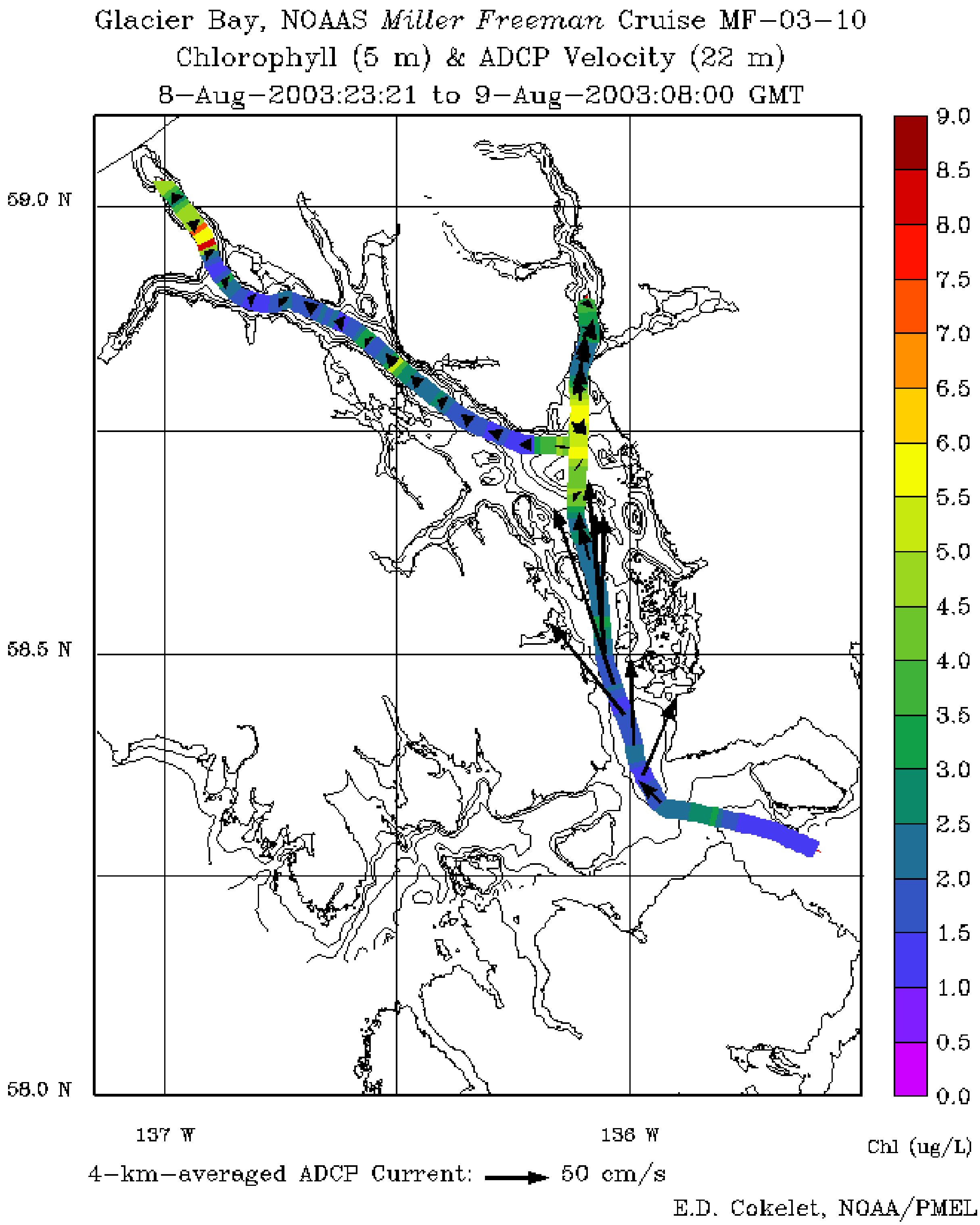

Figure 11(b). Chlorophyll at 5 m and ADCP velocity vectors at 22 m during the outgoing Glacier Bay transect. Depth is contoured at 0, 50, 100, 200, 300 and 400 m.

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