Factors affecting seasonal and regional patterns of surface water oceanographic properties within a fjord estuarine system: Glacier Bay, AK

Photo by Bill Eichenlaub

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Summary

Glacially influenced fjord systems are highly complex estuarine environments due to their diverse bathymetry (e.g., multiple sills and basins), high rates of freshwater discharge, high sedimentation rates, and narrow contractions. The complexity of fjords makes them interesting oceanographic systems due to the heterogeneous characteristics of water column parameters along their axes as well as with depth. The oceanographic system of Glacier Bay, Alaska is of particular interest due to the rapid deglaciation of the Bay and the resulting changes on the estuarine environment. Determining seasonal and regional patterns of various abiotic factors in the Glacier Bay estuarine system is the foundation for understanding biological patterns and processes.

A large-scale oceanographic monitoring program within the fjord estuarine system of Glacier Bay, Alaska has been conducted from 1993-2002 covering 24 stations that were sampled throughout the year. The temporal and spatial extent of this data set has allowed us to quantitatively assess the seasonal and regional patterns of oceanographic characteristics, including chlorophyll-a, of the surface waters within Glacier Bay and the factors that are most influential in driving these patterns. These efforts are crucial in understanding the inherent variability in the system, both spatially and temporally, so that interannual patterns can be elucidated. Seasonal and regional patterns of change and their predictors can be further used to assess changes in the biological patterns within Glacier Bay, such as population distribution and abundance and community structure.

Weather data for the oceanographic sampling time period (1993-2002) were obtained from eight stations in the region surrounding Glacier Bay. Monthly air

temperatures for the Glacier Bay region for the years 1993-2002 followed a fairly smooth seasonal curve, with coldest temperatures in January (mean = -2.5 ºC) and warmest temperatures in July and August (means = 13.5 and 13.3 ºC, respectively). Average monthly precipitation varied greatly between months and among the years 1993-2002. May and June exhibited the lowest precipitation rates of the year (means = 0.31 and 0.28 cm d^{-1}, respectively), with low variability between years. September and October had the greatest precipitation rates (0.94 and 1.01 cm d^{-1}, respectively), but varied largely between years. Wind speeds were highly variable among years, with this pattern apparent for all months. Generally, highest winds occurred during May, October, and December (means = 2.79, 2.85, and 2.92 m s^{-1}, respectively), with lowest winds in July and August (means = 2.34 and 2.46 m s^{-1}, respectively).

Oceanographic characteristics of the surface waters of Glacier Bay were relatively similar from November to February, while the periods March through October represented periods of the greatest change, both spatially and temporally. Stratification patterns throughout Glacier Bay, which were dominated by the influence of salinity across all seasons, demonstrated a large seasonal increase in May, followed by high levels of stratification throughout the summer and into the fall. Salinity and the resulting seasonal stratification patterns appear to be driven largely by the general seasonal cycle of freshwater discharge in southeast Alaska, with initial snow-melt starting in May, ice-melt during the summer, and high direct precipitation in the fall. Stratification levels were lowest in the lower Bay region where tidal mixing is high, followed by intermediate stratification within the central Bay. The upper Bay had highly stratified surface waters due to high levels of freshwater discharge, with the East Arm exhibiting stronger stratification than the West Arm. These spatial patterns of stratification suggest potential locations of frontal boundaries at regions of physical and bathymetric discontinuities, where shallower mixed zones are juxtaposed with deep stratified basins. These potential frontal zones, located between the lower and central Bay as well around the mouths of the inlets in the upper Bay, could dictate areas of high primary productivity and accumulation of biological biomass.

Average chlorophyll-a levels did not increase coincidentally with the large increase in surface water stratification occurring in Glacier Bay in May. Instead, an overall increase in chlorophyll-a occurred in March, most likely as a response to an increase in available light (irradiance threshold). Concentrations of chlorophyll-a increased from spring to summer and remained relatively high into the fall. A general decrease in chlorophyll-a was apparent in July and corresponded with peak turbidity levels in surface waters. Highest levels of chlorophyll-a within Glacier Bay were generally found within the central Bay and the lower reaches of the East and West Arms. These regions were likely favorable for phytoplankton populations due to intermediate stratification levels, higher light levels due to decreased sediment concentrations in the water column, and potential nutrient regeneration to the surface waters.

The results of this study demonstrate that there is a large amount of variation in surface water oceanographic conditions in Glacier Bay both seasonally and regionally. Extracting this regional and seasonal variation provides the first necessary step in elucidating interannual variability in the Glacier Bay oceanographic system. This study confirms that patterns of phytoplankton abundance in Glacier Bay are sustained throughout the spring, summer, and fall, suggesting a highly productive system that fuels an abundance of higher trophic levels within this estuarine system. In general, chlorophyll-a abundance could be adequately explained by light levels and stratification in spring and fall, whereas during the summer, the measured physical properties did not explain much of the variation in chlorophyll-a. Overall, after accounting for seasonal and regional variation, the measured external factors explained a large amount of variation in the physical properties of the surface waters. Identifying particular cases where good model fits were not obtained highlights where we are lacking information on factors that could substantially influence oceanographic conditions, and suggests topics of future research. In addition, results from this study further our understanding of where in the Bay we might expect higher levels of productivity as well as accumulation of biological biomass and what physical mechanisms may be driving these patterns.

Introduction

The degree of environmental variation is a defining characteristic of a particular habitat. Therefore, understanding the spatial and temporal patterns of the physical environment and determining how much of the variation in this environment can be attributed to different sources is crucial in understanding the habitat and how it determines biological patterns. Within the marine environment, the physical characteristics of the water column can influence biological patterns and processes in a variety of ways (Mann and Lazier 1996). First, the density differences between parcels of water (determined by salinity and temperature) can determine the structure of the habitat, such as a well-mixed zone, stratified layers, or a front (where two contrasting water masses meet). Additionally, the physical characteristics of the water column can determine movement of materials through the habitat by diffusion, turbulence, tidal currents, and density-driven circulation. Water movement can influence dispersal rates of organisms, transport nutrients and waste materials, and influence encounter rates of predators and prey. Further, the physical characteristics of the water column can determine the distribution and abundance of organisms through physiological tolerance levels (e.g., range of salinity and temperature). One of the primary objectives in understanding the physical-biological coupling in the marine environment is how the characteristics of the water column directly determine rates of primary production by phytoplankton. The water characteristics most influential in determining phytoplankton abundance include: surface water stabilization caused by strong density differences (retaining phytoplankton within the surface layers), amount of available light, and nutrient levels within surface waters. These physical processes influence phytoplankton distribution and abundance in concert with grazing pressure by zooplankton.

The oceanographic properties of an estuary are the result of mechanisms that act to enhance or disrupt the stability of the water column, including solar insolation, wind stress, freshwater runoff, and tidal currents (Legendre et al. 1982, Svendsen 1986). These processes can act on different time scales from daily fluctuations to seasonal patterns to decadal patterns; thus, the relative importance of these factors in causing stability in the water column can change in time. In an estuarine environment, spatial differences in the relative influence of these factors in stabilizing/destabilizing the water column can be expected within a system. Physical parameters that could drive this spatial variability include: distance from sources of oceanic water, bathymetry, proximity to and number of freshwater inputs, wind fetch, surrounding topography, and strength of tidal currents.

Glacially influenced fjord systems are highly complex estuarine environments due to their diverse bathymetry (e.g., multiple shallow sills and deep basins), high rates of freshwater discharge, high sedimentation rates, and narrow contractions. Physical features that are specific to fjord estuarine systems that influence water column stability include sill characteristics (e.g., depth and spatial arrangement relative to basins) and glacier characteristics (e.g., position relative to estuarine waters, advancing or retreating activity)(Syvitski et al. 1987). The complexity of fjords makes them interesting oceanographic systems due to the heterogeneous characteristics of water column parameters along their axes as well as with depth.

Glacier Bay is a recently (<300 years ago) de-glaciated fjord in southeastern Alaska, USA, which is comprised of multiple basins and sills (Figs. 1 & 2). The

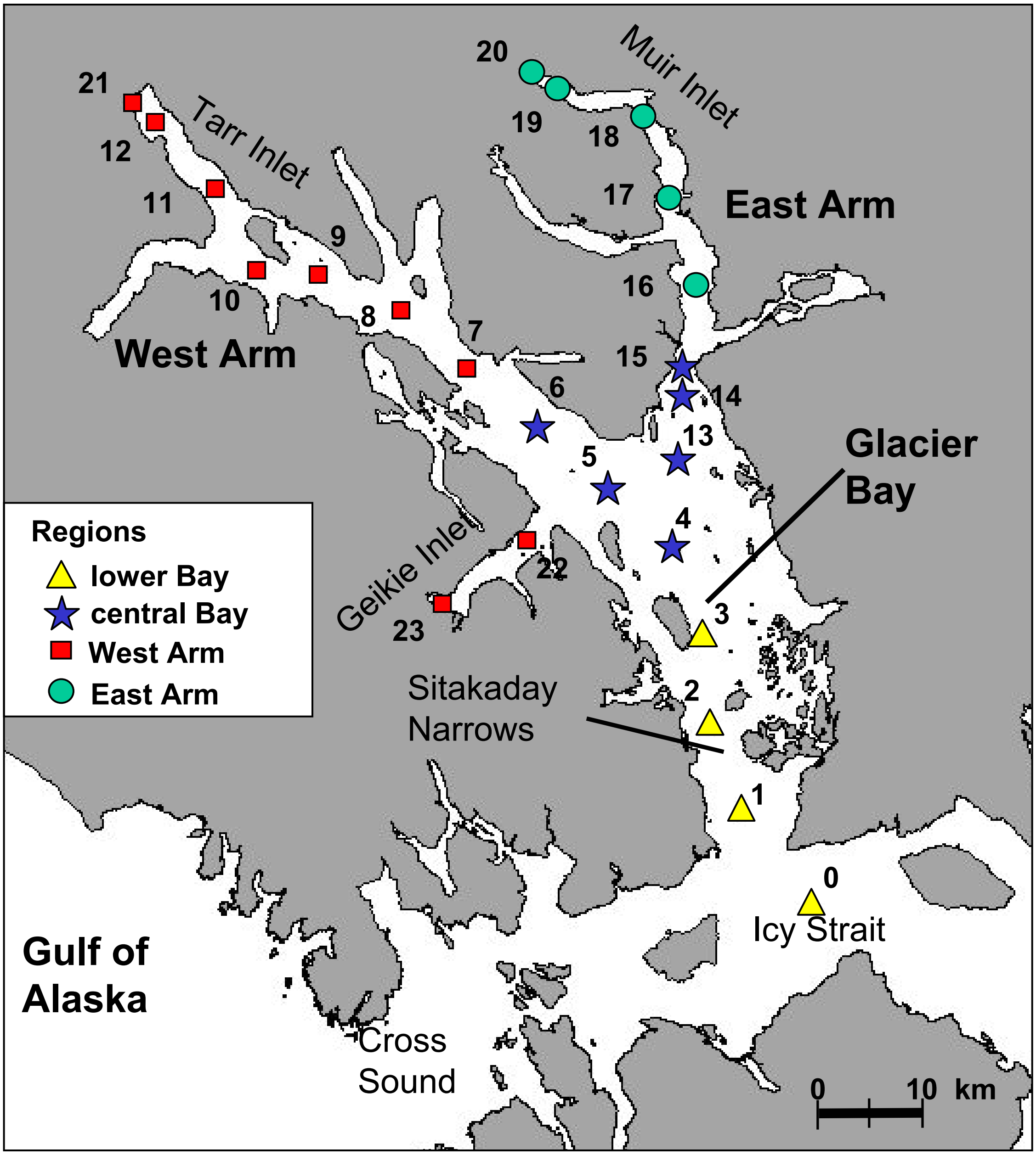

Figure 1. Glacier Bay, Alaska, and the oceanographic sampling stations. Stations were grouped into four Regions based on similarities in bathymetry, relative position to glaciers and source of oceanic waters, and general examination of oceanographic patterns. Regions were defined as lower Bay (Region 1: stations 0, 1, 2, 3), central Bay (Region 2: stations 4, 5, 6, 13, 14, 15), West Arm (Region 3: stations 7, 8, 9, 10, 11, 12, 21, 22, 23) and East Arm (Region 4: stations 16, 17, 18, 19, 20).

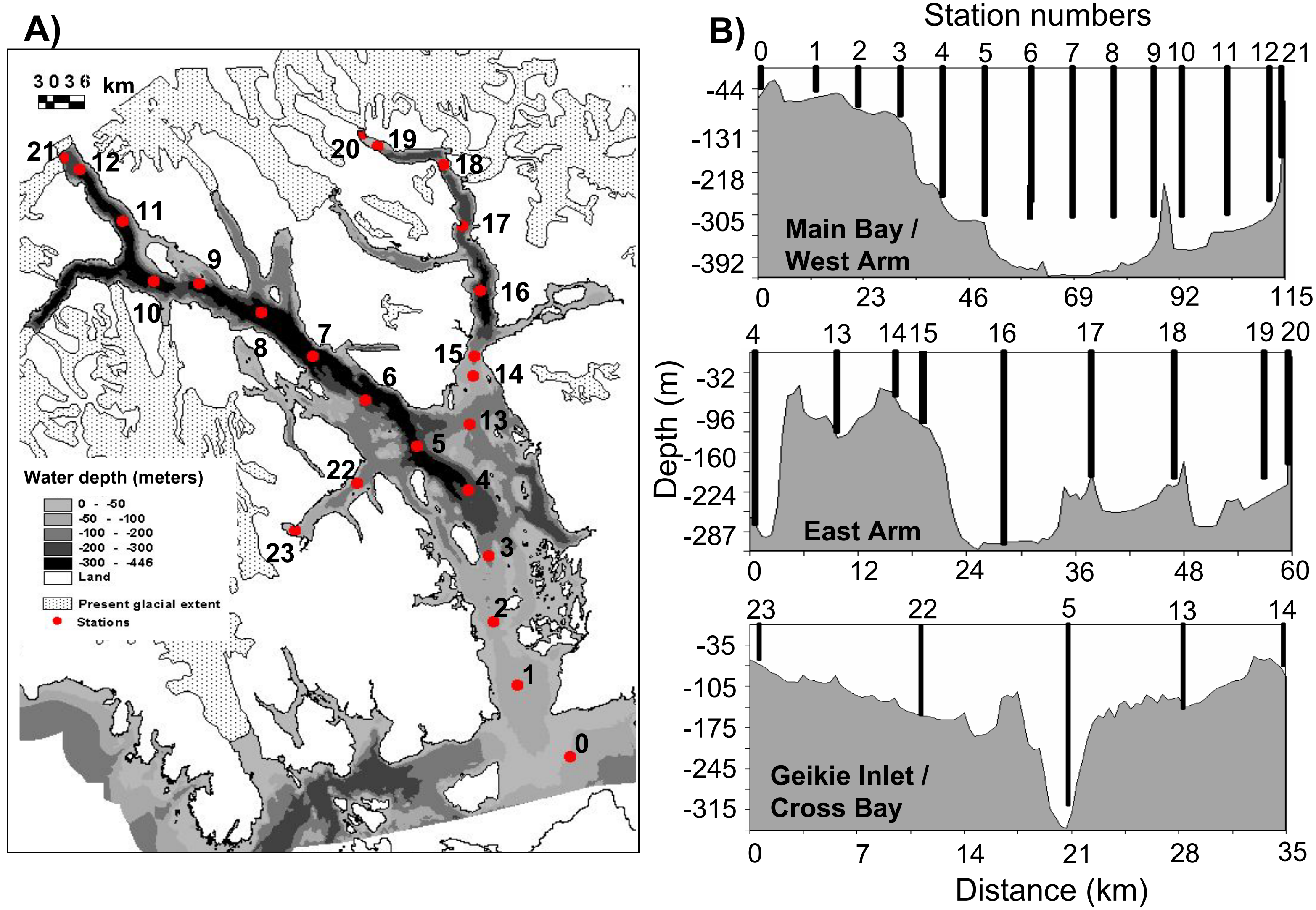

Figure 2. Aerial (A) and cross-section (B) views of Glacier Bay bathymetry. A) Darker gray/black shading represents deeper portions of the Bay, while light gray shading represents shallower depths. Oceanographic stations are numbered. B) Three cross-section views of different axes of Glacier Bay. Vertical black lines denote locations of oceanographic stations showing the approximate depth to which casts are taken. Station numbers are given above each cast location.

deglaciation that has occurred in Glacier Bay over the past ~225 yr is one of the most rapid on record. The Bay is a general Y-shape composed of the main Bay, East Arm and West Arm (Fig. 1). Glacier Bay is surrounded by mountainous terrain, with many sources of freshwater that largely result from glacial discharge, including that from 12 tidewater glaciers. Glacier Bay's most direct connection to the Gulf of Alaska (Pacific Ocean) is through Icy Strait and Cross Sound, a distance of approximately 30km (Figs. 1&2).

General oceanographic conditions vary within the different regions of Glacier Bay. The lower part of Glacier Bay (stations 1-3) experiences intense tidal currents and mixing, with average current speeds of 2.6 and 2.7 m s^{-1} during ebb and flood tides, respectively, with speeds reaching 4.5 m s^{-1} (Hooge and Hooge 2002). These currents are due to the shallow entrance sill (~25 m depth) and the narrowing of the Bay at the mouth. This region exhibits decreased stratification due to the turbulence induced by tidal currents (Hooge and Hooge 2002). In contrast to the lower Bay region, the central Bay exhibits patterns of stratification for much of the year (Hooge and Hooge 2002). The upper regions of Glacier Bay (East and West Arms) are characterized by surface layers of less saline water from glacial melting, which may cause weak entrainment (Hooge and Hooge 2002). Examination of spatial patterns of water masses within Glacier Bay suggests that deep-water renewal within the main basin can occur year-round, replenishing the Bay with outside waters, likely from Cross Sound and the Gulf of Alaska (Hooge and Hooge 2002). It is also hypothesized that the interaction between the well-mixed lower Bay and the stratified central Bay creates a strong tidal front (Hooge and Hooge 2002). Fronts such as these are often associated with enhanced surface nutrients and phytoplankton biomass due to accumulation of materials at the frontal boundary (Pingree et al. 1975, Perry et al. 1983, Parsons 1986, Mann and Lazier 1996) as well as the injection of energy into stratified layers causing the upward movement of nutrient-rich water to the surface (Mann and Lazier 1996).

In examining one annual cycle of chlorophyll-a abundance, Hooge and Hooge (2002) demonstrated that chlorophyll-a levels were fairly sustained throughout the summer (after an initial spring peak and general decline). It was hypothesized that this temporal pattern of sustained phytoplankton abundance throughout the summer was due to continual nutrient replenishment to surface waters. General spatial patterns of chlorophyll-a have been previously described, with highest consistent levels noted in the central Bay and lower arms (Hooge and Hooge 2002). Despite these generalizations, Hooge and Hooge (2002) describe substantial smaller-scale spatial and temporal variation in chlorophyll-a levels within Glacier Bay. The question remains as to the degree of this spatial and temporal variability in chlorophyll-a abundance as well as the factors that are causing this variability.

The temporal and spatial extent of the present oceanographic data set allows us to examine the spatial and seasonal variation in the physical factors that are driving oceanographic conditions within a fjord estuarine system. These efforts are instrumental in determining what causes interannual variation in physical oceanographic conditions and resulting patterns of biological productivity. The objectives of the current study are to: 1) build upon the work of Hooge and Hooge (2002) that described general patterns of oceanographic features within Glacier Bay to generate a more detailed and quantitative description of spatial and temporal patterns of physical oceanographic properties and chlorophyll-a abundance within surface waters, 2) examine patterns of seasonal and annual fluctuations in climatic factors influencing the Glacier Bay system, 3) determine what physical factors are driving physical oceanographic patterns as well as chlorophyll-a levels within Glacier Bay and demonstrate how these relationships vary between seasons and regions.

Methods

Oceanographic sampling

Oceanographic data were collected at 24 set stations within Glacier Bay, Alaska that span the longitudinal axes of the main Bay, the West Arm, the East Arm, and Geikie Inlet, in addition to one station situated outside (southeast) the Bay's entrance (Fig. 1). Not all stations were sampled during all surveys, due to weather and field constraints during the sampling period, as well as the addition of several stations later in the program. Forty-eight separate sampling trips were conducted spanning July 1993 through October 2002 (Table 1). There was an average of 4.8 trips conducted each year, with a range of 2-8 trips per year (Table 1). 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). Detailed descriptions of the sampling procedures and data processing can be found in a fjord oceanography monitoring handbook (Hooge et al. 2000) as well as Hooge and Hooge (2002). 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 (see Appendix 1 for details regarding OBS concentration calculations); 5) fluorescence (mg m^{-3}) – a proxy for chlorophyll-a concentration; 6) density of water (σ_t) – derived from salinity and temperature.

Table 1. Time table of oceanographic data collected at 24 stations within Glacier Bay, AK. Asterisks denote which months of each year were sampled. (a) designates surveys with good coverage of the available sites (≥ 12 sites sampled), while (b) designates low to moderate coverage over all sites (<12 sites sampled); (c) denotes periods when salinity and density data are not available, and (d) indicates times when PAR data are not available (otherwise, PAR available from November 1993-October 2002). OBS turbidity data are available for August 1999 - October 2002. Fluorescence data (chlorophyll-a) are available from May 1994 - October 2002. Seasonal definitions for analyses include spring: February, March, April; summer: May, June, July; fall: August, September, October; winter: November, December, January.

	Jan	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec
1993							* a	* a	* a	* a	* a	* a
1994	* b			* b	* a		* a	* a				
1995										* b,c	* b,c	
1996			* b			* b			* d	* d		
1997					* d		* d				* d	
1998		* d				* a				* a		* a
1999			* a			* a	* a	* a		* a		
2000	* a		* a		* a	* a	* a	* a	* a			* b
2001		* b	* b	* a			* a			* a		
2002	* a		* a	* a			* a	* b		* a		

Weather and external physical data

Daily weather data were obtained from the National Climatic Data Center (NCDC, Asheville, North Carolina). Because there are no weather stations located within Glacier Bay that are representative of the potentially variable conditions from head to mouth of the estuary (Bartlett Cove station at the mouth of the Bay is the only available station), we averaged the weather conditions at eight weather stations that surround Glacier Bay. These stations include: Yakutat Airport, Elfin Cove, Hoonah, Glacier Bay (Bartlett Cove), Gustavus Airport, Auke Bay, Juneau Airport, and Haines (Fig. 3). Several other stations in the region were not included in this set due to inconsistent data sets over the time period of analysis. The following weather parameters were examined: 1) daily average air temperature (ºC), 2) daily precipitation (cm), 3) daily average wind speed (m s^{-1}). Wind data were only available for the Juneau and Yakutat Airport stations; therefore, wind speed represents an average across these two stations alone. Monthly averages were calculated using daily weather data from the available stations (eight stations for temperature and precipitation and two stations for wind speed) for each month from January 1993 – July 2002.

Data on the potential amount of sunlight available each month were obtained from the Astronomical Applications Department of the U.S. Naval Observatory (http://aa.usno.navy.mil/data/). Daily calculations of the number of minutes between sunrise and sunset were averaged over each month. These estimated values of available light do not factor in the influence of local topography (e.g., surrounding mountains) and cloud cover on irradiance; however, they represent the best data available for our

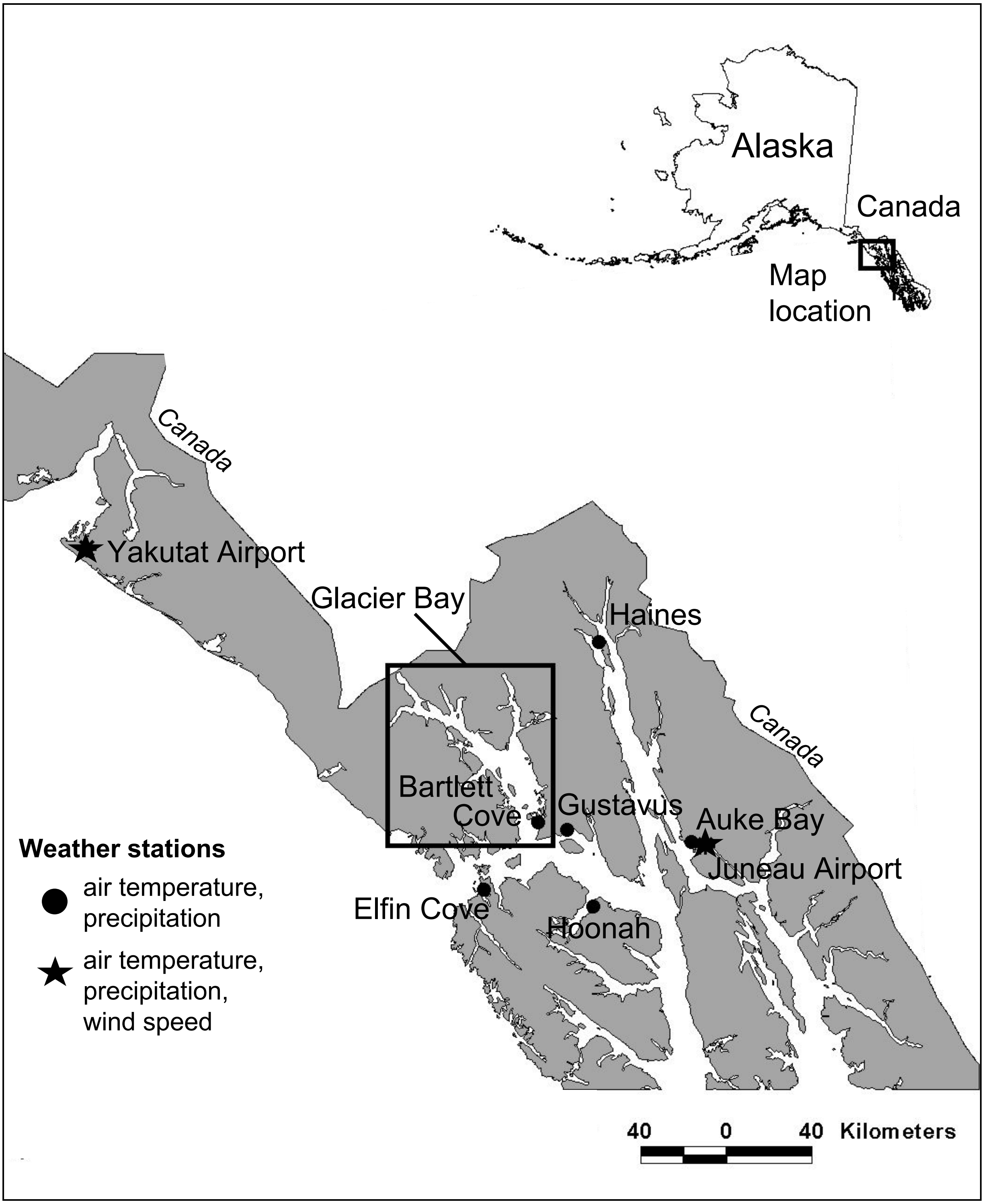

Figure 3. Weather stations in the vicinity of Glacier Bay, Alaska. Data from the eight weather stations were averaged to obtain regional patterns of air temperature and precipitation. Additional data from the Juneau Airport and Yakutat Airport stations were averaged to obtain regional patterns of wind speed.

analysis. Thus, the day length variable represents the seasonal changes in the potentially available light, rather than smaller-scale variations in actually available sunlight.

Tidal cycle characteristics associated with the oceanographic sampling were obtained for 1) height of nearest high tide (m), 2) height of nearest low tide (m), 3) minutes to nearest slack high tide, 4) minutes to nearest slack low tide, and 5) tidal stage (ebbing versus flooding). These tidal data associated with each cast were obtained from the nearest calculated 'tidal station' (Tides and Currents 1997).

Data aggregation and variable calculation

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). Since euphotic depth is measured as a negative number, the absolute value of euphotic depth was used in the analyses to aid in interpretation of parameter estimates (i.e., as the absolute value of euphotic depth gets larger, the euphotic depth increases to a deeper depth). 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 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.

Due to the potentially large amount of spatial variation in oceanographic patterns inherent in fjord systems, as well as previous data illustrating spatial differences (Hooge and Hooge 2002), we divided Glacier Bay into four regions to account for this spatial variability. Regions within Glacier Bay were defined as lower Bay (Region 1: stations 0,1, 2, 3), central Bay (Region 2: stations 4, 5, 6, 13, 14, 15), West Arm (Region 3: stations 7, 8, 9, 10, 11, 12, 21, 22, 23) and East Arm (Region 4: stations 16, 17, 18, 19, 20) based on similarities in bathymetry, relative proximity to glaciers and source of oceanic waters (Fig. 2), and rough examination of oceanographic variables. Further, Hooge and Hooge (2002) demonstrated general differences in oceanographic parameters between these general Regions. Two stations located in Geikie Inlet were included in the West Arm Region due to their similarities of glacial influence to the West Arm stations. Months of the year were grouped into four seasons based on cursory examination of physical weather parameters and the resulting similarity among months: spring =

February, March, April; summer = May, June, July; fall = August, September, October; winter = November, December, January.

Statistical analyses

A path diagram that encompasses the complexity of the explanatory variables and their interactions was drawn to describe the hypothesized relationships between variables in the Glacier Bay estuarine system (Fig. 4). Arrows lead from explanatory variables to the response variables and depict causal rather than correlative relationships. Originally, the entire system was analyzed using path analysis (e.g., Mitchell 1993); however, there was too much missing data (entire observations were excluded from the analysis when any one of the possible twelve variables had missing data) and the overall system model was not a good representation of the data. Instead, separate multiple regression analyses were conducted for several pathways that make up the hypothesized estuarine dynamics for Glacier Bay. The response variables for the individual multiple regression models include: (a) mean salinity 0-15 m, (b) mean water temperature 0-15 m, (c) mean stratification index 0-15 m, (d) mean optical backscatterance 0-15 m, (e) euphotic depth, (f) mean chlorophyll-a 0-15 m (Fig. 4). This approach allowed us to assess the unique contribution of each explanatory variable so that we can determine which factors are most influential in defining the physical oceanographic system and biological productivity of Glacier Bay.

All multiple regression models were analyzed for each combination of Region and season. Explanatory variables in the multiple regression analyses were standardized (with mean=0, variance=1) so that the relative strength of parameter estimates in the

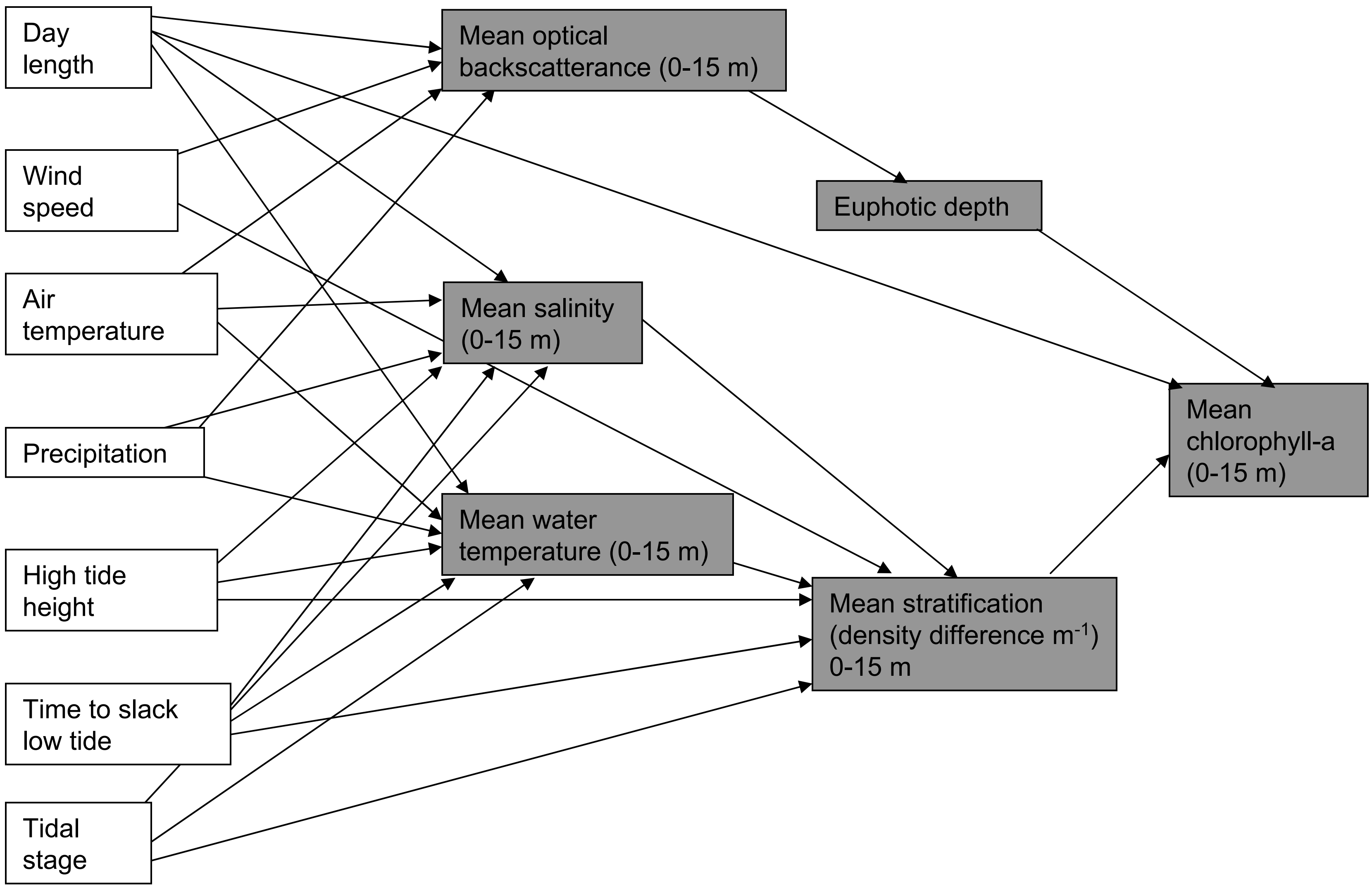

Figure 4. Hypothesized relationships between external physical factors, physical oceanographic parameters, and chlorophyll-a within Glacier Bay, Alaska. The response variables for the six separate multiple regression models are shaded in gray. The arrows connect explanatory variables to response variables, and illustrate all potential causative parameters that were included in the multiple regression selection procedure to determine the best-fit model describing the response variable. Due to a smaller data set and high variability, optical backscatterance was removed as a response variable (see text for details). Euphotic depth was then modeled as a function of the four explanatory variables determining optical backscatterance.

model could be compared (therefore the value of a parameter describes the change in the response variable with one unit increase in the explanatory variable). The response variables were log-transformed when necessary to meet assumptions of normality. Each of the explanatory variables that is shown with an arrow connecting it to the response variable was included in the step-wise backward multiple regression procedure (probability to leave model=0.10, probability to enter model=0.10). All explanatory variables are continuous variables, except for tidal stage, which is a binary descriptor (ebbing=0, flooding=1). Best-fit models were chosen as the simplest model with the largest amount of explained variation (R^2) (using Cp and Adjusted R^2 criteria). Outliers were examined with Cook's D test and were removed when highly influential. Residuals of the models were examined to ensure that model assumptions were met. Quadratic terms were added to the model when preliminary examination of the data indicated that a non-linear quadratic relationship might exist (only for chlorophyll-a and stratification analyses). The sign of the quadratic term determines whether the parabola turns upward (positive term) versus downward (negative term).

In examining the relationships between weather variables (air temperature, precipitation, wind speed, day length) and oceanographic parameters (salinity, water temperature, OBS, stratification index, euphotic depth, chlorophyll-a), we used the average monthly weather values for the month in which the oceanographic sampling was conducted (e.g., if oceanographic sampling occurred on April 10-15, 1998, average weather values for April 1998 were used in the analyses).

Results

Seasonal and annual patterns of weather and physical parameters

Temperature. Monthly air temperatures for the Glacier Bay region for the years 1993-2002 followed a fairly smooth seasonal curve, with coldest temperatures in January (mean = -2.5 ºC) and warmest temperatures in July and August (means = 13.5 and 13.3 ºC, respectively)(Fig. 5). The months of January and February exhibited the highest variability between years, while the rest of the months of the year exhibited less variability between years (Fig. 5). Particularly cold anomalies include January 1996, February 1994, November 1994, and March and April 2002, while noteworthy warmer conditions include January 2001 and February 1997 and 1998 (Fig. 5).

Precipitation. Average monthly precipitation varied greatly both between months and among years from 1993-2002 (Fig. 6). May and June exhibited the lowest precipitation rates of the year (means = 0.31 and 0.28 cm d^{-1}, respectively), and exhibited low variability in precipitation rates among years (Fig. 6). September and October had the greatest precipitation rates (0.94 and 1.01 cm d^{-1}, respectively) (Fig. 6). There was high variability among years during the months of October through December and February (Fig. 6). Noteworthy are the extremely dry conditions in March and April of 2002, as well as the wet conditions in October of 1994 and 1999.

Wind speed. Wind speeds were highly variable among years (1993-2002), with this pattern apparent for all months (Fig. 7). Generally, highest winds occurred during May, October, and December (means = 2.79, 2.85, and 2.92 m s^{-1}, respectively), with lowest

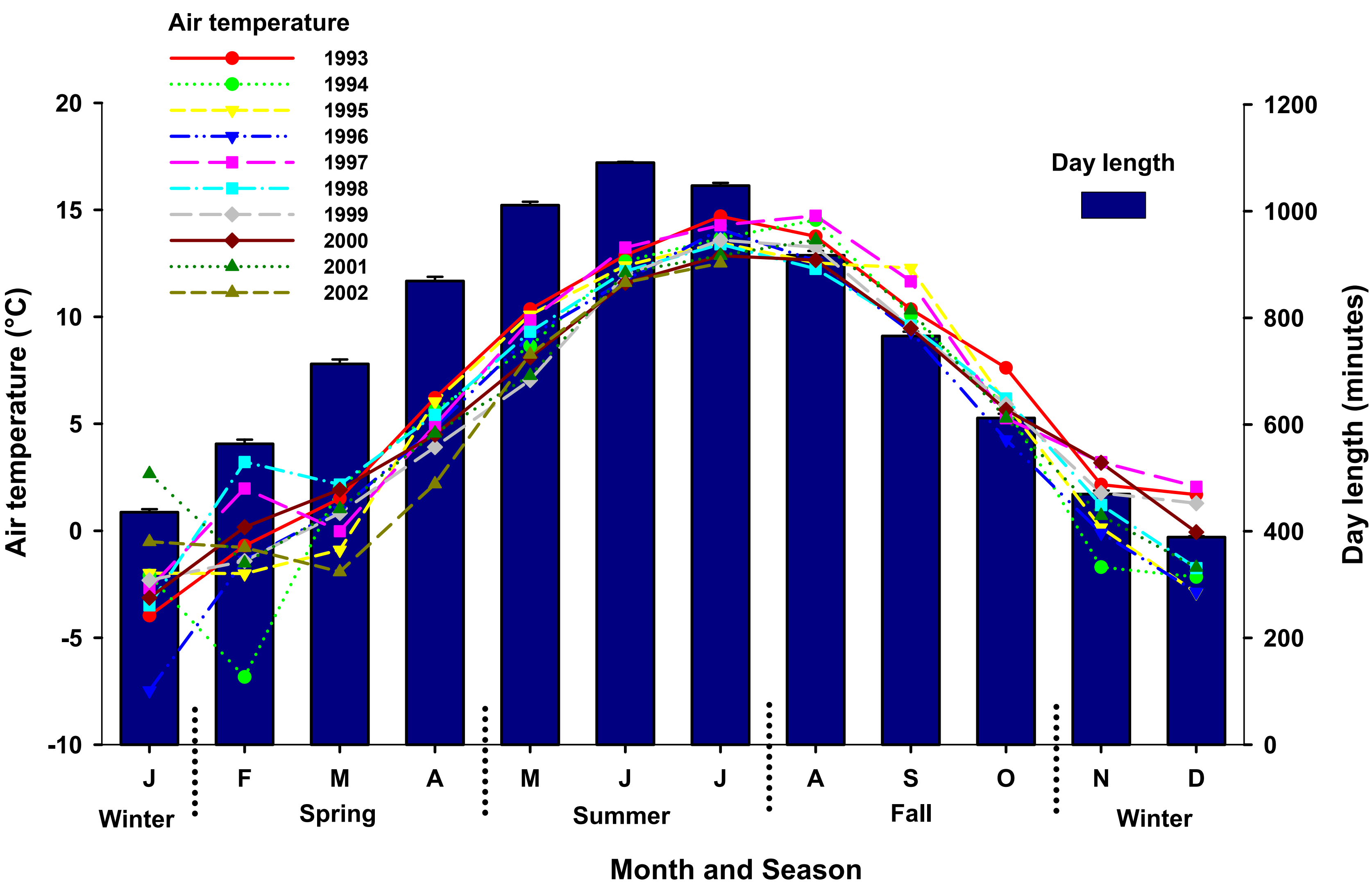

Figure 5. Patterns of air temperature and day length by month and year. Daylength represents the number of minutes per day between sunrise and sunset for Gustavus, Alaska, averaged over one-month periods (+ standard error). Values of air temperature represent monthly means of daily temperature averages from eight weather stations in the vicinity of Glacier Bay, Alaska. Season definitions used in analyses are illustrated.

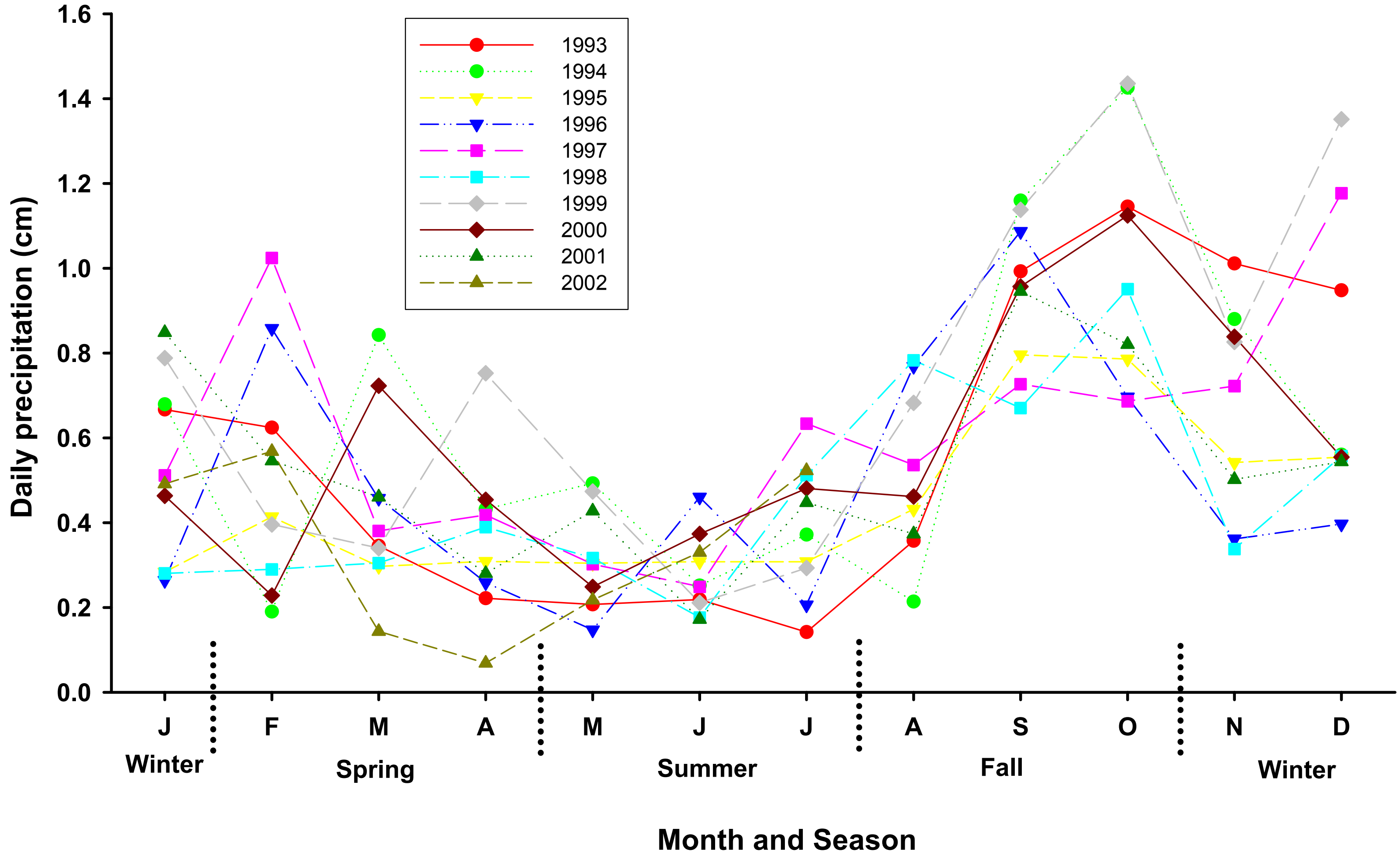

Figure 6. Patterns of precipitation as a function of month and year. Values represent monthly means of daily precipitation rates from eight weather stations in the vicinity of Glacier Bay, Alaska. Season definitions used in analyses are illustrated.

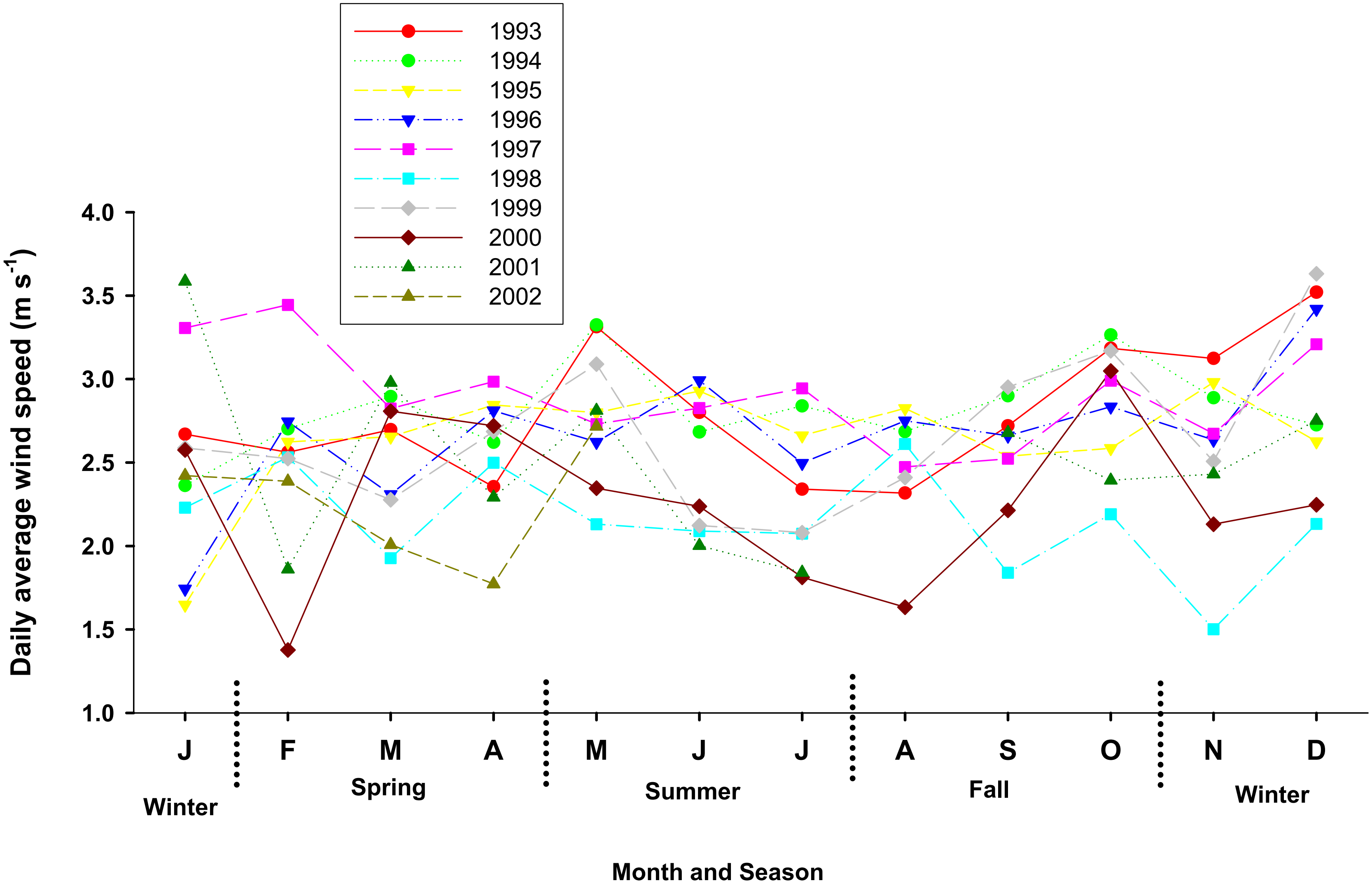

Figure 7. Patterns of wind speed as a function of month and year. Values represent monthly means of daily wind speed averages from two weather stations in the vicinity of Glacier Bay, Alaska (Juneau Airport and Yakutat Airport). Season definitions used in analyses are illustrated.

winds in July and August (means = 2.34 and 2.46 m s^{-1}, respectively). Noteworthy periods of weaker winds are apparent in late summer, fall, and winter of 2000, fall and winter of 1998, and spring 2002 (Fig. 7). Unusually high wind conditions are apparent in January and February 1997 and January 2001 (Fig. 7).

Day length. Within the Glacier Bay region, the average number of minutes of daylight ranges from 389 minutes per day in December to a high of 1091 minutes per day in June (Fig. 5). The months in between exhibit an approximately linear increase or decrease in day length.

Tidal descriptions. The tidal range within Glacier Bay is very large, averaging 3.7 m at Bartlett Cove and 4.2 m within the Upper Bay, at locations midway up the East and West Arms (Hooge and Hooge 2002). Glacier Bay exhibits mixed tides, with two high and two low tides per day, with successive high/low tides of significantly different heights.

Regional and seasonal oceanographic patterns

Factors determining seasonal and regional salinity patterns

Average salinities of surface waters within Glacier Bay were generally highest in spring months, with lower values in winter and summer, and fall exhibiting the lowest salinities of the year (Fig. 8). Regionally, there was a decrease in average surface water salinity moving from the mouth of the Bay (Region 1) to the head of the Bay, with the East Arm (Region 4) exhibiting lower salinity values than the West Arm (Region 3) (Fig. 8). Surface salinity patterns were fairly homogeneous among Regions in spring and to a

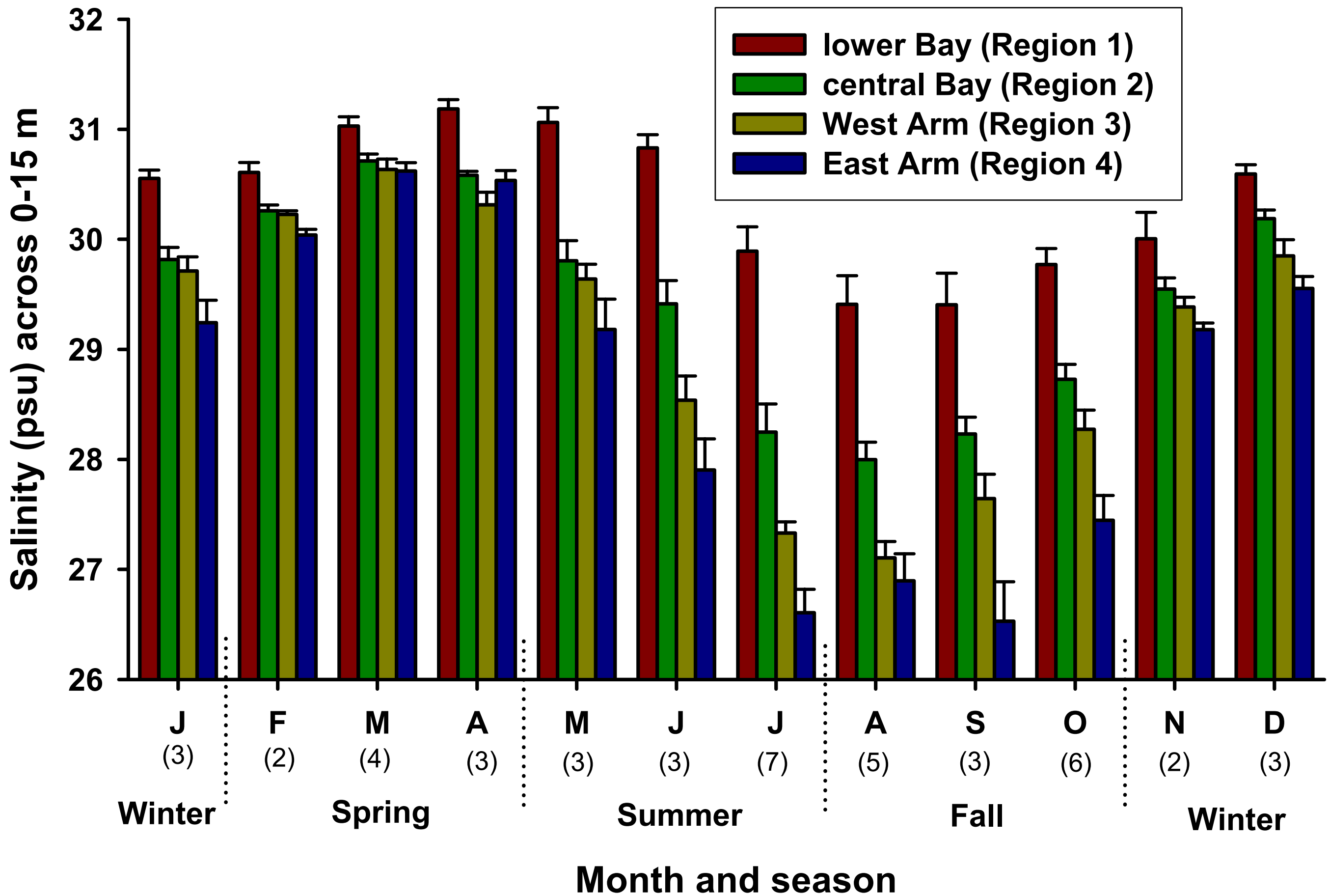

Figure 8. Salinity patterns as a function of month and Region. Values represent means (+ standard error) of salinity from all casts averaged over the top 15 m of the water column across each month for each Region. Season definitions used in analyses are illustrated. The number of years for which salinity data were obtained is indicated in parentheses below each month; numerous casts were taken within each Region during each sampling trip.

lesser degree in winter, but demonstrated large variability between Regions in summer and fall (Fig. 8).

Overall, there were substantial differences among seasons and Regions in the type, strength, and explanatory power of physical variables that influenced salinity within the upper 15 m of the water column of Glacier Bay (Table 2). In spring, summer and fall, the amount of variation in salinity explained by physical variables was greater for Regions 3 and 4 than for Regions 1 and 2 (Table 2). The amount of variation in salinity explained by the measured physical factors ranged from R^2=0.08 (fall Region 1) to R^2=0.87 (spring Region 3) (Table 2). Of the 16 season x Region models, only one did not significantly describe variation in salinity (fall Region 1), while 13 of the 16 models exhibited very high significance values ($p<0.001$). In the summer and winter, there were only a few factors that explain salinity variation, and these were fairly similar among Regions, whereas for spring and fall, there were many different explanatory variables that described salinity patterns and the combination of factors varied among Regions (however, during spring and fall, Regions 1 and 2 models showed similarities, while Regions 3 and 4 models showed similarities; Table 2).

Day length was highly influential in determining salinity patterns of surface waters for all Regions in the winter, Regions 3 and 4 in fall, and Regions 1 and 2 in spring months (Table 2). Air temperature also had a strong effect on salinity, with its influence largely apparent when day length was not a significant descriptor, including all Regions in summer, Regions 1, 2 and 4 in fall, and Region 2 in spring (Table 2). Air temperature and day length had the same directional (negative) influence on salinity patterns, except for three cases where the day length influence was positive (Table 2).

Table 2. Best-fit multiple regression models describing the relationship between physical variables and the mean concentration of salinity for surface waters 0-15 m for each Region x season combination. Region 1 (lower Bay)=stations 0,1, 2, 3; Region 2 (central Bay)=stations 4, 5, 6, 13, 14, 15; Region 3 (West Arm)= stations 7, 8, 9, 10, 11, 12, 21, 22, 23; Region 4 (East Arm)=stations 16, 17, 18, 19, 20. Spring = Feb., March, April; summer = May, June, July; fall= Aug. Sept., Oct.; winter = Nov., Dec., Jan. Tidal stage represents a binary variable (0=ebbing, 1=flooding), whereas all other variables are continuous. The factor 'wind speed' was included in the model selection procedure; however, it was removed from the table since it did not significantly explain variation in salinity for any of the season x region cases.Coefficients represent standardized variables (see text) so that the magnitude of parameters of directly comparable. Parameter estimates are positive, except where noted as "-". Empty cells indicate that a particular independent variable was not included in the best fit model.

Salinity 0-15 m

	Model fit	Day length	Air temperature	Precipitation	High tide height	Time to low tide	Tidal stage
Spring							
Region 1	$R^2 = 0.38$***	0.28*				0.13*	
Region 2	$R^2 = 0.52$***	0.41***	- 0.41***				0.11**
Region 3	$R^2 = 0.87$***			0.10**	- 0.31***		0.11***
Region 4	$R^2 = 0.80$***			0.22**	- 0.36***		0.07*
Summer							
Region 1	$R^2 = 0.20$**		- 0.83*	- 0.68*			
Region 2	$R^2 = 0.27$***		- 1.32***				
Region 3	$R^2 = 0.51$***		- 2.34***				
Region 4	$R^2 = 0.51$***		- 2.46***	- 0.98**			
Fall							
Region 1	$R^2 = 0.08$ (ns)		- 0.68*	- 0.37 (ns)			
Region 2	$R^2 = 0.37$***		- 0.98***	- 0.43***			
Region 3	$R^2 = 0.51$***	- 1.94***		- 0.61***	- 0.38***	- 0.28**	
Region 4	$R^2 = 0.46$***	2.46*	-3.58***	- 0.47*	- 0.52***		- 0.41**
Winter							
Region 1	$R^2 = 0.41$***	- 1.40**		- 0.29**			0.13 (ns)
Region 2	$R^2 = 0.40$***	- 1.83***					
Region 3	$R^2 = 0.17$*	- 1.33*					
Region 4	$R^2 = 0.36$**	- 1.69**			- 0.28*		

(ns) $0.05 > p < 0.10$ * $p < 0.05$ ** $p < 0.01$ *** $p < 0.001$

The negative effect of precipitation on salinity patterns was also fairly pervasive, significantly affecting salinity in all Regions during the fall, Regions 1 and 4 in summer, Regions 3 and 4 in spring (positive effect), and Region 1 in winter (Table 2). Tidal factors had less of a general impact on surface salinity patterns than the other physical variables, demonstrating a greater influence within Regions 3 and 4 (Table 2).

<u>Factors determining seasonal and regional water temperature patterns</u>

Average surface water temperatures in Glacier Bay were lowest in the spring, with the next coldest temperatures in winter months, with both of these seasons demonstrating little Regional differences in average temperature (Fig. 9). Average surface water temperatures were higher in summer and fall, with slight decreases in temperature moving from the mouth of the Bay (Region 1) to the head of the Bay (Regions 3 and 4) (Fig. 9).

Overall, there were substantial differences among seasons and Regions in the type, strength, and explanatory power of physical variables that influence water temperature within the upper 15 m of the water column of Glacier Bay (Table 3). The amount of explained variation in water temperatures ranged from R^2=0.20 (fall Region 3) to R^2=0.83 (winter Region 3). All of the models for the season x Region combinations significantly described variation in water temperature, with 14 of the 16 models exhibiting extremely high significance levels ($p<0.001$).

Day length had a strong influence on surface water temperature patterns for all Regions in fall and spring, Region 4 in summer, and Regions 3 and 4 in winter (Table 3). Air temperature also had a broad influence on water temperature, significantly

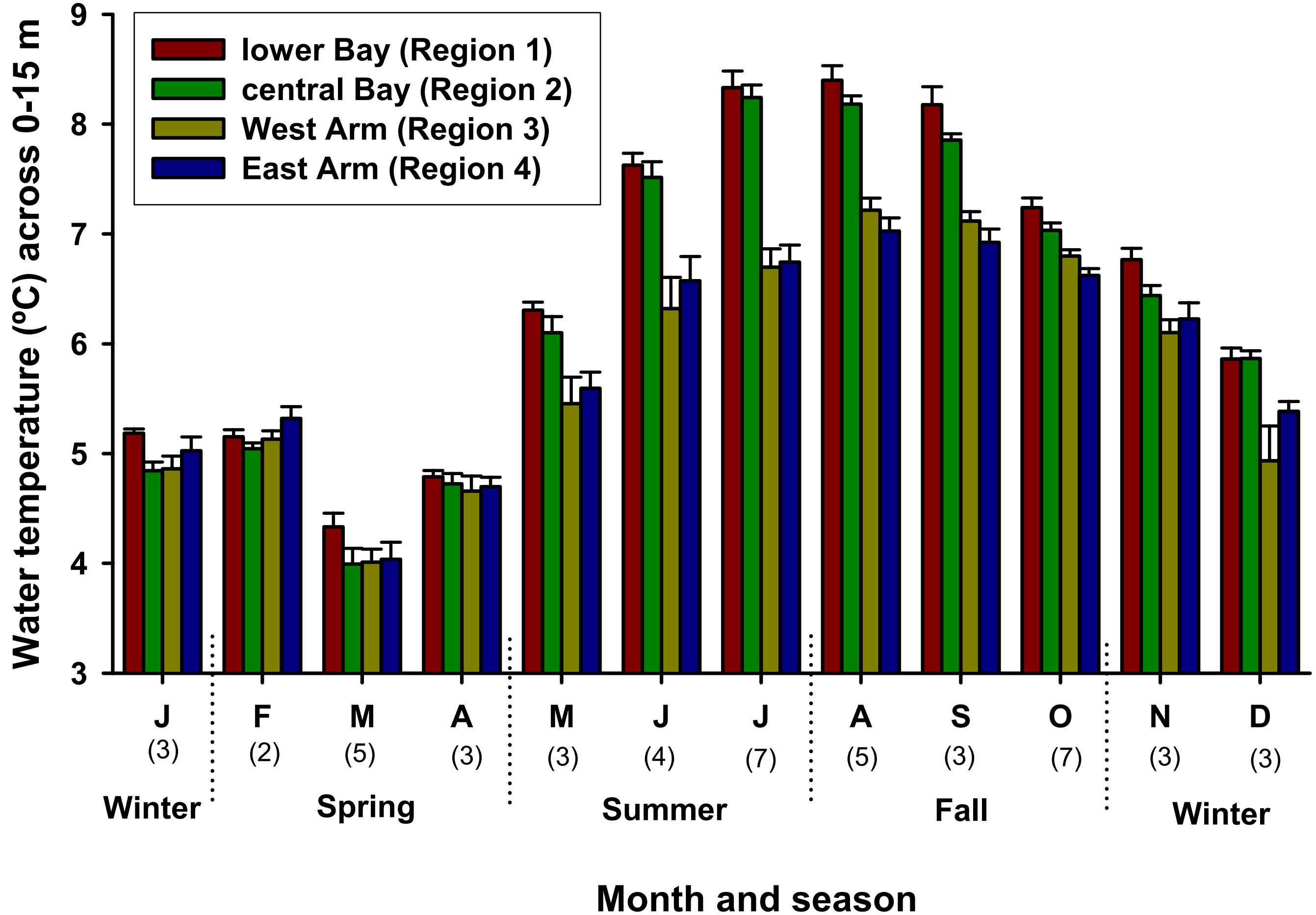

Figure 9. Water temperature patterns by month and Region. Values represent means (+ standard error) of water temperature from all casts averaged over the top 15 m of the water column across each month for each Region. Season definitions used in analyses are illustrated. The number of years for which water temperature data were obtained is indicated in parentheses below each month; numerous casts were taken within each Region during each sampling trip.

Table 3. Best-fit multiple regression models describing the relationship between physical variables and the mean water temperature for surface waters 0-15 m for each Region x season combination. Region 1 (lower Bay)=stations 0, 1, 2, 3; Region 2 (central Bay)=stations 4, 5, 6, 13, 14, 15; Region 3 (West Arm)= stations 7, 8, 9, 10, 11, 12, 21, 22, 23; Region 4 (East Arm)=stations 16, 17, 18, 19, 20. Spring = Feb., March, April; summer = May, June, July; fall = Aug., Sept., Oct.; winter = Nov., Dec., Jan. 'Tidal stage' represents a binary variable (0=ebbing, 1=flooding), whereas all other variables are continuous. The factor 'wind speed' was included in the model selection procedure; however, it was removed from the table since it did not significantly explain variation in salinity for any of the season x Region cases. Coefficients represent standardized variables (see text) so that the magnitude of parameters of directly comparable. Parameter estimates are positive, except where noted as "-". Empty cells indicate that a particular independent variable was not included in the best fit model.

Temperature 0-15 m

	Model fit	Day length	Air temperature	Precipitation	High tide height	Time to low tide	Tidal stage
Spring							
Region 1	$R^2 = 0.39$***	- 0.44*	0.84***		0.15**	- 0.13 (ns)	
Region 2	$R^2 = 0.26$*	- 0.57*	0.97**				- 0.21 (ns)
Region 3	$R^2 = 0.35$**	- 0.44 (ns)	1.08**	- 0.32*			
Region 4	$R^2 = 0.71$***	- 0.76**	2.22***		- 0.49***	- 0.55***	
Summer							
Region 1	$R^2 = 0.50$***		2.02***				
Region 2	$R^2 = 0.63$***		2.11***	0.5*			
Region 3	$R^2 = 0.21$***		1.33***				- 0.33**
Region 4	$R^2 = 0.42$***	2.82**	0.91**	0.56*	- 0.45**	0.35**	
Fall							
Region 1	$R^2 = 0.59$***	1.63***		0.45***			
Region 2	$R^2 = 0.78$***	1.28***		0.32***			
Region 3	$R^2 = 0.20$***	0.53***		0.16*			
Region 4	$R^2 = 0.21$***	0.55***		0.16*			
Winter							
Region 1	$R^2 = 0.44$***		1.34***				
Region 2	$R^2 = 0.53$***		1.3***				
Region 3	$R^2 = 0.83$***	7.52***	1.38***		0.97*		
Region 4	$R^2 = 0.79$***	1.79***		0.28*	- 0.41***		

(ns) $0.05 > p < 0.10$ * $p < 0.05$ ** $p < 0.01$ *** $p < 0.001$

contributing to water temperature variation for all Regions in spring and summer and Regions 1-3 in winter (Table 3). Air temperature and day length influenced water temperature similarly in summer, fall and winter; however, in spring their directional effects were opposite across all Regions (Table 3). Precipitation had a smaller effect on water temperature in spring, summer and winter (significantly contributing to variation at only one or two Regions) compared with its more general influence on all Regions in the fall months (Table 3). Similar to patterns of salinity, water temperature patterns were not as strongly influenced by tidal factors compared to other physical variables, and the area where tidal factors were most influential was Region 4 (Table 3).

Factors determining seasonal and regional stratification patterns

Average surface water stratification patterns within Glacier Bay were lowest in spring and winter, and highest in the summer and fall months (Fig. 10). Stratification increased with distance from the mouth of the Bay, with lowest levels in the lower Bay, moderate levels in the central Bay and highest levels at the head of the Bay; Region 4 (East Arm) exhibited higher average stratification than Region 3 (West Arm) (Fig. 10). Differences in stratification levels among the Regions were highest in summer and fall compared to spring and winter, when all Regions displayed similar water column stability (Fig. 10).

Overall, the measured physical factors explained a relatively large amount of the variation in surface water stratification patterns across the majority of the season x Regions, with measures of explained variation ranging from R^2=0.13 (winter Region 1) to R^2=0.88 (summer Region 4)(Table 4). In only one case was no significant model

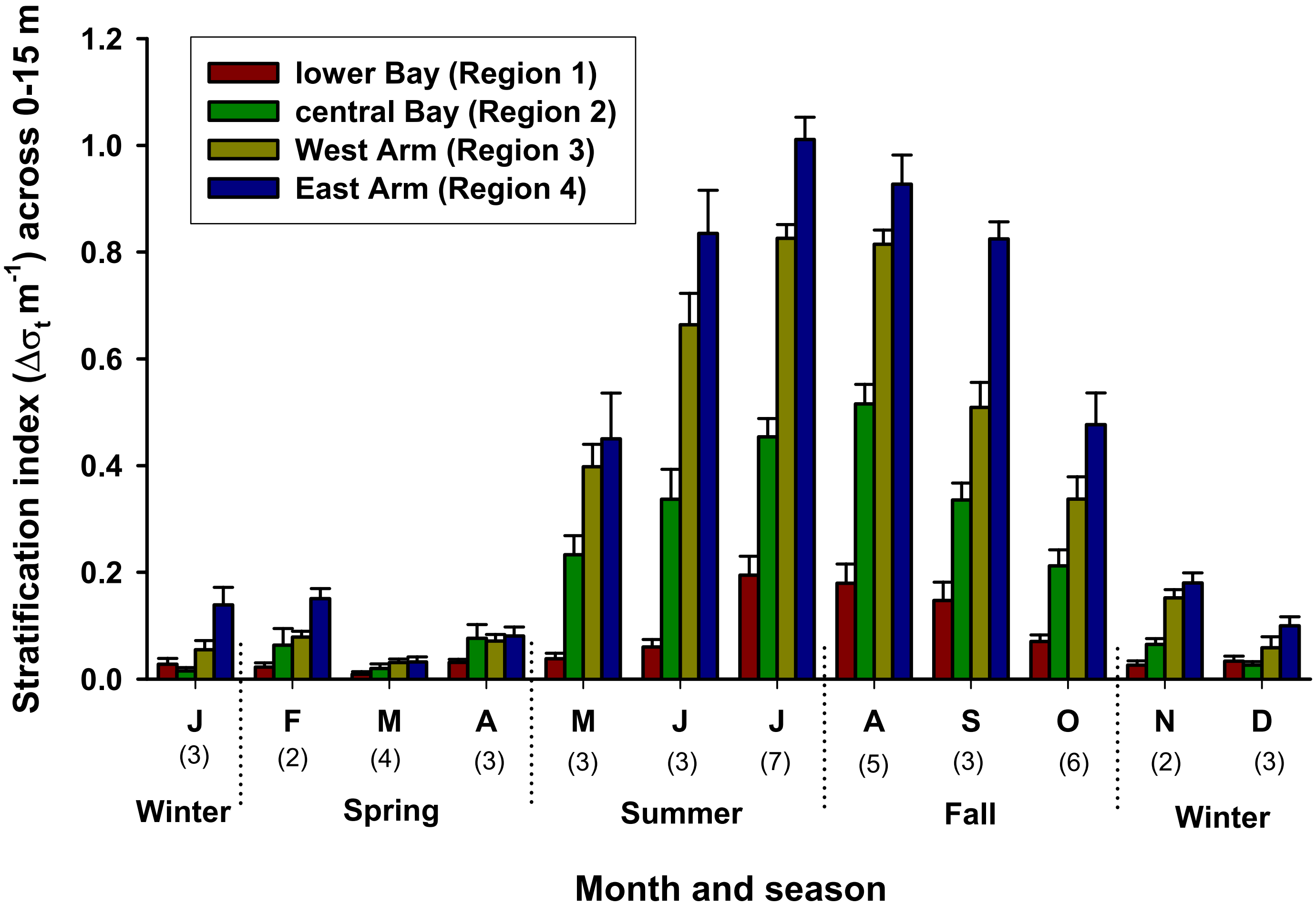

Figure 10. Stratification patterns as a function of month and Region. Values represent means (+ standard error) of stratification from all casts averaged across each month for each Region. The stratification index for each cast represents the mean of the density differences from adjoining 1-m depth bins for the top 15 m of the water column. Season definitions used in analyses are illustrated. The number of years for which stratification data were obtained is indicated in parentheses below each month; numerous casts were taken within each Region during each sampling trip.

Table 4. Best-fit multiple regression models describing the relationship between physical variables and the mean stratification index for surface waters 0-15 m for each Region x season combination. Region 1 (lower Bay)=stations 0, 1, 2, 3; region 2 (central Bay)=stations 4, 5, 6, 13, 14, 15; Region 3 (West Arm)= stations 7, 8, 9, 10, 11, 12, 21, 22, 23; Region 4 (East Arm)=stations 16, 17, 18, 19, 20. Spring = February, March, April; summer = May, June, July; fall = August, September, October; winter = November, December, January. Tidal stage represents a binary variable (0=ebbing, 1=flooding), whereas all other variables are continuous. Coefficients represent standardized variables (see text) so that the magnitude of parameters of directly comparable. Parameter estimates are positive, except where noted as "-". Empty cells indicate that a particular independent variable was not included in the best fit model.

Stratification 0-15 m

	Model fit	Wind speed	Salinity	Water temperature	High tide height	Time to low tide	Tidal stage	Quadratic salinity
Spring								
Region 1	$R^2 = 0.33$**	- 0.07*		0.27**		- 0.09**	0.05 (ns)	
Region 2	$R^2 = 0.27$**		-1.05**					
Region 3	$R^2 = 0.52$***			0.32**		0.09**	- 0.12***	
Region 4	$R^2 = 0.70$***		-1.45***			0.19**		
Summer								
Region 1	$R^2 = 0.75$***		- 0.73***					
Region 2	$R^2 = 0.49$***	- 0.09*	- 0.33***					
Region 3	$R^2 = 0.72$***		- 0.39***					
Region 4	$R^2 = 0.88$***		5.72***					- 6.79***
Fall								
Region 1	$R^2 = 0.58$***		- 0.56***					
Region 2	$R^2 = 0.63$***		- 0.45***	0.44***	- 0.11**			
Region 3	$R^2 = 0.68$***	0.11*	- 0.71***		- 0.28***			
Region 4	$R^2 = 0.64$***		- 0.47***		- 0.26***			
Winter								
Region 1	$R^2 = 0.13$ (ns)	- 0.08 (ns)	- 0.30*					
Region 2	$R^2 = 0.42$***		- 0.35**	0.25***				
Region 3	$R^2 = 0.51$***	0.17**	- 0.70**	0.35**				
Region 4	$R^2 = 0.63$***		- 1.11***					

(ns) 0.05 > p < 0.10 * p < 0.05 ** p < 0.01 *** p < 0.001

found (winter Region 1), while 13 of the 16 multiple regression models exhibited very high significance levels ($p<0.001$)(Table 4).

In general, salinity was the dominant factor determining stratification patterns across all Regions in summer, fall, and winter; however, other contributing factors varied by Region and season, as do those describing stratification in spring months (Table 4). The contribution of wind speed in determining stratification was not broadly apparent, and had a significant effect in various Regions in different seasons (Table 4). Similarly, water temperature significantly explained variation in stratification at some Regions during some seasons (Table 4). The influence of tidal factors on stratification patterns was season-specific (Table 4). For example, the height of the high tide was only influential in describing stratification patterns in fall months, while time to low tide and tidal stage only played a contributing role in salinity patterns in the spring (Table 4).

Patterns of optical backscatterance

Levels of optical backscatterance (OBS) were highly variable in time, and we had a much smaller data set for OBS than the other oceanographic parameters (Table 1). Therefore, we were unable to fit regression models describing the factors that were most influential in determining OBS patterns. As a result, euphotic depth was instead modeled as a function of the four explanatory variables determining optical backscatterance (Fig. 4). Nevertheless, general patterns of turbidity can be described and are useful to correlate with other oceanographic characteristics within Glacier Bay.

Turbidity levels within the surface waters demonstrated peak levels across all Regions in July (with extremely high levels in Regions 3 and 4), while OBS was also higher across all Regions in August and December (Fig. 11). High levels of OBS were demonstrated solely within the East Arm (Region 4) during September and October (Fig. 11). Higher monthly average OBS in Regions 3 and 4 was associated with a large amount of variability, most likely due to high variance between both stations and years. Station-specific patterns of OBS within the surface waters demonstrated that the higher levels within Region 3 were dominated by stations 12 and 21, with higher levels also noted for stations 22 and 23 in Geikie Inlet (Fig. 12). Higher OBS levels within Region 4 were largely driven by high values at stations 19 and 20 (Fig. 12).

Factors determining seasonal and regional euphotic depth patterns

Average euphotic depths within Glacier Bay were shallowest in summer months, followed by fall, with spring and winter exhibiting deeper euphotic depths (Fig. 13). Regional differences in average euphotic depth varied among seasons (Fig. 13). In the summer and fall, Region 1 exhibited the deepest euphotic depth, followed by Regions 2 and 3, with Region 4 demonstrating the shallowest euphotic depth (Fig. 13). During spring and winter months, euphotic depth levels were fairly similar among Regions, with Region 1 having the shallowest euphotic depth and Region 2 having the greatest euphotic depth (Fig. 13). Overall, the euphotic depth varied much less among seasons within Regions 1 and 2 compared with larger seasonal differences in euphotic depth in Regions 3 and 4.

In general, the measured physical variables did not consistently explain variation in euphotic depth across all seasons and Regions (Table 5). In six cases, the physical variables could not significantly explain the variation in euphotic depth (two of these

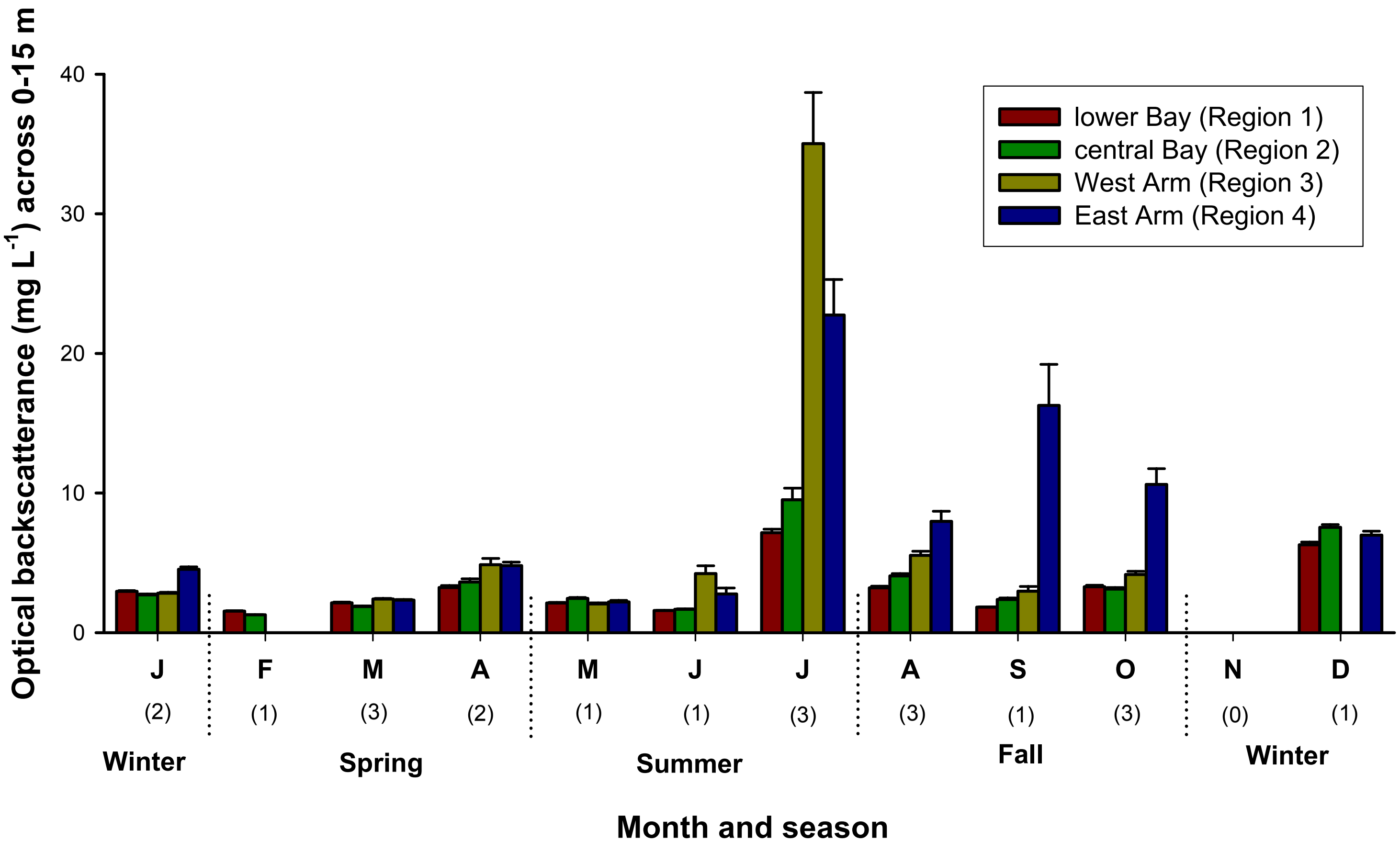

Figure 11. Optical backscatterance (OBS) patterns as a function of month and Region. Values represent means (+ standard error) of OBS averaged over the top 15 m of the water column from all casts and averaged across each month for each Region. Season definitions used in analyses are illustrated. The number of years for which OBS data were obtained is indicated in parentheses below each month; numerous casts were taken within each Region during each sampling trip.

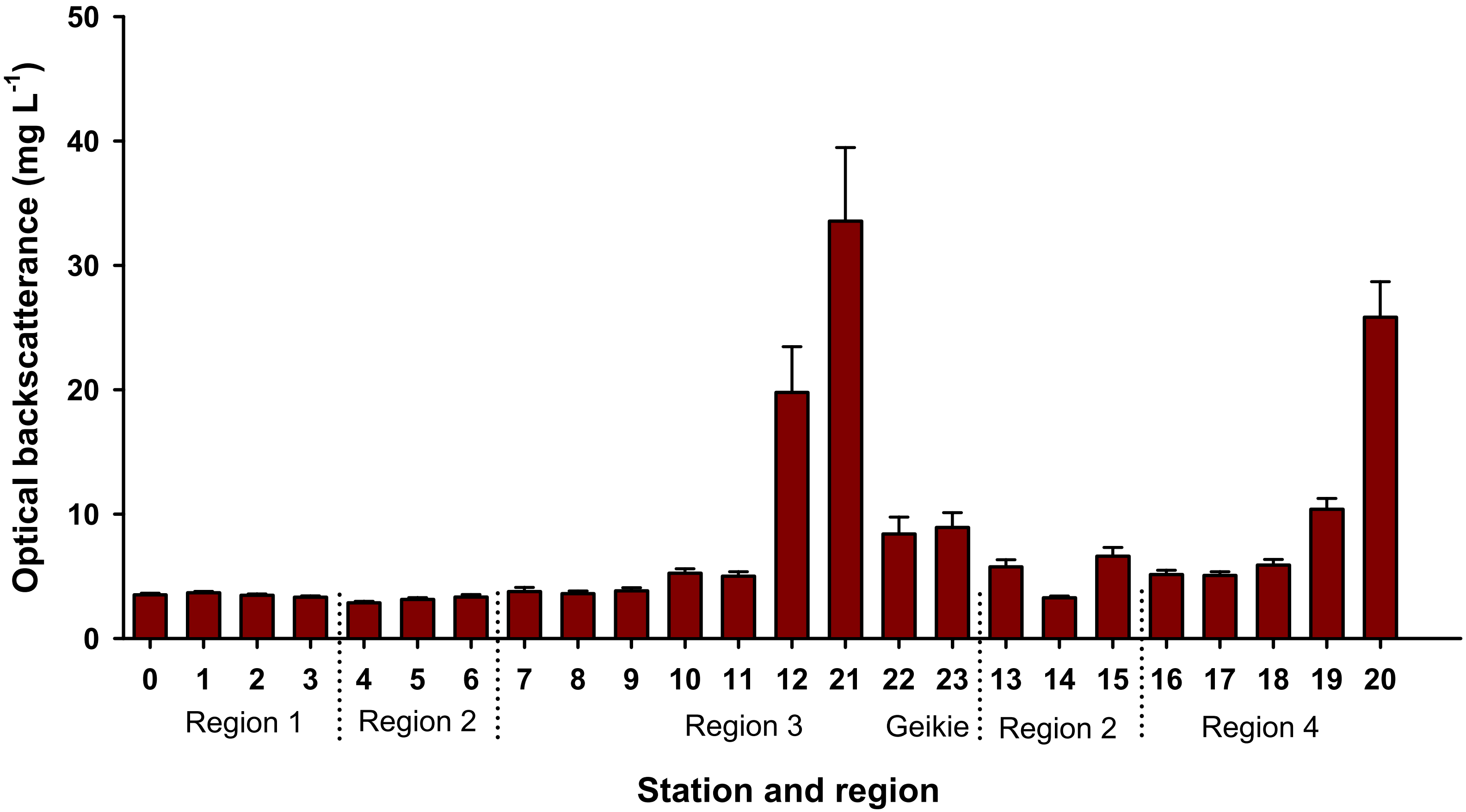

Figure 12. Optical backscatterance (OBS) patterns by station within Glacier Bay. Values represent means (+ standard error) of OBS averaged over the top 15 m of the water column for all casts and averaged by station. Regions (as defined for analyses) are indicated below the station numbers. Stations are 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.

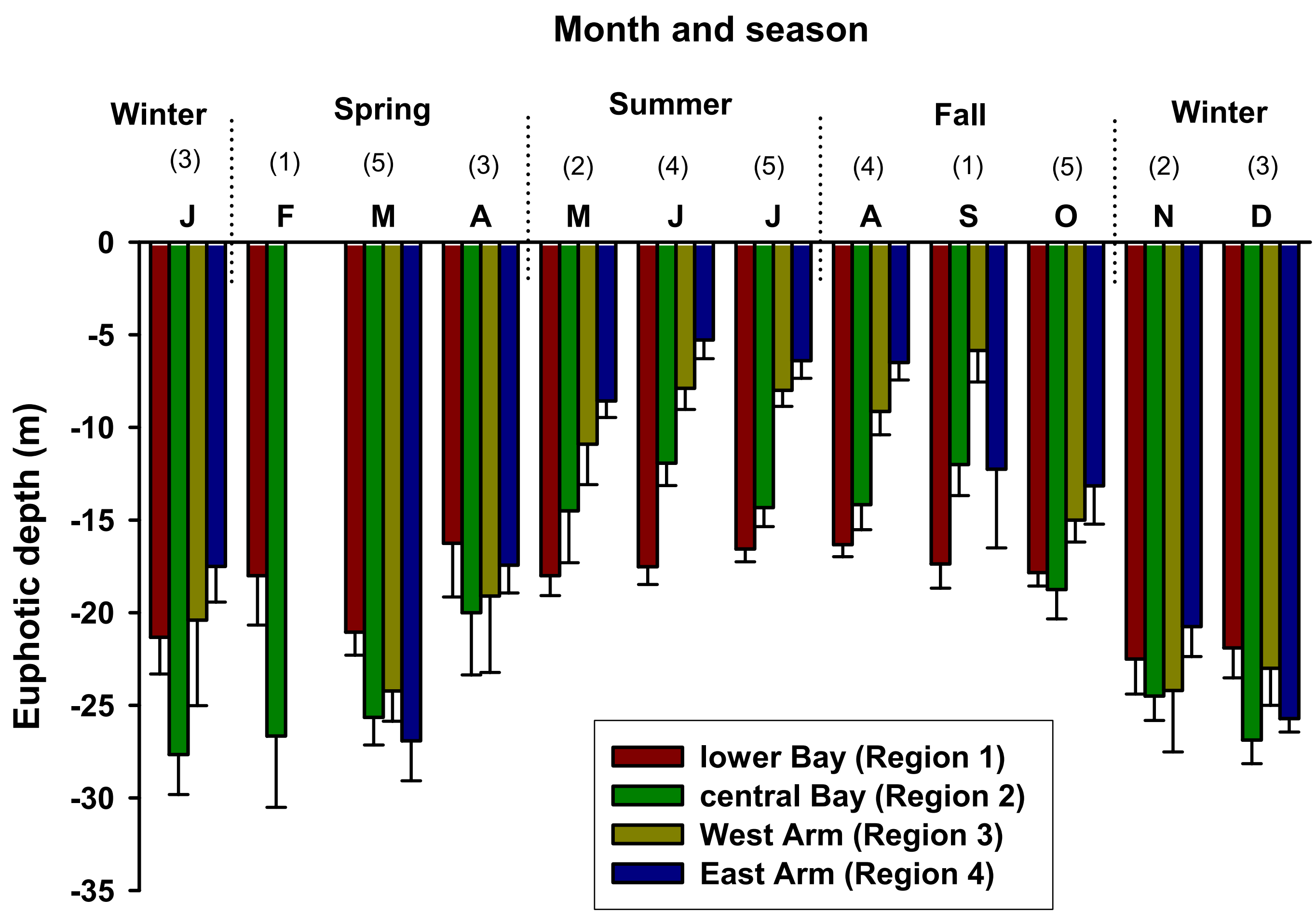

Figure 13. Euphotic depth patterns by month and Region. Values represent means (+ standard error) of the euphotic depth from all casts averaged across each month for each Region. The euphotic depth is defined here as the depth at which the amount of light (photosynthetically active radiation – PAR) available is 1% of that at the surface. Season definitions used in analyses are illustrated. The number of years for which PAR data were obtained is indicated in parentheses below each month; numerous casts were taken within each Region during each sampling trip.

Table 5. Best-fit multiple regression models describing the relationship between physical variables and the absolute value of the euphotic depth (the depth at which the amount of available light equals 1% of that measured at the surface) for each Region x season combination. Region 1 (lower Bay)=stations 0, 1, 2, 3; Region 2 (central Bay)=stations 4, 5, 6, 13, 14, 15; Region 3 (West Arm)= stations 7, 8, 9, 10, 11, 12, 21, 22, 23; Region 4 (East Arm)=stations 16, 17, 18, 19, 20. Spring = Feb., March, April; summer = May, June, July; fall = Aug., Sept., Oct.; winter = Nov., Dec., Jan. Coefficients represent standardized variables (see text) so that the magnitude of parameters of directly comparable. Parameter estimates are positive, except where noted as "-". Empty cells indicate that a particular independent variable was not included in the best fit model.

Euphotic Depth

	Model fit	Day length	Wind speed	Air temperature	Precipitation
Spring					
Region 1	$R^2 = 0.53$***	- 14.58***	6.74***		- 10.42***
Region 2	$R^2 = 0.55$***	- 62.98***	11.13***	40.26***	- 30.08***
Region 3	$R^2 = 0.56$***	- 57.90**	23.57**	35.26*	- 40.72***
Region 4	$R^2 = 0.54$**	- 64.45**		38.08*	- 20.78**
Summer					
Region 1	No models fit the data				
Region 2	No models fit the data				
Region 3	No models fit the data				
Region 4	$R^2 = 0.08$ (ns)	- 8.69 (ns)			
Fall					
Region 1	$R^2 = 0.12$*				1.21*
Region 2	$R^2 = 0.41$***	47.85***	3.99**	- 45.57***	
Region 3	$R^2 = 0.38$***		2.07*	- 7.40***	- 2.29 (ns)
Region 4	$R^2 = 0.51$***				3.94***
Winter					
Region 1	$R^2 = 0.17$ (ns)		- 2.78*	9.35*	
Region 2	No models fit the data				
Region 3	$R^2 = 0.59$*			39.10**	- 15.93*
Region 4	$R^2 = 0.30$**	- 15.91**			

(ns) $0.05 > p < 0.10$ * $p < 0.05$ ** $p < 0.01$ *** $p < 0.001$

cases had nearly significant p values (i.e., >0.05 but <0.10) and warranted selection of a model, while the other 4 cases had higher p values and a model was not fit to the data)(Table 5). The ability of the models to fit the data was poor in summer months for all Regions as well as Regions 1 and 2 in winter (Table 5). Of the remaining ten season x Region cases, R^2 values ranged from 0.30 to 0.56, with eight of these ten cases exhibiting highly significant p values (<0.01) (Table 5).

In spring months, the models that best described euphotic depth patterns were relatively consistent between Regions (R^2=0.53-0.56), with most physical variables significantly influencing patterns of euphotic depth across all Regions (Table 5). During spring, day length and air temperature had opposite directional influences on euphotic depth (air temperature=positive; day length=negative), while wind speed had a positive influence and precipitation had a negative influence on euphotic depth (Table 5). Patterns of euphotic depth in the summer could not be described by the measured weather variables (Table 5). In the fall months, the physical variables that explained euphotic depth differ between Regions, with many of the variables demonstrating opposite influences on euphotic depth than they did during spring (e.g., day length=positive; air temperature=negative; precipitation=positive) (Table 5). During winter, values of euphotic depth within Regions 3 and 4 could only be described by one or two physical variables that differed between the Regions (Table 5).

Factors determining seasonal and regional chlorophyll-a patterns

Average chlorophyll-a levels within Glacier Bay surface waters were lowest and least variable in the winter months and highest in the summer months, with higher levels also found in spring and fall (Fig. 14). During the months of highest chlrophyll-a abundance (March-October), Region 1 had the lowest average chlorophyll-a levels of the four Regions of the Bay in four of the months, while Region 4 had the lowest levels in three of the months. The Region with the highest chlorophyll-a levels changed among seasons (Fig. 14). In the spring months, Region 3 (West Arm) had the greatest concentrations of chlorophyll-a followed by Region 4 (East Arm) and Region 2 (central Bay); however, there was a relatively large amount of variability in chlorophyll-a levels within these Regions (Fig. 14). In the summer, Region 2 had substantially greater average concentration of chlorophyll-a, with similar levels of chlorophyll-a between Regions 1, 3 and 4 (Fig. 14). During fall months, Regions 2 and 3 had similar levels of chlorophyll-a that were substantially higher than Regions 4 and 1 (Fig. 14).

Overall, the amount of variation in chlorophyll-a concentration explained by the measured physical factors was highly variable among Regions within each season, as well as among seasons, with values ranging from R^2=0.08 (summer Region 1) to R^2=0.79 (fall Region 4)(Table 6). For winter months, the physical variables did not significantly describe patterns of chlorophyll-a, while the amount of explained variation was generally lower in summer compared to spring and fall (Table 6). Of the 12 cases for the spring, summer, and fall seasons, 8 cases had highly significant models ($p<0.001$) that describe the chlorophyll-a data (Table 6).

In general, euphotic depth had the most consistent significant contribution to chlorophyll-a levels across seasons and Regions compared with the other measured physical variables (Table 6). Nevertheless, the direction of influence of euphotic depth varied between seasons and Regions, with a negative influence on chlorophyll-a density

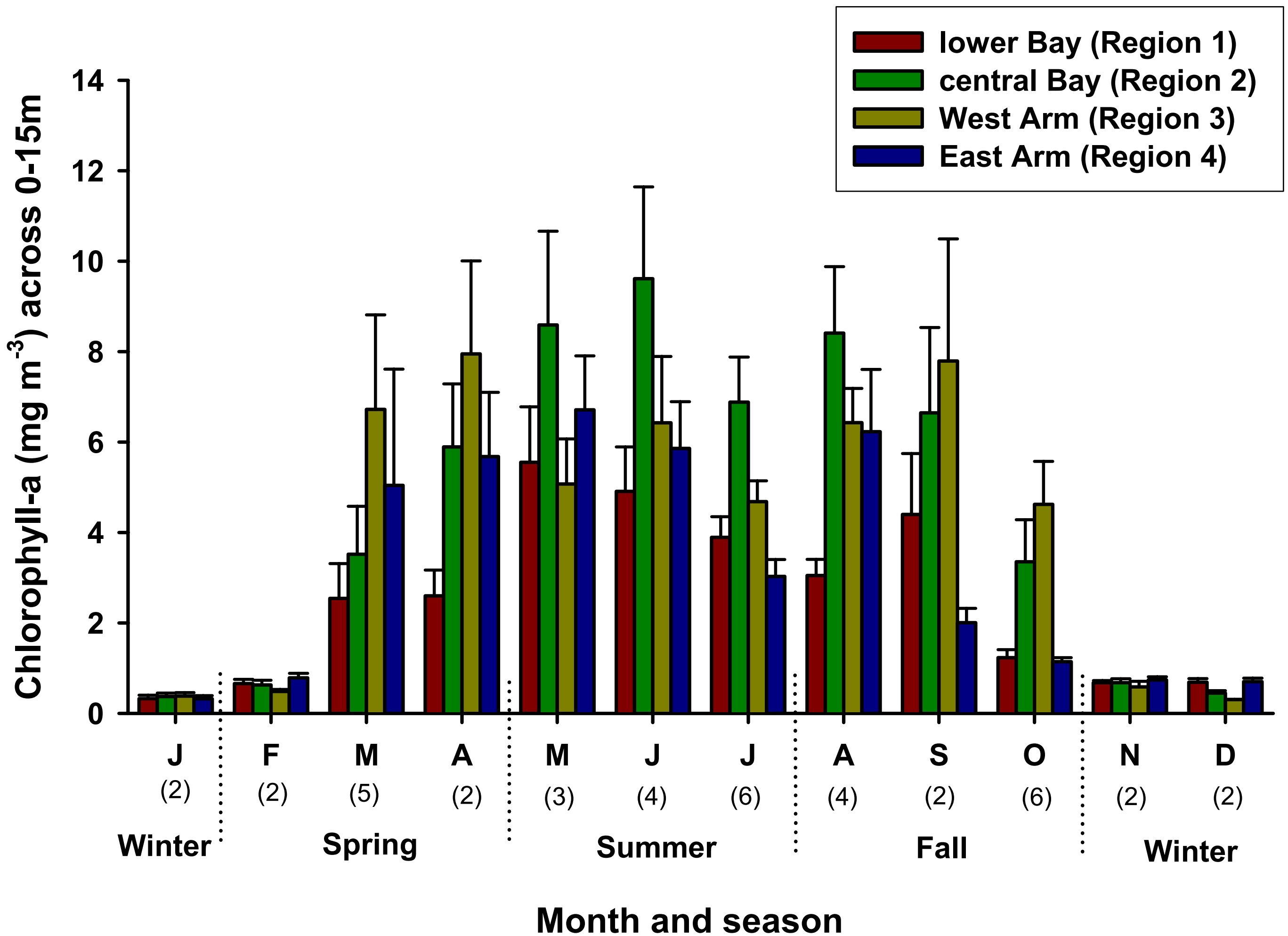

Figure 14. Chlorophyll-a patterns as a function of month and Region. Values represent means (+ standard error) of chlorophyll-a concentration averaged over the top 15 m of the water column from all casts and averaged across each month for each Region. Season definitions used in analyses are illustrated. The number of years for which chlorophyll-a data were obtained is indicated in parentheses below each month; numerous casts were taken within each Region during each sampling trip.

Table 6. Best-fit multiple regression models describing the relationship between physical variables and the mean concentration of chlorophyll-a for surface waters 0-15 m for each Region x season combination. Region 1 (lower Bay)=stations 0, 1, 2, 3; Region 2 (central Bay)=stations 4,5,6,13,14,15; Region 3 (West Arm)= stations 7, 8, 9, 10, 11, 12, 21, 22, 23; Region 4 (East Arm)=stations 16, 17, 18, 19, 20. Spring = Feb., March, April; summer = May, June, July; fall = Aug., Sept., Oct.; winter = Nov., Dec., Jan. Coefficients represent standardized variables (see text) so that the magnitude of parameters of directly comparable. Parameter estimates are positive, except where noted as "-". Empty cells indicate that a particular independent variable was not included in the best fit model.

Chlorophyll-a 0-15 m

	Model fit	Day length	Euphotic depth	Stratification	Quadratic stratification
Spring					
Region 1	$R^2 = 0.16$**	0.82**			
Region 2	$R^2 = 0.66$***	0.71 (ns)	- 0.96***		
Region 3	$R^2 = 0.71$***		- 0.98***	12.29**	- 82.31*
Region 4	$R^2 = 0.43$***		- 1.08***		
Summer					
Region 1	$R^2 = 0.08$*		- 0.43*		
Region 2	$R^2 = 0.18$**		- 0.52**		
Region 3	$R^2 = 0.09$*		0.34*		
Region 4	$R^2 = 0.50$***	2.11**		- 0.57***	
Fall					
Region 1	$R^2 = 0.52$***	0.66***	0.58**	0.51**	
Region 2	$R^2 = 0.28$***	0.97***			
Region 3	$R^2 = 0.28$***			1.62***	- 1.11*
Region 4	$R^2 = 0.79$***	1.47***	0.22 (ns)	1.02**	- 0.94***
Winter					
Region 1	No models fit the data				
Region 2	No models fit the data				
Region 3	No models fit the data				
Region 4	No models fit the data				

(ns) $0.05 > p < 0.10$ * $p < 0.05$ ** $p < 0.01$ *** $p < 0.001$

at Regions 2, 3, and 4 in spring and Regions 1 and 2 in summer months, and a contrasting positive influence for Region 3 in summer and Regions 1 and 4 in the fall (Table 6). Day length also contributed significantly to the amount of chlorophyll-a, exhibiting the most influence in the fall season (Table 6). The degree of surface water stratification demonstrated some influence on chlorophyll-a levels in spring (Region 3) and summer (Region 4), but was most influential in the fall, having a positive influence on chlorophyll-a concentration (Table 6). The quadratic term of stratification had a significant effect on chlorophyll-a levels only at Regions 3 and 4 in the spring and fall (Table 6).

Discussion

Patterns of change in Glacier Bay's oceanographic conditions

Over the ten years (1993-2002) that were sampled, the largest changes in Glacier Bay's physical oceanographic system occurred from May-October. May represents a period of initial late spring/early summer change in southeast Alaska, with a large increase in freshwater runoff due to snow-melt (Royer 1982). Oceanographic changes in May associated with this increased freshwater discharge were a decrease in salinity, increase in temperature, increase in stratification, and decrease in euphotic depth. July and August mark the mid-point of change, leading to reversal of these parameters until October, after which conditions became more similar (both among Regions and among months) from November through April.

The overall changes in salinity, temperature, and stratification did not coincide with changes in chlorophyll-a abundance within Glacier Bay. A similar discontinuity of physical oceanographic characteristics and phytoplankton population abundance has been demonstrated within Auke Bay, AK (Ziemann et al. 1990). In Glacier Bay, average chlorophyll-a concentrations demonstrated a large increase earlier than the substantial changes in physical oceanographic characteristics, dramatically increasing in March rather than May. Chlorophyll-a levels generally increased until June, thereafter gradually decreasing into October, except for a drop in chlorophyll-a concentrations in July followed by an increase in August. During November through February, there were fairly homogeneous low levels of chlorophyll-a among months and Regions of Glacier Bay.

Within Glacier Bay surface waters, the upper fjord Regions (3 and 4) were the areas of greatest change over the course of the year for all measured physical oceanographic factors (salinity, stratification, euphotic depth, turbidity) except for water temperature, which exhibited a greater range of values within the lower and central Bay areas (Regions 1 and 2) than the upper Bay. These regional patterns were most likely due to the stronger influence of freshwater discharge on the upper portions of the Bay. Within the Regions of greatest change, there was increased explanatory power of the measured physical factors in describing the oceanographic parameters, most likely due to the wider contrast in the data.

Freshwater discharge and its influence on Glacier Bay's oceanographic system

Freshwater discharge can play a large role in estuarine systems since it modifies the physical environment through its influence on water column stability and flow dynamics, as well as introduces suspended and dissolved materials (including sediment and nutrients) into the system, drastically altering water column properties and biological activity (Smetacek 1986). In addition to precipitation, stream runoff, and the addition of snow to the water surface, sources of freshwater in glacially fed fjords can also include melting of tidewater glaciers below the surface and melting of icebergs and sea-ice at the surface (Cowan 1992). Since measurements of rates of freshwater discharge are often hard to obtain in remote locations such as Alaska, other external factors, such as air temperature, amount of daylight, and precipitation can be used as a proxy for expected rates of freshwater discharge.

Across all Regions, the seasonal patterns of salinity appear to have been driven largely by the seasonal signal of freshwater discharge that is characteristic of southeast Alaska (Fig. 15; Royer 1982). Freshwater discharge rates result from direct and stored precipitation and ensuing runoff. Average monthly freshwater discharge across the region is lowest in February and March due to cold temperatures and storage of precipitation, while a peak in May is a result of initial snowmelt (Fig. 15; Royer 1982, Burrell 1986). Increases in freshwater discharge throughout the summer are driven by snow and glacial melting, with an annual maximum in freshwater discharge in the fall due to maximum levels of direct precipitation (Figs. 5 and 15; Royer 1982, Burrell 1986). The temporal variation in the mechanisms determining freshwater discharge likely explains the observed strong influence of air temperature and day length on salinity patterns within Glacier Bay during spring, summer, and winter, in contrast to the larger role that precipitation played in determining surface salinity patterns in the fall.

Since stratification patterns in Glacier Bay were dominated by the influence of salinity across all seasons and Glacier Bay Regions, seasonal stratification patterns also appear to have been driven largely by the seasonal signal of freshwater discharge in southeast Alaska (Fig. 15; Royer 1982). The strong influence of freshwater runoff in determining spring stratification patterns has been established in other Alaskan estuaries as well (e.g., Prince William Sound: Vaughan et al. 2001). The large increase in average levels of stratification in May likely corresponded with the increase in freshwater discharge from initial snowmelt, while the continued high stratification levels throughout the summer and fall (May-October) were caused by even greater freshwater discharge due to snow and ice melt, and rainfall.

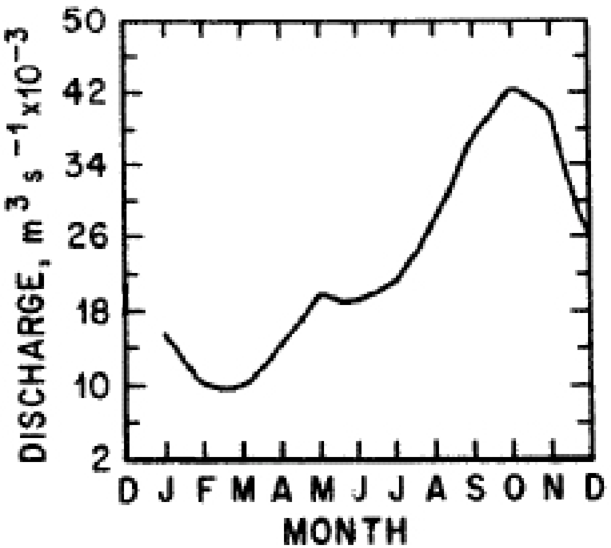

Figure 15. Seasonal pattern of freshwater discharge in southeastern Alaska (reproduced from Royer 1982). The mean monthly values for freshwater discharge do not represent direct measurements, but instead are indirect computed estimates based on mean air temperatures, precipitation, and the drainage area of the Region.

There were regional differences in salinity patterns within Glacier Bay that likely resulted from local differences in freshwater discharge. For example, surface water salinity was consistently lower within the East Arm (Region 4) than the West Arm (Region 3), suggesting that there were differences in the relative influence of direct or stored precipitation in these superficially similar upper-fjord glacial and stream-fed inlets. Alternatively, these salinity differences could have resulted from differences in circulation patterns between the two inlets (see 'Differential oceanographic patterns between East Arm and West Arm' below). The regional differences in salinity levels were mirrored by the difference in stratification patterns between Regions 3 and 4, with surface waters in Region 4 exhibiting greater water column stability than Region 3. In contrast to salinity and stratification, surface temperatures did not vary substantially between Regions 3 and 4 across all seasons.

Freshwater discharge integrates the seasonal and annual changes in atmospheric forcing and represents one of the stronger links between the terrestrial and marine systems. Our current knowledge of how freshwater discharge influences Glacier Bay's oceanographic system is taken from seasonal averages from a hydrology model that covers all of southeastern Alaska (from Cook Inlet to the southern boundary of Alaska) (Royer 1982). To examine the temporal variability in freshwater discharge, we have used measurements of air temperature, day length, and precipitation to approximate the overall role of this factor on the oceanographic system; however, our understanding would be greatly enhanced by direct measurements of freshwater input to the system at various locations within the Bay. Annual changes in the amount of coastal freshwater discharge are linked to the Pacific Decadal Oscillation (PDO) and could have a major influence on biological production in the Northeast Pacific Ocean (Royer et al. 2001). Understanding the dynamics of freshwater discharge in Glacier Bay (an area of fast glacial retreat and thus high freshwater input) would aid in our understanding of the connectivity of Glacier Bay to the Gulf of Alaska ecosystem.

Role of tidal energy in Glacier Bay's oceanographic system

Overall, our results suggest that tidal factors played a relatively small role in determining stability of surface waters within Glacier Bay. Only in fall did the strength of the tide (high tide height) have an influence on stratification levels, while only in spring did the temporal variations in the tidal regime (time to low tide, tidal stage) influence stratification. Bisagni (2000) demonstrated that tides generally play an insignificant role in determining stratification on southern Georges Banks except during spring, when transient stratification is associated with reduced tidal stirring during periods of neap tide. The stronger influence of tides on stratification in spring and fall within Glacier Bay may represent the role of tidal currents in hindering transient stratification events. In contrast, stratification during the summer was relatively constant throughout most of Glacier Bay and tides did not have much influence on water column stability, which was likely largely maintained by high freshwater discharge. Additionally, tides had an overall larger influence on surface water characteristics within Regions 3 and 4 than Regions 1 and 2. This pattern agrees with the larger tidal range within the upper Bay compared with the lower Bay.

Role of winds in Glacier Bay's oceanographic system

In general, results of our analyses suggest that winds were not highly influential in determining the stability of surface waters within Glacier Bay. The decreased influence of winds could be due to strong stratification from high freshwater discharge in most of the Bay throughout much of the year, creating water layers that resist wind-induced mixing. Winds did have a localized negative influence on stratification levels within Region 1 in spring and Region 2 in summer - locations and time periods that are less influenced by freshwater discharge and exhibited lower overall stratification patterns. Alternatively, our results could reflect the potential mismatch between the scales of the wind measurements and the oceanographic measurements. It is possible that winds influence surface water characteristics on shorter time scales, causing destabilization of the water column one day and stratification again the next (Wroblewski and Richman 1987). Through the spatial (two regional stations) and temporal (monthly) averaging of the wind data we may not be able to detect the smaller-scale effects of wind on oceanographic parameters.

In many estuarine systems, the spring phytoplankton bloom is thought to be initiated by the cessation of winds, causing the mixed layer to shallow; this shallowing coupled with increased solar insolation leads to stratification that retains phytoplankton within surface waters (Mann and Lazier 1996). Oceanographic data from Glacier Bay suggest that a mixed layer does not develop in early spring surface waters (L. Etherington unpubl. data), and average monthly weather data do not demonstrate decreased winds during the spring season. In other parts of southeastern Alaska, a mixed layer does not generally form in spring (e.g., Auke Bay, AK, Ziemann et al. 1991), and factors other than winds are influential in the initiation of the spring bloom in these cases (see 'Chlorophyll-a patterns' below; Ziemann et al. 1991).

In contrast to the effect of winds on surface water stratification, wind speed played a substantial role in determining euphotic depth patterns during spring and fall. Within Regions 1, 2, and 3 in spring and Regions 2 and 3 in fall, an increase in wind speed led to an increase (deepening) of the euphotic depth. It is possible that strong winds during these periods were mixing phytoplankton and suspended sediment out of the uppermost layers of the water column where they could be shadowing the lower layers.

Spatial patterns of stratification

Spatial patterns of stratification within an estuarine system could indicate potential locations of fronts (e.g., Perry et al. 1983), which represent the boundary between two water masses. Frontal regions are often associated with higher biological activity, including aggregations of phytoplankton, zooplankton, forage fish, and marine birds and mammals (Largier 1993). Downwelling of water masses at fronts are often apparent, which could directly transfer pelagic nutrients and biological biomass to the benthic system (Largier 1993). Additionally, fronts may act a barrier for larval dispersion or as conduits transporting larvae along the axis of the front (Eggleston et al. 1998), therefore determining settlement and subsequent recruitment patterns of fish and invertebrates with complex life histories. Thus, fronts can act to influence the spatial structure of both the pelagic and benthic communities.

In Glacier Bay, spatial patterns of stratification suggest several zones where fronts may exist. For example, the influence of the high tidal energy at the mouth of Glacier Bay and Sitakaday Narrows was emphasized in the pattern of stratification by station (Fig. 16). Stations 1 and 2 exhibited the lowest stratification levels of all stations within Glacier Bay, demonstrating that surface waters within this area of the Bay are well-mixed due to the shallow sill depth and narrowing of the Bay (Fig. 2; Hooge and Hooge 2002). A substantial increase in stratification was demonstrated between stations 2 and 3, as well as between 2 and 4, supporting the notion that a front resulting from the juxtaposition of two different water masses (well-mixed lower Bay versus more stratified central Bay) likely exists in this area of the Bay (Hooge and Hooge 2002). The relative position of the front in this area may move laterally towards the head or mouth of the Bay, depending on the strength of the tide (spring-neap tide tidal cycle; Pingree et al. 1975, Parsons et al. 1983, Mann and Lazier 1996). Another noticeable increase in stratification between adjacent stations occurred between stations 13 and 14 and the rest of the East Arm (Fig. 16), and suggests that a front could also exist in this area due to tidal turbulence with increased mixing over this shallow sill situated next to a deeper, well-stratified basin (Fig. 2). There also appears to have been a substantial increase in stratification between stations 6 and 7, possibly indicating the position of yet another front (Fig. 16). Although there is not a shallow sill in this area, there is a narrow contraction in the West Arm at this location that could cause higher turbulence and mixing near station 6 and more stratified conditions beyond the contraction near station 7 (Fig. 2). A contraction and sill at the mouth of Geikie Inlet coupled with adjoining highly stratified waters inside Geikie Inlet (Fig. 16) suggest that a frontal boundary may also exist in the lower reaches of

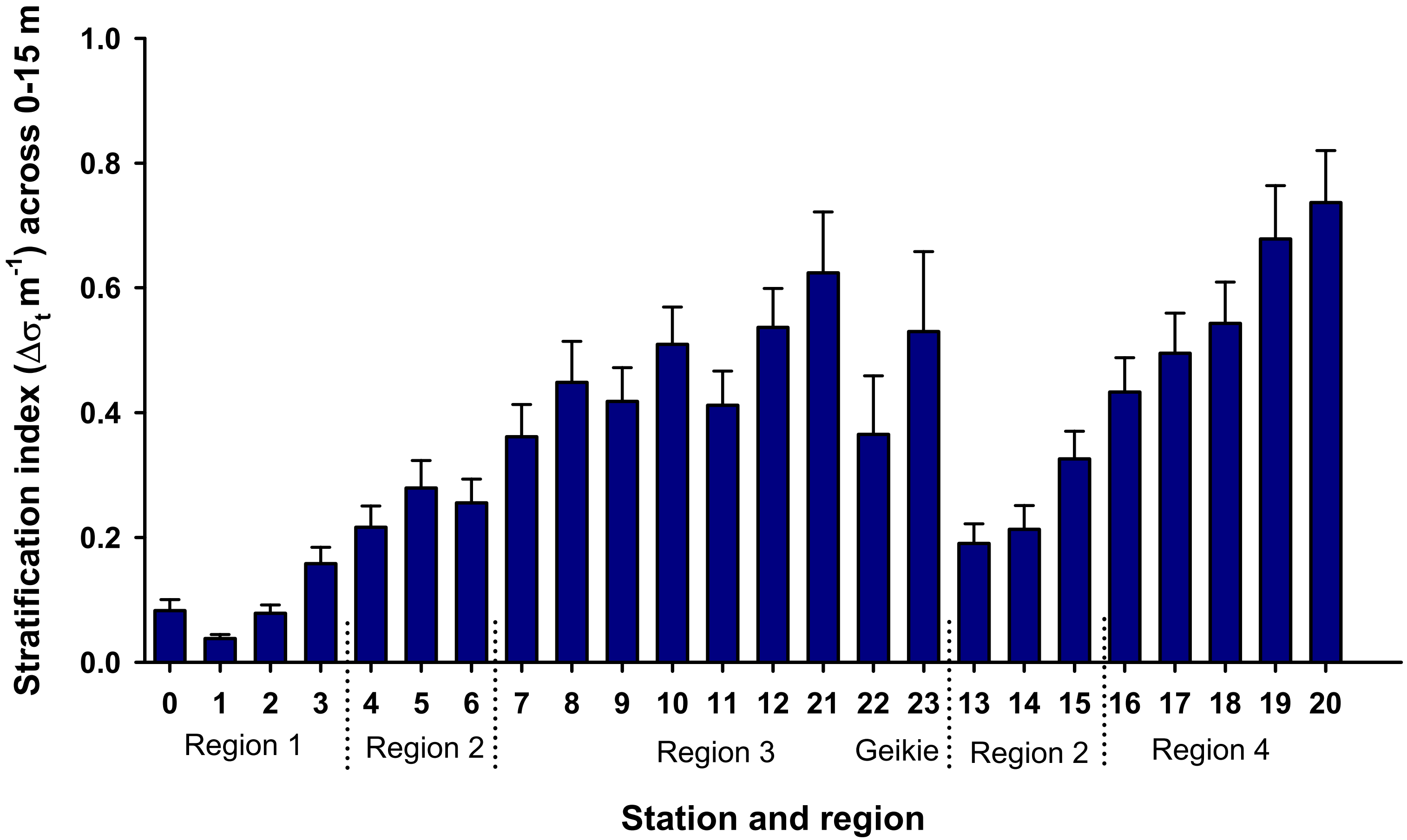

Figure 16. Stratification patterns by station within Glacier Bay. Values represent means (+ standard error) of stratification from all casts and averaged across each station. The stratification index for each cast represents the mean of the density differences from adjoining 1-m depth bins for the top 15 m of the water column. Regions (as defined for analyses) are indicated below the station numbers. 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.

Geikie Inlet. All of these locations with potential fronts were associated with the highest levels of chlorophyll-a in the mid-channel areas of Glacier Bay and exhibited increases from nearby stations. Further work focused on determining the existence and characteristics of these potential frontal zones could provide vital information on many of the biological processes within Glacier Bay, including the spatial aggregation of biological biomass, the behavioral responses of predators and prey, the dispersal and settlement of planktonic larvae, the transfer of pelagic material to the benthic system, and potential mechanisms influencing high phytoplankton abundance.

Chlorophyll-a patterns

<u>Spring bloom</u>

A central objective in biological oceanographic research is to determine the factors influencing the timing and overall magnitude of the spring phytoplankton bloom. It is hypothesized that the onset of the spring bloom is generally the result of 1) favorable light conditions (threshold of radiation) and 2) stabilization of the water column that confines phytoplankton to surface waters where available light can be utilized in photosynthesis (Sverdrup 1953, Mann and Lazier 1996). Thus, in Glacier Bay we might expect an increase in chlorophyll-a concentration during May, when the degree of stratification within the Bay increased dramatically, changing the surface water characteristics from unstable to stable. Instead, we have demonstrated that seasonal patterns of chlorophyll-a abundance did not coincide with patterns of water column stability, since chlorophyll-a concentrations dramatically increased two months earlier than did the stratification index. One explanation for the temporal dissimilarity in chlorophyll-a and water column stability is that the spring bloom was initiated by transient stratification events that did not persist, and therefore, were not detected by the time scale of our oceanographic sampling. Alternatively, it is possible that solar radiation in March reaches a threshold whereby photosynthesis rates dramatically increased, regardless of surface stratification. Other studies in other high latitude fjord systems have also demonstrated that incident light controls the initiation of spring bloom (Ziemann et al. 1991). The results of the current multiple regression analyses suggest that the amount of available sunlight (day length) might have been most influential on spring bloom dynamics within Region 1 and Region 2, while stratification played a larger role within Region 3. These spatially-explicit results agree with the notion that in areas where turbulence transports phytoplankton throughout the water column (e.g., lower reaches of Glacier Bay) and organisms are exposed to nutrients, the spring bloom can be expected to be initiated by the seasonal increase in light rather than stratification onset (Mann and Lazier 1996). Thus, the relative importance of solar radiation and water column stabilization in promoting the spring phytoplankton bloom may vary spatially within Glacier Bay. The negative influence of euphotic depth on chlorophyll-a in spring and summer suggests that the density of phytoplankton provided a negative feedback by decreasing the depth that light can penetrate, therefore limiting photosynthesis. Consequently, the effect of phytoplankton density may have played a large role in the initial spring bloom magnitude as well as summer phytoplankton abundance levels.

Temporal patterns of chlorophyll-a

Results from the current study support the hypothesis proposed by Hooge and Hooge (2002) that chlorophyll-a concentrations within Glacier Bay are sustained throughout the spring, summer, and into the fall. This relatively sustained seasonal pattern contrasts with the more typical pattern of an extreme spring peak followed by depressed levels in summer and a secondary large peak in fall, as observed in many mid-latitude systems as well as in some high latitude estuaries in southeast Alaska (Mann and Lazier 1986; Burrell 1986). Nevertheless, relatively sustained chlorophyll-a throughout the summer is characteristic of shelf-break regions and fjord systems where turbulent mixing at sills replenishes nutrients within stratified surface waters (Parsons 1986). Legendre et al. (1982) also report high levels of chlorophyll concentrations throughout the summer within an Arctic sound in Hudson Bay. Within Glacier Bay, overall levels of chlorophyll were highest in summer, with peak abundance in June. An overall decrease in chlorophyll-a concentration occurred in July, followed by higher concentrations in August and September. Interestingly, turbidity levels within Glacier Bay were highest in July, with a dramatic increase in optical backscatterance compared with June levels, particularly within the upper Bay Regions. In addition, July was the month with the highest stratification levels, so nutrients could become depleted if the stronger stability of the water column inhibits nutrients from moving into the surface waters from intermediate waters. Alternatively, summer patterns of phytoplankton may have been driven by top-down processes (see below).

Sustained higher levels of chlorophyll-a abundance throughout the summer and fall may have been caused by the promotion of stratification from high levels of freshwater discharge, and by the renewal of nutrients from deeper areas into the euphotic zone through localized tidal turbulence, entrainment-driven estuarine circulation, and wind mixing (Syvitski et al. 1987). In summer and fall in those Regions of Glacier Bay exhibiting the highest chlorophyll-a levels, physical factors explained only a small amount of the variation in chlorophyll-a. This lack of relationship suggests that there may have been variables that were not measured that were influential in determining phytoplankton abundance. One hypothesis for the poor explanatory power of the measured physical factors within the Regions of highest chlorophyll-a abundance (Regions 2 and 3) is that phytoplankton abundance was being driven by top-down biological processes (i.e., grazing pressure by zooplankton) during these time periods. This potential explanation for summer and fall chlorophyll-a patterns is in contrast to the spring pattern, when high phytoplankton levels may have been driven by bottom-up physical processes (i.e., available light, water column stability) before zooplankton had responded to the initial bloom.

Temporal patterns of zooplankon that vary between regions (Robards et al. 2003) may play a role in determining summer phytoplankton patterns within Glacier Bay. Robards et al. (2003) demonstrated that the peak of zooplankton within the main Bay (similar to Region 2 in the present study) occurred in May (however, samples were not collected in April) and then decreased over the remainder of the summer season, while zooplankton abundance within the East and West Arms (similar to Regions 3 and 4 in the present study) increased from spring to summer, with highest abundance in July and then a drop in August. Zooplankton abundances in the East and West Arms were very similar, with densities approximately four times greater than densities in the main Bay or Icy

Strait region (Robards et al. 2003). During general time periods when zooplankton abundance was high within the East and West Arms and relatively low in the main Bay (June-August) (Robards et al. 2003), we have demonstrated that chlorophyll-a levels were higher within the central Bay Region compared with the East and West Arms (Regions 3 and 4). These correlations suggest that summer patterns of chlorophyll-a density could have been strongly influenced by zooplankton grazing rates. The potential relationship between the patterns of chlorophyll-a and zooplankton abundance should be viewed with caution, as the spatial and temporal sampling of zooplankton was fairly coarse, and the sampling only covered 5 months of one year. Further work is needed to separate the influence of bottom-up versus top-down forces influencing phytoplankton abundance, as well as how these patterns may change throughout the year as well as throughout Glacier Bay.

Spatial patterns of chlorophyll-a

The monthly averages of chlorophyll-a levels demonstrate that either Region 2 or Region 3 had the highest abundance of chlorophyll-a during all months from March through October. Closer examination of chlorophyll-a levels by station indicates that the highest abundance was generally found within the central Bay (except stations 14 and 15, which exhibited slightly lower levels) and the lower reaches of both the East and West Arms (Fig. 17). The overall highest levels of chlorophyll-a were found within Geikie Inlet, particularly at the mouth of Geikie where it joins the main trunk of the Bay (station 22). On a cautionary note, the two stations within Geikie Inlet (22 and 23) have only recently been added to our oceanographic sampling scheme (first sampled June 1999). It is

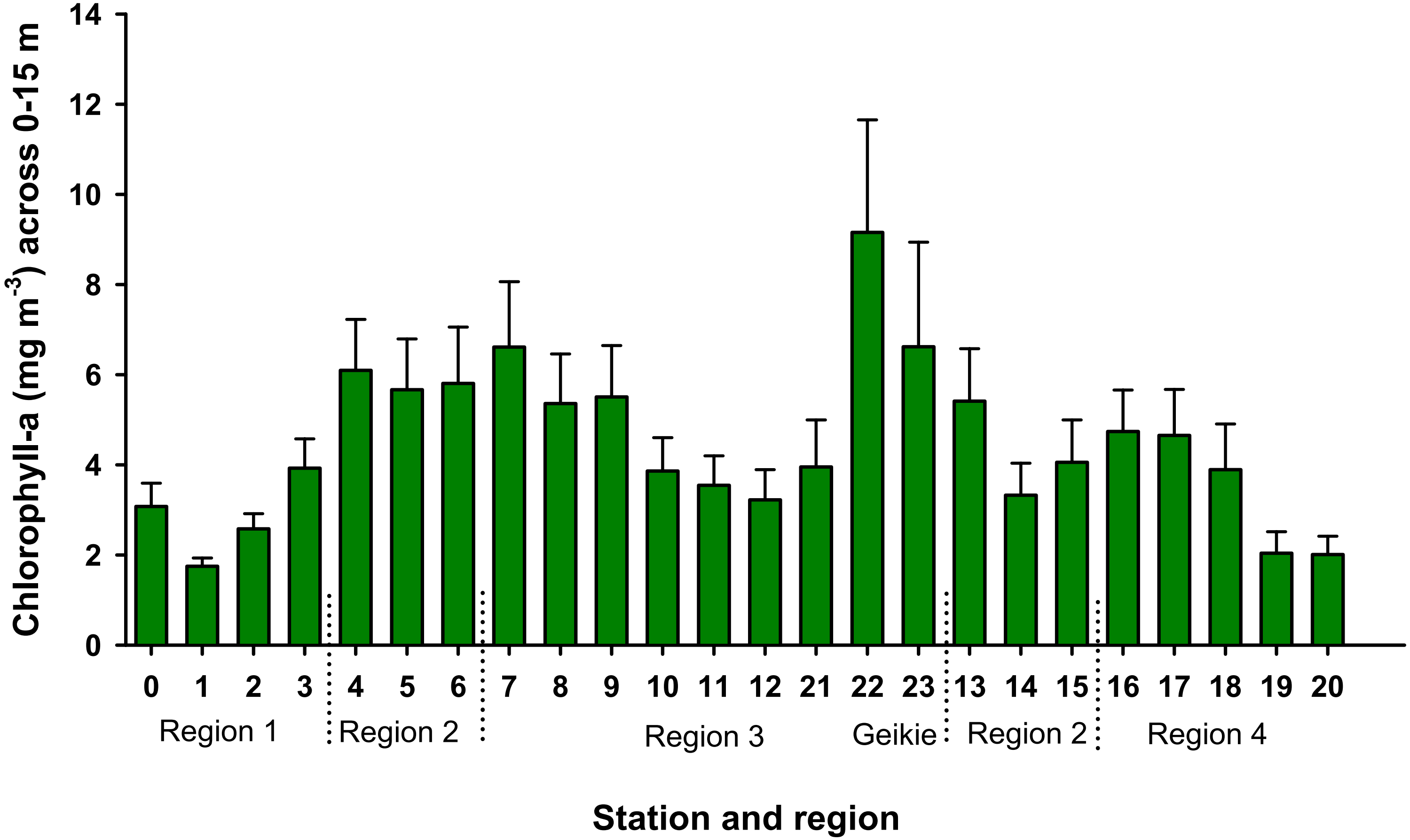

Figure 17. Chlorophyll-a patterns by station within Glacier Bay. Values represent means (+ standard error) of chlorophyll-a concentration averaged over the top 15 m of the water column from all casts and averaged by station. Regions (as defined for analyses) are indicated below the station numbers. Stations 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.

possible that conditions may have been different in the most recent years, compared with average patterns over ten years. 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. Nevertheless, high chlorophyll-a abundance within Geikie Inlet as well as the central Bay and the lower reaches of the East and West arms raises questions regarding the mechanisms causing these spatial patterns.

Several factors may be responsible for the spatial patterns of chlorophyll-a. It appears that conditions within the lower Bay Region may be too turbulent for phytoplankton to remain within surface waters where sufficient light is available for photosynthesis, as illustrated by the lower levels of stratification in this Region throughout the year (present study) and moderate chlorophyll-a levels throughout the water column (Hooge and Hooge 2002). Within Regions 3 and 4 (West and East Arms), highest chlorophyll-a levels were found at intermediate stratification levels (indicated by the negative quadratic term for stratification), and highest stratification levels were associated with low chlorophyll-a abundance. This relationship could be caused by the water column becoming too stabilized for nutrients to be regenerated to surface waters leading to nutrient depletion. Similarly, the Region with the highest chlorophyll-a abundance changed, with Region 3 (West Arm) highest in the late spring and late fall, and Region 2 (central Bay) containing the highest concentrations during summer. In the summer and early fall, stratification levels increased dramatically for Region 3, while the increase in stratification for Region 2 was not as great. It is possible then, that phytoplankton abundance was highest within the central Bay Region (Region 2) during summer because the water column here exhibited intermediate levels of stratification.

Similar spatial patterns of phytoplankton abundance have been observed in an Arctic sound system where lowest chlorophyll was found at the extremes of highest and lowest salinities that were related to lowest and highest water column stability, respectively, and highest chlorophyll abundance was detected at intermediate salinities (Legendre et al. 1982).

The decreased levels of chlorophyll-a in the upper parts of the West and East Arms could also be due to the flushing of surface waters from north to south due to high freshwater discharge and the less dense surface layer moving seaward. Horizontal advection due to freshwater discharge has been demonstrated as a highly influential factor driving phytoplankton distribution in surface waters of other estuarine systems (Stockner et al. 1979). Alternatively, high turbidity levels associated with high stratification levels (both due to high freshwater discharge) could be directly decreasing phytoplankton abundance by causing increased settling rates due to flocculation with sediment particles (Cowan 1995) or indirectly decreasing abundance through decreased light levels.

Overall, higher abundance of phytoplankton within the central Bay and the lower portions of the West and East Arms were likely due to the optimal conditions of moderate stratification (Fig. 16), higher light levels (due to decreased sediment concentrations in the surface waters), regenerated surface nutrients, and potentially lower zooplankton abundance. Further studies are needed to describe the spatial and temporal dynamics of nutrient levels and zooplankton abundance to understand their role in influencing the observed spatial patterns of chlorophyll a.

Differential oceanographic patterns between East Arm and West Arm

Despite the similar topographic characteristics of the East and West Arms of Glacier Bay (e.g., orientation relative to marine waters, proximity to tidewater glaciers), there were substantial differences in oceanographic characteristics between these two Regions. For example, the surface waters of the East Arm (Region 4) were much fresher, but not much colder, than those within the West Arm (Region 3), and the East Arm generally exhibited increased stratification and decreased euphotic depth compared to the West Arm. Additionally, the East Arm generally had lower chlorophyll-a concentrations in surface waters than did the West Arm. Patterns of turbidity varied between seasons, with summer turbidity levels higher in the West Arm than the East Arm and the reverse true in the fall. It is possible that summer optical backscatterance levels were driven by sediment derived from glacial melting, while fall turbidity was most influenced by sediment delivered by run-off due to higher rainfall during this season. Associated with high turbidity levels in Region 4 during the fall (particularly September and October) were decreased levels of chlorophyll-a, compared to higher concentrations of chlorophyll-a within Region 3 during these months.

The differences in the physical and biological oceanographic characteristics between the West and East Arms were likely influenced by the sill heights at the entrances to these inlets. The sill at the entrance of the West Arm is 240 m deep, while the East Arm has multiple sills, with the shallowest at 60 m depth (Hooge and Hooge 2002). The shallower sill at the entrance of the East Arm appears to restrict some movement of more saline water from the central part of the Bay to the East Arm (Hooge and Hooge 2002). Less entrainment of more saline waters into the fresher surface layers of the East Arm would lead to lower salinity levels and resulting increased stratification within this Region. Air temperature and precipitation data recently collected throughout Glacier Bay may shed some light on potential weather differences between the East and West Arm regions (D. Lawson, Cold Regions Research and Engineering Lab, Fort Richardson, AK, unpubl. data). Alternatively, differences in the surface water oceanographic properties between the East and West Arms may be a result of differences in the amount of stored precipitation or surface area of the Inlets between the Regions. The differences in the oceanographic characteristics between the East and West Arm provide some probable causes for differences in biological patterns between these areas, such as in the fish community composition (Robards et al. 2003).

Conclusions

The results of this study demonstrate that over the ten years sampled (1993-2002) there was a large amount of variation in surface water oceanographic conditions in Glacier Bay both seasonally and regionally. Extracting this regional and seasonal variation provides the first necessary step in elucidating interannual variability in the Glacier Bay oceanographic system. The results of this study confirm that patterns of phytoplankton abundance in Glacier Bay are sustained throughout the spring, summer, and fall, suggesting a highly productive system that fuels an abundance of higher trophic levels within this estuarine system. In general, chlorophyll-a abundance could be adequately explained by light levels and stratification in spring and fall, whereas during the summer, the measured physical properties did not explain much of the variation in chlorophyll-a. Overall, after accounting for seasonal and regional variation, the measured external factors explained a large amount of variation in the physical properties of the surface waters. Identifying particular cases where good model fits were not obtained highlights where we are lacking information on factors that have a substantial influence on oceanographic patterns, and suggests topics of future research.

Glacier Bay is a unique estuarine system with strong competing forces influencing water column stability. High levels of freshwater discharge from glacial melt and rainfall promote stratification, while strong tidal currents over shallow sills enhance vertical mixing. Where these two processes meet in the central deep basins there are optimal surface conditions of intermediate stratification, higher light levels, and potential nutrient renewal. These conditions can explain the high and sustained chlorophyll-a levels observed in particular regions of the Bay. Patterns of chlorophyll-a could account for observed patterns of abundance of higher trophic levels within this highly productive fjord estuarine system.

It appears that the greatest degree of change (both seasonally and spatially) in oceanographic properties within Glacier Bay is driven by freshwater input. Rates of freshwater input to the estuarine system are influenced by air temperature and precipitation. Changes in the magnitude or pattern of freshwater discharge could change circulation and stratification patterns within Glacier Bay, which could lead to changes in primary productivity as well as animal distribution and abundance. Understanding how the oceanographic properties of Glacier Bay are influenced by external weather factors and how this varies with different regions and seasons provides crucial information on how this marine ecosystem potentially responds to changes in climate regimes such as the Pacific Decadal Oscillation and larger scale global warming.

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Appendices

Appendix 1. OBS sensor sediment calibrations.

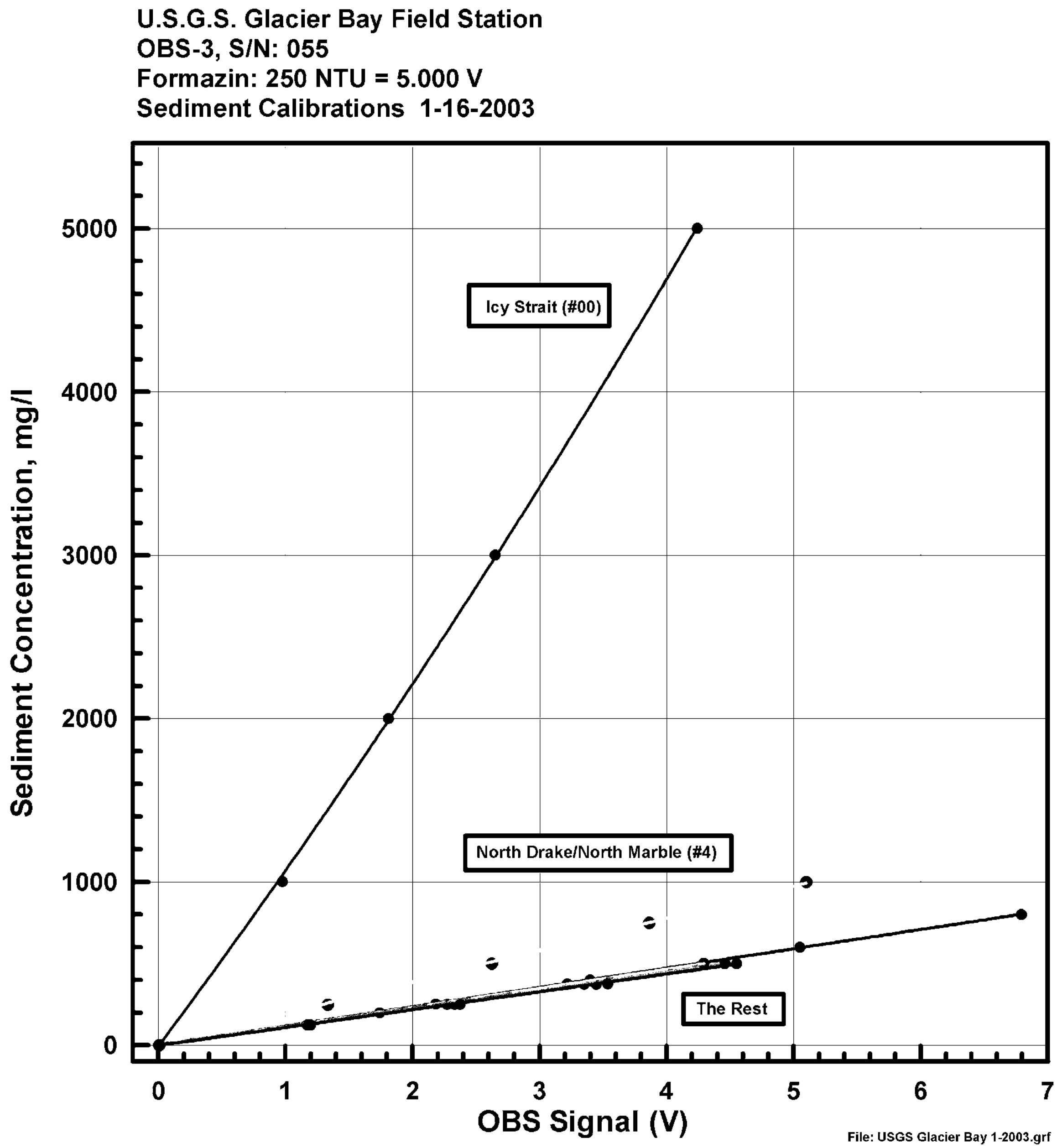
Data from the optical backscatterance (OBS) sensor are collected as raw voltage. These values allow relative comparison of turbidity measurements, but do not provide true sediment concentration values. Previous to this report, all turbidity measurements collected as part of the Glacier Bay oceanographic monitoring program were presented in volts or NTU's (nephelometric turbidity units; relative measurements). In 2002, sediment samples were collected from various locations in Glacier Bay to allow for the calibration of the OBS meters to determine the concentration of sediment particles within the water column. The turbidity values presented in this report represent our first comprehensive understanding of sediment concentration levels for Glacier Bay waters. The following describes the process by which these sensors were calibrated.

Since the relationship between the intensity of the backscatterance signal and sediment concentration is dependent upon the size and color of sediment grains, OBS sensors must be calibrated with representative sediment from the location of sampling. For the purposes of calibrating the OBS sensor, we assumed that the sediment on the uppermost surface of the seafloor of Glacier Bay is representative of the sediment within the water column. In July of 2002, we collected benthic sediment samples using a Shipek sediment sampler from as many of the oceanographic stations as was logistically possible. From this set of samples, we chose locations within Glacier Bay where we expected to see the greatest difference in grain size, and thus, a difference in the relationship between OBS sensor signal and sediment concentration. These locations included stations 0, 4, 7, 10, 17, and 22. These sediment samples were then analyzed by D&A Instrument Company (Port Townsend, WA) for one of our OBS sensors.

The relationships between OBS signal and sediment concentration fell out into three groups (Fig. A1). The relationships were almost identical for stations 7, 10, 17, and 22 (Fig. A1). These stations represent the lower and upper reaches of the West Arm, a station mid-way up the East Arm and the mouth of Geikie Inlet. The slope of the line for station 4 (central Bay) was only slightly different than that for the above group of stations, while that for station 0 (Icy Strait) was dramatically different than all other stations (Fig. A1). We have concluded that the station 0 relationship is so different than the others due to the high tidal currents found in this region, which would provide the energy to keep smaller sediment particles up in suspension in the water column, rather than being deposited on the seabed. Therefore, we are assuming that at station 0 the larger particles that were collected in the benthic sediment grab are not representative of sediment particles that are in the water column. Since tidal currents are strong throughout the lower Bay region, we have concluded that the differences between station 4 and the rest of the samples further up-Bay are also due to higher currents keeping smaller particles in suspension and leaving larger particles on the seafloor. Since the main sources of sediment for Glacier Bay are within the upper reaches of the Bay, we are assuming the sediment in the water column in the lower Bay is similar in composition to the benthic samples collected further up-Bay.

Overall, we feel that the parameters derived from one of our oceanographic stations can adequately describe the relationships for all of our mid-channel oceanographic stations within Glacier Bay. Based on the sediment calibration equations derived from D&A Instruments, we have decided to use the parameters from station #11 (Tarr Inlet) to convert voltage to sediment concentration (mg L^{-1}), since these parameters were closest to the mean parameter values for the group of stations including 7, 10, 17 and 22. Each of the OBS sensors was calibrated separately; therefore there are two separate sets of parameters to convert voltage readings to sediment concentration (Figs. A1 and A2). These equations using parameters derived from sediment from station #11 have been added to an updated version of the oceanographic monitoring handbook (Hooge et al. 2000).

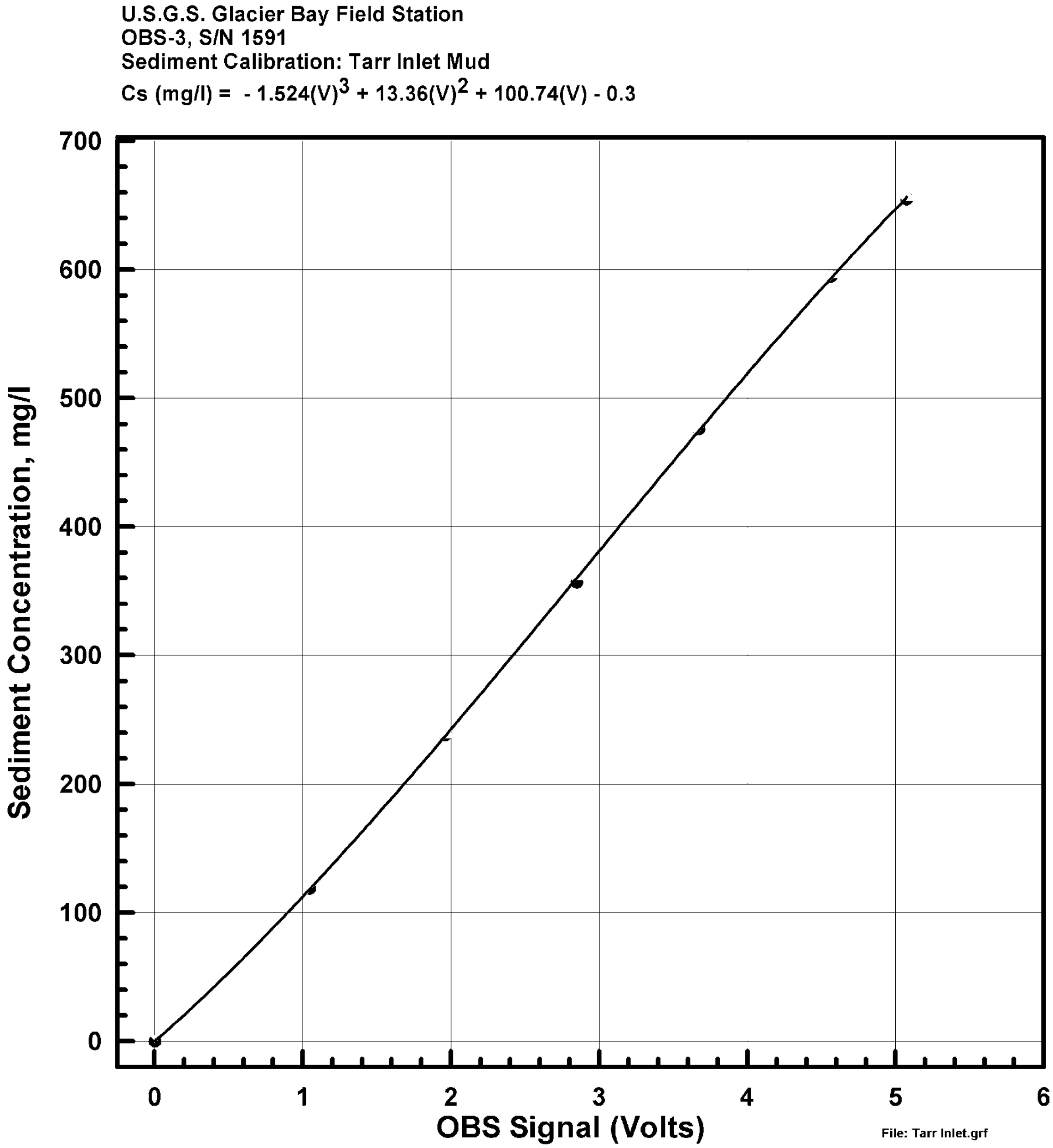
Figure A1



Cs (mg/l) = $A(V)^2 + B(V) + C$

Sediment sample	A	B	C
station **#4**	0	194.968	-1.54
station **#7**	0	118.295	-0.76
station **#10**	0	109.201	-0.80
station **#11**	0	111.945	-0.82
station **#17**	0	116.625	-1.00
station **#22**	0	109.678	-1.05
station **#0**	0	1042.084	-6.07

Figure A2


U.S.G.S. Glacier Bay Field Station
OBS-3, S/N 1591
Sediment Calibration: Tarr Inlet Mud
Cs (mg/l) = - 1.524(V)3 + 13.36(V)2 + 100.74(V) - 0.3
700
600
500
400
300
200
100
0
Sediment Concentration, mg/l
0
1
2
3
4
5
6
OBS Signal (Volts)
File: Tarr Inlet.grf

Appendix 2. Suggestions for future oceanographic sampling to analyze interannual variations.

The original focus of the analysis effort for this report was to examine year-to-year variation in oceanographic parameters within the Glacier Bay system. After close examination of the Glacier Bay oceanographic data set from 1993-2002, we decided that these interannual analyses were not feasible at the present time, and that alternative analyses would be much more productive in our quest to understand the Glacier Bay oceanographic system. Therefore, we decided to conduct a comprehensive and quantitative analysis of seasonal and spatial differences in oceanographic parameters within Glacier Bay. A large amount of variation was detected seasonally and regionally, which could have swamped any signal of interannual differences. Thus, the results obtained in the current study represent the first necessary step in elucidating interannual variability in the Glacier Bay oceanographic system.

In addition to the primary need to thoroughly define seasonal and regional oceanographic variance, there were other reasons for not analyzing interannual patterns. Primarily, the inconsistency in the sampling time from one year to the next, as well as sensor malfunction that removed some available data, made it infeasible to directly examine year-to-year differences. We tried grouping sampling trips into seasons and then looking at differences between years, but again, the timing within the season one year versus the next appeared to make a big difference and could drive the year-to-year differences. Therefore, we felt that it would best at this stage in our understanding of the oceanographic system to use all of the data to more specifically illustrate differences in oceanographic patterns between seasons and regions and to determine quantitatively what is driving variability in these parameters. We feel that these multiple regression analyses are a powerful approach to determine what variables are most important in determining oceanographic patterns as well as how these factors change between seasons and regions.

At this time, we feel that future analyses to examine interannual patterns would be possible for specific months where sufficient data are available. Months that are important in terms of physical and biological processes and that also contain multiple years of data include March, July, and October (Table 1). We would also suggest that a concerted effort be made to sample the same months more consistently in the future. Our suggestion would be to at minimum collect a spring sample in March, a summer sample in July, a fall sample in October and a winter sample in December or January (there is much less variation in oceanographic parameters in the winter; therefore, we feel that either month can adequately represent winter conditions). An additional sample during the summer period in either June or August would also provide beneficial data.