Physical and Biological Oceanographic Patterns in Glacier Bay

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Abstract. As part of a monitoring program, oceanographic sampling has been conducted at 23 stations within Glacier Bay from 1993-2002. Seasonal patterns of salinity, temperature, stratification, turbidity, and euphotic depth are related to seasonal patterns of modeled freshwater input for southeast Alaska. Spatial patterns of chlorophyll-*a* abundance vary throughout the season and are influenced by stratification levels and euphotic depth. High levels of freshwater discharge from upper Bay regions promote stratification from spring through fall, while strong tidal currents over shallow sills enhance mixing. Where these processes meet in the central Bay, there are optimal conditions of intermediate stratification, higher light levels, and potential nutrient renewal. These conditions may explain observed high and sustained chlorophyll-*a* levels, and provide a framework for understanding abundance and distribution of higher trophic levels within Glacier Bay.

Introduction

Oceanographic conditions in high latitude glacially fed estuaries are often complex, due to high rates of freshwater input, dramatic bathymetry (shallow sills and deep basins), and high sedimentation rates. Glacier Bay is a recently (<300 yrs. ago) deglaciated fjord surrounded by mountainous terrain with many sources of freshwater, mainly from glacial discharge (including 12 tidewater glaciers). Glacier Bay's shallow sills (minimum depth = 25 m) are associated with strong currents and water column mixing, while deep basins (maximum depth = 450 m) exhibit stratification throughout much of the year. Previous work suggests that chlorophyll-*a* levels are relatively high and sustained through the summer season (Hooge and Hooge, written commun.).

This paper summarizes the results of a program to monitor oceanographic conditions at 23 stations throughout Glacier Bay from 1993–2002 (fig. 1). The objective of the current work was to quantify the seasonal and spatial patterns of physical oceanographic parameters and chlorophyll-*a* levels within Glacier Bay surface waters.

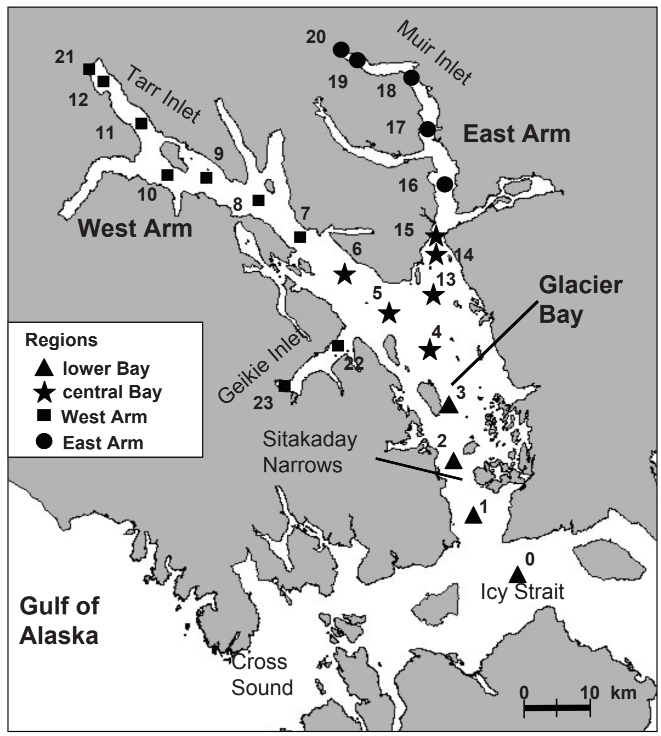

Figure 1. Glacier Bay, Alaska, and the oceanographic sampling stations. Stations were grouped into four Regions and were defined as lower Bay (stations 0, 1, 2, 3), central Bay (stations 4, 5, 6, 13, 14, 15), West Arm (stations 7, 8, 9, 10, 11, 12, 21, 22, 23), and East Arm (stations 16, 17, 18, 19, 20).

Methods

Physical and biological oceanographic samples were collected at 23 mid-channel stations spanning the axes of Glacier Bay (fig. 1). Each station was sampled approximately five times per year from 1993–2002. At each station, conductivity-temperature-depth samples were taken from the surface to the bottom of the water column (continuous record to maximum depth of 300 m). From these samples, we measured salinity, temperature, density (σ_t), fluorescence

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of chlorophyll-*a* (an approximation of phytoplankton abundance), photosynthetically available radiation (PAR; light availability), and optical backscatterance (OBS; measurement of turbidity). To understand spatial variability in the system, we divided Glacier Bay into four regions based on bathymetry, distance from glaciers and oceanic inputs, and qualitative oceanographic patterns. These regions are: (1) lower Bay; (2) central Bay; (3) West Arm; and (4) East Arm (fig. 1). In addition, the calendar year was divided into four seasons based on similar atmospheric conditions. Spring was defined as February, March, April; summer included May, June, July; fall was defined as August, September, October; and winter included November, December, and January. The current study focused on the surface waters, since this region is the most dynamic, represents the region of high biological productivity, and has the highest light levels. Each oceanographic parameters was averaged over this stratum of the water column from the surface to 15 m below the surface. Euphotic depth was defined as the depth to which 1 percent of the surface light reaches, and thus represents the zone of available light within the water column. To quantify the degree of stratification, we calculated a stratification index by calculating the difference in water density between successive 1-m depth layers, and then averaging these values over the top 15 m of the water column, such that our stratification index equals $\Delta\sigma_t$ m^{-1}.

Results

Overall, there was a large amount of seasonal and regional variation in the surface water oceanographic parameters within Glacier Bay (fig. 2). In terms of seasonal patterns, the months May–October represented the period of greatest change in the physical oceanographic conditions, both among months and among the regions. In May, salinity started to decrease, temperature increased, stratification increased, and euphotic depth decreased. July and August generally represented the mid-point of the seasonal change and then patterns reversed through October. The period of November through April exhibited fairly homogeneous patterns in these oceanographic conditions both among months as well as among regions.

In general, the upper Bay regions closest to glacial sources (East Arm and West Arm regions) illustrated the largest amount of change among months (fig. 2). These regions exhibited the coldest water temperatures, the lowest salinity, the highest stratification, the highest turbidity, and the lowest euphotic depth. These characteristics are correlated with the influence of freshwater input into the system through glacial melting, snow and ice melt, as well as direct precipitation. These freshwater inputs are concentrated in the upper-most reaches of the fjord that are most influenced by glacial and snow melt. Despite the similarity in their relative position to glacial sources, the East and West regions exhibited substantial differences in oceanographic patterns, with the East Arm surface waters being fresher, more stratified, and more turbid (fig. 2).

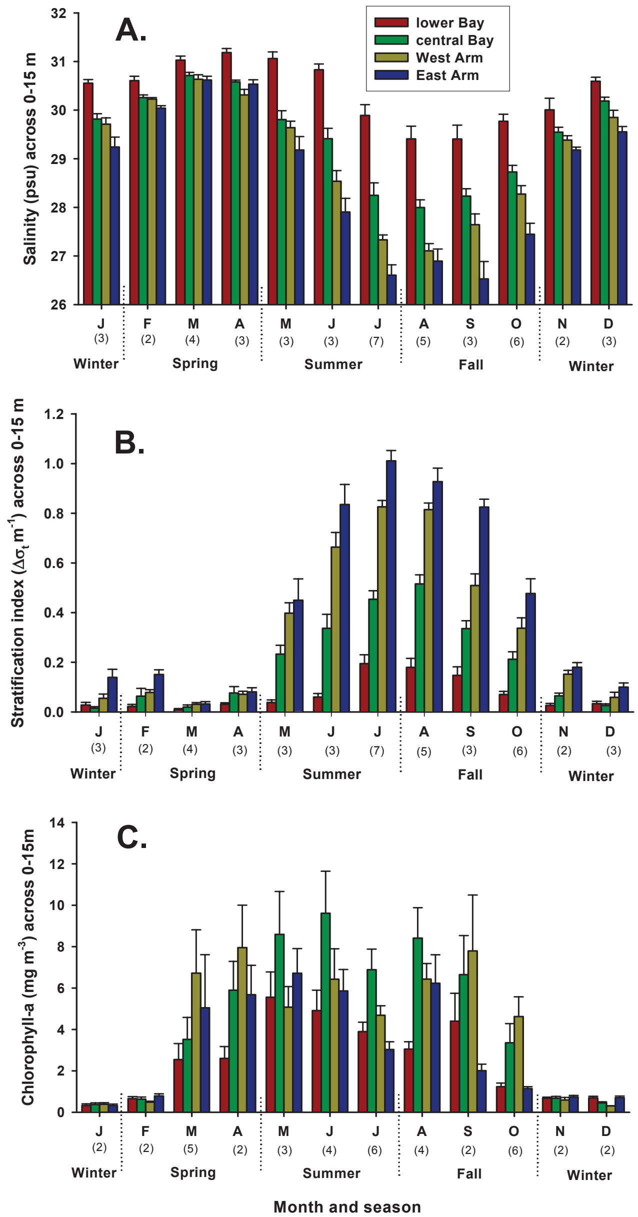

Figure 2. Oceanographic patterns as a function of month, season, and Region. Values represent means (+ standard error) of each of the parameters from all casts averaged over the top 15 m of the water column across each month for each Region. **A.** salinity, **B.** stratification, **C.** chlorophyll-*a*. Season definitions used in analyses are illustrated. The number of years for which data were obtained is indicated in parentheses below each month; numerous casts were taken within each Region during each sampling trip.

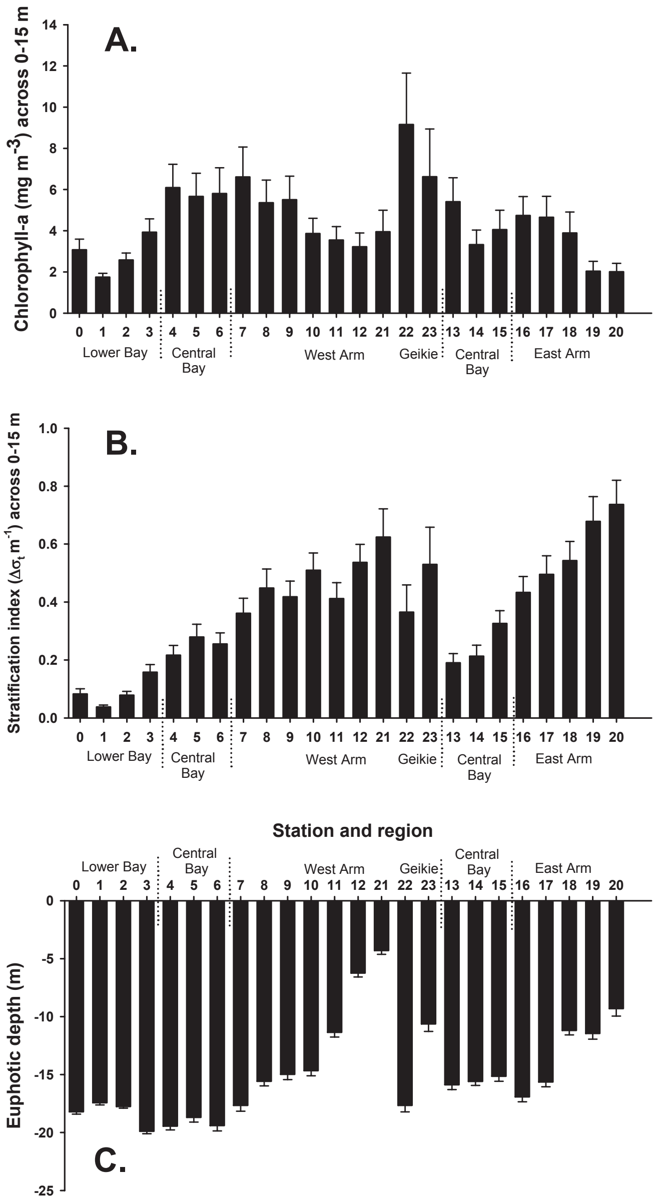

Figure 3. Oceanographic patterns by station within Glacier Bay. Values represent means (+ standard error) of each of the parameters from all casts and averaged across each station. **A.** Chorophyll-*a*, **B.** stratification, **C.** euphotic depth. Regions (as defined for analyses) are indicated below 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.

Patterns of the initial spring increase in chlorophyll-*a* abundance in March did not coincide with the substantial changes in the physical oceanographic conditions in May (fig. 2). Overall highest levels of chlorophyll-*a* were in the central Bay and West Arm regions (fig. 3), particularly in the lower reaches of the West Arm. These spatial patterns of highest levels of chlorophyll-*a* are associated with intermediate levels of stratification and higher light levels (fig. 3). In the spring and fall, highest chlorophyll-*a* levels were in the West Arm region, whereas the central Bay exhibited the highest abundances in the summer season (fig. 2).

Discussion and Conclusions

Overall, there was a high amount of seasonal and spatial variability in oceanographic conditions within Glacier Bay. Further, regions closest to glaciers exhibited the largest variation among seasons, while the lower Bay region exhibited the least amount of variation. These differences illustrate the dominant factors within these contrasting regions—consistent turbulent vertical mixing in the shallow lower Bay region nearest to oceanic inputs, versus high and seasonally variable stratification at the head of the fjord due to freshwater discharge. Therefore, the spatial and seasonal changes in oceanographic patterns in Glacier Bay appear to be largely driven by the amount of freshwater input into the system. Modeled freshwater discharge rates for southeast Alaska indicate an initial peak in May due to snow melt, a general increase throughout the summer as a result of snow and ice melt, and then an ultimate peak in October as a result of direct precipitation (Royer, 1982). This seasonal pattern of modeled freshwater discharge correlates with the seasonal changes observed in Glacier Bay's oceanographic conditions.

It is hypothesized that the onset of the spring phytoplankton bloom generally is 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 in the Bay increased dramatically. Instead, we have demonstrated that seasonal patterns of chlorophyll-*a* abundance did not coincide with patterns of water column stability, because chlorophyll-*a* concentrations dramatically increased two months earlier than did the stratification index. This mismatch may be due to phytoplankton responding to smaller scale transient stratification events that are not detected in our sampling. Alternatively, March may represent a period when a threshold in solar radiation necessary for photosynthesis is reached. Another study in a high latitude fjord system has demonstrated that incident light (rather than stratification) controls the initiation of the spring bloom (Ziemann and others, 1991).

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 stabilizing and mixing forces meet, there are optimal conditions of intermediate stratification, higher light levels (due to decreased sediment concentrations), and potential nutrient renewal. These optimal conditions may explain the relatively high and sustained chlorophyll-*a* levels within particular regions of Glacier Bay. Further analyses will provide insight into the physical factors most influential in driving the oceanographic patterns detected in Glacier Bay

Management Implications

This summary of the oceanographic conditions within Glacier Bay highlights the utility of a monitoring program to understand the basic seasonal and spatial variability in some of the core physical processes that are influential in determining biological patterns within Glacier Bay. The results of this study emphasize the importance of freshwater input in driving the spatial and seasonal patterns in oceanographic conditions within the Bay, and highlight the role of climate and the terrestrial system in influencing Glacier Bay's marine environment. Understanding these linkages provides insight into how this marine ecosystem potentially responds to changes in climate regimes. These findings further our understanding of physical-biological coupling in fjord estuaries and provide some probable explanations for the seasonal and regional patterns in higher trophic levels in this highly productive fjord estuarine system.

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