A Transect of Glacier Bay Ocean Currents Measured by Acoustic Doppler Current Profiler (ADCP)

Edward D. Cokelet[1,4], Antonio J. Jenkins[2] and Lisa L. Etherington[3]

Abstract. We present one of the first shipboard acoustic Doppler current profiler (ADCP) transects of ocean current in Glacier Bay and Muir Inlet. The water temperature, salinity, nitrate plus nitrite concentration and chlorophyll fluorescence also were sampled underway at 5 m depth from the research vessel. These data were combined with conductivity-temperature-depth (CTD) sections made a fortnight later to provide a composite data set. The measurements show that the tidal flow accelerates over Glacier Bay's shallow entrance sill to speeds of 180 cm/s and then slows to a few cm/s in the deeper basin beyond. The near-surface salinity was ~32 psu in Icy Strait and Sitakaday Narrows but freshened up the estuary to ~20 psu in patches, owing to glacial melt water. The nitrate plus nitrite concentration followed a similar pattern with enrichment (~19 µM) in the mixed water over the sill but then depletion (0-2 µM) in Glacier Bay, presumably due to phytoplankton consumption. We postulate that turbulence generated by strong currents over the shallow entrance sill to Glacier Bay mixes deeper, nutrient-rich water into the surface layers and fertilizes the fjord.

Introduction

In recent years, detailed studies of the water properties and density stratification in Glacier Bay. However, owing to a lack of resources and to the technical challenges of making ocean current measurements, little is known about current speeds in the fjord. Fortunately, at the end of a 23-day fisheries oceanography research cruise in the Gulf of Alaska, National Oceanic and Atmospheric Administration (NOAA) ship *Miller Freeman* had 15 hours of ship time to spare as she passed the bay's entrance. Anticipating this we sought permission to enter Glacier Bay on August 8, 2003, and make underway observations.

Methods

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

The near-surface temperature and salinity were measured electronically with a Sea-Bird thermosalinograph (TSG) in water pumped from the ship's sea chest at a depth of 5 m. During the cruise in the Gulf of Alaska, 98 CTD casts were taken. The accurate CTD temperature was subsampled at 5 m and compared to the TSG temperature at the same times. A post-cruise linear regression (r^2=0.98) of the two temperature time series gave a correction to the TSG temperature that took into account sensor differences between the two instruments and warming of the water between the sea chest and the TSG. TSG temperature accuracy was estimated to be about 0.1°C. The ship's CTD salinity was corrected to water bottle samples analyzed with a salinometer. The CTD salinity at 5 m was then compared to the TSG salinity for all CTD casts. Linear regression (r^2=0.98) between the two salinity time series gave a correction to the TSG salinity. Its accuracy was about 0.2 psu. The TSG measurements were recorded every 30 seconds on the shipboard Scientific Computer System.

[1] National Oceanic and Atmospheric Administration, Pacific Marine Environmental Laboratory, 7600 Sand Point Way NE, Seattle, WA 98115

[2] University of Washington, Joint Institute for the Study of the Atmosphere and Ocean, 7600 Sand Point Way NE, Seattle, WA 98115

[3] U.S. Geological Survey, Alaska Science Center, Glacier Bay Field Station, P.O. Box 140, Gustavus, AK 99826

[4] Corresponding author: Edward.D.Cokelet@noaa.gov, 206-526-6820

The underway nitrate plus nitrite (NO_3+NO_2) concentration was measured in the sea chest water with an EnviroTech NAS-2E automated shipboard nitrate measurement package. This research was courtesy of Dr. Calvin Mordy of the University of Washington's Joint Institute for the Study of the Atmosphere and Ocean (JISAO). Measurements were taken every 15 minutes (about every 4.6 km at 10 kt), and a chemical standard was analyzed once per hour to maintain an accuracy of about 1.0 μM. Water samples also were gathered, frozen, and analyzed later for calibration.

A series of 21 standard CTD stations is sampled on a regular basis in Glacier Bay and Muir Inlet (Hooge and Hooge, 2002). Casts were made with a Sea Bird CTD to the protocols set forth in Hooge and Hooge (2002). Refer to their map for station locations.

Results

Currents in a fjord are predominantly tidal; therefore the stage of the tide must be considered when interpreting measurements. Figure 1 shows the tide height at Bartlett Cove in the entrance to Glacier Bay for a 29.5-day lunar cycle in August 2003. Lunar and solar tides add together to give a 14-day spring-neap (large-small range) cycle.

The ADCP transect periods up Glacier Bay and down Muir Inlet are shown as bold curves in figure 1 on August 8–9, 2003 (all times are GMT) during neap tides. *Miller Freeman* entered Cross Sound somewhat earlier (12:27 August 8, 2003) on an ebb tide with the predicted low at 12:58. The transect up Glacier Bay began at the entrance sill at 15:25 with the flood in progress, but the ship anchored in Bartlett Cove at 17:00 awaiting National Park Service permission to enter the bay. She resumed the up-bay transect at 10 kt in mid-channel outside Bartlett Cove at 18:48 and crossed Station 2 (Hooge and Hooge, 2002) at 19:15 with the tide still flooding. Predicted high tide occurred at 19:35 with the ship just north of Willoughby Island at Station 4 in deep water landward of the sill. She reached the northern end of the transect at 23:21, and low tide occurred at 00:59 August 9, 2003. The down-bay transect began in Muir Inlet at 03:16 near Station 16 and continued on the flood tide until 06:38 when the ship entered Icy Strait between Stations 1 and 0. Predicted high tide was at 07:06. The up- and down-bay transects were conducted beneath clear skies with little wind.

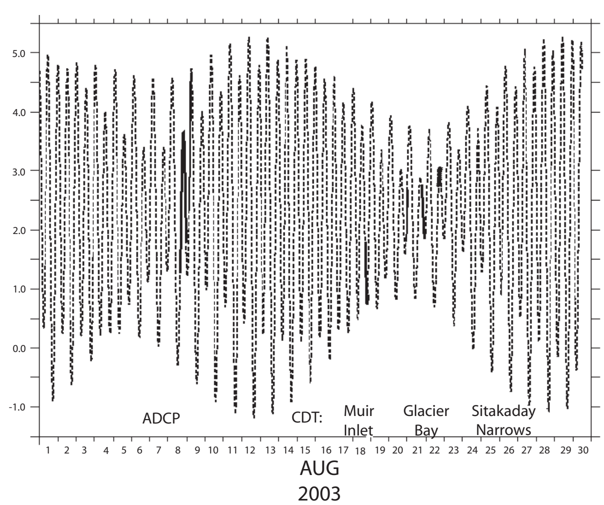

Figure 1. The predicted tidal height at Bartlett Cove shows the spring-neap cycles during a 29.5-day lunar period. Bold lines on 8-9 Aug 2003 represent the Glacier Bay and Muir Inlet ADCP transect intervals, respectively. Bold lines on 18-22 Aug 2003 represent CTD transects in Muir Inlet, Glacier Bay (2 partial transects) and Sitakaday Narrows.

No CTD transects were conducted in conjunction with the ADCP transects, but some were completed 10–14 days later. These provide a reasonable comparison data set because they were done during neap tides and under similar seasonal conditions. A CTD transect up Glacier Bay on the 25-ft vessel *Sigma-t* was run in two parts as shown by the bold curves on August 20–21, 2003 in figure 1. The first part over the entrance sill from Stations 0-4 was run on the incoming flood tide as were our ADCP transects over the sill. The second part covering Stations 5-12 and 21 was conducted during ebb, but that may not matter a great deal in the deeper waters of Glacier Bay where tidal currents are weak.

Figure 2 shows the ADCP vectors at the shallowest depth measured (22 m), averaged along the ship's track every 4 km. These are the first, published shipboard ADCP transects made in Glacier Bay and Muir Inlet (Hooge and Hooge, 2002). The ship was bucking ~60 cm/s currents in Cross Sound, but these changed to flood in North Passage, corresponding to the low tide at Bartlett Cove at 12:58. During the incoming transect over the shallow entrance sill to Glacier Bay the tide was flooding, and the ADCP vectors show strong inflow at 22 m (fig. 2a). The largest observed current was about 160 cm/s just south of Bartlett Cove. The tidal flow accelerated over the shallow entrance sill and then slowed to a few cm/s in the deeper basin beyond. During the remaining up-bay transect, weakly outflowing currents (fig. 2a) were observed, in qualitative agreement with an ebbing tide as shown by the tidal height prediction (fig. 1).

Current measurements confirm that the tide was in flood during the entire transect down Muir Inlet (fig. 1). A maximum flood current velocity of about 180 cm/s was observed in Sitakaday Narrows where the channel narrows and the bottom shoals (fig. 2b). Doubtless, stronger currents can be expected during spring tides.

Salinity usually governs density stratification in Alaskan waters. Figures 2a and 2b show the near-surface salinity transects. Salinities of 31–32 psu water were observed off shore. The salinity remained elevated in Cross Sound and over the entrance sill due to tidal currents that mix up salty, cold water from below. Mid bay, near the junction with Muir Inlet, had some of the freshest, warmest water owing to reduced currents and mixing. The freshest water (19.6–20.0 psu) did not correspond to the coldest water near the faces of tidewater

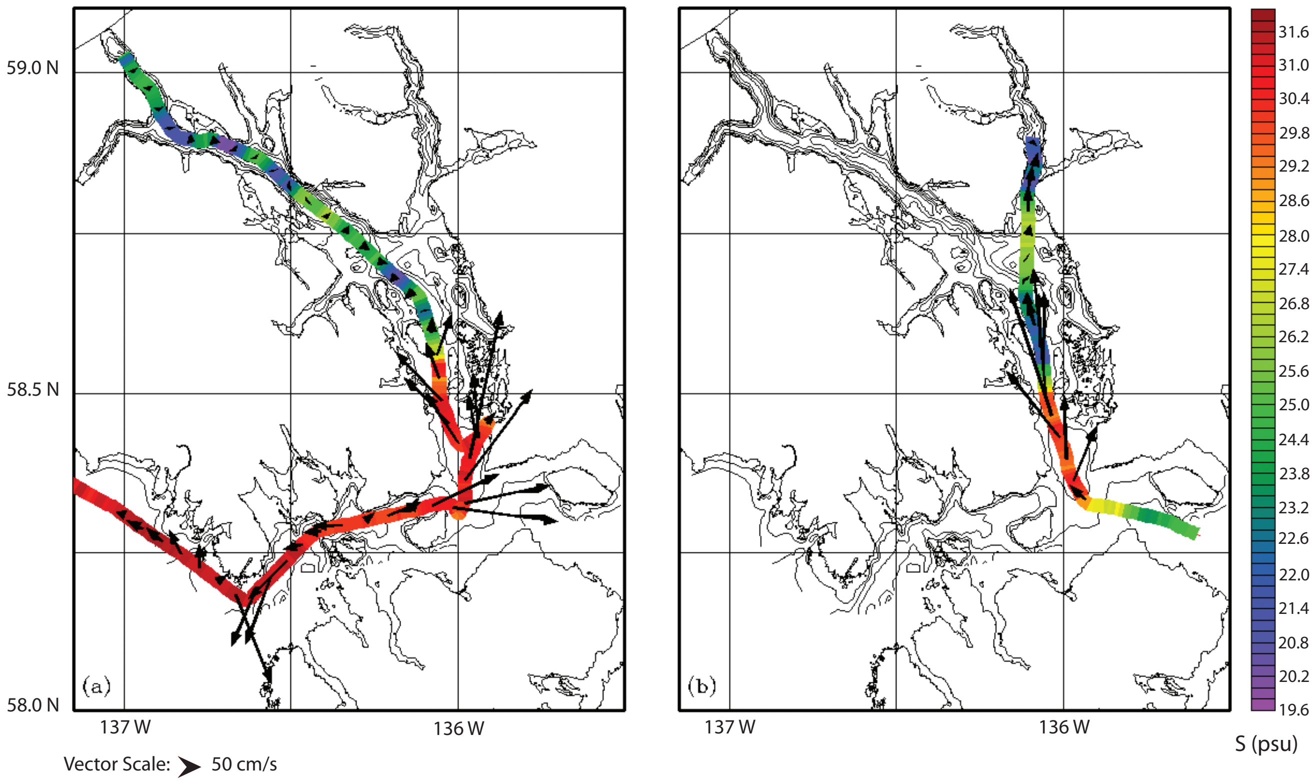

Figure 2. Salinity at 5 m and ADCP velocity vectors at 22 m during the ***A.*** Glacier Bay (August 8, 2003; 15:25–23:21) and ***B.*** Muir Inlet (August 9, 2003; 03:16-06:28) transects. The ADCP vectors are averaged over 4-km segments along the ship track. A 50 cm/s velocity vector scale is shown at the bottom. Depth is contoured at 0, 50, 100, 200, 300 and 400 m.

glaciers in Tarr Inlet, but rather it occurred in patches, presumably as lenses of runoff from glaciers in Geikie, Johns Hopkins, Queen, and Rendue Inlets. Though not shown, the near-surface concentration of nitrate plus nitrite—essential nutrients for phytoplankton production—has a similar distribution to salinity. Nitrate plus nitrite concentrations in Cross Sound and over the Glacier Bay sill were 19–20 µM, the highest observed on the entire Gulf of Alaska cruise.

Figure 3 shows a vertical cross-section of the along-axis or axial velocity on the Muir Inlet transect. In topographically controlled flows, the velocity vectors closely follow the local topography. Therefore, we let the local velocity vector define the axial direction and assign it a positive sign if the vector has a northward component. The Muir Inlet section (fig. 3) was done entirely during flood tide based on the prediction at Bartlett Cove (fig. 1). There is strong flow in Sitakaday Narrows at Station 2 (180 cm/s) where the bottom shoals and the channel constricts. Generally, up-estuary of Station 4 the flow is weak, but there is some acceleration over the Muir Inlet entrance sill (Station 14). Weak down-estuary (negative) flow around Station 16 may indicate that the tide was still ebbing at that location due to the phase lag in the tidal wave as it propagated across the sills. The velocity section along Glacier Bay itself (not shown) also has strong flooding currents in Sitakaday Narrows and weaker flow in deep water.

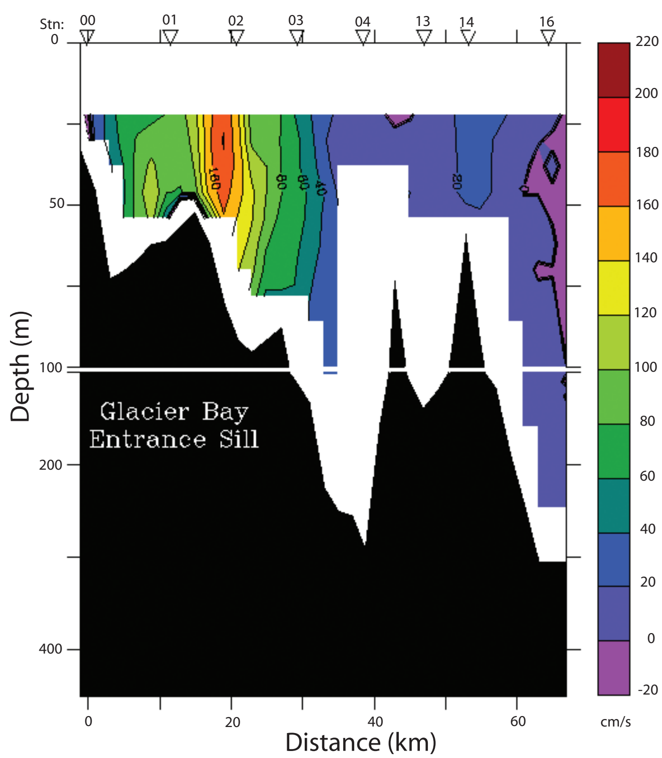

Figure 3. Vertical section of the axial current velocity (positive up-estuary) along the Muir Inlet transect. CTD Station numbers are shown along the top.

Figure 4 shows a vertical cross-section of salinity from the CTD sections of August 20–21 (fig. 1). Though a section along the west arm of Glacier Bay and not simultaneous with the velocity section (fig. 3), it is probably similar with salinity stratification up-estuary of the entrance sill and weaker stratification over the sill due to turbulent mixing caused by strong tidal currents. Several isohalines intersect the free surface near Station 0 which indicates a sharp frontal zone there. Salinity (and density) gradients are weak in the deep water. (Salinity inversions in the deep water along the 31.0 psu surface are suspect. The CTD measurements may not have sufficient accuracy in these weak-gradient regions.).

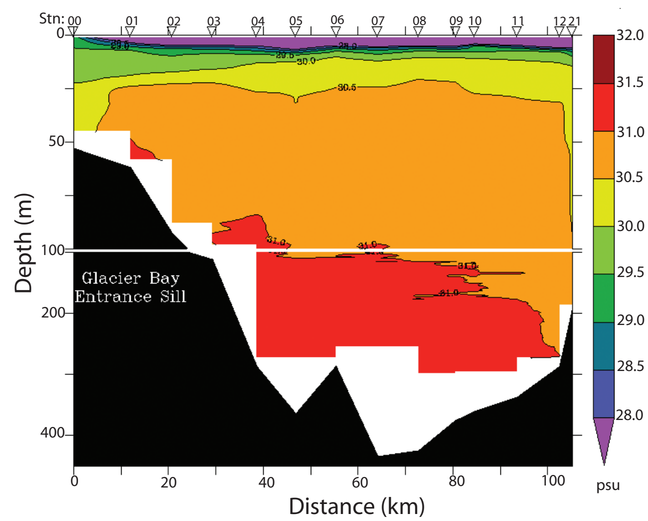

Figure 4. Vertical section of salinity along the Glacier Bay transect. CTD Station numbers are shown along the top.

Discussion And Conclusions

Although the data set is preliminary and very short, it represents the first snapshot of tidal currents in Glacier Bay. Our data indicate that strong currents exist over shallow sills and in narrow channels. They also demonstrate the importance of the tidal phase in determining flow direction. On the outgoing transect, fresher water was seen in Icy Strait than over the Glacier Bay sill or in nearby Cross Sound. If this were generally the case, then it would imply that the salty, oceanic water mixed up from depth in Cross Sound is the nutrient-rich source water for Glacier Bay. Therefore, two factors would be at work: Cross Sound would provide a source of deep oceanic water in close proximity to Glacier Bay, and strong tidal currents would mix it up for entry into the bay.

Management Implications

Currents affect a marine ecosystem in four ways: (1) seawater flow combines with freshwater from runoff and glacial melt to determine water properties—basic ecosystem parameters. (2) Currents affect phytoplankton productivity—the base of the oceanic food chain. They can enhance photosynthesis by mixing nutrient-rich water from depth into upper waters where sufficient light is available. However, mixing also can transport phytoplankton below the photic zone and quench primary production. (3) Currents transport larval fish and crustaceans. (4) Currents affect benthic habitat by sediment transport and scour. Understanding the current field will lead to improved ecosystem understanding and better estuarine management.

Acknowledgments

We thank the captain and crew of NOAA Ship *Miller Freeman*, Bill Floering for his hard work and oceanographic expertise on the cruise, Gary Stauffer for obtaining ship time, Calvin Mordy for nutrient measurements, Jeff Napp and Colleen Harpold for chlorophyll analyses, Mary Kralovec for granting permission for *Miller Freeman* to enter Glacier Bay, Jennifer Mondragon for bathymetric data, Hope Rieden for CTD casts and processing. The *Miller Freeman* cruise was sponsored by NOAA's Ocean Carrying Capacity (OCC) and Global Ocean Ecosystem Dynamics (GLOBEC) programs. This is NOAA/PMEL contribution 2912, NOAA Fisheries-Oceanography Coordinated Investigations contribution FOCI-590, and GLOBEC contribution 284.

Suggested Citation

Cokelet, E.D., Jenkins, A.J., and Etherington, L.L., 2007, A transect of Glacier Bay ocean currents measured by acoustic Doppler current profiler (ADCP), *in* Piatt, J.F., and Gende, S.M., eds., Proceedings of the Fourth Glacier Bay Science Symposium, October 26–28, 2004: U.S. Geological Survey Scientific Investigations Report 2007-5047, p. 80-83.