Dissolved oxygen within Glacier Bay: sources, deep basin values and comparison to other glacial fjords

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Abstract

An examination of the dissolved oxygen values within Glacier Bay, Alaska suggests deep water renewal is occurring by light water from outside the bay. No heavy water is able to enter the bay due to the 25 meter sill at the entrance to the bay. Dissolved oxygen values, which range from 268 μmol/kg to 330 μmol/kg in the bay, are also affected by high, seasonal, fresh water inputs which lower dissolved oxygen values, and by high biological productivity which increase dissolved oxygen values. Both of these influences occur primarily in the surface waters, however mixing and seasonal stratification also influence deeper water. The impacts of other possibly influences such as the exchange of air with sea water at the surface and the thermodynamic effects of melting glaciers were not examined but may also be affecting the dissolved oxygen values in the bay. Other examined silled fjords reveal no pattern to their deep water renewal that suggests any common characteristic.

Introduction

Glacier Bay is an isolated glacial fjord located in northern Southeast Alaska with the Pacific Ocean to the west, Icy Strait to the south, and British Columbia to the north and east. Rapid, dramatic, glacial retreat in the last 225 years has created outstanding opportunities to study tidewater glacial retreat, ecological succession, the effects of climate change, and other physical and biological dynamics of the area (Eckert et al. 2006). Fjords similar to Glacier Bay, which still contain tidewater glaciers, also exist in other places in the world such as Greenland, Chile, the Canadian Arctic, Antarctica and Scandinavia (Syvitski et al. 1987).

Glacier Bay is approximately 100km long at its greatest length and contains over 300 freshwater streams and 1500km of shoreline (Fig. 1). It is a silled fjord with an entrance sill approximately 25 meters deep which is unusually shallow compared to other Alaska fjords as well as other Pacific fjords. There are other shallow sills within the bay and also deep basins, down to 450 meters, between these sills (Hooge and Hooge 2002).

Fjords and associated estuaries are subject to many factors which affect the stability of the water column within the fjord. These include freshwater inputs, tidal currents, wind and weather stresses, sediment inputs and ocean water renewal. All of these factors affect the physical and chemical makeup of the water within the fjord, with subsequent impacts on biology, circulation and overall health of the fjord ecosystem. Dissolved oxygen in seawater is of particular importance to the biology within a fjord. Since Glacier Bay is an important wintering, breeding, nursery and feeding area for many marine organisms, including some on threatened or endangered lists, the oxygen content and renewal of the basin needs further understanding (Etherington et al. 2007).

The main focus of this research is to use dissolved oxygen values in the water column to identify the source water coming into the deep basins within the bay. Previous work done by NOAA and others has determined the possible source water for Glacier Bay coming from the east side of Icy Strait, but that was uncertain according to Nancy Kachel with NOAA. This study also adds to the existing oceanographic database for the bay, supplementing some data and providing new data for other locations and depths, and adds to the general understanding of the hydrographic characteristics of Glacier Bay. Although the bay has been studied for many years, research has been limited in scope and has not determined the dissolved oxygen (DO) content for the basin (Hooge and Hooge 2002). This work also adds to increased understanding about silled fjord structures, and specifically those which have undergone deglaciations in very recent time. Secondary objectives of this work are to build or add to known temperature, salinity and density data for the bay, and also to provide other CTD data available in support of other members of the science group and to the United States Forest Service. The study also examines Glacier Bay in comparison with other fjord-like basins with respect to deep water renewal and circulation.

Methods

Oceanographic data was collected in and near Glacier Bay between 0600 PDT on 18 March 2008 through 2000 PDT on 22 March 2008. A Seabird SBE 9 package was deployed from the R/V *Thomas G. Thompson* mounted on a standard CTD rosette.

At each station (Fig. 1: Table 1) the CTD rosette, equipped with 24, 10 liter Niskin bottles, was launched and lowered to near the bottom, typically within 5m. During descent, the temperature, salinity and density profiles were observed for evidence of stratification, location of thermo and pycnoclines, and to determine the chlorophyll maximum depth. The CTD was raised slightly, and then allowed to stabilize. As it was brought to the surface, Niskin bottles were closed at various depths along the way to obtain water samples as needed for this study and others in the science party. Consideration was given to other's work and the need to close more than one bottle at any needed depth. Duplicate bottles were closed at each depth as a backup, when extra bottles were available. After reaching the surface, water samples were collected from Niskin bottles associated with the depths of interest and placed into high precision dissolved oxygen sample flasks.

At stations near the mouth of Glacier Bay data was needed during both flood and ebb tidal cycles to get a more complete picture of water movement. The original study plan called for us to visit several stations near the mouth of the bay twice, which we were able to accomplish despite time and field constraints.

Due to the need to process the water samples within 48 to 72 hours of being sampled to avoid contamination by gas exchange from the atmosphere, dissolved oxygen titrations were done in the ship-board lab. Water samples taken from several depths on each CTD, as well as several sets of triplicate bottles to confirm accuracy, were titrated using the modified Winkler method (Codispoti 1995; Carpenter 1965). This was done to confirm the accuracy of the DO sensor on the rosette. CTD data gathered by the operating computer was compiled for further processing after returning to the lab. After completion of the cruise, the CTD data compiled by the shipboard computer was examined and converted into a more useable format with Seabird software.

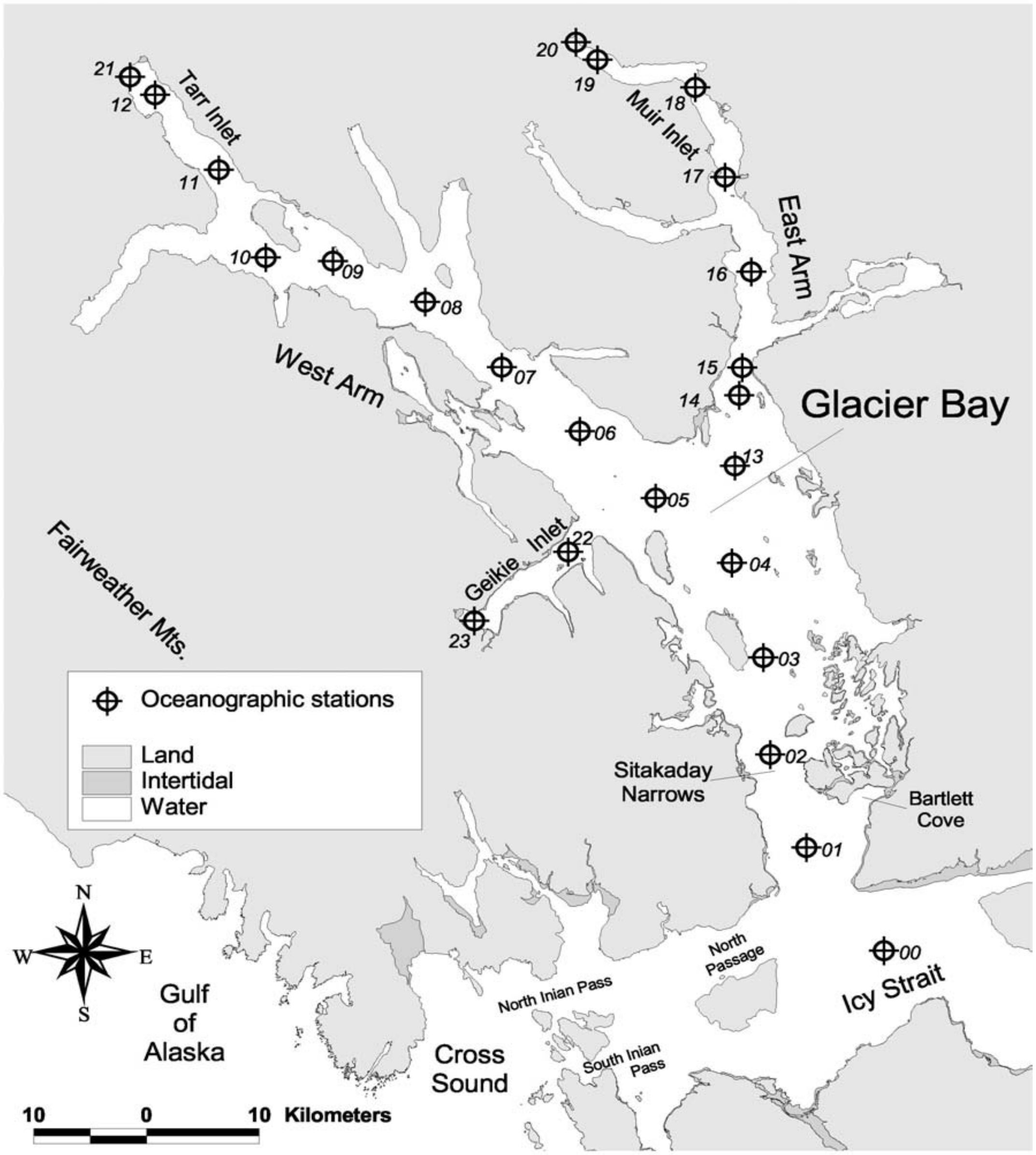

Figure 1: USGS stations within Glacier Bay (adapted from Hooge and Hooge 2002). The small circles are additional stations where CTD sampling was done. Sampling was not done at stations 17 through 20 due to time constraints, and station 23 due to sea ice.

Results

General dissolved oxygen levels in the Glacier Bay area differ greatly depending on location and for stations near the mouth of the bay, tidal stage. Just inside the bay, at stations 1 and 2, dissolved oxygen values fall between about 275 μmol/kg and 281 μmol/kg at all depths (Fig. 4). At station 3, the range is greater, about 285 μmol/kg at approximately 100m, up to 298

Station	Lat	Lon	Location	Depth (m)
A	58.34	-136.05	Mouth of Glacier Bay, outside to west	73
AA	58.3	-136.25	West of mouth of Glacier Bay	219
0	58.33	-135.87	Mouth of Glacier Bay, Icy Strait	53
1	58.41	-135.99	Mouth of Glacier Bay	62
2	58.49	-136.05	Sitakaday	93
3	58.57	-136.06	SE of Willoughby Island	112
4	58.65	-136.11	N of Drake Island & Marble Island	288
5	58.7	-136.23	Between N Drake & SW Tlingit Pt	366
6	58.76	-136.35	E of Hugh Miller Inlet	288
7	58.81	-136.47	N of Blue Moose, W of Tidal	435
8	58.87	-136.59	S of Rendu Inlet	426
9	58.9	-136.73	S of Russell Island	377
10	58.9	-136.84	E of Russell Island	361
11	58.97	-136.91	Tarr Inlet	338
12	59.03	-137.02	Head of Tarr Inlet	288
13	58.73	-136.11	SE of Tlingit Pt, NW of Sturg	146
14	58.79	-136.11	Muir Sill	81
15	58.82	-136.1	W of Muir Pt	116
16	58.9	-136.09	E of Hunter Cove	313
21	59.05	-137.06	Marjorie/Grand Pacific	195
22	58.66	-136.36	Entrance to Geikie	155
23	58.6	-136.5	Head of Geikie	66
0	58.21	-135.34	Icy Strait east/southeast of Glacier Bay	266

Table 1: Stations lat & lon. Location description and depth. Notes: a: station id, b: latitude of station (Nad27), c: longitude of station (Nad27), d: location description, e: depth in meters

μmol/kg near the surface (Fig. 4). Outside the bay at stations 00, A, and AA the range is even greater. Stations 00 and A were visited twice in an attempt to discern tidal differences. At station A-1, during a flood tide, dissolved oxygen ranged from about 272 μmol/kg near the surface, 267 μmol/kg at 75 meters, and about 292 μmol/kg at a depth of about 170 meters (Fig. 4). Station A-2, during a slack tide, has values ranging from about 275 μmol/kg to 281 μmol/kg from the surface down to about 50 meters (Fig. 4). Stations 00-1, on the flood tide, and 00-2, 50 meters, then dropping rapidly below 260 μmol/kg at 50 meters and below and 00-2 ranging from 282 μmol/kg near the surface, down to 280 μmol/kg just above 50 meters, then also dropping rapidly down to 270 μmol/kg below 50 meters (Fig. 4).

For stations 4 through 21, a series running up the west arm of the bay (Fig. 1), the dissolved oxygen values are similar with some differences appearing in the lower stations, specifically 4, 5 and 6. This is particularly true for DO values below about 75 meters, where the range of DO is about 268 μmol/kg to 285 μmol/kg. Above this depth there is similarity, but less so with a much larger range of values from about 268 μmol/kg near 75 meters to almost 330 μmol/kg at the surface for several stations (Fig. 5). In order to more clearly see these subtle differences, a

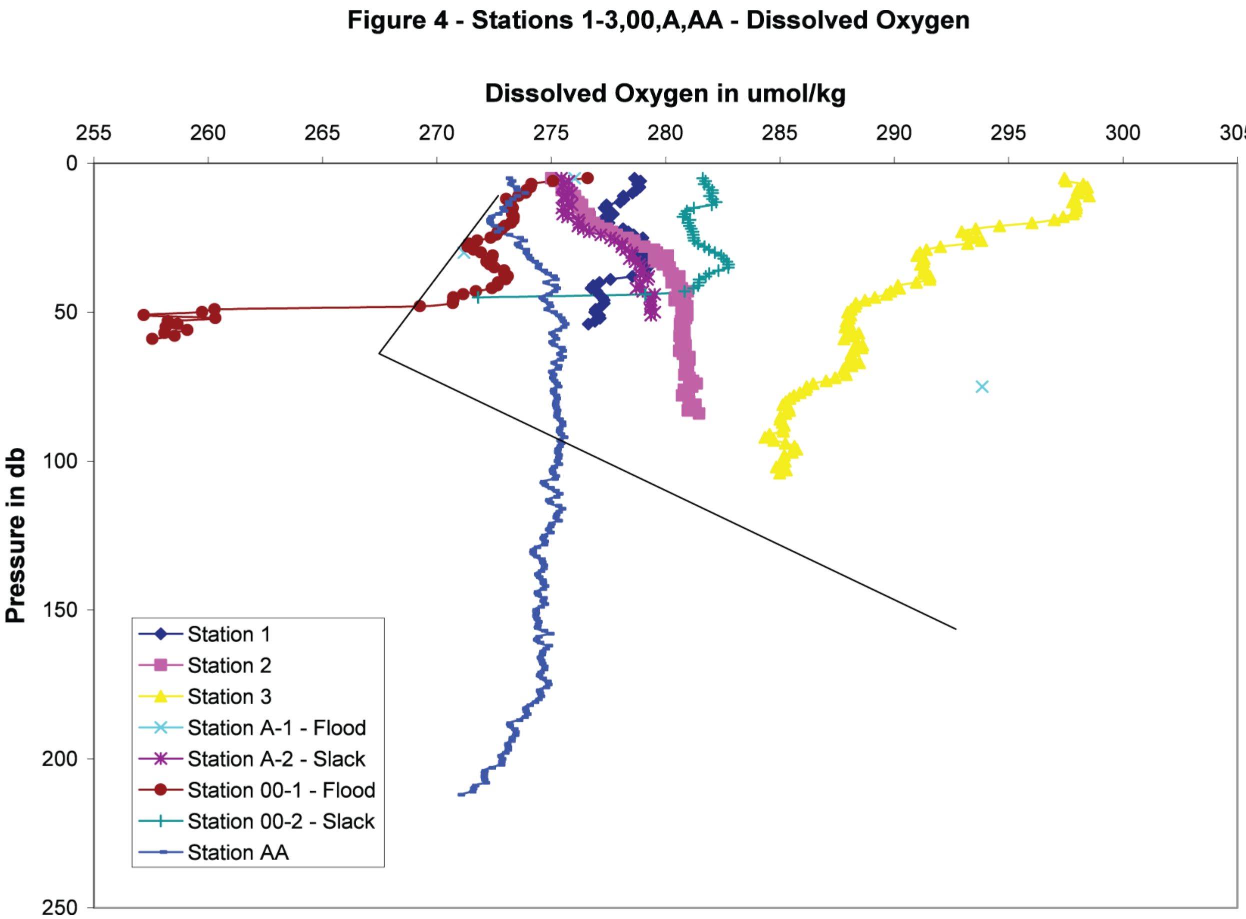

Figure 4: DO plot showing stations 1-3, AA, and 00 and A at two tidal stages. The solid line for station A-1 is caused by having only 3 data points instead of a range every 1m. This was done by using titration data instead of CTD data, due to a problem with the oxygen sensor on the CTD during this cast.

'waterfall' plot was made separating each station by a fixed value (Fig. 6). Stations 1, 2 and 3 were separated further away since they do seem to differ in overall appearance although their DO values are in the same range as stations 4 through 21.

It is also a different world between stations 4 through 21, and stations 3 and below, including the outside stations, when comparing dissolved oxygen and density, or sigma-theta. While the lower end of the DO values for stations 4 through 21 correspond with the DO values for stations 3 and lower, the σ_θ values for stations 4 through 21 go no higher than about 24.8 kg/m^3, while the σ_θ values are all above 24.8 kg/m^3 and go as high as almost 25.2 kg/m^3 (Fig. 8).

σ_θ and potential temperature comparisons have a similar pattern, stations 4 through 21 being colder, as low as about 2.7 degrees C for station 21 near the surface, up to almost 4.6 degrees C for station AA, at its greatest density (Fig. 7).

Discussion

Data Calibration and Exceptions

Using the values obtained by Winkler titration a linear correction factor for the digital CTD dissolved oxygen values was determined. During the calibration, several outlying data points were found (Fig. 2). These were several

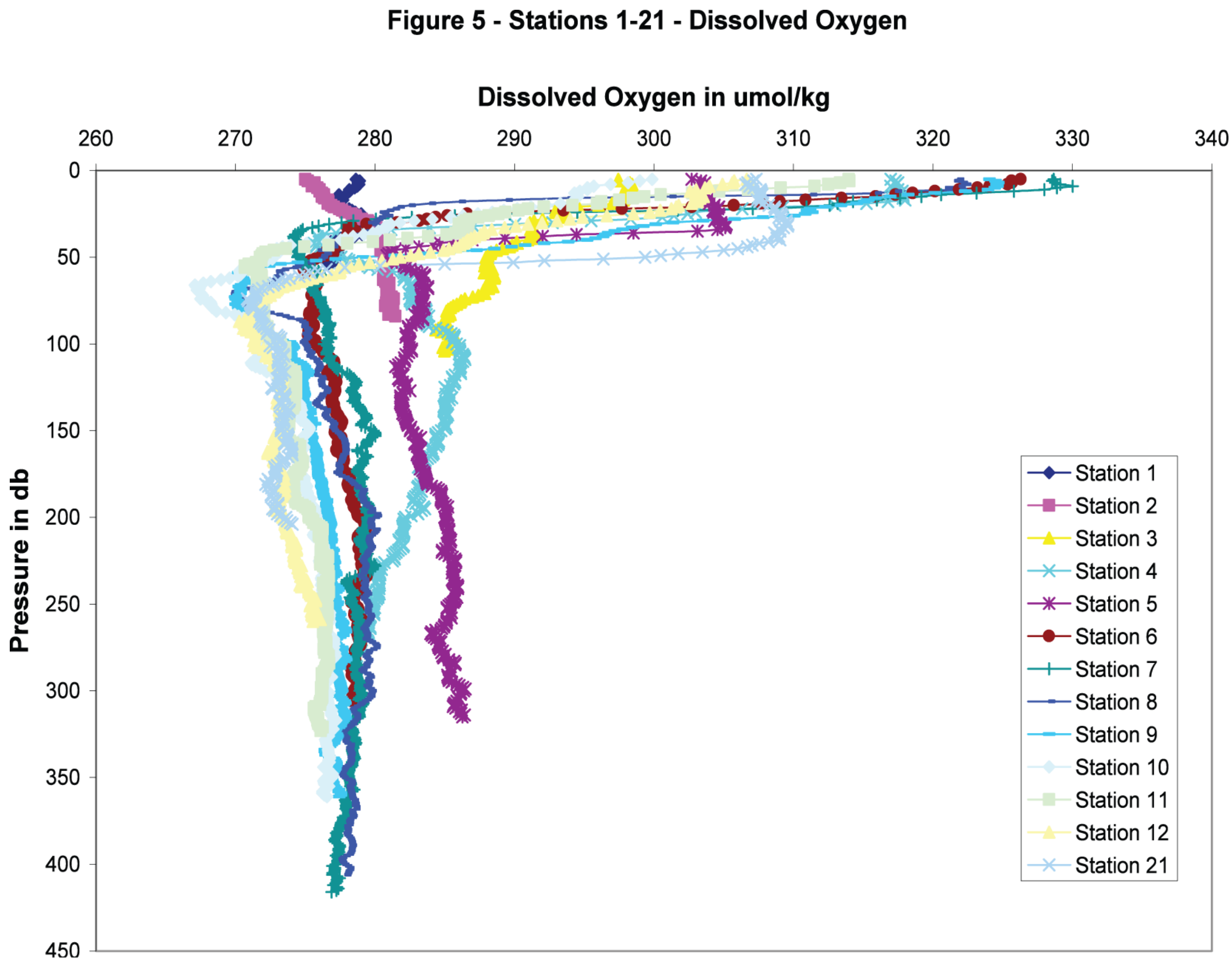

Figure 5: DO plot showing stations 1-21

data points determined to be invalid due to DO sensor problems and two that were invalid due to an unknown cause. Initial calibration including them produced a calibration factor of 0.8874 % which was not felt to be accurate. After their removal the calibration value was 0.9706 % which was a more acceptable value (Fig. 3). The DO values were also converted from the shipboard value of ml/l to umol/kg, a more physical oceanography friendly measure (Appendix I).

At station A-1, visited during a flood tide, the oxygen sensor malfunctioned rendering all digital CTD DO data invalid. The data shown is from only the three depths that were actually sampled using the Niskin bottles and titrated, which show 272 μmol/kg near the surface, 267 μmol/kg at 75 meters, and about 292 μmol/kg at a depth of 170 meters (Fig. 4).

Data Interpretation

The data makes it clear the source water for the deep basins in Glacier Bay is coming from outside the bay, although it doesn't clearly distinguish if it coming from the east or west side of Icy Strait. In fact, depending on the season and storm surges in the region, deep water renewal may be coming from both directions. Although, considering the very shallow sill at the mouth of Glacier Bay, the deepest heavy water outside the bay may never make it over the sill except in

Figure 6 - Stations 1-21 - Dissolved Oxygen

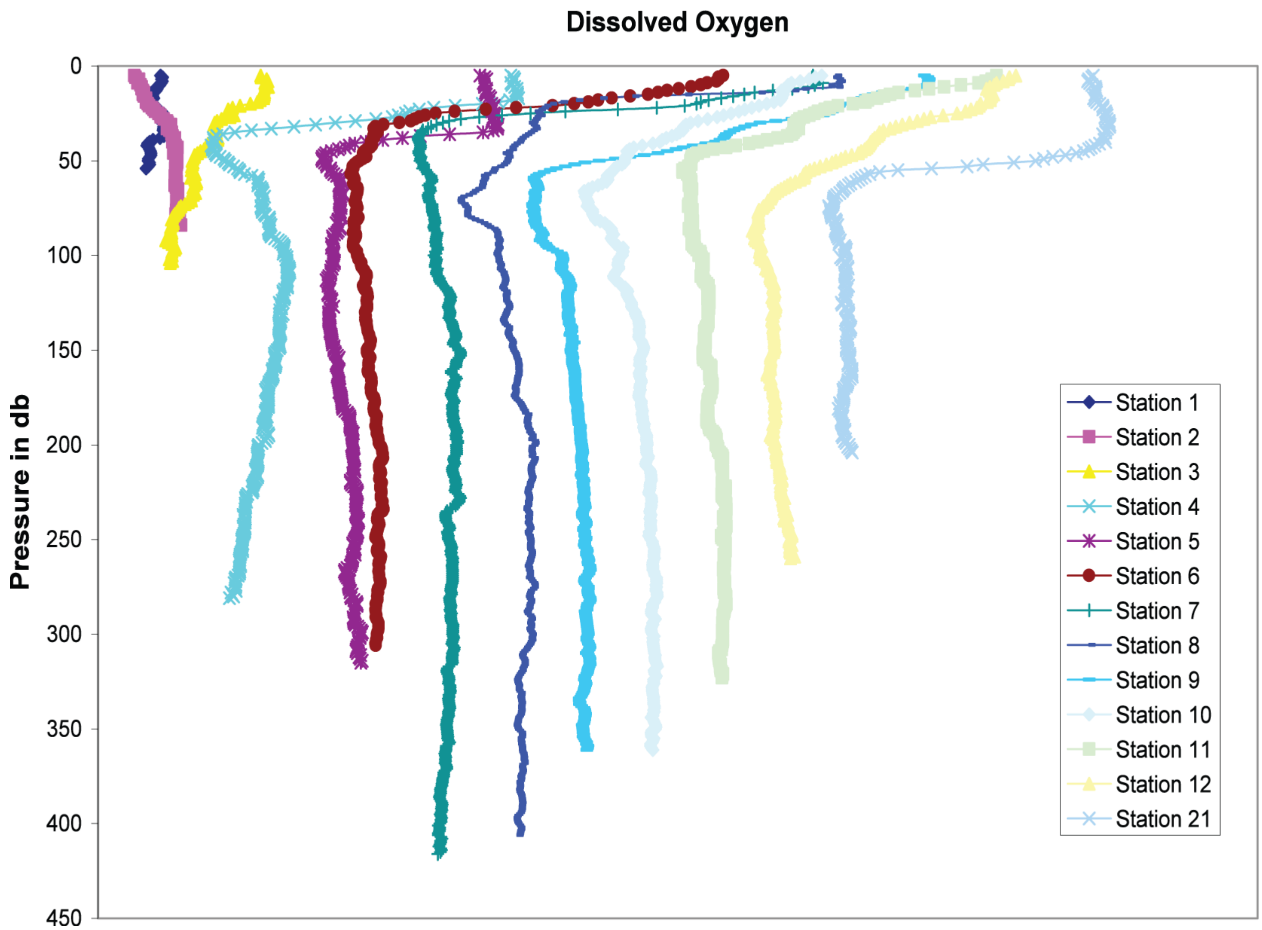

Figure 6: DO waterfall plot showing stations 1-21 separated for more visibility.

extreme storm or surge cases. Based on the deep water characteristics within the bay, regular deep water renewal may only be occurring by lighter water that is able to make it over the sill. Water parcels for stations A and 00 both show DO values similar to the deep DO values for stations 4 and above within the bay (Fig. 4: Fig. 8). However, this is only during the flood tide. During slack water the DO values for both stations increase by almost 10 μmol/kg. Station AA water has almost no stratification at depth suggesting strong currents are keeping it well mixed. It does have a slight oxygen minimum near 50m which maybe the influence of outflow from Glacier Bay. Other stations within Glacier Bay also show this oxygen minimum at about the same depth.

For all the stations within the bay, from station 4 to station 21 in the west arm, there is a general pattern to the stratification and the DO values: an oxygen maximum at depth residual from deep water renewal, a minimum from 50 to 75m caused by fresh water entrainment and mixing, and high oxygen values up to the surface. The minimum at these depths suggest a lot of input from the surface fresh water while the higher values towards the surface are due to biological productivity. If this work had been done several months earlier, there would probably have been much lower surface values

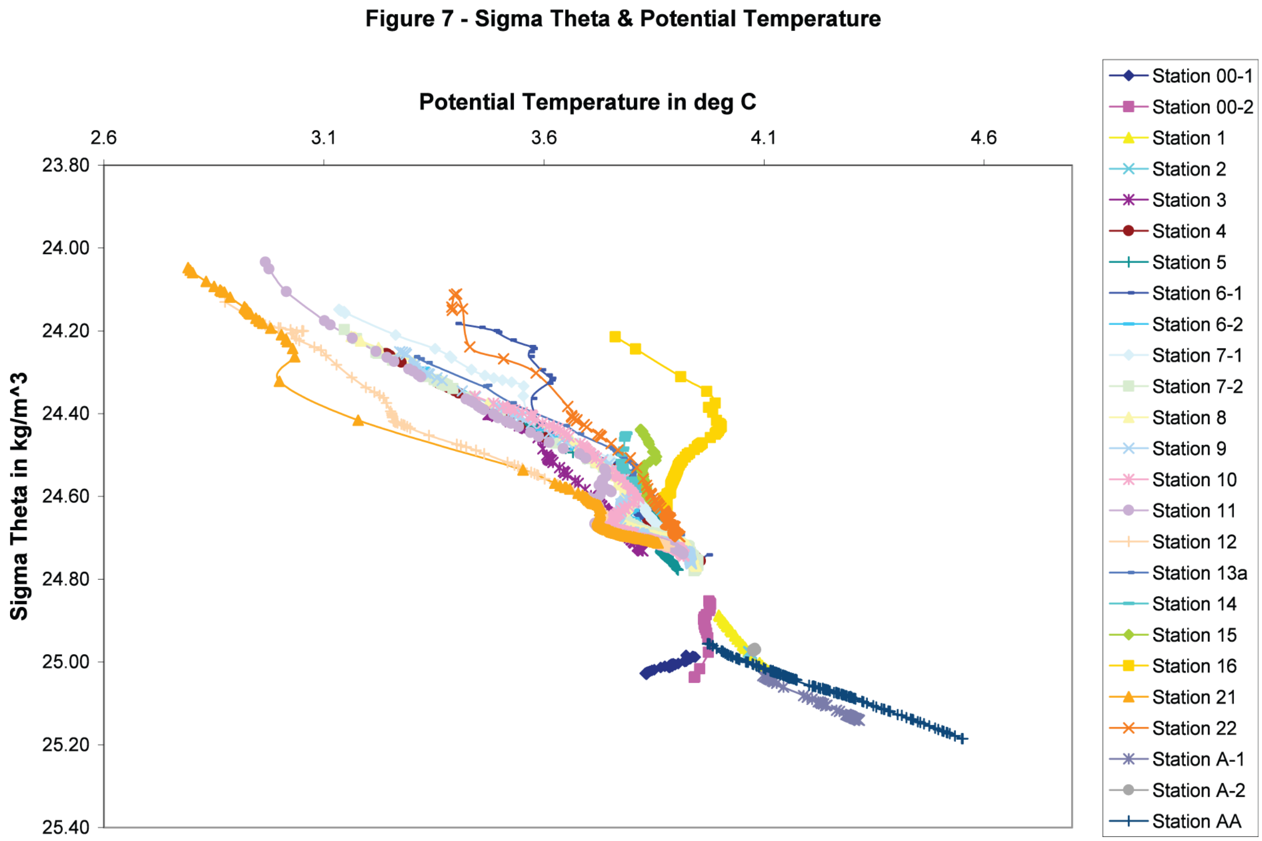

Figure 7: Plot of potential temperature and density, sigma-theta for all stations except 000.

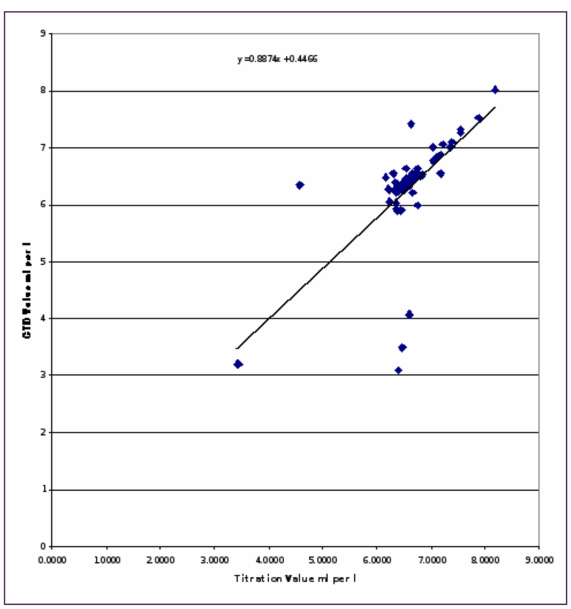

Figure 2: Calibration data with outliers.

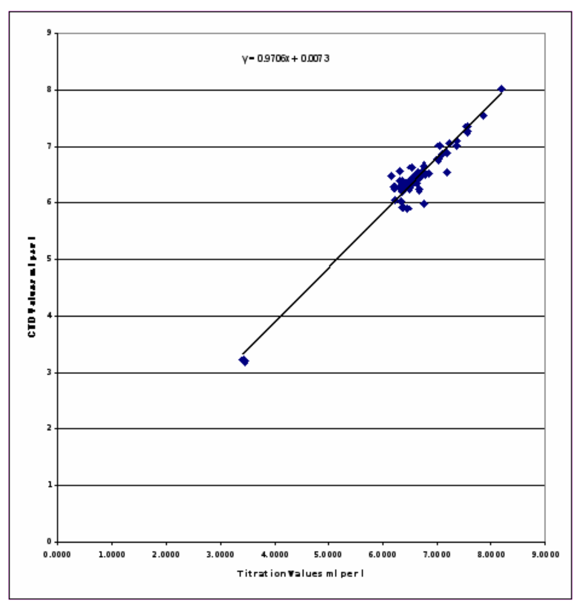

Figure 3: Calibration data no outliers.

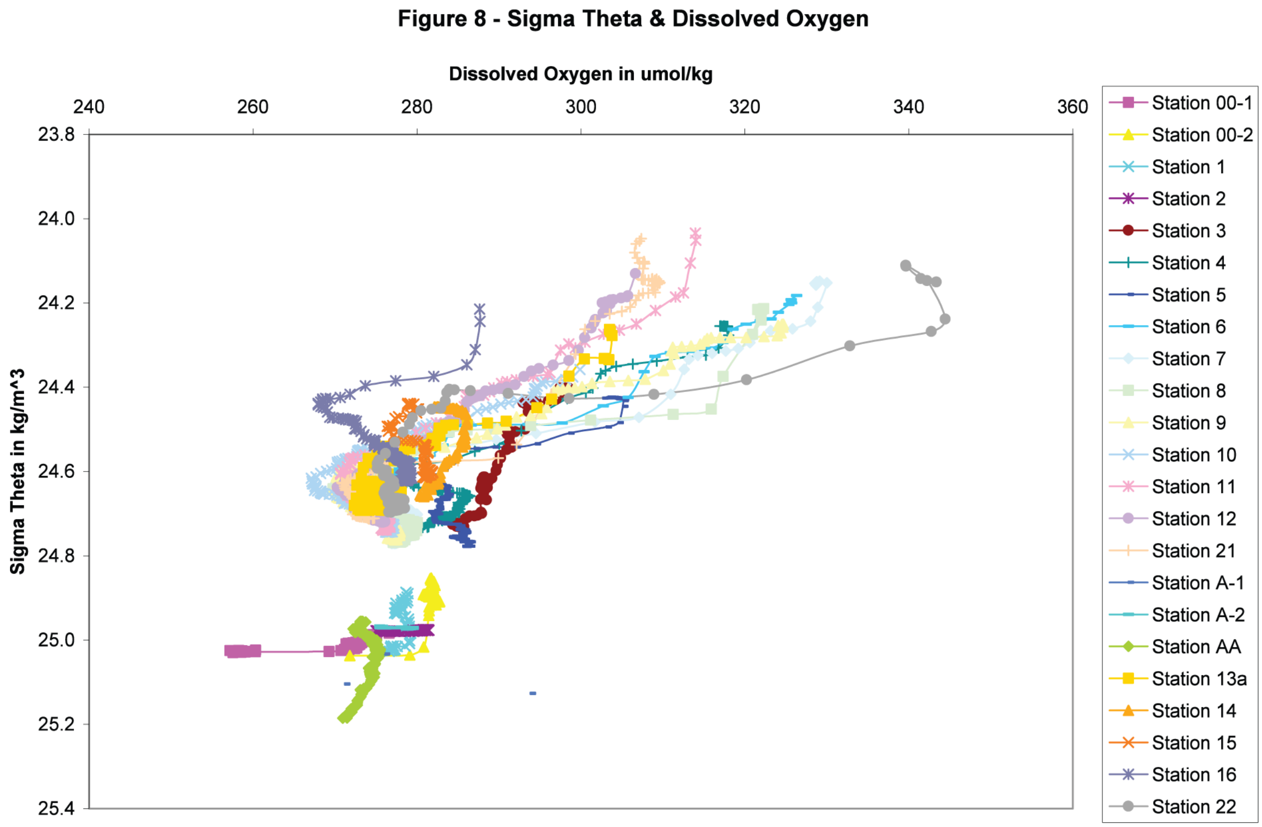

Figure 8: Plot of density, sigma-theta and DO for all stations except 000.

of oxygen since the biology would not have been as active. There would also have been less freshwater outflow, although March typically has the lowest freshwater runoff during the year (Biladeau 2008 not published). Stations 1 and 2 show almost no stratification which is due both to the shallow depths at these stations and the extreme tidal currents through the area, while station 3 has characteristics of both groups of stations (Fig. 4). Glacier Bay stratification typically occurs in March or April each year (Matthews 1981), and although the dissolved oxygen data does indicate some stratification has begun to appear, had this work been done later in the summer the stratification would be more pronounced.

There are other factors which may be influencing the dissolved oxygen values in the bay. These include air-sea gas exchange and the thermodynamic influence of melting ice, neither of which was examined in this work

Other Fjords

Several other fjords similar to Glacier Bay were examined: Gullmar Fjord, Sweden, Hood Canal within Puget Sound, and Loch Sunart, Scotland. All three have shallow sills, varying levels of freshwater input and subsequent varying levels of dissolved oxygen depending on the season.

Gullmar fjord on the west coast of Sweden has a sill at 42m and is 119m in its deepest basin. It has the same three layered stratification that appears in Glacier Bay with deep, oxygen maximum water, mid-level, oxygen minimum water and surface water with high dissolved concentrations (Arneborg et. al 2004: Nordberg et. al 2000). Deep water renewal comes in late winter or early spring and is driven by coastal wind driven upwelling. However, unlike Glacier Bay it has very small tides and therefore

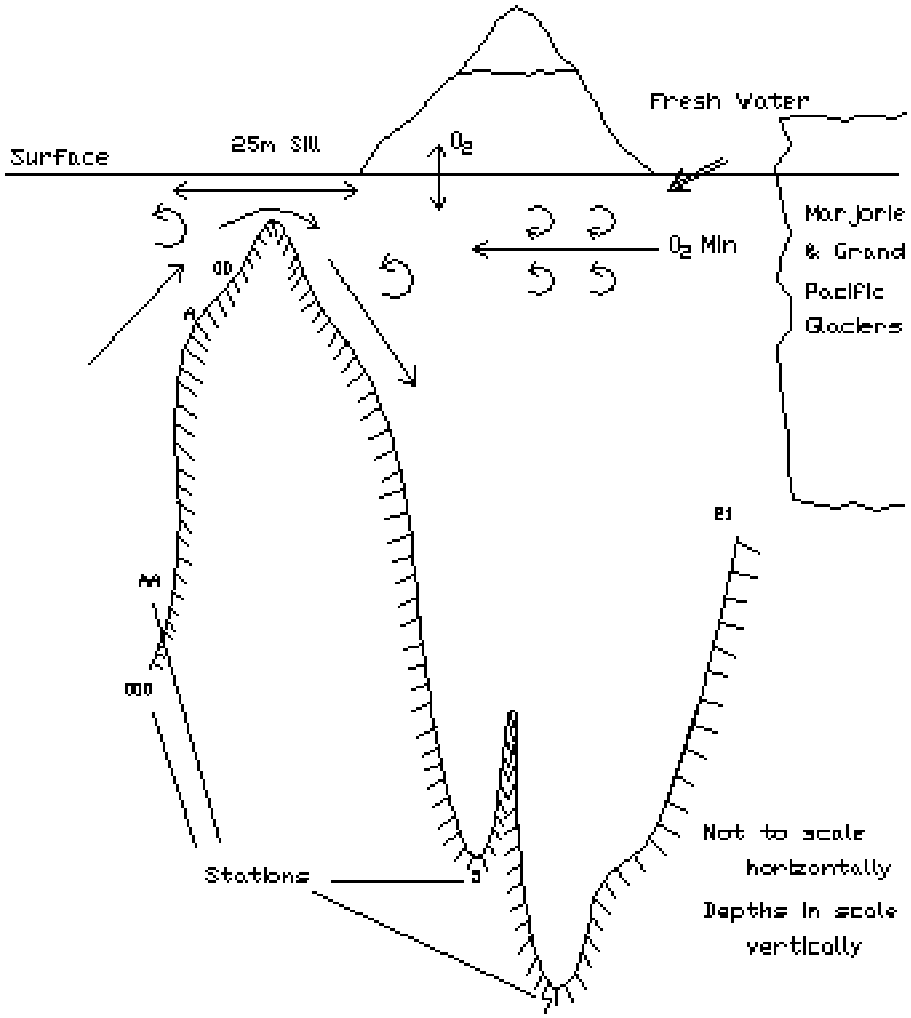

Figure 9: Overview of water renewal in Glacier Bay

much lower tidal currents. It has suffered from extreme low oxygen events in the past, with a deep basin oxygen value falling as low as 9.37 μmol/l in 1979 (Nordberg et. al 2000).

Hood Canal is not an isolated fjord, but part of Puget Sound. While Puget Sound does not exhibit the same characteristics as Glacier Bay due to much deeper sills and higher water exchange rates, Hood Canal has characteristics very similar to Glacier Bay. It has a shallow sill at 50m deep and is 200m in its deepest basin. It typically has deep water renewal in the fall or winter each year, also depending on coastal wind driven upwelling. It also exhibits the same, three layered stratification as Gullmar Fjord and Glacier Bay, but it changes seasonally into a more typical two layered structure (Warner et. al 2001). Hood Canal also suffers from frequent hypoxic and anoxic events, due not only to poor circulation but also to very low freshwater input to the basin, high nutrient input from residential coastal zones with subsequent high productivity.

Loch Sunart on the northwest coast of Scotland is also a deep basin at 124m behind a shallow sill at 33m. However, it has frequent deep water renewals every few weeks due to its exposure to the open sea and its very low fresh water inputs. Atypically, renewals are often interrupted during winter months due to prevailing westerly winds driven by the NAO

(Gillibrand et. al 2004).

Comparing these three basins with Glacier Bay does not clarify the unusual mid-level water renewal seen at Glacier Bay. The initial thought that the shallow sill is the only cause of the deep water renewal behavior for Glacier Bay is not proven by examining these other basins whose sills are equally shallow. There are clearly many variables to consider for each individual basin which control the frequency of the deep water renewal, as well as the characteristics of the water that comes in during the renewal cycle.

Conclusions

The original goals of this work were to determine the source of deep water within Glacier Bay using deep water dissolved oxygen values. At the same time, accumulate dissolved oxygen values to add to the dataset for the bay and also to examine how the bay compares to other similar silled fjord basins around the world. All three of these goals were accomplished with the following conclusions:

- Glacier Bay has deep water renewal by mid-level, light water coming over its unusually shallow sill
- Renewal may only occur during winter months when fresh water outflow is minimal
- Heavy water renewal, from deep sources, may only occur infrequently and only when storm, tidal or a combination causes enough of a surge to exceed the sill depth
- Comparison with other similar silled fjords is inconclusive as each appears to have different deep water renewal patterns even though they share many characteristics with Glacier Bay

Future work suggested in Glacier Bay would be a more thorough study of water movement over the sill with more frequent dissolved oxygen sampling at more locations and during all seasons and tides. It would also be good to add pre-stratification season dissolved oxygen data for the un-sampled stations to complete the baseline dataset.

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