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Hydrography and Circulation of Ice-marginal Lakes at Bering Glacier, Alaska, U.S.A.

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Abstract

An extensive suite of physical oceanographic, remotely sensed, and water quality measurements, collected from 2001 through 2004 in two ice-marginal lakes at Bering Glacier, Alaska—Berg Lake and Vitus Lake—show that each has a unique circulation controlled by their specific physical forcing within the glacial system. Conductivity profiles from Berg Lake, perched 135 m a.s.l., show no salt in the lake, but the temperature profiles indicate an apparently unstable situation, the 4°C density maximum is located at 10 m depth, not at the bottom of the lake (90 m depth). Subglacial discharge from the Steller Glacier into the bottom of the lake must inject a suspended sediment load sufficient to marginally stabilize the water column throughout the lake. In Vitus Lake, terminus positions derived from satellite imagery show that the glacier terminus rapidly retreated from 1995 to the present resulting in a substantial expansion of the volume of Vitus Lake. Conductivity and temperature profiles from the tidally influenced Vitus Lake show a complex four-layer system with diluted (~50%) seawater in the bottom of the lake. This lake has a complex vertical structure that is the result of convection generated by ice melting in salt water, stratification within the lake, and freshwater entering the lake from beneath the glacier and surface runoff. Four consecutive years, from 2001 to 2004, of these observations in Vitus Lake show little change in the deep temperature and salinity conditions, indicating limited deep water renewal. The combination of the lake level measurements with discharge measurements, through a tidal cycle, by an acoustic Doppler Current Profiler (ADCP) deployed in the Seal River, which drains the entire Bering system, showed a strong tidal influence but no seawater entry into Vitus Lake. The ADCP measurements combined with lake level measurements established a relationship between lake level and discharge, which when integrated over a tidal cycle, gives a tidally averaged discharge ranging from 1310 to 1510 $m^3 s^{-1}$.

Introduction

As a result of global warming, glaciers are receding and thinning world wide, (Dyurgerov and Meier, 1997; Arendt et al., 2002; Meier and Dyurgerov, 2002). Consequently, existing ice-marginal lakes are expanding and new ones are forming, examples include Mendenhall Lake, Alaska (Motyka et al., 2002) and Tasman Lake, New Zealand (Purdie and Fitzharris, 1999). As these lakes evolve, the associated lacustrine ecosystems will be controlled by the physical conditions that occur in each lake. The ice-marginal lakes of Bering Glacier provide a unique natural laboratory for the study of ice-marginal lakes, because the region contains numerous lakes of varying sizes and characteristics. In addition, Bering Glacier is a surging glacier (Post, 1969). The last surge ended in 1995, which resulted in an extended glacier position that was more out of equilibrium with the local climate than would have occurred if the glacier had not surged. Also, in recent years, south-central Alaska has experienced exceptionally warm summers (Alaska Climate Research Center). All of these factors have combined to produce extremely rapid thinning and retreat of the glacier. Hence, the ice-marginal lakes at Bering Glacier are expanding at a rate faster than would normally be expected, and as such, they act as high-speed analogs for other ice-marginal lakes.

Bering Glacier is the largest and longest glacier in continental North America, with an area of approximately 5175 km^2 and a length of 190 km. The entire glacier lies within 100 km of the Gulf of Alaska. Figure 1 shows the extent of Bering Glacier and the location of some of the landmarks mentioned in this paper. Bering Glacier alone is more than 6% of the glacier-covered area of Alaska and may contain 15 to 20% of Alaska's total glacier ice (Molnia, 2000). Because of its size and large freshwater discharge, it is a major component of the marine and terrestrial ecosystems of the Gulf of Alaska and its discharge is an important driving mechanism of the circulation in the Gulf of Alaska (Royer, 1979).

Bering Glacier exhibits surging behavior: a short period (1 to 2 yr) of rapid advance followed by a longer period (decades) of gradual retreat. It is the largest surging glacier in America, having surged at least five times in the 20th century, most recently from 1993 through 1995. Molnia and Post (1995) give a thorough review of the Holocene history of Bering Glacier up to the 1993–95 surge. The latest surge reversed the retreat of Bering Glacier, which had been taking place since the previous surge in 1968. However, Muller and Fleisher (1995) correctly anticipated that this advance would only be temporary and that the glacier would once again retreat after the surge had subsided. Our observations show that Bering Glacier is thinning and the terminus is retreating, continually increasing the size of Vitus Lake. Our measurements

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describe the retreat of the Bering Glacier terminus and the current hydrologic conditions that result from the complex interaction of tidewater glacier dynamics with both freshwater and seawater in a complicated bathymetric setting.

The entire Bering Glacier terminus region is also of great interest to the US Bureau of Land Management (BLM), which is mandated with managing this area under the pressure of competing interests. Anthropogenic activity in this region continues to increase, with observable impacts on pristine and unique natural habitats. The last 100 years have brought significant changes to the number of people and their methods of access to the Bering Glacier area. In the early 1900s most of the people visiting the glacier were subsistence hunters, fisherman, trappers, and gold prospectors. Oil exploration in the 1960s added the development of temporary roads. The passage of the Alaska Native Claims Settlement Act in 1971 began the process of conveying land under BLM administration to Alaska Natives. As part of this process, mineral rights in land near Berg Lake were conveyed to a local Native corporation which in turn sold the rights to an Asian corporation interested in developing the coal and oil potential. The 1990s brought sport fishing and big-game hunting cabins and lodges into the area. Two public-use cabins on the shores of Vitus Lake, built in 2002, have resulted in increased ecotourism in the area. Understanding the physical changes occurring in the ice-marginal lakes of the Bering Glacier system is necessary for BLM to formulate a management plan for this biologically diverse and environmentally significant wilderness area.

Berg Lake and Vitus Lake are of particular interest because their sizes and circulations are dominated by glacier advance or retreat, ice melting, subglacial and surface runoff, iceberg calving, terminus disarticulation, and a large sediment flux. Each lake has a significant portion of its margin at a calving glacier ice wall that extends to the deepest parts of the lakes. Furthermore, each lake receives surface runoff and subglacial discharge that probably carry a large sediment load. The lakes are different in that Vitus Lake is at sea level and is brackish, whereas Berg Lake is 135 m above sea level (a.s.l.) and is entirely fresh. An ice-penetrating radar study, carried out by D. Trabant, USGS and reported by Molnia (1993), showed that the bedrock below the medial moraine area between the Steller and the Bering lobes rises up to hydrologically separate the two lakes.

This paper presents the results of a bathymetric and hydrographic study of Berg and Vitus lakes that was carried out to determine the primary mechanisms that control the circulation, exchanges, and aquatic conditions in each lake. The data provide baseline information for future studies to understand changes in the physical setting as well as changes in fish and marine mammal distributions and populations. Indeed, Savarese (2004) has shown that the number or harbor seals in Vitus Lake can reach a population of 1000. The hydrographic measurements were made in August of 2001, 2002, 2003, and 2004. Analysis of these data have revealed surprising convective mechanisms, driven by the effects of suspended sediment, and the interaction of melting ice with both fresh water and salt water.

Bathymetric Data Collection and Analysis

DATA COLLECTION SYSTEM

Bathymetric data for Berg Lake and Vitus Lake was collected using a portable bathymetric survey system. This system includes an integrated survey-grade differential global positioning system (DGPS), fathometer, and surface temperature sensor. The fathometer transducer transmitted a 130 dB conical beam at 200 kHz with a width of $\pm 20^\circ$, and a laptop computer integrated and recorded the data. The complete system is roughly the size of an average suitcase and easily transported to remote locations, and we deployed the system in a 5-m inflatable survey boat.

BATHYMETRIC DATA COLLECTION

The bathymetric survey system was configured to take spatially referenced depth and temperature measurements at a time interval of once per second, which, at the typical speed of the survey boat (3.6 m s^{-1}), gave one data point approximately every 3.6 m. The comparatively small size, shallow water, and simple shape of Berg Lake simplified the bathymetric data collection, and the entire survey was completed in 2 days during 2001, resulting in over 12,000 data points. In contrast, because of the size, complex shape, and icebergs blocking portions of Vitus Lake, the complete survey required three field seasons—2002, 2003, and 2004. The resulting bathymetric data set contains approximately 100,000 data points.

There are several potential sources of error in the bathymetric data. In the deep basins, the fathometer would "lose" the bottom. This was particularly true of Vitus Lake where depths can exceed 150 m and where the bottom in deep basins bottom consists of a layer of loosely consolidated fine-grained glacial sediment that attenuates rather than reflects the acoustic signal. We obtained samples of the bottom sediment using oceanographic Niskin bottles and also found bottom sediment adhering to the Conductivity-Temperature-Depth instrument (CTD) after a deep cast. Where submerged portions of icebergs obscured the view of the lake bottom, a "double bottom" was detected, including a weak signal indicating the response from the ice and a stronger signal indicating response from the lake bottom.

Following data collection, we identified and corrected erroneous data points in two ways. If the error was due to depths exceeding the maximum detectable by the fathometer, the local maximum known depth was assigned to that location. Likewise, where a "double bottom" was identified, the deeper measurement was assigned. In contrast, if the depth value is invalid because the transition between lake bottom and open water was too gradual, a manual linear interpolation was applied between the nearest points of known depth (commonly over short distances). If the source of error could not be identified or easily fixed, the data point was removed from the dataset.

BATHYMETRIC INTERPOLATION

The objective of collecting bathymetric data is to generate a uniformly gridded surface that accurately represents the bottom of both Berg and Vitus lakes. Combining the bathymetry data with other spatial data, CTD observations for example, in a geographic information system (GIS) results in a powerful tool to organize and analyze the large amount of spatial and temporal that has been acquired from Bering Glacier lakes. The derivation of a uniformly gridded surface from the survey transects requires an interpolation technique that can adapt to highly convoluted shorelines and spatially varying depth samples along irregularly spaced transects. We used ordinary kriging, which offers the advantage of customizing the interpolation weights to the dataset as well as providing an estimate of the error in the predicted depth. Landsat 7 imagery provided the lake boundary. The depth was set to zero along the digitized shoreline, while along the glacier terminus, depths were set to the nearest measured depths.

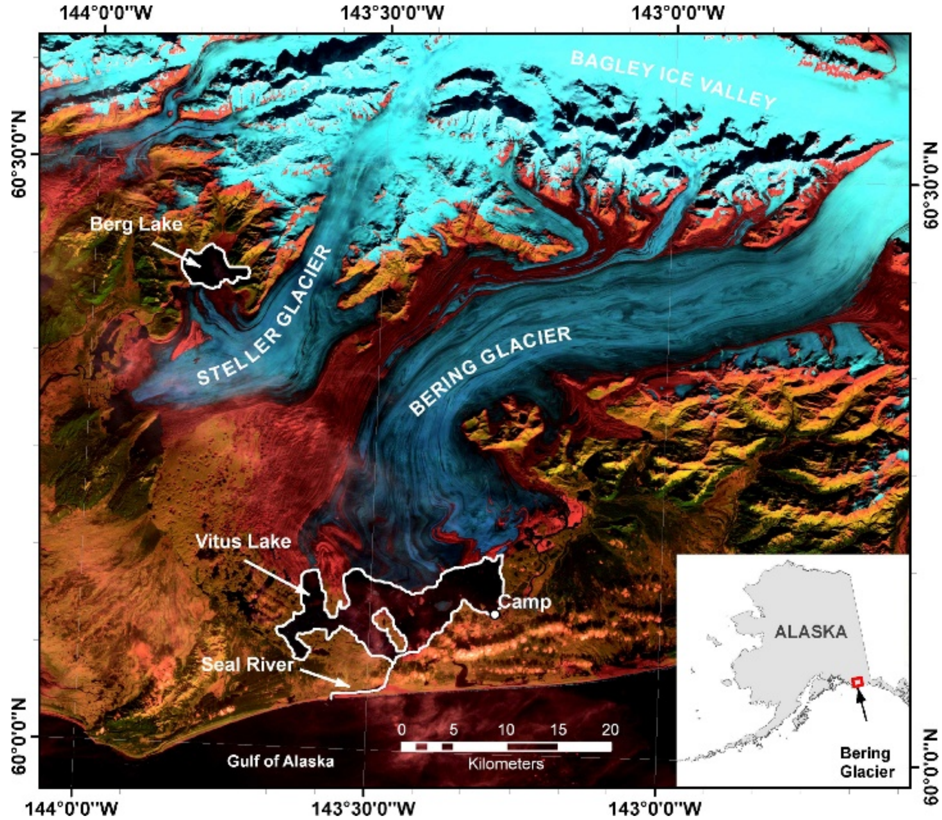

FIGURE 1. A Landsat 7 pseudo-color image from 29 September 2002 showing the Bering Glacier System and the location of several physiographic features cited in this paper.

A separate semivariogram model was developed (optimized using ESRI's Geostatistical Analyst for ArcGIS 9.0) for each lake based on the 12,000 sample points in Berg Lake and the 100,000 sample points in Vitus Lake. The smaller dataset and simple shape of Berg Lake resulting in a straightforward kriging based on a spherical semivariogram model with a major range of 3715 m, a partial sill of 771 m^2, a nugget of 21.9 m^2, a lag interval of 551 m with 12 lags, and a search neighborhood that included at least five points in each quadrant (areas bounded by the cardinal directions) yielding a grid with a 15-m posting. Although the kriging

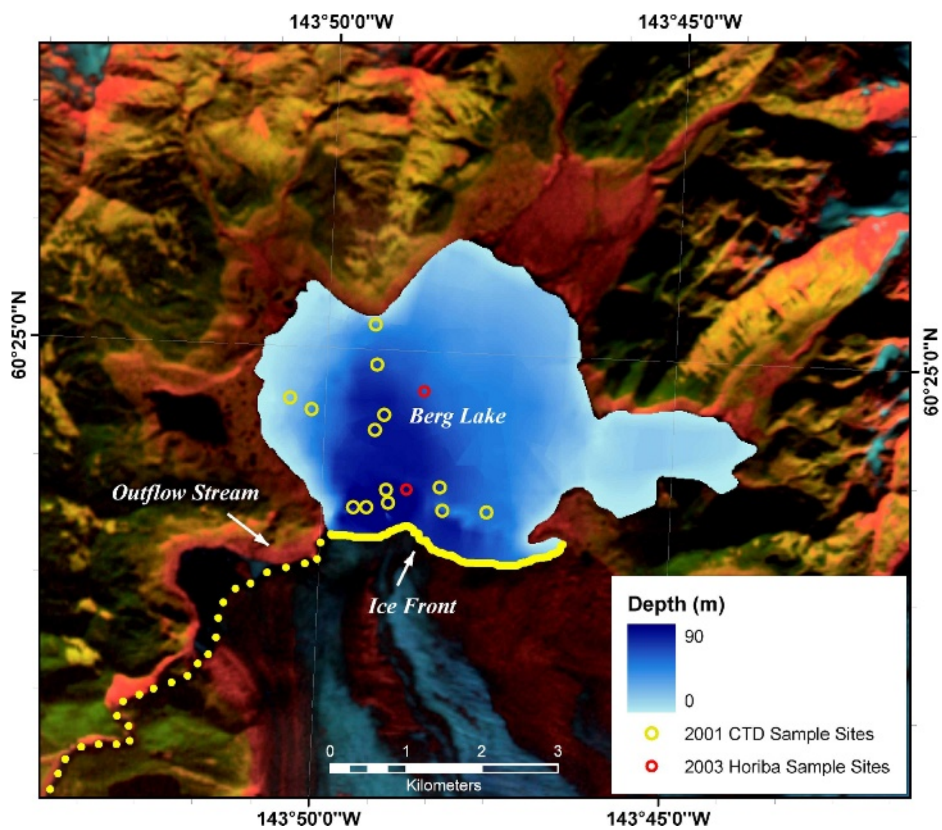

FIGURE 2. Shows the bathymetry of Berg Lake and the locations of the 2001 CTD and 2003 Horiba sampling sites overlaid on a Landsat 7 pseudo-color image from 29 September 2002.

algorithm could accommodate the entire 100,000 point data set from Vitus Lake, the initial interpolation produced a surface in which the survey transects were readily apparent as discrete breaks in the surface. We found that using every 10th sample point produced a natural appearing surface with a 30-m posting. The interpolation was based on an exponential semivariogram model with a major range of 7597 m, a partial sill of 1878.3 m^2, a nugget of 188.54 m^2, a lag interval of 1019.4 m with 12 lags and a search neighborhood that included at least 5 points in each quadrant.

HYDROGRAPHIC AND WATER QUALITY MEASUREMENTS

We used a Seabird oceanographic CTD to measure the depth profiles of salinity and temperature at various locations in each lake. In 2003, we measured the vertical distribution of pH, temperature, dissolved oxygen (DO), turbidity, total dissolved solids (TDS), and conductivity with a Horiba U-20 XD Series Water Quality Monitoring probe. A vertical water quality profile was generated by sampling every 1 to 2 m to a depth of 10 m and then sampling every 5 m to the bottom of the lake. These measurements, which are temperature corrected, were limited to a depth of 100 m due to the length of the instrument cable. Hand-held GPS receivers gave the location of each CTD and water quality parameter profile, and these spatially located data were incorporated into the Bering Glacier GIS. In 2003 and 2004, we used a USGS Acoustic Doppler Current Profiler (ADCP) to measure the discharge of the Seal River, which drains the entire Bering Glacier system into the Gulf of Alaska, and the Abandoned River, which emerges from the glacier terminus near the east end of Vitus Lake. Two Ott water-level gauges measured the water level in Seal River and at the east end of Vitus Lake near the BLM Bering Camp. For measurements in Berg Lake, a helicopter transported all of the equipment, including the boat to the lake. The observations in Vitus Lake were carried out from inflatable boats based out of the BLM field camp. Standard meteorological data, air temperature, wind velocity, barometric pressure, and relative humidity were collected throughout each summer season at a weather station at the Bering Camp airstrip.

Berg Lake

Berg Lake is perched at approximately 135 m a.s.l. behind an ice margin that is part of the Steller Glacier terminus (Figs. 1, 2). The ice front is oriented nearly east–west and is about 3 km long. The ice cliff is about 60 m above lake level and the western portion is the most dynamic with active calving and ice velocities towards the lake of approximately 1 m d^{-1}. There are numerous small streams in the valleys to the north that drain into Berg Lake. The only outlet stream flows to the west between the ice margin and a steep bedrock shore. Hence, a small glacier advance can dam the stream causing a rapid rise in lake level.

The lake level and size has varied considerably over the past century. Early maps of the region (Molnia and Post, 1995) show the Steller Glacier terminus much farther to the north, filling the present-day Berg Lake which created several ice-dammed lakes backed up in valleys that now contain streams. Strandlines on the mountains surrounding the lake indicate that the lake level has been as much as 140 m above its present level. A comparison of USGS vertical photography acquired during the 1993–95 surge period of Bering Glacier and in 2002 shows that the Steller Glacier terminus was 500 m farther north than its current position. In this advanced position, the terminus dammed the outlet stream located at the southwest corner of the lake, between the terminus and a bedrock promontory. From mid-March 1993 to mid-May 1994, the lake level rose from 140 m, which is near its current level, to 198 m. Failure of the ice dam in late May 1994 produced an outburst flood that inundated approximately 300 to 400 km^2 to the west. Photography from 7 September 1994 shows the lake level near 2001–03 levels.

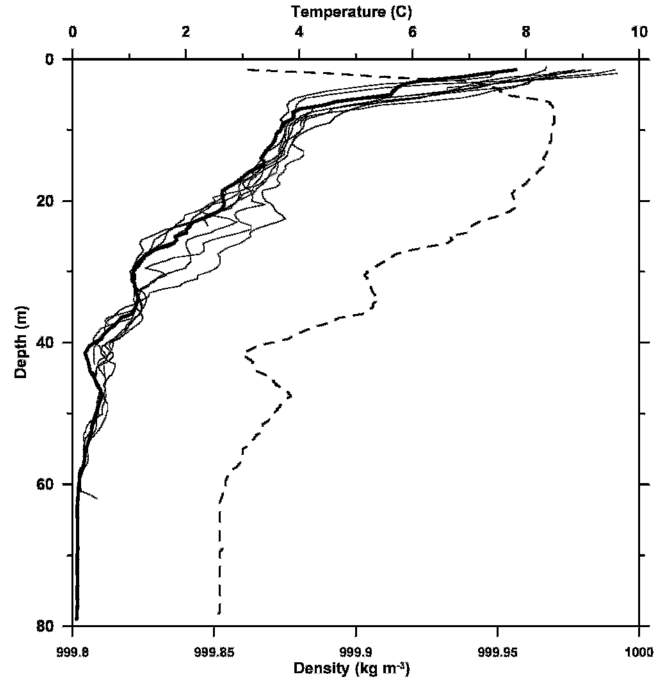

FIGURE 3. Temperature and density profiles from Berg Lake. The darker line is the profile from the deepest cast, the dashed line is the density profile from this cast using the equation of state for freshwater, and the fine lines are the temperature profiles from all of the casts.

BERG LAKE BATHYMETRY

Because of the small size of Berg Lake and its widely scattered icebergs, we were able to carry out the bathymetric survey in 2 days, 7–8 August 2001. Figure 2 shows the color-coded bathymetry of the lake merged with a portion of a Landsat 7 scene. The deepest part of the lake is approximately 90 m, located in the southwest portion of the lake, immediately adjacent to the most actively calving and fastest flowing part of the glacier terminus: A comparison of this bathymetry with that obtained by Austin Post of the USGS in 1996 (pers. comm., 2002) shows that no significant changes have occurred in either lake extent or in depth since that time. With the bathymetry processed into a grid, as described previously, we computed the 2001 volume of Berg Lake to be 0.48 km^3.

BERG LAKE HYDROGRAPHY

Surface Temperature

Situated in an amphitheater of mountains, open to the south, Berg Lake receives considerable solar radiation through the summer that warms its surface layers. The surface temperatures, which were measured by the temperature sensor on the acoustic depth sounder, reached nearly 14°C in the shallow bays away from the glacier terminus, particularly on the east side. These regions may be important fish habitats.

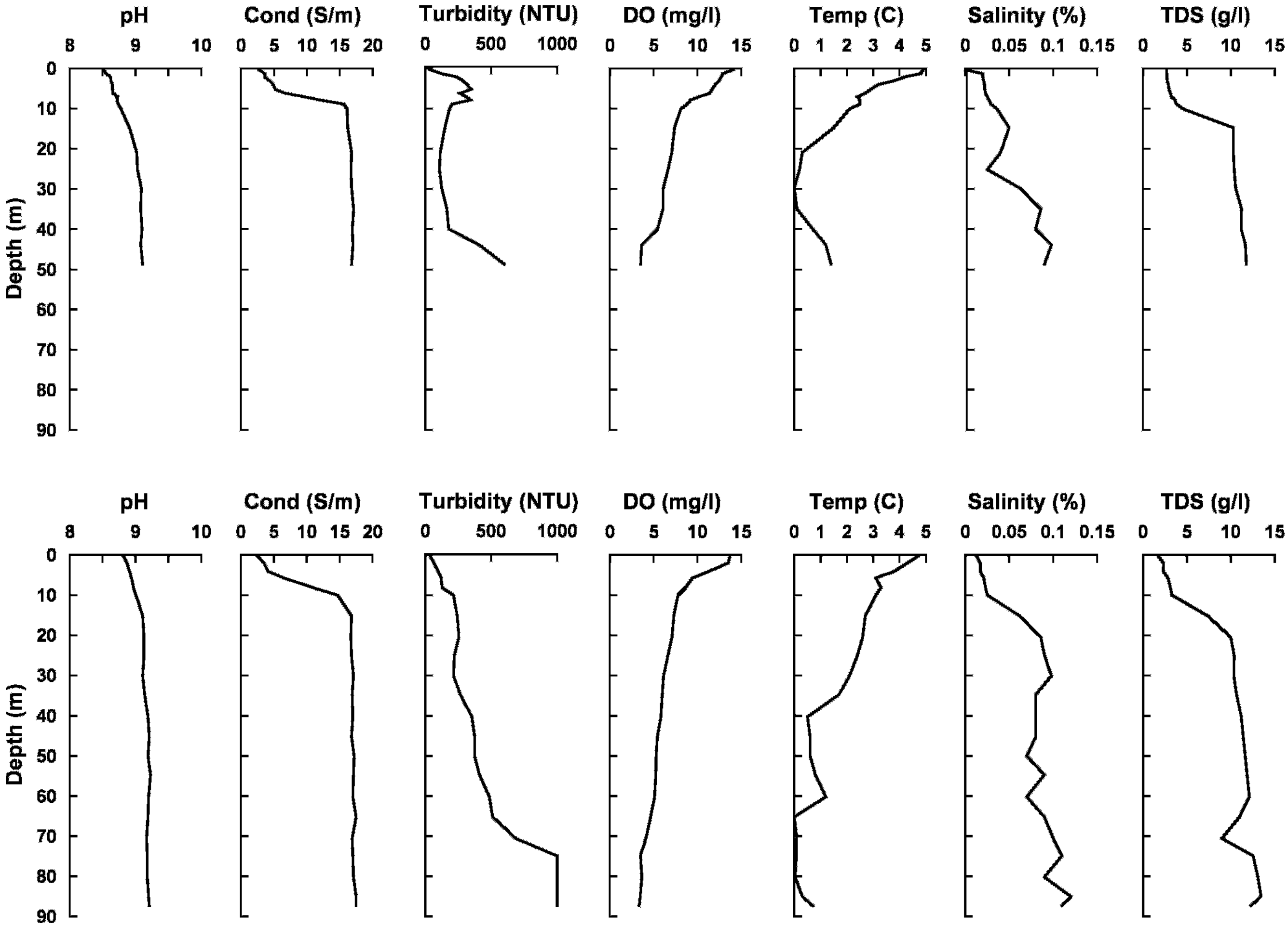

FIGURE 4. Water quality profiles for two deep casts in Berg Lake from 2003 (Measurements in the upper set were taken near the middle of the lake; the lower set was taken from closer to the ice edge in southwest Berg Lake, see Fig. 2.)

Vertical Structure

To determine the vertical temperature structure in Berg Lake we made nine CTD casts, the locations of which are denoted by the open yellow circles on Figure 2. Figure 3 gives the profiles. As expected, because the lake is well above sea level, we detected no appreciable salt in any of the casts. The general temperature structure found in Berg Lake consists of three layers. The upper layer extends from the surface to approximately 8 m, where the temperature equals the temperature of maximum density for freshwater, 4°C. In this layer the temperature decreases uniformly and rapidly with increasing depth, and the resulting strong stratification and turbid water act to contain the solar heating to this layer. The middle layer spans the depth region from 8 to 50 m, where the temperature decreases from 4°C to nearly 0°C, with high variability between casts. This layer contains numerous steps and inversions, with a vertical scale of 1 to 10 m that are characteristic of convective overturning, and the temperature can fluctuate by as much as 1°C about its mean value, particularly between 20 and 30 m in depth. The third layer extends from 50 m to the bottom, at 80 m, where the temperature remains nearly constant at slightly above 0°C.

At first inspection, these temperature profiles indicate an unstable situation with the densest water, that near 4°C, overlying less dense water, that colder than 4°C, as the dashed line in Figure 3 shows. The stabilizing factor is the discharge of sediment rich water from beneath the glacier into the bottom of the lake. The water quality measurements from Berg Lake, discussed in the next section, show that turbidity increases with increasing depth. Hence, the subglacial discharge that enters Berg Lake from beneath the Steller Glacier must contain a suspended sediment load that is sufficient to stabilize the water column. As the sediment settles out, convective instabilities form and overturning occurs, which produces the temporal and spatial variability observed in the temperature profiles. Also, the bottom of Berg Lake contains fine-grained soft sticky mud, which we found clinging to the CTD upon retrieving the instrument after each deep cast.

An additional component of the circulation in Berg Lake is the vertical convection generated by melting of the ice wall that forms its southern boundary and icebergs. The flow may be upwards or downwards depending on the water temperature within a few meters of the ice (Josberger and Martin, 1981), a result of the 4°C density maximum. For water temperatures between 0 and 4°C the meltwater is lighter than that at 4°C resulting in only upward flow. Water temperatures greater than 8°C produce only negatively buoyant meltwater and downward flow. For temperatures between 4 and 8°C, the buoyancy distribution across the boundary layer is both positive and negative, resulting in bidirectional flow. Given the vertical temperature distributions observed in Berg Lake (Fig. 3), the warm upper layer will cause rapid melting and the convection will be characterized by upward and downward flows. Below 10 m, the melt rate will decrease with decreasing water temperature, and only downward convection will take place.

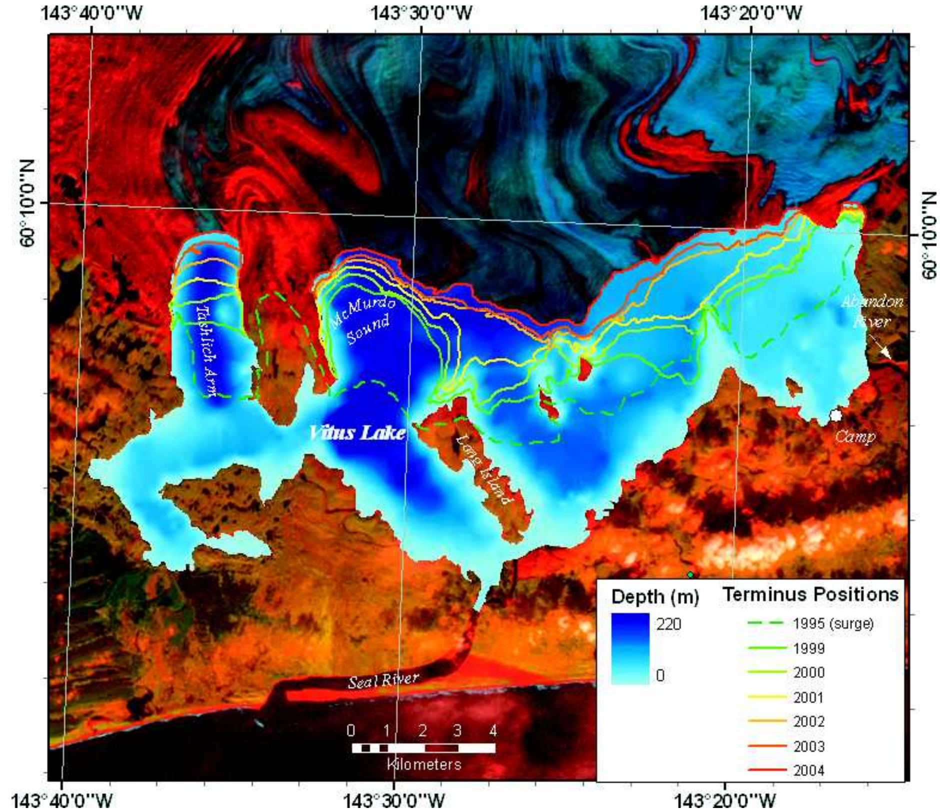

FIGURE 5. Terminus retreat of Bering Glacier from 1995 to 2004 and the bathymetry of Vitus Lake superimposed on a Landsat 7 pseudo-color image from 29 September 2002.

BERG LAKE WATER QUALITY MEASUREMENTS

In 2003 we measured water quality at two sites in Berg Lake, shown in Figure 2, and the profiles are shown in Figure 4. The observations show a relatively high pH value of 9 that is constant with depth. The conductivity, which is influenced by sediment in the water, is close to zero at the surface and reaches a maximum at 10 m. The turbidity values, which also reflect sediment in the water column, are quite high (250 NTU or greater) and increase with depth, a result of the both the previously described input of sediment laden water entering the lake from beneath the base of

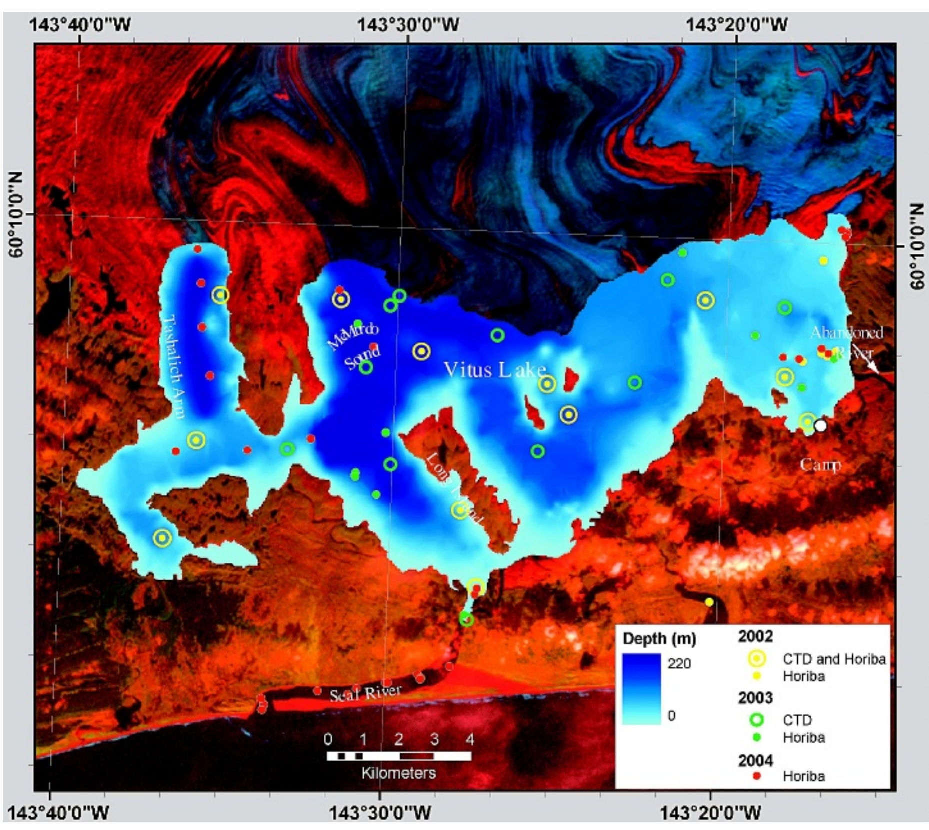

FIGURE 6. CTD and Horiba sampling locations in Vitus Lake for 2001 through 2004 superimposed on the bathymetry, with a pseudo color Landsat 7 image from 29 September 2002 as background.

TABLE 1

Volume and area of Vitus Lake during the study period (note: the elapsed time between 2002 and 2003 was only 5 mo).

	Volume			Area		
		Percent Change			Percent Change	
Year	km^3	Annual	Cumulative	km^2	Annual	Cumulative
1995	2.6	—	—	58.4	—	—
1999	4.4	67.0	67.0	80.6	38.0	38.0
2000	4.9	12.2	87.3	89.0	10.4	52.4
2001	5.4	10.4	106.8	96.2	8.1	64.7
2002	6.2	14.9	137.5	105.8	9.9	81.1
2003	6.4	4.0	147.0	108.8	2.9	86.3
2004	6.9	6.5	163.1	114.0	4.8	95.3

the glacier. The dissolved oxygen profiles show near saturation values in the surface layers that decrease rapidly to about 6 mg L^{-1} at 10 m and then slowly decrease with increasing depth. The temperature profiles, to the accuracy of the instrument, indicate no super cooled water at depth, which is consistent with the CTD temperatures from the previous year. The TDS profile for the site away from the ice, in general, follows the conductivity profile. The TDS profile near the glacier terminus also follows the conductivity profile, except for a minimum observed at a depth of 40 to 55 m. The cause of this minimum is not understood, but there are similar perturbations in the temperature and salinity profiles, which may be the result of the previously described circulation.

Vitus Lake

Vitus Lake (Figs. 5, 6) undergoes rapid changes in size, volume, and water characteristics with the Bering Glacier surge and retreat cycle. Situated nearly at sea level, we found that the lake contains seawater from the Gulf of Alaska, and it is a holding basin that receives the majority of water from the Bering Glacier system (Merrand and Hallet, 1996). Although Fleisher et al. (1998) describe some glacier discharge that enters the Tsiviat Lake Basin, to the east of Vitus Lake, Vitus Lake receives a large number of icebergs from the calving glacier terminus, subglacial discharge, and surface runoff from the glacier as well as runoff from the surrounding land. There is a large input of sediment-rich water at the surface from the Abandoned River at the far eastern end of the lake. The system drains into the Gulf of Alaska through the 8-km-long, 10-m-deep Seal River. As Bering Glacier rapidly retreats, Vitus Lake is rapidly expanding. Our bathymetry measurements act as a baseline measurement with which to gauge sedimentation rates as Vitus Lake expands.

VITUS LAKE BATHYMETRY

Vitus Lake continues to rapidly expand in both area and volume since the last surge ended in 1995. Due to the size and difficulty of navigating in the iceberg-clogged regions of the lake, it took three field seasons to fully map the bathymetry of Vitus Lake. Figure 5 shows bathymetry of Vitus Lake and retreat of the Bering Glacier terminus from 1995 to 2004, superimposed on a Landsat 7 false-color image acquired 25 April 2003. A comparison of this bathymetry to presurge measurements by Austin Post (pers. comm., 2005) shows that two are in general agreement. The deepest water in the lake is generally found adjacent to the glacier terminus, particularly in the central basin called McMurdo Sound, and farther west in Tashalich Arm where the depths reach and exceed 150 m. There is a sill at 50 m that restricts the circulation between the deep portions of Tashalich Arm from the rest of the lake, which results in very different deep water properties.

With a continuous surface representation of the bathymetry of Vitus Lake, calculating water volume is straightforward. Assuming that the bathymetry of the lake is relatively static over the 3-yr survey period, volume change can be estimated as a function of time as the glacier terminus retreats, which is derived from Landsat 7 imagery, generally from late summer or early fall of each year. Table 1 gives the lake area and volume estimates from 1995 through 2004.

Between 1995 and 2004, the volume of water in Vitus Lake increased by over 260% and the lake area increased 195%. The annual rate of increase in water volume has increased each year between 1995 and 2002, assuming the annual rate of change between 1995 and 1999 is constant as the glacier terminus retreated. Because the time interval between the 2002 and 2003 data points is only 5-mo, the rate of change appears to have decreased slightly.

VITUS LAKE HYDROGRAPHY

The surface temperatures for most of Vitus Lake range from near 0 to +2°C, except in an isolated bay in the far southwest end of the lake where, when, in the summer of 2001, the temperature reached 7°C. The surface temperatures are considerably colder than those observed in Berg Lake and likely results from large amounts of glacial melt water entering the lake at the surface and at depth. In addition, the Bering Lobe reflects, rather than absorbs solar radiation, as is the situation at Berg Lake, which tends to result in a cold katabatic flow down glacier onto the lake.

The CTD measurements in Vitus Lake, at the locations shown in Figure 6, revealed a complex vertical structure that is the result of the interaction of freshwater, seawater, and glacier ice in a complex bathymetric setting. Figure 7a shows three CTD casts in the deepest part of the main basin of the lake, McMurdo Sound The cast from 2001 was from the east side of Long Island (Fig. 5) because dense concentrations of icebergs conditions prevented us from entering McMurdo Sound which we were able to enter in 2002, 2003, and 2004. The hydrographic conditions below approximately 60 m have remained remarkably uniform over 3 yr, with a small change observed in 2004, which will be discussed later.

The basic structure of the water column consists of four distinct layers, which beginning at the top are:

Layer 1: A fresh surface layer from 0 m to about 30 m, with temperatures ranging from 0 to 2.5°C, and salinities ranging from 2 to 2.5 practical salinity units (psu).

Layer 2: A very cold intermediate layer from 30 m to about 55 m where the temperature is 0°C or less, and the salinity rapidly increases from 2 to about 18 psu.

Layer 3: A layer with remarkably uniform temperatures and salinities from about 55 m down to near the bottom. The salinity is near 18 psu, approximately one half the salinity of the Gulf of Alaska seawater, and the temperature ranges from 1 to 1.4°C.

Layer 4: A turbid bottom layer, as much as 10 m thick, which is composed of a high concentration of suspended, fine silt, from 30 to 300 gm L^{-1}.

This basic structure is found throughout the lake, the structure in shallower regions is a truncated version of that

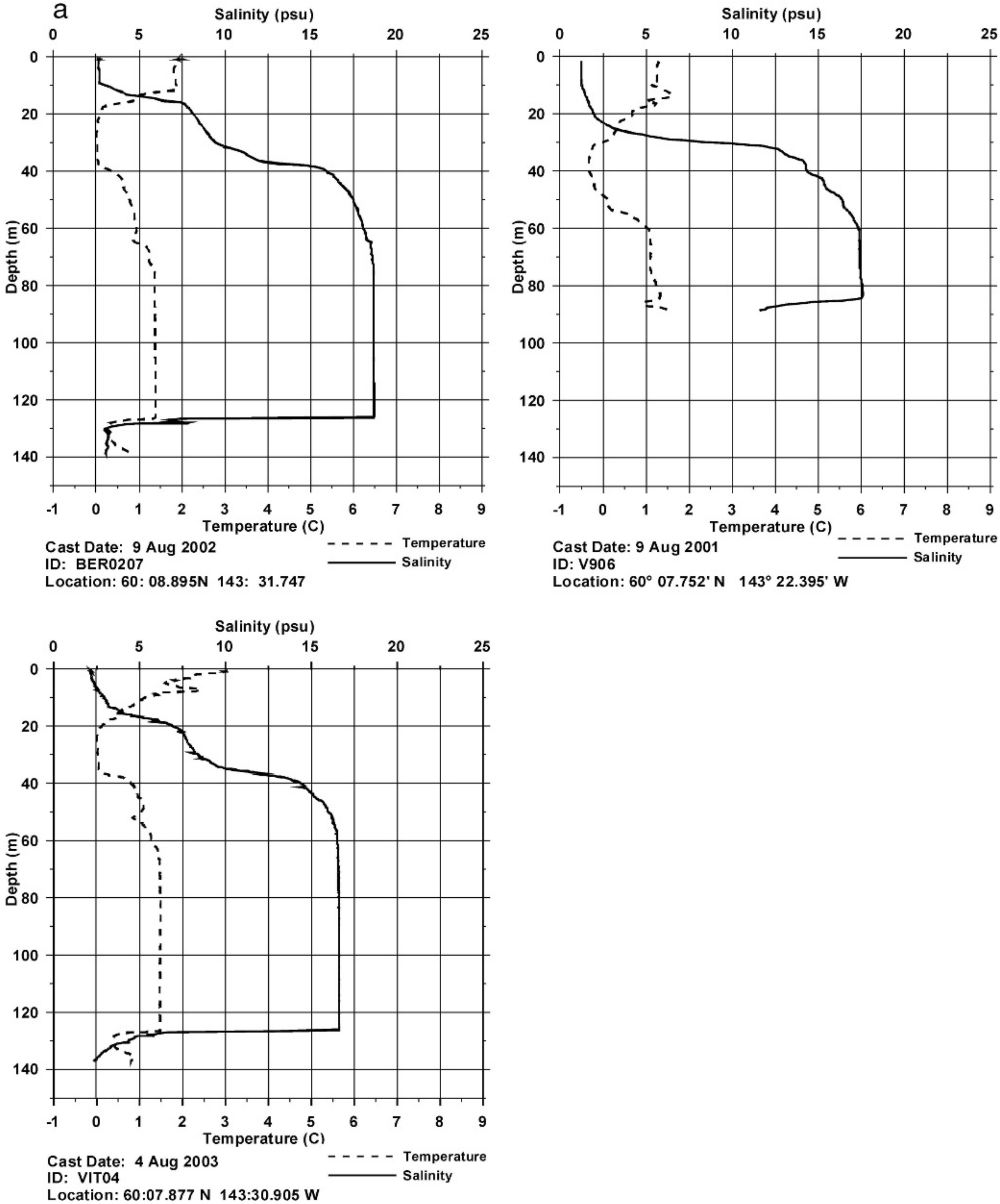

FIGURE 7a. Deep CTD profiles from Vitus Lake, for 2001, 2002, and 2003.

observed in the deep areas, except for Tashalich Arm where the aforementioned sill restricts deep water exchange below 50 m, which will be discussed later. The most spatially and temporally variable layer is the surface layer, which is modified by solar radiation, precipitation, and surface run off.

In the intermediate layer, the salinity distribution produces a highly stratified layer, which inhibits vertical exchange between the surface water and the deep water, thus isolating the surface layer from the deep layer. The temperature-salinity characteristics of the intermediate layer result from the combination of dilution

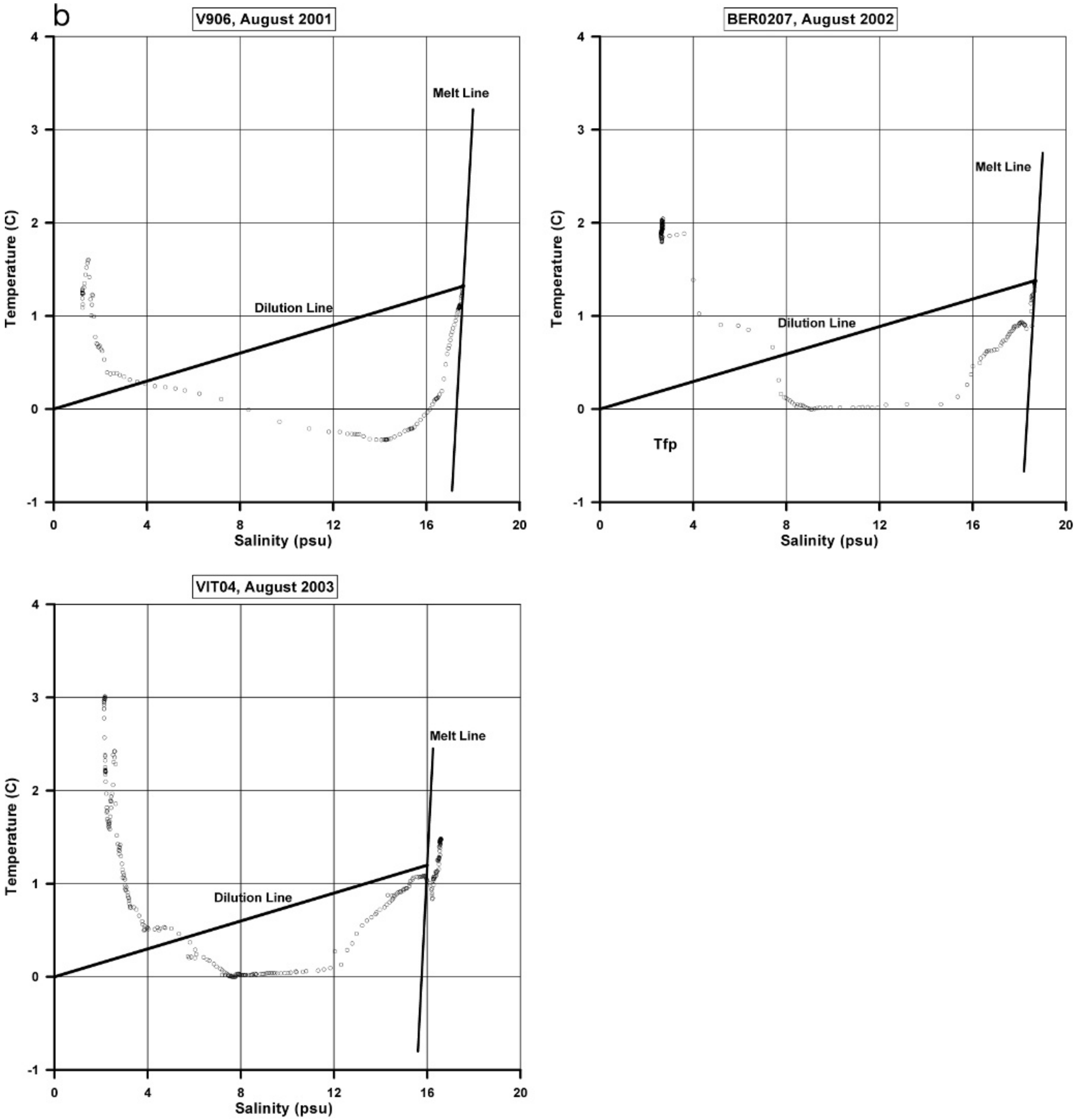

FIGURE 7b. Temperature and salinity (T-S) diagrams from Vitus Lake for 2001, 2002, and 2003, showing the internal water mass structure and its relation to the dilution line and the melt line.

of the deep layer with cold freshwater and glacier ice melting. When freshwater near 0°C mixes with the deep water, the case for subglacial discharge, the resulting mixture must lie on the dilution line shown on the T-S diagrams (Fig. 7b). Greisman (1979) and Gade (1979) show that when ice melts in salt water, the resulting mixture lies on a different line, called the melt line, the slope of which depends on the water temperature and salinity. For the cold saline deep layer, the melt line is quite steep (Fig. 7b), because the heat necessary to melt ice in cold water requires cooling a large amount of water.

As Figure 7b shows, the T-S properties for the intermediate layer lie between the dilution line and the melt line. The water at the bottom of the intermediate layer has the characteristics of melting, while water in the upper part of the layer takes on more of the characteristics of dilution. The T-S diagrams also indicate a change in the relative proportion between dilution and melting for the different years. In 2001, the intermediate layer was more characteristic of melting than of dilution, for both 2002 and 2003. The temperature for 2001 was below zero Celsius from 30 to 50 m, indicating a greater impact from melting for this year. This trend may be the result of several factors. First, the lake greatly expanded in volume over these years. Second, the number and concentration of icebergs in the lake decreased, which suggests a reduction in the amount of upwelling generated by deep melting.

The convection in Vitus Lake is also generated and controlled by dilution and melting processes. As shown by Walters et al.

(1988) and Motyka et al. (2003), temperate tide-water glaciers in this region generate large subglacial discharges that rise in a plume next to the glacier terminus. Also, the discharge typically occurs in the deeper regions of the lake entraining water from the deep saline layer as it rises. This results in a mixture that is denser than the surface layer and flows horizontally away from the glacier terminus as it encounters the strong pycnocline at the bottom of the surface layer (Huppert and Josberger, 1980; Neshyba and Josberger, 1980; Josberger and Martin, 1981). In our surveys we did not notice specific upwelling plumes along the ice front, which suggests that if plumes exist they do not reach the surface but rather flow out laterally when they encounter the strong capping pycnocline.

VITUS LAKE WATER QUALITY MEASUREMENTS

Figure 6 also shows the location of the water quality profiles made in 2002, 2003, and 2004. Figures 8 and 9 show a representative water quality data set, profiles of dissolved oxygen (DO), pH, total dissolved solids (TDS), and turbidity measurements plotted with co-located profiles of temperature and salinity, one from McMurdo Sound and one from Tashalich Arm. In McMurdo Sound the pH is uniform with depth, at a value of just under 6. However, TDS follows the salinity distribution; at a minimum of just under 3 g L^{-1} in the surface layers and increases to a maximum of 19 g L^{-1}. The DO has a surface value of approximately 11 mg L^{-1}, then decreases to 7.5 mg L^{-1} at a depth of 20 m, then slightly increases to 8.2 mg L^{-1} for the rest of the profile. We only obtained two turbidity values (NTU) for McMurdo Sound due to sensor problems, but those values at 40 and 50 m depth indicate clear, relatively sediment-free, highly oxygenated water, which could support a robust set of aquatic organisms, as indicated by the rapidly growing population of harbor seals. This clear water is a result of the removal of the suspended sediments by flocculation when it mixes with the saline water in Vitus Lake.

Tashalich Arm is the deepest basin in Vitus Lake with water depths exceeding 150 m, the length of line used to lower the CTD. It is frequently filled with large icebergs that calve off the western portion of the Bering Lobe. As observed in 2004, catastrophic calving events across the entire terminus can rapidly fill the fiord with icebergs of all sizes. Prior to this event, we noted water lines that result from wave-induced heat transfer (Josberger, 1978) on the terminus face bowing upward, indicating the ice was deforming as a result of flotation. Waves from the calving event of 2004 stranded floating ice blocks with a characteristic size of 1 m, high and dry on the beach above the water level.

Temperature, salinity, and water quality profiles in Tashalich Arm (Fig. 8) are dramatically different from those observed in McMurdo Sound (Fig. 9), especially below 18 m. For the surface layer, above 18 m, both parts of the lake have similar properties, but from this depth to 55 m, the sill depth, the temperature and salinity are nearly constant at +0.1°C and 6.1 psu in Tashalich Arm, while the salinity in McMurdo Sound rapidly increases to 15 psu and greater. The deep water of Tashalich Arm, >55 m, is isothermal at −0.16°C and isosaline at 1.9 psu, which is water at its salinity determined freezing point. This is the result of the large amounts of ice at depth, large ice bergs, and a deep terminus, and little exchange of water with the main basin. The large flux of ice into Tashalich Arm and the likelihood of a great deal of subglacial discharge will generate only outflow over the sill, thus preventing the more saline water of Vitus Lake from entering the arm.

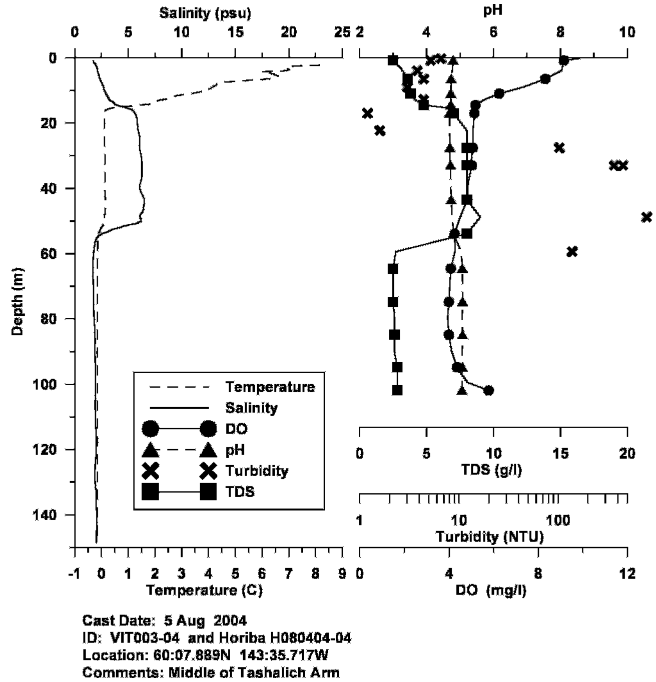

FIGURE 8. Vertical profile of CTD sampling in Tashalich Arm plotted along with coincident Horiba parameters (pH, DO, Turbidity, and TDS).

Figure 8 also demonstrates the impact of the sill and little exchange with the main portion of the lake. The dissolved oxygen has a surface value of approximately 8.5 mg L^{-1}, which decreases rapidly to 5 mg L^{-1}, and then remains at this value to 100 m. In the main basin, DO remains near 8 mg L^{-1} at all depths. Likewise, TDS values are quite low at depth in Tashalich Arm, about 2.5 g L^{-1}, but near 18 g L^{-1} in McMurdo Sound. The pH values for Tashalich Arm are approximately uniform with depth at a value of 5, while in the main basin the pH is at 6. (Recall that the pH for Berg Lake was near 9.) The turbidity values for Tashalich Arm indicate the surface water is relatively clear of glacier rock flour, but the turbidity increases in the isohaline layer to values of 20 NTU.

LAKE LEVEL AND ADCP MEASUREMENTS

To determine the conditions necessary for seawater to enter Vitus Lake through Seal River, the only reasonably possible source, we measured water levels, using an arbitrary datum, in Seal River and Vitus Lake and carried out Acoustic Doppler Current Profiler (ADCP) discharge measurements in Seal River. Figure 10 shows the measured time series of water levels from both sites, Seal River and Vitus Lake, and the NOAA tidal predictions for Yakutat, 220 km to the east, for the period 1–12 August 2003. The tide at Yakutat is a combination of semidiurnal (~12 h) and diurnal (~24 h) components with a mean range of 2.38 m and a spring range of 3.07 m.

For Seal River, both the semidiurnal and diurnal components are clearly evident, although the tidal range is attenuated to approximately 2 ft. (Water levels are in feet because the NOAA tidal predictions are given in feet and our instruments record in feet.) The peaks and troughs in the record from Seal River are nearly in phase with the NOAA predictions for high and low water at nearby Wingham Island, 50 km to the west. At the east end of the lake, the tidal range is further attenuated to about 1 ft and the semidiurnal portion of the signal is virtually gone. The diurnal

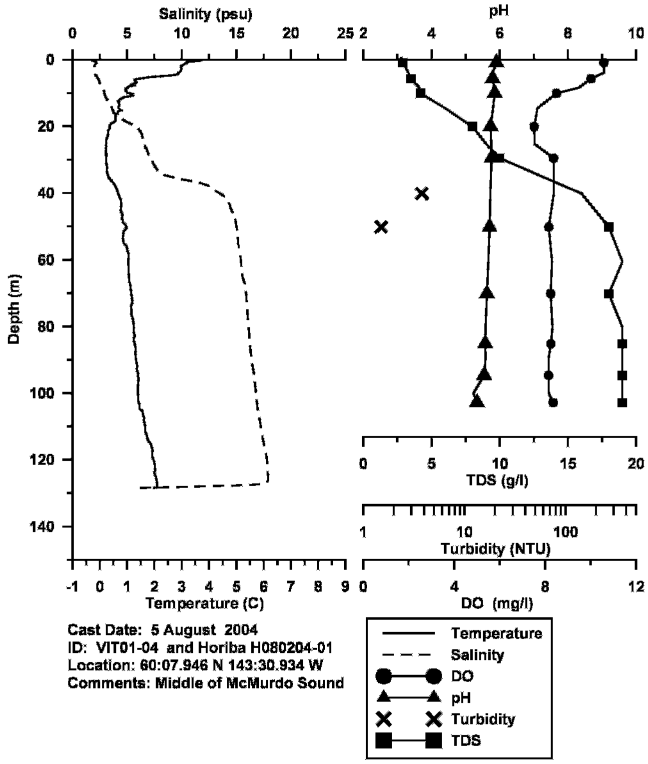

FIGURE 9. **Vertical profile of CTD sampling in McMurdo Sound plotted along with coincident Horiba parameters (pH, DO, Turbidity, and TDS).**

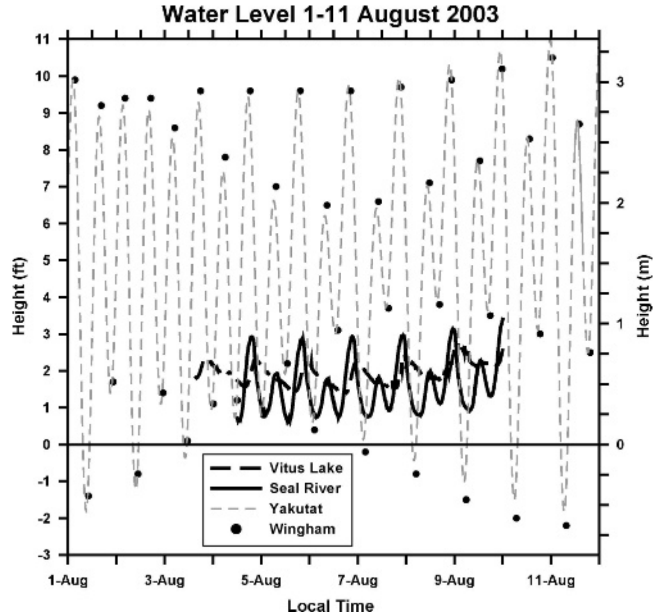

FIGURE 10. **Times series plot of the lake level variations from Seal River and Vitus Lake, sites and the NOAA tidal predictions for Yakutat and Wingham Island. Note the Seal River and Vitus Lake time series are plotted at an arbitrary height.**

signal has more of a sawtooth shape, where the lake level rises rapidly and then slowly decreases. Towards the end of the record the average lake level rose in response to the increase in tidal level. Precipitation was not the cause of the rise in lake level; records from the BLM Camp weather station show that the last significant precipitation event was on 30 July 2003 when 3.8 cm of rain fell.

To measure the discharge of both Seal River and the Abandoned River we used a USGS Acoustic Doppler Current Profiler (ADCP), deployed from an inflatable boat. At Seal River on 4 August 2003, we carried out 16 transects across the river, which spanned a flood tide (Fig. 11). On 7 August, we carried out an additional 8 transects during the early part of an ebb tide. The flow in Seal River strongly depends on the tidal level in the Gulf of Alaska. Figure 11 shows that the river discharge slowed to near zero at high tide and reached a maximum of 2039 m^3 s^{-1} at low tide. Observations near high tide (9.6 ft [2.93 m], 1925 ADT, 5 August 2003, at Wingham Island) showed that the surface flow in Seal River did reverse and flowed into the lake at the time of high tide. We measured the surface velocity by tracking the drift of our inflatable boat with a GPS. The river centerline surface velocities were 1.5 km h^{-1}, and there was no wind during the drift period. Five CTD casts, over the time span from 1850 to 2000 ADT, while the river flow had reversed, found uniform vertical temperature and salinity conditions of 2.5°C and 2.8 psu, which were characteristic of the upper 10 m of Vitus Lake. We found no evidence of Gulf of Alaska seawater entering the lake at the bottom of the river.

Our measurements show that the discharge from Vitus Lake to the Gulf of Alaska, through the Seal River occurs as a tidally driven series of pulses (Fig. 12). To compute the average discharge of Seal River averaged over a tidal cycle, we used the time series of water level measurements from Seal River with the ADCP flow measurements to establish a tidally varying relation ship between river height and discharge (Fig. 11). This is analogous to a conventional hydrologic rating curve except that it is inverted, when the water level increases, the flow decrease, and conversely. As shown in Figure 12, we used our rating curve to compute a time series of discharge, and then numerically integrated the discharge time series over the tidal cycle to obtain the average. The average flow over a tidal cycle ranged from 1310 to 1510 m^3 s^{-1}. The average discharge has a decreasing trend which is a result of increasing tidal heights (Fig. 10). Using these values for discharge and the measured lake volume gives an estimate for the residence time of approximately 2 mo.

At Abandoned River, we made four discharge transects on 5 August 2003, during the period 1415 to 1450 ADT, and the

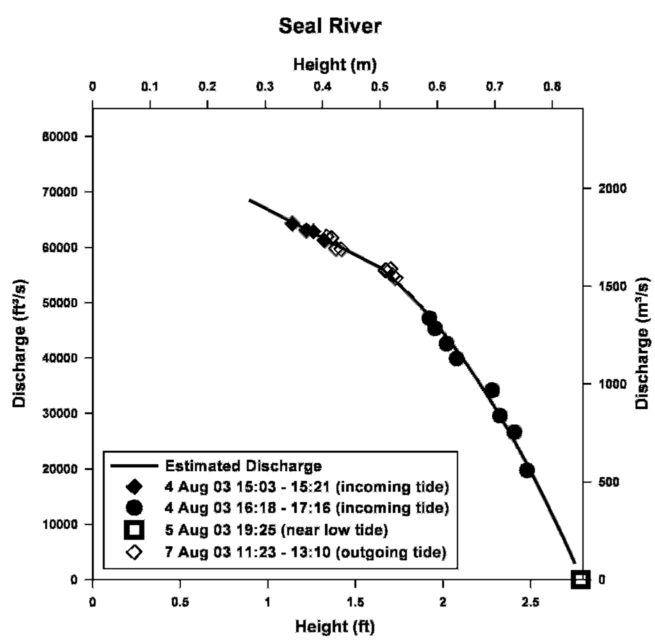

FIGURE 11. **Stage-discharge relationship for Seal River.**

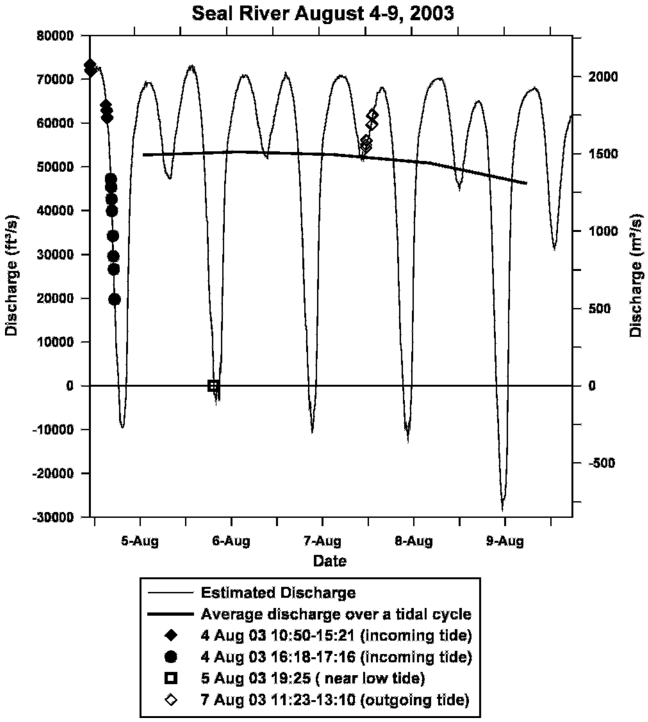

FIGURE 12. Tidally varying discharge and discharge averaged over the tidal cycle for Seal River computed from the river stage and discharge relationship. The symbols show when the discharge measurements were made through the tidal cycle.

average discharge was 585 $m^3 s^{-1} \pm 12 m^3 s^{-1}$. We made the measurements at the mouth of the river rather than in the river because river conditions were too hazardous. The surface velocity was about 10 km h^{-1} with 0.3 to 0.6 m standing waves. By doing so we missed a small branch of the river that was too shallow to measure; we estimate that the flow in this branch was less than 5% of the measured flow.

For 2002 and 2003, we took surface water samples in the main stream of Abandoned River to determine the sediment load. The USGS Cascade Volcano Observatory analyzed these samples and the sediment concentration was 2520 and 2829 mg L^{-1}, respectively. When combined with the ADCP measurements yields a sediment flux of approximately 127,000 metric tons per day (t d^{-1}) (or with a nominal sediment density of three times that of water, yields approximately 4.3×10^4 $m^3 d^{-1}$) into Vitus Lake during summer discharge conditions. Furthermore, this value represents a minimum flux on this day as the sediment concentration increases with depth. Fleisher et al. (2003) estimate the average sediment flux from the section of the glacier to be 227 $\times 10^6$ m^3 for the 10-yr period 1991 to 2000, for a daily average of 6.2×10^3 $m^3 d^{-1}$. Given that our determination was made during peak summer flows and that of Fleisher et al. (2003), included the winter months when the flow is low, these sediment flux values are in reasonable agreement.

As Merrand and Hallet (1996) describe, the majority of the sediment flux into Vitus Lake remains in the lake. The large grains settle out immediately at the mouth of the river, while the very fine grained material spreads throughout the lake where salt, even in low concentrations, causes the sediment to flocculate, and settle in the deep basins of Vitus Lake. This process, for all sediment sources, produces the 10-m-thick bottom layer in the deeper basins of the lake that we observed in the CTD measurements as layer 4.

When compared to the flow of the Abandoned River into Vitus Lake, the outflow by Seal River is 2.5 to 3 times greater. Hence, there must be significant inflow from other sources to maintain a nearly constant lake level. Immediately prior to and during these measurements there was no rainfall. Hence, a subglacial discharge of approximately 1000 $m^3 s^{-1}$ must be occurring along the extensive terminus front, probably from a series of subglacial channels (Fleisher et al., 1998). Walters et al. (1988) determined the seasonal subglacial discharge from nearby Columbia Glacier, also a tide-water glacier. There the discharge for the summer reached 300 $m^3 s^{-1}$ and approached 0 during the winter when the hydrologic system is frozen.

SEAWATER ENTRY INTO VITUS LAKE

The presence of salt in Vitus Lake is not surprising considering the lake is nearly at sea level. The intriguing question is, What circumstances allow Gulf of Alaska seawater, with a typical salinity of 32 psu, to enter the lake and form the deep water with a salinity of about 18 psu? Certainly, high tides are necessary to allow salt water to enter the lake. Observations in Seal River on 5 August 2003, at the time of a +2.9 m tide at Wingham Island, show a 2 km h^{-1} flow into the lake. However, CTD observations showed that the entering water had the same salinity and temperature as the upper 10 m of the lake; hence the inflowing water had pooled at the mouth of the river and was returning. Furthermore, it would take seawater more than 3 h to traverse the 9-km-long Seal River and reach the lake. In this amount of time the tide would have ebbed sufficiently and the flow will once again be out of the lake.

Seawater entry is highly episodic and most likely during the winter when the melting of snow and ice ceases and the flux of freshwater entering the lake virtually ceases. However, the 3-yr CTD record shows a remarkably well mixed deep layer that is nearly constant over 2 yr. The complete absence of vertical structure indicates that the current state is probably the result of a single mixing event, rather than numerous events which would have certainly generated vertical variations in both the salinity and the temperature.

The most likely singular event that may have produced the deep water is the impact of the remnants of typhoon Oscar, on the Bering region of the Alaska coast in the fall of 1995, just after the surge had ended. At this time Vitus Lake was at a minimum size, at one half its 2003 volume. Anecdotal reports from aircraft pilots familiar with the area reported that the land separating Vitus Lake from the Gulf of Alaska was completely inundated by the associated storm surge. It is possible that other mechanisms may introduce seawater into Vitus Lake, but we believe that the most plausible is reverse flow through the Seal River during extreme events.

Concluding Remarks

This study has used hydrographic observations to define the primary mechanisms that drive the circulation and exchanges in the ice-marginal lakes at Bering Glacier, Berg Lake, and Vitus Lake. Striking differences were found between each lake. In Berg Lake, we have found that the circulation is driven by the input of fine-grained sediments from subglacial water entering the lake. For Vitus Lake, salt from Gulf of Alaska seawater, a complicated bathymetry, sediment input, and ocean tides act to produce a highly complex circulation. The presence of salt in Vitus Lake acts to confine the input of fine-grained sediment in the lake by promoting flocculation and settling, resulting in a clear blue lake. In contrast, Berg Lake, which has no salt, is quite turbid and significant amounts of the fine-grained sediment input leaves the lake via the outlet stream. Berg Lake has remained nearly constant in size; while Vitus Lake has rapidly increased in both size and volume and is likely to continue do so. The surface temperatures in Vitus Lake rarely exceeded 3°C, while in Berg Lake surface temperatures reached 14°C in the shallow bays away from the glacier terminus, particularly on the east side; these regions may be important fish habitats. With the diverse conditions observed in these two lakes, they represent analogs to other ice-marginal lakes during a period of deglaciation.

Wang et al. (2004) have stated: "The freshwater discharge into the Gulf of Alaska (GOA) has an important effect on coastal circulation." These authors also estimate that the mean annual total freshwater discharge into the Gulf of Alaska is between 19,000 and 31,000 $m^3 s^{-1}$. Given this recent estimate for the entirety of the Gulf of Alaska, our measurement of the relative contribution of the Bering Glacier system, through the Seal River discharge, is significant. The discharge of the Bering Glacier system, at peak summer melt, is on the order of 5 to 7% of the total average annual flow into the entire Gulf of Alaska (Schumacher and Reed, 1980; Royer, 1979, 1981). Hence, the Bering Glacier discharge is a significant driving mechanism of the local circulation in the Gulf of Alaska.

The calculated sediment flux into Vitus Lake through the glacial discharge of the Abandoned River was on the order of 127,000 t d^{-1}. Given this large flux of glacial sediment, significant bathymetric changes to the lake and its associated ecosystem should be anticipated. Fortunately, a previous hydrographic survey of Vitus Lake was completed, prior to the surge of 1993 (Austin Post, pers. comm., 2005). Due to the recent and rapid retreat of the postsurge ice edge, it now appears that the size and extent of Vitus Lake is now similar to the time of Post's survey. Similarly, the recorded bathymetry is also comparable. It is anticipated that the large sediment flux will begin to modify this bathymetry. The bulk of the sediment load from the abandoned river is deposited in the eastern most basin of Vitus Lake and is blocked to the west by the presence of a north–south trending, subsurface ridge.

Given current climate change scenarios, as exemplified by recent record setting hot summers in south-central Alaska, we expect that the Bering Glacier system may undergo dramatic changes in the next few decades. The strong negative glacier mass balance in the region (Arendt et al., 2002) and the resulting glacier thinning may extend the time between surges by Bering Glacier, or possibly eliminate the surge behavior entirely. In either case, Bering Glacier will continue to retreat to the point where the bedrock topography is at sea level. Ice-penetrating radar measurements reported by Molnia and Post (1995) show that bedrock topography reaches sea level approximately 40 km up valley from its 2004 position. Our measurements show that the average rate of terminus retreat is approximately 1 km a^{-1}. Hence, we expect that in the coming decades Vitus Lake will greatly expand in size and volume. Increasing lake volume will alter the circulation in the lake; the impact of seawater intrusions will be reduced. Furthermore, there will be relatively less ice in the lake which will reduce the amount of melt-driven vertical convection. These changes will have unknown ramifications on the extent and diversity of the ecosystems in and around Vitus Lake.

The hydrography of Berg and Vitus lakes and the associated ecosystems are dominated by the dynamic processes of Bering Glacier. The hydrological data collected and reported in this paper serves as a baseline to understand future changes in the rapidly evolving system. The established GIS framework will continue to serve as a tool to provide insight into environmental habitat changes due to glacier dynamics as the hydrological system is monitored on an annual basis.

Acknowledgments

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