Glacier Wastage and the Marine Ecosystems of the Gulf of Alaska

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Introduction

Figure 1. The Gulf of Alaska is a rich and complex ecosystem with many competing interests.

The large glaciers that border the Gulf of Alaska are integral components of the rich marine ecosystems of the region that range in size from estuaries to major ocean circulation features, such as the Alaska Coastal Current. Accelerating glacier wastage will have significant effects on the various ecosystems in the region as illustrated in figure 1. The retreat of tide water glaciers will generate new fjord-like estuaries with complex physics that include the interaction of sea water, glacier melt, and basin runoff. Observations from Glacier Bay show that glacier-fed estuaries can be highly productive systems, but Vitus Lake at Bering Glacier remains oligotrophic. Royer and Grosch (2006) show that the water in the Gulf of Alaska is freshening and becoming more stratified, which is consistent with the observed glacier wastage that is occurring in this region (Ahrendt and others, 2002). Furthermore, the Alaska Coastal Current will accelerate in response to additional coastal runoff, and possibly shift the coastal ecosystem 300 kilometers to the west (Royer and Grosch, 2006). This shift, when combined with increased stratification and decreased salinity will impact the entire marine ecosystem of the Gulf of Alaska, including the economically important salmon and halibut fisheries.

Bering Glacier is the largest and longest glacier in continental North America, with an area of approximately 5,175 square kilometers, and a length of 190 kilometers (fig. 2). Bering Glacier alone covers more than 6 percent of the glacier covered area of Alaska and may contain 15–20 percent of Alaska's total glacier ice. Because of its size, it is a major component of the marine ecosystems of the Gulf of Alaska. Bering Glacier also is the largest surging glacier in America, having surged at least five times in the 20th century, with the last surge occurring from 1993 to 1995. Bering Glacier is now rapidly retreating and thinning as a result of processes that are accelerating due to a warming climate (fig. 3). The USGS and Michigan Technology Research Institute (MTRI) developed and directed a multidisciplinary study of the Bering Glacier for the U.S. Bureau of Land Management to provide baseline observations of glaciological, hydrological, and biological properties and to investigate critical governing physical processes.

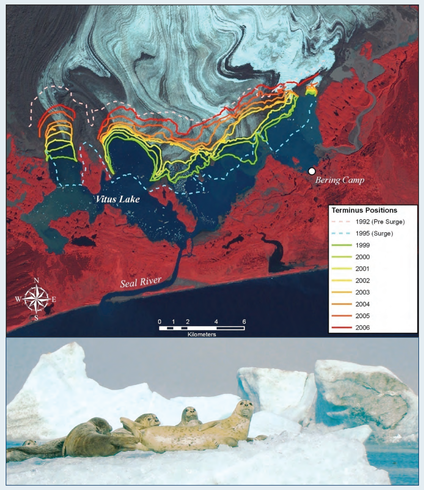

Figure 3. The retreat of Bering Glacier from 1992 to 2006 mapped from visible and radar satellite imagery. On average, the retreat has been approximately 0.5 kilometer per year. During this period, the harbor seal population in Vitus Lake grew from near 0 to 1,000 animals. The seals use icebergs as haul outs where they rest and "pup." The ice bergs are safe havens from brown bears.

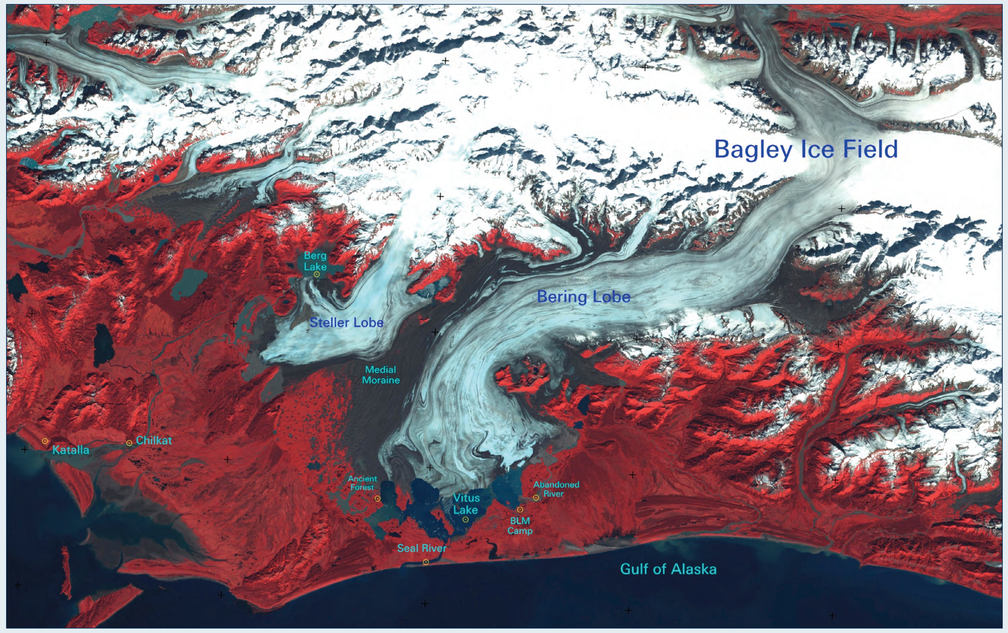

Figure 2. A false color Landsat-7 satellite image of Bering Glacier, September 2001.

Estuary Formation and Modeling, or: How and When Does the Salt Get into Vitus Lake?

The Bering Glacier – Vitus Lake system is the largest proglacial system in the world and Vitus Lake, located at sea level, is expanding rapidly as the terminus thins and disintegrates. This program has measured the bathymetry of the lake, the lake level, the discharge of Seal River, and the temperature and salinity distributions within the lake on an annual basis for 6 years as shown in figure 4. The harbor seal population has increased to about 1,000 animals as the glacier has retreated. The seals use icebergs to haul out on and to give birth or "pup." The lake is more than140 meters deep, and contains a stratified mixture of sea water and fresh water. Furthermore, the amount of sea water varies from year to year. The stratification will greatly influence the circulation within the lake and hence the lacustrine ecosystem.

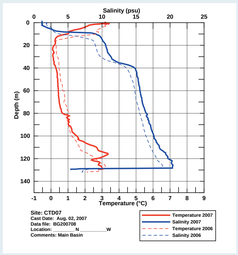

Figure 4. Temperature and salinity profile from Vitus Lake for 2006 and 2007. The amount of sea water varies from year to year. Salt water in a lake plays a key role in maintaining the stratification and reducing the mixing between the upper and lower layers, which in turn will determine the nature of the lacustrine ecosystem.

To understand the exchange of water between the Gulf of Alaska and Vitus Lake, this investigation developed a model of the water-level fluctuations in Vitus Lake (η) in response to sea-level variations in the Gulf of Alaska and the runoff from the Bering Glacier Basin. The governing equation is a damped forced oscillator, governed by:

$$\frac{d^2\eta}{dt^2} + k\frac{d\eta}{dt} + \Omega_0^2\eta = \Omega_0^2\eta_{ocean} + \frac{k}{A}Qg$$

where $\Omega_0^2 = \frac{gwd_s}{LA}$, k is the friction coefficient, g is gravity, w and L are the width and length of Seal River, d_s is the depth of Seal River, A is the area of Vitus Lake and Qg is the runoff from the Bering Glacier Basin. The unknown friction factor is determined by matching the model output to measured lake levels and flow measurements in Seal River made with an Acoustic Doppler Current Profiler (ADCP).

The model is rich in solutions that correspond to distinct physical mechanisms that occur, including tidal forcing, response to storm surges, variations in runoff and changes in lake, and river geometry as shown in the following examples.

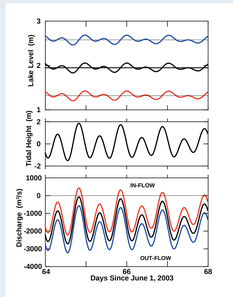

Figure 5. Changes in lake level and flow in Seal River as a result of increasing or decreasing the basin runoff by one-third.

Figure 5 shows the results of increasing or decreasing the basin runoff by one-third, or 500 cubic meters per second, as determined by the ADCP measurements. The middle panel shows the tidal forcing, which is the same for each case and the solid black lines in the upper and lower panels are the corresponding current baseline case. The top panel shows the response of the lake level. For increased runoff, the mean lake level rises (the blue curve), and for reduced runoff, lake level declines (the red curve). A change of 500 cubic meters per second results in a mean lake-level change of 0.6 meter. The lower panel of figure 5 shows the response of the flow in Seal River. An increase in runoff increases the net outflow of the river, as it must; for reduced runoff, the opposite occurs, and weak reversals occur near high tide (the red line).

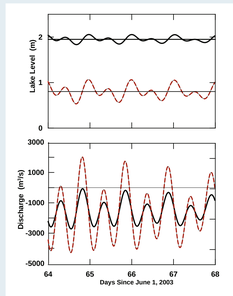

Figure 6. Changes in lake level and flow in Seal River if the long shore barrier bar were breached.

Figure 6 shows the changes in lake level and flow in Seal River that would occur if the long shore barrier bar were breached, shortening Seal River from 8 to 3.5 kilometers. Such a scenario is far from impossible, maps from the past century show that the bar can dramatically change length, possibly as a result of changes in sediment supply and vigorous storms in the Gulf of Alaska. In this case, as before, the heavy black line is the current baseline case and the red/black lines represent the case with a shorter river. The mean level of Vitus Lake declines by 1 meter and the tidal excursions in the lake become greater. Finally, the exchange through Seal River nearly doubles with significant inflow occurring during the higher tides, which would likely inject Gulf of Alaska seawater into Vitus Lake.

Glacier Melt and Its Impact on the Alaska Coastal Current

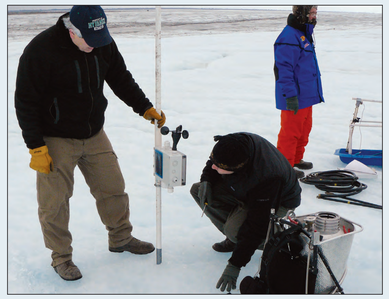

Figure 7. Installing an automatic glacier ablation sensor and weather station on Bering Glacier.

One of the primary glaciological measurements made by the combined USGS – MTRI program at Bering Glacier was to measure the summer ablation or melt from near sea level to 1,200 m above sea level (fig. 7) from 2004 to 2008. Measurements were made on an hourly basis by automated gages and the total summer ablation ranged from 6 to 10 meters and was nearly independent of altitude. Furthermore, the summer melt for each year strongly correlates with the melt degree days computed from the National Weather Service at Yakutat, Alaska. Melt degree days are analogous to heating degree days, except the reference temperature is 0°C. It is a measure of the sensible heat flux to the ice and it is commonly used in driving melt models for snow and ice (Hock, 1999).

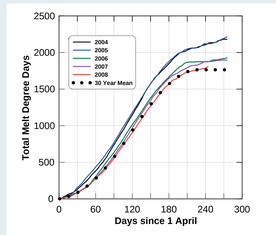

Figure 8. Melt degree days computed from the Yakutat temperature record for 2004 through 2008 and the 30-year mean.

Using the total melt degree days for the period of each bulk melt measurements, which span a 5-year period, give an average transfer coefficient of 3.96E-3 for ice and 2.90E-3 for snow (meters per melt degree day). To estimate the total melt contribution from the glacier to the Gulf of Alaska, this study mapped the snow and ice coverage at the end of each summer for the Bering Basin using the Moderate-Resolution Imaging Spectroradiometer (MODIS) 16-day snow and ice composite, and determined the total melt degree days (TMDD) from the daily mean temperature at Yakutat for 2004 through 2008 (fig. 8).

Volume of water, in cubic kilometers				
Year	TMDD	ICE MELT	SNOW MELT	TOTAL
2004	1886	1.46E+10	6.70E+09	2.13E+10
2005	1900	1.47E+10	6.75E+09	2.15E+10
2006	1692	1.31E+10	6.01E+09	1.91E+10
2007	1668	1.29E+10	5.93E+09	1.88E+10
2008	1593	1.23E+10	5.66E+09	1.80E+10
Climatology	1590	1.23E+10	5.66E+09	1.80E+10
Climatology+2°C	1966	1.52E+10	6.98E+09	2.22E+10
Climatology+4°C	2323	1.80E+10	8.25E+09	2.62E+10

Table 1. Total Melt Degrees Days (TMDD) and snow and ice melt for Yakutat for 2004–2008, the 30-year climatology, and a +2 °C and +4 °C warming scenarios.

Table 1 shows that ablation of the Bering Glacier system releases approximately 2E+10 cubic kilometers of water each year, which is 3 percent of the total freshwater transport in the Alaska Coastal Current. In addition, there are significant inter-annual variations that are representative of the region, which could have significant impacts on the Alaska Coastal Current. The recent very warm summers of 2004 and 2005 have been replaced by cooler summers, with 2008 being very similar to the 30-year average. For glacier ablation, 2004 or 2005 represent an increase in mean temperature of 2°C, the ablation was approximately 20 percent greater than the 30-year mean.

Conclusion:

The retreat of glaciers on the south coast of Alaska will generate new and complex estuarine and coastal ecosystems that will greatly vary in productivity. Studies of Bering Glacier have provided baseline characteristics of an expanding fjord system and a model of the exchange processes between the emerging fjord and the Gulf of Alaska. The model is being used to evaluate the impact of increased glacier ablation, variations in sea level, and changes in geometry. On the scale of the NE Pacific, accelerated glacier wastage could have a major impact on the intensity of the Alaska Coastal Current and its ecosystem. Ablation studies at Bering Glacier show that the resulting freshwater flux has a large inter-annual variability, in response to relatively small changes in summer temperature.

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