2-2014

Melt water input from the Bering Glacier watershed into the Gulf of Alaska

Edward G. Josberger
Michigan Technological University

Robert Shuchman
Michigan Technological University

Liza K. Jenkins
Michigan Technological University

K. A. Endsley
Michigan Technological University

Recommended Citation

Josberger, E. G., Shuchman, R., Jenkins, L. K., & Endsley, K. A. (2014). Melt water input from the Bering Glacier watershed into the Gulf of Alaska. *Geophysical Research Letters, 41*(3), 886-890. http://dx.doi.org/10.1002/2013GL058734
Retrieved from: https://digitalcommons.mtu.edu/mtri_p/7

Follow this and additional works at: https://digitalcommons.mtu.edu/mtri_p
Part of the Environmental Monitoring Commons, and the Glaciology Commons

AGU PUBLICATIONS

Geophysical Research Letters

RESEARCH LETTER
10.1002/2013GL058734

Key Points:
- In-situ melt, temperature, and satellite data used to estimate glacier discharge
- Annually 40 km^3 freshwater discharged to Gulf of Alaska from Bering Watershed
- Derived melt coefficients can be applied to estimate melt from N.A. glaciers

Supporting Information:
- Readme
- Table S1
- Figure S1

Correspondence to:
E. G. Josberger,
josberger@harbornet.com;
egjosber@mtu.edu

Citation:
Josberger, E. G., R. A. Shuchman, L. K. Jenkins, and K. Arthur Endsley (2014), Melt water input from the Bering Glacier watershed into the Gulf of Alaska, *Geophys. Res. Lett.*, *41*, 886–890, doi:10.1002/2013GL058734.

Received 3 DEC 2013
Accepted 12 JAN 2014
Accepted article online 16 JAN 2014
Published online 5 FEB 2014

Melt water input from the Bering Glacier watershed into the Gulf of Alaska

Edward G. Josberger[1], Robert A. Shuchman[1], Liza K. Jenkins[1], and K. Arthur Endsley[1]

[1]Michigan Tech Research Institute, Michigan Technological University, Ann Arbor, Michigan, USA

Abstract The annual runoff from the melting of large glaciers and snow fields along the northern perimeter of the Gulf of Alaska is a critical component of marine physical and biological systems; yet, most of this freshwater is not measured. Here we show estimates of melt for the watershed that contains the largest and longest glacier in North America, the Bering Glacier. The procedure combines in situ observations of snow and ice melt acquired by a long-term monitoring program, multispectral satellite observations, and nearby temperature measurements. The estimated melt is 40 km^3 per melt season, ± 3.0 km^3, observed over the decadal period, 2002–2012. As a result of climate change, these estimates could increase to 60 km^3/yr by 2050. This technique and the derived melt coefficients can be applied to estimate melt from Alaska to Washington glaciers.

1. Introduction

The wastage of the glaciers along the Gulf of Alaska (GoA) is an important factor in sea level rise as well as a significant physical and biogeochemical component of the rich marine ecosystem of this region, yet it is poorly known. Physically, the combined snow and glacier melt generates the Alaska Coastal Current [*Royer*, 1979; *Arendt et al.*, 2002; *Arctic Monitoring and Assessment Programme* (*AMAP*), 2011]. Biologically, glacier melt water also provides primary productivity-limiting nutrients [*Royer*, 1979]. The waters overlying the continental shelf and slope of the GoA are some of the most productive in the world and are home to some of the United States' most important commercial and recreational fisheries [*North Pacific Research Board* (*NPRB*), 2005; *Royer and Grosch*, 2006]. Coastal waters of the GoA serve as important breeding, nursery, and forage habitats for many valuable species such as salmon, cod, herring, Pacific halibut, sablefish, walleye, pollock, shrimp, and crab [*NPRB*, 2005]. The ecosystem and world-renowned fisheries in this region of the GoA thrive, in part, due to an abundant supply of nutrients. Over the next few decades there is likely to be an increase in glacier-dominated freshwater discharge, followed by a decrease as glaciers recede [*AMAP*, 2011; *Hinzman et al.*, 2005] which has the potential to adversely affect the ocean circulation and ecosystem in this region.

The late spring and summer melting of snow and glacier ice in southeastern Alaska generates the Alaska Coastal Current that sweeps cyclonically around the GoA. From oceanographic measurements, *Royer* [1979] estimated that the freshwater runoff was 23,000 m^3 s^{-1}. *Wang et al.* [2004] used elevation and meteorological data to simulate the freshwater flux into the GoA and found that ungauged sources along the coast yield 74% of the freshwater flux. Numerous studies [*Arendt et al.*, 2002; *Meier and Dyurgerov*, 2002; *Josberger et al.*, 2006] have shown that the glaciers in this region are rapidly losing mass. Indeed, *Royer and Grosch* [2006] have shown that the water on the shelf of the GoA has warmed and become less salty over the past 40 years, strengthening the Alaska Coastal Current. The *AMAP* [2011] give an extensive pan-Arctic assessment of glacier retreat and found that nearly all glaciers have shrunk over the past century.

The glaciers and ice fields of the Wrangell-St. Elias mountain ranges along the southern coast of Alaska contain the greatest amount of glacier ice outside of Antarctica and Greenland, with the Bering Glacier being the largest contributor. Bering is the largest and longest glacier in continental North America, with an area of approximately 5000 km^2 and a length of 190 km, and the Bering Glacier system covers more than 6% of the glacier-covered area of Alaska and may contain 15–20% of Alaska total glacier ice [*Molnia and Post*, 2010].

In this study, ice and snow melt from the Bering Glacier system has been estimated from 2002 to 2012 using daily air temperature to calculate melt degree days (MDD), melt coefficients for ice and snow derived from 6 years of in situ observations, and end-of-season snow- and ice-delineated land cover obtained from satellite

10.1002/2013GL058734

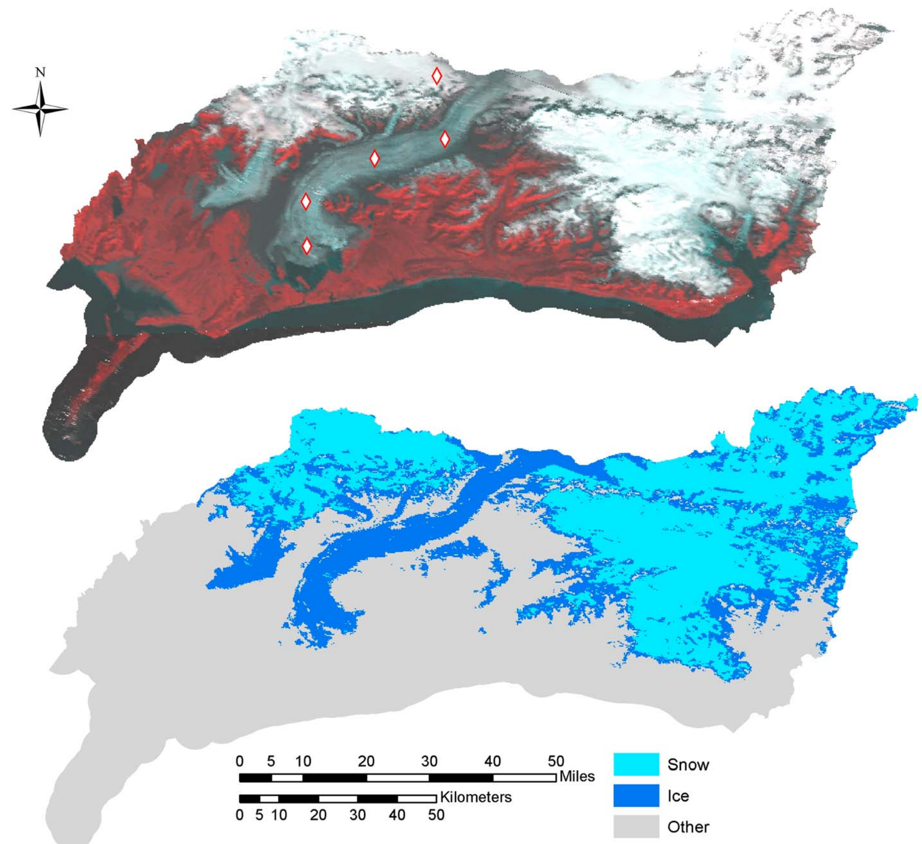

Figure 1. Snow and ice cover were estimated from end-of-melt-season MODIS 8 day composites. MODIS bands 1 and 2 were used to classify snow versus ice. Shown in this figure is an example MODIS (top) false-color image and (bottom) classification from 2007. Top image shows approximate GASS deployment locations. Areas shown in this figure correspond to the Bering Glacier watershed.

data. This decade-long record shows interannual variation in freshwater production with no apparent trend. Our results, when driven by regional climate predictions, indicate a significant increase in melt over time.

2. Methods

2.1. In Situ Glacier Melt Data

In situ data were obtained using a specialized Glacier Ablation Sensor System (GASS) that was designed and fabricated to measure key physical parameters of the system [*Shuchman et al*., 2010] (www.BeringGlacier.org/gass). Each autonomous unit measured and recorded hourly the distance from the sensor package to the ice with an acoustic ranging sensor. GASS units also provided GPS and meteorological data (temperature, wind speed, humidity, barometric pressure, and light intensity). The units were deployed on the glacier at the beginning of the melt season 0.5 m above the ice on interlocking aluminum poles set in steam-drilled holes 10 m deep. Figure 1 shows the approximate location of the GASS sites. Periodically during the summer melt season, the GASS units were lowered on their poles to keep the sensors close and nearly perpendicular to the ice surface. During these visits, conventional stake measurements were also taken at the sites to measure bulk ablation. Concurrently, we deployed and recovered water level gauges in Vitus Lake and the Seal River which are the main reservoirs and conduits to the GoA for Bering Glacier melt water. These data were used to further document the freshwater discharge from the Bering Glacier system.

GASS observations showed only slight interannual and intra-annual variation in glacier melt. The average ablation was 5.5 cm/d ± 0.5 cm/d independent of local weather conditions (e.g., wind, clouds, and precipitation). Additionally, the melt record showed little variation along the main stem of the glacier, except for high melt rates near the terminus which is at sea level near ice-free, low-albedo terrain. Conversely, lower melt rates were measures in the Bagley Ice Field, high-albedo terrain above the equilibrium line altitude (ELA).

Table 1. Melt Coefficient (10^{-3} mweq/MDD) Were Derived From Hourly GASS Data[a]

Site	2004	2005	2006	2007	2008	2010	Average	SD	Elevation (m)
B01	4.70	4.27	5.96	3.90	3.97	4.00	4.47	7.87 E-1	241
B02	4.13	3.43	3.28	NA	3.59	3.82	3.65	3.34 E-1	388
B03	4.15	4.40	3.16	3.19	3.60	3.20	3.62	5.40 E-1	602
B04	3.96	NA	3.35	3.44	NA	3.38	3.53	2.89 E-1	792
B05	5.66	4.07	3.64	3.58	3.73	2.94	3.93	9.22 E-1	1,143
B06	NA	3.10	2.08	3.28	3.13	2.19	2.76	5.73 E-1	1,242

[a]Sites B01, B02, B03, B04, and B05 were installed in the glacier ice below the equilibrium line altitude (ELA). Site B06 was installed in the snow above the ELA (see Figure 1 for approximate GASS locations).

2.2. Melt Model

Glacier melt is modeled exceptionally well by the MDD method, otherwise known as the temperature index method [*Ohmura*, 2001; *Hock*, 2003; *Bidlake et al*., 2010]. *Ohmura* [2001] shows that glacier and snow melt are dominated by the sensible heat flux and the short wave solar heat flux from the lower atmosphere. Bering Glacier is no exception. The MDD approach totals the average daily temperatures that are above 0°C during the summer melt period. The melt coefficient, which is the quotient of total observed change in snow or ice height, corrected for the respective density, divided by total MDD, linearly relates the amount of melt over a given period to the MDD accumulated over that period. Table 1 gives the calculated melt coefficients for all years and all sites. The value for a given year and location is the average value from three or four bulk ablation measurements made through the melt season. The melt coefficients are generally uniform for sites B02 through B05, both spatially and interannually, with an average value of 3.68×10^{-3} m of water equivalent per MDD (mweq/MDD). The ice coefficient used is an average from GASS sites B02, B03, B04, and B05, while the single B06 site is used for the snow coefficient.

2.3. Remote Sensing-Derived Estimates of Snow and Ice Cover

To estimate discharge, yearly snow and ice extents were needed. Electro-optical satellite data provided by the NASA Moderate Resolution Imaging Spectroradiometer (MODIS) sensor can be used to provide synoptic observations of snow and ice area. Eight day composite images from the end of the melt season (approximately mid-September each year) were used to conduct an unsupervised classification of snow and ice extent within the Bering Glacier watershed (USGS Unit 19010402) from 2002 to 2012. MODIS bands 1 and 2 were used for the classification based on their spatial and spectral resolutions (250 m and red and near-IR, respectively). Figure 1 shows the ice and perennial snow fields mapped from 2007 MODIS data.

2.4. Total Freshwater Melt Calculation

For each year, the melt coefficient describes the amount of melt per MDD—melt per input unit of sensible heat. The satellite-delineated snow and ice areas are multiplied by their respective melt coefficients, generating a volume of melt that is scaled by the total MDD to obtain the total freshwater melt per season. Contributions to discharge from precipitation were also included by scaling liquid precipitation from April to September over the yearly ice extent within the watershed. For additional details on these calculations, see supporting information.

3. Results

The estimated annual discharge over the decadal period from 2002 to 2012 (Figure 2) ranged from 36 to 45 km^3. Surprisingly, the decadal record shows little annual variation around an average estimate of 40 km^3 with a standard deviation of 3.0 km^3. Observed annual variations are largely explained by differences in MDD (Figure 2). Precipitation is included in these estimates; without it, the average annual discharge over the decadal period is 36 km^3. To estimate possible future discharge in 2050, four scenarios were calculated for +1°, +2°, +4°, and +6°C increases in the daily long-term climatology record from the National Weather Service. These estimates are based on temperature only and not changes in cloud cover or precipitation. Future estimates ranged from approximately 41 to 62 km^3. This is roughly a 50% increase over the current decadal average estimate.

The average yearly freshwater discharge estimate of 40 km^3 for the Bering Glacier watershed is approximately equal to the average yearly discharge of the Nile River in Egypt (40 km^3) [*Dai and Trenberth*, 2002]. For comparison, the Mississippi River discharges roughly 500 km^3 to the Gulf of Mexico every year, Yukon River

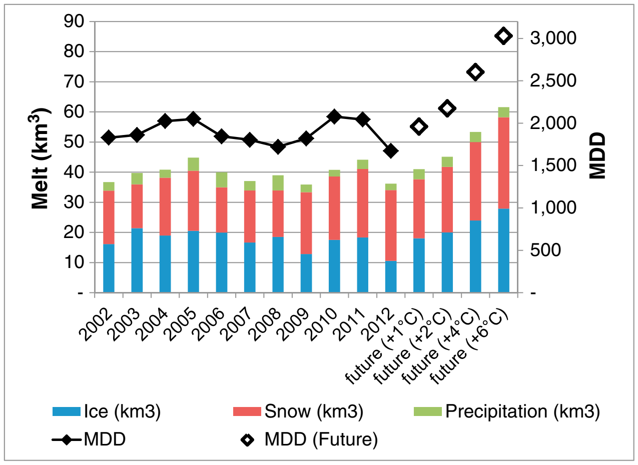

Figure 2. Total estimated annual discharge from the Bering Glacier into the Gulf of Alaska from 2002 to 2012 ranged from 36 to 45 km^3. Also included are the annual melt degree days (MDD) which drives the discharge estimates.

200 km^3, and the St. Mary's River 70 km^3 that drains Lake Superior in the Laurentian Great Lakes [*Dai and Trenberth*, 2002]. Other comparable estimates include the Copper (34 km^3), the Susitna (45 km^3), and the Colorado (12 km^3) Rivers [*Dai and Trenberth*, 2002].

Annual discharge estimates were partially validated using a Bering Glacier-specific hydrodynamic model as described by *Josberger et al*. [2010]. The model, which was validated using acoustic Doppler current profiler measurements, estimates discharge only in the Seal River (main conduit for Bering Glacier melt discharge) as a function of water level in Vitus Lake, a large ice-marginal lake at the terminus of Bering Glacier. The daily discharge estimates from the hydrodynamic model, which represent only a portion of the total watershed, were summed and favorably compared to these remote sensing-derived estimates.

4. Discussion

As we have shown for Bering Glacier, local temperature data from a nearby weather station can be used to effectively model snow and ice melt using the temperature index method. In the absence of direct temperature observations, regional temperature data can easily be obtained from reanalysis data sets such as are provided by National Centers for Environmental Prediction (NCEP) [*Kistler et al*., 2001].

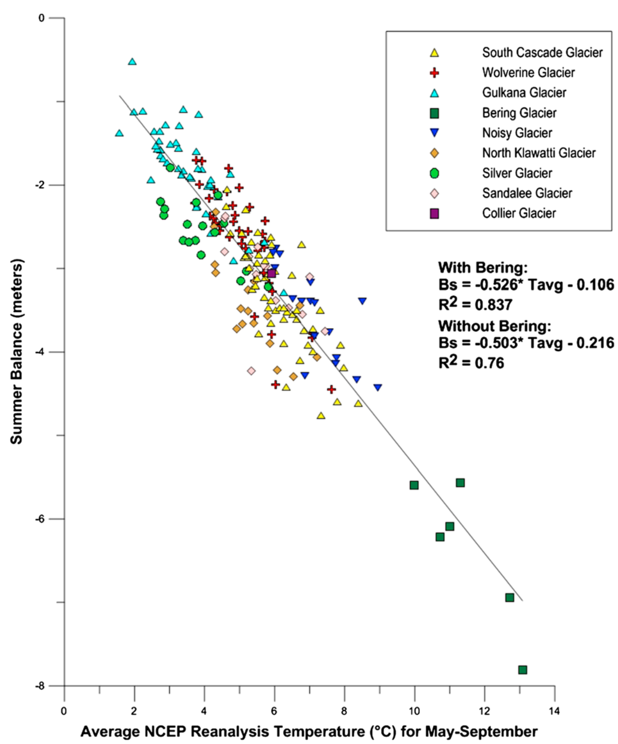

Figure 3. A strong linear relationship between summer mass balance and average NCEP reanalysis temperature from May to September for Bering Glacier and eight other glaciers from Alaska to California [*Rasmussen and Conway*, 2004]. The addition of Bering Glacier extends the range of observations to glaciers located in warmer temperatures, at lower elevations, and with faster melt rates.

The GASS summer ablation observations were combined with previous work by *Rasmussen and Conway* [2004] to extend the range of observations to glaciers located in warmer temperatures, at lower elevations, and with faster melt rates. *Rasmussen and Conway* [2004] developed a relationship between the summer mass balance and the average summer temperature at the ELA using NCEP reanalysis data. We applied their technique to observations from eight glaciers located in the Northeast Pacific (from Alaska to California) and from Bering Glacier (Figure 3). Bering Glacier reinforces the linear trend between temperature and melt and improves the correlation coefficient (increase in R^2 from 0.76 to 0.83). The slope of least squares fit in Figure 3 corresponds to a melt coefficient of ~0.003 mweq/MDD, which is within the range of the values found in this study, thus validating the use of the temperature index method to estimate glacier melt over large areas when combined with remote sensing observations.

In summary, the in situ observations made at Bering over a 6 year period indicate the Glacier melts at a fairly constant rate between 4 and 6 cm/d with a variance of only 7 mm/d. This melt rate occurs largely independent of cloud cover, wind speed, and precipitation. MDD account for most of the variation in the observed ablation, thus allowing for total glacier melt to be estimated fairly accurately using local, regional, or global temperature measurements, or from regional temperature databases such as NCEP.

The Bering Glacier system produced between 36 and 45 km^3 or Gigatons (Gt) of freshwater annually for the GoA over the last decade with an interannual variation of 3 km^3. This amount of water will potentially increase upward to approximately 60 km^3 in the 2050 time frame under a +6° temperature increase as a result of the warming climate in southeastern Alaska. The annual discharge estimates were calculated using air temperature records converted to MDD, multiplied by a melt coefficient determined from the in situ sensors. To complete the discharge calculation, satellite observations were used to identify areas of snow and ice cover within the Bering Glacier system. This technique can be applied worldwide to better understand the contribution of glacier melt to sea level rise and oceanic circulation.

Acknowledgments
The authors would like to thank the following agencies and organizations for their partial support of this Bering Glacier study: United States Bureau of Land Management, United States Geological Survey, Michigan Technological University, and the Eddie Bauer Explorers Club Expedition Stipend program. The following individuals are also thanked for supporting the field program and data analysis: John Payne, Scott Guyer, Chris Roussi, Ben Hart, and Patrick Williams.

The Editor thanks Kristine Crossen and an anonymous reviewer for their assistance in evaluating this paper.

References

AMAP (2011), Snow, water, ice and permafrost in the Arctic (SWIPA): Climate change and the cryosphere.

Arendt, A. A., K. A. Echelmeyer, W. D. Harrison, C. S. Lingle, and V. B. Valentine (2002), Rapid wastage of Alaska glaciers and their contribution to rising sea level, *Science*, *297*(5580), 382–386.

Bidlake, W. R., E. G. Josberger, and M. E. Savoca (2010), Modeled and measured glacier change and related glaciological, hydrological, and meteorological conditions at South Cascade Glacier, Washington, balance and water years 2006 and 2007, U. S. Geological Survey.

Dai, A., and K. E. Trenberth (2002), Estimates of freshwater discharge from continents: Latitudinal and seasonal variations, *J. Hydrometeorol.*, *3*(6), 660–687.

Hinzman, L. D., et al. (2005), Evidence and implications of recent climate change in northern Alaska and other arctic regions, *Clim. Change*, *72*(3), 251–298.

Hock, R. (2003), Temperature index melt modelling in mountain areas, *J. Hydrol.*, *282*(1), 104–115.

Josberger, E. G., R. A. Shuchman, G. A. Meadows, S. Savage, and J. Payne (2006), Hydrography and circulation of ice-marginal lakes at Bering Glacier, Alaska, USA, *Arct. Antarct. Alp. Res.*, *38*(4), 547–560.

Josberger, E. G., R. A. Shuchman, G. A. Meadows, L. K. Jenkins, and L. A. Meadows (2010), Hydrologic processes of Bering Glacier and Vitus Lake, Alaska, in *Bering Glacier: Interdisciplinary Studies of Earth's Largest Temperate Surging Glacier, Geological Society of America Special Papers*, vol. 462, pp. 105–127, Geol. Soc. Am., Boulder, Colo.

Kistler, R., W. Collins, S. Saha, G. White, J. Woollen, E. Kalnay, and M. Fiorino (2001), The NCEP-NCAR 50-year reanalysis: Monthly means CD-ROM and documentation, *Bull. Am. Meteorol. Soc.*, *82*(2), 247–267.

Meier, M. F., and M. B. Dyurgerov (2002), How Alaska affects the world, *Science (Washington)*, *297*(5580), 350–351.

Molnia, B. F., and A. Post (2010), Introduction to the Bering Glacier System, Alaska/Canada: Early observations and scientific investigations, and key geographic features, in *Bering Glacier: Interdisciplinary Studies of Earth's Largest Temperate Surging Glacier, Geological Society of America Special Papers*, vol. 462, pp. 105–127, Geol. Soc. Am., Boulder, Colo.

NPRB (2005), *North Pacific Research Board Science Plan*, North Pacific Research Board (NPRB), Anchorage, Alaska.

Ohmura, A. (2001), Physical basis for the temperature-based melt-index method, *J. Appl. Meteorol.*, *40*(4), 753–761.

Rasmussen, L. A., and H. Conway (2004), Climate and glacier variability in western North America, *J. Clim.*, *17*(9), 1804–1815.

Royer, T. C. (1979), On the effect of precipitation and runoff on coastal circulation in the Gulf of Alaska, *J. Phys. Oceanogr.*, *9*(3), 555–563.

Royer, T. C., and C. E. Grosch (2006), Ocean warming and freshening in the northern Gulf of Alaska, *Geophys. Res. Lett.*, *33*, L16605, doi:10.1029/2006GL026767.

Shuchman, R. A., E. G. Josberger, C. R. Hatt, C. Roussi, P. J. Fleisher, and S. Guyer (2010), Bering Glacier ablation measurements, *Geol. Soc. Am. Spec. Pap.*, *462*, 83–104, Geol. Soc. Am., Boulder, Colo.

Wang, J., M. Jin, D. L. Musgrave, and M. Ikeda (2004), A hydrological digital elevation model for freshwater discharge into the Gulf of Alaska, *J. Geophys. Res.*, *109*, C07009, doi:10.1029/2002JC001430.