Contribution of glacier runoff to freshwater discharge into the Gulf of Alaska

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[1] Watersheds along the Gulf of Alaska (GOA) are undergoing climate warming, glacier volume loss, and shifts in the timing and volume of freshwater delivered to the eastern North Pacific Ocean. We estimate recent mean annual freshwater discharge to the GOA at 870 km^3 yr^{-1}. Small distributed coastal drainages contribute 78% of the freshwater discharge with the remainder delivered by larger rivers penetrating coastal ranges. Discharge from glaciers and icefields accounts for 47% of total freshwater discharge, with 10% coming from glacier volume loss associated with rapid thinning and retreat of glaciers along the GOA. Our results indicate the region of the GOA from Prince William Sound to the east, where glacier runoff contributes 371 km^3 yr^{-1}, is vulnerable to future changes in freshwater discharge as a result of glacier thinning and recession. Changes in timing and magnitude of freshwater delivery to the GOA could impact coastal circulation as well as biogeochemical fluxes to near-shore marine ecosystems and the eastern North Pacific Ocean.

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1. Introduction

[2] Quantifying runoff from northern rivers is crucial for constraining freshwater budgets in regions where the hydrologic cycle is undergoing pronounced changes with climate warming [*Arctic Climate Impact Assessment*, 2006]. Freshwater discharge (FWD) in northern high-latitude rivers has increased in recent decades [*Peterson et al.*, 2002; *McClelland et al.*, 2006], although these increases are not uniform across the Arctic [*Dery and Wood*, 2005]. Increases in Arctic discharge have been attributed to greater northward transport of moisture as a result of global warming [*McClelland et al.*, 2004]. In contrast to the Arctic, few studies have quantified changes in FWD from subarctic regions such as the Gulf of Alaska (GOA). Rivers discharging into the GOA have recently demonstrated shifts in volume and timing of water delivered to the eastern North Pacific Ocean [*Royer and Grosch,* 2006; *Hodgkins,* 2009]. These rivers are strongly influenced by glacier runoff and glaciers in this region have some of the highest glacier volume loss (GVL) rates on earth [*Arendt et al.*, 2002; *Larsen et al.*, 2007; *O'Neel et al.*, 2005].

[3] The magnitude of FWD into the GOA is critical because it is a first order driving mechanism for coastal circulation [*Royer*, 1981]. Inputs of freshwater along the GOA reduce salinities that control along shore currents resulting from density gradients and wind stress [*Royer*, 1982]. Additionally, freshwater discharge into the GOA has been identified as a potentially important component in the freshwater budget of the eastern Bering Sea shelf and the Arctic Ocean [*Weingartner et al.*, 2005] and has been linked to primary productivity and salmon productivity in Alaska [*Royer et al.*, 2001]. Moreover, accurate estimates of the magnitude and distribution of freshwater inputs to the GOA are important for improved estimates of biogeochemical fluxes similar to those developed for arctic rivers [*Frey et al.*, 2007; *Raymond et al.*, 2007].

[4] Freshwater discharge to the GOA is difficult to quantify because the majority of runoff comes from small distributed sources as opposed to large river basins that are amenable to gauging [*Wang et al.*, 2004]. Previous estimates of FWD along the GOA have been relatively consistent (~730 km^3 yr^{-1}) despite using different methodologies [*Royer*, 1982; *Wang et al.*, 2004]. However, recent reanalyses have adjusted these estimates of FWD upward due to rapid GVL in Alaska [*Royer and Grosch*, 2006]. The objectives of this study were threefold: 1) to provide a spatially distributed estimate of FWD from the GOA drainage area using a combination of measured discharge and improved models of precipitation, 2) to estimate the proportion of runoff from small, distributed coastal streams versus large continental rivers, and 3) to evaluate the percentage of FWD to the GOA derived directly from glaciers. In contrast to previous studies, we focus on spatial variations in annual-averaged discharge rather than on temporal variations in FWD to the GOA, and we emphasize the importance of climate-sensitive glacier runoff in the freshwater budget of the GOA drainage region.

2. Methods

2.1. Study Area

[5] We define the GOA drainage basin as the area (420,230 km^2) extending from the southeast border of Alaska to Kupreanof Point on the Alaska Peninsula. For the purpose of this analysis, we divided the GOA drainage basin into seven geographic regions: Southeast, Central Coast, Copper River, Prince William Sound, Knik Arm/Kenai, Susitna River, and W. Cook Inlet/Kodiak, three of which extend into Canada (Figure 1).

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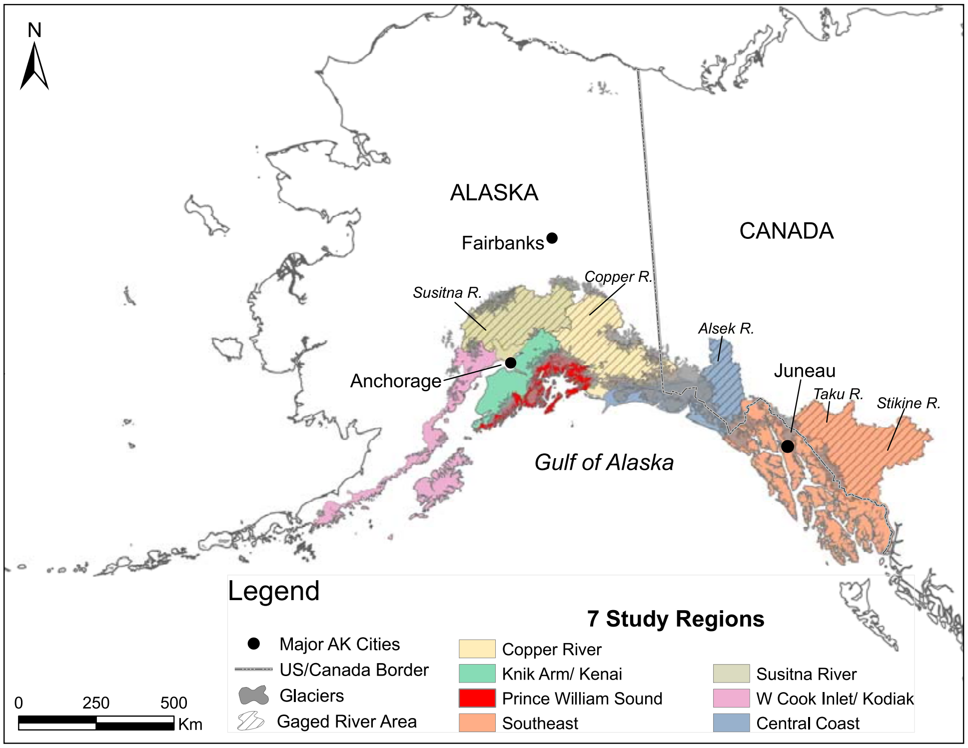

Figure 1. Map of the seven study regions within the Gulf of Alaska drainage basin. The area of glaciers and the gauged watershed extent for the five largest rivers draining to the GOA are also shown.

2.2. Runoff Data Sources

[6] Regional freshwater discharge was estimated using a combination of measured discharge, runoff derived from precipitation models calibrated with regional streamflow data, and runoff from estimates of GVL. For measured discharge, we used U.S. Geological Survey (USGS) gauge records for the five largest river basins in the GOA drainage: the Susitna, Copper, Alsek, Taku, and Stikine Rivers (Figure 1). Together these rivers drain 50% of the GOA watershed. All of these rivers have 16 or more years of discharge data within the period 1974–2007 with the exception of the Copper River (8 years of record). For distributed estimates of precipitation, we used the Parameter-elevation Regression on Independent Slopes Model (PRISM) precipitation models for Alaska, the Yukon Territory and British Columbia (http://www.climatesource.com) in combination with 30–90 m^2 Digital Elevation Model datasets (http://ned.usgs.gov/). Drainage basin delineations correspond to the 5th and 6th level Hydrologic Unit codes (HUCs) defined and compiled by the Watershed Boundary Dataset (http://datagateway.nrcs.usda.gov) and published in the USGS National Hydrography Dataset (http://nhd.usgs.gov/index.html). The PRISM data are annual average precipitation for 1960–1990 gridded at 2 km^2 [*Simpson et al.*, 2005]. Estimates of GVL were generated using data from *Arendt et al.* [2002] for the period mid-1990s to 2001.

[7] Data were chosen based on the best available comprehensive data sources for the GOA region. The PRISM precipitation model is considered to be the best estimate of precipitation distribution available for Alaska [*Simpson et al.*, 2005] and *Arendt et al.*'s [2002] dataset is the only available GVL dataset covering the entire GOA drainage basin.

2.3. Freshwater Discharge Calculations

[8] Annual runoff from the five large rivers was calculated from USGS data as the average annual discharge for the period of record for each river. Because the Susitna and Copper River gauges are located upstream of where the rivers enter the GOA, discharge for these rivers comprised most, but not all of the annual FWD estimates for the Susitna and Copper River Regions. Alsek River discharge contributed to the FWD estimate for the Central Coast region and Taku and Stikine River discharge contributed to the FWD estimate for the Southeast region. The error terms associated with the gauge data for each of the five rivers was estimated as the standard error of the mean annual discharge for the period of record.

[9] Annual runoff from the ungauged region of the GOA drainage basin was estimated from the volume of precipitation within each watershed in a study region. Precipitation volumes for each watershed were converted to runoff estimates by calibration with streamflow data from USGS gauging stations within the study area. Selection of calibration gauges within this sparsely gauged area was limited to 50 gauges having 10 or more years of discharge record within the 1960–1990 period covered by the PRISM data. Calibration watersheds ranged in area from 5–5350 km^2 and in glacier coverage from 0–66% and were thus representative of the watersheds in the ungauged portion of the study region. Annual precipitation volume (PRISM data) and an-

Table 1. Basin Area and Mean Annual Runoff From the Seven Geographic Regions That Discharge Freshwater to the Gulf of Alaska[a]

Region	Area (km^2)	Percent GOA Basin Area	Mean Annual Runoff (km^3)	Specific Runoff (m)	Percent GOA Runoff	Ratio of % Runoff to % Area
Southeast	153,884	37%	370 ± 23	2.4 ± 0.2	43%	1.2
Central Coast	55,568	13%	200 ± 13	3.6 ± 0.2	23%	1.8
Copper River	65,056	15%	65 ± 3	1.0 ± 0.1	8%	0.5
Prince William Sound	19,898	5%	95 ± 12	4.7 ± 0.6	11%	2.2
Knik Arm/Kenai	29,227	7%	36 ± 5	1.2 ± 0.1	4%	0.6
Susitna River	53,789	13%	46 ± 2	0.9 ± 0.1	5%	0.4
W Cook Inlet/ Kodiak	42,807	10%	54 ± 3	1.3 ± 0.1	6%	0.6
GOA Total	420, 230	100%	870 ± 61	2.1 ± 0.2	6%	1.0

[a]Error estimates for Mean Annual Runoff and Specific Runoff were conservatively estimated as the sum of the errors computed for 1) large river runoff, 2) annual runoff, and 3) glacier volume loss with in each region (see methods for description of error estimates).

nual runoff volume (USGS gauge data) were calculated for each of the 50 calibration watersheds. Because GVL was calculated separately (see below), we used watershed glacier area and glacier thinning rates for mid-1990s to 2001 [*Arendt et al.*, 2002] to calculate mean annual GVL in each of the glacierized calibration watersheds (n = 23). GVL was subtracted from the annual runoff volume for glacierized calibration gauges to avoid double counting this component of glacier runoff in our estimates. The measured mean annual runoff volumes from calibration gages were divided by the mean annual precipitation volume from the PRISM data to obtain correction factors (CFs). These CFs were used to convert PRISM precipitation volumes into runoff estimates for all ungauged watersheds in the study area. Two correction factors were used for watersheds in and to the east of Prince William Sound; one for watersheds with average elevations over 500 m (15 gauges; CF = 1.06 ± 0.07) and one for watersheds with average elevations under 500 m (14 gauges; CF = 0.98 ± 0.07). Correction factors near or >1 suggest that PRISM data underestimate the volume of orographic precipitation in steep coastal watersheds along the eastern GOA. For watersheds west of Prince William Sound, we used a single correction factor (21 gauges; CF = 0.66 ± 0.04). Runoff errors from each watershed were estimated as the standard error of the correction factor used to convert precipitation volume to runoff volume. The error estimates for all of the watersheds within a region were summed to obtain a conservative error estimate for runoff from each of the seven study regions.

[10] Two components of annual runoff from GOA glaciers were estimated: 1) glacial runoff – the annual runoff derived from glaciers assuming steady-state mass balance and 2) glacier volume loss - runoff derived from glacier thinning and retreat. Glacial runoff and associated errors were estimated using calibration factors and methods described above to convert the volume of PRISM precipitation that fell on the glacier area of watersheds within each region to glacial runoff. Regional glacier area and estimates of annual GVL were calculated from *Arendt et al.* [2002]. The GVL calculated within the drainage areas of the five large gauged rivers was removed from the regional annual runoff estimates as this runoff was captured in the streamflow data for these rivers. Errors for regional GVL estimates were determined by recalculating the error estimates of *Arendt et al.* [2002] for the seven geographic regions in this study.

3. Results and Discussion

[11] The annual average FWD of 870 km^3 yr^{-1} we report for the GOA drainage basin (Table 1) is greater than previous estimates that averaged approximately 730 km^3 yr^{-1} [*Royer*, 1982; *Royer et al.*, 2001; *Wang et al.*, 2004], but similar to a recent estimate of the average annual freshwater transport by the Alaska Coastal Current (880 km^3 yr^{-1} [*Weingartner et al.*, 2005]). *Wang et al.* [2004] used methods similar to ours to calculate FWD, although their study included a larger drainage area (470,800 km^2 vs. 420,230 km^2) encompassing a portion of the coast south of the Alaska/Canada border. The lower FWD calculated by *Wang et al.* [2004] is likely a result of interpolation of relatively sparse climate data and the fact that they did not use gauge data to calibrate their runoff estimates for the multitude of small streams draining into the GOA. Our estimates of FWD to the GOA did not include precipitation falling on the coastal ocean because of a lack of data for this region. However, an analysis of PRISM precipitation data for the inside waters of the Southeast region indicated that ~60 km^3 $yr^{-1}$of freshwater enters the coastal ocean directly as precipitation. Thus coastal ocean precipitation may make a substantial contribution to inputs of freshwater along the GOA.

[12] Freshwater discharge across the GOA exhibits a strong east to west gradient with the majority of discharge originating in regions from Prince William Sound to the east. The Central Coast and Southeast regions had the greatest FWD with a combined total of 570 km^3 yr^{-1} or 66% of total FWD despite comprising only 50% of the GOA drainage area (Table 1). In contrast, the three regions in the western portion of the GOA (W Cook Inlet/Kodiak, Susitna, and Knik Arm/Kenai) accounted for only 136 km^3 yr^{-1} or 15% of total FWD despite representing 30% of the GOA drainage area. Three regions (Central Coast, Southeast, and Prince William Sound) had annual specific runoff that exceeded 2 m and all three of these regions had runoff to area ratios >1 meaning that they contribute disproportionately to runoff along the GOA (Table 1). Patterns in FWD are consistent with atmospheric circulation patterns that force intense low pressure systems to track onshore predominantly in the Central Coast and Southeast regions of the GOA.

[13] Despite having an area of just ~420,000 km^2, the FWD of the GOA watershed is greater than any of the large continental rivers draining into the Arctic Ocean. The largest Arctic river, the Yenisey (2,580,000 km^2) has an annual average discharge of 620 km^3 yr^{-1} [*Peterson et al.*, 2002] and a specific runoff of 0.24 m yr^{-1}, which is just 11% of the specific runoff for the GOA basin (2.1 m yr^{-1} (Table 1)). Similarly, the annual FWD to the GOA exceeds the annual average discharge for the Yukon and Mackenzie rivers combined (501 km^3 yr^{-1} [*Raymond et al.*, 2007]) despite having only 16% of the drainage area of these large arctic rivers. The extreme runoff rates in the GOA basin are exemplified by the fact that specific runoff for the GOA is approximately two- to six-fold higher than the Amazon (~0. 9 m yr^{-1} [*Richey et al.*, 1989]) and Congo (0.33 m [*Amarasekera et al.*, 1997]) rivers.

Table 2. Area and Annual Runoff for the Five Large River Basins in the Gulf of Alaska Drainage Area[a]

Streamflow Station	Period of Record	Drainage Area (km^2)	Percent GOA Basin Area	Mean Annual Discharge (km^3)	Specific Discharge (m)	Percent GOA Discharge
Stikine River near Wrangell, AK	1976–2007	51,593	12%	50 ± 1.1	1.0	5.7%
Taku River near Juneau, AK	1987–2007	17,094	4%	12 ± 0.4	0.7	1.4%
Alsek River near Yakutat, AK	1991–2007	28,024	7%	28 ± 0.8	1.0	3.2%
Copper River near Cordova, AK	1988–1995	62,678	15%	56 ± 2.0	0.9	6.4%
Susitna River at Susitna St., AK	1974–1992	50,246	12%	45 ± 1.3	0.9	5.2%
Total		209,634	50%	191 ± 5.6	0.9	22%

[a]Error estimates for Mean Annual Discharge were estimated as the standard error for the annual discharge of each river over the period of record.

[14] The annual FWD for the five largest rivers within the GOA basin ranged from 12 – 56 km^3 yr^{-1} (Table 2). The gauged drainage area of these five large rivers encompasses 50% of the GOA drainage area and delivers ~22% of the FWD (191 km^3 yr^{-1}). Our findings are consistent with *Wang et al*. [2004] who estimated that 26% of the FWD to the GOA was derived from the five large GOA rivers, with smaller distributed sources accounting for the remaining 74% of FWD. Because coastal ranges along the GOA act as an orographic barrier to precipitation, specific runoff values for the five larger GOA rivers that penetrate coast ranges (Table 2) are substantially less than those of the coastal watersheds. Overall, the high specific discharge for the coastal GOA drainage basins is a result of several factors including: 1) high levels of orographic precipitation, 2) relatively low levels of evapotranspiration, and 3) the predominance of relatively short, steep watersheds within the basin.

[15] Compared to many of the largest watersheds draining into the Arctic, FWD in the GOA watershed is heavily influenced by glacier discharge. In total, glaciers cover 75,300 km^2 or 18% of the GOA drainage basin and account for 47% of FWD. The glacier contribution (glacier runoff plus GVL) to FWD ranges from 7.3 km^3 yr^{-1} in the W. Cook Inlet/Kodiak region to 170 km^3 yr^{-1} in the Central Coast region (Table 3). Glacier runoff comprised >50% of total FWD in three of the seven regions of the GOA (Central Coast, Prince William Sound, and Copper River), and glacier runoff in these three regions accounted for 31% of total FWD to the GOA. The GVL component of FWD varied from 0.9 km^3 yr^{-1} in the W. Cook Inlet/Kodiak region to 22 km^3 yr^{-1} in the Southeast region (Table 3), and GVL accounted for 12–42% of the total glacier runoff across the seven regions. The total annual GVL we estimated for the GOA basin (88 km^3 yr^{-1}) indicates that ~90% of the annual GVL for Alaska and Canadian glaciers (96 km^3 yr^{-1}) estimated by *Arendt et al.* [2002] flows to the GOA as opposed to discharging to the Bering Sea and Arctic Ocean.

[16] The changes to be expected in glacier runoff are larger than those generally projected for other components of the water cycle [*Intergovernmental Panel on Climate Change*, 2007]. For example, in Iceland *Adalgeirsdottir et al.* [2006] modeled an increase in annual runoff from the Hofsjökull and southern Vatnajökull ice caps of up to 60% until about 2100 followed by a rapid decrease thereafter. The fact that glacier runoff accounts for 47% of total FWD to the GOA, suggests that changes in glacier volume have the potential to substantially alter fluxes of freshwater to the GOA. Our results identify the region of the GOA from Prince William Sound to the east, where glacier runoff constitutes a large percentage of the total FWD, as being most vulnerable to future changes in FWD. Moreover, the fact that annual GVL along the GOA increased by approximately 39 km^3 yr^{-1}during the last several decades of the 20th century [*Arendt et al*., 2002] indicates FWD to the GOA may be increasing at rates comparable to the six largest Arctic rivers combined (~2 km^3 yr^{-2} for the period 1936–1999 [*Peterson et al.*, 2002]).

[17] Recent estimates of GVL based on digital elevation data from the 2000 Shuttle Radar Topography Mission (SRTM) for the Kenai Peninsula [*VanLooy et al.*, 2006] and southeastern Alaska [*Larsen et al.*, 2007] indicate that rates of GVL in these regions are at least two-fold higher than earlier estimates for similar regions by *Arendt et al.* [2002]. Therefore, our estimates of discharge due to GVL are likely less than current rates, particularly in regions of the GOA with an abundance of 1) tidewater and lacustrine glaciers and 2) low elevation glaciers. Recent increases in GVL rates

Table 3. Glacier Area and Annual Glacial Runoff and Volume Loss From the Seven Geographic Regions Within the Gulf of Alaska Drainage Basin[a]

Region	Glacier Area (km^2)	Glacier Cover	Runoff From Glacier Area (km^3 yr^{-1})	Glacier Volume Loss (km^3 yr^{-1})	Total Glacier Contribution to Regional Runoff (km^3 yr^{-1})	Percent of Regional Runoff From Glacier Area
Southeast	16,753	11%	77 ± 5.3	22 ± 8.0	99 ± 13	27%
Central Coast	24,570	44%	150 ± 10	20 ± 7.1	170 ± 17	85%
Copper River	14,084	22%	30 ± 2.8	15 ± 5.6	45 ± 8.0	69%
Prince William Sound	7216	36%	37 ± 2.5	20 ± 7.3	57 ± 10	60%
Knik Arm/Kenai	4197	14%	9.8 ± 0.4	7.2 ± 2.6	17 ± 3.0	47%
Susitna River	5390	10%	7.8 ± 0.3	2.6 ± 1.0	10 ± 1.3	22%
West Cook Inlet/Kodiak	3069	7%	6.4 ± 0.2	0.9 ± 0.3	7.3 ± 0.5	14%
GOA Total	75,279	18%	320 ± 22	88 ± 32	410 ± 50	47%

[a]Error estimates for glacier runoff and glacier volume loss were calculated as described in the methods and were summed to obtain a conservative error estimate for total glacier runoff.

along the GOA suggest that continued climate warming will increase the GVL contribution to FWD in regions of the GOA containing substantial glacier coverage. Presently there are few long-term river discharge records along the coastal GOA, however, discharge has increased in coastal watersheds with glaciers concomitant with a North Pacific climate shift in 1976 [*Neal et al.*, 2002; *Hodgkins,* 2009]. Our results provide guidance for an improved hydrological observing network to monitor these changes.

[18] Climate driven changes in the FWD along the GOA also have the potential to alter biogeochemical fluxes to near-shore marine ecosystems and the eastern North Pacific Ocean as small, coastal watersheds have been shown to yield high mass loadings to the coastal oceans [*Destouni et al.*, 2008]. Recent studies have evaluated the potential impacts of climate warming on riverine fluxes of dissolved organic matter and reactive nitrogen and phosphorus to the Arctic Ocean [*Frey et al.*, 2007; *Walvoord and Striegl*, 2007], however similar studies are largely lacking for the GOA drainage region. Changes in landcover associated with the loss of glacial ice in watersheds in southeastern Alaska have been shown to affect the physical and biogeochemical properties of coastal streams [*Hood and Berner*, 2009] as well as riverine fluxes of both water and reactive nutrients [*Hood and Scott*, 2008]. Thus changes in regional FWD associated with GVL along the GOA have the potential to effect changes in the riverine and near-shore biogeochemistry of this region. Estimating biogeochemical fluxes across the GOA drainage basin remains a challenge because of the distributed nature of the runoff in this region. Our results provide a starting point for estimating the spatial distribution of riverine material fluxes across the GOA and how they may be affected by future changes in climate.

[19] **Acknowledgments.** Anthony Arendt provided data on glacier volume loss. Glenn Hodgkins and Shad O'Neel provided helpful comments on an earlier version of the manuscript. Funding came from the Geographic Information Network of Alaska at the University of Alaska Southeast, the U.S.G.S. Alaska Science Center, and the U.S. National Science Foundation (EAR-0838587).

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