AGU ADVANCING EARTH AND SPACE SCIENCE

JGR Biogeosciences

RESEARCH ARTICLE
10.1029/2020JG005725

Key Points:
- Southeast Alaska rivers export 430 km^3 of freshwater and 1.17 Tg of dissolved organic carbon per year to estuaries and the Gulf of Alaska
- Watershed type, geographic location, and hydrograph are important controls on freshwater and dissolved organic carbon flux patterns
- Understanding marine productivity is enhanced by understanding the seasonal and geographic patterns of carbon and water outputs

Supporting Information:
- Supporting Information S1
- Table S1

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Citation:
Edwards, R. T., D'Amore, D. V., Biles, F. E., Fellman, J. B., Hood, E. W., Trubilowicz, J. W., & Floyd, W. C. (2021). Riverine dissolved organic carbon and freshwater export in the eastern Gulf of Alaska. *Journal of Geophysical Research: Biogeosciences*, *126*, e2020JG005725. https://doi.org/10.1029/2020JG005725

Received 28 FEB 2020
Accepted 29 SEP 2020
Accepted article online 27 OCT 2020

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Riverine Dissolved Organic Carbon and Freshwater Export in the Eastern Gulf of Alaska

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Abstract The coastal zone of southeast Alaska contains thousands of streams and rivers that drain one of the wettest, carbon-rich, and most topographically varied regions in North America. Watersheds draining temperate rainforests, peatlands, glaciers, and three large rivers that flow from the drier interior of the Yukon Territory and British Columbia discharge water and dissolved organic carbon (DOC) into southeast Alaskan coastal waters. This area, which we have designated the southeast Alaska drainage basin (SEAKDB), discharges about twice as much water as the Columbia or Yukon Rivers. An understanding of the timing, location, and source of water and DOC guides research to better understand the influence of terrestrial outputs on the adjacent marine systems. Additionally, a spatially extensive understanding of riverine DOC flux will improve our understanding of lateral losses related to terrestrial carbon cycling. We estimate 1.17 Tg C yr^{-1} of DOC enters the adjacent marine system along with 430 km^2 of freshwater that influences estuary, shelf, and Gulf of Alaska hydrology. We estimate that 23% to 66% of the DOC entering coastal waters is bioavailable and may influence metabolism and productivity within the marine system. The combination of the large and spatially distributed water and DOC input, long and complex shoreline, large enclosed estuarine volume, and bounded nearshore coastal currents suggests that the physiographic structure of southeast Alaska may have a significant impact on the metabolism of riverine DOC in coastal marine ecosystems.

Plain Language Summary The coast of southeast Alaska drains coastal rainforests, glaciers, and interior basins in Alaska, British Columbia, and the Yukon. High precipitation, glacier melt, and large interior watersheds combine to discharge an annual volume of freshwater greater than that of the Columbia or Yukon Rivers, which drain basins 3.5 and 4.5 times larger. This large amount of water entering the Alexander Archipelago estuaries and coastal shelf creates currents and density gradients that influence how the river discharge and organic matter in it enter the Gulf of Alaska in the northern Pacific Ocean. Along with the large amount of water there is 1.17 Tg of dissolved organic carbon (DOC), which can be taken up by bacteria and other microbes and turned into carbon dioxide or food that can be incorporated into the marine food web. A portion may settle into marine sediments to be stored for long periods of time. The amount and type of DOC and its entry into the marine ecosystem are controlled by watershed characteristics within the southeastern coast of Alaska. A better understanding of where and when DOC and freshwater enter the ocean may help us understand its importance to marine processes.

1. Introduction

Coastal margins are ecotones between land and sea where abundant terrestrial organic matter flows into estuaries and coastal waters. Mixing of riverine dissolved organic carbon (DOC) in estuaries and shelf waters results in high rates of carbon cycling that impact global carbon cycles disproportionately to their areal extent (Fennel et al., 2019; Najjar et al., 2018; Smith & Hollibaugh, 1993). Identifying terrestrial carbon sinks that offset increases in atmospheric C (carbon accounting) is an emerging research priority, particularly where transfers occur across ecosystem boundaries. A preferred method of carbon accounting is net ecosystem carbon balance (NECB; Chapin et al., 2006), which includes all components of the carbon cycle including lateral carbon fluxes (Cole et al., 2007). Recent summaries of inland water carbon budgets substantially

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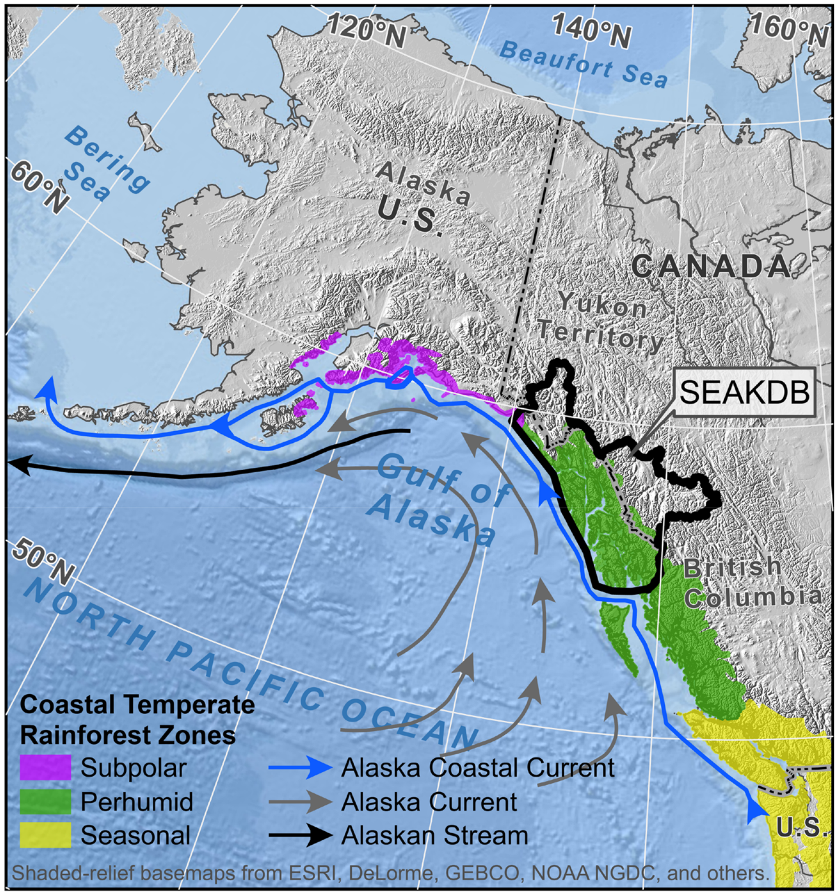

Figure 1. Location of the SEAKDB, coastal temperate rainforest zones, and Gulf of Alaska ocean currents. Source: ocean currents adapted with permission from Weingartner et al. (2005). Rainforest zones adapted with permission from vector data set "CTRF" by Ecotrust, Pacific GIS, and Conservation International, and Wolf et al. (1995).

improved total carbon budget estimates calculated in the Second State of the Carbon Cycle Research report (SOCCR2) compared to the previous report (Hayes et al., 2018). Estimates for the terrestrial flux of carbon to inland waters have increased to >5 Pg C yr^{-1} (Butman et al., 2018; Drake et al., 2017; Sawakuchi et al., 2017). These results illustrate the importance of lateral DOC transfers in determining the net regional and global terrestrial carbon balance. Likewise, accounting for riverine inputs into coastal margins improves carbon accounting and provides insights into the potential role of riverine DOC on marine productivity.

The coast of southeast Alaska provides a compelling template to study land-sea interactions, but little research has combined riverine DOC and freshwater export with estimates of estuarine or coastal carbon cycling, such as bacterial carbon demand. Southeast Alaska, which encompasses the northernmost portion of the perhumid coastal temperate rainforest (PCTR) (Figure 1; Wolf et al., 1995), comprises two distinct physiographic divisions (U.S. Department of Agriculture, 2004): (1) the extended islands and fjords of the Alexander Archipelago and (2) the southern Alaska coastal mountains along the continental margin. Within the Archipelago, over a thousand large and small islands surround 30,000 km^2 of estuarine waters (U.S. Fish and Wildlife Service, 2009) and contain about 15% of the 50 United States' coastline (U.S. Department of Commerce, National Oceanic and Atmospheric Administration, 1975; U.S. Geological Survey, 2019). The estuarine system is a complex of abundant embayments, channels, and fjords where continental outputs can be retained and assimilated into marine food webs. There is about a half kilometer of shoreline for every km^2 of forest (Edwards et al., 2013) stimulating land-water interactions over large areas. The coastal mountain area contains steep, high-relief terrain and drains some of the largest glaciers and icefields in North America (Ziemen et al., 2016). Three large river systems, which have continental headwaters,

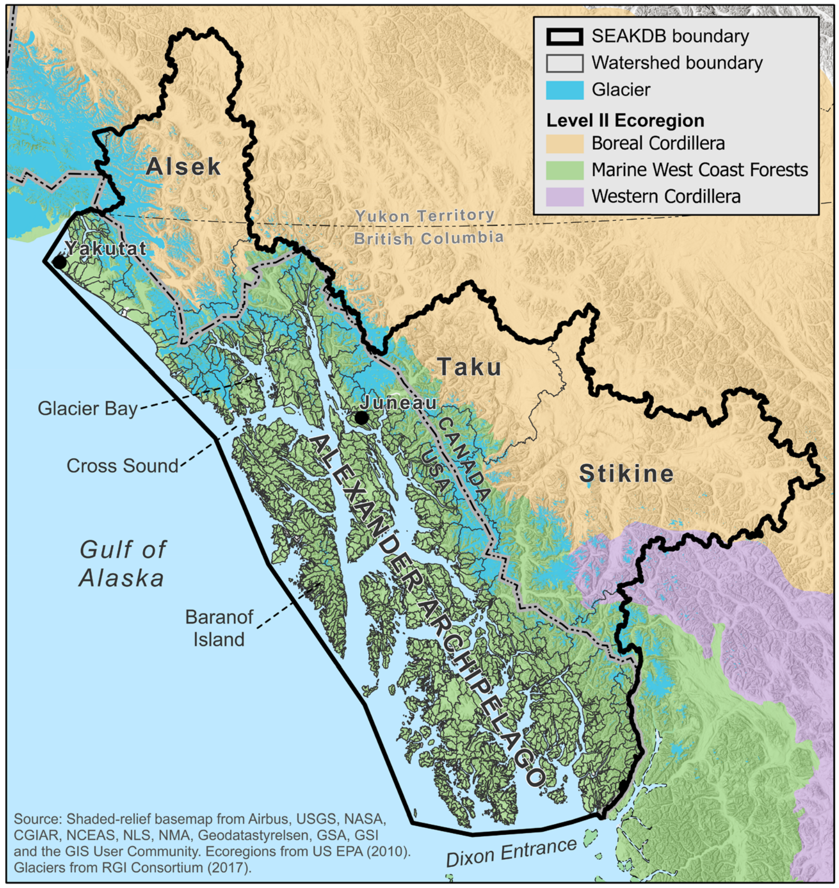

Figure 2. SEAKDB watersheds and area geography.

drain through the mountains and empty into the archipelago (Stikine and Taku Rivers) or directly into the coastal ocean (Alsek River). We define the contributing area for this region as the southeast Alaska drainage basin (SEAKDB; Figures 1 and 2).

Ultimately, terrestrial runoff enters the coastal shelf where entrained materials enter the Alaska Coastal Current (ACC) and are transferred northward to the south central Alaska coast or out into the Gulf of Alaska (GOA; Figure 1). The productive southeast Alaska coastal zone supports a fishery valued at 700 million dollars (McDowell Group, 2017), but the influence of terrestrial and riverine outputs on this valuable fishery is poorly documented. The extent to which DOC in freshwater runoff impacts marine metabolism and productivity, and the influence of the geographic template on utilization patterns is unknown, partly due to the lack of detailed estimates of DOC flux within this large and varied region. Although several studies have documented high rates of DOC flux within the perhumid rainforest (D'Amore et al., 2015; Oliver et al., 2017), existing regional flux estimates (Stackpoole et al., 2017) have not been calculated with sufficient spatial and temporal resolution to potentially explain observed marine processes that vary in space and time.

This study was designed to model the spatial and temporal dynamics of the land-to-ocean water and DOC flux to aid in interpretation of coastal margin studies. Our objectives were to (a) generate spatially and temporally explicit water and DOC flux estimates from discrete watersheds to provide order of magnitude estimates of loss from terrestrial ecosystems and (b) describe the relationship between watershed type and location (proximity to ocean, position within climatic gradients, etc.) and potential influence on the adjacent marine ecosystem. We present monthly estimates of water and DOC output across three distinct watershed types with differing land cover and hydrology. Our results are based on numerous distributed streamwater DOC samples that enable us to parse the spatial and temporal dynamics of carbon movement to the marine ecosystem. This approach allows us to better estimate where and when continental outputs may influence the adjacent marine ecosystem.

2. Materials and Methods

2.1. Study Area

The SEAKDB is approximately 188,829 km^2 and includes southeast Alaska, northwest British Columbia, and southwest Yukon Territory in Canada (Figure 2). The three largest SEAKDB watersheds, the Alsek, Taku, and Stikine Rivers, originate in the Boreal Cordillera Level II North American ecoregion (U.S. Environmental Protection Agency, 2010), which has a continental-to-moderate climate, ranging from cold, subhumid to semiarid, and is buffered by pacific maritime influences to the west. The landscape includes mountains and plateaus supporting boreal forests, grasslands and alpine tundra vegetation, icefields, glaciers, perpetual snow, bare rock, and permafrost (Wiken et al., 2011). The lower portions of these three-watersheds, and much of the remaining SEAKDB, flow through the Marine West Coast Forests ecoregion, a dominantly perhumid environment with mean annual rainfall of 3,380 mm (481–13,593 mm; AdaptWest Project, 2015). The perhumid region is 56% of the study area, with 30% in a maritime-to-continental transition zone encompassing steep mountains with barren slopes, glaciers, and icefields, alpine tundra, scrub/shrub vegetation, and coniferous forest. The remaining 26%, the coastal fringe, is a temperate rainforest complex of coniferous forests dominated by hemlock, spruce, and cedar species mixed with numerous peatlands, alder shrub communities, alpine tundra, estuaries, and smaller pockets of deciduous forest (Gallant et al., 1995).

2.2. GIS Data Sets

Four geographic information systems (GIS) data sets were used in our analysis, (1) watershed boundary polygons, (2) a digital elevation model (DEM), (3) glacier extent polygons, and (4) a grid of mean monthly runoff. Watershed polygons were the analysis unit used to derive landscape attributes and calculate DOC flux for the SEAKDB. Watershed boundaries were compiled from U.S. Watershed Boundary Dataset 12-digit hydrologic units (WBD; Watershed Boundary Dataset, 2012) and British Columbia Freshwater Atlas Watershed Groups (British Columbia Ministry of Forests, Lands, Natural Resource Operations and Rural Development [BC FLNRO], 2012). These boundaries were edge matched across the U.S.-Canada border, subbasins were merged into whole headwater-to-saltwater watersheds, and the data set was clipped to an approximate mean high water shoreline. Many drainages along the coastal fringe do not meet the WBD 12-digit minimum mapping size criteria of 40.5 km^2. Consequently, these smaller watersheds are lumped into single hydrologic units up to approximately 162 km^2 (U.S. Department of Agriculture, Natural Resources Conservation Service, 2004; U.S. Geological Survey and U.S. Department of Agriculture, Natural Resources Conservation Service, 2013). For this analysis we treat these lumped hydrologic units and individual watersheds identically. The resulting layer contains 2,455 independent watersheds that define the SEAKDB. We derived the attribute “proportion of watershed in 0-to-5 degree slopes” from AKPCTR_DEM (Biles, 2016). AKPCTR_DEM is a 50-m, bare-earth DEM with seamless coverage across the SEAKDB. Source data for AKPCTR_DEM originated from the U.S. Geological Survey (USGS) 2-arc sec National Elevation Dataset (NED), 25-m British Columbia Terrain Resource Information Management (TRIM), and 0.75-arc sec Canadian Digital Elevation Data (CDED) DEMs. Watershed glacier cover was determined using version 6 of the Randolph Glacier Inventory (RGI Consortium, 2017). SEAKDB watershed attributes and watershed boundaries are available in Biles et al. (2020, see Table A and GIS data set).

2.3. Freshwater Discharge Estimation

We generated mean monthly runoff estimates from the distributed climate water balance model (DCWBM), a monthly water balance model described in Moore et al. (2012). Moore et al. applied the model, a recoded version of the USGS Thornthwaite water balance model (McCabe & Markstrom, 2007), to ungaged basins in British Columbia and found that the model provided reasonable estimates of the average hydrologic conditions in watersheds ranging from 0.8 to 6,760 km^2. Moore et al. (2012) calculated the water balance on a 400-m grid, using climate normals obtained from the ClimateBC tool (Spittlehouse, 2006) to estimate average monthly runoff depth for each grid point.

We revised the domain of the DCWBM to include all British Columbia and Alaska watersheds that discharge to the GOA (Figure S1). We extracted 400-m gridded 1981–2010 climate normals (monthly mean high and low temperatures and monthly mean precipitation) from the ClimateWNA tool (Wang et al., 2012) to drive the model, an expansion of the ClimateBC output used in Moore et al. (2012). The revised model domain required an expanded land cover source because Moore et al. (2012) used only British Columbia data. We used the European Space Agency (ESA)'s GlobCover data (Arino et al., 2012) for 400-m land cover to identify glaciers, open water, alpine terrain, and moderate and closed canopy regions.

To apply the DCWBM to the GOA region, we calibrated the Moore et al. (2012) model based on measured discharge from watersheds in the region. To support this process, we recoded DCWBM into C++ for high-speed operation and created an open-source package for the R programming language (R Core Team, 2017). The model is available for any R user to install from GitHub (https://github.com/jwtrubil/DCWBM). We matched simulated and observed monthly runoff for the 1981–2010 normal period in 72 unregulated GOA basins that had at least 10 years of streamgage data from 1981–2010. Gage data were obtained from the USGS (U.S. Geological Survey, 2015) and the Water Survey of Canada Hydat database (Environment and Climate Change Canada, 2015). Calibration basins ranged from 3.6 to 15,800 km^2.

The median Nash-Sutcliffe model efficiency (NSE; Nash & Sutcliffe, 1970) for the 72 test basins was maximized using the model independent calibration software "Ostrich" (Matott, 2017). We used Ostrich to manipulate nine model parameters in the DCWBM:

1. Open, moderate, and closed canopy snowmelt factor;
2. Open, moderate, and closed canopy rain/snow interception factor;
3. Soil moisture storage factor;
4. Temperature threshold signifying 100% rain;
5. Temperature threshold signifying 100% snow.

After calibration, the 72 test basins had a median NSE value of 0.78 for predicting the average monthly runoff, indicating an acceptable reproduction of typical flow conditions across the region. Figure S2 shows simulated and observed monthly runoff for test basins within the SEAKDB and Alaska. To investigate the seasonal impact of model error, we also calculated the mean square error and mean absolute error between DCWBM model output and observations, by month, for the 72 calibration basins (Table S1).

Using ArcGIS (ESRI, 2014), the 400-m, monthly DCWBM grids were nearest-neighbor resampled to 50 m before computing mean monthly runoff by watershed. Total monthly discharge volume was calculated by multiplying watershed monthly runoff with watershed area.

2.4. Partitioning of Watersheds Into Glacier and Nonglacier Hydrologic Regimes

In southeast Alaska, DOC concentrations from streams where runoff is dominated by glacier meltwater are significantly lower and less variable than concentrations measured from streams in nonglacier watersheds (Fellman et al., 2014). For this study we identified watersheds as either "glacier" or "nonglacier" to assign appropriate DOC concentration models and compute flux. Annual hydrographs of streams dominated by runoff from glacier and high-elevation snow melt are distinct from hydrographs of streams where glacier and high-elevation snow cover is very low or absent (Edwards et al., 2013). We used the flow regime of a watershed's outlet stream to determine watershed type (glacier or nonglacier). First, we assessed hydrograph differences (e.g., shape and seasonality) between glacier and nonglacier watersheds for 62 gaged streams within our study area by examining graphs of mean monthly discharge at or near saltwater outlets (Figure 3; U.S. Geological Survey, 2017). To facilitate comparison of flow regimes among different watersheds, discharge was normalized as the ratio of mean monthly discharge to mean annual discharge then multiplied by 12 (Pardé coefficients; Pardé, 1955). Next, the monthly Pardé coefficients were used as the response variable in a multivariate regression tree analysis (MRT; R software package *mvpart*; De'ath et al., 2014; R Core Team, 2017) to predict flow regime type. We chose predictor variables assumed to be important in controlling glacier flow regimes: percent of watershed area covered by glacier (glacier%), total watershed area covered by glacier, watershed area, maximum watershed elevation, mean watershed elevation, and mean watershed slope. Streamflow and basin characteristics for the gaged watersheds are available at Biles et al. (2020, Table C). The MRT analysis partitioned the gage data set into glacier and nonglacier flow regimes based on the variable glacier%, where watersheds with glacier cover ≥0.81% were classed as having a glacier flow regime (Figure S3; see Text S1 for additional details). SEAKDB watersheds were then classified as either glacier or nonglacier based on this 0.81% glacier cover criterion.

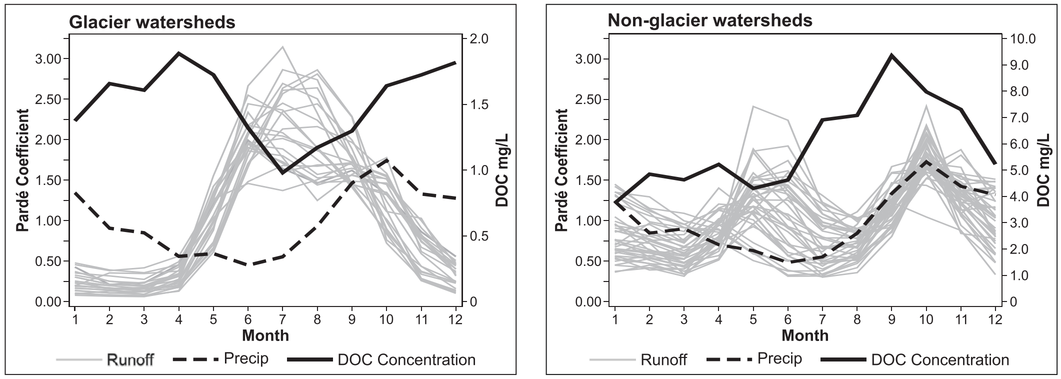

Figure 3. Mean monthly runoff, precipitation, and DOC concentration for glacier and nonglacier watersheds. Runoff and precipitation are normalized as Pardé coefficients (mean monthly discharge divided by mean annual discharge, times 12). Compared to glacier watersheds, freshwater discharge from nonglacier watersheds is higher in the winter, much lower in the summer, and either closely mimics the precipitation hydrograph, or generally follows the precipitation hydrograph but has an additional spring snowmelt peak. Glacier watersheds discharge a much higher proportion of their annual flow beginning in midspring and through summer and store significantly more precipitation over the winter. Precipitation source: PRISM mean monthly precipitation, 1981–2010 (Pacific Climate Impacts Consortium, University of Victoria, and PRISM Climate Group, Oregon State University, 2014).

2.5. DOC Seasonality

Glacier and nonglacier watersheds alike have a "low DOC concentration season" (LCS) and a "high DOC concentration season" (HCS) (Fellman et al., 2014; Hood & Berner, 2009), but the timing differs (Figure 3). To incorporate this seasonal variability, we developed separate models to predict DOC concentration for each glacier and nonglacier LCS and HCS period (see *Predicting DOC Concentration and Watershed Fux*).

We determined LCS/HCS season breaks by examining plots of individual DOC concentration samples and mean monthly concentration (Figure S4). The plots contain 1,876 individual DOC measurements, with 1,106 taken from 34 different glacier streams and 770 taken from 108 nonglacier streams. Values were compiled from data downloaded from the USGS (U.S. Geological Survey, 2018a) and the British Columbia Water Portal (British Columbia Ministry of Forests, Lands, Natural Resource Operations, & BC Oil and Gas Commission, 2017), mined from the literature (D'Amore et al., 2016; Fellman et al., 2014; Gaillardet et al., 2003; Hood & Berner, 2009; Loder, 1971; Loder & Hood, 1972; Nagorski et al., 2014; Spencer et al., 2014; Stubbins et al., 2012; Sugai & Burrell, 1984) and from samples collected by the authors (Biles et al., 2020, Table B). We set the season breaks as follows: glacier watershed LCS = June–September and HCS = October–May; nonglacier watershed LCS = December–June and HCS = July–November.

2.6. Predicting DOC Concentration and Watershed Flux

We predicted mean monthly stream DOC concentration for all but two watersheds using ordinary least squares regression models. All streamwater samples for DOC analyses in this study were taken above marine influences. Different concentration models were applied for glacier versus nonglacier watersheds and whether a month fell in the LCS or the HCS (Table 1). We were unable to compute flux for 117 of the 2,455 watersheds because the coarse resolution (400 m) of the DCWBM did not capture some small (<0.5 km^2) watersheds and islands. The 117 watersheds accounted for <0.01% of the total SEAKDB area, a loss unlikely to appreciably effect our DOC flux results.

2.6.1. Glacier Models

Regression models shown in Table 1 for glacier watersheds were developed using DOC measurements from 14 independent SEAKDB streams with watershed glacier cover ranging from 0.9% to 74.2% (Table S2). The LCS model included 326 DOC samples and the HCS model had 392, with the number of measurements from any site and season combination ranging from 3 to 76 (complete data set available in Biles et al., 2020, Table D). We used the mean LCS and HCS DOC concentration for each site as the response variable in the regression and glacier% as the predictor. For three sites containing censored observations (values

Table 1
Seasonal Regression Models Used to Predict Mean Monthly Stream DOC Concentration (mg L^{-1}) for SEAKDB Glacier and Nonglacier Watersheds

Model	Flow regime type	Season	Intercept (*t* value) (95% CI)	Slope (*t* value) (95% CI)	R^2 (EDF)
DOC = Slp0–5	Nonglacier	LCS: Dec–Jun	2.80 (7.38, $P < 0.001$) (2.04, 3.56)	11.99 (8.21, $P < 0.001$) (9.59, 14.40)	0.628 (59)
DOC = Slp0–5	Nonglacier	HCS: Jul–Nov	4.77 (8.97, $P < 0.001$) (3.70, 5.83)	13.53 (7.70, $P < 0.001$) (10.01, 17.05)	0.528 (53)
DOC = Ln Glacier%	Glacier	LCS: Jun–Sep	2.91 (13.44, $P < 0.001$) (2.44, 3.38)	−0.662 (−8.58, $P < 0.001$) (−0.83, −0.49)	0.860 (12)
DOC = Ln Glacier%	Glacier	HCS: Oct–May	3.20 (7.48, $P < 0.001$) (2.27, 4.13)	−0.617 (−4.05, $P = 0.002$) (−0.95, −0.29)	0.578 (12)

Note. Slp0–5 is the proportion of watershed in 0° to 5° slopes. Ln glacier% is the natural logarithm of watershed percent glacier cover. LCS = low DOC concentration season. HCS = high DOC concentration season. EDF is the model error degrees of freedom.

below the lab instrument detection limit), season means were computed using the quasi minimum variance unbiased estimator of the maximum likelihood estimate (R software package *EnvStats*, function *elnormAltCensored*, method = *qmvue*; Ganser & Hewett, 2010).

The glacier models were used to predict DOC concentration for 225 SEAKDB watersheds. Eight of these had glacier% coverage outside the range of the model (i.e., glacier% > 74.2). In four cases, where extrapolating outside the model generated negative estimates of DOC concentration, we substituted a value of 0.1 mg L^{-1}. This was the lowest measured DOC value we have found from any SEAKDB glacier stream and was assumed to be the minimum concentration for these systems.

2.6.2. Nonglacier Models

We used the top-ranked 1-variable spring (LCS) and fall (HCS) regression models produced by D'Amore et al., 2016, p. 389) to predict mean monthly stream DOC concentration for the 2,228 SEAKDB nonglacier watersheds. Both models use the proportion of watershed in 0° to 5° slopes as the predictor variable (Table 1).

For each glacier and nonglacier watershed, monthly total DOC flux was estimated by multiplying the mean monthly DCWBM runoff with mean monthly DOC concentration. Monthly fluxes were added to estimate watershed mean annual DOC flux. Monthly and annual fluxes were divided by watershed area to determine mean DOC yield.

2.6.3. Other Watersheds

Three large glacier watersheds span the U.S.-Canada boundary: the Alsek, Taku, and Stikine Rivers (Figure 2). The Taku and Stikine river basins together account for approximately 15% of the annual freshwater discharge to the ocean for the SEAKDB region. Because of the influence these watersheds could impose on total regional flux, we used measured discharge and DOC concentration (Biles et al., 2020, Table B; U.S. Geological Survey, 2018a, 2018b) to estimate DOC flux for the Taku and Stikine Rivers (complete data set available in Biles et al., 2020, Table E). Concentration-discharge relationships were modeled from field measurements using the *loadreg* function in the R package *rloadest*, and monthly fluxes were generated using the *predLoad* function (Lorenz et al., 2017; Runkel et al., 2004). The Alsek River contributes 12% of the total annual SEAKDB runoff; however, there were not enough DOC measurements available for a *rloadest* calculation. Therefore, DOC flux estimates for the Alsek followed the method for glacier watersheds described above. The Alsek, Taku, and Stikine are the three largest watersheds in the SEAKDB; henceforth, we will refer to these three transboundary watersheds as the "Big3." Although the Big3 watersheds are glacier watersheds (6% to 20% glacier cover), because of their unique characteristics, including large size, high runoff, and predominately Boreal Cordillera headwaters, we considered the Big3 as a third watershed type for grouping results and discussion.

3. Results

3.1. Discharge

Our estimate of mean annual freshwater discharge from the SEAKDB using the DCWBM is 430 km^3 (Table 2), which is 41% of the total input into the GOA estimated by Neal et al. (2010). Neal et al. estimated a mean annual discharge of 370 ± 23 km^3 from their Southeast region, which agrees well with the DCWBM estimate of 358 km^3 over the same extent. The total output of freshwater from the SEAKDB is lowest during November–April (Figure 4a and Table S3), increases rapidly from May to August, and drops back to the

Table 2
Estimated Annual DOC Flux and Freshwater Runoff for SEAKDB Watersheds

Watershed class	Area (km^2)	Area (% total)	Total flux (Tg C)	Total flux (% total)	Yield (g C m^{-2})	Runoff (km^3)	Runoff (% total)	BDOC (%)	BDOC flux (Tg C)
All	188,829	100	1.17	100	6.2	430.1	100		0.23–0.39
All (No Big3)	92,372	49	0.95	82	10.3	317.2	74		
Big3 only	96,457	51	0.22	18	2.2	112.9	26		
Alsek	28,818	15	0.05	4	1.8	50.9	12		
Stikine	50,831	27	0.15	13	2.9	50.7	12		
Taku	16,808	9	0.02	1	0.9	11.3	3		
Nonglacial	47,401	25	0.79	67	16.6	132.6	31	23–35	0.18–0.28
Glacial (with Big3)	141,428	75	0.38	33	2.7	297.4	69		
Glacial (no Big3)	44,971	24	0.17	14	3.7	184.5	43	26–66	0.04–0.11

Note. Glacier watersheds, which include the Big3, are watersheds with ≥0.81% glacier cover. BDOC = bioavailable DOC.

annual low during September–October. However, the percent contribution by the different watershed types varies widely over the year. Glacial rivers supply 69% of the annual total discharge with the Big3 comprising 27% of the total (Figures 4a and 5a and Table 2). The Big3 rivers contribute 8% to 12% of total runoff from December to April and increase rapidly during May and June to a maximum of 37% in July and August (Figure 4a). The remaining glacial watersheds follow a similar pattern but always have a larger proportion of total runoff than the Big3 (Figure 4a). Discharge from the nonglacial watersheds varies from 12% to 71% of the monthly total and dominates runoff from November to April. Compared to the glacial rivers, discharge from nonglacial watersheds is evenly distributed over the year; therefore, their proportion of total monthly freshwater runoff to the marine environment is determined by the much larger changes in glacial watershed runoff.

Although most of the annual discharge comes from glacial watersheds, specific water yields from the Big3 are much lower than most of the remaining, smaller glacial watersheds (Figure 5b). Glacial watersheds contribute 69% of total annual discharge from 75% of the SEAKDB contributing area in contrast to the nonglacial watersheds, which provide 31% of the total annual discharge from 25% of the area (Table 2). Half of the SEAKDB watershed area lies in the Big3, but they contribute only 27% of the annual discharge because a large proportion of their upper drainages lie within the drier Boreal Cordillera ecoregion. Excluding the Big3, the remaining glacial watersheds provide 43% of total discharge from only 24% of the watershed area.

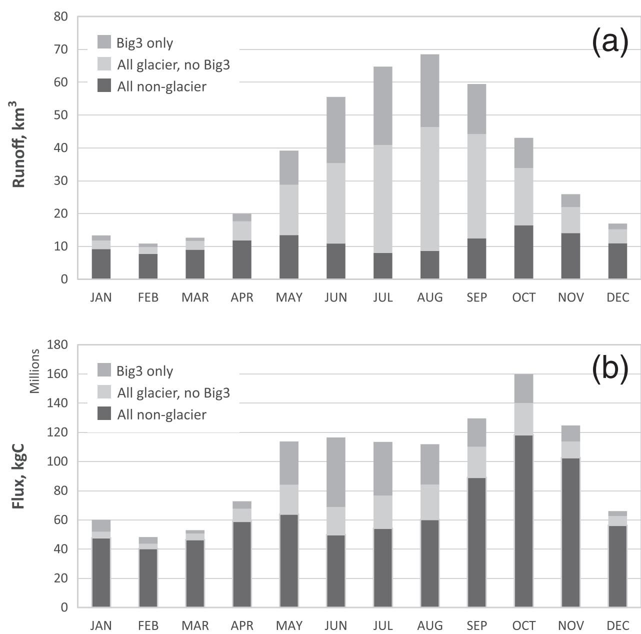

Figure 4. Monthly distribution of (a) mean freshwater discharge and (b) DOC flux from the SEAKDB watersheds.

3.2. DOC Flux

The mean total annual DOC flux into the marine ecosystem from the SEAKDB is 1.17 Tg C yr^{-1} (Table 2). Monthly totals vary from 0.05 to 0.16 Tg C and are lowest from December to April (Figure 4b and Table S3). Sixty seven percent of the total annual C flux comes from nonglacial watersheds (Table 2), whereas 33% comes from glacial basins. Nonglacial basins export from 54–88% of total DOC in any given month except during June and July when they account for less than half of the total flux (Figure 4b). Annual carbon fluxes are highest in larger watersheds (Figure 6a), but yields are lower (Figure 6b). Average yields from the watershed classes vary from 0.9 to 16.6 g C m^{-2} yr^{-1} with a mean of 6.20 g C m^{-2} yr^{-1} (Table 2). The Big3 transboundary rivers have the lowest mean carbon yields at 2.2 g C m^{-2} yr^{-1} followed by the remaining glacial watersheds at 2.7 g C m^{-2} yr^{-1}. The nonglacial watersheds average much higher yields at 16.6 g C m^{-2} yr^{-1} but individual catchments vary widely from 2.0–60.7 g C m^{-2} yr^{-1} (Figure 6b).

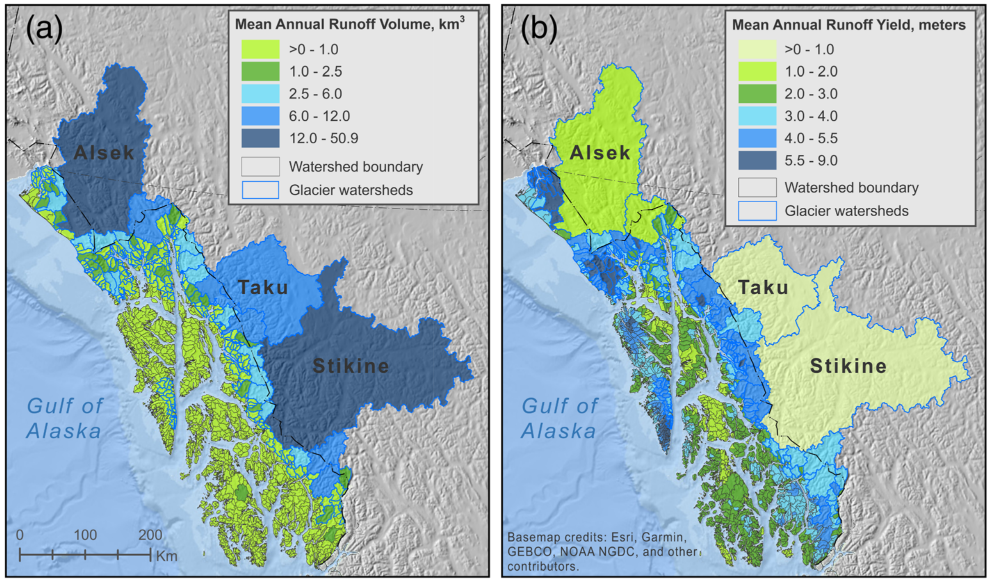

Figure 5. Distribution of mean annual freshwater runoff volume (a) and yield (b) from SEAKDB watersheds.

3.3. Error Estimates

Table S4 contains the monthly, annual, and seasonal runoff, DOC concentration, and DOC flux estimates we generated for all SEAKDB watersheds, along with lower and upper 95% prediction intervals for each monthly concentration estimate. Note that although Table S1 provides a measure of uncertainty for monthly runoff estimates and Table S4 includes prediction intervals for monthly DOC concentrations, we were unable to provide combined error estimates for DOC flux for all but the Taku and Stikine watersheds due to the different construction of the runoff and concentration models. DOC fluxes for the Taku and Stikine were estimated using *rloadest* to directly model concentration-discharge relationships. The monthly output from *predLoad* does not include DOC concentration, but does include 95% prediction intervals for monthly flux.

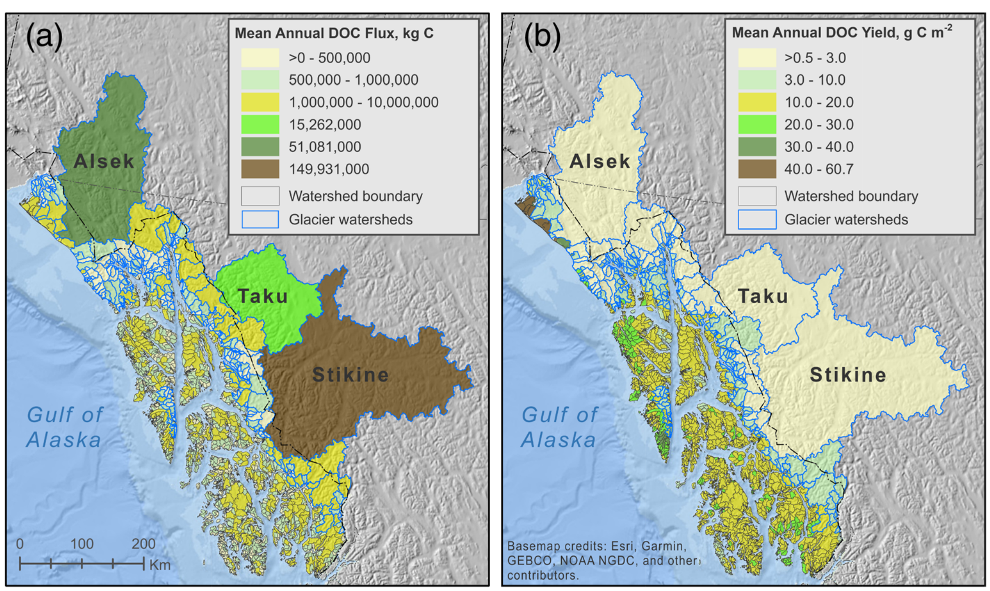

Figure 6. Distribution of mean annual DOC flux (a) and DOC yield (b) from SEAKDB watersheds.

4. Discussion

4.1. Continental DOC-Marine Interactions

The massive SEAKDB DOC flux is 17–20% of that from the contiguous 48 U.S. states (Stets & Striegl, 2012), 4.4% of the total North American continental DOC flux (Dai et al., 2012), and 0.5–0.7% of the estimated global riverine DOC export (Harrison et al., 2005; Li et al., 2017). Previous estimates of total regional DOC flux from southeast Alaska (D'Amore et al., 2015; Stackpoole et al., 2017) and coastal British Columbia (Oliver et al., 2017), which also lies in the PCTR and is similar in size to the SEAKDB, are all approximately 1 Tg C yr^{-1} but were derived using different upscaling methods. The integration of DOC flux across the different watershed types is one of the most comprehensive comparisons of the timing and magnitude of DOC flux across widely varying terrestrial ecosystems. Comparisons with other studies are complicated by large differences in the size and type of watersheds, total drainage area, and whether the flux calculated includes particulate organic carbon (POC), dissolved inorganic carbon (DIC), and evasion. Yields, which are normalized to watershed area, are more appropriate to compare than total fluxes in studies when there are several order of magnitude differences in extent. Stets and Striegl (2012) reported carbon flux and yields from rivers across the conterminous United States. The majority of DOC yields from over 100 U.S. basins were less than 3 g C m^{-2} yr^{-1} with a small number as high as 9 g C m^{-2} yr^{-1}, compared to the SEAKDB average of 6.2 g C m^{-2} yr^{-1} and a high value of 60 g C m^{-2} yr^{-1}. From the 10 largest basins total organic carbon (TOC) yields ranged from about 0.8 to <4 g C m^{-2} yr^{-1} (Stets & Striegl, 2012). DOC is the dominant form of TOC, but the DOC/TOC ratio can be as low as 0.55 (Stets & Striegl, 2012).

When individual watershed fluxes are integrated across the larger landscape, the resulting flux estimate better reflects the varying landscape controls on DOC, making total flux comparisons between comparably sized areas more useful. The Gulf of Maine (GOM) drainage area (179,000 m^2; Huntington et al., 2016) is similar in size to the 189,000-km^2 SEAKDB. DOC yields in the largest 10 rivers in the GOM watershed were about 4.3 g C m^{-2} yr^{-1}, which is 70% of the SEAKDB average yield of 6.2 g C m^{-2} yr^{-1}. Extrapolated to the entire GOM watershed, the total estimated DOC flux was 0.77 Tg C, about 81% of the SEAKDB flux. Comparing the portions of the SEAKDB dominated by temperate rainforest to a tropical rainforest system, the tropical Siak River in Indonesia (Baum et al., 2007) has a slightly higher DOC flux than the temperate rainforest. DOC yields in major tributaries of the Siak River varied from 1.7 to 70.4 g C m^{-2} yr^{-1}, with the highest value from the Mandau River, a lowland blackwater tributary. These values are comparable to the rainforest catchments within the SEAKDB, and our highest yields were similarly from low relief catchments containing high proportions of peatlands. Because of the higher proportion of peatland in the Mandau River watershed, the area-integrated flux in the tropical rainforest is proportionally higher than in the SEAKDB. Baum et al. (2007) calculated an annual DOC flux of 0.27 Tg C from the 11,500-km^2 Siak watershed versus 0.79 Tg C we calculated from the 47,400 km^2 of nonglacial temperate rainforest streams (Table 2). Hope et al. (1997) reported slightly less total export (0.68 Tg) from British rivers from an area about 20% larger than the SEAKDB, with median yields of 3.2 g C m^{-2} yr^{-1}. The nonglacial watersheds alone within the SEAKDB export 16% more DOC than Great Britain watersheds from an area only 21% as large. Although our sampling captured seasonal changes in DOC associated with different baseflow conditions, we do not have samples from floods, during which DOC concentrations can increase 25–400% (Fellman et al., 2009). Thus, our calculations may underestimate the true flux. Although comparisons with other regions are difficult owing to extreme differences in the size of watersheds and regions, and whether estimates are for individual watersheds or scaled to a region, SEAKDB DOC yields bracket the range of reported values.

In contrast to other regions that export large masses of DOC to marine ecosystems, most DOC exported from the SEAKDB enters an enclosed body of water within the Alexander Archipelago where riverine inputs mix with saltwater and are retained before eventually draining through ocean openings onto the coastal shelf (Figure 6a). This area, within the Riverine Coastal Domain (Carmack et al., 2015), may be significant at a continental scale in linking coastal riverine inputs along the coastal margin. The large output of water and DOC from the SEAKDB reflects the huge source pool in the carbon-rich peat soils and high precipitation within the rainforest (D'Amore et al., 2016). Freshwater runoff, which is twice that of the Yukon or Columbia Rivers, drives coastal currents (Royer, 1982; Stabeno et al., 2004), creates cross shelf exchanges (Auad & Miller, 2008), influences timing of coastal algal blooms (Stabeno et al., 2016; Strom et al., 2016), and forms coastal eddies that move out into the gulf or northward to the Alaskan Stream (Thomson & Gower, 1998). The entrained DOC, which contains biologically available organic matter (Fellman et al., 2010; Hood et al., 2009), has a potentially significant impact on marine metabolism.

Knowing where and when water and DOC are exported across the SEAKDB has implications for predicting the ultimate fate of the transported carbon. Once transferred to the marine system, DOC may be precipitated to sediments, respired to CO_2 (Fellman et al., 2010), or incorporated into food webs before entering the coastal shelf (Arimitsu et al., 2017). These pathways are influenced by the quality of the DOC and physicochemical conditions in the mixing zone. Total discharge from June–October is driven primarily by runoff from glacial watersheds, which contribute 79–88% of the runoff. The impact of this freshwater on coastal currents is well recognized (Royer, 1982) and may influence conditions as far away as the Arctic Ocean (Weingartner et al., 2005). In the northwest portion of the SEAKDB the Alsek River and several coastal watersheds empty directly into the coastal shelf, where exports are entrained in the ACC or Yakutat eddies with little estuarine processing and ultimately delivered to the Alaska Stream (Auad & Miller, 2008; Figures 1 and 2). This is in contrast to the inland waters of the Alexander Archipelago, where increased residence time within the estuary likely facilitates deposition or processing. Most of the watersheds in northwest SEAKDB are glacial, which export biolabile DOC (Hood et al., 2009) that is readily incorporated into marine food webs (Arimitsu et al., 2017). In contrast, nonglacier watersheds are the primary source of direct DOC input to the shelf from watersheds along the western edge of the SEAKDB south of Cross Sound (Figure 2). Except for a cluster of small glacial watersheds on the south end of Baronof Island, glacial watersheds are continental. The contrasting DOC source areas could provide an opportunity to quantify differences in DOC fate on the coastal shelf.

An annual spring algal bloom off southeast Alaska (Waite & Mueter, 2013) produces a large proportion of the annual primary production in the area (Strom et al., 2016). The intensity and composition of the spring bloom varies from year to year, and researchers speculated that this interannual variation is explained by changes in the freshwater output during that interval (Strom et al., 2016). Freshwater outputs in April are dominated by nonglacial watersheds, but glacial inputs increase rapidly in May; therefore, interannual variation in the timing of this increase could be the source of the observed variation in coastal response. As icefields and glaciers in southeast Alaska diminish (McGrath et al., 2017; Ziemen et al., 2016), resulting changes in the timing and magnitude of the summer discharge pulse may impact the predictability of this annual coastal bloom.

Although riverine outputs can be used to interpret marine process dynamics in the region, our results also suggest caution in attributing cause to terrestrial outputs. Stabeno et al. (2016) used Taku River discharge as an index of the variation in timing of continental water outputs at Cross Sound during spring blooms in May 2011 and 2013. However, the Taku River on average supplies only 2.7% of the freshwater discharge during May and its mouth is located about 210 km from Cross Sound. Most of the freshwater leaving through Cross Sound at that time likely comes from a combination of glacial watersheds in Glacier Bay and lower elevation nonglacial watersheds much closer to the ocean opening (Martin, 1969; Washburne, 1989), all of which have different annual hydrographs than the Taku River. Therefore, interpretations of spring coastal chlorophyll trends based on the Taku River hydrograph are problematic. Overlooking the fact that much of the water comes from the aggregated discharge of thousands of small watersheds with widely varying hydrographs confounds explanations of observed coastal responses involving freshwater runoff.

4.2. Physiographic Template

Excluding the western margin of the SEAKDB, most of the freshwater and carbon outputs empty into the estuarine waters of the Alexander Archipelago. The glacial outputs are mainly along the mainland margin and the nonglacial outputs are distributed more widely among the islands within the estuary. Although currents are complex (Washburne, 1989) and water retention times within the estuary poorly known, we can assume that retention in the estuary allows for greater local processing or deposition than in the northwest coastal portion. Dividing the DOC flux by the estuarine surface area provides an areal estimate of riverine inputs to compare with other carbon sources and locations. This annual subsidy, which is 32 g C m^{-2} of estuarine surface yr^{-1}, is about 35% of what Herrmann et al. (2015) estimated for total (including POC) riverine inputs to estuaries of U.S. East Coast. Although there are few measurements of carbon fixation by primary production within the Alexander Archipelago, this SEAKDB riverine carbon subsidy is about 20% of the median value reported for worldwide estuarine primary production (Cloern et al., 2014).

Although a detailed analysis of DOC composition from thousands of rivers is not feasible, existing studies from streams within the region suggest that a variable but significant portion of DOC is available to estuarine heterotrophs. Depending on land cover in the source watershed, 23–66% of riverine DOC is bioavailable (BDOC) and is rapidly removed from solution as it mixes with saltwater (Fellman et al., 2010; Hood et al., 2009). These studies showed that DOC was more bioavailable with increasing glacial coverage but decreased in concentration as glacial area increased. By applying the range of values for glacial- and wetland-dominated watersheds published by Hood et al. (2009) and Fellman et al. (2010), we estimated that 0.28–0.47 Tg bioavailable C enters the marine ecosystems from rivers every year. Therefore, riverine DOC subsidies to the estuary may significantly influence metabolism.

Glacial watersheds export this biolabile DOC primarily during the summer (Figure 4b). Entering the eastern edge of the estuary during the growing season, the bioavailable DOC will likely be rapidly taken up and retained or mineralized within estuarine waters. Thus, it may have little influence on the coastal shelf but is potentially important to estuarine CO_2 efflux and pH. The bioavailability of the Big3 river DOC is unmeasured but its delivery to the inland portions of the estuary suggests that any metabolically active component is used primarily within the estuary. Although DOC from nonglacial watersheds has a smaller proportion of bioavailable carbon, the higher concentrations mean that a larger mass of biologically available organic matter is exported from them to the estuary. Within the SEAKDB, 67% of DOC and 59–64% of BDOC is estimated to come from nonglacial watersheds, which are widely distributed within the Archipelago. In contrast to glacial watersheds, the carbon-rich, nonglacial systems export higher concentrations of DOC throughout the year and are the dominant source from September through April (Figure 4b). Individual nonglacier watersheds vary widely in DOC yield (Figure 6b); therefore, the importance of DOC outputs to estuarine metabolism may be greatest in the estuaries in the immediate vicinity of the high DOC yield watersheds.

4.3. Vulnerability of Carbon Flux to Climate Change

The flux of DOC is derived from a large terrestrial organic carbon stock undergoing episodes of seasonal drought, intense Pacific storms, and an altered growing season. All of these influences have implications for the production of DOC and the trajectory of future DOC fluxes from SEAKDB watersheds. For example, many hydrologic regimes may shift from snow and ice dominated to rainfall dominated systems, with concomitant changes in the annual discharge cycle and more frequent and larger storms (Littell et al., 2018). As temperatures rise, snow depths decrease, and snowlines increase in elevation, watersheds will store less water as ice and snow during the winter and glacial watersheds will shift to hydrographs more similar to snow and rain dominated watersheds (Sergeant et al., 2020). The unfrozen, dense, and deep reactive terrestrial organic matter is susceptible to decomposition with rising temperatures (Fellman et al., 2017). Therefore, changes in the timing and source (precipitation vs. meltwater) of freshwater delivery and potential for mobilization of the large terrestrial carbon stock will alter the timing and magnitude of freshwater and DOC delivery associated with coastal currents, with unknown consequences for oceanographic processes.

5. Conclusions

Rivers in the SEAKDB export 430-km^3 freshwater and 1.17 Tg of DOC per year to the Alexander Archipelago and GOA. This huge outflux of material has an impact on marine processes at a variety of scales, some well documented and others poorly studied. The variability in watershed type and geographic position are important controls on streamflow and DOC flux patterns with important implications for the marine system. Understanding of the role of freshwater outputs from the SEAKDB to the coastal ocean has been hindered by a lack of data on the location, source, and timing of water outputs. The Alexander Archipelago estuary is 88% as large as the entire eastern U.S. estuarine area (Herrmann et al., 2015), but the Alexander Archipelago is almost completely unstudied in comparison. The area is large, there are thousands of rivers and streams draining into it, detailed understanding of tidal and nontidal water movements is lacking, and the complexity, remoteness, and physical hazards in the area complicate sampling and large-scale modeling efforts. Despite the difficulties in research in an estuary of this size, the economic and social importance of productivity within the estuary, and its potential to influence production out into the GOA, indicate that a greater effort be made in understanding the estuarine ecology of the region. Our results suggest that such research should be conducted with a realization of the importance of the physiographic template on the fate of continental outputs and their influence on the marine ecosystem. The potential for climate change to profoundly alter the amount, timing, and quality of water and material fluxes within this productive system calls for coordinated research between terrestrial, estuarine and ocean disciplines.

Conflict of Interest

The authors have no competing interests to declare.

Data Availability Statement

The runoff model used in this paper can be accessed from GitHub (https://github.com/jwtrubil/DCWBM). Supporting data used for developing the models used in this paper, including watershed attributes, DOC concentration, freshwater discharge, previously unpublished DOC measurements collected by the authors, and a GIS data set of SEAKDB watershed boundaries, can be found at https://doi.org/10.2737/RDS-2020-0045 (Biles et al., 2020).

Acknowledgments
We would like to thank two anonymous reviewers whose comments helped us improve the manuscript. Any use of trade or product names is for descriptive purposes only and does not imply endorsement by the U.S. or Canadian government.

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