A hydrological digital elevation model for freshwater discharge into the Gulf of Alaska

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[1] Freshwater discharge into the Gulf of Alaska (GOA) has an important effect on coastal circulation. In order to incorporate freshwater discharge into a three-dimensional ocean circulation model with both point sources (big rivers) and line sources (gridded coastlines) a digital elevation model (DEM) was developed to simulate freshwater discharge into the GOA under forcing of daily air temperature and precipitation data from National Centers for Environmental Predication/National Center for Atmospheric Research reanalysis during 1958–1998. This GOA-DEM includes glacier, snow storage, and melting processes. Coastal freshwater discharge into the GOA displays a very strong seasonal cycle and interannual variability. The comparison of simulated runoff with gauged (observed) river discharge was conducted for two major rivers (Copper River and Susitna River), showing a good agreement on seasonal cycle and interannual variability. The simulated annual mean of the total freshwater discharge into the GOA ranges from 19,000 to 31,000 m³ s⁻¹ (with a mean of 23,100 m³ s⁻¹) for the period 1958–1998. In the winter season (November to April), precipitation is mainly stored as snow, and freshwater discharge remains as a small base flow with some occasional changes due to short-term temperature increase. Freshwater discharge starts to rise sharply from May because of increasing precipitation and above-freezing temperatures and remains high from June through September because of snowmelt and some melting glaciers. In October the discharge decreases rapidly, to a basic flow in December as the temperature drops below the freezing point. Freshwater discharge into the GOA can be divided into the point sources (big rivers) and the line sources (ungauged numerous small streams and creeks due to melting of snow and glaciers). The model shows that five major rivers (point sources) account for about 50.6% of the total drainage areas, while the line source accounts for 49.4% of the drainage area. However, our new finding is that the point sources only account for 26%, while the line sources contribute 74% to the total runoff. Thus discharge from line sources (ungauged small rivers, streams, and creeks) is 2.8 times greater than from the point sources (five large rivers).


1. Introduction

[2] The southern coast of Alaska has rugged terrain with numerous high peaks in excess of 3000 meters within 60 km of the ocean. Moisture-laden air masses that strike mountains produce extremely high coastal rainfalls with large variances in different regions on the seasonal to interannual timescales. Coastal freshwater discharge plays an important role in the coastal oceanographic environment. It carries sediments and organic matter to the sea [Ding and Henrichs, 2004], and modifies the characteristics of marine environments that can
support specific communities of organisms. These waterways discharge fresh water into the sea and freshen sea surface waters, which can produce coastal (alongshore) currents, such as the Alaska Coast Current (ACC), due to a horizontal density gradient (difference). Although the annual averaged freshwater runoff of 20,000 to 30,000 m$^3$ s$^{-1}$ is small compared to the transport of the Alaska Stream or Alaska Slope Current (that is at an order of 27 Sv; 1 Sv = $10^6$ m$^3$ s$^{-1}$ [Onishi and Ohtani, 1999]) and ACC (that is about 0.25 Sv), coastal freshwater discharge has been identified as a primary driving mechanism of local coastal circulation in the Gulf of Alaska [Schumacher and Reed, 1980; Royer, 1979, 1981].

The strength of ACC is closely related to the existing ecosystem pattern. If this coastal current becomes stronger or weaker, the ecosystem will adjust to the changing environment. For example, in Prince William Sound, Alaska, two kinds of the current patterns exist: river/lake scenarios, which are related to strong/weak ACC through-flow associated with freshwater runoff [Mooers and Wang, 1998; Wang et al., 2001]. The lake-like scenario can retain much more zooplankton in Prince William Sound than the river scenario [Eslinger et al., 2001; Wang et al., 2001]. The lake/river-like pattern can partly explain the observed seasonal and interannual variability of zooplankton in Prince William Sound.

Freshwater is also important to the ocean circulation of the northeast Pacific. Tully and Barber [1960] treated the freshwater runoff as an estuary. Royer [1982] discussed the effect of precipitation and runoff on the coastal circulation in the Gulf of Alaska (GOA) using a simple hydrological model driven by air temperature and precipitation data from the National Weather Service. The model forcing data were divisionally averaged into two regions: southeastern and southern coast divisions. The model uses an actual drainage area that covers a coastal area of approximately 600 km $\times$ 150 km strip. A seasonal cycle of freshwater runoff was computed for the period of 1930–1980, with a maximum in October. Interannual variability was also discussed. A correlation of ocean dynamic height with runoff was found. Royer [1979, 1981] also applied a box model discharge model to the region and discussed the sources of the discharge and the effects on the salinity of the coastal current, because freshwater discharge into coastal seas plays a more important role in the subpolar ocean than in the subtropical and tropical oceans. Royer [1982] estimated that freshwater discharge from this 600 km $\times$ 150 km area in northeast Pacific Ocean is about 23,000 m$^3$ s$^{-1}$, which includes the line source and possibly some of the point source watersheds, because this model does not distinguish the line source from the point source. This freshwater was estimated to be at least 40% of the total discharge in the northeast Pacific.

The question of how freshwater runoff is accurately implemented into an ocean circulation model in the subpolar and polar oceans has always been difficult because the line source is not negligible compared to the point source. For example, freshwater discharge into the pan-Arctic Basin was estimated to be 2546 km$^3$ yr$^{-1}$ (gauged) and 1718 km$^3$ yr$^{-1}$ (ungauged), respectively, which originates from both inland (1007 km$^3$ yr$^{-1}$) and islands (711 km$^3$ yr$^{-1}$) [Carmack, 2000]. Thus the gauged and ungauged freshwater accounts for 60% and 40%, respectively, part of which is of the line source. It should be noted here that the Arctic drainage has extensive river networks in contrast to the Gulf of Alaska, which has only interior basin river drainage networks. This differs from tropical and subtropical freshwater discharge of the point source origin with river runoff dominating in spring [Wang et al., 1999]. Several conventional ways of implementing point source (river) freshwater runoff into ocean circulation models have been discussed by Wang et al. [2001]. However, there exists no accurate way to impose a line source freshwater discharge into an ocean circulation model in the GOA, except by nudging the modeled surface salinity to the observed data or climatology [Wang et al., 2001]. This is one of our major motivations to develop this GOA-digital elevation model (DEM): for accurately calculating freshwater discharge of both point source and line source origins, which are distributed along the coast of the Gulf of Alaska. The freshwater fluxes at these grid points from the lateral boundaries will drive an ocean circulation model in a realistic, physically sound fashion. If this goal can be realized, the implementation of freshwater discharge into the subpolar and polar ocean circulation models will be substantially advanced.

Large-scale hydrological modeling advanced rapidly to include some important physical processes [Vorosmarty et al., 1989; Hagemann and Dumenil-Gates, 2001]. In the pan-Arctic region, several sophisticated models have been developed to study freshwater discharge into the ocean [Dumenil et al., 1997; Bowling et al., 2000]. These models were calibrated using the gauged river runoff and estimated freshwater from the line source as well in a coarse-resolution grid. The simulated seasonal time series of the Arctic rivers/watersheds show maxima in summer. These global models cannot resolve the GOA watershed. Thus a fine-resolution hydrological model is necessary to study the hydrological process in this region.

In this paper, a high-resolution digital elevation model (DEM) is developed on the basis of a Prince William Sound DEM model [Simmons, 1996], to determine the watershed and drainage area of each pour point along the coast of the GOA. Under forcing of the National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) daily air temperature and precipitation data, the daily runoff at each pour point and the total runoff into the GOA can be simulated. This is an important step to numerically determine the runoff distribution along the coast and provide a possibly realistic input to the circulation model of the GOA.

This paper is organized as follows. Section 2 describes the model and numerical scheme. Section 3 examines the use of the forcing functions. Section 4 investigates the model results and comparison with the gauged river runoff. Section 5 summarizes our findings and discusses the existing problems.

2. Description of the Gulf of Alaska Digital Elevation Model (GOA-DEM)

2.1. Model Domain

A DEM is used to calculate watershed and coastal freshwater runoff. The model domain includes the region
from 159°–130°W longitude to 53°–64°N latitude (Figure 1a). A 4° × 2° spherical coordinate was used with zonal grid being along the x axis (positive eastward) and meridional grids along the y axis (positive northward). The land elevation was interpolated from the National Geographic Data Center’s (NGDC’s) ETOP05 data set (www.ngdc.noaa.gov). This drainage area is much larger than that used by Royal [1982], which excludes most noncoastal (interior) river input.

2.2. Calculation of Watershed

[10] Flow over a topographic surface is in the direction of the steepest descent. The first step in determining contribution area is to calculate the direction of maximum downward gradient for every cell in the DEM. Computation of a slope at a single cell is accomplished by computing the greatest drop (i.e., the steepest descent) per unit distance to each of the cell’s eight neighbors (Figure 2). [11] For a realistic surface, a watershed is defined as the upslope area contributing to drainage to a pour point. For a single cell (a pour point) in the DEM, a watershed can be defined as a set of all cells that contribute drainage to that cell.

2.3. Discharge in a Cell

[12] The model areas are divided into glacier and nonglacier areas. Glacier areas account for 0–100% in a grid. In nonglacier areas, the amount of snowmelting must not be larger than the snowpack. In glacier areas,
For nonglacier areas, if there is no snow in a grid, $CC$ is set to 0 and snowpack is also 0. Then, when $T_{air}$ is above $TT$, precipitation is allowed to run off; if $T_{air}$ is below $TT$, precipitation is stored as snowpack. The algorithms can be expressed below.

1. When $CC(i)$ is equal to 0 and $T_{air}$ is greater than $TT$, then

\[
\text{snowmelt} = K \times (T_{air} - TT) \times dt,
\]

\[
rg = \text{snowmelt} + P_f \times P \times dt.
\]

For nonglacier areas, if snowmelt < snowpack, then

\[
ra = \text{snowmelt} + P_f \times P \times dt,
\]

\[
\frac{\partial \text{snowpack}}{\partial t} = -K(T_{air} - TT).
\]

For nonglacier areas, if snowmelt ≥ snowpack, then

\[
ra = \text{snowpack} + P_f \times P \times dt,
\]

\[
\text{snowpack} = 0,
\]

where $K$ is temperature melt index. It has a value of 0.0045 m°C$^{-1}$ d$^{-1}$. This value was obtained from regression of field data on Wolverine and other glaciers near Prince William Sound [Mayo, 1986]. $P$ is precipitation (m d$^{-1}$); $P_f$ is precipitation factor whose values in different height zone are shown in Table 1. In the model, we linearly interpolated $P_f$ in the eight zones into continuous values in all elevation levels. That is different from previous DEM [Mayo, 1986; Mayo and Trabant, 1979; Simmons, 1996]. Here $dt$ is time step (set to 1 day).

2. When $CC(i)$ is less than 0, then

\[
ra = 0
\]

\[
rg = 0.
\]

For nonglacier areas,

\[
\text{snowpack} = \text{snowpack} + P_f \times P \times dt.
\]

### 2.4. Discharge in a Pour Point

The discharge in a pour point ($D_{pour}$) is the sum of all the watershed points contributing to the same outlet into the sea:

\[
D_{pour}(x_p, y_p, t_p) = \sum_{x,y} D_{cell}(x, y, t) C_{loss}(x, y, t_p, t),
\]

where $(x_p, y_p)$ are the coordinates of pour point, $t_p$ is the time (units in days) when the freshwater discharge in cell

<table>
<thead>
<tr>
<th>Elevation, m</th>
<th>$P_f$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–500</td>
<td>1</td>
</tr>
<tr>
<td>1000</td>
<td>1.14</td>
</tr>
<tr>
<td>1500</td>
<td>1.27</td>
</tr>
<tr>
<td>2000</td>
<td>1.41</td>
</tr>
<tr>
<td>2500</td>
<td>1.54</td>
</tr>
<tr>
<td>3000</td>
<td>1.68</td>
</tr>
<tr>
<td>3500</td>
<td>1.81</td>
</tr>
<tr>
<td>4000</td>
<td>1.95</td>
</tr>
</tbody>
</table>

### Figure 2

Schematic diagram of selecting a direction of steepest descent, whose direction is from 98 m, 42 m, to 16 m. The horizontal resolution (model grid size) is $4' \times 2'$, i.e., about $4.7 \times 3.7$ km in the zonal and meridional directions.

There is no limit in the snowmelting. The base flow is defined as

\[
\text{Base flow} = r_{min} \times A_a + 2 \times r_{min} \times A_g,
\]

where $r_{min}$ is the base flow coefficient, $1.5 \times 10^{-5}$ m d$^{-1}$, taken from annual low flow values from streams in south-central Alaska; in glacier areas, $r_{min}$ is twice that of the nonglacier areas, as Mayo [1986] suggested that glacier basins have base flows approximately twice that of alpine basins due to pressure and friction. $A_a$ and $A_g$ are nonglacier and glacier areas in a grid cell. The total runoff in a grid cell is

\[
D_{cell}(x, y, t) = \text{Base flow} + ra \times A_a + rg \times A_g,
\]

where $ra$ and $rg$ denote water discharges from nonglacier and glacier areas. The method to calculate these two parameters is described in the following.

We use a set of algorithms to reproduce melting processes. Parameter snowpack ($x, y$) (in meters) is used to denote snow thickness accumulated in each grid cell. For glacier areas, snowpack is always greater than zero. For nonglacier areas, snowpack is positive when snow exists and is zero when snow is all melted. When snowpack is greater than zero, we use cold content ($CC$) to sum up the daily air temperature minus melting threshold temperature:

\[
\frac{\partial CC}{\partial t} = T_{air} - TT,
\]

where $T_{air}$ is air temperature (°C) and $TT$ (°C) is melting threshold temperature ($TT$) adjusted by land elevation [Mayo and Trabant, 1979]:

\[
TT = H \times 2.25/500,
\]

where $H$ (m) is land elevation.

When $CC$ is greater than 0, $CC$ is set to 0. Thus $CC \geq 0$ is valid only when $T_{air} \geq TT$. When $CC$ is equal to zero, snowpack is allowed to melt. If $CC$ is less than zero, the precipitation is stored as snowpack.
\[(x, y) \text{ at time } t \text{ (units in days) arrives at the pour point, which is the sum of time through each grid, i.e., the distance divided by velocity estimated by elevation gradient (with a mean of 1 m s}^{-1}. \text{\(C_{loss}\) is the coefficient of the water losses on the way to the pour point including evaporation and infiltration, a function of air temperature, traveling time, etc. Considering a constant loss every day on the way to the sea, we have}

\[
C_{loss} = 0.8 - 0.06 \times (t_p - t),
\]

where \(C_{loss}\) is restrained with a minimum value of 0.4 and a maximum of 0.7 [Simmons, 1996].

### 3. Atmospheric Forcing: Air Temperature and Precipitation Data

[19] Two kinds of air temperature and precipitation data in the Gulf of Alaska are available to drive the GOA-DEM. In the previous DEM in Prince William Sound, Alaska [Simmons, 1996], the precipitation and air temperature data at one station were used to drive the model. This is due to the fact that the climate system and synoptic weather system are usually assumed uniform in such a small region (about 150 \times 150 \text{ km}^2). Nevertheless, in the Gulf of Alaska, meteorological data at one station are not representative of other stations due to the nonuniform distribution of synoptic weather system in space. Thus Royer [1982] used two divisionally averaged data (southeast and southern coast) from coastal stations to drive his model. As shown in section 3.1, even in Valdez, data collected from several stations around this small city have quite pronounced differences because of orographic effects and complicated terrain distribution.

#### 3.1. National Climate Data Center (NCDC) Station Data

[20] Table 2 shows data records from several stations in Valdez, Alaska. The weather varied widely with location and time, even in such a small city. There was more precipitation in the coastal area than in the inland area. Both coastal and inland areas account for more than 10% of annual variances. The maximum monthly precipitation could occur in July, August, or September on the basis of the data.

[21] Station data have an advantage because they are from direct measurement. However, these stations are sparse in Alaska and are not evenly located. Because of complicated terrain, it is difficult to determine the spatial scale that atmospheric forcing at a station can represent [Royer, 1982]. Thus it is necessary to use the gridded reanalysis data to cover all the grids in the model domain.

#### 3.2. NCEP Reanalysis Data

[22] The NCEP reanalysis is the product based on available observations and a state-of-the-art data assimilation system. The data covers a 41-year (1958–1998) period with 1,904 × 1,875 (longitude/latitude) degree grids with daily or twice daily interval. Thus the NCEP data were used for driving the GOA-DEM. Because there are no data in some very high mountains, the air temperatures of such points were interpolated from the neighboring gridded data. Then, a linear descent of air temperature with elevation ranges was used to convert the surface air temperature to the elevation. Thus, in this study we extended this DEM from single station forcing [Simmons, 1996] to gridded data forcing, which covers every grid point of the DEM. Although the NCEP data contain some uncertainties, it is still widely used as external forcing of global hydrological models. Hagemann and Dumenil-Gates [2001] estimated that the NCEP reanalysis generally overestimates summer precipitation and evapotranspiration for most parts of the Northern Hemisphere, while European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis underestimate 2-m temperature in high latitudes during winter and spring. We will compare and discuss the uncertainties of both NCDC and NCEP data in the GOA in section 4.2.

#### 3.3. Seasonal Variations of the Large-Scale Weather and Climate System

[21] To better understand the climate system related to precipitation, we constructed the typical seasonal cycle of sea level pressure (SLP) in the North Pacific (Figure 3). There is strong seasonal variation. In winter, the Aleutian Low was deep and the surface winds tend to follow the isobars in a counterclockwise (cyclonic) sense with a turning angle of about 18° toward the low-pressure center. The surface winds are able to transport the warm, moist air over the Pacific Ocean to the Gulf of Alaska and adjacent region (Figure 4), persisting throughout the winter. Thus heavy precipitation occurs in winter that is accumulated as snowpack along the coast of southern Alaska. In spring the Aleutian Low weakens because a high-pressure system
develops with a center at the southeastern Pacific (off the California coast) because of solar heating.

In summer, the Aleutian Low disappears because of the further expansion of the high-pressure system. This high-pressure system dominates and persists throughout the summer and result in little precipitation in the GOA region. During the summer the surface wind blows from the continent to the ocean, transporting relatively dry air (i.e., less precipitation) to the study region. In autumn, the Aleutian Low develops because of the ocean-land temperature contrast in the northern hemisphere with a weak high center located west of San Francisco (see the dotted location). The transition periods are in spring and autumn, during which the winter low-pressure system (Aleutian Low) transits to the high-pressure system in summer, vice versa from summer to winter.

Figure 4 shows the explosive cyclone tracks during a typical wet season (October 1979 to May 1980). A total of 57 cyclones were found during this period (Figure 4a). Cyclogenesis location distribution is also shown for January 1980 (Figure 4b; units are in cyclones month$^{-1}$, with interval being 0.05). The cyclones, most of which were generated around the extension of Kuroshio in the western Pacific, moved across the North Pacific, carrying vast warm, moist air and dumping the precipitation in the GOA. In addition to the high cyclogenesis in the western part near Japan and Kuroshio extension, the GOA is one of the highest cyclogenesis regions.

4. Model Results and Calibration

4.1. Watershed of the Gulf of Alaska

Figure 1 shows the land elevations of the model domain (Figure 1a) and the watershed of the line sources (in yellow) and five big rivers (in colors, Figure 1b). Mt. McKinley and the Alaska Range are located in the northern boundary of the watershed. The Chugach Mountains are located north of Prince William Sound, while the Wrangell Mountains are close to the southern coast of

Figure 4. Explosive cyclone tracks during a typical wet season (October 1979 to May 1980). (a) A total of 57 cyclones were found during this period. (b) Cyclogenesis location distribution is also shown for January 1980 (units are in cyclones month$^{-1}$, with interval being 0.05) (Courtesy of Li [1990].)
Alaska. One large watershed, surrounded by the Alaska Range and the Chugach Mountains, forms a drainage area for the Susitna River, which empties into Cook Inlet near Anchorage. The other large watershed is surrounded by the Chugach Mountains (part of the Alaska Range) and the Wrangell Mountains, and forms the drainage area for the Copper River to the east of Prince William Sound (Figure 1). To the east of the model domain, a watershed is the source of the Taku River near Juneau. The watershed area can be calculated in the study region for each pour point and divided into the line sources and the point source (Figure 1b). The five big watersheds form the five big rivers in the region (Figure 1b, colored areas from left to right): the Susitna, Copper, Alsek, Taku (near Juneau), and Stikine.

[27] The total watershed area for the Gulf of Alaska can be determined by locating the mountain summits (Figure 5a). On the seaward side, all freshwater flows into the Gulf of Alaska, while on the other side, freshwater sustains or forms inland rivers that eventually flow into the Bering Sea through the Yukon River.

[28] To understand the total pour points along the southern coast of the Gulf of Alaska, we computed the percentage of the watershed at every pour point to total watershed of the Gulf of Alaska (Figure 6a). Of the total watershed, the five big rivers account for 10.6% (Susitna), 15.5% (Copper), 6.0% (Alsek), 3.7% (Taku), and 14.8% (Stikine), respectively (see Table 3, column 4).

[29] We calculated the watersheds of the five biggest rivers of the point source origin, which account for about 50.6% of the total watershed. The rest (49.4%) of the watershed is contributed by numerous small rivers, streams, creeks, snowmelt freshwater along the coast, which are defined as the line source. This line source...
of freshwater runoff, which differs from the river point source in low and middle latitudes, contributes significantly to the coast current system, such as ACC [Royer, 1979, 1981; Wang et al., 1999]. This line source of freshwater has not previously received attention in the Gulf of Alaska, except for the study of Royer [1982]. Thus this study will fill the gap of this topic in this region.

[30] In terms of watersheds, we calculated the five biggest drainage areas (Figure 6b). The total drainage area was estimated to be 470,810 km², while the point source drainage area was estimated to be 238,230 km². Table 3 compares our model results to the available observations. The comparisons in the Susitna and Taku Rivers are very good, while there is a 14% discrepancy for the Copper River. This may be due to the fact that the river gauge is good, while there is a 14% discrepancy for the Copper River. A difference can be noticed that the 2-m temperature derived from the NCEP is generally lower than the NCDC data inside the watersheds by linearly interpolating the neighboring data points available, weighted by distances (Figure 1b).

[31] Table 4 shows the monthly watershed-accumulated precipitation for both line and point sources (sum of the five big rivers). It is observed that (1) both NCDC and NCEP data have a maximum precipitation in October, (2) the annual precipitation (last column) shows that the NCDC data (587 km³) is slightly larger than the NCEP (570 km³), and (3) the line source from the NCDC data (403 km³) is larger than that from the NCEP reanalysis (336 km³), while the point source from the NCDC data (185 km³) is smaller than that from the NCEP reanalysis (235 km³). Note that although the maximum precipitation occurs in October, it does not mean that the model-predicted freshwater runoff has a maximum rate in October. The reason is that precipitation accumulated as snow from November to March (Table 4 and Figure 7) is about three times larger than the October maximum precipitation. The melting of the accumulated snow (see Table 5 and Figure 8) from spring to summer, together with precipitation as rainfall during the same period (see Table 4), provides vast runoff discharge into both point and line source drainage during summer (Figure 7).

[32] Table 4 also shows that the annual accumulated precipitation (923 km³) in the whole GOA estimated using the NCEP reanalysis. The precipitation is larger than, but comparable to, that of the GOA watersheds. Its peak occurs in September (101 km³), while precipitation in October and August are also high, because more cyclonic storms produce high precipitation in the GOA, which originate from the Northwestern Pacific and Kuroshio extension (see Figure 4).

[33] Corresponding to Table 4, Table 5 shows the monthly watershed-averaged 2-m temperature. From April to October, the temperature is above freezing point, thus all the precipitation is in the form of rainfall. During November to March, all the precipitation is stored in the form of snow if air temperature is below the freezing point. A difference can be noticed that the 2-m temperature derived from the NCEP is generally lower than the NCDC. For example, the April temperature derived from NCEP is below the freezing point, while NCDC data is

![Figure 6](image-url)  
(a) Model-simulated percentage of the watershed at every pour point to total watershed (%) and (b) model-simulated drainage area of each pour point along the southern coast of the Gulf of Alaska.

4.2. Model Input

[34] To ensure that the model forcing (precipitation and 2-m temperature) derived from the NCEP reanalysis and National Climate Data Center (NCDC) stations (locations shown in Figure 1b) has similar features in terms of amplitude and timing in a seasonal cycle, we constructed seasonal climatology using NCDC stations data for the period of 1930–1990 and the NCEP reanalysis for the period 1948–1998. We calculated the monthly means of NCDC data inside the watersheds by linearly interpolating the neighboring data points available, weighted by distances (Figure 1b).

Table 3. Modeled Drainage Areas, Their Percentage of the GOA Drainage and Comparison With Available Observations (Drainage Areas and Annual Mean River Flues)

<table>
<thead>
<tr>
<th>River</th>
<th>Modeled</th>
<th>Observed</th>
<th>Modeled/GOA Percentage, %</th>
<th>Observed Annual Mean Flux, m³ s⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Susitna</td>
<td>4.990</td>
<td>5.030</td>
<td>10.6</td>
<td>1400</td>
</tr>
<tr>
<td>Copper</td>
<td>7.304</td>
<td>6.270</td>
<td>15.5</td>
<td>1800</td>
</tr>
<tr>
<td>Alsek</td>
<td>2.836</td>
<td>6.0</td>
<td>5.0</td>
<td>3.7</td>
</tr>
<tr>
<td>Stikine</td>
<td>2.110</td>
<td>1.710</td>
<td>12.0</td>
<td>450</td>
</tr>
<tr>
<td>Total</td>
<td>23.823</td>
<td>20.6</td>
<td>50.6</td>
<td></td>
</tr>
</tbody>
</table>
both NCDC and NCEP temperatures have a similar seasonal cycle, although a large difference in amplitude exists (Figure 8). Thus, with the uncertainties in the forcing data the modeled results must be calibrated by gauged discharge data.

The daily precipitation and 2-m temperature were used as input to the GOA-DEM. Figure 9 shows the total watershed (Figure 5a) averaged monthly time series for precipitation and 2-m temperature for the period of 1958–1998. A strong seasonal cycle is the dominant feature. The annual averaged precipitation is about 1.15 m yr$^{-1}$ and the averaged temperature is $-1.35{}^\circ C$ (Figure 10). It is noted that there was large interannual variability in both precipitation and temperature. Nevertheless, they were not always in phase. For example, before 1978, precipitation was out of phase to temperature, while they were almost in phase after 1978, which is known a climate shift occurred in 1978 in the North Pacific, particularly in the Bering Sea and the GOA region [Minobe, 1999].

### 4.3. Seasonal Climatology

The seasonal cycle of total freshwater discharge into the Gulf of Alaska over 41-year (1958–1998) simulations was simulated under the forcing of daily NCEP/NCAR reanalysis data (Figure 11). From January to March, a period that is still considered winter in the subpolar region, freshwater discharge is low ($<1 \times 10^4$ m$^3$ s$^{-1}$). Starting in April, as solar heating increases, freshwater discharge rapidly increases, reaching a maximum of $4.8 \times 10^4$ m$^3$ s$^{-1}$ in July.

<table>
<thead>
<tr>
<th>Month, km$^3$</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>Annual Mean, km$^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>LS</td>
<td>NCDC</td>
<td>33.88</td>
<td>29.05</td>
<td>27.31</td>
<td>24.36</td>
<td>23.29</td>
<td><strong>19.50</strong></td>
<td>24.30</td>
<td>32.79</td>
<td>46.56</td>
<td><strong>57.89</strong></td>
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<td>40.22</td>
</tr>
<tr>
<td>NCEP</td>
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### Table 4. Seasonal Cycle of the Regional (Monthly) Accumulated Precipitation Over the Line Source (LS) and Point Source (PS) Regions Derived From NCDC Station Data and NCEP Reanalysis

Psea 66.89 66.69 58.61 **57.30** 61.64 81.80 88.35 90.80 **100.77** 96.55 76.72 81.04 927.17

aThe last row is the monthly accumulated precipitation over the entire GOA water. Maxima and minima are in bold and italics.

Figure 7. Monthly climatology of watershed-accumulated precipitation (in km$^3$) derived from NCDC station data (S) and the NCEP reanalysis (N) for both line (L) and point (P) sources.
which is about five times the discharge in winter season. This large discharge rate persists throughout August. After August, the discharge rate rapidly declines, almost linearly with time to November (about $1.1 \times 10^4$ m$^3$ s$^{-1}$). The annual mean discharge rate from the GOA-DEM is estimated to be $23,100$ m$^3$ s$^{-1}$, consistent with the previous estimate of $23,000$ m$^3$ s$^{-1}$ [Royer, 1982]. It should be pointed out that Royer’s [1982] seasonal cycle peaks in October, probably because the seasonal cycle has been adjusted to oceanic freshwater storage, which is estimated using a reference ocean salinity and has a maximum freshening in October [Wang et al., 2001]. The maximum discharge rate occurring in June–August is consistent with the previous studies in Prince William Sound [Simmons, 1996] and in arctic watersheds/rivers [Bowling et al., 2000; Hagemann and Dumenil-Gates, 2001].

Large variability (standard deviation) occurs from June to October, ranging from $0.3–0.6 \times 10^4$ m$^3$ s$^{-1}$. The variability (standard deviations) accounts for 13–26% of the annual mean discharge rate. During the months with large standard deviations, signals of interannual variability can be identified.

The line source and point source were also simulated using this GOA-DEM (Figure 11). Discharge from the line source is 2.8 times the point source discharge. Similarly, the standard deviations of the line source are about three times the point source standard deviations. This indicates that the major source of the variability comes from snow cover, accumulation and melting, and glacier-melting processes, controlled mainly by the 2-m temperature field. The maximum of the point source ($1.5 \times 10^4$ m$^3$ s$^{-1}$) occurs in June to July, persisting to September, while the maximum of the line source ($3.4 \times 10^4$ m$^3$ s$^{-1}$) lags about one month, occurring in July to August, consistent with most Arctic and subpolar gauged river runoff and model prediction [Bowling et al., 2000; Hagemann and Dumenil-Gates, 2001].

To calculate the annual discharge into the Gulf of Alaska, the accumulation of the freshwater discharge over a 12-month seasonal cycle was conducted (Figure 12).

### Table 5. Seasonal Cycle of the Regional (Monthly) Averaged 2-m Temperature Over the Line Source (LS) and Point Source (PS) Regions Derived From NCDC Station Data and NCEP Reanalysis

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*The last row is the monthly averaged temperature over the entire GOA water. Maxima and minima are in bold and italics.*
The total annual freshwater discharge is 705 km$^3$, to which the line source and point source contribute 520 km$^3$ and 185 km$^3$, respectively; that is, the line source is 2.8 times the point source. Therefore the line source contributes about 74% of the total freshwater into the Gulf of Alaska, while the point source contributes only 26%.

4.4. Monthly Mean Discharge and Interannual Variability: Model Calibration

[41] Using the available gauged river runoff, we can compare the modeled results with observations. Because of a USGS budget cut, some previous river gauges were discontinued. Fortunately, we were able to obtain discharge data of the Susitna River and the Copper River at the Million Dollar Bridge. The modeled daily mean discharge (dashed, Figure 13a) compares well with the time series of daily discharge (solid) of the Susitna River during 1975–1993. The simulated seasonal cycles over 1975–1993 (Figure 13b) indicates a reasonable performance of the model. The modeled time series capture the observed phenomena. Maximum discharge ranges from 3500–5000 m$^3$ s$^{-1}$, while the base flow is about 250 m$^3$ s$^{-1}$.

[42] Interannual variability of the discharge rate was clearly captured (Figure 13c). There were three peaks in 1977, 1979–1981, and 1989–1990. From 1977 to 1978, there was a sudden drop due to a sudden decline of precipitation. The two largest peaks spanned about ten years (a decadal time signal), while the interannual variability was also obvious. The maximum annual discharge rate was about 1550 m$^3$ s$^{-1}$ (Figure 13c), while the maximum seasonal discharge rate was 5000 m$^3$ s$^{-1}$ (Figure 13b). Therefore the interannual variability in freshwater discharge into the Gulf of Alaska should be significant in affecting ACC [Royer, 1979, 1981].

[43] The Copper River is the largest point source in the Gulf of Alaska. The simulated daily runoff discharge captures the observations (Figure 14a). The daily discharge rate is comparable to the Susitna River. Similarly, the seasonal cycle compares well with the gauged discharge (Figure 14b). The interannual variability in the model also captures the observations (Figure 14c).

[44] Because 74% of the freshwater into the Gulf of Alaska is ungauged, it is very important when applying the GOA-DEM to quantitatively simulate (or hindcast) the total freshwater runoff, based on the model-data verification, as discussed above. The total daily discharge rate (Figure 15a) can reach a maximum as high as 80,000 m$^3$ s$^{-1}$ in summer. This vast freshwater discharge into the Gulf of Alaska not only influences the ACC [Royer, 1981], but also the ecosystem and fisheries. The monthly mean discharge over the period from 1958–1998 (Figure 15b) can be obtained by conducting the monthly average. Thus the climatology of seasonal cycle (Figure 11) can be calculated, with an annual mean of 23,100 m$^3$ s$^{-1}$.

[45] Annual mean freshwater discharge (Figure 15c) reveals interannual variability. There was higher-than-normal freshwater discharge during 1958–1966, and lower-than-normal freshwater discharge in two periods: 1972–1976 and 1981–1987. The largest peak (32,000 m$^3$ s$^{-1}$) occurred in 1964, about 28% higher than its climatology (23,100 m$^3$ s$^{-1}$). This was not because of anomalous high precipitation in 1964, but because of anomalous high temperature, which contributed to more melting of glaciers covering about 29% of the total watershed (by comparing Figure 15c to Figure 10b).

4.5. Line Source Versus Point Source

[46] Because the line source accounts for 74% of the total freshwater into the Gulf of Alaska, we should pay attention to this major baroclinic (freshwater) forcing of the ACC [Royer, 1981; Wang et al., 2001]. The GOA-DEM is a powerful and accurate tool to quantitatively simulate this component from land. It is natural to separate the line source from the point source. Figure 16a shows the line source monthly, and Figure 16b shows the annual mean discharges into the Gulf of Alaska, while Figure 17 shows the similar time series of the point source origin, with their seasonal climatologies over the period from 1958–1998 (Figure 11).
By and large, both line source and point source time series have similar temporal variations to the total freshwater discharge on both seasonal and interannual timescales, because the climate or weather system is controlled by the Aleutian Low (Figure 3) and cyclone activity over the North Pacific (Figure 4). The mean discharge rates are 17,050 m$^3$/s and 6050 m$^3$/s, respectively for the line source and point source, with the former being 2.8 times the latter. This significant line source (accounting for 74% of the total fresh water based on this study) has long been ignored until Royer [1982] examined it.

5. Conclusions and Discussion

A GOA-DEM has been developed under forcing of 41-year daily NCEP reanalysis gridded data. The model captures major hydrological processes. The model successfully simulated the freshwater runoff into the Gulf of Alaska over the period from 1958–1998. The total drainage area in this model was estimated to be 470,810 km$^2$ and the total annual mean river discharge rate into the Gulf of Alaska is 23,100 m$^3$/s. The simulated river discharge compared reasonably well to observations at the two biggest rivers, the Susitna River and the Copper River. On the basis of our investigations, we can draw the following conclusions.

1. Although the drainage area for the point source accounts for 50.6% of the drainage area, the annual mean freshwater discharge rate of the point sources is only 26% of the total discharge rate. The discharge rate of the line sources, which includes all the ungauged small rivers, creeks, and streams, accounts for 74% of the freshwater runoff into the Gulf of Alaska. High mountains near the coast block and receive more rainfall than the interior drainage areas for rivers, i.e., because of the uneven distribution of precipitation.

2. A seasonal cycle has been simulated over the period from 1958–1998 with the peak discharge...

Figure 11. Model-simulated monthly climatology (seasonal cycle) of freshwater discharge derived from the 41-year simulations (1958–1998) and standard deviations (vertical bars).

Figure 12. Accumulation of monthly climatology of freshwater discharge from January to December. The 12-month sums are 705, 520, and 185 km$^3$, respectively, for the total, line source, and point source discharges.
48,000 m$^3$ s$^{-1}$ in July. The standard deviations are high from June to October, ranging from 13 to 26% of the annual mean discharge rate. The total annual discharge into the Gulf of Alaska is 705 km$^3$. The line source discharge rate has a maximum of as high as 34,000 m$^3$ s$^{-1}$ persisting from July to August, while the point source maximum rate of 15,000 m$^3$ s$^{-1}$ occurs in June (i.e., the line source maximum occurs one to two months later than the point source.) The line source has the largest standard deviation in August, while the point source largest standard deviation occurs in June. The total annual discharge into the Gulf of Alaska is 520 and 185 km$^3$, respectively, from the line source and point source. Thus the line source is about 2.8 times the point source. The 1-month lead of river maximum runoff rate (in June) to the line source (in July) may be explained by the late spring-summer rainfall and that the maximum melting of glaciers occurs in July.

Interannual variability can be observed in the simulated time series of freshwater discharge. There was significant higher-than-normal freshwater discharge during 1958–1966, and lower-than-normal freshwater discharge during two periods: 1972–1976 and 1981–1987. The interannual variability in freshwater discharge not only significantly affects the coastal current due to the horizontal density gradient (such as ACC), but also influences chemical compounds, organic and inorganic concentrations, the ecosystem, and fisheries in the region.

Figure 13. Time series of (a) daily mean, (b) monthly mean, and (c) annual mean discharges of Susitna River from 1975 to 1993. Dashed lines are modeled results, while solid lines are observed data of the USGS Susitna River station at Susitna Station.

Figure 14. Time series of (a) daily mean, (b) monthly mean, and (c) annual mean discharges of Copper river from 1988 to 1995. Dashed lines are modeled results, while solid lines are observed data from the USGS Copper River station at Million Dollar Bridge.

Figure 15. Model-simulated time series of (a) daily mean, (b) monthly mean, and (c) annual mean discharges into the Gulf of Alaska from 1958 to 1998.
This GOA-DEM is the first trial in accurately simulating the total freshwater discharge rate into the Gulf of Alaska. This model provides an opportunity to investigate the vast discharge mainly from the ungauged line source (74%) due to snow storage, melting, glacier process and numerous small streams and creeks. River discharge, i.e., the point source of such rivers in low and middle latitudes, is more easily gauged compared to the line source. This study also provides an opportunity to examine the transport of the chemical organic and inorganic materials from land into the ocean, and furthermore the response of the marine ecosystem and biology to this vast transport. The U.S. GLOBEC program is one of the many research programs with a goal of understanding the coastal biological response to atmospheric and terrestrial forcing.

This GOA-DEM may be applied to the similar subpolar and polar regions, such as the Bering Sea, the Sea of Okhotsk, the northern Sea of Japan, and the Beaufort Sea. In those regions, there exist several ocean circulation models under forcing of only river runoff. The major freshwater (baroclinic) forcing of the line source origin has possibly been ignored. In this regard, this GOA-DEM may significantly improve the ocean circulation models in these subpolar and polar coastal seas.

As discussed in the previous sections, atmospheric forcing contains some uncertainty. Although the NCDC and NCEP data have a similar seasonal cycle, their amplitudes have certain differences. Thus the forcing data should be used with caution, and the simulated results should be carefully validated using gauged discharge data. Even in a small city (Valdez, Alaska), NCDC station data (Table 2) show large differences due to complex orographic effects. This would become worse if these station data are interpolated to the model grid points of variable terrain, which features complex topography and inland watersheds. This uncertainty remains until either a denser observing system or a new, high-resolution NCEP reanalysis product resolving orographic effects and glacier/ice/land processes is accomplished.

Acknowledgments. We appreciate the Exxon Valdez Oil Spill (EVOS) Trustee Council for financial support through the Gulf Ecosystem Monitoring (GEM) project awarded to Jia Wang and the IARC-Frontier Research System for Global Change for partial support and for providing coastal resources. JW appreciates Harper Simmons for providing the Prince William Sound DEM code. We also appreciate two anonymous reviewers for their constructive comments that helped improve the presentation of this paper.

Figure 16. Model-simulated time series of (a) monthly mean and (b) annual mean discharge of the line source into the Gulf of Alaska from 1958 to 1998.

Figure 17. Model-simulated time series of (a) monthly mean and (b) annual mean discharge of the point source into the Gulf of Alaska from 1958 to 1998.

References


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