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## **Oceanographic Conditions during 1973 in Russell Fjord, Alaska\***

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Russell Fjord appears to be in the process of being dammed and isolated from marine influence by the advancing Hubbard Glacier. This study was initiated to understand the present circulation of the fjord and to provide a basis for comparison in the event that closure should occur. Observations made during 1973 indicate that the deep water is continuously renewed by near-surface source water added over the sill. 'NO' (Broecker, 1974) appears to be useful in tracing these additions. The probable consequences of glacial damming are considered.

### **Introduction**

Russell Fjord, located at the head of Yakutat Bay on the southcentral Alaska coast (Figure 1), is unique among Alaskan fjords because the Hubbard Glacier has advanced in recent years across the mouth of the fjord to within 200 m of Osier Island (Figure 2) and is projected to isolate the fjord from marine influence within the next few years. Information assembled from earlier reports (Tarr & Martin, 1914; Miller, 1964) indicates that Russell Fjord may have experienced a similar glacial closure as recently as 200 years ago. The position of the glacier face at several times between 1895 and 1972 is shown in Figure 2; the 1973 position of the glacier is essentially identical to that indicated for 1972 and represents some balance between glacial advance and erosion by swift tidal currents (about  $3 \text{ m s}^{-1}$ ) along the glacier face. This study is an attempt to understand the present circulation of the fjord and to provide a basis for comparison in the event that closure should occur.

Oceanographic observations were made in Russell Fjord during April, June-July and September 1973, periods representing late winter, spring-summer and late summer. Due to the constriction of the fjord mouth by the glacier, it was impossible to use a conventional research vessel in these studies. The sampling was accomplished using a 19-foot inflatable boat operated from a base camp at the southern end of the fjord. All gear was transported to and from the fjord by light aircraft.

During each of the cruises, stations were occupied and standard bottle casts were taken at the positions indicated in Figure 3. Salinity, temperature, dissolved oxygen and nutrients were measured at each of these stations. Vertical plankton tows using a small four-net frame were made at these same stations. Analytical methods are described and the data compiled in Muench *et al.* (1974).

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## General characteristics

### *Topography*

Russell Fjord, a 50 km by 3 km fjord estuary, communicates with the Gulf of Alaska through Yakutat Bay where the controlling sill depth is 70 m.

The fjord is divided into several basins by a series of 150–200 m sills and has an entrance sill depth of 30 m (Figure 4). Our soundings show more features than Wright's (1968) previous work, indicating that we may have observed features that do not extend across the fjord. Nunatak Fjord, whose area amounts to about 20% of the Russell Fjord system, has no sill at its mouth. The fjord is isolated from the coastal forelands by 1000 to 1500 m mountains at all but the northern and southern ends. The southern end is rimmed by a terminal moraine with elevations of about 100 m. Persons familiar with the local terrain indicate that channels with elevations of 30 m or less are present through this moraine.

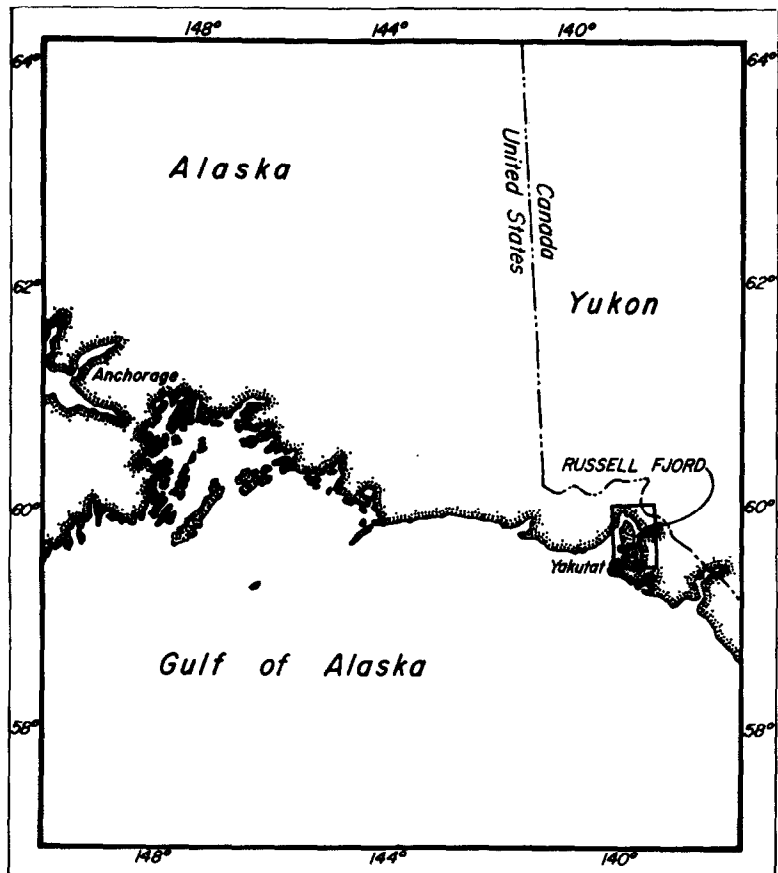


Figure 1. Geographical location of the Russell Fjord region.

### *Freshwater input*

Freshwater input to the fjord appears to be uniformly distributed, entering through some 70 small streams located around the perimeter. The larger streams, like Beasley Creek and those entering at the head of Nunatak Fjord, are glacially fed; their plumes are clearly visible in the fjord due to suspended sediments.

Because of the lack of streamflow records and meteorological data within Russell Fjord, freshwater inputs can only be estimated. The nearest weather station is at Yakutat, some 30 km from the southern end of the fjord on the coastal forelands. Neglecting possible orographic effects of the mountains and assuming the glaciers and snowfields to be in a steady state, the mean annual precipitation measured at Yakutat can be applied to Russell Fjord for runoff estimates. Fog and low temperatures in the area suggest that evaporation and transpiration are small terms in the fjord's water budget. The total annual precipitation at Yakutat is high,  $330 \text{ cm yr}^{-1}$ , with a maximum in October (50 cm) and a minimum in June (14 cm). Snow and ice melt dominate runoff, with a maximum occurring in July or August. The drainage area surrounding Russell Fjord is estimated to be  $1.6 \times 10^3 \text{ km}^2$ , or approximately 8 times the fjord area. The  $330 \text{ cm yr}^{-1}$  precipitation figure from Yakutat applied to the drainage area gives a mean annual freshwater input rate of  $170 \text{ m}^3 \text{ s}^{-1}$ . Expressed as a vertical height change in the fjord, the runoff rate is  $28 \text{ m yr}^{-1}$ .

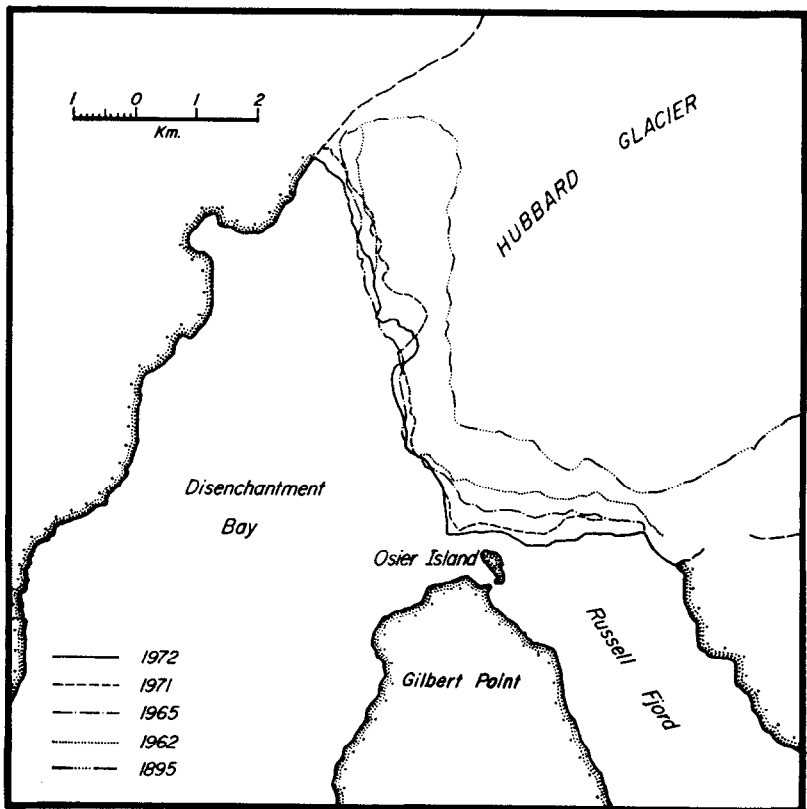


Figure 2. Stages of advance of the Hubbard Glacier terminus from 1885 through 1972 (from Austin Post; personal communication).

#### *Marine source waters*

No oceanographic observations are available from the Gulf of Alaska in the vicinity of Yakutat. Seasonal variations in the Gulf of Alaska shelf water characteristics farther west have, however, been reported by Royer (1975). Ongoing field work in the northern Gulf of Alaska has in addition identified a  $20\text{--}30 \text{ cm s}^{-1}$  westerly flow along the coast. Temperature and salinity undergo little variation along the direction of this flow, apparently being affected

very little by diffusive relative to advective processes (Royer, personal communication). Figure 5 gives temperature and salinity as a function of time over a two-year period at a station in the Gulf of Alaska about 550 km west, or downstream, of Yakutat Bay. Based on the apparent constancy of temperature and salinity along the coast, the conditions shown in Figure 5 are taken as representative of those off Yakutat Bay.

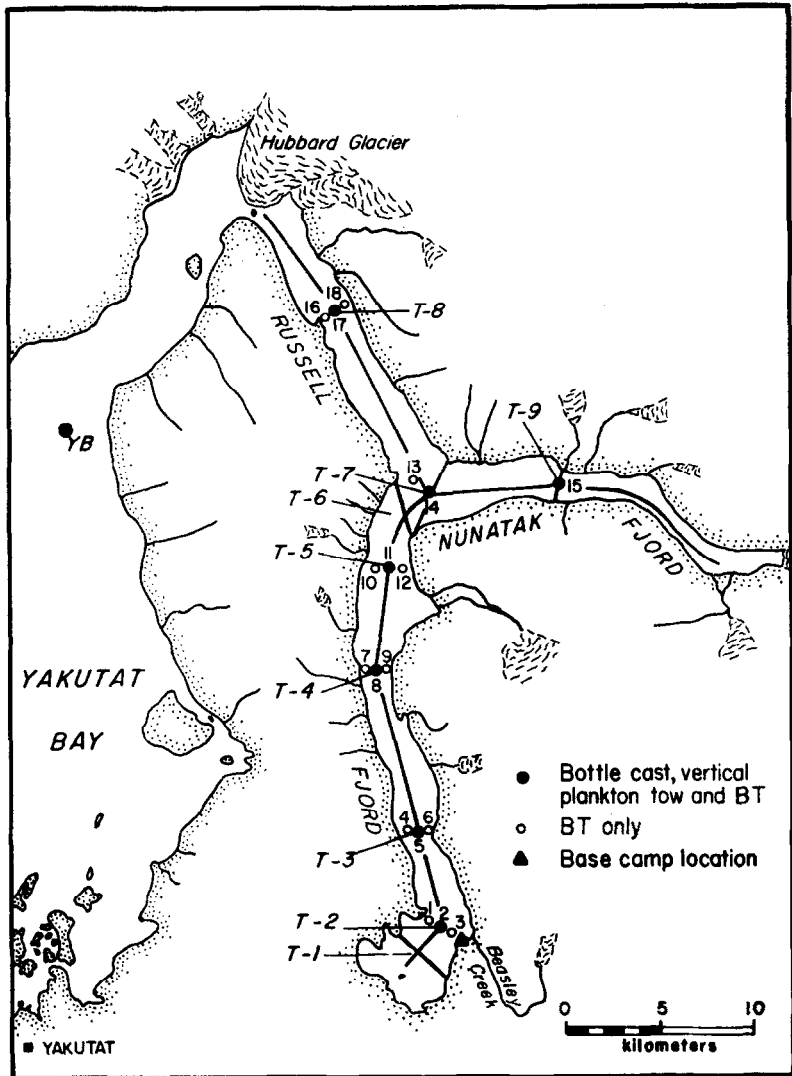


Figure 3. Station locations and bottom profiling tracks in Russell Fjord and Yakutat Bay (YB).

If we consider the upper 70 m of Royer's plots to represent source waters for Yakutat Bay and Russell Fjord, it is seen that these shelf waters undergo an annual cycle of temperature and salinity variation. The densest (coldest and most saline) waters occur on the shelf during March and April, while the least dense waters occur during August and September.

Three oceanographic stations were occupied in Yakutat Bay just prior to the April field work in Russell Fjord. These stations, represented by the one closest to Russell Fjord

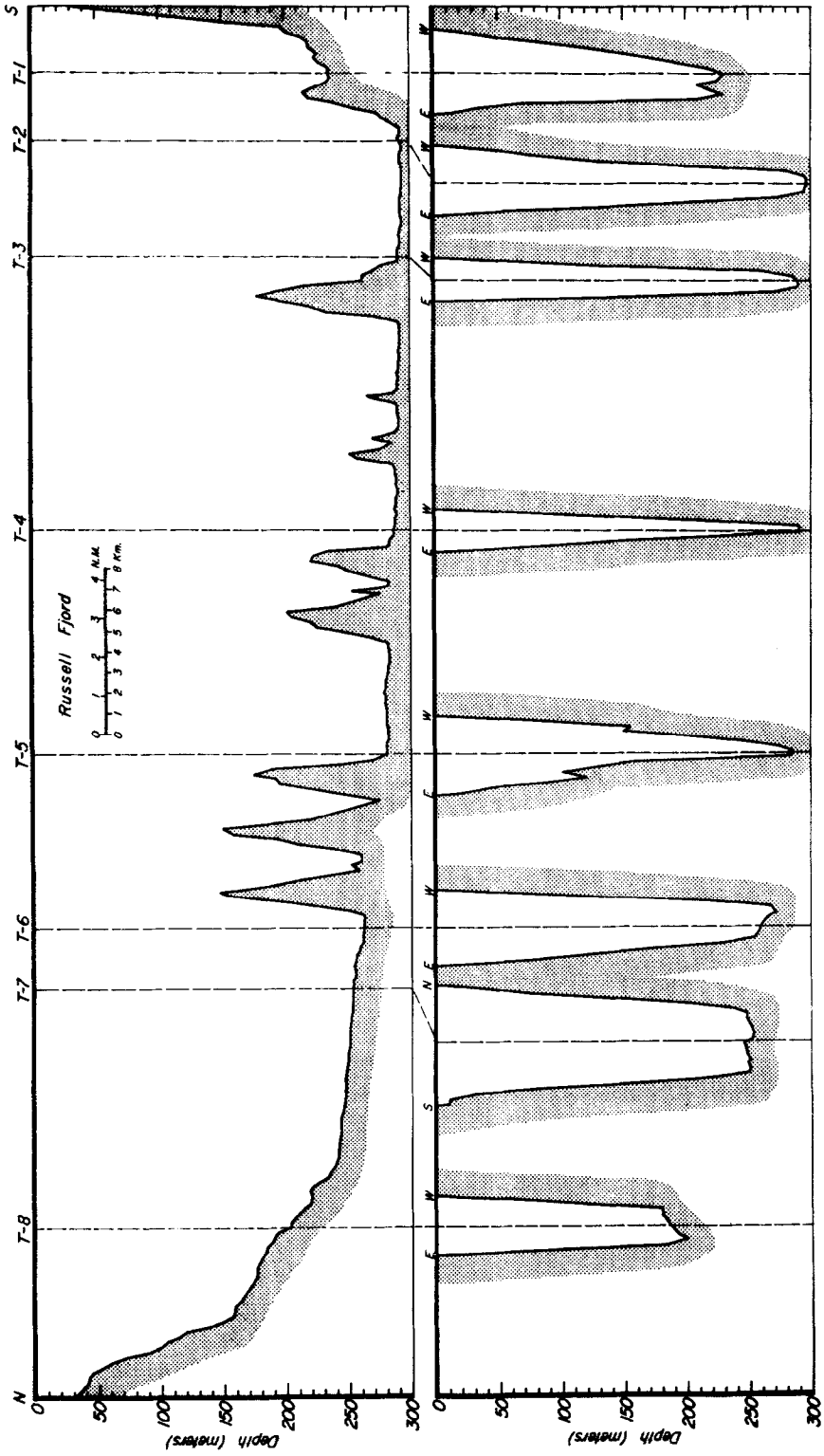


Figure 4. Bottom profiles in Russell Fjord.

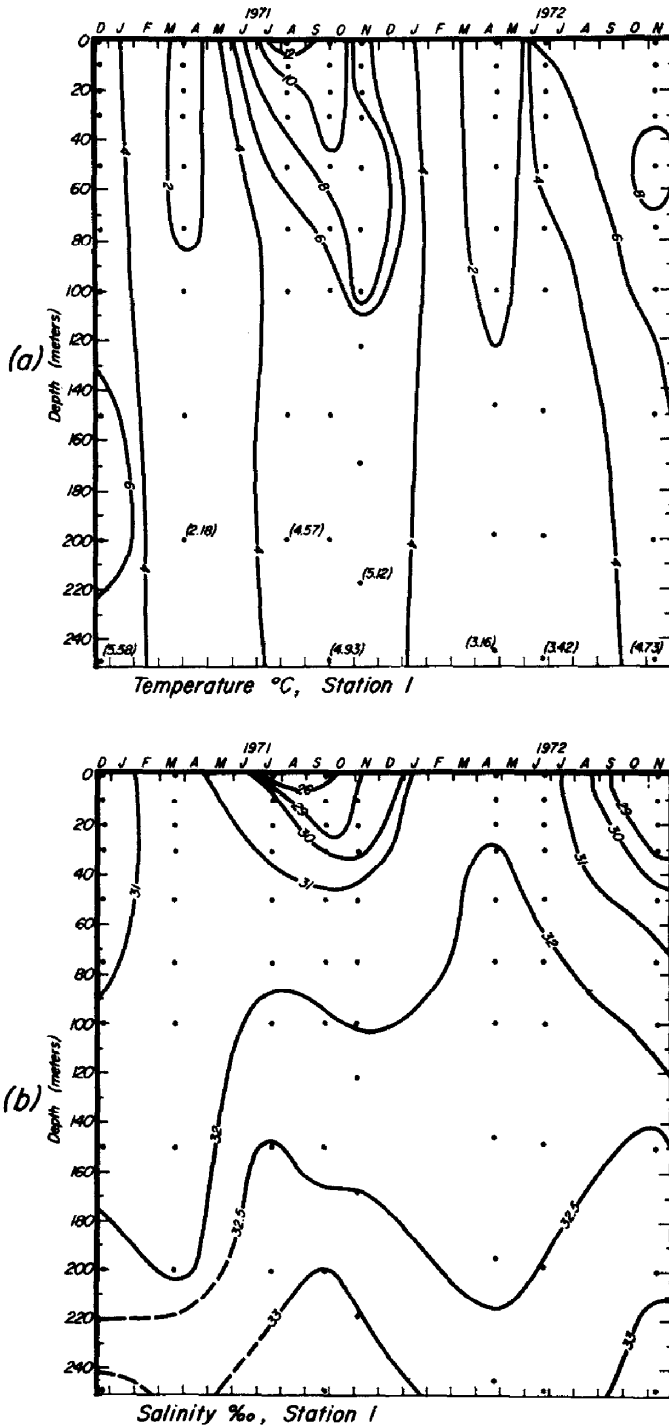


Figure 5. Temporal variations in temperature and salinity on the Gulf of Alaska shelf (from Royer, 1975).

(Figure 3) indicated temperatures and salinities compatible with Royer's plot (Table 1). The elevation of temperatures by about 1 °C above values for the Gulf may have been due either to annual variability or to warming from insolation in Yakutat Bay. The salinities in Yakutat Bay (31–31.6‰) fell within the ranges indicated on Royer's plot.

### *Winds and tides*

These shelf source waters can be driven into Russell Fjord through Yakutat Bay by winds or tides. No observations of winds in the fjord are available, but it is known that they are channelled by the surrounding mountains into an axial direction. Katabatic winds, which can approach 185 km/h on occasions during the winter in other coastal fjords, have been reported by local inhabitants but were not observed during the field studies. Meteorological observations in other southcentral Alaskan marine areas (Searby, 1969) indicate that wind measurements cannot be extrapolated over even relatively short distances due to topographic and other local effects such as katabatic winds. Therefore, no attempt was made to apply Yakutat wind data to Russell Fjord.

TABLE 1. Temperature, salinity and sigma-*t* at a station in Yakutat Bay on 5 April 1973

| Depth (m) | Temperature (°C) | Salinity (‰) | Sigma- <i>t</i> |
|-----------|------------------|--------------|-----------------|
| 0         | 3.26             | 31.04        | 24.75           |
| 10        | 3.11             | 31.17        | 24.86           |
| 20        | 3.09             | 31.29        | 24.96           |
| 30        | 3.34             | 31.57        | 25.16           |
| 50        | 3.36             | 31.66        | 25.23           |

Qualitative weather observations were made during the field work. There was a pronounced development of northerly afternoon winds during clear weather, with relative calm at other times of day. Winds were estimated to be about 5 m s<sup>-1</sup> during these wind periods. Several minor storms observed during the field work exhibited winds of this same order. Such storm winds were often, however, southerly rather than just northerly as were the diurnal winds.

The importance of tides can be estimated using the 2.37 m mean range for Yakutat (National Ocean Survey, 1973). Although attenuation of the tides might be expected by the construction of the fjord mouth, ranges observed in the fjord were similar to those predicted at Yakutat. The average tidal prism is  $4.53 \times 10^8$  m<sup>3</sup>, or 1% of the fjord volume. Tides therefore contribute about 60 times more water to the fjord on an annual basis than runoff. Sea ice formation has not been reported for Russell Fjord, though glacial ice can be carried some 10 km into the fjord with each flood tide.

### **Results**

Bathythermograph data obtained at the axial stations and at 11 other locations (Figure 3) showed no cross-fjord temperature gradients, indicating that the axial stations provided an adequate description of the fjord. Sections summarizing the distribution of temperature, salinity, dissolved oxygen, silicate, phosphate and nitrate are shown in Figures 6–10. Observations were made in Yakutat Bay prior to April, but were not possible due to ice conditions and lack of a suitable research vessel during June–July and September. Due to a shipping oversight, it was not possible to sample nutrients during April.



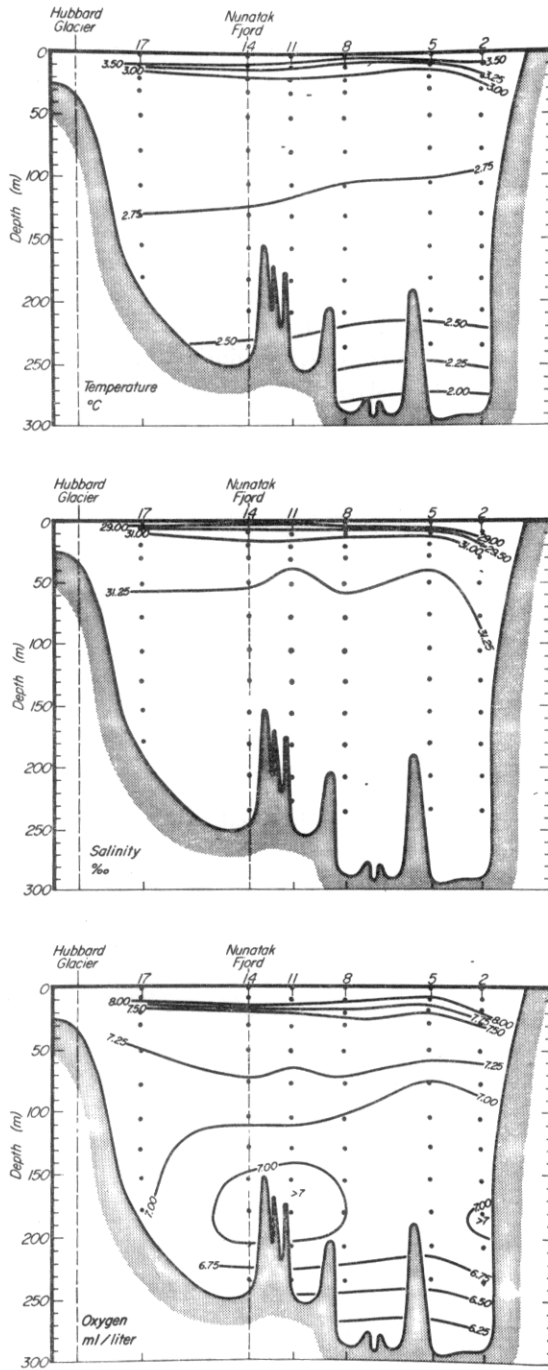


Figure 6. Distribution of temperature, salinity and oxygen in Russell Fjord during April 1973.

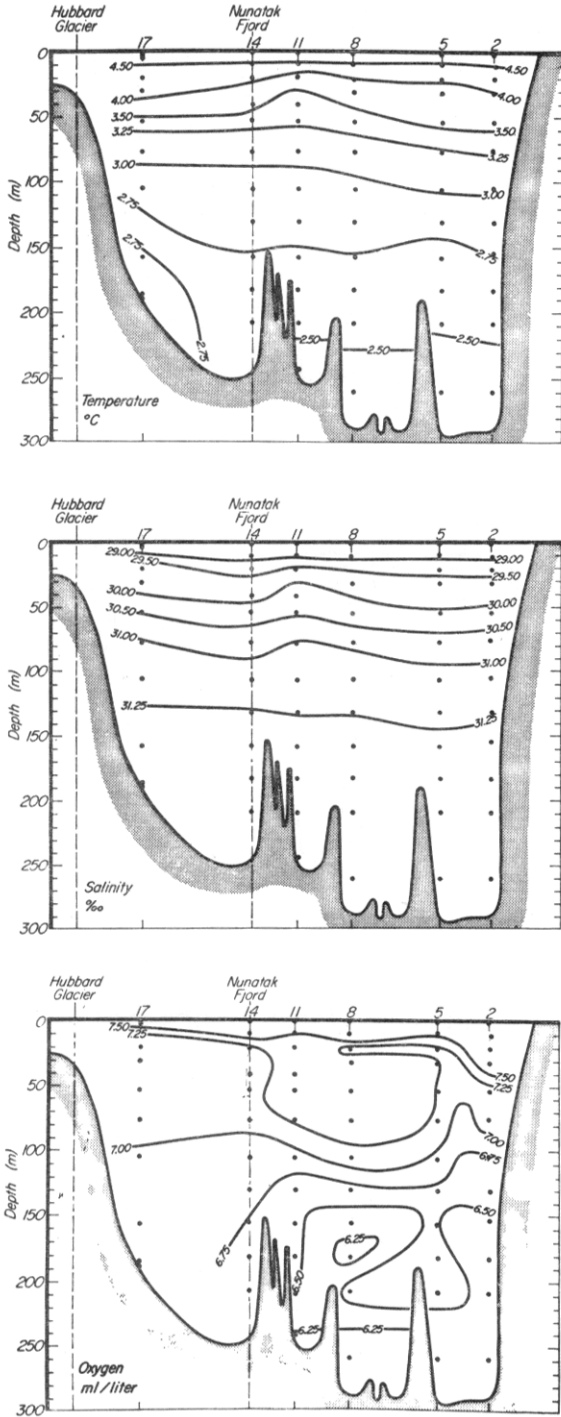


Figure 7. Distribution of temperature, salinity and oxygen in Russell Fjord during June–July 1973.

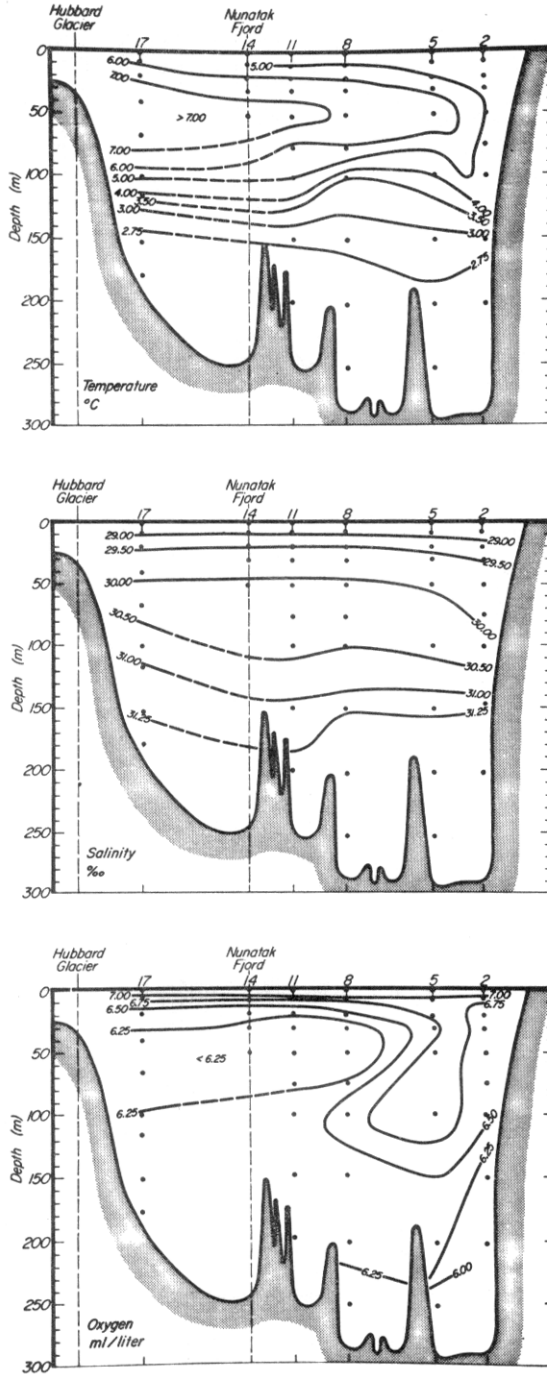


Figure 8. Distribution of temperature, salinity and oxygen in Russell Fjord during September 1973.



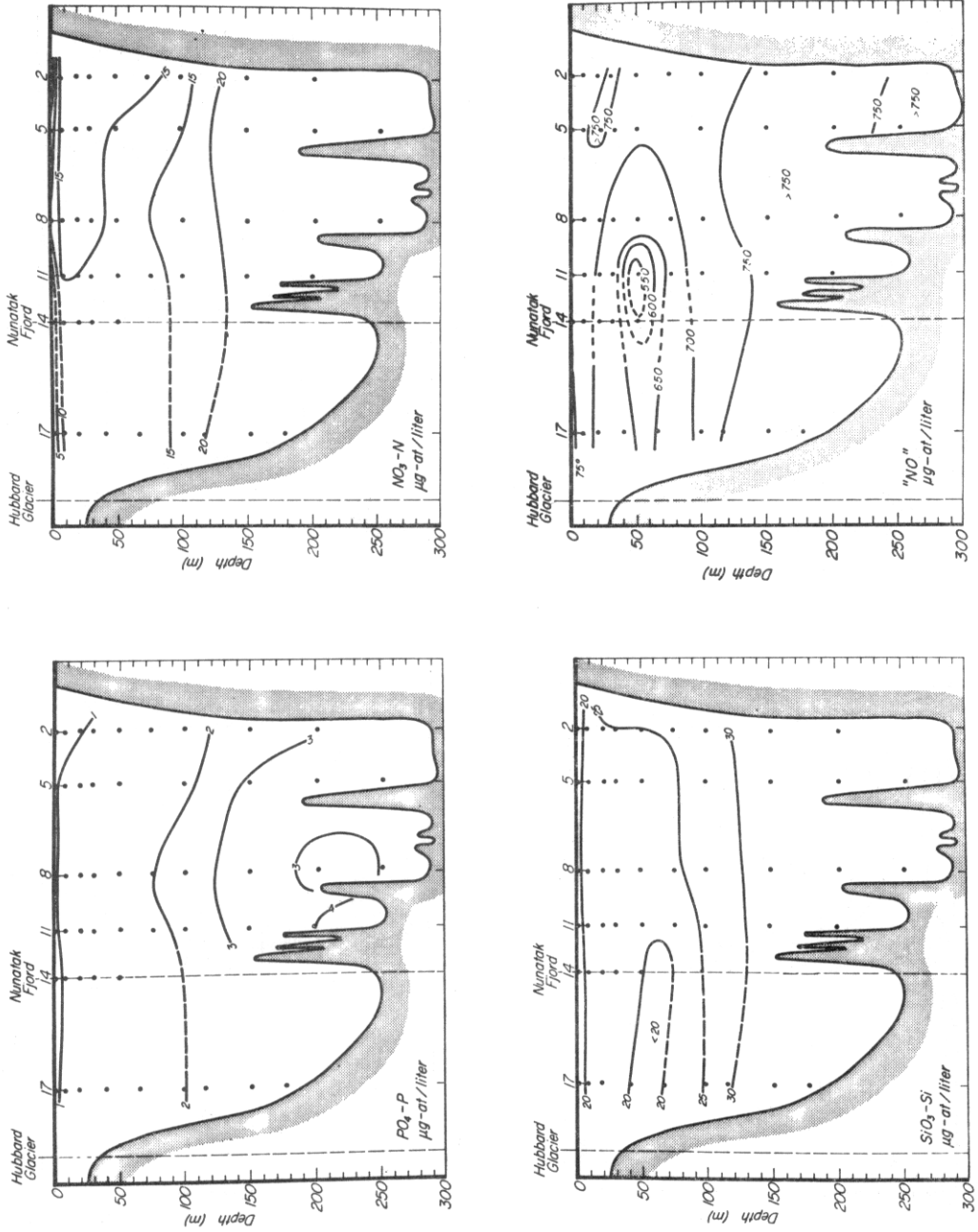


Figure 10. Distribution of phosphate, nitrate, silicate and 'NO' in Russell Fjord during September 1973.

Several general features are apparent in the sections as follows.

- (1) No longitudinal salinity gradient was observed in the near-surface waters. This was probably due in part to the near-uniform areal distribution of freshwater input to the fjord and leads to the assessment that entrainment flow was probably not important as a circulation process.
- (2) The bottom waters were well-oxygenated throughout the observation period. Oxygen consumption rates ranging between 4 and 6 ml l<sup>-1</sup> yr<sup>-1</sup> have been reported for lower latitude fjords (Barnes & Collias, 1958; Coote, 1964) so that absence of a continuous bottom water renewal mechanism for Russell Fjord could be expected to cause noticeable oxygen depletion.
- (3) Significant warming and freshening were apparent at depth as the summer of 1973 progressed. The presence of maxima and minima in the vertical profiles for adjacent stations suggested that horizontal advection was occurring.
- (4) Dissolved oxygen and nutrient concentration showed considerable patchiness. This patchiness may either be depicted as disconnected boluses as shown, or as continuous layers. The former contouring was selected because continuous layers would have required isolines to intersect the isopycnal surfaces as inferred from temperature and salinity. Detailed work in Dabob Bay, Washington has moreover shown that such boluses, rather than layers, are characteristic of distributions of non-conservative parameters below sill depth in fjords (Ebbesmeyer, 1973). Dimensions of the boluses are admittedly subjective due to station spacing. They appeared to occur at depths near 200 m during April, between 150 and 50 m during June–July and near the surface in a tongue-like distribution during September.

The near-surface tongue observed in September coincided with a low temperature tongue. It is unlikely that this tongue formed *in situ* by cooling, since by mid-September appreciable cooling of other southcentral Alaskan coastal waters has not yet commenced (Muench & Schmidt, 1975). An apparent influence of Nunatak Fjord on the Russell Fjord hydrography, as suggested by the nutrient values during June–July, was not reflected in the temperature, salinity or oxygen distributions.

## Discussion

Russell Fjord is geographically and physically similar to Endicott Arm, a fjord some 80 km southeast of Juneau subject to similar marine and atmospheric conditions. Nebert (1972) has proposed a circulation model for Endicott Arm that appears to be applicable to Russell Fjord. In Nebert's model tidal flow dominates the influence of river runoff, resulting in a circulation where dense water is added over the sill with each flood tide. The dense water sinks upon entry and less dense surface water is removed on the subsequent ebb tide. This circulation results in a near-continuous renewal of bottom water in the fjord and a net surface out-flow that is relatively independent of freshwater input. Nebert's analysis was based on differences in water characteristics on either side of the Endicott Arm sill. He concluded that tidal mixing and freshwater input maintained a density gradient across the sill that allowed the dense inflows to occur regularly throughout the year. Even in low run-off periods, inflow occurred because of the seasonal increase in the source water density.

Source water data are available from Yakutat Bay only for early April (Table 1). Density of this water at sill depth was about 25.2 sigma-*t* units, with a corresponding salinity and temperature of 31.6‰ and 3.3 °C. Water of this high a density and salinity was found only below 150–200 m in Russell Fjord during April. Lower temperatures deep in the fjord (2.5–2.75 °C) than in Yakutat Bay may reflect mixing processes during inflow. This evidence,

in conjunction with the high dissolved oxygen tongue at 150–200 m in the fjord, suggests that source water was flowing inward over the sill and occupying its own density level inside the fjord, in agreement with Nebert's model for Endicott Arm.

During the remainder of the summer the density structure within the fjord remained monotonically increasing with depth and showed little change in density values. While no data were available from Yakutat Bay after April, the Gulf of Alaska source water decreased in density during this period. Continuing inflow into Russell Fjord would have resulted in interleaving of the progressively less dense source water at shallower depths as the season progressed. The boluses or tongues shown by the oxygen and nutrient distributions suggest that this was in fact occurring and lend additional support to our circulation hypothesis.

To further support this proposed circulation for Russell Fjord, it is necessary to show that the nutrient and oxygen boluses originated outside the fjord and were not solely the result of *in situ* production or consumption. A conservative water mass tracer other than salinity or temperature is therefore needed. Broecker (1974) has proposed using 'NO',  $9 \text{ NO}_3^- + \text{O}_2$ , as a conservative water mass tracer and has demonstrated its use in Atlantic Ocean sections. When a mole of organic matter with a C : N ratio of 105 : 15 is oxidized, 7 moles of  $\text{O}_2$  are consumed in oxidizing the carbon to  $\text{CO}_2$  and 2 moles of  $\text{O}_2$  are consumed in oxidizing the ammonia or amino nitrogen to  $\text{NO}_3^-$ . Thus 9 moles of  $\text{O}_2$  are consumed in the production of one mole of  $\text{NO}_3^-$  from one mole of organic matter. The sum  $9 \text{ NO}_3^- + \text{O}_2$ , accounts for decreases in  $\text{O}_2$  due to carbon and ammonia oxidation but uses the more commonly measured  $\text{NO}_3^-$  as an indicator. 'NO',  $9 \text{ NO}_3^- + \text{O}_2$ , cancels alterations in each of the measured parameters, can be regarded as nearly conservative and should be modified only by mixing or advection in the absence of photosynthesis or air-sea gas exchange. Variations in the C : N ratio of organic matter will cause small deviations in the value of the coefficient 9, hence the qualification 'nearly'. Broecker has shown that 'NO' is similar to preformed  $\text{NO}_3^-$  and points out that the concept is not new. Use of 'NO' does, however, avoid the use of  $\text{O}_2$  saturation tables needed in calculating preformed nutrient concentrations and can be calculated directly from observed parameters.

For waters near the surface of Yakutat Bay, the summer utilization rate of nitrate by phytoplankton can be expected to be large relative to the rate of mixing with deeper waters. This nitrate uptake in conjunction with oxygen exchange with the atmosphere should lead to low 'NO' values during summer. Somewhat higher 'NO' values can be expected during winter. The deep waters of Russell Fjord originate in the surface 30 m of Yakutat Bay and should therefore show seasonal variations in 'NO'. Figure 11 shows the seasonal variation of 'NO' in the surface 30 m at the Gulf of Alaska station shown in Figure 5 (D. Heggie, personal communication). 'NO' ranged from values of  $600 \mu\text{g-at l}^{-1}$  in summer to a winter high of over  $800 \mu\text{g-at l}^{-1}$ .

The sections of 'NO' for June–July and September show low 'NO' boluses congruent with those in the nutrient sections (Figures 9 and 10). The background level for 'NO' showed an apparent decrease between June–July and September from  $800 \mu\text{g-at l}^{-1}$  to  $750 \mu\text{g-at l}^{-1}$ , which would have required replacement of about 25% of the fjord volume with  $600 \mu\text{g-at l}^{-1}$  'NO' water. The depths of the boluses in the fjord as a function of season, their nutrient and 'NO' content and finally the decrease in 'NO' between June–July and September all support the hypothesis that they were not formed by mixing or reactions in the fjord and must therefore have originated from outside. Thus, bottom and intermediate waters may have been added to Russell Fjord over the sill throughout the year, resulting in a circulation similar to that proposed for Endicott Arm.

Non-conservative solutes have been used over short time intervals in similar problems by Broenkow (1969). 'NO' may not always be applicable as a conservative tracer in coastal waters because of nitrate uptake in the photic zone, but in this instance it appears to be useful in showing origins of waters as well as giving some idea of mixing time scales.

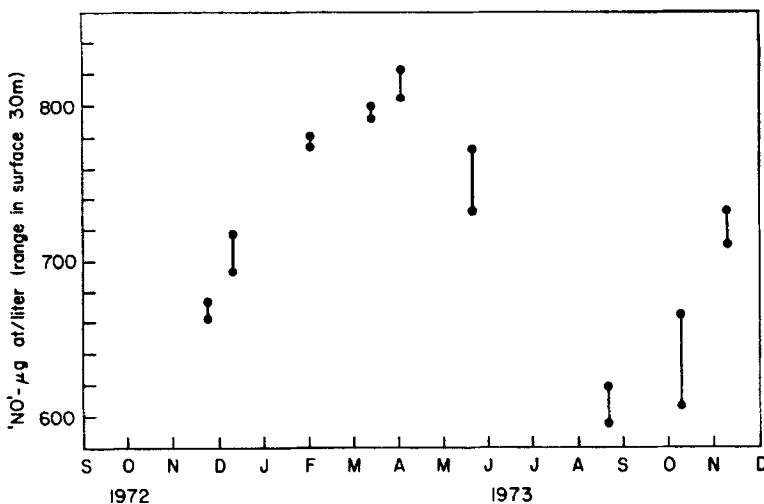


Figure 11. Temporal variation of 'NO' in the surface 30 m of Gulf of Alaska shelf waters.

Four size classes of the net plankton community were examined; Table 2 gives the formalin dry-weight standing stocks and standard deviations. The fjord was divided arbitrarily into northern (stations 13, 14, 15, 17) and southern (stations 2, 5, 8, 11) portions to determine whether circulation had any discernable effect on biomass or species composition. The large animals ( $>0.571$  mm) consistently contributed the greatest portion of the biomass retained by the 0.112 mesh net. This assemblage was dominated numerically by the copepods *Metridia lucens* and *M. okhotensis* and the chaetognath *Sagitta elegans*. The size class from 0.216 to 0.571 mm consisted almost entirely of copepods of the genus *Pseudocalanus*, while the 0.112 to 0.216 mm size class was represented by eggs, nauplii and small copepodites along with the centric diatom *Coscinodiscus oculis iridis* and the dinoflagellate *Peridinium depressum*.

The net zooplankton community in Russell Fjord appeared similar to those reported for southeastern and southcentral Alaska (Wing & Reid, 1972; Cooney *et al.*, 1973). The mid-summer and fall increase in standing stock of intermediate sized zooplankton probably reflects reproduction and growth of *Pseudocalanus*. Seasonal variability was most pronounced for the largest animals sampled in the northern end of Russell Fjord. It is impossible to determine from the data whether this variability was related to circulation or to biological processes. Members of the genus *Metridia* are known to be strong diurnal migrators and could be selectively removed from the northern end of the fjord by surface currents.

We are unable to explain why so few boluses are present in the fjord and why they are present as boluses rather than thin layers. Winds, for which we have no observations, coupled with tides and the nearly uniform density distribution below the pycnocline may be responsible for their formation and preservation. Detailed sampling in space and time is needed to solve this question. Considering the small size of the present fjord mouth, Russell Fjord is remarkably well flushed.



TABLE 2. Standing stocks ( $\text{g m}^{-2}$  formalin dry-weight) of net plankton in Russell Fjord, with standard deviations within each size class and period for all four stations

|                         | >0.571 mm   | >0.216 mm<br><0.571 mm | >0.112 mm<br><0.216 mm | <0.112 mm    |
|-------------------------|-------------|------------------------|------------------------|--------------|
| <i>Northern section</i> |             |                        |                        |              |
| April                   | 1.69 ± 0.63 | 0.51 ± 0.08            | 0.98 ± 0.50            | 3.18 ± 0.91  |
| June-July               | 7.02 ± 5.43 | 2.54 ± 1.53            | 1.45 ± 0.80            | 11.02 ± 7.65 |
| September               | 3.73 ± 2.65 | 1.21 ± 0.33            | 0.30 ± 0.03            | 5.24 ± 2.97  |
| Mean                    | 4.15 ± 3.83 | 1.42 ± 1.19            | 0.91 ± 0.69            | 6.48 ± 5.42  |
| <i>Southern section</i> |             |                        |                        |              |
| April                   | 6.56 ± 1.61 | 0.54 ± 0.15            | 1.68 ± 0.86            | 8.78 ± 1.70  |
| June-July               | 6.32 ± 4.52 | 3.04 ± 1.78            | 1.28 ± 0.35            | 10.49 ± 3.54 |
| September               | 5.90 ± 0.03 | 2.50 ± 0.83            | 0.50 ± 0.09            | 8.90 ± 0.71  |
| Mean                    | 6.25 ± 2.53 | 1.79 ± 1.15            | 1.15 ± 0.71            | 9.20 ± 2.30  |

#### *Speculation on future conditions in Russell Fjord*

Since this study was undertaken partly to provide a basis for comparison should glacial closure occur, it is of interest to speculate briefly on conditions that might be observed if Russell Fjord were isolated from marine influence.

If the fjord becomes completely closed, i.e. the Hubbard Glacier overruns Osier Island and comes to rest against Gilbert Point, rapid accumulation of freshwater runoff would be expected. The water level in the fjord would rise at a rate of about  $28 \text{ m yr}^{-1}$  until water flowed around or through the glacier or through channels in the terminal moraine at the southern end of the fjord. The reported presence of channels, with elevations estimated to be 30 m or less, in the moraine indicates that water would probably not accumulate to a point where the 150-m thick Hubbard Glacier would float. With accumulation of freshwater runoff and no renewal of bottom water, the fjord should stratify strongly and the bottom waters should become anoxic within less than two years. With strong salinity-maintained stratification, it should be possible for the surface waters of the fjord to cool strongly enough to freeze. The altered salinity and light conditions would be fatal to intertidal organisms and to those members of the plankton community unable to tolerate prolonged low salinities or low oxygen conditions. Whether anadromous fishes would continue to use the fjord through a modified or different outlet remains a question. As long as the glacial dam remained intact, the fjord would evolve toward a condition similar to Powell Lake as reported by Williams *et al.* (1961).

Under conditions of less complete closure, i.e. grounding of the glacier on Osier Island, the fjord would still communicate with Yakutat Bay through the shallow (less than 3 m) gut between Osier Island and Gilbert Point. During summer, runoff could cause outflow currents through this channel exceeding  $6 \text{ m s}^{-1}$ , so tidal inputs might be overcome or greatly diminished. The fjord might be expected to undergo a seasonal variation in water level coincident with runoff fluctuation. During winter, salt-water renewal could take place, but whether the renewal rate would be high enough to prevent the deep water from becoming anoxic is unknown. Partial closure of the fjord would probably not permit freezing and both organisms able to tolerate low salinities and anadromous fishes should experience no difficulty surviving.

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