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SOME ASPECTS OF THE HYDROGRAPHY OF ALASKAN AND NORWEGIAN FJORDS*

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Fjorded coastlines exist in several parts of the world at higher latitudes. They have similarities because of their common origin as glacically eroded structures in a mountainous coastline. Oceanographically fjords fall into a separate class of estuaries which has been defined by Prichard(1) as follows, "A fjord is an elongated indenture of the coastline containing a relatively deep basin with a shallower sill at the mouth". The deepness of fjords and their upper circulation patterns are features which set them apart.

Unlike other classes of estuaries, fjords have received relatively little attention from oceanographers. The majority of the previous work has been concerned with fjords of Norway(2, 3) and the fjord inlets of British Columbia and Alaska(4, 5, 6, 7, 8, 10, 11). Oceanographic data on other fjord regions is very scarce(12, 13, 14). This paper is concerned with contrasts and similarities in fjord oceanography in two of the better studied regions, Alaska and Norway.

We have been studying Alaskan fjords with the ultimate aim of producing a numeric model of fjord estuarine circulation. To allow of better testing of a numeric model we have collected and catalogued data from all fjord regions. Information on Southeast Alaskan fjords is based on summer circulation data as reported by Pickard(10) and on seasonal data from our physical oceanography group. Many of these latter data have appeared or will shortly appear in the masters theses of Quinlan(15), Gleason(16), Standtmann(17) and Nebert(18).

Several factors influencing fjord circulation have been identified by earlier workers. Topography of the inlet, its length, depth and sill depth, for example all have considerable influence. The quality and quantity of water masses available to the fjord are also important. This includes knowledge of

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both freshwater runoff and surrounding ocean water masses. The climate and meteorology of the area also play a part in water mass circulation. Tides can vary greatly from fjord to fjord and can also have a big effect on fjord circulation. In comparing representative Norwegian and Alaskan fjords circulation each of these factors will be considered.

FACTORS INFLUENCING CIRCULATION

Topography - At present we are constructing a fjord catalogue listing the more important fjord inlets of the world. The information is computer stored and manipulated for easy access. In addition to geographical location and principal connections to the ocean and other inlets, the dimensions, number of sills and basins and their depths and the surface areas are listed. The catalogue for Alaska and Norway is almost complete. It shows that Norwegian fjords are generally both deeper and longer than Alaskan fjords. Depths of nearly 1000m are not uncommon in Norway whereas 400m depths are quite rare in Alaskan fjords. The longest Norwegian fjord, Sognefjord is 200km in length. Some inlets in both countries have deep or non-existent sills and therefore fall outside Pritchard's definition of a fjord, our observations in Alaska have shown that the sill acts to restrict entry of saline water into the inlet.

Available Water Masses

The availability of freshwater and seawater to the inlet affects the circulation pattern. Runoff in both Alaska and Norway is strongly seasonal. Both countries have a summer high runoff and winter low runoff. Figure 1 shows

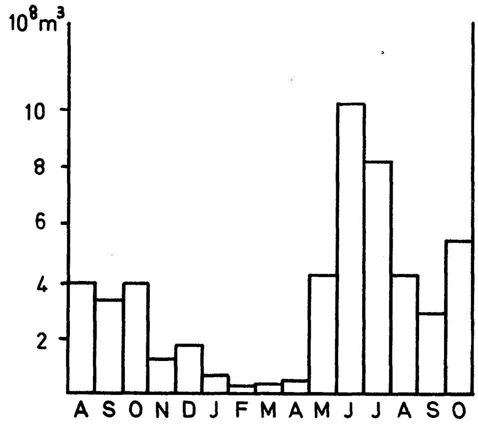

Fig. 1 Discharge of Eio, Kinso, Opa and Tysso Rivers into inner Hardnager fjord (after Saelen(3))

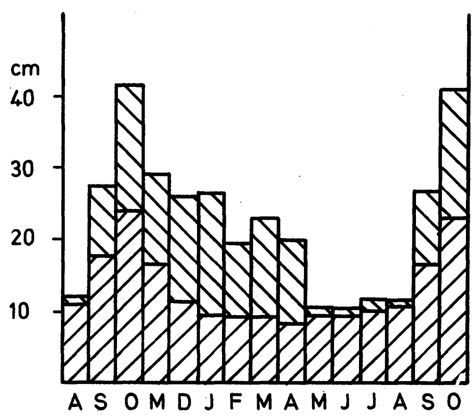

Fig. 2 Mean monthly precipitation patterns for Annette Island (\\\\) and Juneau (////), Alaska

the runoff into upper Hardanger fjord (after Saelen(3)). There is a marked minimum for January, February, March and April and peaks in June/July and October. The same pattern of twin peaks in summer and fall with the winter-spring minimum is observed in Alaska. Runoff falls drastically in November and December as the winter freeze begins to lock precipitation up as ice or snow. The actual precipitation shows the October peak but the spring peak is missing. Figure 2 shows precipitation for Annette Island (with higher precipitation) and Juneau. The spring runoff peak in May, June and July is no doubt a result of spring thawing. Actual runoff figures are not available for Alaskan inlets so that the foregoing comparison should be treated with caution. However the main features, the peaks and mininima and their timing, are very similar.

The salinity of the North Pacific off Alaska is usually close to 33 ‰. The North Atlantic ocean off the Norwegian coast is of the order of 35 ‰ salinity. This higher salinity and also the slightly higher ocean temperatures are direct results of the origins of coastal waters in the Gulf Stream. These differences in salinity and temperature between Alaskan and Norwegian coastal waters are sufficient to cause quite significant patterns of fjord circulation.

Meteorology

Norway's fjord region stretches from about 59°N latitude to 71°N, British Columbia's fjords start at about 49°N and the most northerly Alaskan fjord is at 61°N. One would expect the climate of Norway to be generally colder than Alaska's. However the effects of the North Atlantic Drift is to temper Norway's climate. It effectively makes the climate one equivalent to a 10° latitude shift further South. The overall climatic conditions, allowing for this 10° latitude shift, are quite comparable.

As one progresses northwards colder winter conditions are found and the importance of winter thermohaline circulation in fjord water masses probably increases. We have not found thermohaline circulation to be very important except in exceptional years. In 1965 Rosenberg(19) noted that mixing by thermohaline convection down to 150m had probably occurred after an unusually cold winter in Taiya Inlet, Alaska. The inlet was reported to have an ice cover during the coldest period, a very unusual event.

In fjord regions wind effects can also be important for surface mixing. Föhn winds funneling down from ice fields can reach velocities of 50m/sec down certain fjords. These winds are a function of overall pressure patterns and the local topography and therefore vary from fjord to fjord.

The seasonal nature of precipitation has already been mentioned. In Alaska, glaciers which reach to tidewater are a further unknown variable. Tidewater glaciers, which do not occur in Norway, lock up large quantities of water and release it on both annual and erratic cycles.

Tides

Tides in inlets produce a diurnal or semi-diurnal current ebb and flow. This ebbing and flowing of water masses is a major mechanism for transport and water exchange. Depending on sill depths it can also determine the degree of turbulent mixing of waters passing over a sill.

Generally the Norwegian tidal ranges are smaller than those for North American fjords. Tidal ranges for a few ports along the North American and Norwegian fjord coasts are shown in table 1. There is a tendency for the tides in the central fjord region in both countries to be larger, the ranges in Alaska being about twice those of corresponding Norwegian ports. The tides flowing through constricted channels can produce exceptionally large currents as in the famous maelstrom in Norway or Wrangell Narrows in Alaska.

TABLE 1

TIDAL RANGES, NORWAY AND ALASKA

degrees N. lat.	Norwegian Port	Range centimetres Mean	Spring	degrees N. lat.	North American Port	Range centimetres Mean	Diurnal
59.9	Oslo	30	33	49.3	Vancouver B.C.	-	195
60.4	Bergen	97	124	50.9	Bute Inlet B.C.		350
63.4	Trondheim	198	265				
66.3	Ranen fjord	183	238	57.7	Wood Spit, Alaska	396	457
68.4	Narvik	201	265	58.9	Muir Inlet, Alaska	424	503
69.6	Tromso	186	241	60.5	Ocra Inlet, Alaska	301	378
70.7	Hammerfest	189	241	61.1	Valdez, Alaska	286	360

OCEANOGRAPHIC FEATURES

Alaskan Inlets

The major oceanographic features of Alaskan fjords have been described elsewhere(10, 11). Our work has been concerned with inlets having tidewater glaciers and we will use one of these, Muir Inlet, as a typical example. Although it contains tidewater glaciers it has been shown(11) that the effect of the glacier is mainly as a heat sink and source of cold, oxygenated freshwater. The water masses of inlets with tidewater glaciers fall on the temperature-salinity diagram into a distinctive area which is both colder and less saline than the area covered by TS diagrams of other Alaskan and British Columbian Inlets(10, 11). Figure 3, taken from Matthews and Quinlan's(11) report, gives the water masses of North American fjords. Three groups are southern British Columbia, Northern British Columbia and Alaska. Alaskan fjords with tidewater glaciers (ICE on figure 3) fall into a distinct fourth group on the TS plot.

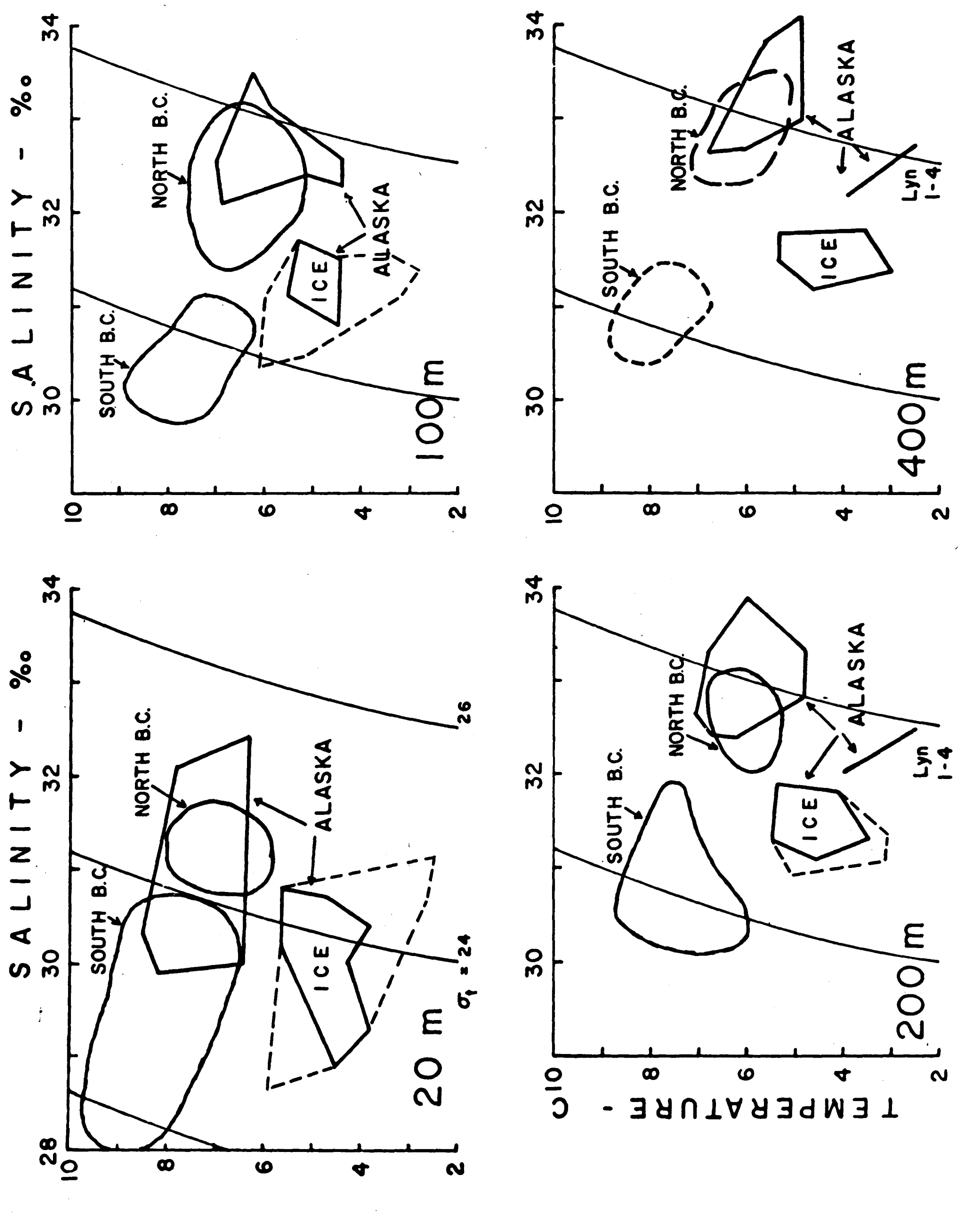

Figure 3. TS diagrams of fjord water masses of Northwest America (after Pickard(10) and Matthews and Quinlan(11).

Norwegian fjord water masses when plotted on figure 3 would fall to the right of North American water masses. Hardanger fjord at about 60°N latitude has water masses for depths 100m deeper which fall near the 34.5 to 35.5 ‰ salinity and 6° to 8° temperature ranges. This is the result of the higher salinity Norwegian coastal water mentioned earlier.

Seasonal Fjord Water Masses

Alaska - Two distinct oceanographic conditions have been found to exist in Alaskan fjords. All the fjords we have studied show the effect and we shall use Muir Inlet, which has tidewater glaciers, as an example.

The most notable condition is the winter-spring homogeneous condition. This is most pronounced in February. At that time 70% of the water mass falls within the narrow ranges 31.0 to 31.2 ‰ salinity and 3.1 to 3.5°C temperature. In June and July when runoff reaches its first peak we find the heterogeneous summer-fall condition. At this time cold, fresh or brackish water is found at the surface overlying a deeper more saline warmer layer. It is noteworthy that our work(11) has shown that between February and July while the surface layers become much fresher, the deeper waters actually become more saline.

The glacier acts as a source of cold fresh oxygenated water and as a heat sink for the deep warm saline waters. The oxygen content of the deep water decreases slightly from July to November. However from February to July the deep waters increase in both salinity and oxygen content which indicates a renewal of deep waters from outside the inlet.

The depth to which the effects of the summer runoff are felt depends on the particular inlet. Sill depth and turbulent mixing over the sill are important considerations. In Muir Inlet the thermocline is at about 40m depth in February below which depth the homogeneous conditions apply. In summer surface mixing penetrates to about 150m depth. Muir Inlet has a sill depth of 62m. Endicott Arm, another fjord with tidewater glaciers, shows the effects of surface mixing to about 75m depth. The entrance sill of Endicott Arm is 18m depth. The means by which the homogeneous conditions typified by February's data are reached is not yet known. Probably both thermohaline convection due to surface cooling and the inflow of denser waters driven by tidal motion contribute to the process. This will be discussed again later in the paper.

Conditions in other Alaskan fjords follow similar, seasonal cycles but, as was pointed out in figure 3, conditions do not become quite so cold or brackish in non-glacial inlets.

Norway - Norwegian fjords appear to follow similar cycles to Alaskan fjords but, in at least one case, with significant differences. Oslofjord has been investigated most fully of the Norwegian fjords but because of its location it is somewhat anomalous. Gade(2) reports high salinity 100m for Outer Olsofjord in January. From January to July the salinity at all depths decreases. At 100m July salinity is 34.4 ‰ compared with 35 ‰ in January. The salinity below 75m depth remains constant from July to December. The minimum surface temperature of 0.95°C is observed in February compared with a 12°C temperature in May.

Inner Oslofjord does not show such extreme variations probably because of its 19.5m deep sill. Outer Oslofjord has freer access to oceanic waters. The water masses probably have greater stability than Alaskan fjord waters as a result of the intrusion of more saline Atlantic water.

Hardanger fjord is considered to be representative of the central and western Norwegian fjords. It has a 150m sill depth and a free access to the ocean. The summer conditions show the familiar heterogeneous conditions with surface salinities ranging from 2.15 ‰ at the head to 31.3 ‰ at the mouth. The deep water has uniform salinity of about 35 ‰.

The February condition is fairly homogeneous with surface salinities of 33.92 ‰ at the head and 33.79 ‰ at the mouth of the fjord. This slight decrease towards the mouth is somewhat unusual. The deep water throughout the fjord is constant at 35 ‰ salinity.

Nord fjord another central west Norwegian fjord shows the typical annual intrusions in its outer basin. The inner basin, separated from the outer by a 125m deep sill, shows a renewal of deep waters only once every seven or eight years. Saelen(3) believes that outer basin deep water is renewed each year by water entering from the ocean. This water is not normally able to penetrate into the inner basin. The oxygen content of the deep water of the inner basin falls steadily under these conditions. About once every seven years unusual oceanic conditions bring denser water into the outer basin. In the case of Nord fjord the denser water is less saline (34.5 ‰ instead of 35.0 ‰) but much colder (5.5°C instead of 7.2°C). This denser water is able to penetrate the inner basin and renew its deep waters. The oxygen content of the deep basin shows this clearly in its rapid rise from 40% to 90% saturation.

FJORD CIRCULATION

Conditions in both Alaskan and Norwegian fjords indicate that at least three mechinsms are important in the circulation of the waters. Thermohaline convection due to winter cooling, probably with ice formation, may mix the surface waters in winter to depths of 150m. Entrainment flow caused by runoff waters can lead to the removal from the fjord of brackish water in volumes 5 to 10 times the runoff volume. Density flow over the sill at certain times of the year, or in certain years, may renew the whole water mass. Because the deep water dominates the fjord water mass(11) this renewal of the deep water must be a particularly important mechanism.

Our detailed work in Endicott Arm has been aimed at determining the mechanism of water mass renewal. Gleason(16) pointed out some unexpectedly high ebbing surface currents in February during the low runoff period. The increase in deep water salinity in Muir Inlet between February and July(11) has been mentioned earlier, Nebert's(17) work on the circulation of Endicott Arm indicates that the deep water renewal, occuring in winter and spring in Alaskan fjords, is driven by the large tidal motions in these waters.

An illustration of the tidal mechanism is shown in figure 4. Normalised current amplitudes at 30m and 150m are shown. The currents are normalised so that 1.0 corresponds to 24cm/sec. Much higher currents are found near the surface than at depth. Only peak velocities have been plotted without respect to direction. The lead and lag of the currents has been neglected so that all points are at time intervals of T/4 where T is the tidal period. The currents are quite strongly elliptical so that resolution into transverse and longitudinal currents has not been carried out. The currents were measured at a station in the centre of the inlet some 22km from the entrance.

It appears that throughout the year there is a net outflow at the surface and a net inflow at depth. The density of the waters outside the sill, as in the case of Nord fjord, determines whether the inflow will occur. In the Alaskan case the relatively higher tidal volume strengthen and speed the intrusion process. Figure 4 does indicate that both surface and deep water currents do follow a tidal cycling. One would expect the surface currents to be less than the deep currents but why they should be out of phase is not so certain. This is only a preliminary report and more detailed analysis is still being carried out(17).

CONCLUSIONS

The fjords of Norway and Alaska do have many similarities. The principal differences are the higher tidal ranges and lower salinities of Alaskan fjords and the absence of tidewater glaciers in Norwegian fjords.

These differences appear to be capable of providing explanations of the observed fjord circulations. The more saline water and lower tide ranges give greater stability to the deep waters of Norwegian fjords. For example, the renewal of inner Nord fjord takes place only when exceptionally dense water is present outside the sill. In Endicott Arm the 4.5m mean diurnal tidal range is sufficient to bring saline water over the very shallow sill to renew the waters and overall and localized meteorological conditions.

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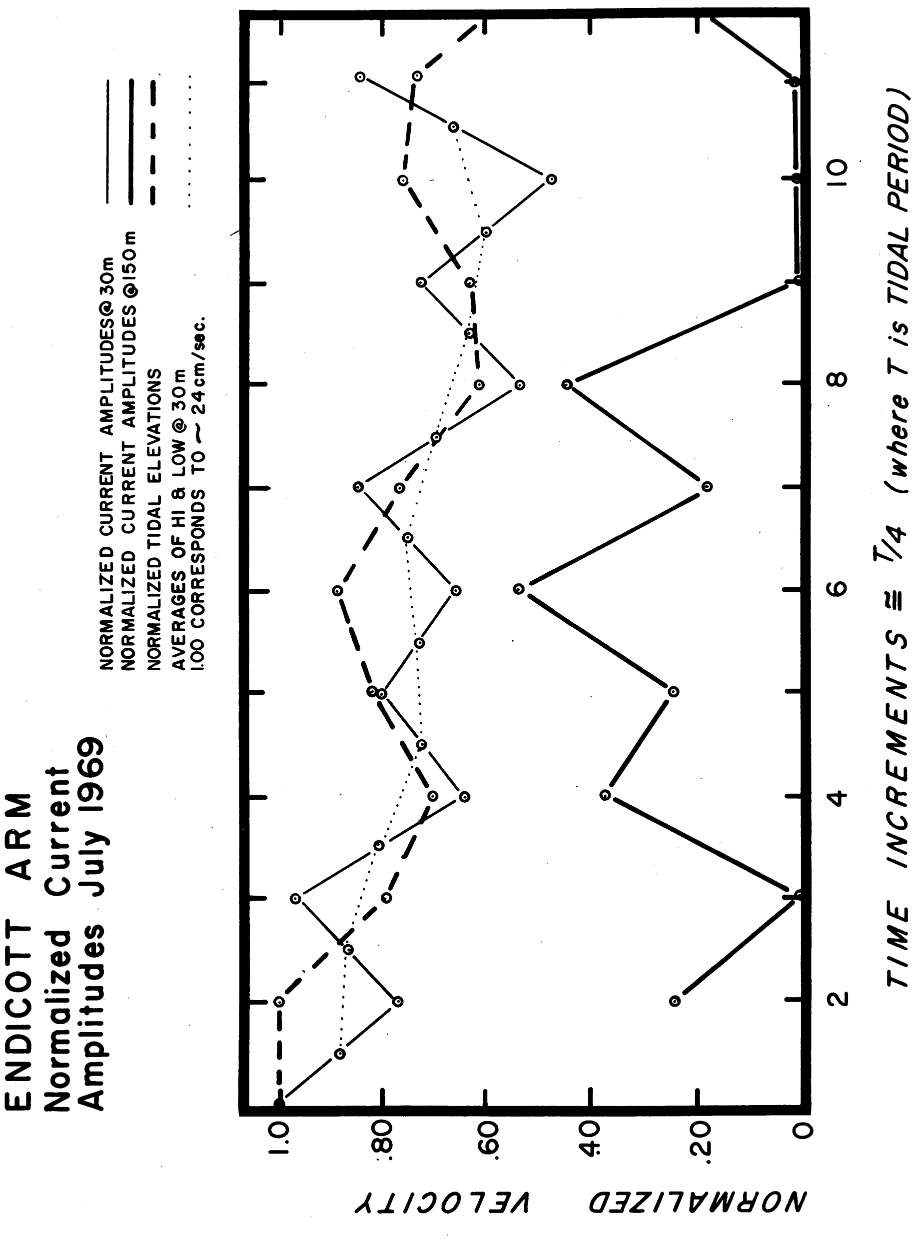

Figure 4. Normalized current amplitudes for Endicott Arm, Alaska.

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REFERENCES

1. PRITCHARD D.H. 1952

Estuarine Hydrography
In Advances in Geophysics. H.E. Landsberg(Ed.) Vol. 1. Academic Press N.Y.

2. GADE H.G. 1963

Some hydrographic Observations of the Inner Oslofjord during 1959
Hvalradets Skrifter 46:1-62

3. SAELEN Q.H. 1967

Some features of hydrography of Norwegian fjords
In Estuaries, G. Lauff(Ed.) Am.Assoc.Adv.Sci., Wash.D.C. p 63-70

4. TULLY J.P. 1949

Oceanography and prediction of pulp mill pollution in Alberni Inlet
Bull.Fish.Res.Bd. Canada. 83 1-169

5. TABATA S & G.L. PICKARD 1957

The physical oceanography of Bute Inlet, British Columbia
J.Fish.Res.Bd. Canada 14 487-520

6. GILMARTIN, M. 1962

Annual cyclic changes in the physical oceanography of a British Columbian fjord
J.Fish.Res.Bd. Canada. 19:921-974

7. WALDICHIK M. 1957

Physical oceanography of the Strait of Georgia
J.Fish.Res.Bd. Canada. 14:321-486

8. PICKARD G.L. 1961

Oceanographic features of inlets in the British Columbia mainland coast
J.Fish.Res.Bd. Canada. 18:907-999

9. JONES R.B. 1964

Oceanographic investigations of Port Nellie Juan Fjord, Alaska
Report to U.S. Dept. of Commerce, E.S.S.A., C & GS 46pp

10. PICKARD 1967

Some oceanographic characteristics of the larger inlets of Southeast Alaska
J.Fish.Res.Bd. Canada. 24:1475-1502

11. MATTHEWS J.B. & A.V. QUINLAN 1972

Seasonal water mass characteristics of Muir Inlet, a fjord with tidewater glaciers
J.Fish.Res.Bd. Canada (In Press)

12. NUTT D.C. & L.K. COACHMAN 1956

The oceanography of Hebron Fjord, Labrador
J.Fish.Res.Bd. Canada 13(5):709-758

13. NEW ZEALAND OCEANOGRAPHIC INSTITUTE 1964

Studies of a southern fjord
T.M. Skerman(Ed.) New Zealand Dept.Sci. & Ind.Res., Bull 157, Mem 17
102pp

14. PICKARD G.L. 1971

Physical oceanography of inlets of Chile
submitted to J.Fish.Res.Bd. Canada

15. QUINLAN A.V. 1969

Seasonal and spatial variations in the water mass characteristics of
Muir Inlet, Glacier Bay, Alaska
M.S. Thesis, University of Alaska 145pp

16. GLEASON R.R. 1971

Surface currents and iceberg photogrammetry in Endicott Arm, Alaska
M.S. Thesis, University of Alaska, College, Alaska

17. NEBERT D.L. 1972

The circulation of Endicott Arm, an Alaskan fjord
M.S. Thesis, University of Alaska, College, Alaska

18. STANDTMANN R.L. 1972

Sub-surface currents in Endicott Arm, Alaska
M.S. Thesis, University of Alaska, College, Alaska

19. ROSENBERG D.H. J.B. MATTHEWS & D.W. HOOD 1967

Numeric Model of a Fjord estuary
Unpublished progress report to Office of Naval Research contract
Nonr 3010(05)
Inst.Marine Sci., University of Alaska College Ak. U.S.A.