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Seasonal circulation in some Alaskan arctic lagoons

Alaskan lagoons
Season currents
Ice formation

Lagunes de l'Alaska
Courants saisonniers
Formation de glace

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ABSTRACT

This paper collates physical oceanographic data into a description of a seasonal cycle for lagoons in the Beaufort Sea. Shallow (1-5 m) coastal lagoons are a common feature of Alaska's arctic coast. They are formed between barrier islands and low coastal tundra. They are ice covered for all but three summer months and are underlain by permafrost. During the spring and summer seasons they are used extensively by breeding birds and fish. The waters are brackish (20-25 ‰) in summer due to runoff from the numerous small rivers and have temperatures in excess of 8 °C. By September, runoff has ceased and cold (0 °C), saline (30 ‰) arctic ocean water begins to freeze in the lagoons. By early November ice is 50 cm thick with salinities of 32-34 ‰ and temperatures at the freezing point. Salinities increase at a rate of 0.04 ‰ per day due to the brine rejection of ice formation. Currents are sluggish (~ 1 cm/sec.) and show a seaward transport of brine.

By April ice is about 2 m thick with most of the lagoon frozen to the bottom. Salinities in deep parts can exceed 100 ‰. Coastal runoff occurs over a 10-day period in early June with sediment-laden river water overflowing the coastal ice. River channels and lagoons are flushed with fresh water in a few hours and remain brackish until the coastal ice breaks up in July. In the open water season currents are wind-driven and waters are generally well mixed in lagoons. prevailing winds from the northeast produce westward flowing currents at 3 % of the wind speed.

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RÉSUMÉ

Circulation saisonnière dans les lagunes arctiques de l'Alaska.

Cette communication recense des données océanographiques et physiques pour décrire des cycles saisonniers des lagunes de la mer de Beaufort. Les lagunes côtières de la côte arctique de l'Alaska sont généralement peu profondes (1 à 5 m), elles se sont formées entre des îles barrières et des côtes basses à toundra. Elles sont couvertes de glace pendant la plus grande partie de l'année sauf pendant 3 mois, et sont caractérisées par la présence d'un permafrost. Pendant le printemps et l'été, les lagunes servent de lieu de reproduction pour les poissons et les oiseaux. Les eaux saumâtres (20-25 ‰) en été du fait des eaux de ruissellement en provenance de nombreuses rivières et la température peut dépasser 8 °C. En septembre, le ruissellement a cessé et les eaux froides (0 °C) et salées (30 ‰) de l'océan arctique commencent à geler dans les lagunes. Début novembre, la glace atteint 50 cm d'épaisseur avec des salinités de 32 à 34 ‰ et des températures proches du point de congélation. Les salinités augmentent à raison de 0,04 ‰ par jour à cause de la tendance à la sursalure qui accompagne la formation de glace.

En avril, la glace a environ 2 m d'épaisseur et presque tout le fond de la lagune est gelé. Les salinités dans les parties profondes peuvent excéder 100 ‰. Les ruissellements côtiers reprennent pendant 10 jours au début de juin avec des charriages de sédiment. Les chenaux des rivières et des lagunes sont alors remplis par l'eau douce en quelques heures et se maintiendront à l'état saumâtre jusqu'à ce que la glace de la côte se rompe en juillet. En eau libre, les courants saisonniers sont contrôlés par les vents et les eaux des lagunes sont généralement bien mélangées. Les vents dominants du Nord-Est produisent des courants en direction de l'Ouest d'une vitesse égale à 3 % de celle du vent.

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INTRODUCTION

Since the first discovery of oil near Prudhoe Bay, Alaska in 1969 this part of the coast of the Arctic ocean has been the site of intense development. Further exploration has centered around the Prudhoe Bay region and since 1974 a program of research has moved onto the nearby continental shelf. The studies aimed at identifying the potential environmental impacts of oil development have been supported by the United States Bureau of Land Management (BLM) and the National Oceanic and Atmospheric Administration (NOAA) under the Outer Continental Shelf Environmental Assessment Program (OCSEAP). This paper presents some of the physical oceanographic aspects of the OCSEAP studies in a first attempt to examine the seasonal circulation.

The location of the studies is shown in Figure 1. Though the study area is only a small part of the Arctic Coast of Alaska it is believed that this region is representative of the entire coastline. The region has a flat tundra plain ending in low cliffs of about 1 m height. The broad continental shelf has several groups of barrier islands which form lagoons of 3-5 m depth and 2-10 km in width. The sea is ice covered for 9 months. The seasonal ice cover and the mean position of the arctic ice pack are shown as shaded areas in Figure 1. The whole region is underlain by permafrost which is retreating under the sea-covered region. River runoff is low and occurs only during the 3-month summer season. It is during this summer season that storms attack the melting permafrost cliffs resulting in a mean annual coastal retreat of 1.4 m (Dygas, Burrell, 1976) although rates of 40 m have been documented for a single event (Short, 1973). These storms result in surges of 1-5 m height with flooding up to 1 km inland (Reimnitz, Maurer, 1979).

Mean tidal range is only 10-15 cm along the Alaskan Arctic Coast (Matthews, 1981 *b*).

When the proposed oil lease development areas were announced very little was known about the region. In the first two-year research program a carefully focused study was clearly needed. I have described elsewhere (Matthews, 1980) the ecological process study whereby only processes likely to be impacted by oil and gas development were studied. A comprehensive program of studies was developed for Simpson Lagoon using ecosystem process modelling as a tool for guiding the field program to make observations of important processes. The project was unique in the United States in that the project used a computer model to test the hypotheses and identify data gaps. Thus research priorities could shift at the twice-yearly multi-disciplinary modelling workshops. Full details of this study have now been published as a final report (Johnson, Richardson, 1981).

It was determined that birds and fish were the only important species likely to suffer impact. During the early spring and summer the coastal lagoons are used as breeding, feeding and moulting areas by large populations of eider and old squaw. Arctic char and cisco are commercially fished in the region and migrate through the protected lagoons.

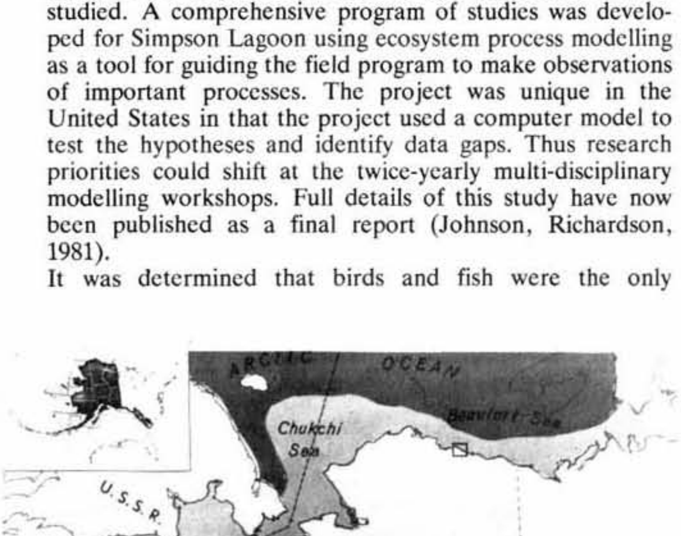

Figure 1

Location map of the study area showing seasonal sea ice (lightly shaded) and the mean position of the arctic pack ice (dark shading).

The physical conditions, salinity, temperature, current structure and sediment load, are important to understanding this ecosystem process. Initial work concentrated on the open water season since this is the time when the birds and fish are present. Examples will be taken from the lagoon systems from Simpson Lagoon in the west to Stefansson Sound in the east (Fig. 2).

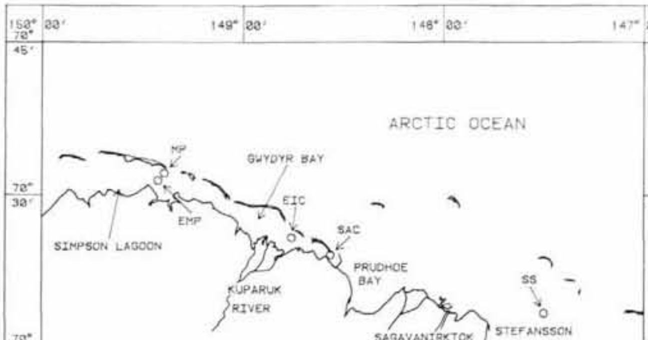

Figure 2

Beaufort sea lagoons showing station locations.

SUMMER ; OPEN WATER SEASON

East Milne Point (EMP ; Fig. 2) is a typical station in Simpson Lagoon. Figure 3 shows salinity, temperature, current vector and sea level during July and August 1978. Salinity is generally less than 30 ‰ having periods of brackish water with salinity less than 20 ‰. The fresher water masses are associated with higher temperatures (> 7 °C). The 24-hour solar insolation at this time leads to very warm temperatures on land. This leads to a strong sea breeze effect (Kozo, 1979) and relatively warm river water. The sea-breeze driven currents can be seen very clearly on the current record for the first few days in August. Note that on 10 August the salinity increased as the temperature fell. This is associated with a period of winds from the east. Currents of 25 cm/sec. or more flowed towards the southwest (Fig. 3) and at the same time sea levels fell by about 40 cm. These onshore currents continued for about 10 days.

Thus, Figure 3 illustrates typical summer conditions. Warm brackish water derived from river runoff and arctic surface waters occupies the lagoons. Currents during non storm periods are on and off shore resulting from a strong sea breeze regime. Storms passing through the region produce strong easterly or westerly wind-driven currents which mask the sea breeze effects. The prevailing winds are from the east resulting in a mean longshore westward flowing current. It is during storms that the bulk of the annual coastal erosion occurs.

The prevailing westerly currents carry river water along the shore. Matthews (1980) traced a bolus of water from the Sag River through Prudhoe Bay and into Gwydyr Bay by using current meters and infra-red satellite photographs. Figure 4 shows this bolus of water as it moved past a current meter, SAC in Figure 3, at 60 cm depth in 120 cm water. The front between the two water masses is very sharp as shown by the

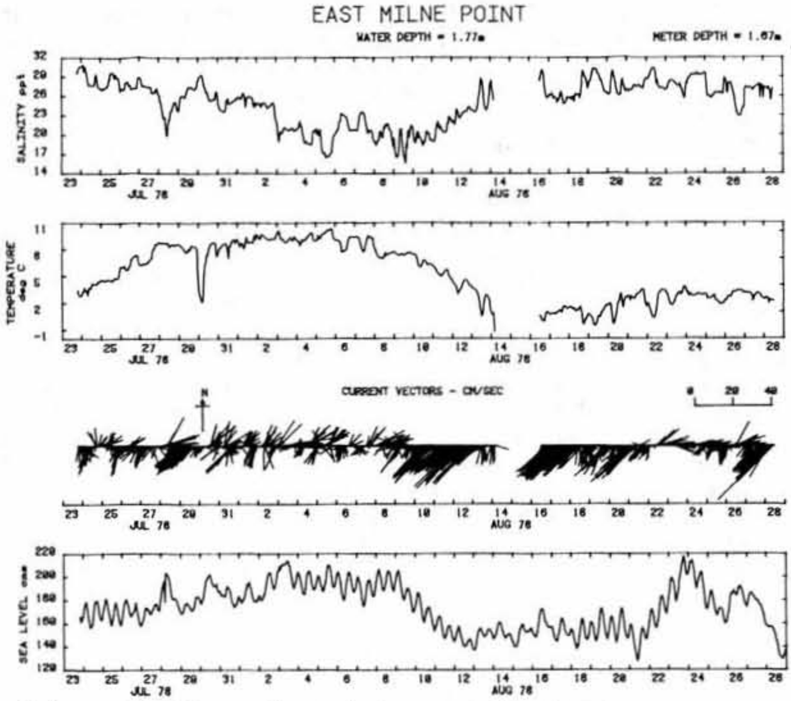

Figure 3

◀ *Salinity, temperature, current vectors and sea level for East Milne Point (EMP), 23 July-28 August 1978.*

salinity profile. The steady southerly current flow into the entrance (SAC) of Gwydyr Bay is shown in Figure 4.

These boluses of warm, brackish water are believed to be important for anadromous fish migrating along the coast between rivers and lagoons (Johnson, Richardson, 1981). The strong westward currents which are a feature of the coastal flow lead to the concentration of brackish water closes to the coast.

During periods of strong winds such as in mid August 1978 (Fig. 3) the water in the lagoons travels rapidly (30 cm/sec.) through the lagoons towards the west. This could be important for the movement of any oil spilled during

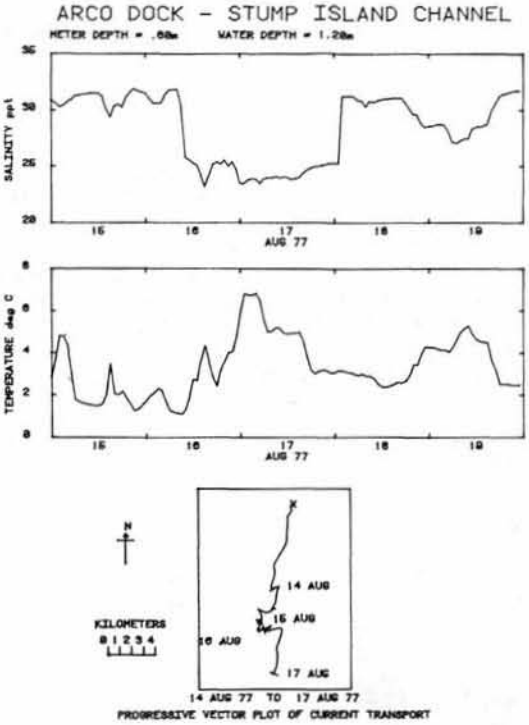

Figure 4 ▲

Salinity, temperature and progressive current vectors in the Arco Dock — Stump Island Channel (SAC) entrance to Gyrdyr Bay, 15-19 July 1977.

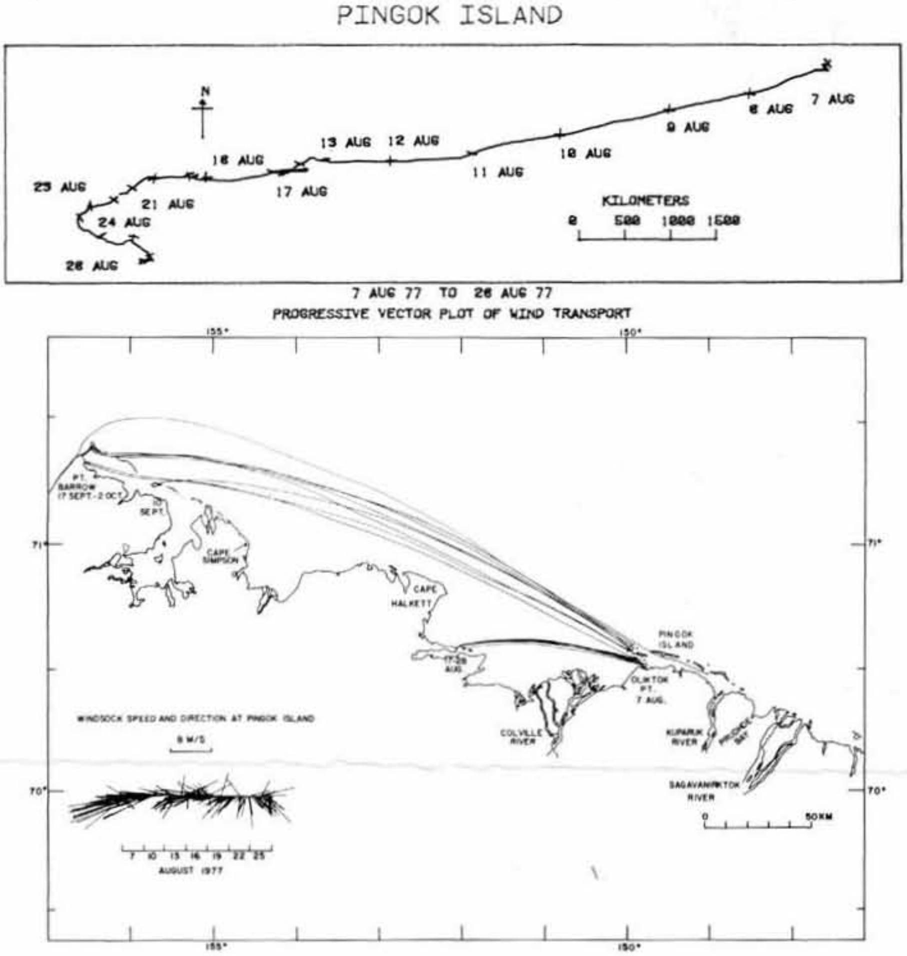

Figure 5

Idealized surface drifter trajectories and progressive wind vector plot August 1977.

development of the oil field. Surface drifters released in Simpson Lagoon in early August 1977 had reached Point Barrow 300 km to the west by early September (Fig. 5). Matthews (1981 *a*) showed that these drifter movements were consistent with a surface drift of 3 % of the wind speed in the same direction. Clearly, spilled oil could have a major impact along the entire coastline during the open water season.

FREEZE-UP

No data are available for the period of ice formation during September. By the end of August the salinity rises towards 30 ‰ and the temperature falls towards 0 °C (Fig. 3). Ice is seen to form skim ice in early September which can result in a fast ice cover if cold, calm weather predominates. Stormy conditions during freeze up can result in the break-up of skim ice and the driving of arctic pack ice onto the outer shores of barrier islands. These storms are thought to be responsible for sediment laden ice formation (Barnes, Fox, 1979), as reported below. The period between September and November is a clear data gap in the physical oceanographic field at the present.

WINTER

By mid-November the ice on the lagoons reaches 50 cm thickness. This is sufficient to bear the weight of a helicopter. We have developed modular current meter moorings to allow easy deployment through the ice of helicopter-borne equipment. A typical deployment through the ice of Stefansson Sound (SS in Fig. 2) is shown in Figure 6. Surface temperatures can be − 20 °C with 10 m/sec. winds which requires protective covering for personnel and equipment. Moreover there are only about 4 hours daylight giving only a short time on the ice. From late November to early February the sun does not rise above the horizon.

The schematic (fig. 7) shows the instrument array below the ice surface. Data from the lower instrument are shown in Figure 8. The salinity increases fairly steadily throughout the record from 32.5 ‰ to 34.5 ‰ at a rate of about 0.04 ‰ per day. This is consistent with ice growth at the rate of 1 cm per day (Matthews, 1981 *b*). The temperature falls from − 1.9 to − 2.0 °C and is very close to the freezing point for the salinity. Sea level shows a sea level range of 150 cm which is an order of magnitude greater than the mean tidal range of 15 cm.

Perhaps the most striking feature of the record is the current vectors. The currents have a mean value of 0.9 cm/sec. at 50° true. This direction is directly off-shore. Similar results were shown on the upper meter. This suggested a two-layer

Figure 6

Deployment of current meters and tide gauge from fast ice in Stefansson Sound (SS) in November 1978.

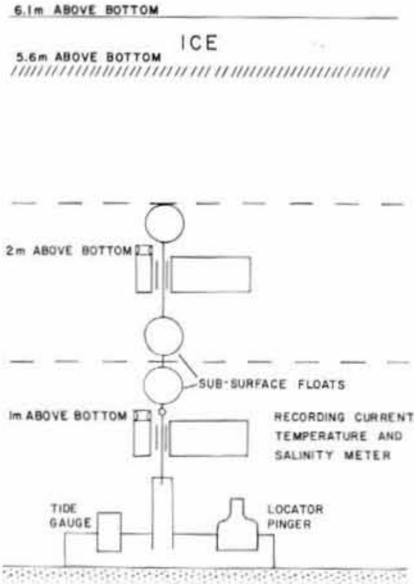

Figure 7

Schematic diagram of instrument array in Stefansson Sound.

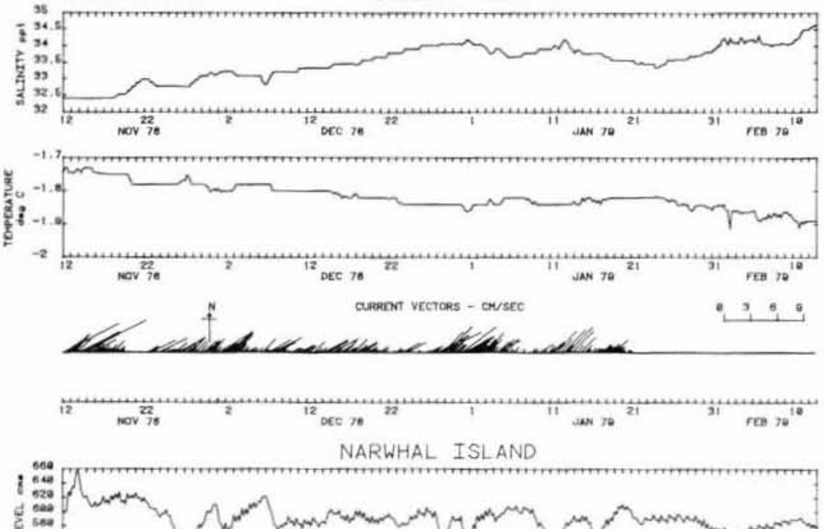

Figure 8

Salinity, temperature, current vectors and sea level, November 1978 to February 1979, in Stefansson Sound (SS).

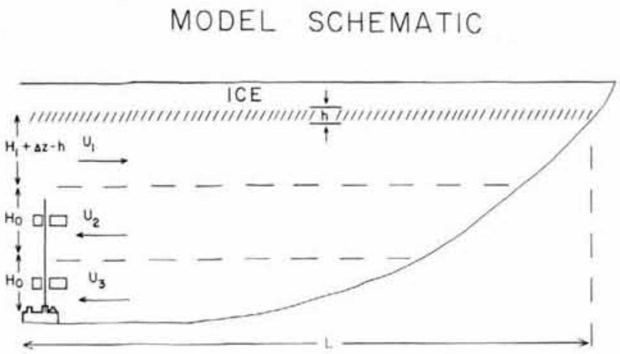

Figure 9

Model schematic for under ice brine drainage.

circulation due to brine drainage ; a saline, seaward-moving lower layer with a return, landward current under the ice (Matthews, 1981 *b*). Figure 9 taken from the paper cited illustrates the brine drainage model. Currents observed on the instruments U_2 and U_3 were used in the continuity equation to derive the return current (Fig. 10). The currents show tidally dominated pulses of offshore currents up to 10 cm/sec. with return currents in the upper layer up to 20 cm/sec. The larger currents are associated with changes in sea level resulting from storm surges. Mean currents observed were 1-2 cm/sec. and computed currents in the upper layer 5 cm/sec.

These are only the first measurements of currents under ice in the Arctic Lagoon. However, they are more important than originally was believed. In the deeper lagoons (> 3 m) where ice does not extend to the bottom, there is a permanent flora and fauna. In Stefansson Sound a boulder patch supporting a population of Laminaria was the scene of much research. Dunton (1980, pers. comm.) has shown that these laminaria grow during the winter when the insolation is zero. They serve as a substrate for several species of fish which deposit their eggs on the kelp fronds. Clearly drilling muds or spilled oil could be a serious impact on these active communities in winter. Moreover recent work by Payne (1981) has shown that Prudhoe Bay crude spilled in winter does not evaporate higher aromatics as it does in warmer waters. These and other fractions dissolve in the water column and could pose a serious threat to benthic organisms as well as resident pelagic species. This is another area which needs further study to clarify the important processes.

BREAKUP

By April or May the ice has reached a thickness of 2 m. The shallow lagoons are frozen to the bottom. Salinities in isolated pockets in these lagoons can reach very high values (> 100 ‰) (Schell, 1974). Figure 11 shows the area of Gwydyr at the mouth of the Kuparuk River. The entire bay except for the Egg Island Channel is frozen to the bottom in late spring.

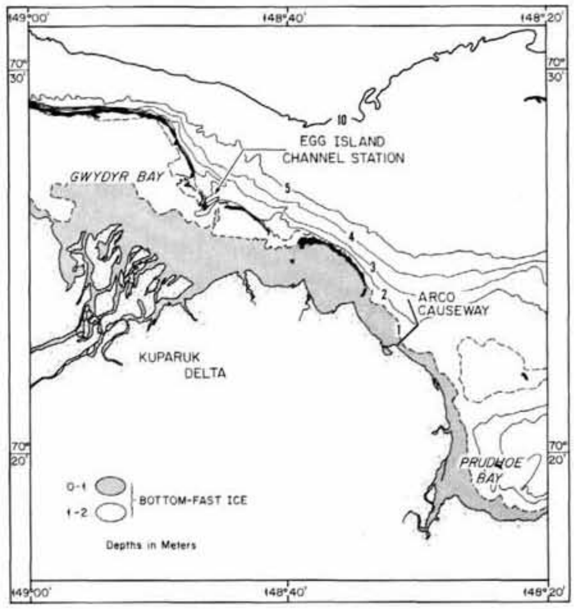

Figure 11

Gwydyr Bay and Egg Island Channel showing shorefast ice regions.

A block of ice was taken from Egg Island Channel in May 1978 (EIC in Fig. 2). The upper half of the ice contains a heavy sediment load. It is believed that this results from sediment suspended during a September storm during which ice was forming (Barnes, Fox, 1979). This extensive sediment load can clearly have consequences for epontic algae under the ice.

In late May and early June, the 24-hour solar insolation results in the melting of snow on the arctic tundra. The arctic rivers produce 80 % of their annual flow in a 10-day

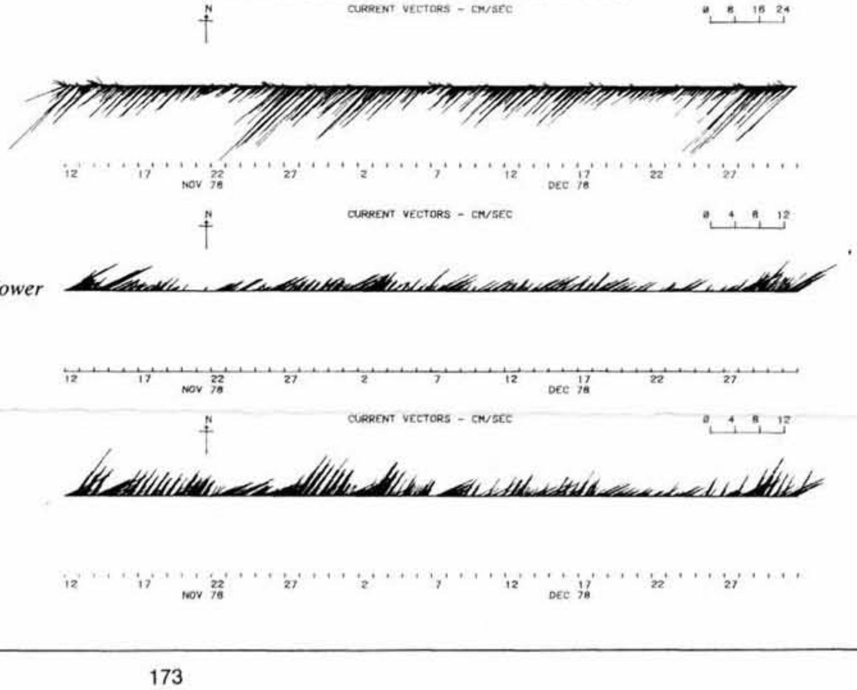

Figure 10

Computed upper layers current vectors and observed lower layers' current vectors in Stefansson Sound.

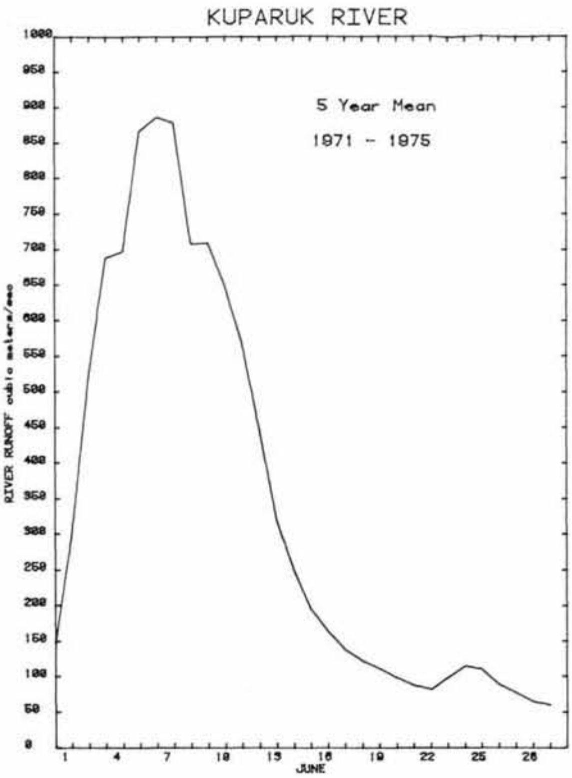

Figure 12
5-year mean river runoff, Kuparuk River.

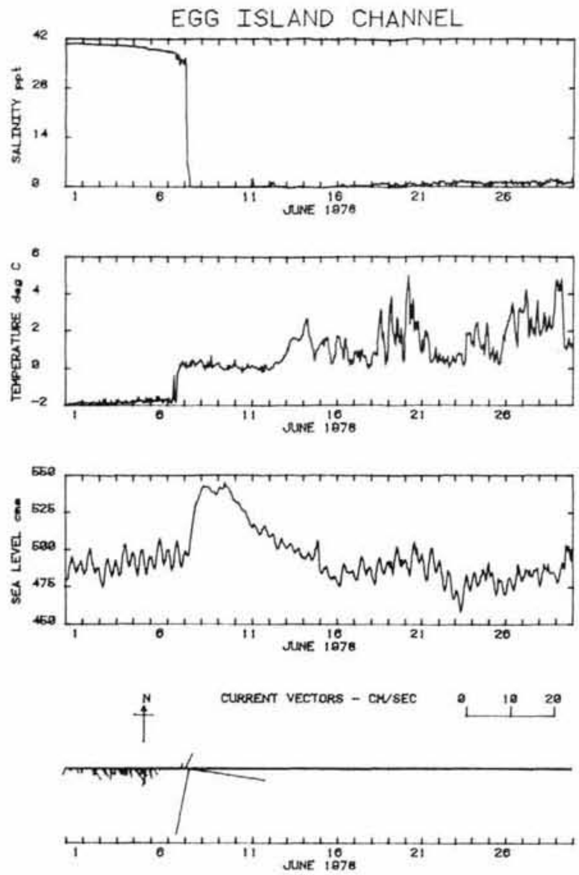

Figure 13
Salinity, temperature current vectors and sea level in Egg Island Channel (EIC), June 1978.

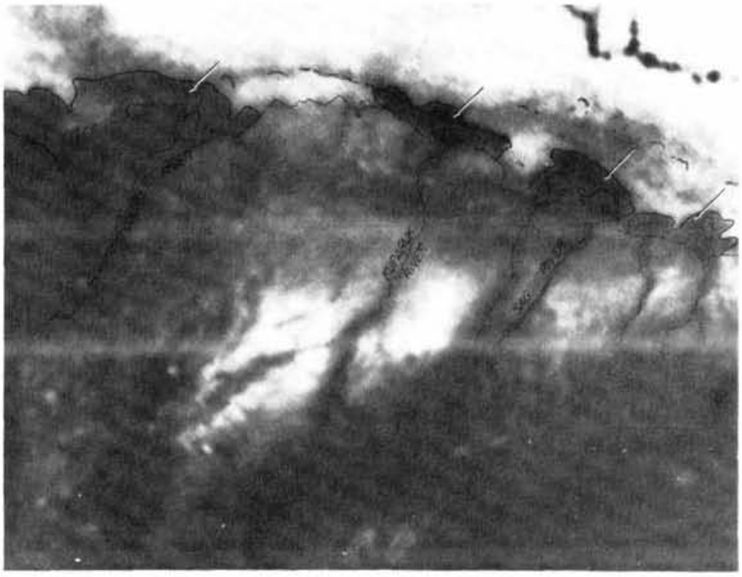

Figure 14
Satellite view of Beaufort Sea Coast at 0645 hours local time 15 August 1977 showing coastal rivers overflowing landfast ice.

period in early June (Carlson, 1977). Figure 12 shows the mean river runoff for the Kuparuk River over a 5 year period 1971-1975. Peak flow is remarkably consistent from year-to-year occurring between 5 and 8 June.

A current meter and tide gauge moored in Egg Island Channel yielded data shown in Figure 13. In early June the salinity was over 41 ‰ with the temperature of − 1.9 °C- nearly the freezing temperature. Sea level showed a normal semi-diurnal tide. Currents were sluggish at about 1 cm/sec. or less. On June 7 the sea level began to rise 50 cm above normal, the temperature rose to 0 °C first then the salinity dropped to zero. Currents of 20 cm/sec were measured for a short time. By 13 June the water temperature showed excursions above 0 °C and by 16 June the sea level had fallen to a normal level.

Clearly the Kuparuk River had over-flowed the winter ice and flushed the Egg Island Channel with river water. A visual inspection of the current meter later revealed that a pebble had stopped the rotor from turning. The river water carries a heavy sediment load which shows up on satellite photographs. Figure 14 was taken at 0645 hours local time on 15 June 1977. All the coastal rivers can be seen overflowing the landfast ice. The Kuparuk River covers Gwydyr Bay, the eastern part of Simpson Lagoon and western part of Prudhoe Bay.

The flushing of the Egg Island Channel occurs very rapidly. The salinity change from 40 to 0 ‰ occurred within a 15-minute sampling interval. Species of amphipods which were found in large quantities in Egg Island Channel must be well adapted to these natural rapid salinity and temperature changes.

The fresh water condition continued in Egg Island Channel until 13 July during which temperatures reached a high of 7 °C (Fig. 15). Sea level dropped 35 cm from 10 to 13 July

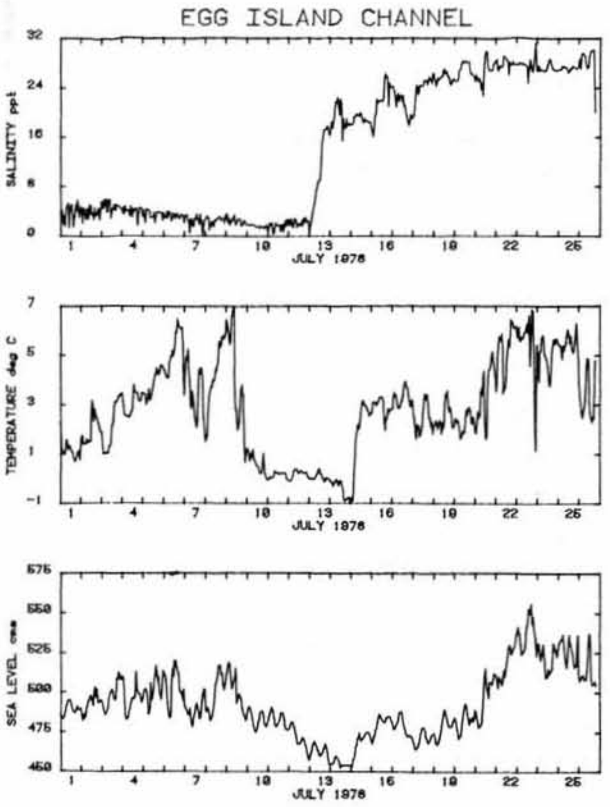

Figure 15

Salinity, temperature and sea level in Egg Island Channel (EIC) in July 1978.

suggesting onshore winds. This is confirmed by the temperature drop and the appearance of oceanic water on 13 July. This is the time that the rotten ice is blown from the lagoons and the current reverses in Egg Island Channel. The channel now acts as a major inlet for ocean water to the Gwydyr Bay — Simpson Lagoon complex.

No data are available for Simpson Lagoon in 1978 but Figure 16 shows temperature, salinity and current vectors in 1979 off Milne Point (MP in Fig. 2) in Simpson Lagoon. Here the lagoon shows high salinity in mid May which falls in late May. This probably results from the influence of the Colville River, the largest in the Alaskan arctic (Carlson, 1977). Temperatures rise in early June and rapidly in mid May which falls in late May. This probably results from the influence of the Colville River, the largest in the Alaskan arctic (Carlson, 1977). Temperatures rise in early June and rapidly in mid July. Large currents (> 30 cm/sec.) begin on 5 July.

This suggests that melting of ice is occurring in June and July. By early July the current meter had melted free of ice. The warm water in mid July is probably water from the Kuparuk River and Gwydyr Bay as Egg Island Channel opens. We anticipate that more saline water would appear in a few days as the ice is carried out of the lagoon.

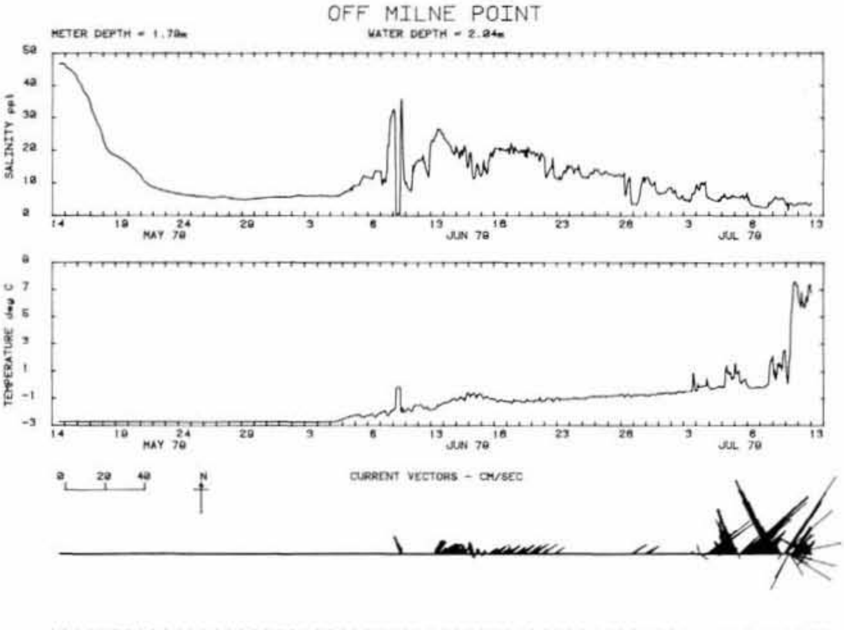

Figure 16

Salinity, temperature and current vectors in Simpson Lagoon off Milne Point (MP), 14 May 1979 to 13 July 1979.

CONCLUSION

Two distinct circulations exist for the ice free and ice-covered periods. In the 3-month open-water season currents are approximately 3 % of the wind-speed and flow predominantly towards the west. Currents in excess of 30 cm/sec. are common and salinity fluctuates from brackish (< 25 ‰) and warm (> 7 °C) to saline (> 25 ‰) and cold (0 °C) oceanic water. By September the salinity exceeds 30 ‰ as freeze-up begins.

By mid-November ice is growing at 1 cm/day and has 50 cm accumulation. Ice growth results in a brine drainage to seaward. Currents are sluggish (1-2 cm/sec.) and salinity increases at 0.04 ‰ per day. By May ice thickness is 2 m and salinities in excess of 40 ‰. In the deeper lagoons there appears to be a two-layer flow induced by brine drainage seawards over the sea floor.

River runoff flushes the lagoons beginning in early June. By mid July the landfast ice is removed from the lagoons and summer circulation is reestablished.

Many details of the seasonal cycle especially during freeze-up and breakup remain to be examined. The lagoons are an interesting and unique environment in which to examine environmental impacts of oil and gas development.

Acknowledgements

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REFERENCES

Barnes P., Fox D., 1979. Sediment-laden first-year sea ice, central Beaufort coast, Alaska, in : *Geological processes and hazards of the Beaufort Sea Shelf and coastal regions,* edited by P. Barnes and E. Reimnitz, Annual Reports of Principal Investigators, National Atmospheric and Oceanic Administration (NOAA), Environmental Research Laboratory (ERL), Boulder, Colorado, Appendix E, 13 p.

Carlson R., 1977. *Effects of seasonability and variability of stream flow on nearshore coastal areas,* Annual Reports of Principal Investigators, Outer Continental Shelf Environmental Assessment Program (OCSEAP), Boulder, Colorado, Vol. XIV, 96-250.

Dygas J. A., Burrell D. C., 1976. *Dynamic sedimentological processes along the Beaufort Sea coast of Alaska, assessment of the arctic marine environment. Selected Topics,* Institute of Marine Science, Univ. Alaska, Fairbanks, 189-203.

Johnson S. R., Richardson J. W., 1981. *Beaufort sea-barrier island-lagoon ecological process studies, final report Simpson Lagoon,* Final Reports of Principal Investigators (P.I.), Research Unit (RU) 467, NOAA, Office of Marine Pollution Assessment (OMPA), Boulder, Colorado, February 1981, 2 Vol. : N° 7, 678 p. and N° 8, 359 p.

Kozo T. L., 1979. Evidence for sea breezes on the Alaskan Beaufort, *Sea Coast. Geophys. Res. Lett.,* **6,** 849-852.

Matthews J. B., 1980. Modelling and verification of circulation in an arctic Barrier Island-lagoon system — an ecosystem process study, in : *Mathematical modelling of estuarine physics,* edited by J. Sundermann and K. P. Holz, Springer-Verlag, New York, 220-231.

Matthews J. B., 1981 *a.* Observations of surface and bottom currents in the Beaufort Sea near Prudhoe Bay, Alaska, *J. Geophys. Res.,* **86,** C7, 6653-6660.

Matthews J. B., 1981 *b.* Observations of under-ice circulation in a shallow lagoon in the Alaskan Beaufort Sea, *Ocean Management,* **6,** 223-234.

Payne J. R., 1981. *Multivariate analysis of petroleum weathering in the marine environment,* Principal Investigators Report, Research Unit 597, Science Applications, 1200 Prospect Street, La Jolla, California, 358 p.

Reimnitz E., Maurer D. K., 1979. Effect of storm surge on the Beaufort Sea coast northern Alaska, *Arctic,* **32,** 229-344.

Schell D., 1974. Seasonal variation in the nutrient chemistry and conservative constituents in coastal Alaskan Beaufort Sea waters. Chapter 7, in : *Environmental studies of an arctic estuarine system,* Institute of Marine Science, Univ. Alaska, Fairbanks, Rep. R74-1, 233 p.

Short A. D., 1973. Beach dynamics and nearshore morphology of the Alaskan Arctic coast, *Ph. D. Thesis, Louisiana State Univ.*