YUKON DELTA OCEANOGRAPHY AND METEOROLOGY

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Final Report
Outer Continental Shelf Environmental Assessment Program
Research Unit 519

1983

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The Yukon River discharges 1,000,000 f^3s^{-1} of fresh water during its peak flow in late spring through 12 active delta distributaries (Dupré, 1977) and a number of sloughs shown as unconnected streams in Fig. 1. The sloughs between the north fork (A) and the ❑iddle fork (C) are shown to be disconnected by late July in Fig. 2. The mouths of each distributary and slough (during peak flow periods especially) behave as estuaries since they connect to the open sea and sea water is measurably diluted by freshwater derived from land drainage (Jones and Kirchoff, 1978). Excluding the ice dominated season (Fig. 3), the mouths of main distributaries are river controlled estuaries by late May of each year with circulation and stratification patterns primarily determined by the rate at which river water is being added at their heads. Seasonal variations in response to their runoff cycles can be observed; and from early August to early November (Fig. 3) these main distributary estuaries are controlled by a combination of storm tides, astromonical tides and river runoff. Slough mouths, however, undergo a transition from river control in May to tide control in late summer. Evidence for these transitions (Jones and Kirchhoff, 1978) is the relatively clear waters off the sloughs in August (Fig. 4) indicating little upstream input of sediment-laden fresh water and lack of connection to the major distributaries. Opaque sediment-laden water was seen off Apoon (A), Kawanak (C) and Kwikluak (B) mouths (Fig. 1), which are the end points of the major distributaries.

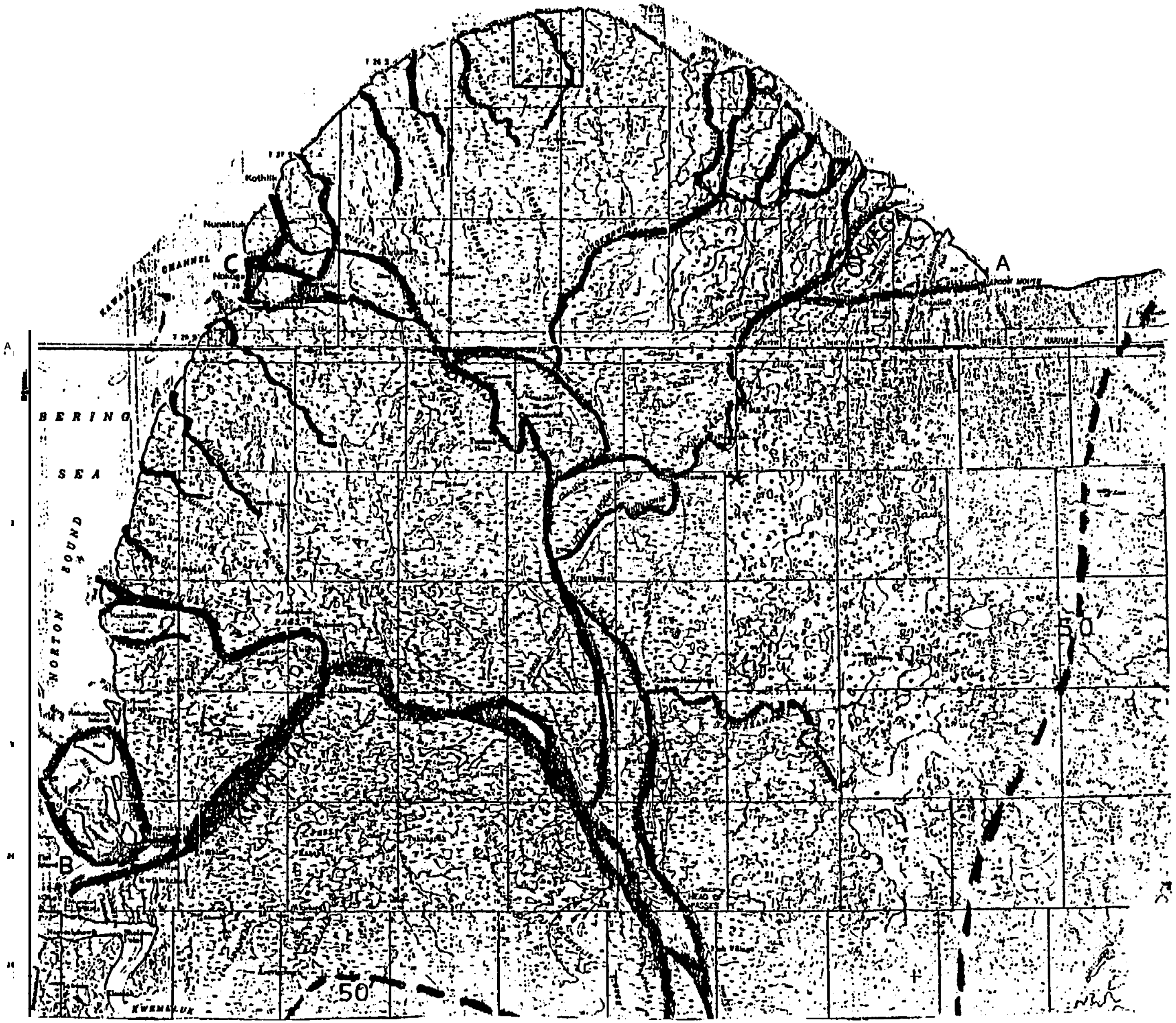

Figure 1. Yukon River distributaries **and** sloughs with approximate 50′ elevation contour.

YUKON RIVER DELTA PHOTOGRAPHED IN SUMMER (July 22, 1975).
(Delta area from Stuart Island to South Mouth of Yukon River.)

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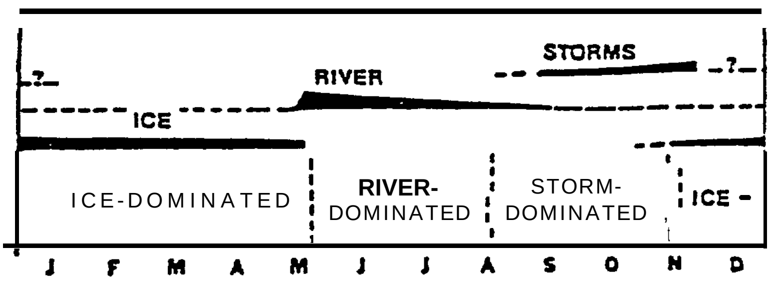

Figure 3. Seasonal variability of coastal processes in **the** Yukon **Delta** region of Norton Sound (from **Dupré** and Thompson, 1979) .

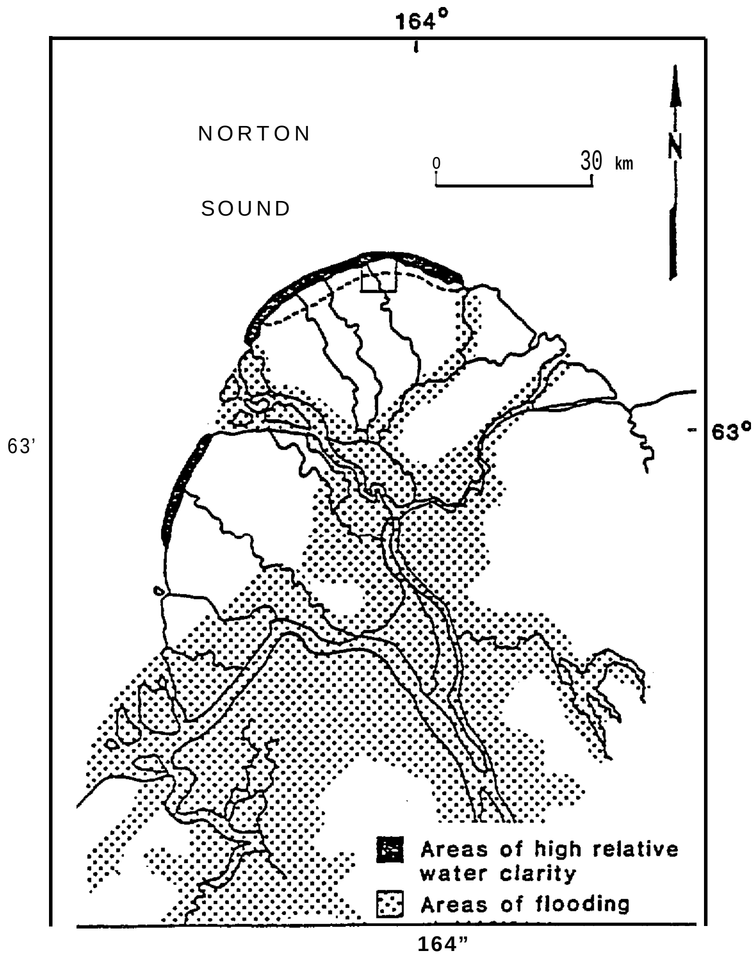

Figure 4. The Yukon Delta showing **interdistributary** clear **waters** and extent of storm surge flooding (Jones and **Kirchhoff,** 1978).

A. **Sloughs**

Using limited data (Jones and Kirchhoff, 1978) an attempt to predict the upstream extent of oceanic salt intrusions **in** sloughs has been made. The mouth of Uwik slough (enclosed in rectangle, top of Fig. 1) had a salinity of 4 $^0/_{00}$, and 12 km inland, it showed "barely a trace" of salt at high tide. Its depth ranged from 3 ❑ at the mouth to .38 m at its head (more than 24 km inland). The tidal range is ~ 1 m and of the mixed (mainly diurnal) type (NOS chart, 16240 Rev. May 1982, and Defant, 1960). Silvester (1974) has devised a mathematical technique to estimate tidally driven salt intrusion distances upstream as follows (see Fig. 5):

$$D \equiv \text{Eddy Diffusion Coefficient} = (x'V_r/2)/\ln(\bar{s}/s_o) \quad (1)$$

Where $V_r \equiv$ mean river velocity

$s_o \equiv$ salinity of source (coastal water)

$s \equiv$ salinity of river mouth during low water slack

$x' \equiv$ distance offshore of source salinity at low tide (its most seaward position)

$$x' = \frac{T\sqrt{gd}}{2\pi}\,[1 - \cos(2\pi t/T] \quad (2)$$

Where T ≡ period of tide ~ (86,4000 seconds for diurnal period)

$g \equiv$ acceleration of gravity = 9.8 ins^{-2}

$t \equiv$ time of tidal cycle in seconds

$d \equiv$ depth of river or slough

$L_{lws} \equiv$ length of intrusion of water with salinity s′ at low water slack tide (lws)

$$L_{lws} \equiv x' \left(K\sqrt{D/V_r x'} - 1\right) \qquad (3)$$

Note: K = 3 for $\frac{s^1}{s^*}$ = .01 (1 % of source)

At high water slack tide (hws) the bulk of water of given salt concentration is forced upstream a length L_{hws} by the amount of tidal excursion (H). According to Ippen (1966):

$$L_{hws} - L_{lws} = \left(\frac{T\sqrt{gd}}{2\pi} - L_{lws}\right)(1-\exp[-H/d])$$

Note: This equation does not include frictional effects and assumes H/d < 1.

Since V_r has not been measured, we make assumptions that the slough is comected to the distributaries in August to arrive at an upper bound value. The Yukon River flow in August is ~ 400,000 f^3s^{-1} (Carlson, 1977). Dividing this flow rate by 2 allows for shunting (electrical analog) water to the south mouth (A) and the middle (C) and north (A) mouths combined (Fig. 1). Dividing the resultant half flow rate by 3 allows for shunting water to the 3 main distributaries between the north and middle mouths. If the four sloughs to the northwest of the Okshokwewhik distributary are connected to it and it branches off to feed 5 minor distributaries to the northeast (Fig. 1) we must divide its flow rate by (4 •2)8. This gives an approximate river flow rate for Uwik Slough (rectangle, Fig. 1) of 8333 f^3s^{-1} or 236.1 m^3s^{-1}. An idealized rectangular river of 250 m •3m cross section (N.O.S. chart, 16240, and Jones and Kirchoff, 1978) would have a river current (V_r) of ~ .3 ins-l (computed from flow rate divided by cross section). If we assume that the salinity of 4°/00 is reduced to 2°/00 during low water slack at the Uwik Slough mouth and it goes back up to 4°/00 1 hour later, equation (2) can be written:

$$x' = \frac{86400\sqrt{9.8 \cdot 3}}{2\pi} (1-\cos[360 \cdot 1/24])$$

$x' = 2.535 \cdot 10^3 m$ seaward of the mouth

From equation (1)

$$D = \frac{-.3}{2} (2535)/\ln(.5)$$

Where $V_r = -.3$ (due to negative direction, Fig. 5)
$D = 548.6\ m^2s^{-1}$

Inserting these results into (3) and solving for the distance where the salinity is .01 so

$$'_{lWS} = 2535(3\sqrt{548.6/.3(23535)} - 1)$$

$= 3.924 \cdot 10^3 m$ at low water slack
(rein distance upstream)

Using equation (4)

$$L_{hws} - L_{lws} = (74560 - 3924)[1-\exp(-1/3)]$$

$$= 20.023 \cdot 10^3 m$$

or $L_{hws} = 23.947 \cdot 10^3 m$ inshore from the mouth for a salinity of $\frac{s_o}{100}$ or .04%

Since a salinity of $.04°/_{oo}$ can be considered "barely a trace" (Jones and Kirchoff, 1978) and the calculated ~ 24 km distance inshore doesn't include frictional effects and actual depth changes, it is apparent that Silvester's techniques (above) can be used for ❑ odelling salinity intrusion distances in sloughs.

B. Major Distributaries

The first major distributary, Okwega Pass (counter clockwise from A, Fig. 1), has its bottom depths recorded (N.O.S. Chart, 16240, rev. May 1982) and averages at least 6 m depth from its mouth to Hamilton (* on Fig. 1). At Hamilton, a distance of ~ 50 km, saline water has been found underlying the surface freshwater (Norton Sound, E.I.S., 1982) as in Part A above, the August total Yukon flow rate of 400,000 f^3s^{-1} is divided in 2 at the first major bifurcation. The next 3 major shunts divide it by 3. Finally the Apoon mouth distributary and the Okwega Pass distributary act to divide the flow by at least 2. Therefore 400,000/12 yields a flow rate of 33333 f^3s^{-1} or 945 m^3s^{-1} at the mouth of Okwega Pass. An idealized rectangular river of $1.5 \cdot 10^3$ m $\cdot 6$ m (N.O.S. Chart 16240) cross section results in an estimated river current (V_r) of $[945/(1.5 \cdot 10^3 \cdot 6)] \sim .1$ ins-l.

If we again assume that a recorded salinity of 4°/00 is reduced to 2°/00 during low water slack at the river mouth, and it takes 3 hours to get back to 4°/00 after low water slack (more than 3 times the volume in Part A) Equation (2) can be used as:

$$x' = \frac{86400\sqrt{9.8 \cdot 6}}{2\pi} (1-\cos[360 \cdot 3/24])$$

$$x' = 30.833 \cdot 10^3 \text{ m seaward of the mouth}$$

From equation (1) (V_r expressed as a (-) velocity, Fig. 5)

$$D = \frac{(-.1)}{2} (30833)/\text{in}.5 = 2227.7 \ m^2s^{-1}$$

Inserting these results into (3) and solving for the distance where the salinity is $.01\ s_o$

$$L_{lws} = 30883\ (3\sqrt{2227.7/.1(30883)}-1)$$

$$= 47.805 \cdot 10^3 \text{ m at low water slack}$$

Using equation (4)

$$L_{hws} - L_{lws} = (105444-47805.2)\ (1-\exp[-1/6])$$

$$= 8.849 \cdot 10^3 \text{ m}$$

or $L_{lws} = 56.653 \cdot 10^3$ m inshore from the mouth ($s_o/100 = .04\ ^o/_{oo}$)

It must be noted that any initial salinity s_o can be used. Again, these simple approximations effectively model the salinity intrusion distance upstream.

The Okwega Pass estuary can become predominantly tidally driven by late August. For a tidal range (H) of 1 m, a depth (d) of 6 m and a diffusion coefficient of 2227.7 m^2s^{-1} (above), pollutant concentrations after tidal cycles can be estimated (Silvester, 1974):

$$U \equiv \text{mean tidal current} = \frac{(Hg^{1/2})}{2d^{1/2}}\ \frac{2}{\pi} \qquad (5)$$

$U \equiv \dfrac{1(9.8)^{1/2}}{(6)^{1/2}\pi} = .41\ ms^{-1}$ (4 x the estimated river current from above)

$$C \equiv \text{concentration} = \frac{M}{\rho A(4\pi Dt)^{1/2}}\ \exp[-(x-ut)^2/4Dt]$$

Where M ≡ pollutant mass

A ≡ cross section

e ≡ density of water (ambient fluid)

t ≡ time

Assuming that at the river mouth (x = 0), the concentration of pollutant is well mixed after two tidal cycles (water soluble fraction of an oil spill for example) and is measured, then the concentration one week after the spill can be estimated.

at 2T (tidal cycles)

$$C_1 = \frac{M}{\rho A(4\pi D \cdot 2T)^{\frac{1}{2}}} \{\exp[-(0-.41 \cdot 2T)^2/(4D\cdot 2T)]\}$$

at 7T (one week for diurnal tide)

$$C^* = \frac{M}{\rho A(4\pi D \cdot 7\ T)^{\frac{1}{2}}} \{\exp[-[0-.41 \text{ “} 7T)^2/(4D.7T)]\}$$

or $$C_2/C_1 = \frac{1}{(7/2)^{\frac{1}{2}}} \exp\{[(.41)^2/4D][T(-7+2)]\}$$

inserting $D = 2227.7\ m^2 s^{-1}$ and T = 86400s

$C_2/C_1 =$ .00015 or .015% of the well mixed original concentration.

Assuming that the parameters have been selected properly, a week's time would disperse most pollutants. However, toxicity levels for specific pollutants are not estimated here.

C. <u>Significant Information Needs</u>

Investigators will need to determine the missing parameters indicated in Parts A and B above. These are:

1) Salinities of the distributary and slough mouths at both high and low water slack
2) Salinities of the distributary and slough interiors at both high and low water slack
3) The time for the salinity to reach the high water slack value after low water slack
4) River currents and depths (survey data)
5) Accurate tidal excursions
6) The time of the year when sloughs are effectively disconnected from main distributaries

EFFECTS OF STORMS, WAVES, AND CURRENTS

Though storms may hit the delta in any season, there is an actual storm dominated season existing from August to November (Fig. 3). During this period frequent high speed southwesterly winds with longer fetch distances result in high wave energy particularly on the western side of the delta. In addition, due to wave refraction, wave energy is concentrated by delta formations (Bascom, 1964). This combination of high wave energy and rapidly decreasing sediment discharge from the Yukon causes significant coastal erosion (Dupré and Thompson, 1979).

Though long time series of surface wind data have not been collected in the Yukon Delta area, Kozo (1984) has shown that wind data from Alaskan surface wind stations (Fig. 6) separated by distances less than 200 km

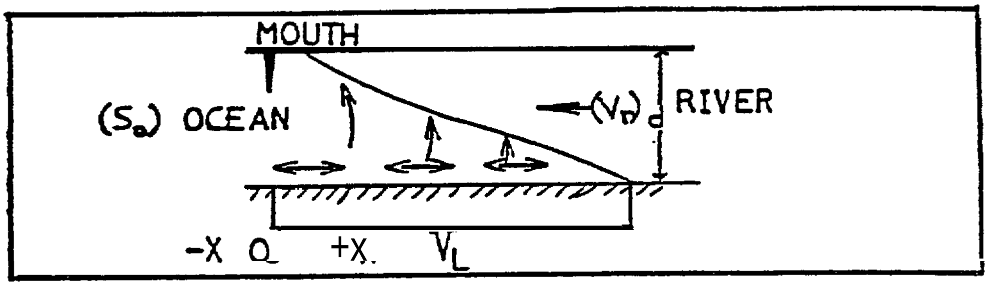

Figure 5. Sketch of interaction of ocean waters and **river** waters at an estuary **mouth** under **tidally induced mixing** V_r ≡ **river** current, so ∿ Salinity **at** high water slack at mouth of estuary.

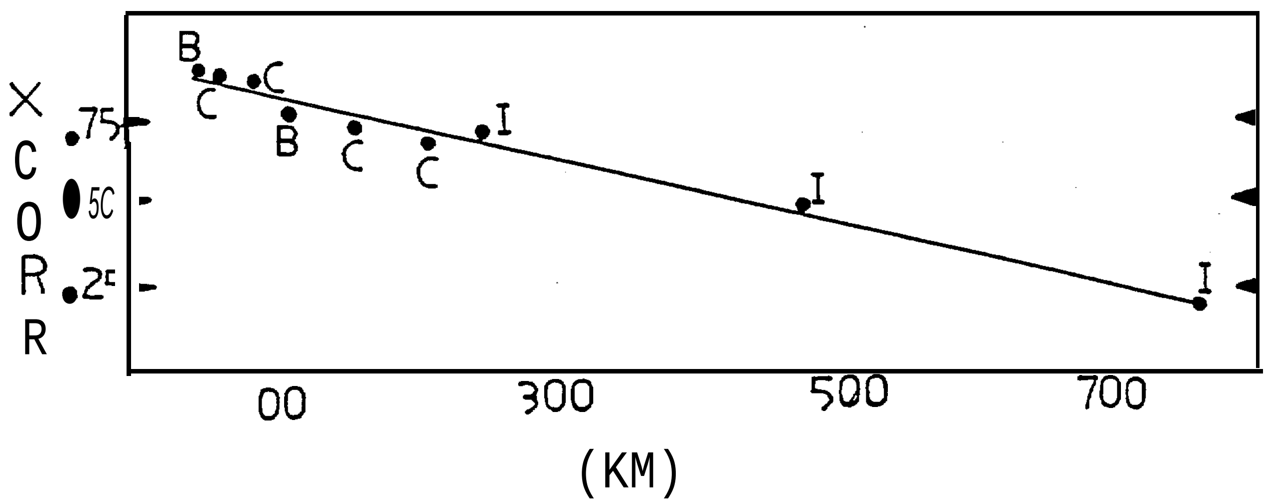

Figure 6. Wind velocity cross correlation values for land wind stations versus distance (km) of separation. B ≡ Beaufort coast, C ≡ **Chukchi** coast, I ≡ Islands **in Bering** Sea.

have cross correlation values of .75 at 0 lag time. This criterion is ❑et by both Unalakleet (~ 170 km from the Yukon Delta) and Cape Romanzof (~ 125 km from the Yukon Delta). They both have orographic wind channeling in the winter months under stable atmospheric conditions but in the summer months when atmospheric stability approaches neutral and synoptic wind conditions promote southwesterly flow, they definitely represent Yukon Delta wind conditions.

A closer examination of the synoptic and mesoscale meteorology shows that the average large scale wind vector switches from the northeast in winter to the southwest for the open water periods of July and August (Brewer *et al.*, 1977). This accomplishes two things since the current flow also has the same general direction (Fig. 7). The first, is that surface contaminants southwest of the Yukon Delta can be pushed by the wind and currents toward shore. At the same time, surface contaminants in the Lease Sale 57 area (Fig. 7, near shaded area in Norton Sound) will be pushed away from the Yukon Delta most likely impacting on the coast to the east of Nome (**, Fig. 7, Samuels and Lanfear, 1981) or moving to the northwest out of Norton Sound under winds and prevailing currents combined. The second, is that the average summer wind field promotes a downwelling and shoreward transport of outershelf water and with concomitant increase in the water level at the coast. This increased water level allows waves which are focused by the delta to push contaminants further inshore.

Summer mesoscale winds, in particular sea breezes, can dominate the local meteorology 25% of the time and reach speeds up to 15 ins-l

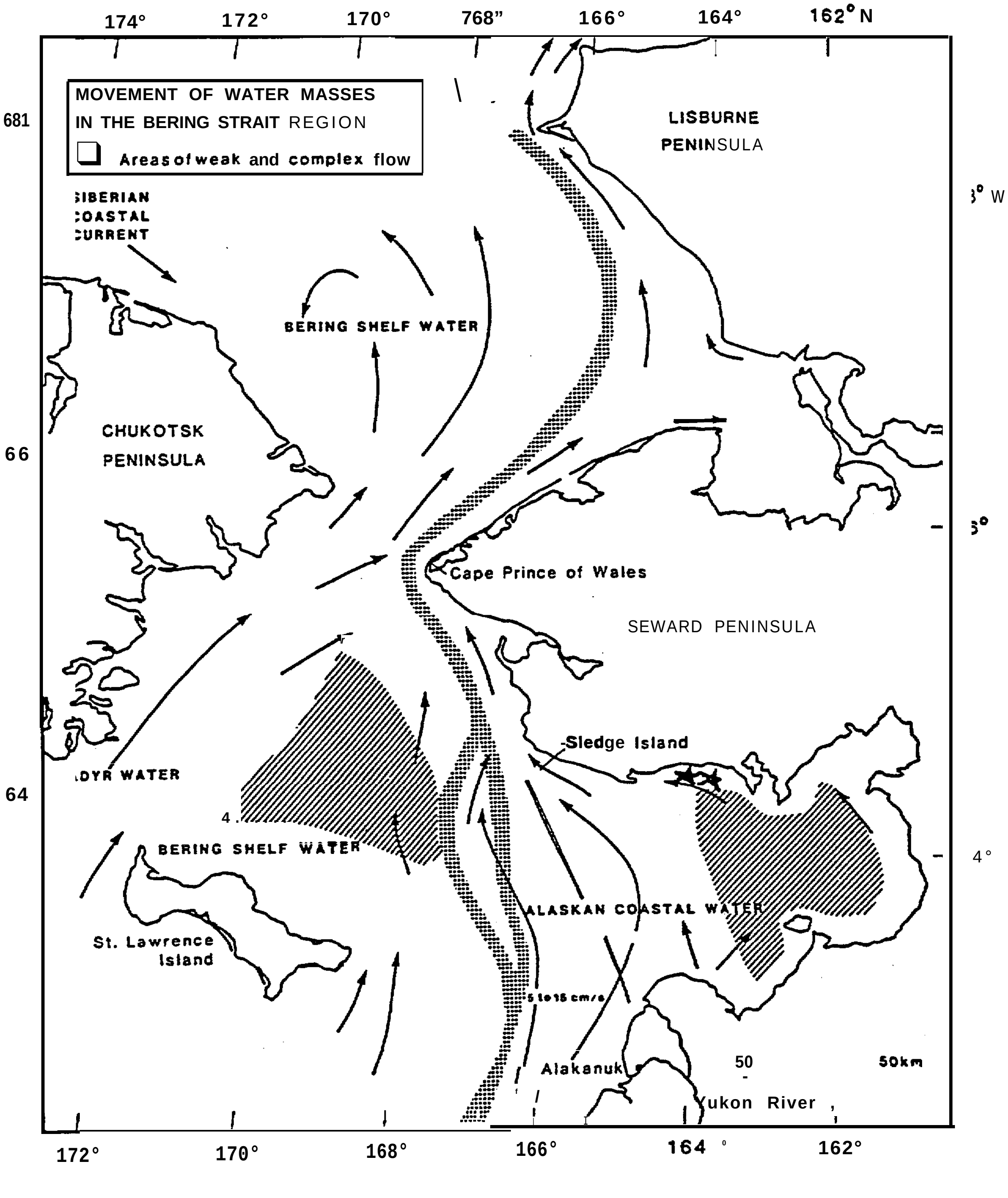

Figure 7. Movement of water masses in the Bering Strait region (Drury *et al.*, 1981).

(Zimmerman, 1982). They also promote a shoreward transport of surface contaminants in a 20 km zone (Fig. 8) seaward of the coast (Kozo, 1982). The convex curvature of the Yukon Delta (opposite to that of a bay) also promotes focusing of thermally driven wind systems (as well as ocean waves, see above) which tend to blow perpendicular to coastlines (McPherson, 1970).

A. Storm Surges

Rises in water level due to strong winds (setup) are of major concern. Abnormal setup in nearshore regions will not only flood low-lying terrain, but provide a base on which high waves can attack the upper part of a beach and penetrate farther inland (U.S. Army Shore Protection Manual, 1977). Accretion and erosion of beach materials, cutting of new inlets through barrier beaches and shoaling of navigational charnels can occur.

The Bering Sea has an average of 3.5 cyclonic events in the 15-20 ins-l range (David Liu, Rand Corporation, pers. comm.). Given the average wind direction, the probability of oceanic and atmospheric events occurring in tandem, and the Yukon Delta geomorphology, it has a high vulnerability to storm surge events. Figure 9 shows the coastline of Alaska divided into 25 coastal sectors (Wise *et al.*, 1981). Sector 10 has limited data to compute surge height-frequency interval curves. Data from Figure 6, however, indicate that the interval curve (Fig. 10) for sector 9 can be applied since wind frequencies are proportional to storm surge heights. It should also be noted that the large percentage of

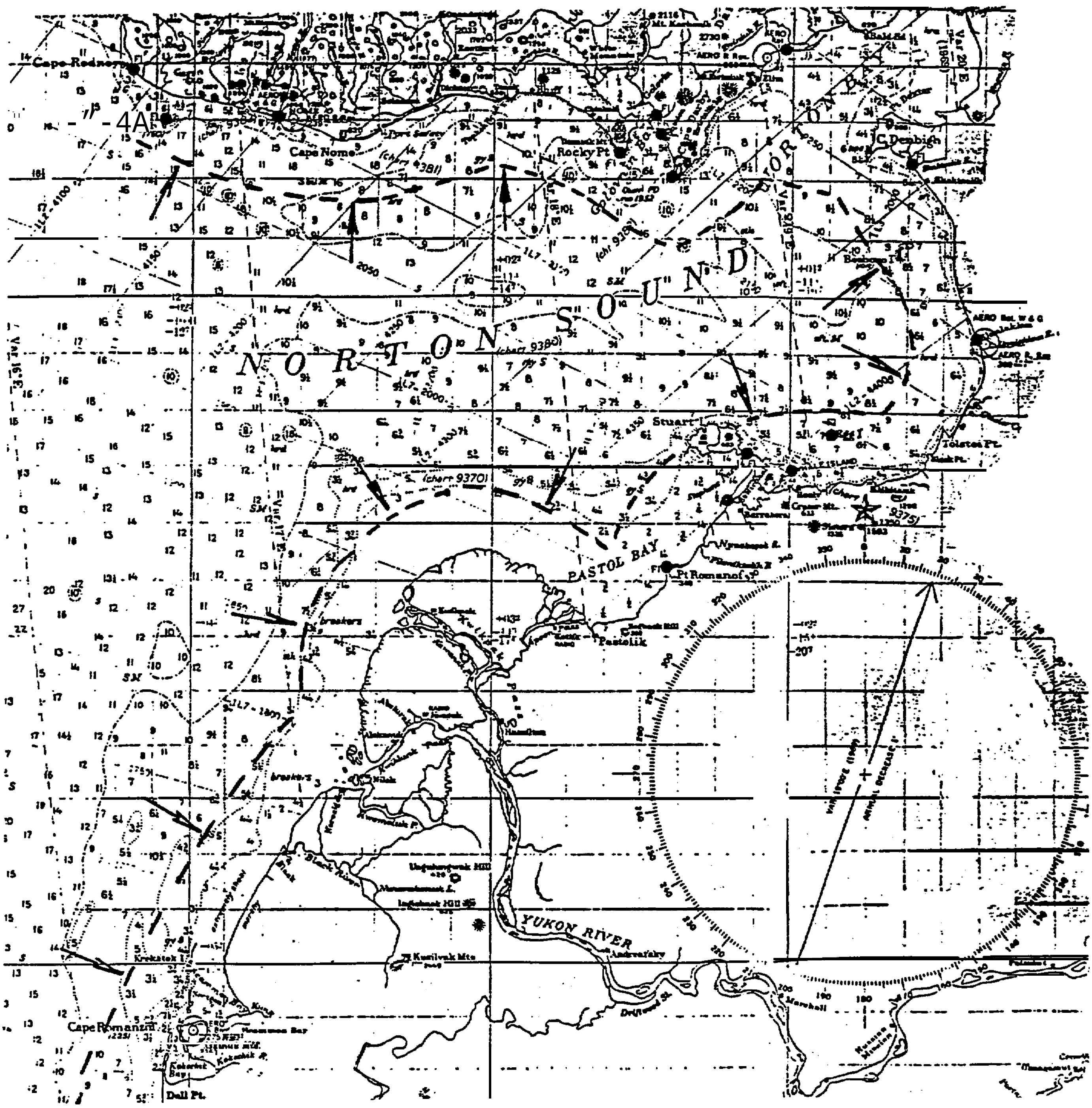

Figure 8. Local winds perpendicular to the shoreline caused by thermal contrast in a 20-km nearshore zone (dashed line). These will dominate when large-scale winds are less than 5 knots (2.5 m/s). Soundings are in fathoms (Coast and Geodetic Survey, 9302, 1968).

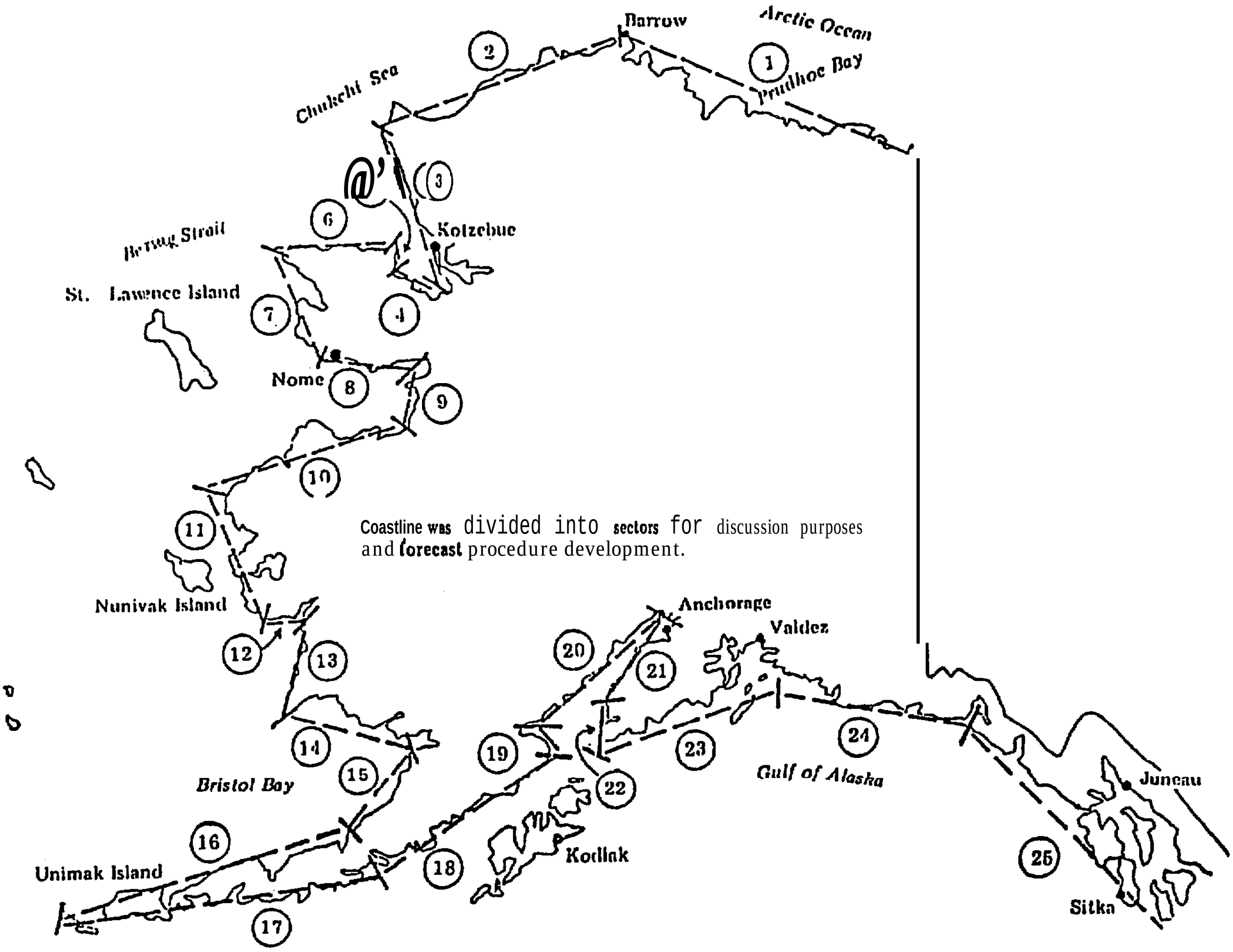

Figure 9. Coastal sectors (Wise *et* al. , 1981).

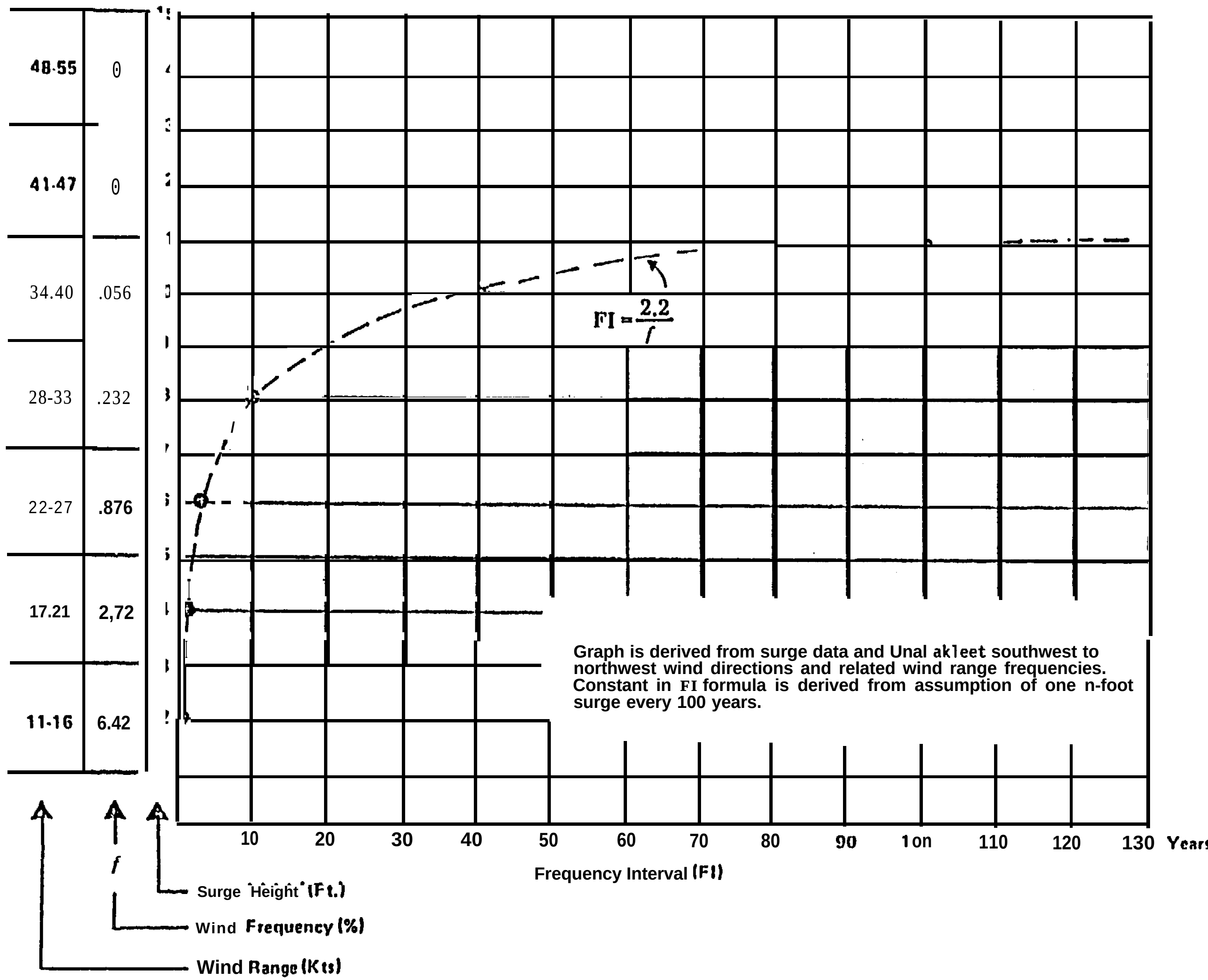

Figure 10. Surge height-frequency interval curve, Sector 9 (Wise *et al.*, 1981).

atypical easterly orographic winds at Unalakleet in winter months are not included in Figure 10 since only winds from the southwest to northwest quadrant are used to construct the curve (favorable fetch directions, Wise *et al.*, 1981).

The proportionality equation is (Wise *et. al.*, 1981):

$$FI = \frac{K}{f}$$

Where FI ≡ frequency interval

f ≡ wind frequencies for a given wind speed class and set of directions

K ≡ constant of proportionality for a given area such as sector 9

A typical storm surge forecast for August can be made using data from storm case histories (Wise *et al.*, 1981) and duration tables (Brewer *et al.*, 1977). Assume a cyclonic gale force wind of 35 knots (17.5 ms-l) from the southwest. The preliminary surge height from Figure 10 is 9 ft (20-year return period). Duration tables (Brewer *et al.*, 1977) show that at least 5% of the August wind events greater than 20 knots last 12 hours. The preliminary surge height must be reduced by 10% to 8.1 for a 12-hour duration (see Appendix A, Part II C). Typical low pressure centers are 970 mb from storm case histories. Appendix A, Part II E, states that the surge height should be raised 1 ft. for every 30 mb increment below 1004 mb. Therefore the surge height must be raised 1.1′ to 9.2′. It will be assumed that high water (astronomical tide) is coincident with the surge so no further corrections are made. This sea level rise (2.8 m) is consistent with actual reports in the area (Zimmerman, 1982).

B. Waves

The above wind speeds and direction, with unlimited fetch for the above duration produce significant wave heights (deep water) of 24 ft (Pierson *et al.*, 1971) as seen on co-cumulative spectra charts for wind speeds as a function of duration. This wave height in shallow water for a 10 sec. period converts to a wave of 30 ft. or 9.1 m (Table Cl, U.S. Army Shore Protection Manual, Vol. 111, 1977). The surge height in A, above, coupled to the shallow water significant wave height totalling 39.2 ft. or 11.9 m shows that 40 km inland penetration in the delta (Zimmerman, 1982) is very possible since the 50′ contour is ~ 100 km inland (Fig. 1 and U.S. Geological Survey charts for Kwigak and St. Michael, Alaska, 1952).

C. Significant Information Needs

Investigators will need to determine missing data histories as indicated in Parts A and B above. These are:

1. Surface winds at the south, middle and north distributary mouths coincident in time with Unalakleet surface wind measurements. Note: This will accomplish two things: first, the applicability of Unalakleet winds to the Delta area (there may still be orographic effects at Unalakleet in the summer); second, wind focusing of the mesoscale sea breeze can be measured at the three mouths.
2. Meteorological and astronomical tides should be measured at the 3 major mouths.

3. Synoptic weather charts should be examined during the experimental season and back in history as a hindcast procedure. In particular the chronologies of previous storm surges recorded in Wise et al. (1981) should be compared to weather charts.

4. Currents and wave lengths should be measured at appropriate coastal locations.

SEA ICE

The sea and river ice dominated season in the Yukon Delta extends from mid-November to mid-May (Fig. 3). It is easily seen as the season of greatest length, but it is also the season where movement of pollutants is most restricted. Positively bouyant oil spills occurring under an ice canopy require current speeds in excess of 20 cm s^{-1} to move against the opposing friction of the ice skeletal layer and in a week's time can become incorporated into the skeletal layer through the winter freezing process. The Norton Sound is well within the 75% probability of sea ice cover from December 1 until May 15 (Figs. 11 and 12) and is considered as an ice factory supplying up to ten times its area of ice to the -Bering Sea (Thomas and Pritchard, 1981). As ice leaves the Sound, it moves either north, following the generally northward moving currents (Fig. 7), or south under the influence of northerly winds. These southward periods could become relevant to Yukon Delta operations.

Though sea ice in Norton Sound is mainly first year (less than 1 m thick), large ice rubble field features have been seen indicating total ridge thicknesses of 24 m caused by ice pile-up (Thomas and Pritchard,

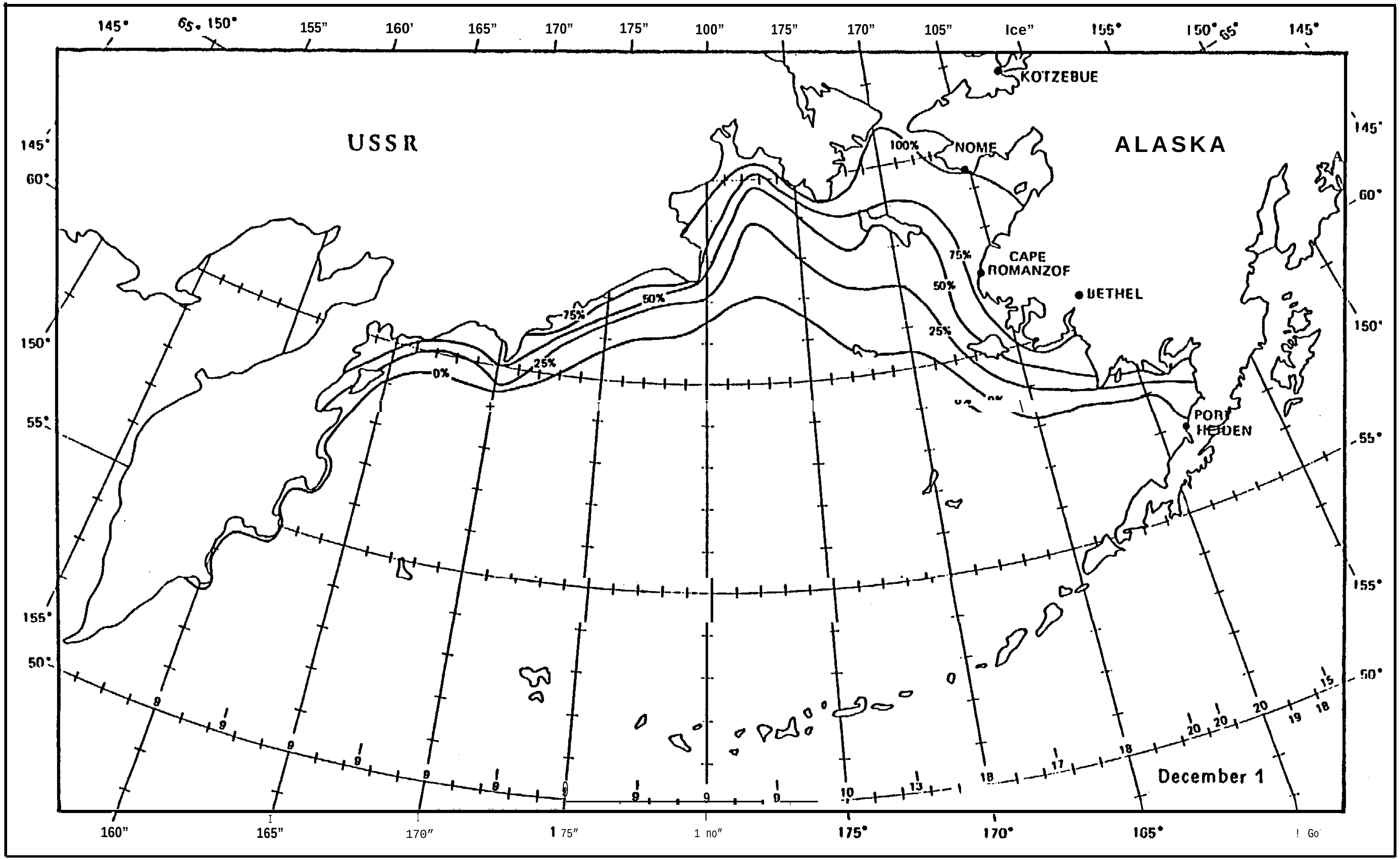

Figure 11. Empirical probabilities of the ice limit for December 1 (Webster, 1981).

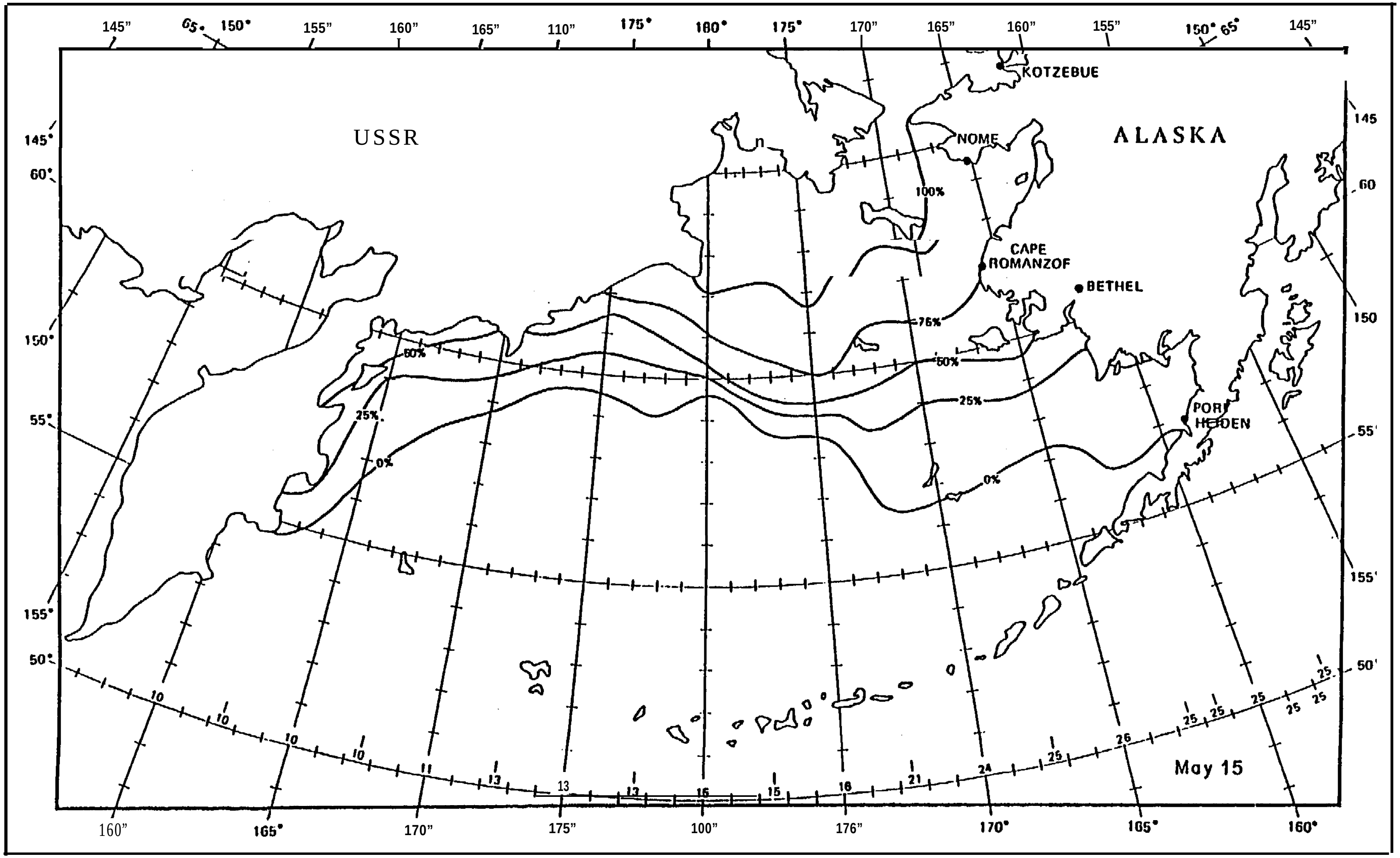

Figure 12. Empirical probabilities of the ice limit for May 17 (Webster, 1981).

1981). The largest concentration of these piles are in shoal areas off the Yukon **Delta.** Periodic strong winds can move these rubble piles seaward *and* they can represent extreme ice hazards to transiting ice breakers which ordinarily cannot crash through ice greater than 4 m thick. Also, if they impinge on drilling structures, the structure will be destroyed. Another source of ice thicker than 1 m is Arctic pack ice (2 to 3 m thick) moving through the Bering Strait from the **Chukchi** Sea after "breakout" periods caused by northerly winds and/or current reversals.

There is a major zone west of the Yukon Delta in water depths of 3 to 14 m characterized **by** periods of ice deformation and accretion during westerly winds and by periods of offshore ice movement and large **polynya** development during easterly winds **(Dupré,** 1980). This area is significant because it is offshore of the south and middle Yukon Delta mouths which have sub-ice channels connected to the **polynya** area. These charnels are considered active during the ice season, from recent **observations (Dupre,** 1980) of suspended sediments.

A. Sub-ice Channels

The sub-ice channels are extensions of the major distributary channels **(Dupré,** 1980) and are most common on the western margin of **the** Delta. Significant amounts of suspended sediments have been measured beneath the ice canopy in the channels in winter **(Dupré,** 1980). The channel geometry is ~ $1.5 \cdot 10^3$ m wide **by** ~ 10 **m** deep and they can extend up to 20 km beyond the shoreline. The flow rate for the Yukon in mid winter is approximately 40,000 f^3s^{-1} or

10% of the August rate (Carlson, 1977). The method of dividing the flow rate by the number of distributaries used in part I (B) above gives a hypothetical distributary current of .02 ins-l (2 ems-l) moving at a depth below the river ice and running into a sub-ice channel. The tidal current can now be estimated in a subsurface channel under a 1 meter tidal excursion. Though the underice channel to the sea is topped by a sea ice lid, a tidal excursion of 1 m can produce a pressure difference which will force sea water and sediment into the channel and shoreward. The situation is approximated as a classical Poiseville flow in a pipe driven by a pressure differential. The equation (6) (Lamb, 1945) is:

$$U = \frac{\Delta p}{4\rho D l}(a^2-r^2) \equiv \text{velocity in the channel} \qquad (6)$$

Where $\Delta p \equiv$ the pressure differential caused by the tidal excursion (H)

$\Delta p \equiv \rho g H$, ρ = density of sea water

$D \equiv$ turbulent diffusion coefficient

$l \equiv$ length of the channel (sub-ice) (taken here as ~ 10km from N.O.S. chart 16240)

$a \equiv$ radius of an equivalent pipe that approximates the channel (since [$1.5 \cdot 10^3$ m $\cdot$ 10 m] = $1.5 \cdot 10^4$ m letting $\pi a^2 = 1.5 \cdot 10^4$ m gives a = 69 m for an equivalent pipe radius)

$r \equiv$ radial length from the center of the pipe (r = 0) to the side (r = a)

$g \equiv$ acceleration of gravity

Using the above information and substituting into (6) we have:

$$U = \frac{9.8 * 1 * (69)^2}{4 \cdot D \cdot 10^4} \quad \text{(at r = 0 center of channel)}$$

D is calculated from the method in Part I using equations (1) and (2) and the .02 ins-l river current estimated above. The time for the salinity offshore at the ice-channel mouth to reach the salinity at high water slack was chosen as ~ ½ hour (less than any other season due to limited volume output). This gives a diffusion coefficient (D) equal to 16.8 m^2s^{-1}, which can be used above to give a U = .07 ins-l within the subice channels. U which depends on D is very speculative but while not moving oil under an ice canopy (less than 20 cms^{-1}) it could move water soluble fractions and some sediment types. Kuenen (1950) shows that a $.07ms^{-1}$ current will transport particles up to .9 mm in diameter which includes muds and fine sand. The motion would be shoreward at high tides and offshore at low tides.

B. Breakup and Freezeup

The breakup period which terminates the ice dominated season signals the beginning period when ice floes containing oil are highly mobile being subject to both winds and currents. Ice in the shore fast ice zone ablates and can also move. River flooding causes freshwater to overflow the shore fast ice areas. A concomitant change in albedo causes increased radiational ablation which together with the above-mentioned mechanical ablation speeds the near shore ice destruction. River sediment can deposit on the ice itself and float beyond the imer shelf. The breakup sequence has a short time scale but it is perhaps the most dynamic part of the year since storm and river influence can also play a role.

The freezeup period is also dynamic since late fall storms may fracture new thin ice and move it out of the area, leading to new manufacture of ice with later small scale winds blowing offshore due to to land breeze effects. Thermohaline ocean circulation will be at its peak nearshore, leading to small scale circulation cells perpendicular to the shelf. The flow will be offshore at depth and onshore under the ice (Kozo, 1983). These density driven flows will be augmented in subice channels which have greater bottom slopes.

C. Significant Information Needs

The freezeup and breakup periods usually have the least amount of available data, both before a study has begun and after several years of study. Since they are so dynamic, they are the most hazardous to men and equipment. Specific needs are:

1. Synoptic atmospheric pressure chart studies during ice "breakout" events (may move *ice* from the Chukchi to the Bering and possibly toward the Yukon Delta) both as an ongoing program and as post analysis combined with satellite imagery.
2. Current, salinity, and temperature measurements in the sub-ice charnels and delta front during the winter months to determine diffusion coefficients and flow directions of sediment.
3. Monitoring the frequency of occurrence of the West Yukon Delta Polynya and thermohaline circulation associated with it.
4. Dumping tracers into the sub-ice channels in winter and monitoring the nearshore distributary bottoms to detect movement of "pollutants" under tidal oscillations.

5. Monitoring currents and sediment transport on top of and below the ice canopy during breakup.
6. Fall freezeup: monitoring currents in existing sub-ice channels before the ice canopy thickens to check for accelerated thermohaline movement due to the greater bottom slopes.

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APPENDIX A

Forecast Procedures (Wise *et al.*, 1981)

I. DEFINITIONS

A. **Surge**

The height of the ocean's surface above forecast (tidal) levels.

B. Favorable Relative Fetch Wind Direction

Assume the coastal configuration to be straight line segments as shown on Figure 9. When facing seaward the *relative* wind direction is measured clockwise **from** the coast. Thus the coast to the left is 0°; seaward +090°; to the right 180°. If to the left and offshore, it has negative values. Favorable relative wind directions are:

Sector	Favorable Direction
1	-020 to 090
2	-020 to 090
3	080 to 140
4	010 to 050
5	-050 to -010
6	040 to 090
7	020 to 090
8	120 to 190
9	030 to 100
10	-020 to 080
11	-020 to 120
12	050 to 150
13	-020 to 090
14	070 to 120
15	010 to 090
16	-020 to 090

In an idealized model the most favorable directions are from -020 to 090 but topography working in conjunction with gravity acting on anomalous sea surface slopes creates surges [generally of lesser magnitude) in areas wherein the wind is not blowing from an idealized "favorable" direction. The favorable directions shown above are those relative directions where the wind creates an anomalous sea height somewhere nearby that, in turn, affects the sector of interest.

C. Fetch

An area in which wind direction and speed are reasonably constant and do not vary past the following units:

1) The wind direction or orientation of the isobars does not change direction at a rate greater than 15° per 180 nmi and the total change does not exceed 30°.

2) The wind speed does not vary more than 20 percent from the average wind speed in the area of the direction fetch being considered. Example: average wind is 40; acceptable range is 32 to 48.

D. Fetch Duration

The number of hours a coastal area is subjected to fetch winds.

E. Lowest Pressure

The lowest pressure coincident with fetch induced surge.

F. Sea Ice Coverage (minimum expected during storm).

Percent of sea ice coverage in tenths.

G. <u>Sea Ice Character</u>

Primary concern is thimess and weakness. Thin or unconsolidated ice can be destroyed by storm action.

H. <u>Boundary Layer Stability</u>

The difference between the sea and air temperatures. The boundary layer temperature difference should be used when estimating the fetch wind speed. The following guidelines are suggested:

Correction to Geostrophic Wind for the Sea-Air Temperature Difference

$T_s - T_a$	Percent of geostrophic winds used
O or negative	60
0 to 10	65
10 to 20	75
20 or above	90

II. PROCEDURE

A. **Determine**

1. Fetch wind (speed, and direction). Consider boundary layer conditions. If direction is favorable continue with determination of:

   a. fetch duration

   b. ice cover

   c. lowest pressure

   d. tidal variation if over 1 foot

B. **Preliminary Surge Height**

Using wind speed, read correlated surge height from appropriate coordinate tables (Fig. 10).

C. Duration Adjusted Surge Height--if fetch duration is less than:

1. 3 hours reduce surge by 60 percent
2. 6 hours reduce surge by 40 percent
3. 9 hours reduce surge by 20 percent
4. 12 hours reduce surge by 10 percent
5. 12+ hours no reduction

D. Ice Cover Adjusted Surge Height--if ice cover is less than:

1. 1.5 tenths no reduction
2. 3.0 tenths reduce surge by 20 percent (cumulative to above)
3. 5.0 tenths reduce surge by 50 percent (cumulative)
4. 10.0 tenths reduce surge by 75 percent (cumulative)
5. Surges to 3 feet with 10 tenths ice cover have been reported with ice to 3 feet thick between October and January. Also, consider sea ice character. Thin ice, weak, ice, or unconsolidated ice can be effectively destroyed during storm conditions--particularly in the northern Bering Sea, with subsequent surges to 9 feet.

E. Pressure Adjusted Surge Height

Raise the surge height one foot for every 30 mb pressure increment below 1004 mb.

F. Tidal Adjusted Surge Height

Check tidal tables or other sources. If peak of surge is reasonably coincident with normal high water, make no correction. If surge misses normal high water, subtract as appropriate from surge height.