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A CHARACTERIZATION OF ARCTIC NEARSHORE/LAGOON SYSTEMS

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The physical setting of the Beaufort Sea is such that the Beaufort shelf is virtually completely covered by ice for all but two to three months of the year. The ice cover tends to insulate the underlying waters from both the atmospheric temperature and wind fields and to provide a source of dense brine in the winter and fresh meltwater in the spring and summer. Spring melting of the sea ice coincides with a massive influx of freshwater run-off from the land, both of which tend to stabilize the upper surface water, retain solar heat, and further enhance sea ice melting. Depending on the wind field for a particular year, the open water lead along the coastline may be as wide as 100-200 km and extend the entire length of the Beaufort Sea. The wind field in the western Beaufort is typically dominated year-round by easterly or northeasterly winds, whereas the eastern Beaufort exhibits dominant easterly and northerly winds in the summer and westerly or southwesterly winds in the winter. This wind pattern in the eastern Beaufort tends to move surface waters and ice offshore in the summer and onshore in the winter.

The shelf in the central and western Beaufort is relatively narrow with the shelfbreak typically occurring 80-90 km offshore. Lagoon systems which characterize this region of the Beaufort coastline have been termed "open" lagoons, open to the wind-driven longshore transport and to onshore/offshore transport due to numerous large openings in their offshore barrier island systems.

in the eastern Beaufort the shelf is slightly more narrow (approximately 40-60 km). The barrier island systems tend to be closer to the coastline, more extensive, and closed to direct flowthrough by the longshore current, thus limiting the exchange of water between the longshore currents and the lagoons to a small number of openings in the barrier island system (limited exchange lagoons). In many of these limited exchange lagoons, the exchange of water is restricted to one or two major entrances. These lagoons, which typically have very narrow entrances, exhibit highly localized current jets at the entrances in response to Periodic tidal forcing and have been termed "pul sing" lagoons.

Patterns of water movement on the shelf tend to exhibit strong continuity in the longshelf direction (Paralleling isobaths) and large zonal variabil ity in the cross-shelf sense (crossing isobaths). Following Aagaard (1981), the region of the shelf landward of the 40-m i sobath which exhibits one set of characteristics wil l be referred to as the "inner" shelf. That area of the inner shelf landward of the 20-m isobath with activity marked by ice and/or surface waves, and which exhibits higher summer temperatures and lower salinities than the water between 20 and 40 m, will be referred to as "nearshore", fol 1 owing Truett (1981).

The Beaufort coast in general experiences relatively smal 1 changes in sea level due to astronomical tides (approximately 0.1-0.3 m); however, meteorologically induced variations may range from as much as +3.0 to -0.9 m (Schaeffer, 1966; Matthews, unpublished data). The largest setup typically occurs in the fal l when long stretches of open water are common and the winds have become predominantly westerly, driving water onto the shelf.

Inner Shelf

Although current measurements on the inner shelf are extremely sparse due to the difficulty of maintaining moorings in the presence of sea ice, recent drifter data reported by Matthews (1981) and current meter measurements made by Aagaard (1981) give some indication of both open water and i cc-covered water movements. It has been general 1 y agreed that water movement on the Beaufort inner shel f is wind-driven. This hypothesis is further suPPorted by Matthews' drifter data which suggests that the motion of all recovered dri fters resulted from prevail ing wind-driven currents, both for open water and under-ice releases. Drifter travel times and computed current speeds were consistent with values of approximately 3-4 Percent of the wind transport for the same periods with under-ice motion being signifi - cantly less. Aagaard (1981), in direct winter current measurements on the inner shelf near Narwhal Island, al so reports that the under-ice water movement was quite slow but that the observed (0.1-0.3 cm/s) net movement was observed to be directed toward the west consistent with the mean wind direction. Daily current speeds and directions, however, were observed to be as high as 5-10 cm/s and closely followed the variability of local wind patterns.

If these conditions can be extrapolated to the eastern Beaufort Sea then Current Patterns on the inner eastern shelf would be expected to show a more event distribution of both easterly and westerly currents. As discussed previously, prevail ing winds along the central and western Beaufort are from the ENE during al 1 seasons. However, in the eastern Beaufort the distribution Of winds is more bimodal . At Barter Island, for example, the average winds are from the ENE to E for 35 percent of the time and from the WSW to W for 25 percent of the time (Scary and Hunter, 1971) with winds predominantly from the west during the winter and from the east during the open water season (Bower et al., 1977). If the inner shelf waters in the eastern Beaufort fol low the local wind patterns one cou1 d expect to observe mean current patterns to the east in the winter and to the west in the summer fol lowing local wind patterns.

Nearshore and Lagoons

Considerable research has been accomplished in the Beaufort nearshore and lagoon regions. Results of two such programs are summarized in Matthews (1979) and Hachmeister and Vinelli (1983). Results of these field measurement programs in the central Beaufort between Fl axman 1s1 and and 01 iktok Point, and the eastern Beaufort between Barter Island and Demarcation Bay are consistent with present understanding of lagoon and nearshore flow. Winter conditions find dense brine (more than 40 o/oo) co1 lected in Simpson Lagoon (an open lagoon type) waters deeper than 2 m with temperatures near -2 “C, moving slowly in response to tidal forcing. Complete flushing of the lagoon occurs during river overflow in early June (6-8 June yearly average). Following this, saline water appears again in the lagoon and high solar radiation heats nearshore and lagoon waters to as high as 10-12 °C. Matthews (1979) notes that the month of August is marked by the appearance of cold and Saline frontal systems rapidly moving through Simpson Lagoon and alternating with warmer brackish water. The presence of storms vertically mixes the shallow nearshore and lagoon waters but the frontal systems continually reestablish themselves throughout the summer months. Hachmeister and Vinelli (1983), on the other hand, find that currents within Angun Lagoon and Pokok 8ay in the eastern Beaufort (pulsing lagoons) are quite sluggish except near the lagoon entrances where high (> 1.5 kt) currents pulse in and out of the lagoons in response to tidal forcing. Dense brine collection has not been documented in these and other pulsing lagoons, possibly due to deep channels located at the lagoon entrances.

Observed currents in the lagoons and nearshore appear to be predominantly wind-driven. Superimposed on these mean wind-driven currents are short-term effects of storm passages and tidal effects which are dominated by diurnal M2 forcing. Current speeds are such that flushing rates in open-type lagoons similar to Simpson Lagoon may be on the order of 3-4 days with mean easterly winds, but water exchange in pulsing-type lagoons similar to Angun Lagoon may be considerably less.

Cross-Shelf and Longshore Exchange

On the inner shelf, currents have been demonstrated to be primarily wind-driven. In the western Beaufort beyond Barter Island this would indicate year-round mean currents to the west along the coastline, as shown by drifter studies by Matthews (1981) and Barnes and Toimil (1979). However, in the eastern Beaufort winds are more bimodal and currents will exhibit a bimodal distribution with a mean eastward flow in the winter and a mean westward flow in the summer (Brewer et al., 1977); this is typical Of eight to ten summers according to Kozo (1982).

During open water periods wind conditions will tend to induce a cross-shelf movement of Beaufort nearshore and surface waters offshore to be replaced by subsurface inner shelf waters and, under some conditions, to induce upwelling on the outer shelf as observed by Hufford (1974) and others. Upwelled waters on both the eastern and western outer shelf may then be further transported landward to the inner shelf and nearshore regions by estuarine flow or, under average wind conditions for the 8eaufort, by off-shore movement of wind-driven nearshore and surface waters, as described above.

Longshore transport of water has also been demonstrated to be primarily wind-driven (see Figure 1). This implies mean longshore transport to the west during the open water season with easterly reversals occurring as mean wind conditions are modified by the passage of localized weather systems.

The inner shelf long- and cross-shelf circulation is therefore characterized as being Primarily driven by the local wind fields with long-shore current speeds on the order of 3-4 percent of the wind speed. In the western 8eaufort, this implies net westward water movement; in the eastern 8eaufort this implies a bimodal distribution of currents with eastward currents dominating in the fal 1 and winter and westward currents dominating in the summer. Mean year-round wind speeds cluster about 5 m/s in the 8arter Island area although Kozo (1982) does indicate some reduction in winds eastward toward Demarcati on 8ay. These average wind speeds imply mean wind-driven transport at character stic speeds of 15-20 cm/s i n the open water period. Both Aagaard (1981) and Matthews (1981) indicate that under-ice speeds would be greatly reduced for this wind speed.

Lagoon/8 arrier Island Characterization

The basic lagoon types appearing on the Beaufort coastline are illustrated in Figure 2. The first type discussed in this report is the open l agoon, i .e. those lagoons open to longshore transport as wel 1 as to cross-shelf exchange between multiple large openings in the barrier islands. The second lagoon type discussed is the pul sing lagoon, i.e. those lagoons with one major entrance through the barrier island. These lagoons are a subset of the 1 imited exchange lagoons which have only 1 imited longshore current throughput via one or more larger openings in the barrier island System. These lagoons are closed to longshore throughput; exchange with the

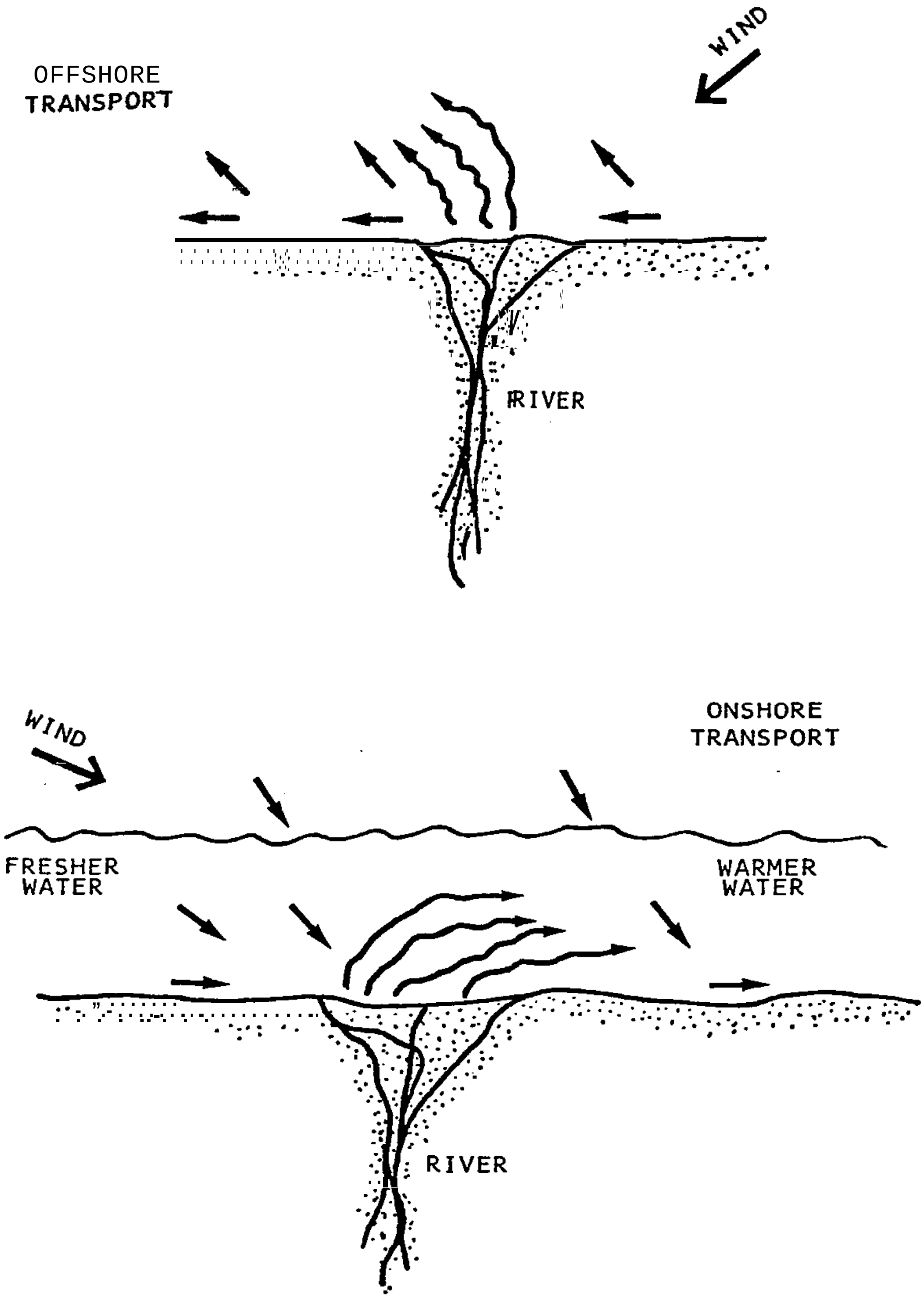
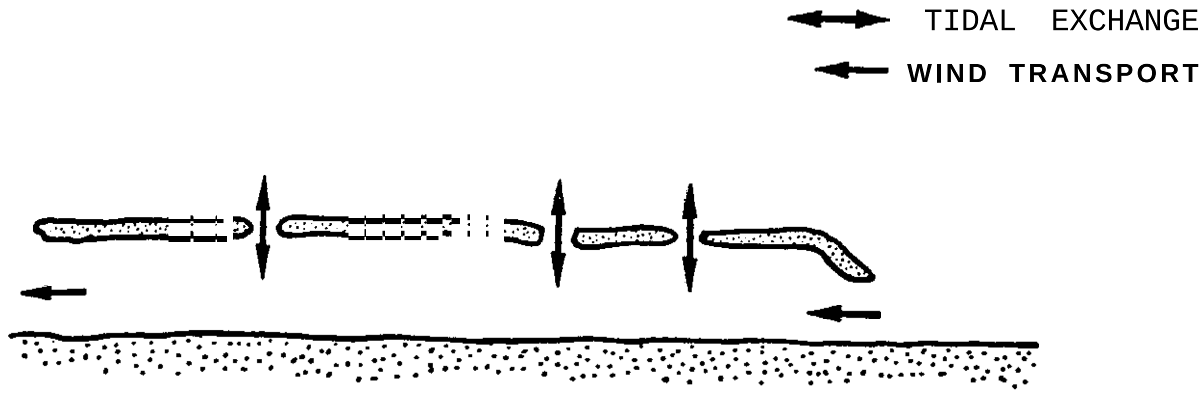
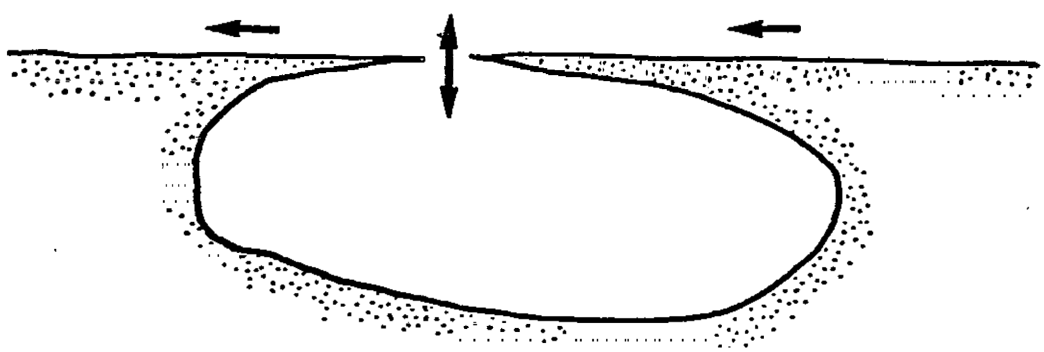


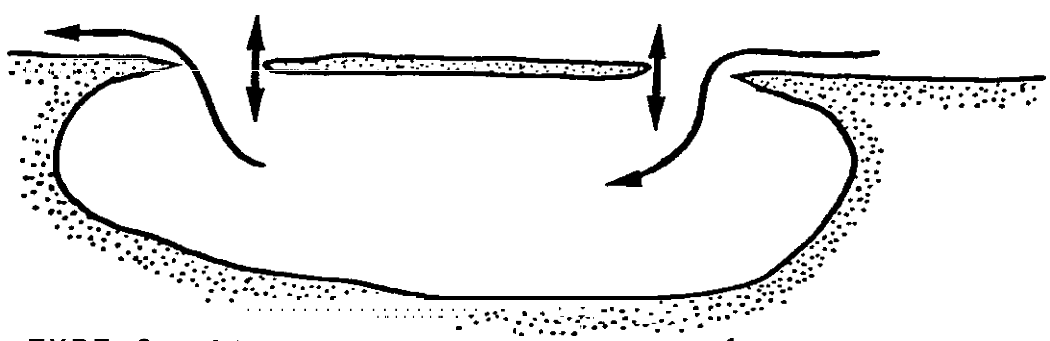
Figure 1. Lagoon circulation nearshore, showing general wind effects on onshore and offshore transport.



TYPE 1. OPEN LAGOON (OPEN TO LONGSHORE CURRENT)



TYPE 2. PULSING LAGOON (CLOSED TO LONGSHORE CURRENT)



TYPE 3. LIMITED EXCHANGE LAGOON (LIMITED LONGSHORE CURRENT EXCHANGE)

Figure 2. Basic lagoon types: open, pulsing and limited exchange.

nearshore waters occurs primarily via tidal pumping of water through several major entrances, although some smaller amount of exchange may also occur through shallow breaks in the barrier islands. One or more small rivers or streams typically empty into these lagoons providing a source of freshwater, particularly in early spring.

Open Lagoons

The most extensively studied example of an open lagoon system is Simpson Lagoon. Considerable data have been collected on both the biological and physical environments in multi-Year OCSEAP-sponsored field programs of the Simpson Lagoon and nearshore region. This discussion will, however, address only results pertaining to a description of the physical environment of the lagoon. Figure 3 illustrates the effects of the mean summer wind conditions on Simpson Lagoon circulation patterns. In general, nearshore water enters the lagoon in the eastern and central portion and is advected through the lagoon in a manner similar to the wind-driven longshore transport seaward of the barrier island chain. Multiple large openings in the lagoon system and the open end allow considerable flowthrough of the nearshore waters. Exchange is therefore largely due to advection of new water masses through the lagoon rather than input/local mixing/output, as typifies a limited exchange lagoon.

Tidal effects (Figure 4) are superimposed upon the wind-driven component Of the circulation and periodically modulate that component's effect. Depending on the strength of the wind-driven currents in a particular break in the barrier islands, the tide may only modulate the mean flow in the entrance or it may actually reverse the flow during the opposing cycle of the tidal current.

Matthews (1979) has estimated that the flowthrough in Simpson Lagoon occurs at 3-4 percent of the mean wind speed which would indicate lagoon water turnover on the order of 3-4 days for mean wind conditions Of 10 kt. The net wind-driven transport of waters east to west through the lagoon are accompanied by some offshore transport of the warm fresh Surface

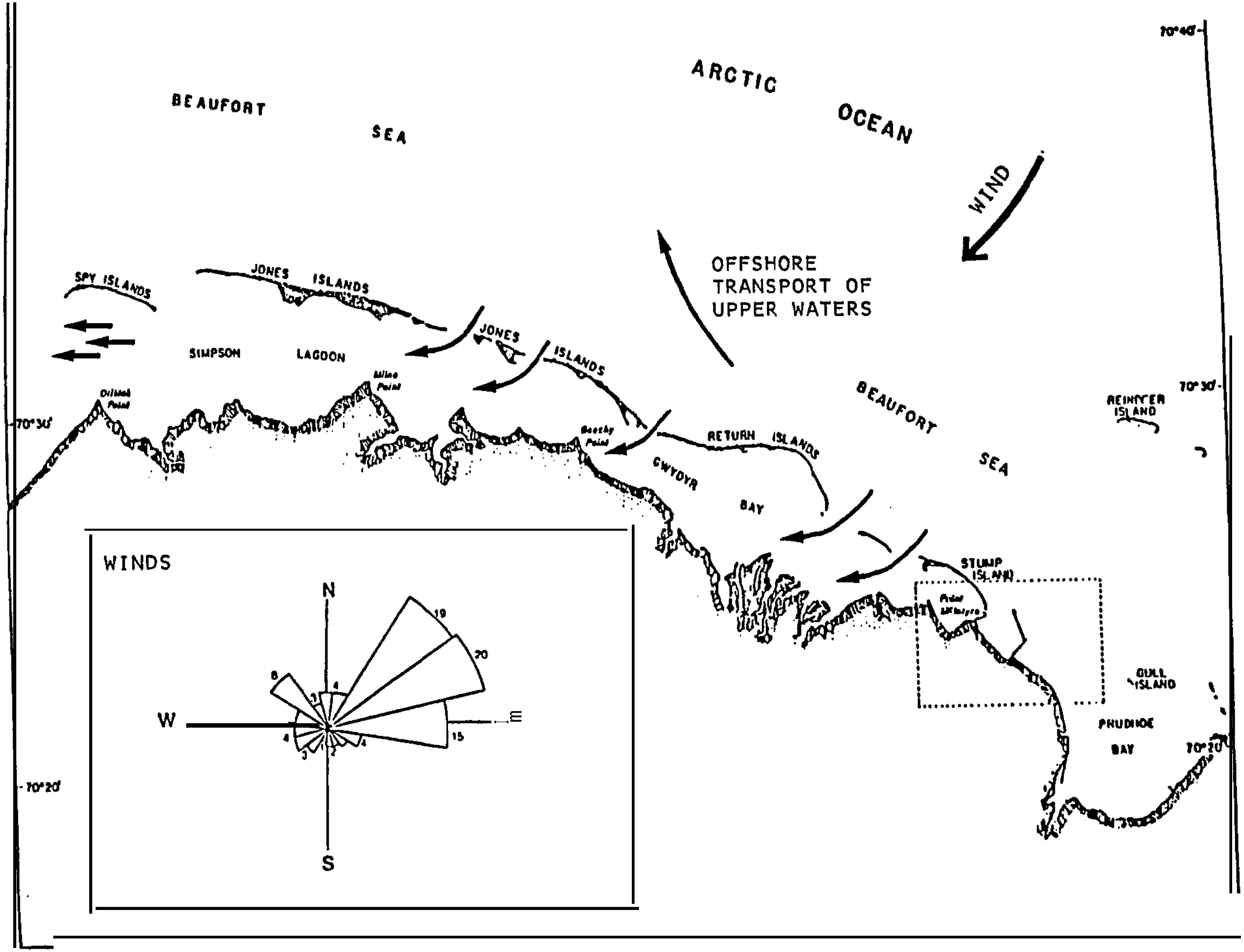


Figure 3. Effects of mean summer wind conditions on Simpson Lagoon circulation patterns.

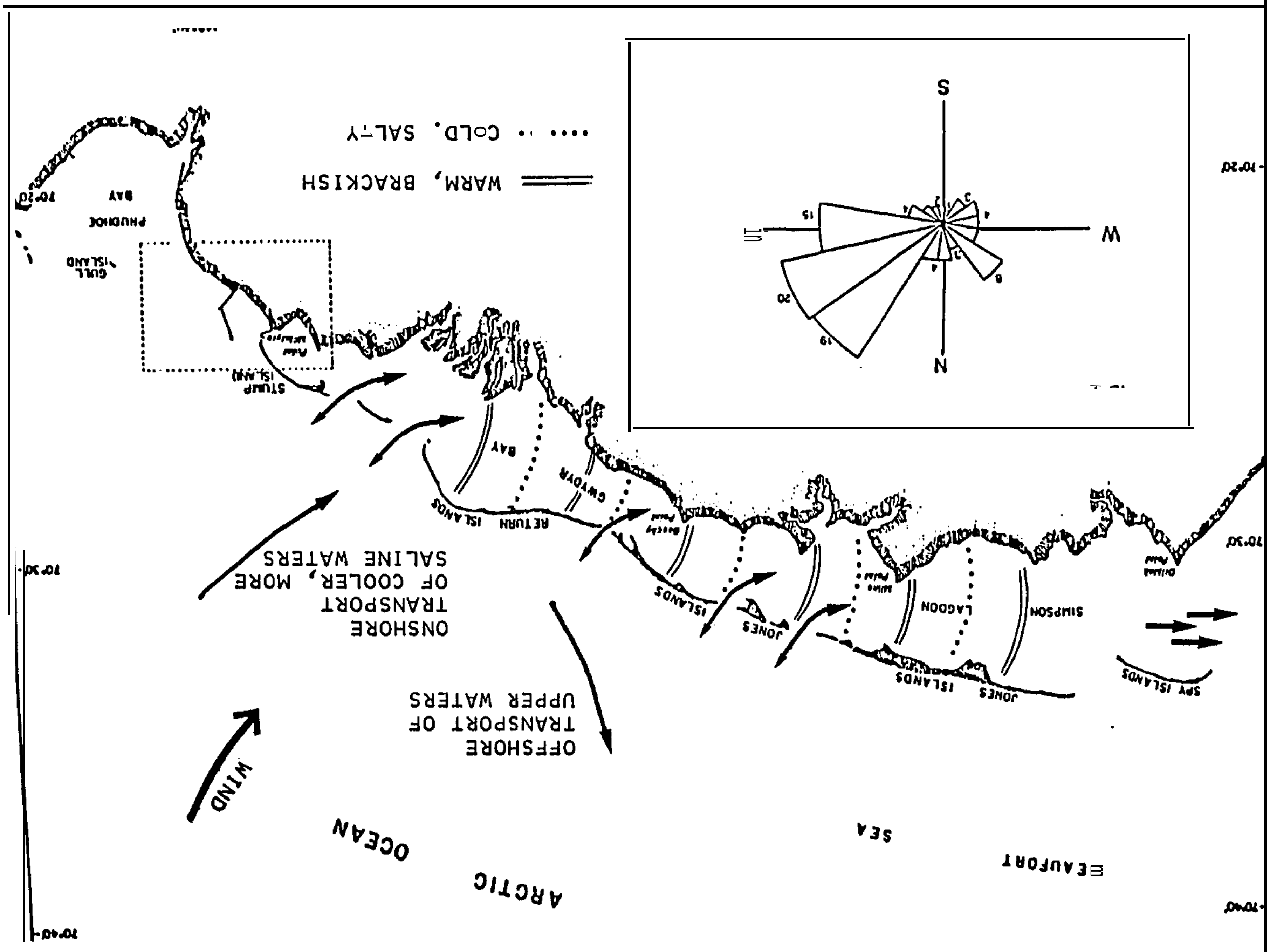


Figure 4. Combined effects of wind and tide on Simpson Lagoon circulation.

nearshore waters and replacement by cooler saltier offshore waters. Tidal currents selectively introduce this nearshore water to the lagoon interior at each entrance on successive flood tides. On ebb tides, the net westward fl ow is reduced and 1 agoon waters col lect near the eastern entrances of the l agoon to form Poo's of warmer fresher water. On successive flood and ebb tides, these pools of alternating cooler saltier nearshore water and warmer fresher lagoon water (formed by mixing of nearshore water from previous cycles and fresh water from river runoff) experience a net westward transport through the lagoon interior. A more detailed analysis of this data is presented in Hachmeister and Vinel l i (1983).

When an abrupt change is observed in the mean northeasterly wind pattern during east to west lagoon flow, causing a reverse in the direction of the mean flow through the lagoon, a corresponding abrupt change is observed in the characteristics of the lagoon waters. The shift from northeasterly to northwesterly winds retains the warm fresher 1 agoon waters in the nearshore region where exchange with the 1 agoons continues and nearshore and 1 agoon waters become almost identi Cal. This in turn is accompanied by the disappearance of the alternating nearshore and lagoon water masses through the lagoon (as nearshore and 1 agoon waters become identical) and observance of uniform warm intermediate-sal inity water. An accumulation of nearshore water along the coastl ine would al so lead to the observed sea level increase of 50-100 cm. The reestablishment of the mean easterly wind field would reestablish the differential between lagoon and nearshore waters. Matthews (1979) reported more detailed data which substantiate this description of circulation in a lagoon such as Simpson (Figure 5).

Pulsing Lagoons

The pulsing lagoon type was the focus of study in a more recent field program (Hachmei ster and Vinel 1 i , 1983). Figure 6 illustrates the combined wind and tidal effects of available exchange in this type Of lagoon using Angun Lagoon and Pokok 8ay from the Eastern 8eaufort coa stl ine as examples. Il lustrated in this figure are mean summer conditions with winds predominantly from the east. In a manner similar to the open lagoon case,

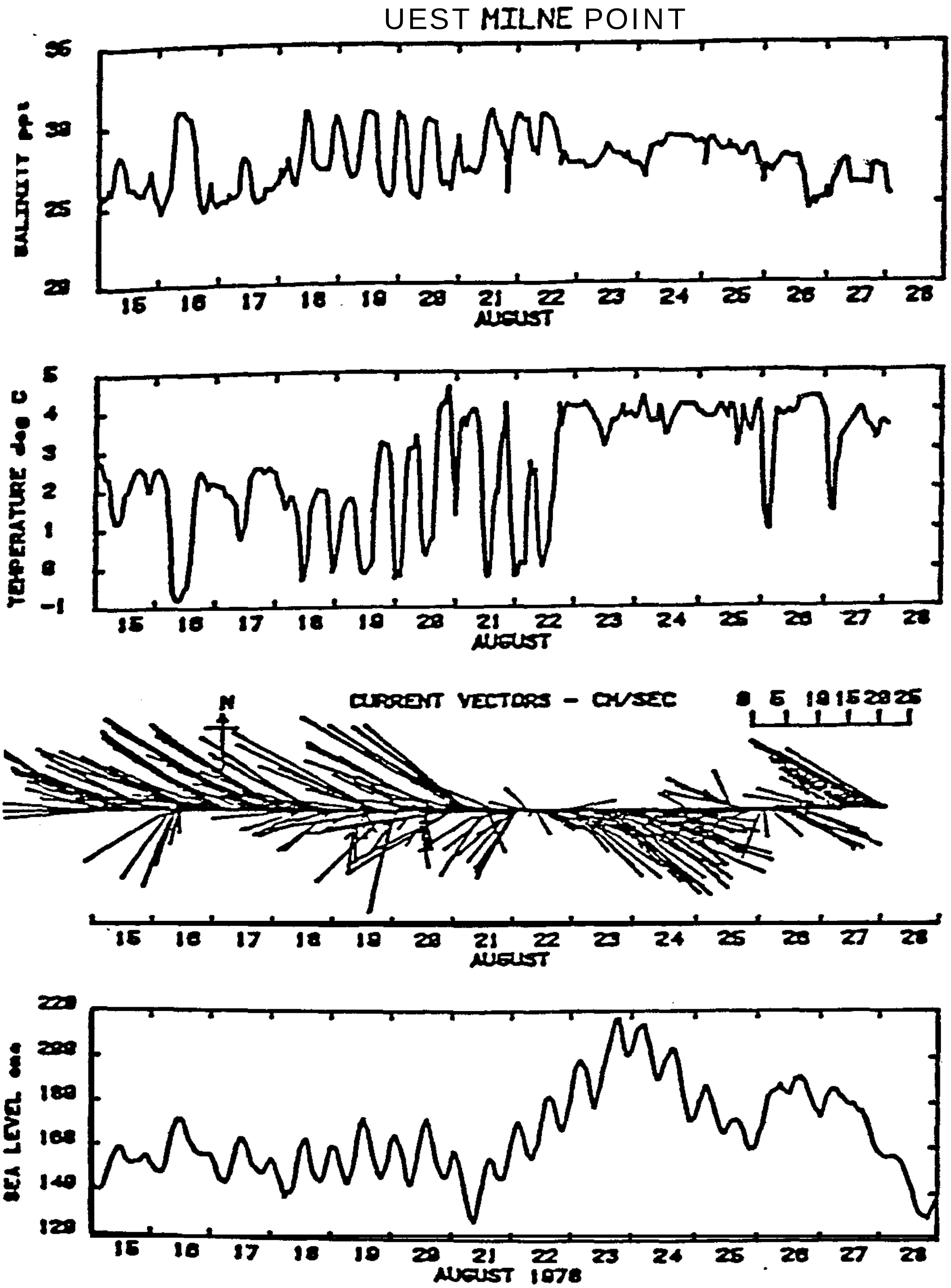


Figure 5. Temperature, salinity and current measurements taken at Milne Point, August 1978 (from Matthews, 1979).

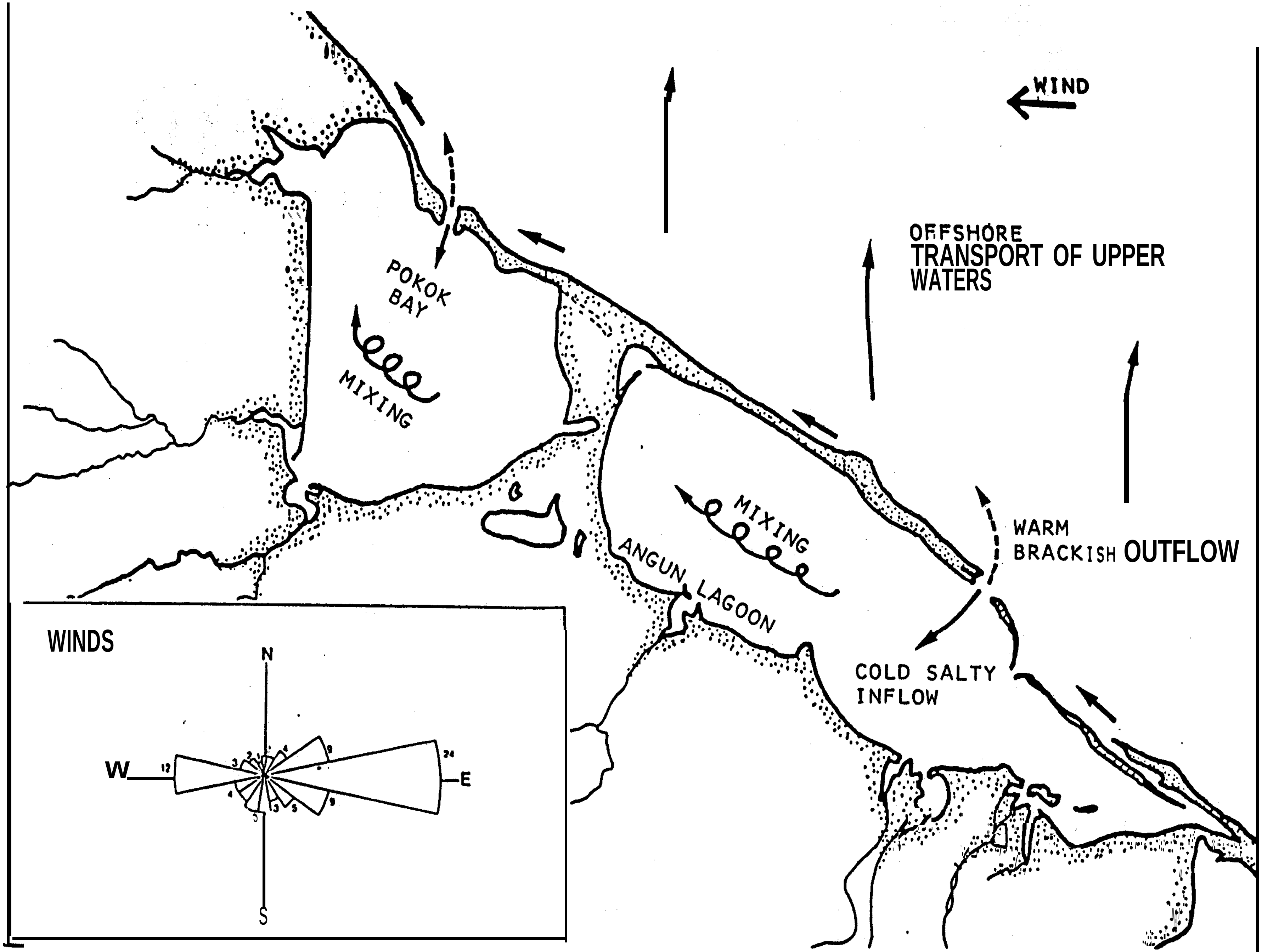


Figure 6. Combined wind and tidal effects in a pulsing lagoon such as Pokok Bay and Angun Lagoon.

easterly winds result in somewhat higher nearshore salinities and lower nearshore temperatures for tidal exchange with the lagoon. In addition, as' discussed in Section 7.1, circulation in the lagoon itself may depend on the lagoon geometry with greater mixing observed for a lagoon with the geometry of Pokok Bay than for a l agoon with the shape of Angun Lagoon.

Figure 7 illustrates the circulation patterns anticipated for westerly winds. As in the open lagoon case, the fresher warmer nearshore water is maintained on the coast and advected eastward i n the 1 ongshore current.As observed in the Simpson Lagoon data, during westerly winds the nearshore water i s warmed to temperatures equal to 1 agoon water and the nearshore and 1 agoon entrance waters become almost identical. However, when easterly winds are reestablished the nearshore waters cool as warm water is driven offshore and the pulsing ef feet of cool -water- in/mi xi ng/warm-water-out is observed. Because there is no net fl owthrough of the waters entering the pulsing lagoons, sensors placed in the interior of Angun Lagoon and Pokok Bay do not experience the alternating patterns of nearshore and lagoon water observed in Simpson Lagoon (Hachmeister and Vinel 1 i, 1983).

Physical models developed to study circulation and flushing in lagoons and smal l embayments provide useful information for interpreting measurements made in the present study. Recent work by Nece et al. (1979) studied the effects of pl anform geometry and the size and placement of lagoon entrances on flushing efficiencies of smal 1 embayments. Figure 8 shows an example of the distribution of exchange coefficient (percent water exchange per tidal cycle) in an embayment similar to Pokok Bay in geometry. Note the uniform distribution of the flushing properties in this case. The average flushing efficiency for a lagoon with this shape, according to thi s study, ranges from 90 to 100 percent. For comparison, flushing efficiency for pokok Bay was crudely estimated at 15 to 20 percent near the l agoon Center. It should be noted, however, that the tidal ranges uti l i zed by Nece were a factor of ten greater than those observed in the Beaufort Lagoon system. Flushing efficiencies might therefore be expected to be greater in the model Studies than in the actual lagoons. Regardless, the results for Simpson Lagoon are Considerably different, giving estimated exchanges on the

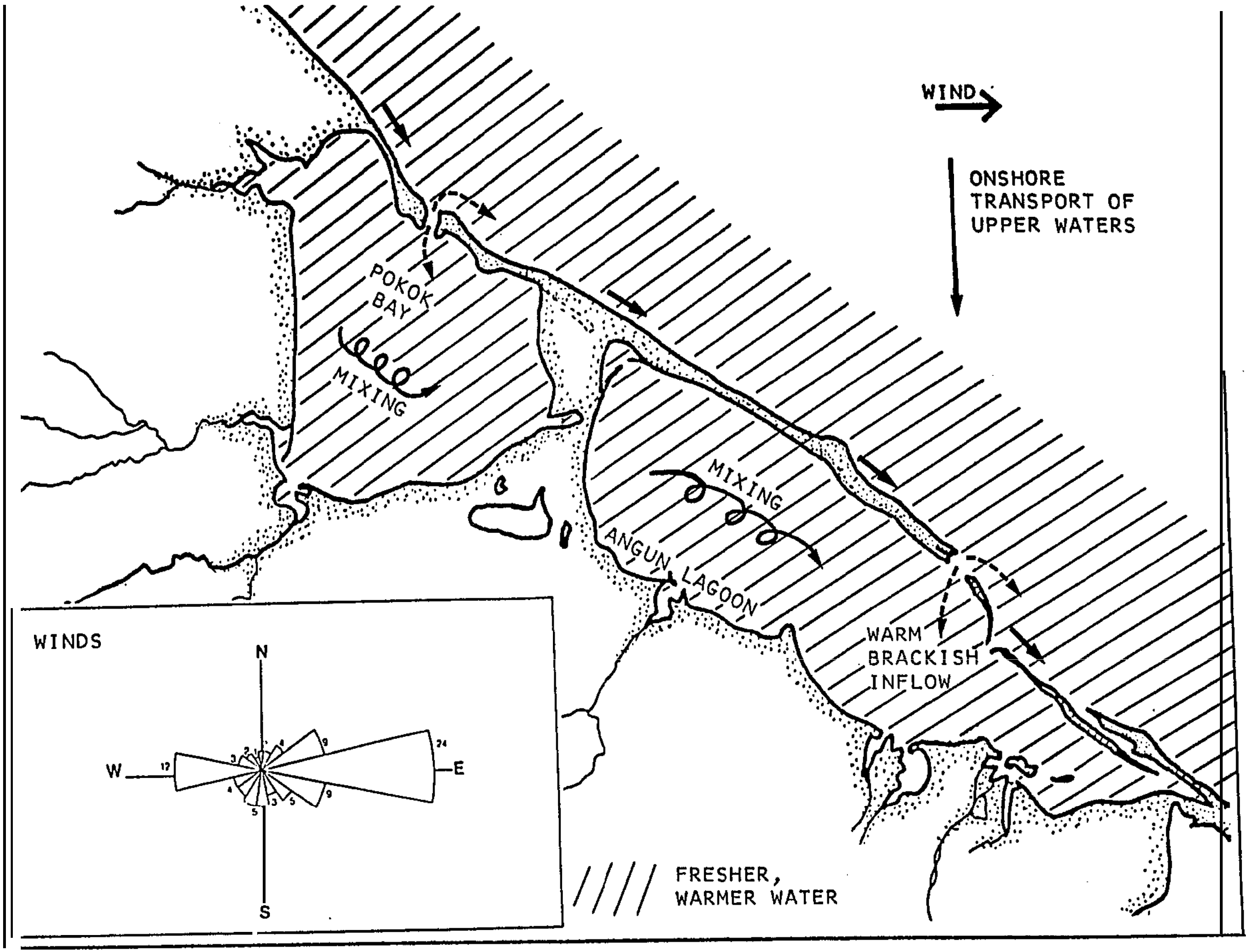
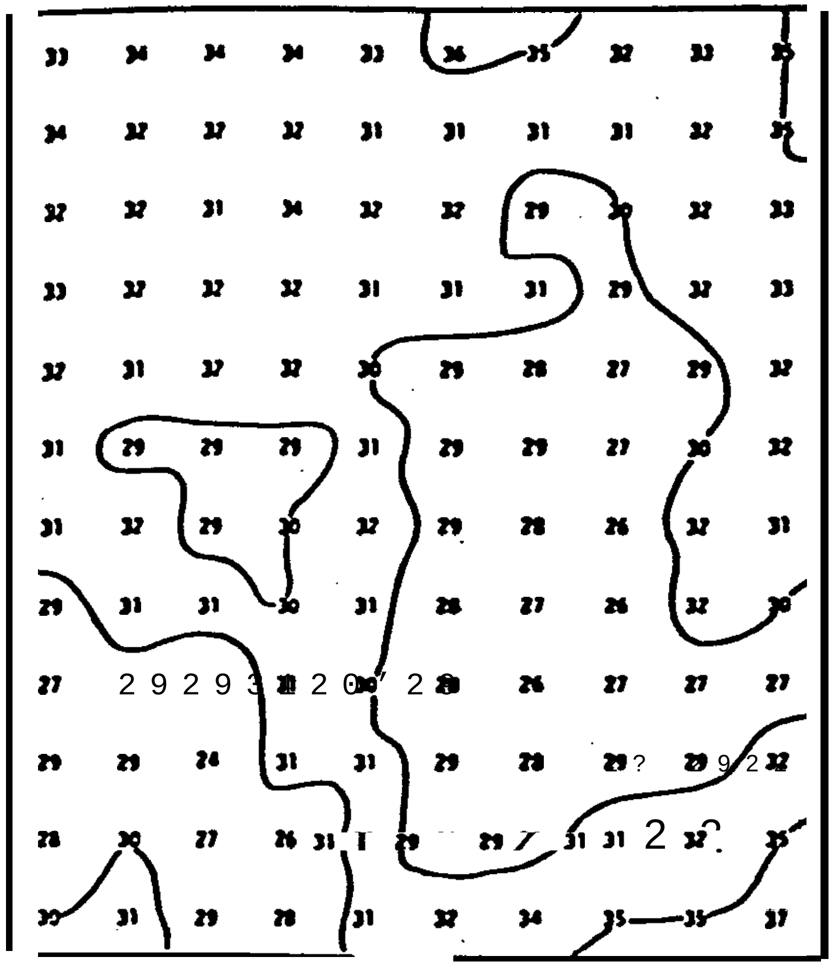


Figure 7. Combined wind and tidal effects for a pulsing lagoon during westerly winds.



AVERAGE EXPERIMENT EXCHANGE COEFFICIENT = 31%
IDEAL EXCHANGE COEFFICIENT = 31%
FLUSHING EFFICIENCY = 100%

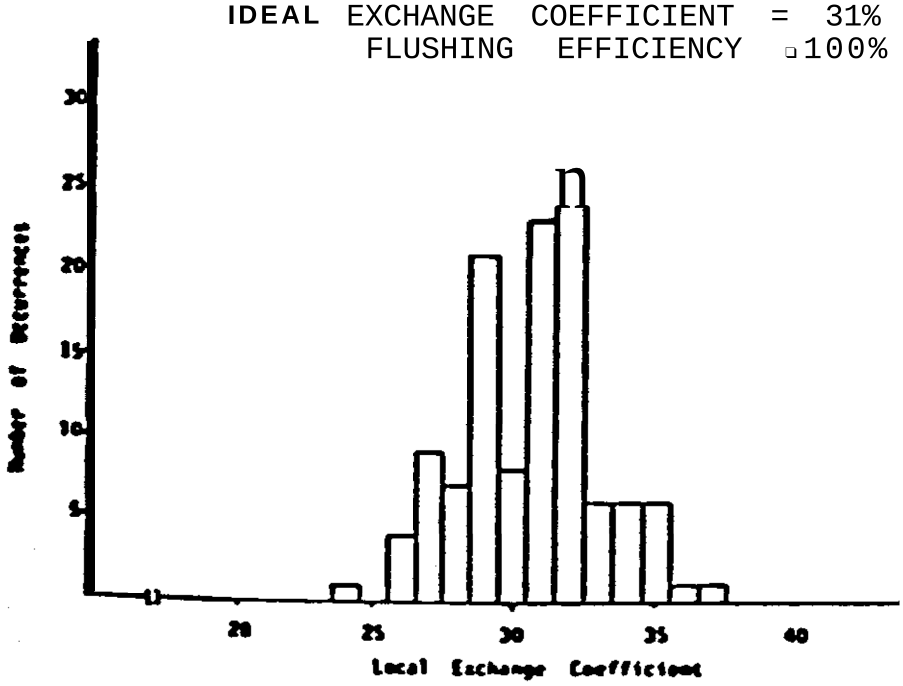


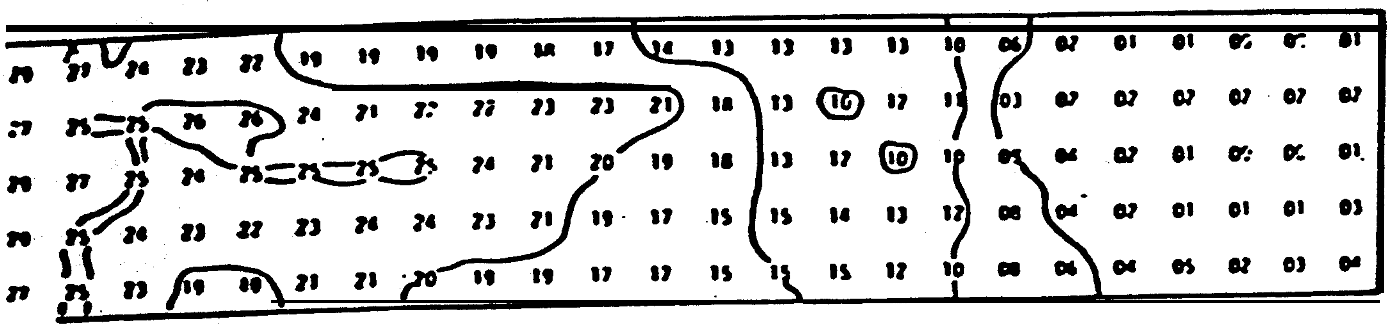
Figure 8. Example of exchange coefficient distribution in an embayment similar to Pokok Bay (from Nece et al., 1979).

order of 3 to 4 days (8 to 10 days for ideal tidal flushing) which yields over a z00 percent efficiency compared to tidal flushing alone.

If a planform model geometry similar to Angun Lagoon is used, an interesting phenomenon arises. Nece et al . (1979) found that multiple circulation cel 1s develop in the lagoon when lagoon length-to-width ratios are greater than three; as a result, cells furthest from the entrance do not participate fully in the exchange processes and exhibit reduced flushing efficiencies. (The existence of these cells in Angun Lagoon has been implied earl ier in this paper.) In a lagoon with a geometry similar to Angun Lagoon (length-to-width ratio = 5) three circulation cells are observed. Figure 9 illustrates the results of a model study with an embayment having approximately the same geometry as the western portion of Angun Lagoon. The results indicate that near the lagoon entrance exchange coefficients may be as high as for the Pokok model results (23-27 percent). However, exchange .ss low as 1-2 percent is observed at the far end of the 1 agoon away from the entrance. The overall flushing efficiency due to tidal effects alone therefore would be on the order of 48 percent, which is less than half of the efficiency predicted for a pul sing lagoon similar to Pokok Bay. The region of the lagaoon furthest from the lagoon entrance is, however, virtually isolated from the exchange processes, showing efficiencies as l ow as 8-10 percent. As in the case of the Pokok model, however, modeled tides are a factor of 10 greater than those observed in Angun Lagoon and actual flushing effi ciencies are expected to be considerably less than those modeled.

Of particular note is the fact that current measurements in the far western end of Angun Lagoon show persistent north-northeast Current direction (Hachmeister and Vinell i , 1983) indicating a mean clockwise ci rculation and the cel 1 immediately adjacent to the entrance should exhibit clockwise circulation. This is substantiated by visual observations Of inflowing currents and surface drifter motions near the lagoon entrance.

It must be remembered at this point that these results are for tidal flushing only and that considerable wind mixing may occur in addition to the exchange which, is enhanced by the input of freshwater into the surface waters at the i sol ated end of An gun Lagoon. However, in the absence of



AVERAGE EXPERIMENTAL EXCHANGE COEFFICIENT = 15%
IDEAL EXCHANGE COEFFICIENT = 31%
FLUSHING EFFICIENCY = 48%

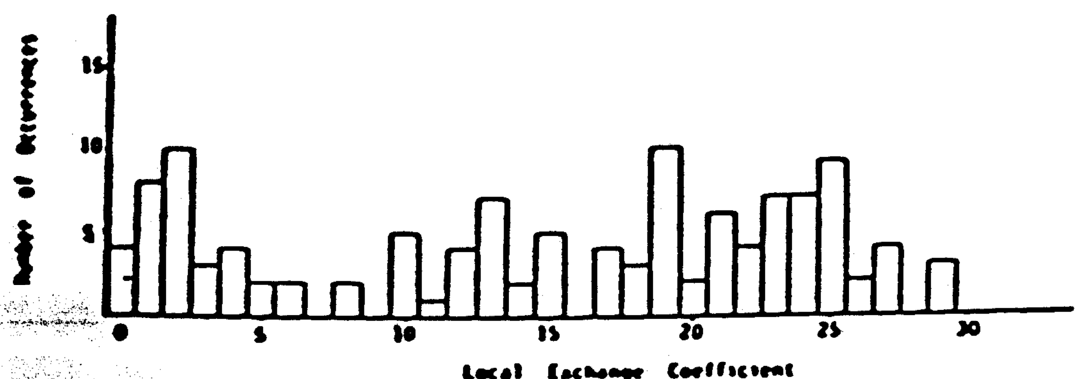


Figure 9. Example of exchange Coefficient distribution in an embayment similar to Angun Lagoon (from Nece et al., 1979).

large quantities of freshwater as might be expected in the late summer and fall under mean easterly wind conditions, flushing of lagoons similar to Angun Lagoon might be considerably lower than indicated by typical ideal flushing estimates based on volume exchange alone. Perhaps another 15 percent of the coastline can be accounted for by Pulsing lagoons in this region. Further study of the flushing characteristics of these lagoons is clearly warranted. In contrast, the lagoons in the western Beaufort from Barter Island to Pt. Barrow are almost all of the open type similar to Simpson Lagoon.

In the Chukchi Sea the nearshore is comprised almost exclusively of limited exchange lagoons which have extensive barrier island systems and multiple small entrances distributed along the coastline. A recent study of Peard Bay, a two-entrance limited exchange lagoon in the NE Chukchi Sea, shows enhanced flushing over pulsing lagoons including net transport through the lagoon entrances which is presumably wind-driven. Figure 10 shows the results of a model study of a small embayment with two small entrances (one entrance is twice the size of the other), similar to Peard Bay; the predicted flushing efficiency for a lagoon with this geometry is B4 percent which compares to 48 percent for a single entrance lagoon with the geometry of Angun Lagoon. In addition, given two entrances and the relationship of the Peard Bay geometry to the local wind field, enhanced flushing due to flow-through of nearshore waters during strong easterly or westerly wind events (as has been observed) is highly probable.

limited Exchange Lagoons

Limited exchange lagoons, of which the pulsing lagoons are a subset, are defined by a capacity for throughput of nearshore waters which is limited by nearshore barrier island systems. An example of this type is Beaufort Lagoon which is actually composed of several small interconnected narrow lagoons with an extensive barrier island system. The barrier island system there (commonly designated as Icy Reef) has a relatively small number of openings distributed along its extent but several of the openings are quite large, allowing the possibility of net wind-driven flowthrough of the

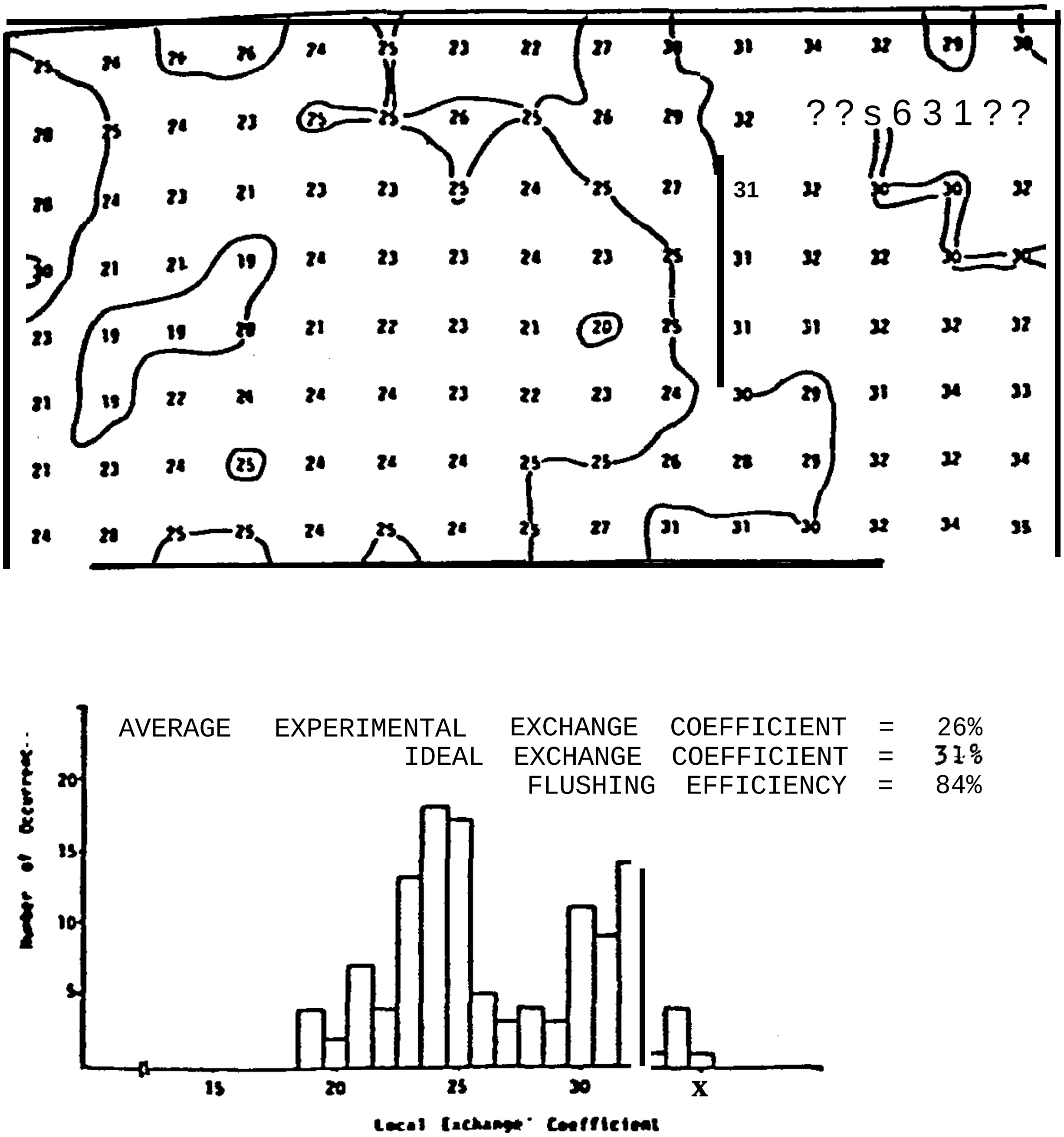


Figure 10. Example of exchange coefficient distribution in a small embayment with two entrances similar to Peard Bay (from Nece et al. , 1979).

waters from the longshore current. At the far western end of Beaufort Lagoon is Nuvagapak Lagoon, foil owed by (moving eastward) Egaksrak Lagoon, Siku Lagoon, Pingokraluk Lagoon, and final ly Demarcation Bay. Major entrances include Nuvagapak entrance to the west (which actually consists of two openings: one narrow and quite deep, the other wider but relatively shallow), Egaksrak entrance, Si ku entrance, and the mai n entrance to Demarcation BaY.

Flowthrough, i.e. Purely advective exchange as was discussed for the open lagoon tYPes, is expected to be considerably less than observed for Simpson Lagoon. However, considerably more advective exchange than for the pul sing lagoons is indicated. The observed range of flushing efficiency calculated for oPen and pulsing lagoons has been estimated at 20D percent and 15-20 Percent , respectively, for Simpson and Pokok Lagoons. If model results for pokok Bay and Angun Lagoon geometries scale the same (100 percent flushing efficiency for Pokok Bay and 48 percent average efficiency for Angun Lagoon) then actual average efficiencies for Angun Lagoon may be as low as 7-10 percent given a 15-20 percent estimate for Pokok Bay. Therefore, a considerable gain in flushing efficiency might be expected for the 1 imited exchange lagoons dependent on the degree of wind-driven advection through the lagoons. For example, if advection in Nuvagapak Lagoon is only 0.5 percent of a 3 m/s easterly wind (1.5 cm/s) as compared to 3-4 percent observed in Simpson Lagoon, then flushing efficiency could be increased to 75 percent with water exchange occurring in as little as 12 days.

A considerable number of 1 imited exchange lagoons exist in the eastern Beaufort including those lagoons typical ly considered as forming Beaufort Lagoon and the lagoon systems inside Icy Reef to Demarcation Bay. To the west, Oruktal ik, Tapkaurak, and Jago Lagoons are of similar configuration, Those limited exchange lagoons, whose entrances may or may not exhibit some phenomenon characteristic of pul sing lagoons depending on the degree of wind-driven advection through the particular lagoon encompass over 75 Percent of the coastline of the Beaufort nearshore east of Barter Island.

Concluding Remarks

Lagoon/barrier island geometries vary between the eastern and western Beaufort Shelf, with open lagoons being the dominant form along the western nearshore regime and pulsing or limited exchange lagoons being the dominant form along the eastern Beaufort and NE Chukchi Seas. The largest flushing efficiencies for the three lagoon types occur in the open lagoons similar to Simpson Lagoon in the western Beaufort. These lagoons are open to flowthrough by the coastal longshore currents and may exhibit flushing efficiencies equal to 200 percent of tide-induced exchange alone.

Flushing efficiencies for pulsing or limited exchange lagons are, however, expected to be considerably less. For example, the flushing efficiency of pokok Bay (a pulsing lagoon that should exhibit good flushing characteristics with a centrally located entrance and a length-to-width ratio of approximately 1) may be as low as 15-20 percent in the absence of enhanced baroclinic flow. On the other hand, Angun Lagoon (a pulsing lagoon with a length-to-width ratio of 5 and an off-center entrance, thus predicted poor flushing characteristics) may show average overall flushing efficiencies which are half of those observed for Pokok Bay. In addition, Angun Lagoon contains some isolated regions away from the entrance which may have tidal flushing efficiencies only 10 percent of those calculated for Pokok Bay.

However, under the influence of wind forcing and particularly under the influence of westerly winds which forces water onto the nearshore region and into the lagoons, vertical mixing and increased horizontal exchange occurs which may temporarily increase the exchange efficiencies of these types of lagoons to equal that observed for Pokok Bay. The critical wind speed required to vertically mix the lagoon waters appears to be on the Order of 10 kt for early spring stratifications and is anticipated to be Considerably less for late summer conditions when vertical Stratification is reduced. In either case, however, flushing efficiency for these eastern Beaufort Lagoon types is considerably less than that observed for the open Western lagoons and seems to be only a fraction (15-20 percent) of that which would be estimated from volume-exchange calculations alone. These reduced flushing rates make the eastern Beaufort and NE Chukchi Seas lagoon systems more vulnerable to impact by oil and gas exploration activity due both to disruptions in the exchange processes which renew the lagoon properties via interactions with the nearshore waters and to direct contamination by oil or dril 1 ing byproducts.

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