ARCTIC
VOL. 36, NO. 4 (DECEMBER 1983) P. 328-340

Under Landfast Ice

THOMAS K. NEWBURY[1]

ABSTRACT. The layer of water under landfast ice has unique oceanographic characteristics, as described in this review of recent assessment information for the central Alaskan Beaufort Sea coast. Water circulation is very slow, usually near the lower threshold of current meters. Barometric storms cause infrequent surges of water. The weak thermohaline-driven circulation is the reverse of that in ice-free estuaries. Water temperatures are always close to the slowly declining freezing point, and salinity gradually increases to high levels in bays because of flushing times of a month or more. Biological processes during the dark third of the year when there is no photosynthesis are dependent primarily on detritus and stored energy. Detritus is decomposed slowly by bacteria, and consumed by epibenthic invertebrates. Invertebrates and their main predators, fish, both reproduce under the ice cover. Food may limit biological activity in late winter, even in nearshore areas. Spring under-ice primary production totals possibly one-third of annual production with production of epontic algae attached to the bottom surface of the ice equalling only 5% of annual production. During breakup, river floods quickly flush under-ice areas; nearshore salinity drops to zero, and the wintertime thermohaline circulation is reversed. Year-to-year physical variations in the habitat cause the populations of three resident animals to vary up to sevenfold, but there are no regular cycles in abundance. Knowledge of these under-ice characteristics is important for understanding the Beaufort Sea coastal ecosystems, even for the relatively short open-water period.

Key words: Arctic, Beaufort Sea, Alaska, winter, coastal, landfast ice, under-ice, oceanography, food web

RÉSUMÉ. La couche de l'eau sous glace attachée à la terre ferme a des caractéristiques océanographiques uniques. Ceci est décrit dans cette étude des informations les plus récentes de la mer Beaufort costale de l'Alaska central. Les courants d'eau sont très faibles, généralement approchant les plus bas courants définis par les instruments mesurant le courant d'eau. Les tempêtes barométriques de temps en temps entrainent des houles d'eau. La circulation des faibles courants, chassés par le thermohaline, est a l'envers de celle trouvée dans les estuaires sans congélation. La témperature des eaux est toujours près de congélation. La salinité remonte graduellement a un niveau très élevé dans les baies résultant des basses circulations pendant un mois ou plus. Pendant le sombre tiers de l'année, quand il n'y a pas de photosynthésis, le procès biologique dépend surtout de détritus et de l'énergie accumulée. Le détritus est décomposé lentement par des bactéries et consumé par des invertèbres épibenthiques qui le sont a leur tour par leurs prédateurs principaux poissons, tous reproduits sous la glace. Le volume de nourriture peut limiter l'activité biologique a la fin de l'hiver, même dans les lagons côtiers. Au printemps la production primaire sous la glace répresente peut-être un tiers de la production annuelle, et la production annuelle représente seulement 5%. Pendant le dégel les rivières en crues changent rapidement les endroits sous la glace. Près des cotes la salinité baisse à zéro et les courants thermohalines de l'hiver sont renversés. D'une année à l'autre les variations physiologiques de l'habitat peuvent changer le nombre de la population indigène des trois espèces indigènes jusqu'à sept fois, mais il n'existe pas des cycles abondant réguliers. La connaissance de ces caractéristiques sous la glace est importante pour comprendre l'écosystème de la mer de Beaufort costale pour la courte durée même de l'eau ouverte.

Mots clés: Arctique, mer de Beaufort, Alaska, hiver, les côtes, glace attachée a la terre ferme, glace, au desous-blace, l'échelle de nourriture

Traduit par H. Froehlich.

INTRODUCTION

The layer of water under landfast ice exists for about 3/4 of the year along most coastlines in the Arctic. In spite of this, knowledge of coastal waters is focused primarily on the open-water period. Insight into the characteristics of these coastal waters, even for the open-water period, requires knowledge of the biological and physical conditions under the winter ice cover.

The landfast ice zone is important also because of recent oil industry activity in the Beaufort Sea. This zone is the offshore area that is being explored first. The emphasis on winter operations along the Alaskan portion of the Beaufort Sea coast constitutes further reason for understanding conditions under the ice cover.

Large, year-round research programs have investigated the Beaufort Sea coastal waters. During the last decade the U.S. Departments of Interior and Commerce have jointly administered the Outer Continental Shelf Environmental Assessment Program (OCSEAP), oil companies in the U.S. and Canada have sponsored operations-oriented research studies, and Environment Canada has funded similar research in the eastern Beaufort Sea. The large amount of recently collected information, its relatively limited distribution, and the fact that it is necessary to insure safe industrial operations led to the preparation of this article reviewing current knowledge of the water under landfast ice along the Beaufort Sea coast.

The paper begins with a definition of the landfast ice zone and a review of its seasonal formation and geographical extent. Second, it examines the physical characteristics of the water under floating landfast ice during fall and winter. Some of these include water temperature and salinity, circulation in both the outer and the inner portion of the zone, and turbidity of the water column and the ice cover. Third, a review is provided of the biological characteristics of the water under landfast ice during fall and winter, some of which include sources of biological energy, structure of the food web, and wintertime food supply. The latter two aspects are reviewed from the primary consumers of detritus through the top carnivores in the under-ice food web. Fourth, physical and biological events are reviewed together for the periods of early spring breakup and then late breakup. The paper ends with an analysis of year-to-year environmental variability in the landfast ice zone.

DELINEATION OF THE LANDFAST ICE ZONE

This review is based on the premise that the zone under landfast ice essentially reforms each fall only after there is an extensive, dense ice cover. This type of ice cover, even if it is a dense layer of slush (grease) ice, removes the influence of

[1]P.O. Box 1406, Eagle River, Alaska 99577, U.S.A.

the wind from the water (Thomas, 1981), thereby giving the under-ice zone unusual oceanographic characteristics. Some of the simultaneous changes in physical and biological processes during freeze-up are diagrammed by Barnes (1980) and by Broad (1980).

The process of freeze-up occurs over several months and can vary from year to year. Broken ice conditions may persist until December, long after formation of an extensive ice cover. Examples of the temporal variations in the formation of a landfast ice cover have been recorded by bowhead whale observers who fly almost daily along large portions of the Alaskan Beaufort Sea coast throughout September and early October (Ljungblad *et al.*, 1980; Ljungblad, 1981). Their observations over several years show that the time of formation of an extensive dense ice cover in the central region varied from late September to mid-October. Freeze-up along the

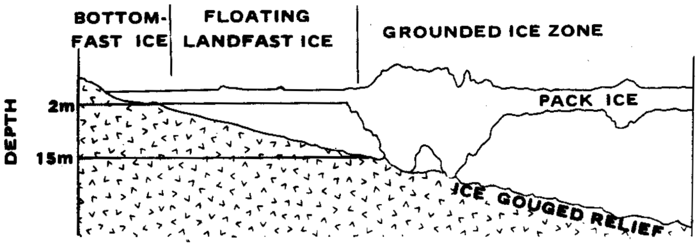

FIG. 1. Cross-sectional diagram of the landfast ice zone, showing the regions of: 1) grounded ice; 2) floating landfast ice; and 3) layer of water under floating landfast ice (redrawn from Kovacs, unpublished, and from Shapiro and Barry, 1978). A three-dimensional cross-section of the floating landfast ice zone is shown in Reimnitz *et al.* (1978).

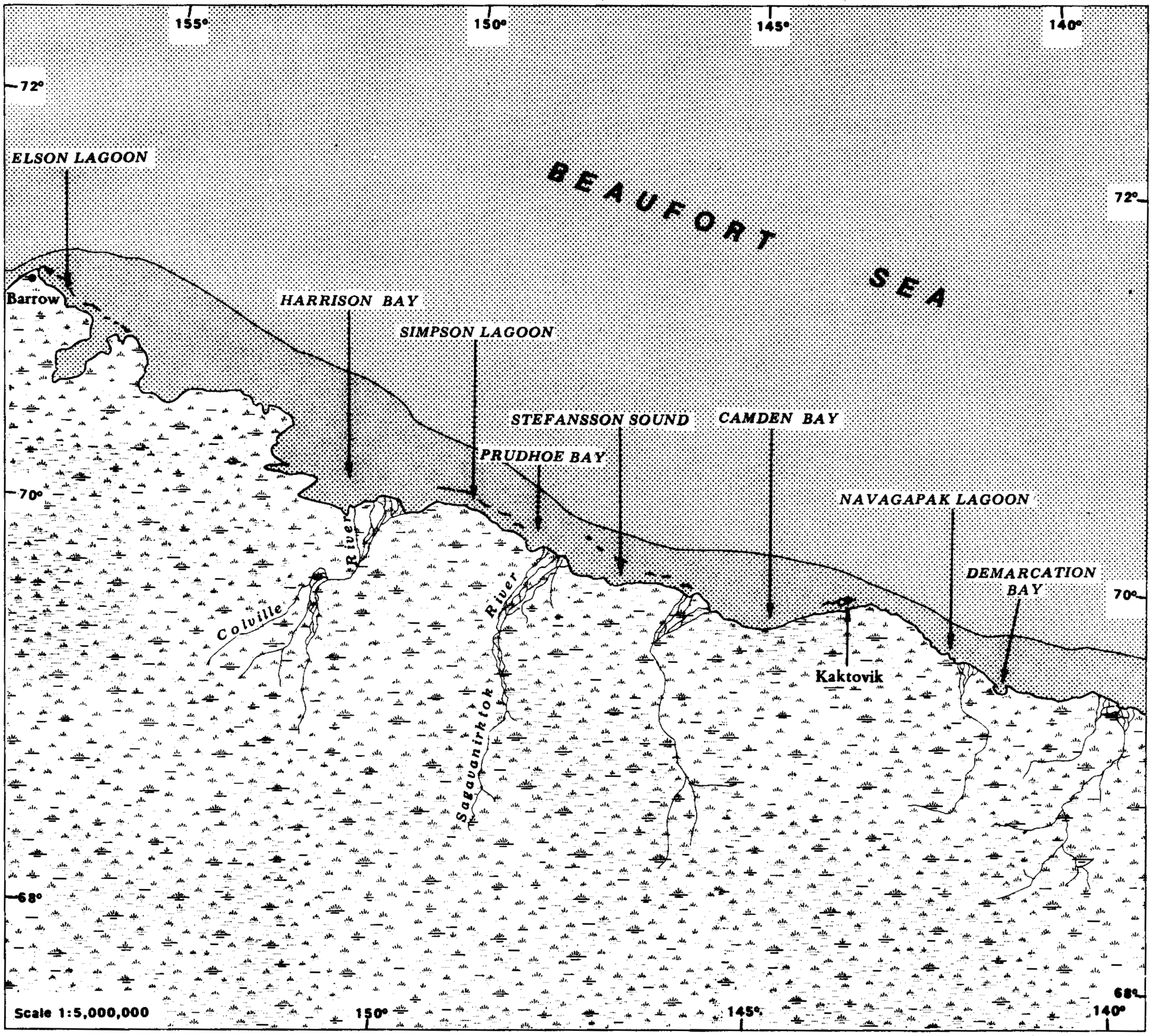

FIG. 2. Average width of the landfast ice along the Beaufort Sea coast as determined with Landsat imagery. Landsat imagery was analyzed by Stringer (1978); figure is redrawn from Shapiro and Barry (1978). The landfast ice edge was determined by combining data on locations of leads and major ice ridges. While the map shows only the average width of landfast ice zone, the range of variation and extreme inner limit of pack ice incursions into the landfast ice zone have also been determined (Stringer, 1982).

eastern, Canadian portion of the Beaufort Sea coastline usually occurs a few weeks later than in the western portion near Point Barrow (Markham, 1975). According to Kovacs and Mellor (1974), the extreme limits of freeze-up at Point Barrow have been as early as the first of September and as late as mid-December.

The width of the landfast ice zone, which determines the amount of water that is covered by floating landfast ice, is influenced mainly by the inner limit of the pack ice. Where the rotating pack ice grinds against the landfast ice, pieces of ice are upended. The upended pieces of ice become grounded in shallow water. Usually in 15 to 23 m of water the density of grounded pieces of ice becomes sufficient to restrain the relatively thick (4 m) pack ice and protect the remaining, relatively thin floating landfast ice (Fig. 1). Ultimately, then, the amount of water covered by the floating landfast ice zone is determined primarily by sea bottom morphology. A minor factor which also influences the width of the landfast ice is the seasonal force exerted by the pack ice. For example, in early winter the zone is usually wider than in late winter (Stringer, 1982). The same investigator found that there is much year-to-year variability; during 25% of recent winters the landfast ice near Stefansson Sound remained about one-quarter again as wide as the average.

The landfast ice zone along the Beaufort Sea coast is usually about 15 km wide near Pt. Barrow and Demarcation Point (Fig. 2); it extends about 60 km offshore near Harrison Bay and the offshore barrier islands along the central Alaskan coastline (Stringer, 1978). Compared to the maximum width (60 km) and maximum depth along the outer edge (23 m), the layer of water under floating landfast ice is very long: 600 km long in the Alaskan portion of the Beaufort Sea. In both the Canadian portion of the Beaufort Sea and the Chukchi Sea there are approximately similar amounts of landfast ice. The overall shape of the layer of water under floating landfast ice is that of a long ribbon.

PHYSICAL CONDITIONS UNDER THE LANDFAST ICE COVER DURING FALL AND WINTER

The layer of water under floating landfast ice develops unique salinity and temperature characteristics during fall and winter. During initial freeze-up, the salinity of the water is about 32‰, the salinity of Beaufort Sea surface water. The drainage of about 3/4 of the solutes out of the ice as it freezes raises the salinity of the remaining water under the ice, which depresses the freezing point. For example, the salinity of Stefansson Sound water was 32.0‰ with a freezing point of -1.7°C in early November 1978 (Matthews, 1981a). By December, the salinity had risen to 33.2‰ with a calculated freezing point of -1.85°C. During the remainder of Matthews's investigation, the temperature of the water column under landfast ice was always within 0.1°C of the calculated freezing point for the observed salinity.

The drainage of solutes from sea ice, and the proximity of the water column temperature to the freezing point, lead to two interesting under-ice phenomena. One is the formation of stalactites on the bottom surface of flat ice (Fig. 3). The stalactites form where brine drains downward from the interior of the ice cover. Measurements of the brine that drained from the ice cover in Resolute Bay, N.W.T., indicated a salinity of about 65‰ (Lewis and Milne, 1977). Simultaneous measurements of the ice sheet showed a decreasing temperature gradient of $0.1°C \cdot cm^{-1}$ away from the ice/water interface. The drainage of such cold, dense brines downward from the ice sheet into the seawater near the freezing point causes the surrounding molecules of seawater to freeze together in cylindrical stalactites. The stalactites are quite common under flat ice that is flooded after freezing, e.g. near ice leads and under artificially flooded and thickened ice roads (Toimil, pers. comm. 1982).

FIG. 3. Underwater photograph of clear flat ice in Stefansson Sound showing stalactites on the bottom surface of the ice. This photograph was taken for Bob Britch of Northern Technical Services; the environmental conditions are described fully in Northern Technical Services (1981). The probable mechanism of formation, and the focus of biological activity around the stalactites, are described by Lewis and Milne (1977). Stalactites are illustrated also in reports by Horner and Schrader (1981) and by Reimnitz and Dunton (1979).

Another result of the proximity of the water column temperature to the freezing point is that frazil ice crystals form on almost any object in the water column. During under-ice studies, frazil ice formation has been observed on submerged mooring lines, fish nets, and oceanographic instruments (Fig. 4). Apparently frazil ice formation on a current meter tripod created sufficient buoyancy on one occasion to lift the tripod off the sea floor (Naidu and Larsen, 1980). Similar amounts of frazil ice have been observed frequently in the Antarctic. The importance of frazil ice formation as a mechanism by which natural objects on the sea bottom may be floated up to, and incorporated into, the ice cover is further discussed for the Beaufort Sea by Reimnitz and Dunton (1979).

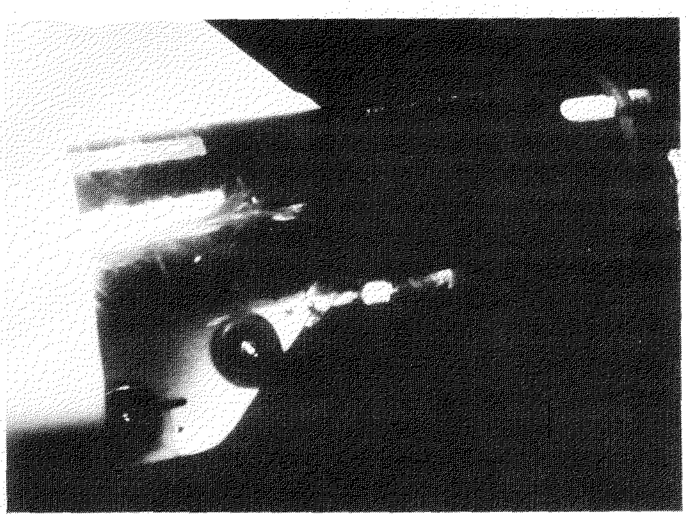

FIG. 4. Frazil ice on the vanes of an underwater current meter in Prudhoe Bay during March 1979. This photograph by Woodward-Clyde Consultants is described in Mangarella *et al.* (1979). Note the angle of the mooring line due to buoyancy of the iced instrument and weak currents.

Another unique characteristic of the layer of water under landfast ice is the circulation pattern. As stated earlier, the formation of an extensive landfast ice cover in autumn removes from the water the effect of the wind, which is the main driving force of summer nearshore circulation. Under the central part of the floating landfast ice, current velocities after freeze-up drop to a low level of about 2 cm·sec^{-1} (Barnes and Reimnitz, 1973; Thomas, 1981). Another study found that by late winter at similar water depths (7 m), current velocities were usually even less than 2 cm·sec^{-1}, which was below the effective threshold of the investigators' current meters (Mangarella *et al.*, 1979). Infrequent surges of water at velocities over 2 cm·sec^{-1} were observed along shore in both directions: i.e., WSW or SE. The driving force of the surges of water in both directions is not clearly known. They may possibly be related to the Beaufort Current which occasionally flows in a transition zone inside of the Beaufort Gyre (Thomas, 1983: Aagaard, 1981; Huggett *et al.*, 1975).

Another possible driving force of the water surges under the outer landfast ice cover is tidal action. Astronomical tides along the central Alaskan Beaufort Sea coast are only about 15 cm, so probably account for only a small portion of the observed water surges. On the other hand, meteorological tides due to low pressure storms can be over 10 times the magnitude of regular astronomical tides (Matthews, 1981a). Therefore, atmospheric pressure changes on the ice cover probably account for most of the water movement under the outer landfast ice cover.

Under the inner landfast ice cover, the circulation differs from that under the outer portion. In the inner landfast ice zone, water velocities up to 25 cm·sec^{-1} are created by tidal pumping through channels between barrier islands and in river deltas (Barnes and Reimnitz, 1973). The surges of water are rapid enough to erode scour depressions in the soft silt around cobbles (Toimil and England, 1982), and some surges are large enough to flood the surface of the bottomfast ice along the shorelines.

Another distinguishing characteristic of the nearshore circulation is the two-layered, onshore-offshore thermohaline circulation. Thermohaline circulation results from dense brine, excluded from ice during freezing, which sinks to the bottom and flows offshore in low topographic areas. Observations that illustrate the thermohaline circulation are: 1) the water close to the sea bottom in some parts of coastal regions such as Harrison Bay and Stefansson Sound is slightly more saline than the rest of the nearly isohaline water column (Kinney *et al.*, 1971; Reimnitz and Dunton, 1979; Toimil and England, 1982); and 2) the water right at the bottom in the middle of Stefansson Sound flows consistently offshore throughout the winter (Matthews, 1981a). The slowness of the offshore bottom current is illustrated by the observation that currents at the same site in Stefansson Sound were insufficient to displace bottom drifters between March and May (Barnes *et al.*, 1982). Matthews (1980) calculated that the offshore flow is about two orders of magnitude slower than the surge currents during early winter storms. The complementary onshore flow of relatively light seawater next to the ice surface has velocities calculated (Matthews, 1980) as averaging a more rapid 6 cm·sec^{-1}.

A significant aspect of the two-layered under-ice thermohaline circulation is that the circulation pattern is the reverse of that found in coastal areas without an ice cover. Typically, the circulation in ice-free estuaries involves the onshore flow of seawater near the bottom and the offshore flow of relatively light freshwater near the surface. The under-ice circulation pattern contrasts also with the summer open-water circulation pattern, which is typically shore-parallel rather than shore-normal.

Another important aspect of the two-layered thermohaline circulation is that, in basins where offshore drainage of the dense solutes is restricted, the salinity may rise to very high levels. During late winter, salinities near 70‰ were measured within a small basin in the center of Prudhoe Bay (Horner *et al.*, 1974). Salinities between 80 and 100‰ were measured behind the barrier islands in Simpson Lagoon (Aagaard, 1978), and water with a salinity of 182.8‰ was collected during late winter behind a gravel bar in Elson Lagoon (Schell, 1975).

High salinities indicate a lack of natural seawater drainage and little flushing action. This means that highly saline water is relatively isolated and stagnant (Newbury, 1979). For example, the salinity rises to 40‰ away from the mouth of Dease Inlet and Elson Lagoon (Schell, 1975); on the basis of the salinity budget, Schell calculated that the flushing time was approximately seven days. Similar calculations for Stefansson Sound indicate a flushing time of at least a month during springtime (Schell, 1982).

A third aspect of the under-ice circulation is its influence on the movement of dissolved substances. The onshore-offshore circulation may serve as a "nutrient pump" (Schell, pers. comm. 1979) that transports phosphate-rich offshore water into phosphate-deficient coastal lagoons. This transport plus microbiological mineralization in coastal sediments leads to a steady accumulation of nutrients in coastal waters throughout winter (Dunton *et al.*, 1982).

The dissolved oxygen concentration is also influenced by the pattern of under-ice water circulation. Dissolved oxygen can become quite depleted under ice where there is no circulation and rapid biological utilization, in spite of the freeze-induced concentration of oxygen in the water (Campbell, 1981). However, where there is some circulation, dissolved oxygen concentrations under the floating landfast ice are not depleted to levels that limit biological activity. For example, the concentration in inner Smith Bay at the end of the winter was 2 mL $O_2 \cdot L^{-1}$, about 1/5 of the summer saturation levels (Schell, 1975).

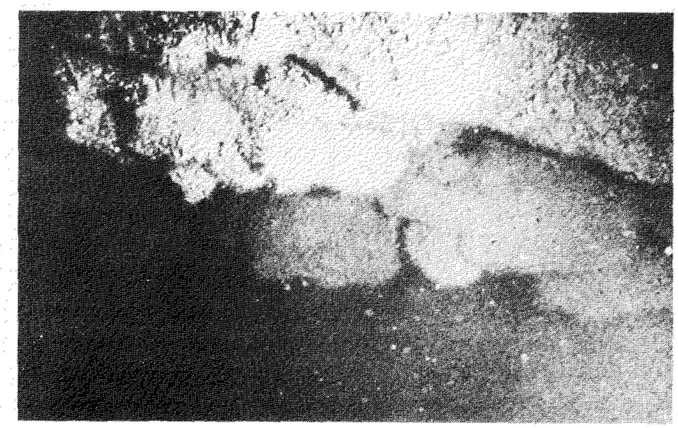

FIG. 5. Underwater photograph of billows of sediment-laden slush ice under a solid ice canopy. The layer of slush ice is 0.5-2.0 m thick. The field across the photograph at the limit of visibility is 2-3 m. The photograph was taken in Stefansson Sound by Ken Dunton in February 1979, and is described in Reimnitz and Dunton (1979). Another underwater photograph of sediment-laden slush ice is shown in Dunton *et al.* (1982).

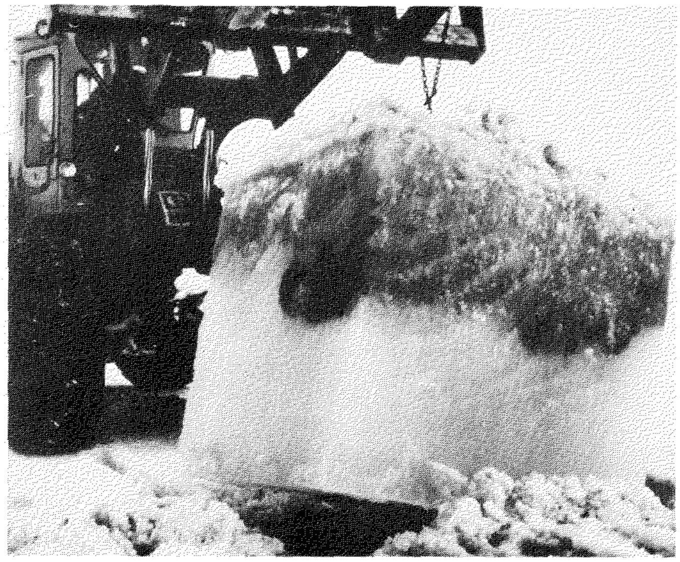

FIG. 6. Block of sea ice containing a surface layer of sediment-laden slush ice. The photograph is from Northern Technical Services (1981). The block, which is approximately 2 × 3 × 2 m, was cut from the ice in Stefansson Sound during April 1979.

Water under landfast ice undergoes seasonal changes in turbidity. During midwinter the water is usually very clear; transmissivity measurements are equal to those for air, even nearshore in 3 m of water (Mangarella *et al.*, 1979). Occasionally, turbid layers of water have been observed, which are probably due to infrequent storm surges or possibly to frazil ice formation on sedimentary particles (Toimil, pers. comm. 1982). In contrast to their midwinter clarity, coastal waters are often very turbid during freeze-up as a result of sediment mixing during frequent fall storms. Frazil ice which freezes during fall storms may concentrate sediment in the water (Larsen, 1980), and during storms it is apparently blown under ice rafts in large billows (Fig. 5) which eventually become frozen into the ice cover (Fig. 6). Sediment-laden ice was estimated to cover as much as 2/3 of Stefansson Sound during the winter of 1978-79 (Schell, 1982; Barnes and Fox, 1979), but there was an order of magnitude less during the winter of 1980-81 (Barnes *et al.*, 1982). Because sediment in ice greatly reduces light transmission, the geographical extent of sediment-laden ice has important biological consequences.

BIOLOGICAL CONDITIONS UNDER THE ICE COVER DURING FALL AND WINTER

There are continuing low levels of biological activity throughout fall and winter in spite of fluctuating salinities, low temperatures, and the absence of direct sunlight from mid-November until early February (Broad, 1980). The low light levels preclude almost all photosynthesis. Chlorophyll levels in phytoplankton cells are barely detectable from November to March (Horner and Schrader, 1982). There is an exception to the absence of primary productivity during fall and winter in some years: a brief bloom of epontic algae (algae attached to the bottom surface of the ice) can occur just after freeze-up and before sunlight intensities decline below threshold levels (Schell, 1982). Also, kelp which grow in a few patches along the coast of the Beaufort Sea increase in length during winter (Dunton *et al.*, 1982); however, investigators attribute the elongation of kelp fronds to translocation of stored carbohydrates rather than to primary production.

In the absence of photosynthesis, other sources of biological energy under the landfast ice in winter are utilized. The importance of the alternate sources is partly related to apparently low food supply conditions during the winter, in contrast to summertime when food generally is not a limiting factor on the level of biological activity.

One temporary source of biological energy for winter predation activity is consumption of organisms in the lower trophic levels which have generally increased rapidly in biomass during the preceding summer. This source of food means that during at least the beginning of the period of ice cover predators are probably not food-limited.

Another temporary source of biological energy for animals is the fat stored within them, e.g. layers of blubber on marine mammals and fat globules within the bodies of arctic invertebrates (Dunbar, 1968).

A third source of biological energy for the food web under floating landfast ice is detritus, or dead organic matter. Much detritus is available in nearshore areas, primarily from erosion of low coastal peat banks and from discharge of rivers. The addition of detritus to the nearshore food web means that the food web is essentially "fossil fuel" subsidized (Schell, 1982). In fact, Schell's calculations indicate that over half of the total annual carbon input to the nearshore marine food web apparently comes from peat banks and rivers. The erosion rate of coastal peat banks averages 1.6 $m \cdot yr^{-1}$, but up to 30 m has eroded during some fall storms (Hopkins and Hartz, 1980; Barnes and Hopkins, 1978). After formation of an ice cover, the erosion process is stopped, and a large supply of detritus is literally sealed into coastal lagoons for the winter.

The main consumers of detritus under floating landfast ice are bacteria. Bacterial activity is greatest where the amount of detritus is greatest: in the sediments near coastlines and especially near river deltas (Griffiths and Morita, 1981). Their work has also shown that there are distinct seasonal trends in the activity level of bacteria, but there are no consistent differences in cell concentration. Both the maximum potential uptake rate of substrate and the concentration of metabolic enzymes are lower in January than in August by a factor of 10. The influence of temperature on the level of activity has been investigated experimentally by Griffiths and Morita (1981). The observed 3°C decrease in coastal bottom water temperature between August and January changes the activity level by a factor of only 2, not 10. The investigators concluded that possibly the quantity or quality of available substrate is partly responsible for the tenfold midwinter decrease in bacterial degradation rates.

Other consumers that are heavily dependent on detritus as part of their diet, and which are also active in the under-ice food web during the dark period of fall and winter, are the epibenthic invertebrates. Most of the detrital material that they ingest is assimilated indirectly from the bacteria, but some is assimilated directly. For example, the epibenthic amphipod *Gammarus setosa* assimilates up to 90% of the detrital organic matter that it ingests (Schneider, 1980b). In general, though, the uptake of terrestrially-derived material by epibenthic invertebrates is indirect; about 90% of the peat probably is assimilated first by bacteria (Griffiths and Morita, 1981). Still, carbon isotope ratios show that coastal epibenthic invertebrates are composed of 20% terrestrially-derived carbon at the beginning of the period of ice cover (Schell, 1980b). On the basis of this low ratio, Schell (1983) has concluded that epibenthic invertebrates utilize only small amounts of terrestrially-derived carbon. However, at the end of the winter, after a long period with no marine primary production of "recent" carbon or preferred animal tissue, the epibenthic invertebrates under the inner landfast ice cover may be composed of a much larger percent of terrestrially-derived carbon. Similar seasonal changes in the isotope composition of body carbon of anadromous fish have been measured by Schell.

Aside from the amphipod *G. setosa*, other epibenthic invertebrates which are very active under the ice cover in coastal lagoons are the amphipods *Onisimus litoralis* and *Boeckosimus affinis* (Fig. 7). Two mysids, *Mysis litoralis* and *M. relicta*, are also abundant and active in shallow water during fall but migrate offshore during midwinter to spawn. The isopod *Saduria entomon* has been identified as a "keystone" epibenthic invertebrate in the food web under the outer part of the floating landfast ice cover (Robilliard and Busdosh, 1979).

These epibenthic invertebrates show many adaptations to the

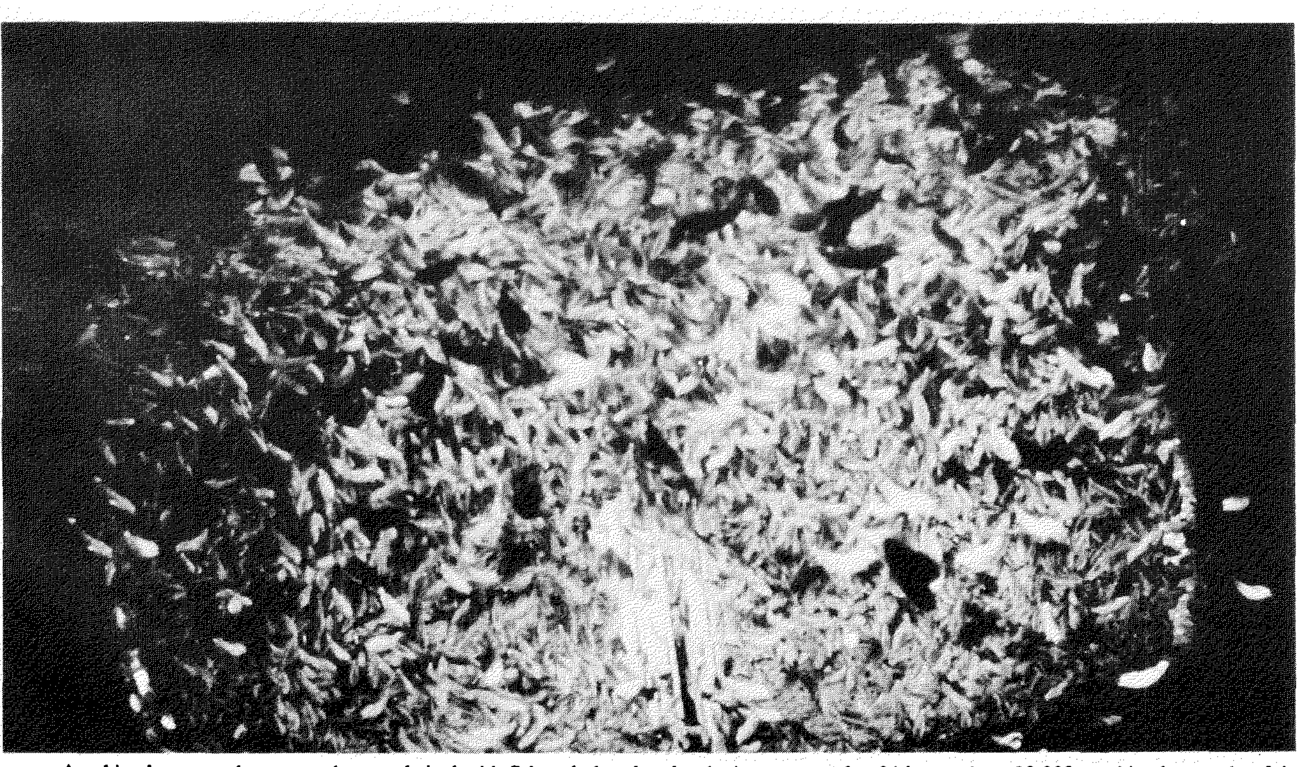

FIG. 7. Amphipods attracted to a trap that was baited with fish and placed under the ice cover. After 24 hours about 20 000 amphipods, mostly of the species *Boeckosimus affinis*, were around the trap. The photograph was taken by Woodward-Clyde Consultants; the situation is described fully in Busdosh *et al.* (1979).

environment under the landfast ice cover. Being mobile, they are not killed by the thickening ice cover as it freezes to the bottom in areas less than 2 m deep (see Fig. 1). The frequent disturbance of the seafloor by ice keels and summer storms does not kill them either. Further, epibenthic invertebrates tolerate a wide range of salinities and temperatures. For example, *Onisimus litoralis* tolerates salinities from 5 to 65‰ Schneider, 1980a). This same investigator showed that *B. affinis* remains active at the low temperature of -2.8°C.

The level of activity of epibenthic invertebrates throughout the winter has been examined by Griffiths and Dillinger (1981) and Robilliard and Busdosh (1979). Both mysids and isopods have been observed feeding under the ice cover. Amphipods were found to congregate under rough ice, where they probably feed on the organic matter in the slush ice (see Fig. 5) and on the small copepods which are also near the undersurface of the ice (Carey, 1981; Cross, 1982). For three common species, the average length of individuals continues to increase slowly throughout the winter.

Other organisms that consume detritus include the benthic infauna, such as polychaetes and bivalves. The distribution and abundance of benthic infauna along the central Alaskan Beaufort Sea coast have been examined by Broad (1979). The biomass of benthic infauna is equal to the biomass of epibenthic invertebrates in coastal lagoons in areas over 2 m deep (Craig and Haldorsen, 1981). However, these same authors point out that only a few predators, such as isopods, consume the infauna, so the infauna may be relatively unimportant in the under-ice food web. A factor which probably reduces both the productivity of infauna and their relative importance in the food web is the continual disturbance of the benthic habitat by ice. One source of disturbance is gouging by ice keels. Survey tracklines generally show more than 100 gouges per km of trackline in the grounded ice zone (Barnes, 1981). Because the gouges average 7.5 m in width, approximately 3/4 of a typical trackline in that zone is disturbed by recent, recognizable gouges. Two more sources of disturbance of the benthic habitat in shallow water are ice gouging during breakup and resuspension during fall storms, which completely overturn the typical muddy, sandy substrate to a depth of about 30 cm at intervals of 5-10 years (Barnes *et al.*, 1981). In water less than 2 m deep, the benthic habitat is also disturbed by the ice cover, which annually freezes to the bottom.

Sessile organisms, while not very abundant or widespread, form special habitats. In a few areas under the landfast ice cover there are kelp communities that include diverse assemblages of attached benthic organisms. Though the kelp is not photosynthetically active during midwinter, the associated animals are active. Divers usually find the polyps of the soft coral *Gersemia rubiformis* in an open, feeding position (Toimil and England, 1982). The snailfish *Liparis* sp., which was always observed close to kelp fronds, spawns on the kelp during midwinter (Beehler *et al.*, 1979; Tarbox and Thorne, 1979).

The largest and densest kelp community in the Alaskan Beaufort Sea is located in Stefansson Sound near Narwhal Island. The kelp is distributed over about 100 km², but the densely colonized area shown in Figure 8 is only about 40 m in diameter. During three years of close observation, variation in the distribution and abundance of kelp in this area has been unnoticeable (Dunton *et al.*, 1982). According to the same investigators, other kelp areas along the U.S. Beaufort Sea coast are southeastern Stefansson Sound near Belvedere Island, near Flaxman Island, in Camden Bay, in Nuvasapak Lagoon, and in Demarcation Bay.

FIG. 8. Patch of kelp in Stefansson Sound (photograph by Ken Dunton). The kelp is mainly the species *Laminaria solidungula* with fronds up to 2 m long. A sponge is in the center of the photograph. Other photographs of the Stefansson Sound kelp patch are included in Dunton *et al.* (1982).

The very restricted distribution of kelp and other attached organisms is a function of several factors. In areas less than 2 m deep the ice cover freezes to the bottom. In areas over 13 m deep there is much bottom scour from floating pieces of ice. Another factor is the rarity of solid substrata. The small patch of kelp in Stefansson Sound is attached to stones that were left after erosion of the glacial deposit (Hopkins, 1981, pers. comm. 1983). Finally, in nearshore areas around river deltas and near naturally eroding barrier islands, there is enough sedimentation and resuspension to bury attached organisms. Excessive rates of sedimentation, though they may occur only infrequently, are probably sufficient to eliminate kelp in some regions because of the kelp's slow rates of recolonization (Dunton *et al.*, 1982). Small amounts of natural sedimentation on the kelp and substrata to which they attach seem to be cleaned off during the winter, possibly by the water surges under the ice cover.

The next section reviews information on fish, a main under-ice consumer of epibenthic invertebrates. The fish in the water under landfast ice along the Alaskan Beaufort Sea coast have been described thoroughly by Craig and Haldorsen (1981) and by Tarbox and Thorne (1979). To summarize their findings, there are only two abundant marine species: the arctic cod, *Boreogadus saida*, and the fourhorn sculpin, *Myoxocephalus quadricornis*. Both are relatively small, generally less than 10 g in weight. Fourhorn sculpins, which occur mainly under the outer landfast ice cover, consume mostly isopods and some amphipods in winter. Arctic cod, which occur under both the outer and the inner landfast ice cover, consume primarily mysids and amphipods. The amphipods on which they prey are abundant in the frazil ice on the undersurface of rough ice as well as near the sea bottom (Carey, 1981; Bradstreet and Cross, 1982).

The fish under the ice cover remain reproductively active throughout the winter. For example, arctic cod move offshore in midwinter to spawn and often congregate in large schools. In February they release pelagic eggs which hatch under the ice in early spring (Broad, 1980). In contrast, fourhorn sculpin have adhesive eggs which are deposited on solid substrata.

Anadromous fish species along the Beaufort Sea coast overwinter primarily under the ice cover in a few seawater-filled river basins that do not freeze completely. For example, arctic ciscoes and least ciscoes overwinter in relatively deep, unfrozen pockets of water under the ice cover in the Colville River delta. The anadromous fish that overwinter in river deltas apparently feed actively but do not reproduce during winter. Their active feeding is indicated by the changes in carbon isotope ratio of their body tissue; the turnover rate of body carbon in least ciscoes during the long winter period averages half of the summertime rate (Schell, 1983).

The ringed seal, *Phoca hispida*, is another major consumer in the under-ice food web, eating both fish and some invertebrates. The most important wintertime food source of ringed seals in the Beaufort Sea is arctic cod (Lowry *et al.*, 1980); in spring ringed seals in coastal areas consume primarily euphausiids (Burns and Eley, 1978; Lowry and Frost, 1981).

The distribution and density of ringed seals in winter are closely related to the characteristics of the sea ice as well as to the food supply. For bearing and nursing young, breeding adults prefer stable ice. Regions with extensive floating landfast ice therefore usually have major ringed seal populations (see Fig. 2).

In summary, the under-ice food web during wintertime is short: ringed seals feed primarily on arctic cod and some invertebrates; arctic cod and other fish feed on epibenthic invertebrates; epibenthic invertebrates feed on decaying detritus and small invertebrates. Most of the animals remain reproductively active; and midwinter metabolic activity levels, as indicated by metabolic rates of bacteria, drop to 1/10 of summer levels.

While food appears to be abundant for all consumers in coastal waters during the summer (Truett, 1981), during winter the supply of food may be low even in nearshore areas, as indicated by the following observations. First, the levels of bacterial activity during January were lower by a factor of 10 than during April, when spring under-ice primary production generally begins (Griffiths and Morita, 1981). This change in level of activity is probably not related to temperature because water temperatures under the ice are still very cold in April. Second, food shortage in late winter is indicated by an observed steady decrease in gut fullness in epibenthic isopods through February, March, and April (Robilliard and Busdosh, 1979). Third, the biomass of the main epibenthic invertebrates decreased from 62.1 to 0.2 mg ash-free dry weight$\cdot$m^{-2} between November and February during the 1978-79 winter. The decrease is possibly evidence for the hypothesis that most of this low trophic level may have been consumed during winter. This information on the under-ice food web indicates that food supply and metabolic activity in general may decline to a nadir in late winter, before rising with springtime under-ice primary production.

SPRING BREAKUP CONDITIONS UNDER THE ICE COVER

The biological and physical characteristics of the water under landfast ice during the spring breakup period will be reviewed chronologically through the spring months from the beginning of under-ice epontic algal production to final breakup in mid-July.

The spring period under the ice cover differs biologically from the fall and winter period primarily in the presence of sufficient light to make photosynthesis possible. After mid-May there is direct sunlight for 24 hours a day, but the amount of sunlight that penetrates through the ice cover is influenced greatly by the thickness of the snowcover on the ice and the amount of sediment incorporated in the ice during fall storms. Even small amounts of sediment in the ice appear to block light transmission and algal growth (Schell, 1980a). The amount of sediment-laden ice in Stefansson Sound in 1978-79 must have greatly depressed nearshore under-ice primary production. Schell (1980a) concluded that the zone of maximum under-ice primary production may generally be the outer landfast ice zone where the ice is usually clear and the snowcover light.

Under clear ice, algae begin growing in late March, forming a yellow-brown epontic layer in approximately the lower 30 cm of the ice column (Horner and Schrader, 1981). These investigators found that the productivity of this epontic layer peaked in May, during which time it was about twice as high as the phytoplankton productivity in the water column. The total amount of epontic algal primary production is estimated to average about 1/20 of the annual total primary production for the nearshore zone (Schell and Horner, 1981). While the amount of epontic primary production is relatively small, it is important because of its occurrence early in spring when food is in short supply.

Springtime epontic primary production forms the basis of a temporary food web on the undersurface of the ice. Epontic algae are fed upon by small copepods (Bradstreet and Cross, 1982; Kern, 1982). Epibenthic amphipods are also important consumers of epontic algae and copepods. In May epibenthic amphipods were twice as abundant near the undersurface of the ice as near the sea bottom (Carey, 1981), and they were frequently observed within under-ice stalactites and brine drainage channels (Lewis and Milne, 1977). Further along the food web, both copepods and amphipods are fed upon by arctic cod, and arctic cod and amphipods are fed upon by ringed seals (Bradstreet and Cross, 1982; Dunton and Schonberg, 1980).

The physical breakup of the ice cover in late spring usually occurs over a 2-1/2 month period of time. First, the ice cover on the rivers melts suddenly and predictably during late May and early June. Because the nearshore sea ice is still bottomfast at this time, the river melt waters run over some nearshore sea ice. Beyond the bottomfast ice zone in the floating landfast ice zone, the overflow waters surge down through cracks in the ice. The outer extent of the area where melt waters drain down into the layer of water under the ice is about 10 km beyond the delta of the Colville River.

Where the overflow waters surge down through cracks in the ice, the melt waters excavate "strudel holes" in the sea bottom. The holes are up to 4 m deep and 20 m in diameter (Reimnitz *et al.*, 1974), which means that much sediment is resuspended. This resuspension, plus the silt in the overflow waters, create turbidity in the water under floating landfast ice in late spring. The effect of the river silt and resuspension on the concentrations of several heavy metals in the nearshore sediments around river deltas has been described by Naidu (1981) and Northern Technical Services (1981).

Beyond the area with strudel holes, the relatively warm, fresh, and probably quite turbid melt waters flow outward just below the ice cover and on top of a layer of saline seawater (Schell and Horner, 1981). The presence of fresh runoff water near Narwhal Island, 17 km offshore, is shown by a salinity at the water/ice interface of only 2.8‰ in June (Carey, 1981). This circulation pattern during breakup, with water flowing outward near the water/ice interface, is the reverse of the wintertime pattern which is landward next to the ice and showly seaward along the sea bottom.

Eventually, fresh runoff waters completely flush from some lagoons the wintertime accumulation of very dense, saline water. For example, the salinity of the water column in Simpson Lagoon changed from 43‰ to 0‰ salinity during one hour in early June; normal seawater of 32‰ eventually returned in early July (Matthews, 1981c). In contrast, very saline water was observed in August in Peard Bay on the northeast Chukchi Sea coastline near Barrow (Wiseman, 1979). In areas with large, sudden changes in salinity there must be severe physiological stress to resident organisms.

During late breakup from mid-June to early July, there are two major physical events that influence the under-ice layer of water. As the ice melts along the coastline, the amount of water exposed to wind increases, and therefore surface water currents increase. Increased current speeds during breakup are shown by under-ice drifters that were placed in the outer landfast ice zone in late May and early June of 1979; they had apparently moved up to 40 km east and west under the ice by the first of July (Matthews, 1981b).

The second major physical event is the melting and overflooding of the nearshore ice cover, which causes the bottomfast ice to float (Pritchard and Stringer, 1981). Flotation of the nearshore ice cover allows greater ice movement, which results in some shallow gouging of the nearshore sea bottom.

Several major biological events occur in the under-ice zone during breakup. First, primary production increases and the depth zone where it mainly occurs deepens. At this stage of breakup the most productive alga cells are in the water column, not on the bottom surface of the ice. The epontic algae on the ice become less productive after breakup of the coastal rivers (Hsiao, 1980; Horner and Schrader, 1982). The latter investigators report that within two days after the fresh river discharge reached their offshore sampling site the layer of epontic algae on the bottom surface of the ice began breaking apart. During this same time the cells in the water column became more productive. The rates of phytoplankton productivity equalled a maximum of 1.5 mg $C \cdot m^{-2} \cdot hr^{-1}$ during early June, which compared with rates of 0.25 and 1.0 in early and late May, respectively (Horner and Schrader, 1982). The main spring phytoplankton bloom begins under the ice cover during June (Schell and Horner, 1981; Schell, 1982). Nutrients in the water column are generally depleted to low levels during June (Dunton *et al.*, 1982); subsequent phytoplankton growth during the summer must depend on relatively slow nutrient regenerative processes. Because the main bloom starts several weeks before final breakup, the total amount of primary production that occurs under landfast ice is possibly 1/3 of the annual total for coastal waters.

A second major biological event during breakup is the recolonization by epibenthic animals of the nearshore areas where the bottomfast ice has floated. For example, many small mysids and amphipods were observed through cracks and holes in the ice cover in 0.5 m and 1 m of water in Simpson Lagoon during late June (Griffiths and Dillinger, 1981). A third event is that anadromous fish, such as least cisco which overwinter in river deltas, migrate out under the sea ice cover. Fourth, the main summertime marine consumers, the seabirds, migrate to the Arctic during June. Oldsquaws and scoters, common diving sea ducks, congregate at shoreleads and feed on epibenthic invertebrates in the under-ice water (Johnson and Richardson, 1981).

The exact time of final breakup and disappearance of the habitat under landfast ice is quite variable, just as is the time of freeze-up. Usually, Stefansson Sound is half free of ice by the first week of July (Schell, 1982), but during some years the ice has failed ever to completely disappear from coastal areas. Two main climatic variables that influence the accumulated thawing-degree days and local rates of breakup each year are air temperature and wind direction (Barry, 1979). The subsequent, relatively short open-water period has important influences on the characteristics of the environment under landfast ice. Coastal areas under a permanent ice cover, such as those in parts of the eastern Beaufort Sea and in the Antarctic, differ substantially from the area under landfast ice along the Alaskan Beaufort Sea coast.

YEAR-TO-YEAR BIOLOGICAL VARIABILITY UNDER THE ICE COVER

Knowledge of the biological variability is important in order to distinguish natural ranges of population fluctuations from industrially-induced changes. Changes in population abundance of up to four orders of magnitude occur in fairly regular three- to six-year cycles in the terrestial food web near Point Barrow (Pitelka, 1957; Batzli *et al.*, 1980). For the coastal marine food web, there are fewer data on population abundance that can be analyzed for magnitude or period of fluctuation. As mentioned previously, the abundance of kelp in central Stefansson Sound has not varied noticeably during three years of close observation. The only really long-term record for a marine species in the Arctic is for harvest of bowhead whales (Marquette and Bockstoce, 1980); however, the whales do not live under the landfast ice cover.

For fish, there are records of the estimated abundance and harvest of anadromous species that have overwintered in the Colville River from 1968 to 1981 (Fig. 9). The records show that there have been only sevenfold, irregular variations in abundance and catch over approximately a decade. Some of the variations in abundance may have been caused primarily by the illustrated variations in fishing effort and catch.

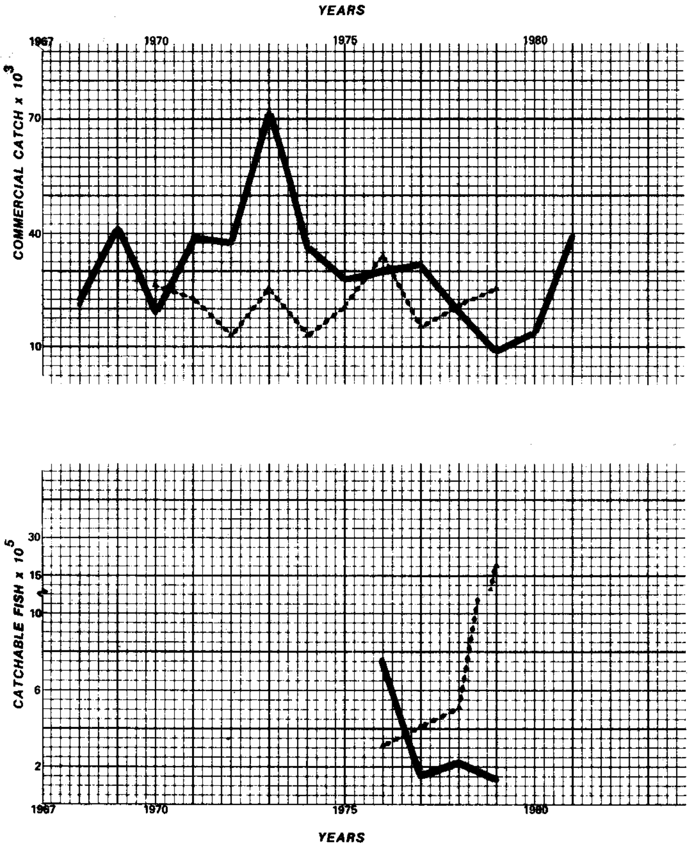

FIG. 9. Commercial catch from 1968 to 1981 and abundance estimates from 1976 to 1979 of arctic cisco (solid lines) and least cisco (dashed lines) in the Colville River delta. The commercial catch data are from Helmericks' commercial fishery. The abundance estimates were determined by a mark/recapture technique. The graphs are redrawn from Gallaway *et al.* (1982) and Craig and Haldorsen (1981).

For ringed seals, there are data on the density of individuals along the Beaufort Sea coast between 1970 and 1981 (Fig. 10). There were up to fivefold decreases in density over approximately a decade, which the investigators attribute to heavy ice conditions during two winters (Burns and Eley, 1978; Burns *et al.*, 1981). Historically, seal populations have probably dropped occasionally to very low levels in local regions, as indicated by Inuit experience with famines.

To summarize, the under-ice populations of fish and seals have fluctuated irregularly in abundance or catch per unit effort by factors of seven and five, respectively, during recent decades. None of the records shows cyclical patterns of abundance similar to the cycles that characterize the terrestial food web near Point Barrow. The magnitude and manner of the fluctuations in abundance of arctic marine populations are probably related to the great variability in the ice cover. An example is the correlation of heavy ice years and low ringed seal density. Other physical factors which have been described are quite variable from year to year and would lead to variable biological conditions under the ice cover. One factor is the erosion rate of coastal peat banks during fall storms; others are the amount of sediment in the ice cover and variations in the width of the landfast ice zone. Variability in these physical factors probably accounts for the observed irregular variability in the populations in the landfast ice zone.

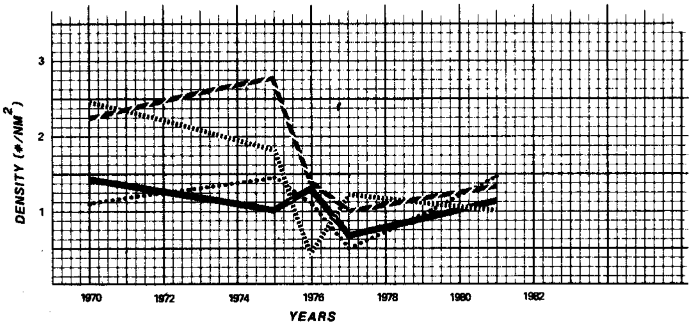

FIG. 10. Average density of ringed seals in units of abundance per square nautical mile in four sectors along the Beaufort Sea coast during five surveys between 1970 and 1981 (data from Burns *et al.*, 1981). The four sectors are Point Barrow to Camp Lonely (short dashes), Camp Lonely to Oliktok Point (dots), Oliktok Point to Flaxman Island (solid), and Flaxman Island to Barter Island (long dashes).

ACKNOWLEDGEMENTS

Many people deserve acknowledgement for helping with this paper. I am most indebted to all of the scientists, principally with the Outer Continental Shelf Environmental Assessment Program (OCSEAP), who have collected the field information and shared their unpublished thoughts with me. I have tried to give specific credit wherever it is due because a main purpose of the paper is to lead readers to the sources of some of this relatively unavailable information. I am also indebted to many people in the Environmental Studies and Environmental Assessment sections of the Minerals Management Service office in Anchorage. They too have shared their thoughts and their knowledge of data sources. Finally, I have written this paper mostly during spare moments at home, which means that mainly my family has tolerated the workload.

REFERENCES

AAGAARD, K. (ed.). 1978. Physical oceanography and meteorology. In: Weller, G., Norton, D. and Johnson, T. (eds.). Interim Synthesis Report: Beaufort/Chukchi. Environmental Assessment of the Alaskan Continental Shelf. National Oceanic and Atmospheric Administration (NOAA), Outer Continental Shelf Environmental Assessment Program (OCSEAP), Rockville, MD. 56-100.

______. 1981. Current measurements in possible dispersal regions of the Beaufort Sea. In: Environmental Assessment of the Alaskan Continental Shelf. Final Reports of Principal Investigators. Vol. 3, Physical Science Studies. NOAA-OCSEAP, Rockville, MD. 1-74.

BARNES, P.W. 1980. Physical processes of winter--Beaufort Sea. In: Schell, D. (ed.). Beaufort Sea Winter Watch. NOAA-OCSEAP Arctic Project Office, University of Alaska, Fairbanks, AK. Special Bulletin No. 29:34-36.

______. 1981. Ice gouging. In: Norton, D.W. and Stackinger, W.M. (eds.). Beaufort Sea Synthesis--Sale 71. Environmental Assessment of the Alaskan Continental Shelf. NOAA-OCSEAP, Rockville, MD. 100-108.

______ and REIMNITZ, E. 1973. The shore fast ice cover and its influence on the currents and sediments along the coast of Northern Alaska. Transactions of the American Geophysical Union 54:1108.

BARNES, P.W. and HOPKINS, D.M. (eds.). 1978. Geological sciences. In: Weller, G., Norton, D. and Johnson, T. (eds.). Interim Synthesis Report: Beaufort/Chukchi. Environmental Assessment of the Alaskan Continental Shelf. NOAA-OCSEAP, Rockville, MD. 101-133.

BARNES, P. and FOX, D. 1979. Sediment-laden first-year sea ice, central Beaufort coast, Alaska. Attachment E, Research Unit 205. In: Environmental Assessment of the Alaskan Continental Shelf. Annual Reports of Principal Investigators, 1979, Vol. 9. NOAA-OCSEAP, Rockville, MD. 231-267.

BARNES, P.W., REIMNITZ, E. and NAIDU, A.S. 1981. Sediments. In: Norton, D.W. and Sackinger, W.M. (eds.). Beaufort Sea Synthesis--Sale 71. Environmental Assessment of the Alaskan Continental Shelf. NOAA-OCSEAP, Rockville, MD. 99-100.

BARNES, P.W., REISS, T. and REIMNITZ, E. 1982. Sediment content of nearshore fast ice--Fall 1980, Beaufort Sea, Alaska. In: Environmental Assessment of the Alaskan Continental Shelf. Annual Report of Principal Investigator. Attachment J, Research Unit 205. NOAA-OCSEAP, Rockville, MD. 7 p.

BARRY, R.G. 1979. Study of climatic effects on fast ice extent and its seasonal decay along the Beaufort-Chukchi coasts. In: Environmental Assessment of the Alaskan Continental Shelf. Final Reports of Principal Investigators. Vol. 2, Physical Science Studies. NOAA-OCSEAP, Rockville, MD. 272-375.

BATZLI, G.O., WHITE, R.G., MacLEAN, S.F., Jr., PITELKA, F.A. and COLLIER, B.D. 1980. The herbivore-based trophic system. In: Brown, J., Miller, P.C., Tieszen, L.L. and Bunnell, F.L. (eds.). An Arctic Ecosystem: The Coastal Tundra at Barrow, Alaska. US/IBP Synthesis Series, Vol. 12. Stroudsburg, PA: Dowden, Hutchinson and Ross. 336-410.

BEEHLER, C., BUSDOSH, M., TARBOX, K. and ROBILLIARD, G. 1979. Occurrence of kelp offshore of Prudhoe Bay, Alaska. In: Environmental Studies of the Beaufort Sea, Winter 1979. Woodward-Clyde Consultants, Anchorage, AK 99503, U.S.A. 36 p.

BRADSTREET, M.S.W. and CROSS, W.E. 1982. Trophic relationships at high arctic ice edges. Arctic 35:1-12.

BROAD, A.C. 1979. A further contribution to knowledge of the benthic and epibenthic fauna of the Beaufort Sea inshore region. In: Environmental Assessment of the Alaskan Continental Shelf. Annual Reports of Principal Investigators, 1979, Vol. 3. NOAA-OCSEAP, Rockville, MD. 371-453.

______. 1980. Biological events - October through June - Beaufort Sea. In: Schell, D. (ed.). Beaufort Sea Winter Watch. NOAA-OCSEAP Arctic Project Office, University of Alaska, Fairbanks, AK. Special Bulletin No. 29:36-39.

BURNS, J.J. and ELEY, T.J. 1978. The natural history and ecology of the bearded seal (*Erignathus barbatus*) and the ringed seal (*Phoca hispida*). In: Environmental Assessment of the Alaskan Continental Shelf. Annual Reports of Principal Investigators, 1978, Vol. 1. NOAA-OCSEAP, Rockville, MD. 99-160.

BURNS, J.J., KELLY, B.P. and FROST, K.J. 1981. Habitat use and winter ecology. Part 2. Trophic relationships, habitat use, and winter ecology of ice-inhabitating phocid sals and functionally related marine mammals in the Arctic.In: Environmental Assessment of the Alaskan Continental Shelf. Annual Report of Principal Investigator. NOAA-OCSEAP, Rockville, MD. 39 p.

BUSDOSH, M., TARBOX, K. and ROBILLIARD, G. 1979. Attraction of amphipods by baited traps. In: Environmental Studies of the Beaufort Sea, Winter 1979. Woodward-Clyde Consultants, Anchorage, AK 99503, U.S.A. 36 p.

CAMPBELL, W.B. 1981. Primary production and nutrients. Part 6, Beaufort Sea Barrier Island-Lagoon Ecological Process Studies. In: Environmental Assessment of the Alaskan Continental Shelf. Final Reports of Principal Investigator. Vol. 8, Biological Studies. NOAA-OCSEAP, Rockville, MD. 199-258.

CAREY, A.G. 1981. The distribution, abundance, composition and variability of the western Beaufort Sea benthos. In: Environmental Assessment of the Alaskan Continental Shelf. Annual Reports of Principal Investigators, 1981, Vol. 2. NOAA-OCSEAP, Rockville, MD. 27-363.

CRAIG, P.C. and HALDORSEN, L. 1981. Fish. Part 4, Beaufort Sea Barrier Island-Lagoon Ecological Process Studies. In: Environmental Assessment of the Alaskan Continental Shelf. Final Reports of Principal Investigators. Vol. 7, Biological Studies. NOAA-OCSEAP, Rockville, MD. 384-678.

CROSS, W.D. 1982. Under-ice biota at the Pond Inlet ice edge and in adjacent fast ice areas during spring. Arctic 35:13-27.

DUNBAR, M.J. 1968. Ecological Development in Polar Regions: A study in evolution. Englewood Cliffs, NJ: Prentice-Hall 119 p.

DUNTON, K., REIMNITZ, E. and SCHONBERG, S. 1982. An arctic kelp community in the Alaskan Beaufort Sea. Arctic 35:465-484.

DUNTON, K. and SCHONBERG, S. 1980. Ecology of the Stefansson Sound kelp community: preliminary results of *in situ* and benthic studies. In: Environmental Assessment of the Alaskan Continental Shelf. Annual Reports of Principal Investigators, 1980, Vol. 1. Appendix 1, Research Unit 356. NOAA-OCSEAP, Rockville, MD. 366-484.

GALLAWAY, B.J., GRIFFITHS, W.B., CRAIG, P.C., GAZEY, W.J. and HELMERICKS, J.W. 1982. An assessment of the Beaufort Sea stock of Arctic cisco (*Coregonus autumnalis*) based upon the Deriso model applied to the catch and effort data from Helmericks' commercial fishery. In: Environmental Assessment of the Alaskan Continental Shelf. Annual Report of Principal Investigator. Research Unit 467. NOAA-OCSEAP, Rockville, MD. 23 p.

GRIFFITHS, R.P. and MORITA, R.Y. 1981. Study of microbial activity and crude oil-microbial interactions in the waters and sediments of Cook Inlet and the Beaufort Sea. In: Environmental Assessment of the Alaskan Continental Shelf. Final Report of Principal Investigator, Research Unit 190. NOAA-OCSEAP, Rockville, MD. 361 p.

GRIFFITHS, W.B. and DILLINGER, R.D. 1981. Invertebrates. Part 5, Beaufort Sea Barrier Island-Lagoon Ecological Process Studies. In: Environmental Assessment of the Alaskan Continental Shelf. Final Reports of Principal Investigators. Vol. 8, Biological Studies. NOAA-OCSEAP, Rockville, MD. 1-198.

HOPKINS, D.M. (ed.). 1981. Gravel sources and management options. In: Norton, D.W. and Sackinger, W.M. (eds.). Beaufort Sea Synthesis--Sale 71. Environmental Assessment of the Alaskan Continental Shelf. NOAA-OCSEAP, Rockville, MD. 169-178.

HOPKINS, D.M. and HARTZ, R.W. 1980. Coastal morphology, coastal erosion, and barrier islands of the Beaufort Sea Coast. In: Environmental Assessment of the Alaskan Continental Shelf. Annual Reports of Principal Investigators, 1980, Vol. 4. Appendix B, Research Unit 204/473. NOAA-OCSEAP, Rockville, MD. 178-181.

HORNER, R., COYLE, K.O. and REDBURN, D.R. 1974. Ecology of the plankton of Prudhoe Bay, Alaska. Institute of Marine Science, University of Alaska, Fairbanks, AK. Report No. R74-2. 78 p.

HORNER, R.A. and SCHRADER, G.C. 1981. Beaufort Sea plankton studies: winter-spring studies in Stefansson Sound and off Narwhal Island. In: Environmental Assessment of the Alaskan Outer Continental Shelf. Final Report of Principal Investigator. Biological Studies. Research Unit 359. NOAA-OCSEAP, Rockville, MD. 138 p.

______. 1982. Relative contributions of ice algae, phytoplankton, and benthic microalgae to primary production in nearshore regions of the Beaufort Sea. Arctic 35:485-503.

HSIAO, S.I.C. 1980. Quantitative composition, distribution, community structure and standing stock of sea ice microalgae in the Canadian Arctic. Arctic 33:768-793.

HUFFORD, G.L. 1974. Dissolved oxygen and nutrients along the north Alaskan shelf. In: Reed, J.C. and Sater, J.E. (eds.). The Coast and Shelf of the Beaufort Sea. Arlington, VA: The Arctic Institute of North America. 567-588.

HUGGETT, W.S., WOODWARD, M.J., STEPHANSON, F., HERMISTON, F.V. and DOUGLAS, A. 1975. Near bottom currents and offshore tides. Beaufort Sea Technical Report No. 16. Dept. of the Environment, Victoria, B.C., Canada V8W 1Y4. 38 p.

JOHNSON, S.R. and RICHARDSON, W.J. 1981. Birds. Part 3, Beaufort Sea Barrier Island-Lagoon Ecological Process Studies. In: Environmental Assessment of the Alaskan Continental Shelf. Final Reports of Principal Investigators. Vol. 7, Biological Sciences. NOAA-OCSEAP, Rockville, MD. 109-383.

KERN, J.C. 1982. Fauna associated with the undersurface of sea ice in the Beaufort Sea, Alaska. Abstract of paper for 45th annual meeting, American Society of Limnology and Oceanography, Lawrence, KS. 31.

KINNEY, P., SCHELL, P., ALEXANDER, V., NAIDU, S., McROY, C.P. and BURRELL, D.C. 1971. Baseline data study of the Alaskan arctic aquatic environments. Institute of Marine Science, University of Alaska, Fairbanks, AK. Report No. R71-4. 176 p.

KOVACS, A. and MELLOR, M. 1974. Sea ice morphology and ice as a geologic agent in the southern Beaufort Sea. In: Reed, J.C. and Sater, J.E. (eds.). The Coast and Shelf of the Beaufort Sea. Arlington, VA: The Arctic Institute of North America. 113-161.

LARSEN, L. 1980. Sediment-laden sea ice: concepts, problems, and approaches. In: Schell, D. (ed.). Beaufort Sea Winter Watch. NOAA-OCSEAP Arctic Project Office, University of Alaska, Fairbanks, AK. Special Bulletin No. 29:58-69.

LEWIS, E.L. and MILNE, A.R. 1977. Underwater ice formations. In: Dunbar, M.J. (ed.). Polar Oceans. Montreal, Québec: The Arctic Institute of North America. 239-245.

LJUNGBLAD, D.K. 1981. Aerial surveys of endangered whales in the Beaufort Sea, Chukchi Sea, and Northern Bering Sea. Naval Ocean Systems Center (NOSC), San Diego, CA 92152, U.S.A. Technical Document 449. 294 p.

______, PLATTER-RIEGER, M.F., and SHIPP, F.S., Jr. 1980. Aerial surveys of bowhead whales, North Slope, Alaska. NOSC, San Diego, CA 92152, U.S.A. Technical Document 314. 181 p.

LOWRY, L.F. and FROST, K.J. 1981. Marine mammals. In: Norton, D.W. and Sackinger, W.M. (eds.). Beaufort Sea Synthesis--Sale 71. Environmental Assessment of the Alaskan Continental Shelf. NOAA-OCSEAP, Rockville, MD. 43-47.

______ and BURNS, J.J. 1980. Variability in the diet of ringed seals, *Phoca hispida*, in Alaska. Canadian Journal of Fisheries and Aquatic Sciences 37:2254-2261.

MANGARELLA, P., CHIN, H. and NIEDORODA, A. 1979. Under-ice water conditions in the Beaufort Sea, relative to the proposed waterflood discharge. In: Environmental Studies of the Beaufort Sea, Winter 1979. Woodward-Clyde Consultants, Anchorage, AK 99503, U.S.A. 252 p.

MARKHAM, W.E. 1975. Ice climatology in the Beaufort Sea. Beaufort Sea Technical Report No. 26. Dept. of the Environment, Victoria, B.C., Canada V8W 1Y4. 87 p.

MARQUETTE, W.M. and BOCKSTOCE, J.R. 1980. Historical shore-based catch of bowhead whales in the Bering, Chukchi, and Beaufort seas. Marine Fisheries Review 42(9-10):5-19.

MATTHEWS, J.B. 1980. Under-ice current regimes in the nearshore Beaufort Sea. In: Schell, D. (ed.). Beaufort Sea Winter Watch. NOAA-OCSEAP Arctic Project Office, University of Alaska, Fairbanks, AK. Special Bulletin No. 29. 16-18.

______. 1981a. Observations of under-ice circulation in a shallow lagoon in the Alaskan Beaufort Sea. Ocean Management 6:223-234.

______. 1981b. Observations of surface and bottom currents in the Beaufort Sea near Prudhoe Bay, Alaska. Journal of Geophysical Research 86(C7):6653-6660.

______. 1981c. Characterization of the nearshore hydrodynamics of the Beaufort Sea and Chukchi Sea. In: Environmental Assessment of the Alaskan Continental Shelf. Annual Reports of Principal Investigators, 1981, Vol. 5. NOAA-OCSEAP, Rockville, MD. 129-149.

NAIDU, A.S. and LARSEN, L.H. 1980. Aspects of sediment dynamics in winter. In: Schell, D.M. (ed.). Beaufort Sea Winter Watch. NOAA-OCSEAP Arctic Project Office, University of Alaska, Fairbanks, AK. Special Bulletin No. 29. 21-23.

NAIDU, A.S. 1981. Aspects of size distributions, clay mineralogy and geochemistry of sediments of the Beaufort Sea and adjacent deltas, north arctic Alaska. In: Environmental Assessment of the Alaskan Continental Shelf. Annual Reports of Principal Investigators, 1981, Vol. 5. Appendix 3, Research Unit 529. NOAA-OCSEAP, Rockville, MD. 207-251.

NEWBURY, T.K. 1979. Possible accumulation of heavy metals around offshore oil production facilities in the Beaufort Sea. Arctic 32(1):42-45.

NORTHERN TECHNICAL SERVICES. 1981. Beaufort Sea Drilling Effluent Disposal Study. Anchorage, AK. 329 p.

PITELKA, F.A. 1957. Some characteristics of microtine cycles in the Arctic. In: Hanson, H.P. (ed.). Arctic Biology. Corvallis, OR: Oregon State University Press. 73-78.

PRITCHARD, R.S. and STRINGER, W. 1981. Ice characteristics and sea ice motions. In: Norton, D.W. and Sackinger, W.M. (ed.). Beaufort Sea Synthesis--Sale 71. Environmental Assessment of the Alaskan Continental Shelf. NOAA-OCSEAP, Fairbanks and Juneau, AK. 81-87.

REIMNITZ, E. and DUNTON, K. 1979. Diving observations on the soft ice layers under the fast ice at DS-11 in the Stefansson Sound Boulder Patch. In: Environmental Assessment of the Alaskan Continental Shelf. Annual Reports of Principal Investigators, 1979, Vol. 9. Attachment D, Research Unit 205. NOAA-OCSEAP, Rockville, MD. 210-230.

REIMNITZ, E., TOIMIL, L. and BARNES, P. 1978. Arctic continental shelf morphology related to sea-ice zonation, Beaufort Sea, Alaska,. Marine Geology 28:179-210.

REIMNITZ, E., WOLF, S.C. and RODEICK, C.A. 1974. Strudel scour: a unique arctic marine geological phenomenon. Journal of Sedimentary Petrology 44:409-420.

ROBILLIARD, G. and BUSDOSH, M. 1979. Biology of the isopod (*Saduria entomon*) at Prudhoe Bay, Alaska. In: Environmental Studies of the Beaufort Sea, Winter 1979. Woodward-Clyde Consultants, Anchorage, AK 99503, U.S.A. 122 p.

SCHELL, D.M. 1975. Seasonal variation in nutrient chemistry and conservative constituents in coastal Alaskan Beaufort Sea waters. In: Environmental Studies of an Arctic Estuarine System. U.S. Environmental Protection Agency, Corvallis, OR 97330, U.S.A. Document No. 660/3-75-026: 233-298.

______. 1980a. Chemical overview of biological-physical process interactions. In: Schell, D.M. (ed.). Beaufort Sea Winter Watch. NOAA-OCSEAP Arctic Project Office, University of Alaska, Fairbanks, AK. Special Bulletin No. 29. 25-30.

______. 1980b. Foodweb and nutrient dynamics studies in nearshore Alaskan Beaufort Sea waters. In: Environmental Assessment of the Alaskan Continental Shelf. Annual Reports of Principal Investigators, 1980, Vol. 2. NOAA-OCSEAP, Rockville, MD. 467-515.

______. 1981. Foodweb and nutrient dynamics in nearshore Alaska Beaufort Sea waters. In: Environmental Assessment of the Alaskan Continental Shelf. Final Report of Principal Investigator. Biological Sciences. Research Unit 537. NOAA-OCSEAP, Rockville, MD. 185 p.

______. 1983. Carbon-13 and carbon-14 abundances in Alaskan aquatic organisms: delayed production from peat in Arctic food webs. Science 219:1068-1071.

______ and HORNER, R.A. 1981. Primary production, zooplankton, and trophic dynamics of the Harrison Bay and Sale 71 area. In: Norton, D.W. and Sackinger, W.M. (eds.). Beaufort Sea Synthesis--SALE 71. Environmental Assessment of the Alaskan Continental Shelf. NOAA-OCSEAP, Rockville, MD. 3-12.

SCHNEIDER, D.E. 1980a. Physiological responses of arctic epibenthic invertebrates to winter stress and exposure to Prudhoe Bay crude oil dispersions. In: Environmental Assessment of the Alaskan Continental Shelf. Annual Reports of Principal Investigators, 1980, Vol. 1. Appendix 2, Research Unit 356. NOAA-OCSEAP, Rockville, MD. 413-475.

______. 1980b. Trophic relationships of the arctic shallow water marine ecosystem. In: Environmental Assessment of the Alaskan Continental Shelf. Annual Reports of Principal Investigators, 1980, Vol. 1. Appendix 5, Research Unit 356. NOAA-OCSEAP, Rockville, MD. 568-578.

SHAPIRO, L. and BARRY, R.G. (eds.). 1978. The sea ice environment. In: Weller, G., Norton, D. and Johnson, T. (eds.). Interim Synthesis Report: Beaufort/Chukchi. Environmental Assessment of the Alaskan Continental Shelf. NOAA-OCSEAP, Rockville, MD. 3-55.

STRINGER, W.J. 1978. Morphology of Beaufort, Chukchi and Bering seas nearshore ice conditions by means of satellite and aerial remote sensing. In: Environmental Assessment of the Alaskan Continental Shelf. Annual Reports of Principal Investigators, 1978, Vol. 10. NOAA-OCSEAP, Rockville, MD. 1-220.

______. 1982. Location of the shear zone in the eastern Beaufort Sea. In: Environmental Assessment of the Alaskan Continental Shelf. Annual Report of Principal Investigator, Research Unit 267. NOAA-OCSEAP, Rockville, MD. 26 p.

TARBOX, K. and THORNE, R. 1979. Measurements of fish densities under the ice in the Beaufort Sea near Prudhoe Bay, Alaska. In: Environmental Studies of the Beaufort Sea, Winter 1979. Woodward-Clyde Consultants, Anchorage, AK 99503, U.S.A. 111 p.

THOMAS, D.R. 1981. Behavior of oilspills under sea ice - Prudhoe Bay. In: Environmental Assessment of the Alaskan Continental Shelf. Annual Reports of Principal Investigators, 1981, Vol. 6. Attachment No. FRC 175, Research Unit 567. NOAA-OCSEAP, Rockville, MD. 61-187.

______. 1983. Potential oiled ice trajectories in the Beaufort Sea. In: Environmental Assessment of the Alaskan Continental Shelf. Final Report of Principal Investigator, Research Unit 567. NOAA-OSCEAP, Rockville, MD. 59 p.

TOIMIL, L.J. and ENGLAND, J.M. 1982. Environmental Effects of Gravel Island Construction, Stefansson Sound, Alaska. Harding Lawson Associates, Anchorage, AK. 62 p.

TRUETT, J.C. 1981. Synthesis, impact analysis, and a monitoring strategy. Part 7, Beaufort Sea Barrier Island-Lagoon Ecological Process Studies. In: Environmental Assessment of the Alaskan Continental Shelf. Final Reports of Principal Investigators. Vol. 8, Biological Sciences. NOAA-OCSEAP, Rockville, MD. 259-359.

WISEMAN, W.J. 1979. Hypersaline bottom water: Peard Bay, Alaska. Estuaries 2(3):189-193.