Oil, Ice & Climate in the Beaufort Sea

E.R. WALKER

Technical Report No. 35

Beaufort Sea Project

OIL, ICE AND CLIMATE IN THE BEAUFORT SEA

E. R. Walker

Frozen Sea Research Group
Ocean & Aquatic Sciences
Department of the Environment
825 Devonshire Road
Victoria, B.C. V9A 4T5

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Beaufort Sea Project
Dept. of the Environment
512 Federal Building
1230 Government St.
Victoria, B.C. V8W 1Y4

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1. SUMMARY

The amount of crude oil which may be released to the environment during drilling in the Beaufort Sea is estimated. The effects of oil in terms of the Beaufort Sea surface heat budget are briefly discussed. Considering the amount of oil likely to be released in exploratory drilling, its movement, and its effect on the surface heat budget, it is estimated that no important climatic effects are likely.

2. INTRODUCTION

Exploratory oil drilling is about to commence offshore in the Beaufort Sea. Oil released to the environment during this drilling may affect the climate in the Beaufort Sea and beyond. In this brief note a superficial survey is conducted of the amounts of oil which could be released to the environment, where it might go in the frequently ice-covered waters and how it might affect the heat balance, hence the climate, in the area.

Although the terms of reference of this study cover only the exploratory drilling, brief mention is made of the production phase which will follow if oil is found.

There is no original work involved. This is merely a 'desk' study.

3. CLIMATE

3.1 Introduction

Climate is defined (Huschke 1959) as the 'synthesis of weather', the statistical collective of weather conditions during a specified time. Man's activities, particularly in agriculture, are closely attuned to present climatic conditions, so that the changes in precipitation patterns presently occurring south of the Sahara have led to starvation of thousands. Any lowering of temperatures in the grain growing areas of Canada, where, in Saskatchewan, the latitudinal gradient of the annual temperature is about 0.01°C per mile obviously may have consequences for its agriculture.

3.2 Global Climate

The present climatic fields of temperature and precipitation are the result of the characteristics, chemical, physical, geometrical, of our earth and sun system. The sun's energy enters the earth's atmosphere, is absorbed in part by the earth's surface, causes energy flows to the atmosphere, until after conversion the same amount of energy is lost by infrared radiation. The crude schematic picture for the whole earth is seen in Figure 1 (after Fletcher 1965). In general terms the energy flow is from the earth's surface in the tropics where much solar energy is absorbed, to the upper layers of the atmosphere, over the whole of the earth, where it is radiated to space. The latitudinal imbalance of solar radiation falling annually on the earth's surface is shown in Figure 2, after Budyko (1974). When energy from this solar radiation has passed through the processes schematically indicated in Figure 1, the meridional

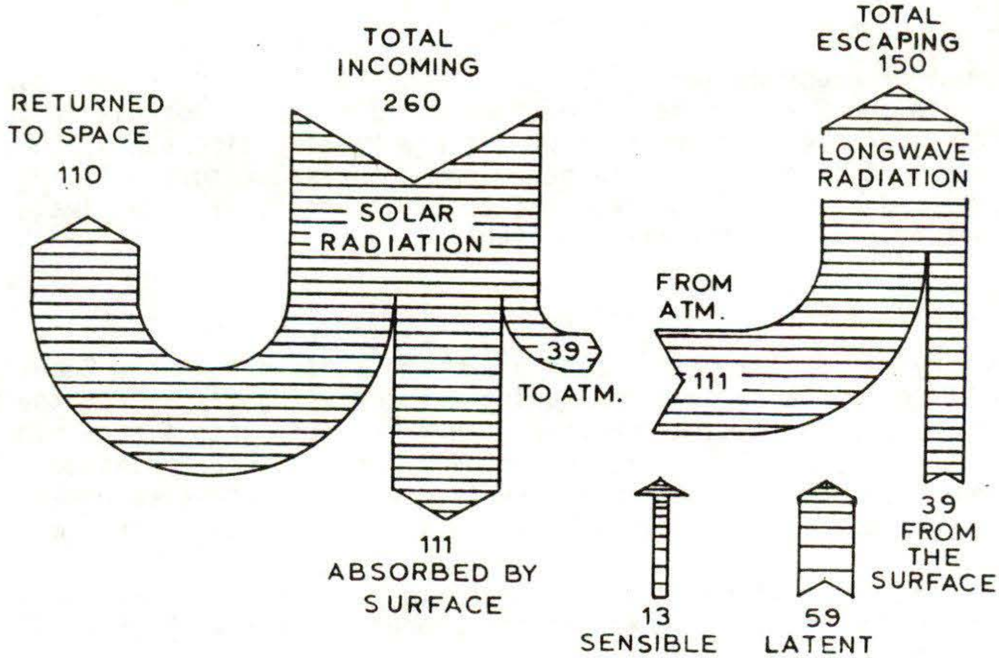

Fig. 1 Annual heat budget of the earth-atmosphere system for the whole planet. Heat flows in kcal $cm^{-2}year^{-1}$, (after Fletcher 1965).

heat flows in Figure 3 (after Kellogg and Schneider, 1974) result. Weather, and its time integration, climate of different parts of the earth are manifestations of the energy flows of these figures. The complexity of the atmosphere, ocean and land surface systems involved in these energy flows is illustrated schematically in Figure 4, also after Kellogg and Schneider (1974).

3.3 Climatic Change

As may be imagined, a machine as complex as that illustrated in Figure 4 does not run perfectly smoothly. The earth's climate is subject to variability on many scales. The fact that life has persisted unbroken for eons, which implies that the earth's temperature has remained within the range 10-25°C (Schwarzback 1973), is almost surprising.

Several reviews of climate and climatic change have recently appeared (Lamb 1972, Kutzbach 1974, N.A.S., 1975, and the many volumes of World Survey of Climatology [Elsevier]). Several recent conferences on the subject have just published or are about to publish proceedings (WMO/IAMAP 1975, International Study Conference on the Physical Basis of Climate, GARP 1975). The following remarks on climatic change are mostly paraphrases (with or without acknowledgement) of the works mentioned above and other relevant recent reviews.

The weather element which has received most attention in studies of climatic change has been temperature, with glacial episodes accompanying low temperatures. Evidence is found for glacial

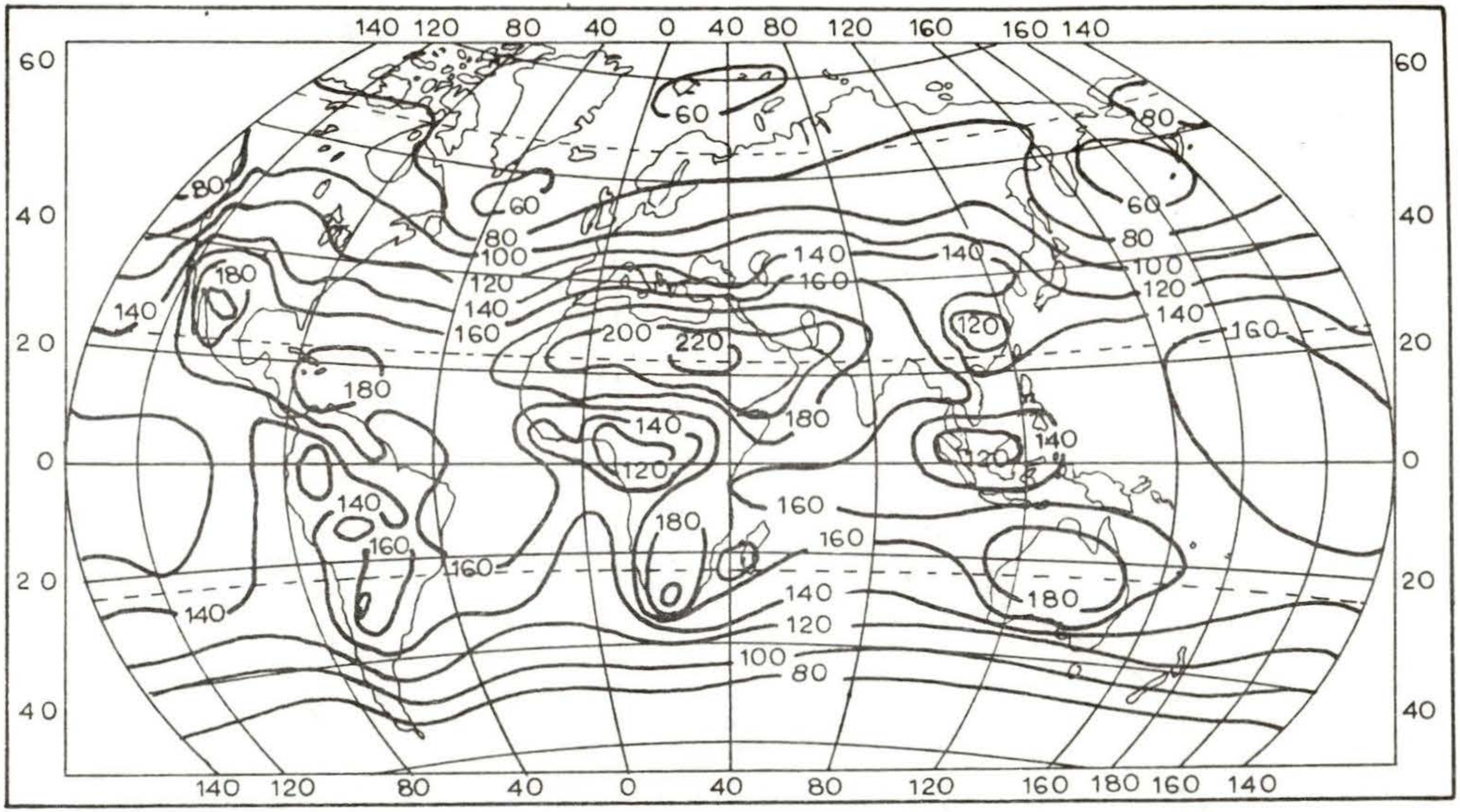

Fig. 2. Total solar radiation received at the earth's surface (kcal cm^{-2} $year^{-1}$), (after Budyko 1974).

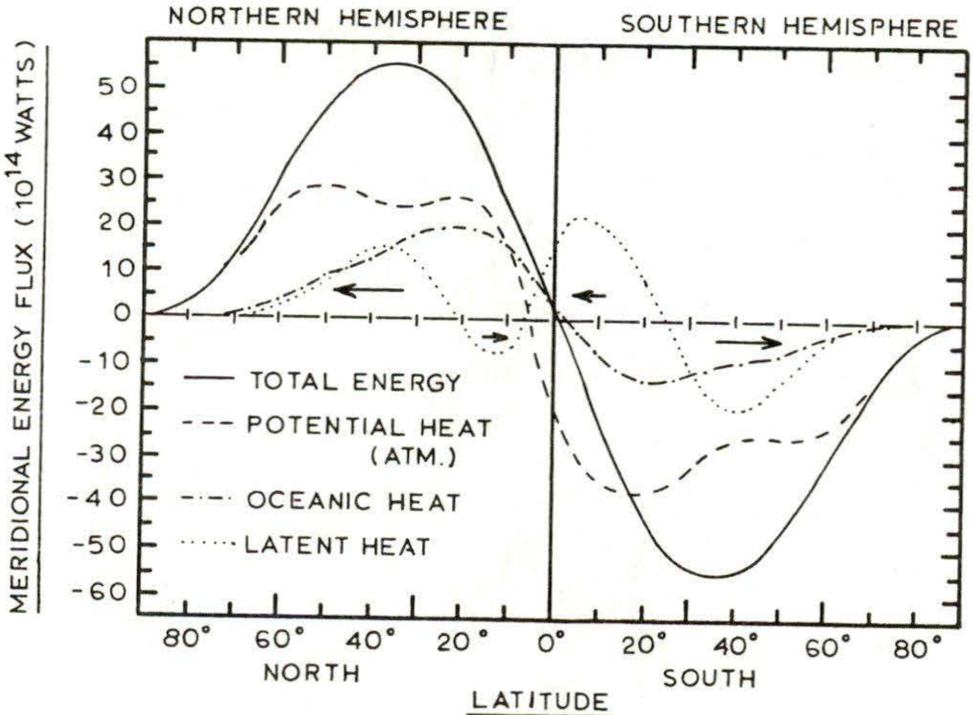

Fig. 3 Annual mean meridional flux of energy for the earth-atmosphere system and breakdown into oceanic flux and that carried by the atmosphere as potential and latent heat (10^{14} W.) (after Kellogg and Schneider 1974).

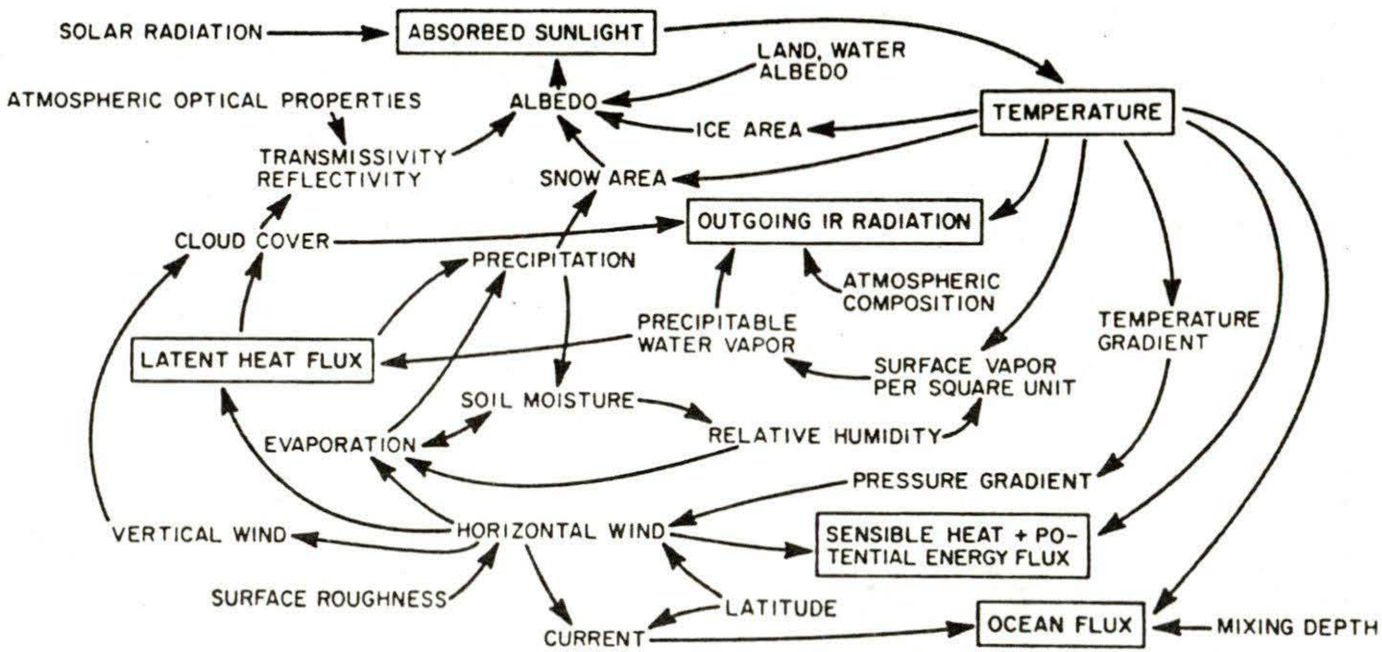

Fig. 4 Climatic feedback linkages IR, infrared, (after Kellogg and Schneider 1974).

episodes as far back as 700 million years. Since the glaciation of Antarctica began 30 million years ago such episodes have perhaps become more common. At the height of the last glaciation, about 20,000 years ago, most of present-day Canada was buried by ice. Various causes for these changes in climate have been suggested. They include changes in the solar output, and changes in the patterns of solar input to earth caused by orbital parameters. Polar wandering, continental drift, mountain building, volcanic activity may be influences. Instabilities may exist in the running of the earth-atmosphere machine. Man's activities which may be beginning to affect the climate include changing the face of the land, pollution of atmosphere and ocean, and for the future, output of heat from nuclear fuels.

Information gained at a recent conference on climatic change (WMO/IAMAP 1975) indicates that striking advances in dating changes in temperature and other climatic elements are coming out of analyses of information in cores from deep-sea sediments. The material, still largely unpublished, is revealing cycles in world wide temperatures at periods of about 20,000, 40,000 and 100,000 years which apparently agree closely with the solar energy input variations caused by orbital parameters (Milankovitch 1941). In fact the workers in this field, amid some skepticism, claimed almost perfect correspondence and predicted another ice age in about 1000 years.

Even in the present inter-glacial period variations occur. In Figure 5 (Dansgaard et al 1975) qualitative observations and records were used to stretch temperature records back a millennium. Even these small temperature variations were important for agriculture. The recent temperature trends in Figure 6 were shown in WMO/IAMAP 1975, with the remark that it was the consensus of those who follow temperatures closely that the trend had turned upwards in the last few years.

It was obvious at this conference that those who were measuring climatic changes were ascendant over those trying to explain the changes, with the hope of forecasting them. The real difficulty is the complexity indicated in Figure 4. Simple models which attempt to short circuit the complexity furnish results whose application to the real world is doubtful. The complicated models of the general circulation may, for the purpose of considering climatic change, be regarded as still in infancy. Excellent reviews of the present status of atmospheric modelling in the field of climatic change include those by Gates (WMO/IAMAP 1975), Schneider and Dickinson (1974) and Smagorinsky (1974).

3.4 Arctic Climate

Energy flows in polar regions differ from those for the globe as a whole as shown in Figure 1. In the Arctic (Figure 7) the annual solar input to the system is roughly half that of the global average. Long wave loss to space is only slightly less than the global average. In polar regions advection of heat by the atmosphere helps maintain this long wave output.

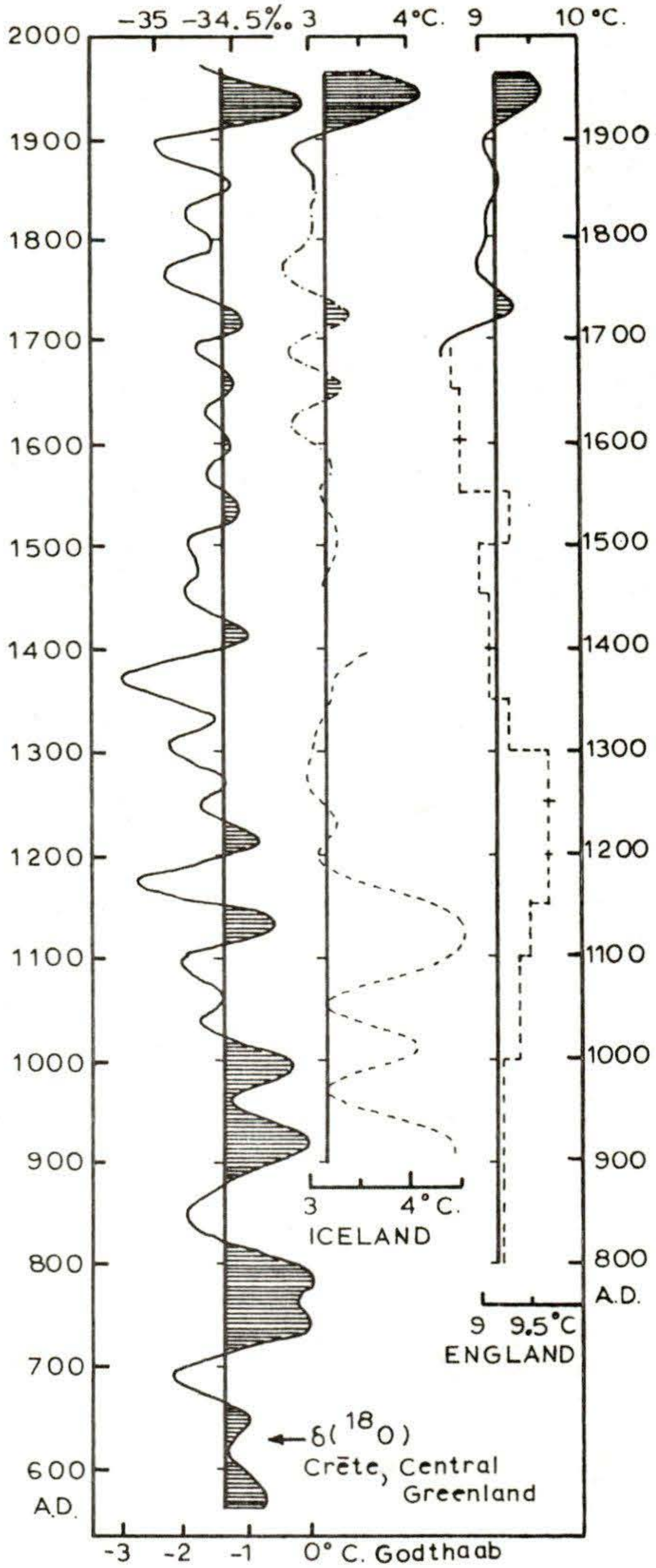

Fig. 5 A millennium of Icelandic and English temperature records with a comparison of ^{18}O concentration in Greenland (after Dansgaard et al 1975).

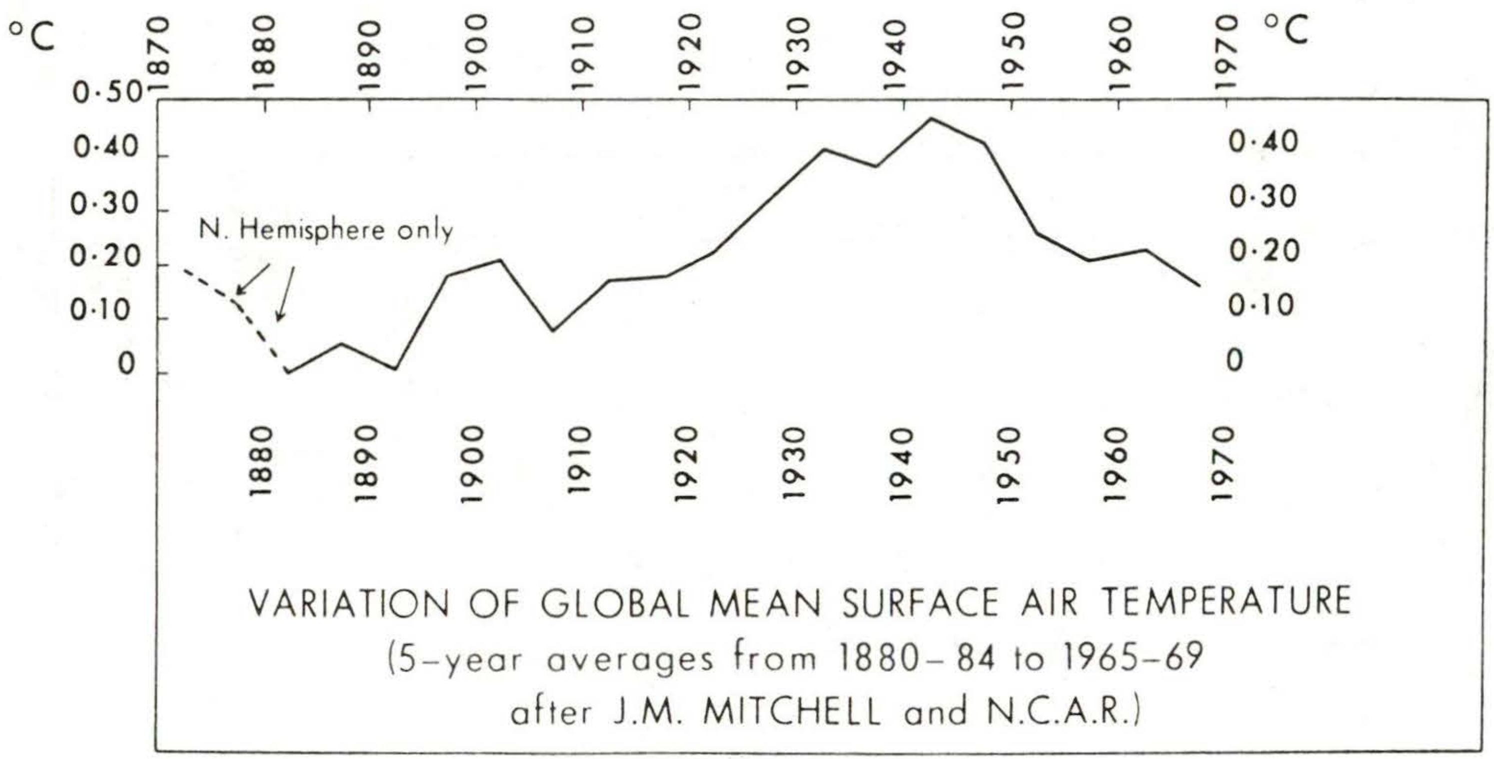

Fig. 6 Recent changes of mean surface air temperatures averaged over the globe (Mitchell, included in Lamb 1975).

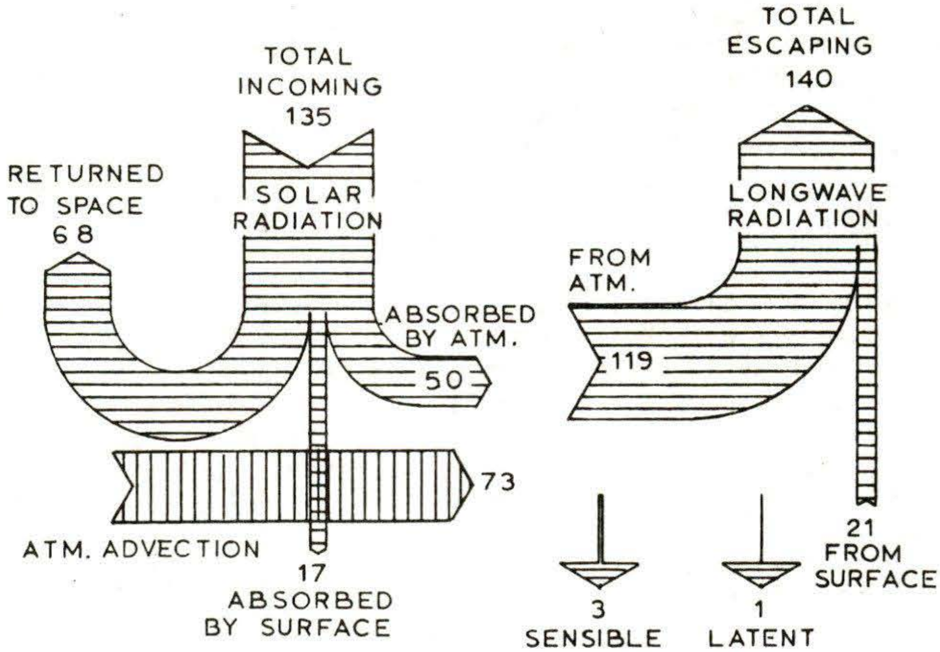

Fig. 7 Annual heat budget of the earth-atmosphere system in the central Arctic. Oceanic heat and melting of snow are assumed to balance and are omitted, (kcal cm^{-2} $year^{-1}$) (after Fletcher 1965).

Since solar input is absent in midwinter there must be great annual variations, largely in the atmospheric advection of heat, to maintain a balance. Meridional oceanic heat advection is small in the Arctic, particularly in the central Arctic, where the water is covered by sea ice. Oort (1974, 1975) has discussed atmospheric advection northward across 60°N and finds interannual variations of up to 10 percent. It appears temperature variations within the polar regions are about five times smaller than would be expected from the differences in atmospheric advection. This suggests variations in radiational cooling, or variations in exchange of heat with the underlying surface, caused by variations in sea ice cover. Data on variation of sea ice cover in the central Arctic, and in the Beaufort Sea are almost non-existent, although Wittmann and Schule (1966) suggest there is appreciable variation in the sea ice cover. It is most probable, of course, that sea ice cover variations in the North Atlantic area are of more significance than those in the polar ocean or Beaufort Sea.

3.5 Arctic Climatic Change

Climatic change in the Arctic may be intimately associated with glaciations, the most striking result of such changes. Several publications are available (Zubov 1943, Fletcher 1965, Fletcher 1966, Doronin 1969, Budyko 1974, Weller and Bowling 1975) in which climatic change in the Arctic is considered specifically. The following remarks consist largely of paraphrases of material from these publications.

Kellogg (1975) has discussed several of the climatic feedback mechanisms from Figure 4 which are peculiar to polar regions. They include among others; (1) Albedo - polar ice cover - temperature, (2) sea ice - air/sea exchange - surface water layer, (3) Albedo - polar cloud cover - temperature, (4) sea ice - ocean circulation - winds. Kellogg makes the point that the loops do not, of course, operate in isolation but are incorporated in the more complete picture of Figure 4.

The one-dimensional model of Maykut and Untersteiner (1971) which is used below deals with Kellogg's loop (1). Work by Fletcher (1965) in which he analyzed heat budgets at the Arctic Ocean surface indicated that albedo is a major factor determining the extent of Arctic sea ice. Fletcher believes that if the Arctic sea ice is removed it is uncertain whether it will reform. Using air mass heat loss figures from lower latitudes, including Hudson Bay, Fletcher implies that if the area of open water is not hundreds of kilometres in diameter sea ice will form. If the Arctic Ocean should remain open then Fletcher judges that increased solar heat absorbed in summer would be largely balanced by increased sensible and latent heat losses. The latter would result in about 30 cm winter evaporation according to Fletcher which may lead to snow accumulation on nearby land. Doronin (1969), Budyko (1974) and others including Rakipova (1966) have carried out similar studies.

Another of the feedback loops, number (2), noted by Kellogg, which involves a change in the density structure of the Arctic Ocean water has recently been revived by Aagaard and Coachman (1975). If the fresh stable surface water layer could be removed (for example by diverting large Siberian rivers southward) then the increased flow to the surface of oceanic heat might be sufficient to ensure an ice-free Arctic Ocean. Otherwise, even if all sea ice were removed the present heat balance and water structure would ensure it reformed.

It may be noted that latest core data (Clark 1971) indicates that the Arctic Ocean has had continuous ice cover for many hundred thousand years. While this may cast doubt on theories (Donn and Ewing 1966) which require an ice-free Arctic Ocean to initiate glaciations, it does not negate glaciation initiation by an ice-free ocean, caused by man's intervention. Large-scale numerical models have been run under glacial conditions (Williams et al 1975, Williams 1975) and under conditions of an ice-free Arctic Ocean (Fletcher et al 1971, Warshaw and Rapp 1973, Newson 1973). Williams' results indicated "air temperatures in July during an ice age (were) more like winter of today".

The work of Newson resulted in the winter temperature differences from present as shown in Figure 8. As noted earlier these models are in their infancy. Indeed Newson ends by remarking:

> "I do not claim that these results necessarily indicate what might happen in the real atmosphere, because the model itself has several shortcomings, and one should not dwell on the results in particular areas because they are almost certainly not quantitatively correct.

The sign of temperature changes in mid-latitudes is perhaps rather unexpected, and the results illustrated that qualitative arguments may be deceptive and unreliable in considering a physical system as complicated as the atmospheric circulation which includes so many non-linear interactions and feed-back mechanisms.

Considerable refinement and elaboration of numerical models will be required before their answers to questions of the kind raised in this letter can be accepted with any confidence. Nevertheless the potential superiority of the numerical approach for the investigation of problems of climatic modification is beyond doubt."

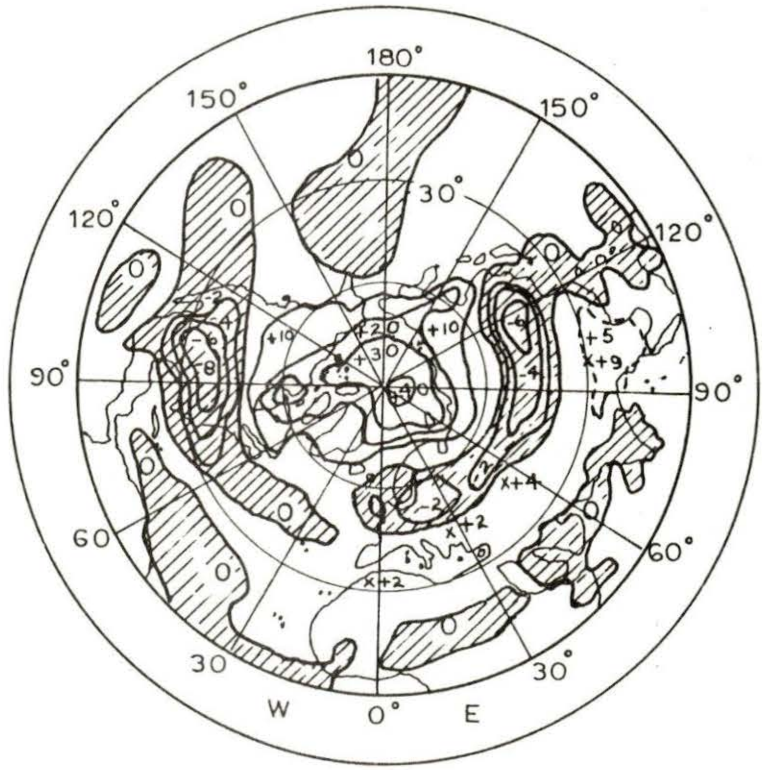

Fig. 8 Temperature differences, in °C near the surface, between the computation for the winter season with an ice-free Arctic and the computation with ice at the mean climatological position. Hatched areas indicate regions of cooling in the ice-free experiment (after Newson 1973).

4. SEA ICE

4.1 Sea Ice in the Beaufort Sea

The heat flows crudely illustrated in Figure 7 result, of course, in very cold temperatures. Warm-month temperatures at stations along the mainland coast are about 6°C while at the northern end of the Beaufort Sea gyre they are near 0°C. Cold-month temperatures are about -30°C and -33°C respectively. Because of the water density structure in which a stable surface layer restricts heat flow up to the water surface, the latter must freeze in the autumn. In the southern parts of the

Beaufort Sea the sea begins to freeze by October and in this area the ice thickens through the winter, growing if undisturbed to a thickness of about 2 m, and extending from shore to about the 25 m depth contour. It generally melts completely the following summer. This ice which melts completely each year is hereafter called first-year ice as compared to perennial or multi-year ice which does not completely melt in summer.

Further north the surface heat balance is such that ice covers most of the sea surface all year. The extended life of this ice enables it to attain a yearly average thickness of about 3 m (Maykut and Untersteiner 1971). This heavier ice is, in contrast to the first-year ice along the shores of the Beaufort Sea, in constant motion. It tends, on the largest scale, to rotate clockwise as a mass in the Beaufort Sea as shown by the Pacific or (more usually) Beaufort Sea gyre in Figure 9 after Dunbar and Wittman (1963). The period of rotation of ice in the gyre is estimated by Campbell and Martin (1973) to range between 7 to 10 years.

The contact region between this northern perennial ice, and the landfast first-year ice stretches for most of the year across the Beaufort Sea roughly northeast to southwest, about 50 to 150 km off the coast. This transition zone (or as Kovacs and Mellor, 1974, term it - seasonal pack ice), is of variable width, frequently out to the edge of the continental shelf (200 to 500 m) from the 25 m depth contour.

The coverage of the sea surface by landfast ice is nearly 100 percent in winter, decreasing to zero in August and September. The transition zone contains frequent leads, and much young ice. The polar pack cover is estimated by Kovacs and Mellor to comprise about 60 to 70 percent multi-year ice, and in winter, 25 to 35 percent new ice with 1 to 5 percent open water. In summer open water replaces much of the young ice between the polar floes. Ridging is at maximum in the ice of the transition zone, at minimum in the southern landfast ice.

The above zones are idealizations or long-term average positions since, because of vagaries of wind and weather, the transition zone can move north or south. The winds in the coast line area tend to be either southeast or northwest, blowing ice which is not firmly affixed to the shore, offshore or onshore. The mean surface water currents are shown in Figure 10, after Wilson (1974). Figure 10 suggests that floating material in the coastal areas may have erratic trajectories in open water situations but that material further out would move with the perennial pack as in Figure 9.

The bottom of sea ice has irregularities on several scales ranging from ridge keels (characteristic horizontal 'wavelength' $l \simeq 1$ km, vertical length $Z \simeq 10$ m), to meso-scale undulations ($l \simeq 10$ m, $Z \simeq 10$ cm) caused by variation in heat balances, to microscale undulations ($l \simeq 1$ mm, $Z \simeq 1$ mm) caused by crystal structure. These structures are important in 'containing' oil under ice.

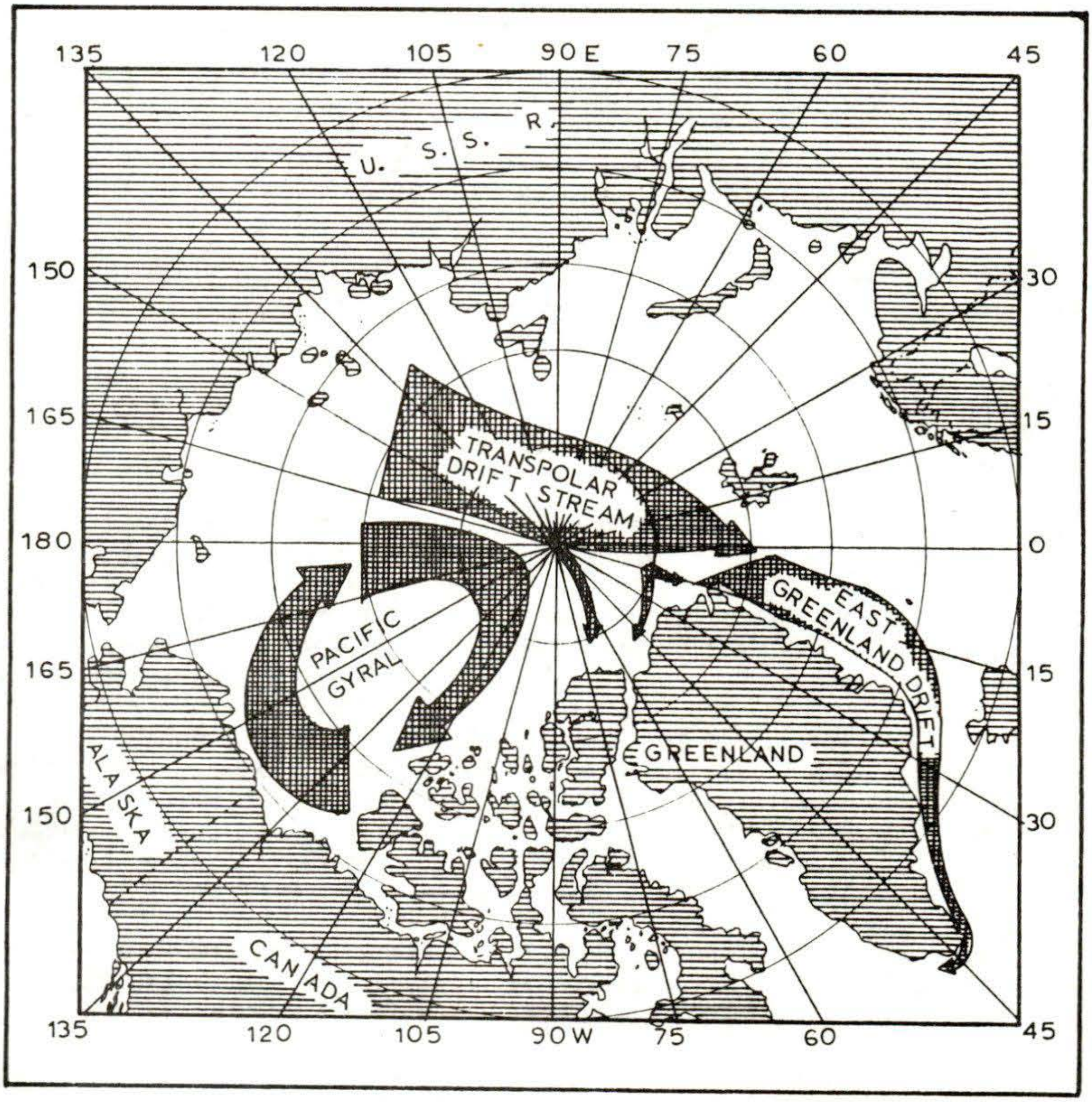

Fig. 9 Schematic of ice movements and surface water currents in the Arctic Ocean (after Dunbar and Wittman 1963).

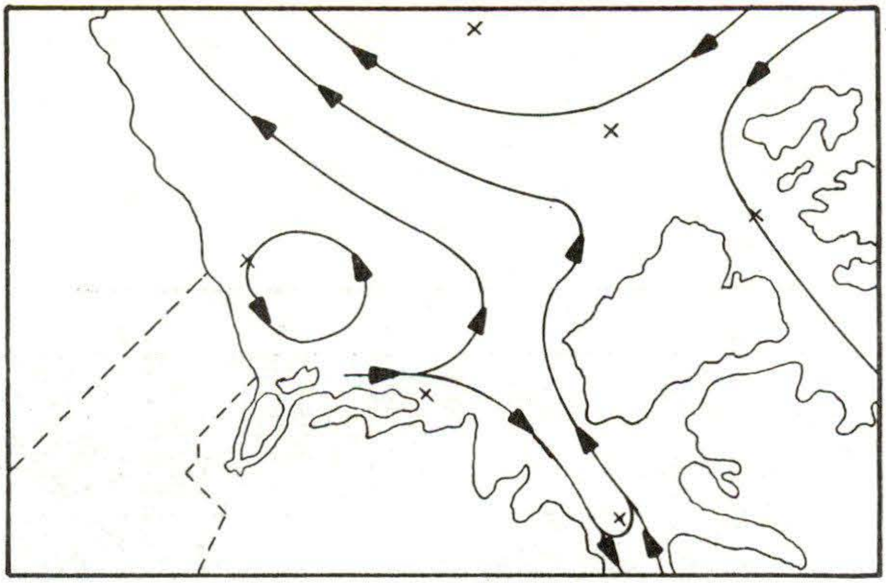

Fig. 10 Schematic of mean water current streamlines in the Beaufort Sea (after Wilson 1974).

5. OIL

5.1 Characteristics of Crude Oils

Crude oils, when fresh, are dark-colored fluids, with densities of 0.8 to 0.9 g cm^{-3}. They are complex mixtures of hydrocarbons. The lighter fractions evaporate fairly readily so crude oil densities and viscosities increase with weathering. Many of their properties, and the rate of evaporation are temperature dependent. Characteristics of, and weathering of crude oils similar to those expected from the Beaufort Sea area are discussed by NORCOR (1975), Chen, Keevil and Ramseier (1975), and for Alaskan Oils by Kinney, Button and Schell (1969), Atlas (1973), Glaeser and Vance (1971). Atlas, for Prudhoe Bay crude on water at Prudhoe Bay, reported loss by weight over five weeks of 31 percent for non-biological loss, and 60 percent for natural losses including biodegradation. By fertilization he was able to raise losses to 80 percent.

Experiments have shown (NORCOR 1975), Chen, Keevil and Ramseier (1975), Rosenegger (1975), that crude oil forms films of thickness 0.5 to 1.0 cm on the bottom of flat sea ice. At a film thickness of 0.5 cm one Imperial Gallon would cover an area of about 1 m^2, one barrel about 35 m^2, 10^6 barrels about 35 km^2 and 10^6 m^3 about 220 km^2. For oil to cover larger under-ice areas it has to be in very small droplets, or in patches. Fresh crude, spilt on a clean water surface is capable of extensive spreading, in some cases until theoretically forming a monomolecular layer (Nelson-Smith 1972). On natural waters spreading never goes so far. For oil in leads Ayers et al (1974) suggests oil film thicknesses will be 0.1 to 1.0 cm.

5.2 Emulsification of Oil

In environments of sufficient energy density, oil and water can be emulsified. The circumstances where the turbulence may be appreciable are in a jet/plume of an underwater blowout, in the jet/plume of a ruptured underwater oil pipe under pressure, and at the open water surface. Emulsions of oil droplets in water tend to coalesce over periods of time depending upon the qualities of oil and emulsion. The emulsions of water droplets on oil appear more stable. The stability is highly dependent upon properties of the oil concerned. With higher viscosity and greater density these water-in-oil emulsions behave quite differently from liquid crude oil.

An emulsion on the water surface would float. Under and in ice the greater density and the higher viscosity of emulsions may cause slower upward migration than for fresh crude oil. Emulsified oil under ice might be moved more easily by under-ice currents. The total area covered by an emulsion should be less than in the case of liquid oil. Emulsions would probably be easier to sink than unemulsified crude oil, but very much more difficult to burn.

5.3 Review of Oil Release Probabilities

The subsea formations extending under the Beaufort Sea to the edge of the continental shelf are estimated to contain from 3×10^9 (EMR 1973) to as much as 4×10^{10} barrels of recoverable oils according to some oil industry estimates. Industry sources estimate this oil may be accompanied by as much as 50 trillion cubic feet of gas.

Exploration has already commenced and will continue at least through 1980. In the exploration until 1980, approximately twenty wells will be drilled from twenty artificial islands in water depths less than 15 to 20 m. Another twenty wells may be drilled from floating platforms or ships in water depths up to 150 m. If significant quantities of gas and particularly oil are found, the level of exploratory activity may double or triple. If no significant finds are made by 1980 the activity may well taper off. The total number of exploratory wells might range from 40 to 50 by 1980 to as many as 120 to 150 by 1990.

The oil industry believes the possibility of a subsea well blowout with a significant escape of oil is very small. If we postulate one blowout which runs wild for one year, then if the release rate is 2500 barrels per day at the start, and 1000 barrels per day after the first month, the blowout will release 382,500 barrels of oil (Hnatiuk, personal communication). Each barrel of oil will be accompanied by 800 cu. ft. of free gas. This blowout could occur anytime during the exploration phase. We may expect additional small releases of fuel oil throughout the exploration phase because of minor spills. We may roughly estimate those as being less than 1000 barrels per year. We might expect losses of oil from artificial islands to occur all around the year. Most releases from ships will probably occur in summer.

It appears from material quoted above that oil spilled in the Arctic will undergo weathering. The rate of this weathering is very important but as yet is relatively unknown. To allow a maximum for weathering and other losses we may guess that oil, when spilled, loses 40 percent by volume per summer. While not unreasonable this figure may well be more appropriate to weathering in the southern part of the Beaufort Sea than in the north. However, for these rates of weathering the amount of oil then expected to be 'at large' during the exploration phase is shown in Figure 11, in which a blowout is postulated to occur in summer 1976. If this oil remains offshore and has a film thickness of 0.50 cm, we may expect roughly the areal coverage shown in Figures 11 and 12. If the under-ice oil film is of the thickness 0.56 cm, found in the field by NORCOR (1975) or the 0.80 or 0.88 cm found in the laboratory by Rosenegger (1975) the area covered will be correspondingly smaller. Similarly if the oil spreads on water to a film thickness of 0.1 cm (Ayers et al 1974), or less the areas involved will be correspondingly larger.

Although the terms of reference of these Beaufort Sea studies cover only the exploration phase it is interesting to speculate upon the amounts of crude oil likely to be released if exploration proves reserves of the size estimated above. The production phase may begin before 1985 and continue at least until 2010. The removal of oil may be as much as 300,000 barrels per day in 1985 and 600,000 barrels per day by 1990. To bring this oil to the surface,from 50 to 200 wells may be producing by 1985 and perhaps 100 to 300 wells may be producing by 1990. The oil will most likely be gathered by sea-bed pipelines.

To estimate the releases of oil during the production phase in a crude way we may assume a loss factor (for all causes) of the total oil likely to be produced. There is considerable dispute about the appropriate loss factor. Martin and Campbell (1974) estimate a loss factor of 0.1 percent. Oil industry sources believe this is high by a factor of 100 which would mean a loss factor of 0.001%. Other estimates of loss factors have ranged in value between these two figures, for example Kinney, Button and Schell (1969) estimated a loss factor of 0.03 percent of the total oil produced or handled in Cook Inlet, Alaska, where there are tanker terminals and refineries as well as offshore wells.

If we use the (perhaps high) figure of 1×10^{10} barrels of oil in the Beaufort Sea, then for the loss factors of 0.1 percent and 0.001 percent the total loss of oil would be 10^7 and 10^5 barrels respectively, or 4×10^5 barrels per year and 4×10^3 barrels per year if the oil release is spread evenly over a production phase of 25 years. The assumption of uniform release rate seems reasonable since the losses during the production phase will probably be many small spills with a remote chance of a larger accident.

These cumulative losses are given in Figure 12 as if they are spread evenly over a 25-year production phase beginning in 1985. Volumes of oil for no weathering and for a 40 percent loss per summer are shown. If the oil is assumed to stay offshore and remains at a thickness of 0.5 cm, the areas covered by this oil in the production

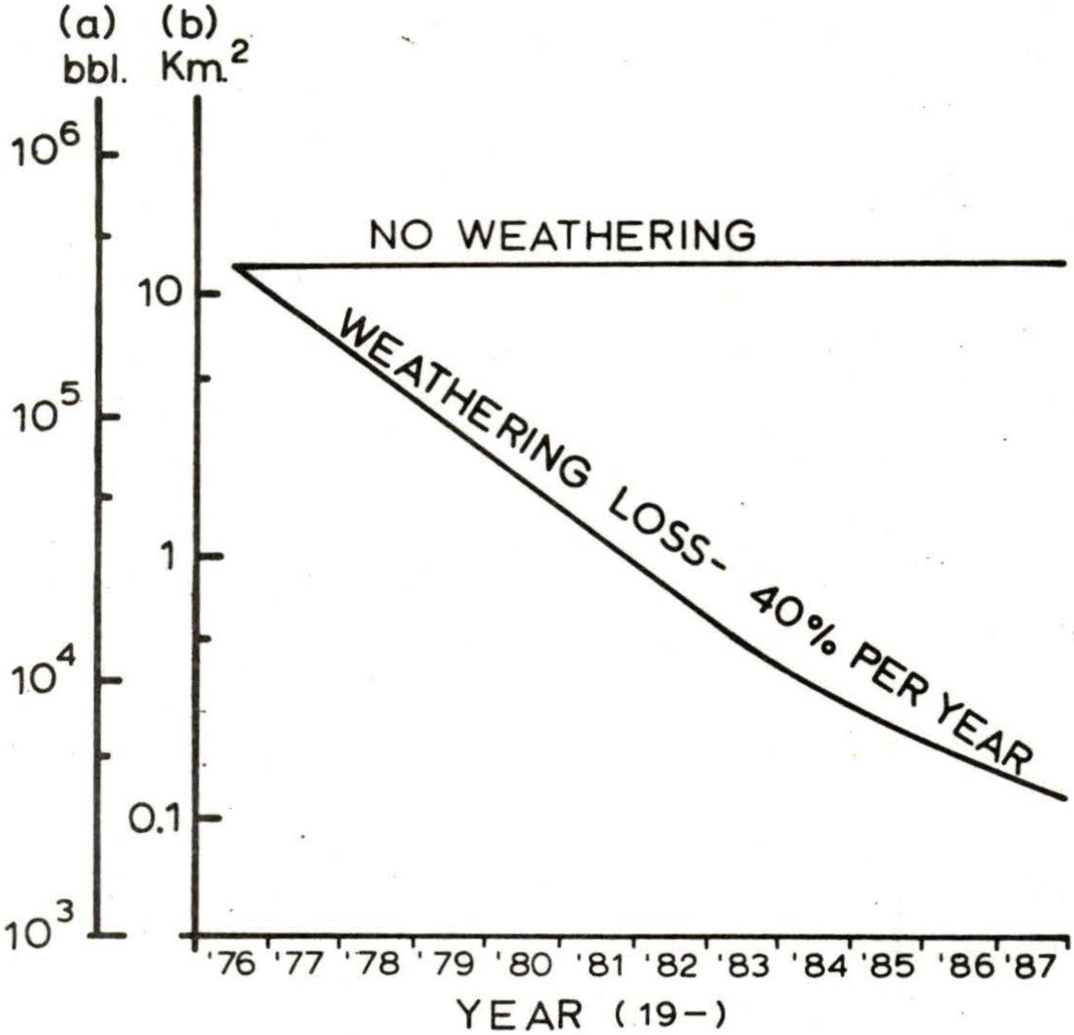

Fig. 11 Scenario of amount of crude oil released during Canadian exploratory drilling in the Beaufort Sea and remaining 'at large' in various years with a blowout assumed in 1976. (a) Oil amount (barrels), (b) Area covered at an oil layer thickness of 0.50 cm (km^2).

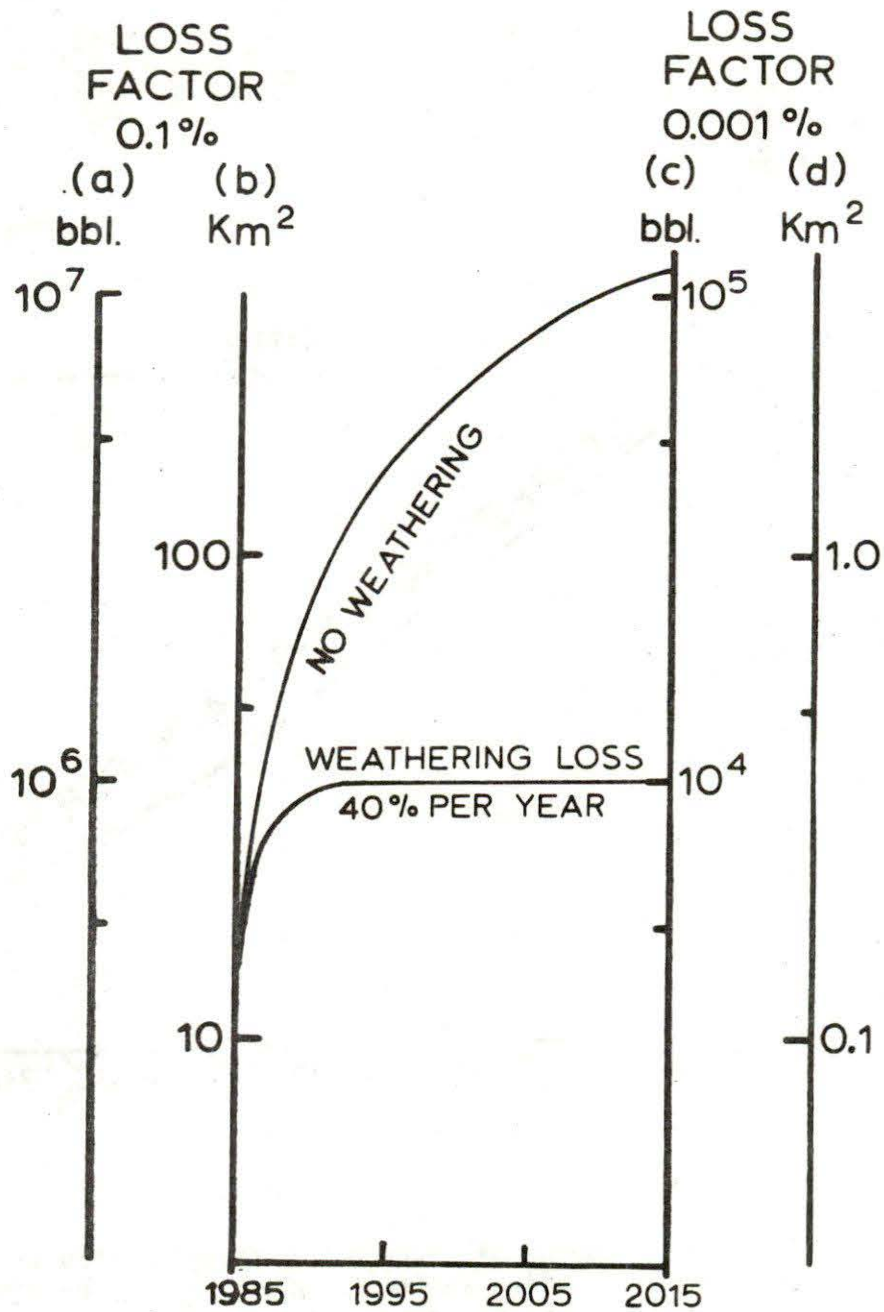

Fig. 12 Scenario of amount of crude oil released during production phase of operations in the Beaufort Sea and remaining 'at large'. (a) Oil amount, loss factor of 0.1 percent, no weathering and weathering loss 40 percent per year, (b) Area covered by oil in (a) assuming oil layer thickness of 0.5 cm, (c) Oil amount, loss factor of 0.001 percent, no weathering and loss of 40 percent per year, (d) Area covered by oil in (c) at oil layer thickness of 0.5 cm (barrels & km^2).

phase is shown. As noted above if the oil film layer thickness is other than 0.5 cm the areas in Figure 12 will be correspondingly changed.

We assume that a blowout on man-made islands is equally likely at any time of year. In summer, oil will presumably escape into open water. In winter, it will probably run out on the top of ice, probably landfast first-year ice. With some luck and forethought oil escaping in the winter could be collected or burned.

Blowouts of wells drilled from floating platforms or ships are most likely to occur over the periods August to October. The probabilities of stopping the flow of oil from blowouts in this situation (if natural bridging-over does not occur) are hard to gauge. They are probably less in incidents occurring toward the end of the season and presumably a blowout could continue to emit oil and gas from one autumn to the next summer.

Oil from such a blowout will initially be released into open water or loose pack ice. Heavier pack ice could move over the site. Depending on the location of the blowout the winter situation could include ice cover ranging from landfast annual ice to polar pack ice.

5.4 Oil on Water

As crude oil has density $\rho \simeq 0.8$ g cm^{-3}, sea ice a density of $\rho \simeq 0.9$ g cm^{-3}, fresh water a density of $\rho \simeq 1.0$ g cm^{-3}, and sea water a density of $\rho \simeq 1.02$ g cm^{-3}, fresh crude will rise if it can, to the surface of ice or water, or if spilled from above will remain there. Oil would form a film or mat on water. The processes which must be considered for oil spilt on water are shown in Figure 13 (after Nelson-Smith 1972). In the Arctic, temperatures drop low enough for the sea water to freeze in which case any surface oil will be incorporated into the upper layer of ice. Ice floes may also be present.

Oil rising from below broken pack ice, or oil on water through which broken pack ice moves, will probably tend to remain on the water surface in leads. Oil film thickness will probably be higher than on open water because of damming by sea ice floes. Wave action of sufficient vigor will splash oil onto the ice. When the water in leads freezes, the oil will be incorporated in the ice. Leads are areas of structural weakness and particularly susceptible to pressure ridging. Since there will be some concentration of oil in the lead areas there should be concentrations of oil in newly formed ridges in oiled ice areas.

5.5 Oil on Snow

Oil spilled on snow forms an oil-snow mixture. In winter it would be covered by later snowfalls. Oil on snow has been investigated by Glaeser (1971) and others (Mackay et al 1975). The latter reports that Alberta crude oil at 0°C is readily absorbed by snow and contaminates an area of about 0.01 m^2 per litre (1.6 m^2 per barrel). Hot oil (60°C) melted through the snow and contaminated an area of about 0.024 m^2 per litre (3.8 m^2 per barrel). In spring, oil-snow

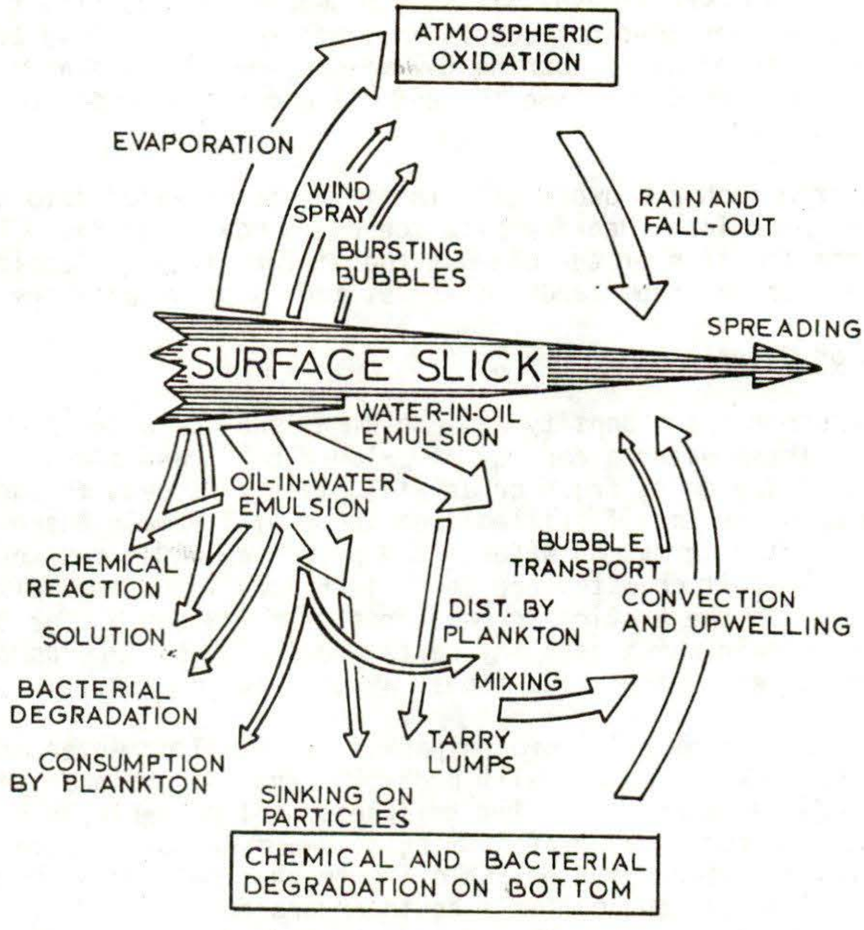

Fig. 13 Factors affecting the spread and weathering of oil on water (after Nelson-Smith 1972).

mixtures could be expected to melt earlier than unpolluted snow. This melting might result in some of the oil being washed into nearby leads. Otherwise presumably it would remain in melt ponds on top of sea ice.

5.6 Oil in First-year Ice

Experiments by Bell (1974) and NORCOR (1975) have shown that fresh Norman Wells and Swan Hills crude, when released under growing first-year ice in small quantities (equivalent to an average depth of 1 cm over the experimental areas) collects on the ice bottom in lenses a few meters across and up to a few centimeters thick. This will locally increase the depth of the under-ice oil film and probably tend to reduce the overall area covered by a given volume of oil. Oil pools, lenses or droplets in these undulations will remain there unless disturbed by appreciable currents along the ice bottom. Preliminary experiments (NORCOR offshore) indicate that currents of 10 cm sec^{-1} (about 1 - 2 m below annual ice bottom) would not displace oil. The stress needed to move oil, in the smaller pockets and shallower film thicknesses may require water currents much stronger than 10 cm sec^{-1}.

The oil is soon entombed in growing sea ice. Apart from fractions which go into solution, or fractions escaping to the air above the ice, both of which seem insignificant, the character of this oil in sea ice apparently remains unchanged until spring.

In spring when the ice temperature approaches freezing, 70 to 90% of the oil from any depth rises, in a period of a week, to the surface of the ice. After sufficient melting of snow and ice, the oil will cover the top of melt pools on the ice. Through absorption of radiation its temperature, when sitting on a melt pool at 0 to 2°C, may attain temperatures of 5 to 10°C.

The spread of oil on ice has been discussed by Glaeser (1971) and Hoult et al (1975). The latter, by analyzing the roughness of the (ridged) ice surface and considering entrapment in ice-top features predict the ice-top spread of a super tanker full of oil (150,000 tons or about 10^6 barrels) to be over an area of 1/4 to 1 sq. mile. In summer when the oil might be carried by melt water, the area could be greater. After the ice melts, oil would remain on top of the water. It would be incorporated in first-year ice in the next winter.

The above remarks are predicated on an oil layer resulting from oil being supplied continuously to a moving ice sheet, or having a given quantity applied to fixed ice. In small areas, near a continuing blowout or leaking oil pipe, the supply of oil to a confined area might be continuous, the resulting situation being different from the oil layer situation described above. In all of the foregoing the presence of the gas which accompanies the oil in a blowout has been ignored. It will probably not affect oil movement in open water or in broken ice. Under a solid ice sheet the gas bubbles may increase the spread of oil under the ice.

5.7 Oil in Multi-year Ice

The structure of multi-year ice is different from thick first-year ice in that the latter's multitude of brine drainage channels is not pronounced in the former. The ice is also thicker. The oil is likely to be incorporated at greater depths in multi-year than in first-year ice. Also in multi-year ice the temperature rise at depth tends to be somewhat slower than in thinner ice (Maykut and Untersteiner 1971). We may expect the migration of oil to the surface of multi-year ice to be slower than through first-year ice. It may not even reach the surface the first summer but even if it depends for migration only on surface ice melting, it should reach the surface within four years (Campbell and Martin 1973). It will probably be in its original form or may have undergone some weathering. Once on the surface it would sit on melt pools for one to two months attaining temperatures well above freezing. It would presumably lose light fractions. In autumn the oil would stay on the ice top and be covered by snow. I would guess it changes little through the winter. The next spring, melting of the surface would occur. The extra absorption of solar energy would result in increased melting of ice. If the oil should continue to compose a continuous cover, with low albedo, most perennial ice would be melted over a very few years as noted below. The oil would then remain on top of the water. In autumn it would be incorporated in first-year ice.

6. OIL SPILLS AND CLIMATE

6.1 Energy Balance of Sea Ice

The law of conservation of energy leads to the following equation which must be satisfied at the surface of the Beaufort Sea.

$$Q_{L\uparrow} + Q_{L\downarrow} + Q_{SA} + Q_E + Q_H + Q_W + Q_{ic} + Q_{if} = 0$$

where $Q_{L\uparrow}$ = upward infrared radiation = $\varepsilon\sigma T_s^4$

$Q_{L\downarrow}$ = downward infrared

Q_{SA} = absorbed solar radiation = $Q_{S\downarrow}(1-A)$

Q_E = evaporation heat flux

Q_H = sensible heat flux

Q_W = water column heat change

Q_{ic} = heat released by cooling of sea ice or absorbed by warming of ice

Q_{if} = heat of phase change water, ice, snow

and ε = infrared emissivity

σ = Stefan - Bøltzman constant

T_s = surface temperature (°K)

$Q_{S\downarrow}$ = global solar radiation, both direct beam and diffuse

A = albedo

The form in which the energy balance equation above is given is essentially one-dimensional. Convention as to the signs of the various terms depends on the problem. The 'net radiation' or 'radiation balance' is the sum of the first three terms. The last three terms represent sinks or sources below the surface.

The term $Q_{L\uparrow}$ is the upward infrared radiation, dependent on emissivity and surface temperature. It is the largest term, but in Figure 7 only the small fraction going to space is shown. The term $Q_{L\downarrow}$ represents long wave radiation from the atmosphere, from moisture and carbon dioxide in the air, and from clouds. It is usually smaller than the upward long wave radiation $Q_{L\uparrow}$. The absorbed solar radiation $Q_{SA} = Q_{S\downarrow}(1-A)$ where A, the albedo, is the fraction of the solar radiation reflected. The magnitude of $Q_{S\downarrow}$ depends on the solar constant, the sun's altitude, atmospheric transmission quality and cloudiness. In summer $Q_{S\downarrow}$ is comparable in size to the long wave terms. In contrast to the infrared radiation, solar radiation has some capability of penetrating ice and water (Maykut and Grenfell 1975) and to a lesser extent snow (O'Neill and Gray 1972). The albedo A is a function of the surface, percentage of solar radiation in the direct beam and the sun's altitude. Table 1 shows representative albedos over various surfaces (after Sellers, 1965 and Orvig 1970). The albedo of snow being high, most solar energy is reflected until the snow melts. Then the difference of albedo between ice ($A \simeq 60\%$) and water ($A \simeq 10\%$) can mean a large difference in absorbed solar radiation as shown in Figure 14.

The sensible heat flux Q_H is the transport of heat between surface and atmosphere. Similarly the latent heat flux Q_E is determined by the transport of water vapor between surface and atmosphere. The water column heat change term Q_W is the change in the heat content of water column below. The magnitude of the term depends on the temperature and density structure in the water column and is limited by the fresh surface layers. Large scale engineering works might change this surface water structure and allow the Q_W term to attain larger values, without the sea freezing, than at present.

Over perennial ice the annual input by the sun, Q_{SA}, is balanced by an excess of upward values over downward values of infrared radiation, the other terms being small. Over open water very large heat losses should occur in winter through the flux of sensible and latent heat. With its present structure the water cannot supply these heat losses without freezing. So areas of open water in mid-winter must be quite small and last only briefly. In the case of first-year ice more solar heat is absorbed by the water in summer than in the case of perennial ice but this is soon lost in autumn through the sensible and latent heat flux terms. No great amount of moisture is evaporated during this period. Otherwise the annual heat budget of first-year ice is similar to that of perennial sea ice.

TABLE 1

Typical values of albedos over various surfaces (after Orvig 1970, Sellers 1965)

Structure	Water Content and Colour	Albedo %		
		Average	Max.	Min.
Freshly fallen snow	dry bright-white clean	88	98	72
Freshly fallen snow	wet bright-white	80	85	75
Freshly drifted snow	dry clean loosely packed	85	96	70
Freshly drifted snow	moist grey-white	77	81	59
Snow, fallen or drifted 2-5 days ago	dry clean	80	86	75
Snow, fallen or drifted 2-5 days ago	moist grey-white	75	80	56
Dense snow	dry clean	77	80	66
Dense snow	wet grey-white	70	75	61
Snow and ice	dry grey-white	65	70	58
Melting ice	wet grey	60	70	40
Melting ice	moist dirty grey	55	65	36
Snow, saturated with water (snow during intense thawing)	light green	35	-	28
Melt puddles in first period of thawing	light blue water	27	36	24
Melt puddles, 30 100 cm deep	green water	20	26	13
Melt puddles, 30 100 cm deep	blue water	22	28	18
Melt puddles covered with ice	smooth grey-green ice	25	30	18
Melt puddles covered with ice	smooth ice, covered with icy white hoar frost	33	37	21
Water surfaces	Winter 60°N	21	-	-
Water surfaces	Summer 60°N	7	-	-
Soil	dark	10	5	15
Soil	moist grey	15	10	20
Soil	dry sand	35	25	45
Cloud	overcast cumuli-form	80	70	90
Cloud	stratus	70	59	84
Cloud	Altostratus	49	39	54
Cloud	Cirrostratus	47	44	50

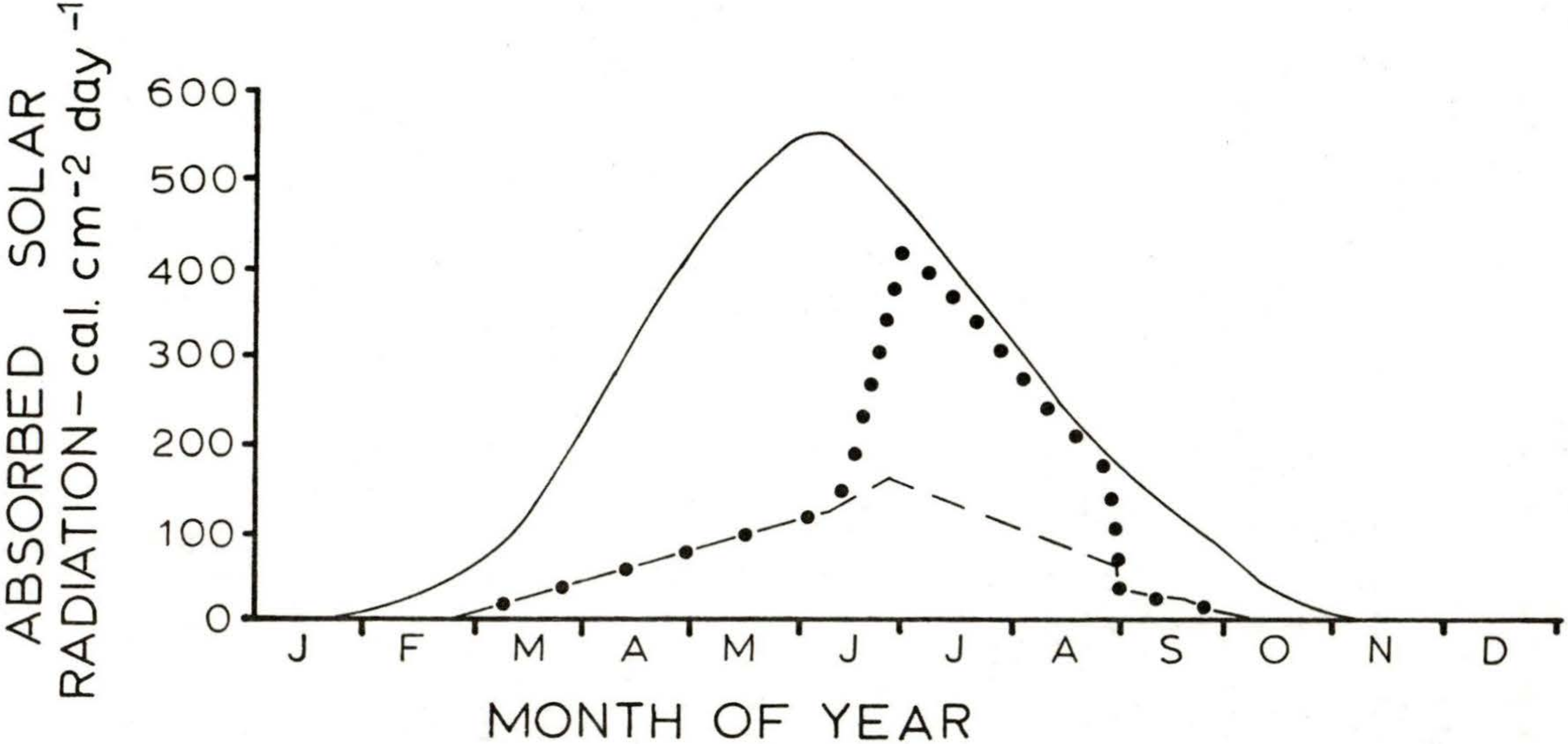

Fig. 14 Estimate of absorbed solar radiation $Q_{SA} = Q_{S\downarrow}(1-A)$ in cal cm^{-2} day^{-1} at 75°N, 140°W. The area under the top curve is the energy available, — — — — is energy absorbed by perennial ice and snow, · · · · is energy absorbed by oiled ice or first-year ice and water. The difference is about 13 x 10^3 cal cm^{-2}.

The real differences in the annual heat budgets are between open water (in winter) and any ice (first-year or perennial) not between first-year ice and perennial ice.

6.2 Oil on Water Effects

Oil on water would change the albedo and infrared emissivity but these effects on the heat budget would be small. It would lessen wave activity and inhibit exchange of sensible and latent heat (Bartholic et al 1967). In a one-dimensional, molecularly-conducting world one could envisage a scenario in which ice formation was greatly impeded. Practically, the formation of ice would not be much delayed. Freezing in the Beaufort Sea frequently occurs after a windy period. These winds would presumably break-up oil slicks and make inhibitory effects on sea freezing very patchy. Indeed, use of thin films on reservoirs to retard evaporation has suffered from the difficulty of maintaining film coverage under wind action. In leads the wind effect might not be so great. Here layers of fresh oil may delay ice formations somewhat, but wind, snowfall and other forces of nature would be expected to ensure fairly quick freezing.

6.3 Oil in Ice Effects

In another Beaufort Sea Project Technical Report (NORCOR 1975) results of an experimental program in which Norman Wells crude oils and Swan Hills crude oils were released beneath growing annual sea ice at Cape Parry, N.W.T., are reported. Bell (1974) reported on a similar experiment at Resolute Bay, N.W.T.

The NORCOR results indicate that, under the conditions of their experiment, oil affected only a few terms in the surface energy budget in the experimental areas.

The thermistor temperature measurements, supposedly through oil layers in the ice, showed (on occasion) an increased temperature gradient. This is to be expected if the oil is conducting heat molecularly. The thermal conductivity of the oil used by NORCOR is about one sixteenth that of sea ice. Over the winter season, NORCOR found no discernible difference in thickness in ice containing oil in the experimental areas and ice in control areas. In the spring when the ice temperatures approached melting, the oil in the NORCOR experimental areas rose rapidly to the surface as had been found by Bell (1974). From the NORCOR (1975) observations it is not possible to evaluate all terms in the heat budget of oiled ice in the spring of 1975. However with some approximations, calculations that were possible showed not enough heat entering the body of the ice to cause much melting. The rapid oil rise cannot be due solely to solar radiation absorption, ice melting, and upward migration. The brine-channelled structure of the annual ice must be largely responsible for the very rapid upward migration of oil in spring.

The albedo over unoiled areas during the period of snow melt dropped from 75 percent to 40 to 50 percent. Over those areas 100 percent covered by crude oil the albedo fell to 8 to 10 percent. Over areas estimated to be about 35 percent covered by oil the albedo was reported by NORCOR as about 20 percent. The oil apparently did not change its characteristics during periods, up to 7 months, during which it was held in the ice. It was observed by NORCOR to flow rapidly over melt pools on the surface. It was quite easily burned.

The entombment of an oil layer beneath growing sea ice has been discussed by Chen et al (1975), Wolfe and Hoult (1974) and Martin (personal communication). Field experiments have included those reported by NORCOR (1975), and by Bell (1974). The reports agree that oil in sufficient quantity forms a layer about 0.5 to 1.0 cm thick beneath flat-bottomed sea ice. It is thicker where it spreads into hollow features in the bottom of the ice. The reports agree further that these layers are incorporated into the growing sea ice with sea ice layers forming below them.

The effect of an underlying oil layer on ice growth would be a retardation because of impeded heat loss from the water column. When the oil layer is in the growing sea ice the effect it will have on ice growth will also presumably depend on the oil qualities and the thickness of the oil layer. The laboratory results of Chen et al (op. cit.), indicate that for thickness approximating the natural thickness of an oil layer, oil layer heat flow is by molecular conduction. As the thermal conductivity of oil is about one sixteenth that of sea ice this implies that a 0.5 cm thick layer of oil is thermally equivalent to a sea ice layer about 8 cm thick, and a 1.0 cm layer of oil equivalent to a sea ice layer about 16 cm thick.

However as noted by Wolfe and Hoult (1974), for thicker oil layers heat transfer through the oil may be by convection with higher values of the Nusselt modulus. To recapitulate, their analysis indicates if the Grashof (Gr) and Prandtl (Pr) numbers are combined to give the Rayleigh number (Ra) = (Gr) · (Pr) where

$$(Gr) = \frac{g\beta(\Delta T)\ h^3}{\nu^2} \qquad (Pr) = \frac{c\mu}{k}$$

and g = acceleration of gravity
β = coefficient of volume expansion (0.001 cgs)
ΔT = temperature difference (across h)
h = thickness of oil layer
ν = kinematic viscosity of oil (0.120)
c = specific heat capacity of oil (0.5)
μ = dynamic viscosity of oil (0.096)
k = thermal conductivity of oil (0.00035)

then for a normal fluid whose density decreases with increasing temperature, convection of the Bénard cell type results for values of the Rayleigh number above 1700. Crude calculations using parameters in the brackets above indicate that this critical value of the Rayleigh number is reached for an oil layer 0.5 to 1.0 cm. thick. Wolfe and Hoult note that for (Ra) $\simeq$ 1700 the Nusselt number is 1.0 and increases as a power of (Ra) through the Bénard cell regime to (Ra) = 42000.

$$(Nu) = 0.107\ (Ra)^{0.3}$$

Other investigations including Malkus (1954) at larger values of the Rayleigh number, when the flow becomes turbulent, have indicated slightly different relationships but they are all alike in that they predict (provided oil remains fluid) that an oil layer in ice will not have a much greater effect on heat flow than a layer 0.5 to 1.0 cm thick conducting molecularly. Examination of NORCOR temperature profiles in which conditions appear steady revealed four steady-state profiles from spill Swan Hills #1-3 in which the oil thickness appeared to be about 3-5 cm and the temperature drop across the oil layer about 3°C. Using the Norman Wells crude oil values shown bracketed above the Nusselt number would be about 6. For one profile from NORCOR spill Norman Wells #1-4 with an oil layer thickness of about 5 cm and temperature drop of about 5°C, the Nusselt number was about 11. In a Swan Hills #1-1 oil spill the Nusselt number appeared to be about 4. For the single steady state Norman Wells spill #4-4 the Nusselt number appeared to have a value of 3.

All these calculations are very rough, being based upon uncertain physical parameters and statistically small samples. Whether the oil layers are convecting or whether the supra-molecular heat flow is due to other causes such as ice-crystal bridging or other two-dimensional effects, may be cleared up by further examination of NORCOR data and closer specification of crude oil parameters. Certainly in the circumstances of the NORCOR experiments the heat flow is larger than one would expect from molecular heat conduction through oil layers.

The foregoing remarks are based on the behaviour of oil in and below first-year ice. For oil that is trapped below solid perennial ice the process of entombment in the bottom of the growing ice should be similar to the processes below new ice, but complications may be caused by freshwater pools which are trapped below perennial ice on occasion. However the oil will be incorporated in perennial ice eventually and the effect on heat transfer through perennial ice should be as discussed above.

The quantities of oil and the bottom features of the ice may cause an oil layer to be in lenses rather than a continuous layer. The natural horizontal scale of ice bottom features under new ice is about 10 m. Under ridged perennial ice the scale might be larger. As the thickness of the ice involved is in the scale about 1 to 3 m, the picture from the thermal point of view is that of thin vertical but sizeable horizontal lenses of oil in a shallow sheet of ice. Rough calculations (after Carslaw and Jaeger 1959) for lenses of oil of $l \simeq 10$ m size conducting molecularly and situated in sea ice showed a flow of heat around the edges of the oil lenses such that the effect of the oil lenses on ice growth be markedly less than the effect of a continuous sheet. To extrapolate, small patches of oil would have less effect than lenses of the size suggested by the natural mesoscale roughness of the sea ice bottom.

When oil in sea ice moves to the surface it flows into the snow cover usually present. The melt of snow cover would be advanced by absorption of solar radiation. The oil remaining on the sea ice would change the radiation properties of the surface. Particularly important, the albedo of the ice as shown by NORCOR (1975) would be reduced from 45 to 65 percent typical of ice to about 10 percent. As on the water the transfer of latent heat and sensible heat would be impeded.

I am not aware of any mathematical models that would adequately describe the effect of oil on top of ice upon the heat budget. We had hoped to obtain a one-dimensional model from T. Hasemi (1975) and amend it, but it arrived too late. As these models seem to take people two or three years to get working properly, I decided we had not time to code one of our own. We have used a one-dimensional model of Maykut and Untersteiner (1971). This model is so elaborately coded in Fortran that it is impracticable to change it in any useful way. We, therefore, used it in a very simple way to investigate only the effect of changed ice albedo upon the decay of thick sea ice.

The model evaluates the heat budget at the surface of perennial sea ice. Because it was designed for investigation of the polar pack regime, some of the parameters are restricted. The main restrictions of importance are in the rigid specification of the external parameters, depending on the atmosphere. Some internal parameters including ice salinity, specific heats, solar radiation absorption and penetration are either specified or approximated. The input of heat from the water column below the ice is also prescribed. Other deficiencies, noted by Maykut and Untersteiner are that the model cannot predict whether ice will return once it has vanished. No provision for treatment of the melt ponds found on top of the ice during summer is included.

With these limitations the model was run on input parameters corresponding to the Cape Parry area, where NORCOR experimental work was carried out, and for inputs corresponding to Maykut's input which he chose as representative of the Central Arctic Basin, and, as such may be representative of the northwest Beaufort Sea. For the examples shown below the albedo of the bare ice was adjusted to the values shown in the Figures below.

Figure 15 shows the effects on the decay of first-year ice of albedo changes of various magnitudes with the input parameters appropriate to Cape Parry. Comparison shows the effect of the increased solar radiation absorption in hastening melting. It is not possible to carry through a detailed comparison with NORCOR's experimental results since their oil was burned on the ice in early June, 1975. It is certain, however, that a continuous cover of oil would result in early removal of first-year ice. With unoiled ice, with a rather high summer albedo of 0.64 the modelled first-year ice did not melt completely until the second summer. As first-year ice melts every summer at Cape Parry this is presumably due to errors in the input parameters, although the time of summer ice melting at Cape Parry may depend on wind factors and additional heat input that does not appear in the model input parameters.

Figure 16 shows the effects of albedo changes upon perennial sea ice decay with input parameters believed appropriate for the northwestern

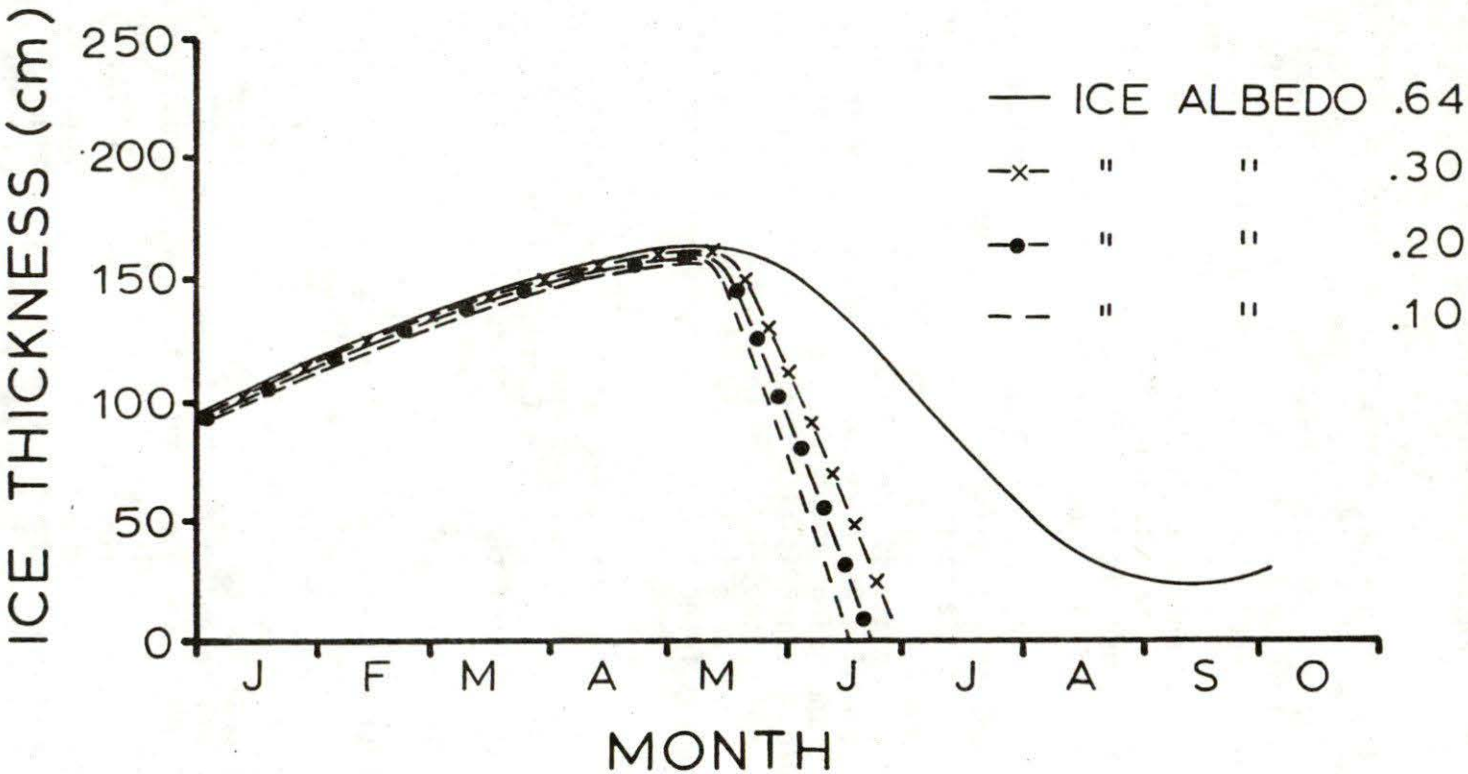

Fig. 15 Effect of various ice albedos on time of decay of sea ice at Cape Parry, N.W.T., using model of Maykut and Untersteiner (1971).

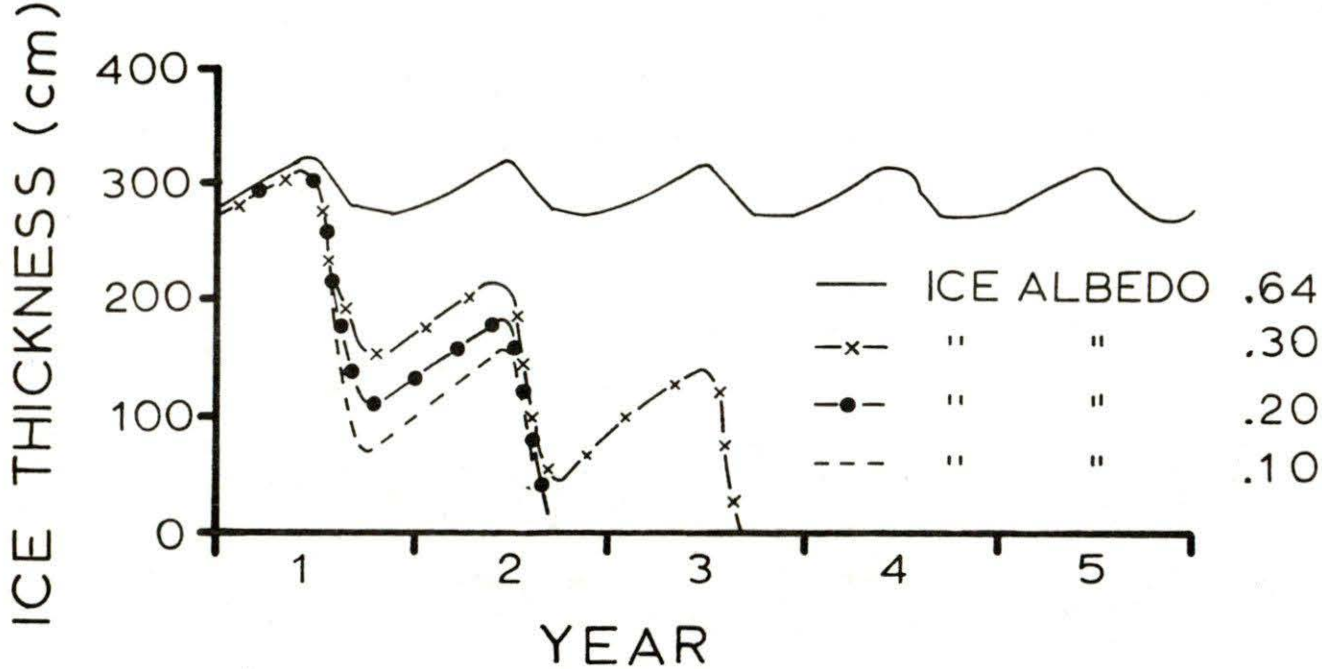

Fig. 16 Effect of various ice albedos on time of decay of sea ice in the Northern Beaufort Sea, using model of Maykut and Untersteiner (1971).

Beaufort Sea (after Maykut and Untersteiner 1971). The relatively rapid removal of perennial ice for a continuing low albedo is quite striking.

The calculations just above are unrealistic in many respects, but do indicate that the presence of continuous dark oil cover on sea ice leads to destruction of perennial sea ice. It was shown earlier that the effect of oil layers within or under the ice is less critical at least for a fairly thin oil layer. It is obvious of course, that the seriousness of all these effects will depend upon the areas covered and the time involved. No account has been taken of the aging of oil, on water or on ice. Presumably this will lead to early, and perhaps continuing, loss of oil on the surface. If this be true then all of the effects noted above will be much reduced in the second and subsequent years of ice growth, in an oil contaminated environment.

It has become obvious that to do useful work in this area a number of models should be coded to deal with the one-dimensional heat flow problem more adequately. The overall practical problem is largely two-dimensional, even for very large spills, so either empirical adjustment of one-dimensional models will be needed, or models developed for further dimensions. This is a major problem.

6.4 Climatic Effects of Oil Release into the Beaufort Sea

The terms of reference of the present Beaufort Sea studies are confined, I believe, to the exploratory phase. In that case the oil release rate shown in Figure 11 is appropriate. The possible climatic effects of oil releases in the Beaufort Sea have been discussed by Campbell and Martin (1973), Ayers, Jahns and Glaeser (1974) and Martin and Campbell (1974). Campbell and Martin's estimate of areas affected by various amounts of oil are large, being in my mind far beyond what is likely. However, to show the magnitude of the effects of the release of oil (Figure 11) using their technique we may adapt relevant parts of the analysis of Campbell and Martin (1973) on consequences of oil release in the Beaufort Sea area. As Campbell and Martin assumed, we assume no evaporation or biological degradation of the oil. The material in Campbell and Martin's (1973) Table 1 may then be scaled down for a release of 60,861 m^3 of oil as compared to their example of 2.4×10^5 m^3 of oil. This scaled down table is shown as Table 2. Perusal of their text indicates that their estimate of the most likely thickness of the oil would be perhaps 10^{-1} cm on open water and therefore the area "affected" would be less than 0.2 percent of the Beaufort Sea. There are, of course, many uncertainties in this analysis, but they are all in such a direction as to increase the area affected by oil.

We further assume that the area affected by the oil from the blowout will remain at about 0.2 percent of the area of the Beaufort Sea. If this is so the albedo will certainly be lowered, particularly in late spring and summer. We may then imagine that 0.2 percent of the area of the Beaufort Sea will have open water in summer and first-year ice during the winter. This will cause changes in the heat balance

TABLE 2

(After Campbell and Martin 1973). The area of both the Beaufort Sea Gyre and the Arctic Ocean affected by an oil release of 6.1×10^4 m (3.8×10^5 barrels). It is assumed that all the oil is uniformly distributed through the open water (also uniformly distributed) in the pack.

Slick Thickness (cm)	Open Water (%)	Area Affected (km)	% Beaufort Sea Affected	% Arctic Ocean Affected
1	10	0.6×10^2	0.00	
1	2	0.3×10^3	0.01	
10^{-1}	10	0.6×10^3	0.02	
10^{-1}	2	0.3×10^4	0.15	
10^{-2}	10	0.6×10^4	0.25	
10^{-2}	2	0.3×10^5	1.52	0.51
1.5×10^{-3}	10	0.4×10^5	2.03	0.51
1.5×10^{-3}	2	2.0×10^5	10.14	2.03

of the area. The changes in the heat balance mean that in the southern Beaufort Sea the ice might melt a week or so earlier, so the water absorbs slightly more solar heat than at present. Ice formation is delayed a week or so while this excess heat is lost. In the northern Beaufort Sea the timing would be similar to that at the Frozen Sea Research Group base in Ellesmere Island, N.W.T., where the ice melts at the end of July and reforms in September. However, natural variations in open water, at all seasons, due to movements of the perennial pack are a few percent of the total area of the Beaufort Sea (Marko 1975, personal communication). This suggests that the oil from a single blowout is very unlikely to have an important effect on the climate of the Beaufort Sea let alone of the Arctic Ocean as a whole, even when considered in the light of Campbell and Martin's analysis which leads to oil contamination of a much larger area than Ayers et al, and the present writer consider possible.

During the possible later production phase of Beaufort Sea oil operations, larger quantities of oil may escape. These are estimated roughly, in Figure 12. The areas the author estimates this escaped oil may cover, using both the loss factor of Martin and Campbell and the much smaller loss factor estimate of an oil company, are about 400 km^2 and 4 km^2 respectively, using an oil thickness of 0.50 cm and no weathering. Even if these estimates are low by an order of magnitude, only a fraction of one percent of the Beaufort Sea gyre will be affected by oil. On the other hand, if we use Campbell and Martin's techniques and loss factor, on an oil reservoir of 1×10^{10} barrels, their (1973) Table 1 will be as shown in Table 3. Here appreciable areas of the Beaufort Sea (and indeed Arctic Ocean) are 'affected' by their definition. However as I have indicated above,

TABLE 3

(After Campbell and Martin 1973). The area of both the Beaufort Sea Gyre and the Arctic Ocean affected by an oil release of 1.6×10^6 m (1×10^7 barrels). It is assumed that all the oil is uniformly distributed through the open water (also uniformly distributed) in the pack.

Slick Thickness (cm)	Open Water (%)	Area Affected (km)	% Beaufort Sea Affected	% Arctic Ocean Affected
1	10	1.6×10^3	.07	
1	2	8.0×10^3	.40	
10^{-1}	10	1.6×10^4	.7	
10^{-1}	2	8.0×10^4	4.0	
10^{-2}	10	1.6×10^5	6.7	
10^{-2}	2	8.0×10^5	40.0	13
1.5×10^{-3}	10	1.1×10^6	53.3	13
1.5×10^{-3}	2	5.3×10^6	100+	53

I believe their estimates of area 'affected' are unrealistic. I feel that oil affected areas are probably going to be less than one percent of the Beaufort Sea gyre and probably will have no climatic effect.

I must remark that this paragraph on the production phase contains much speculation. If, however, oil is found in the quantities predicted then there are going to be sizeable releases. On a scale when an appreciable fraction of the Beaufort Sea gyre or the Arctic Ocean may be affected then potential releases from other areas, such as Prudhoe Bay offshore, and the north Atlantic area should be considered. The extent of weathering of crude oil in the Arctic is very important. Large-scale engineering projects should be watched, in case they divert enough fresh water to destroy the fresh surface layers in the Arctic Ocean.

To sum up, it is certain that during the exploration phase of Beaufort Sea operations not enough oil is likely to be released to affect even local climate.

The effect of oil release upon climate during a possible production phase is less certain. The writer's opinion is that while sizeable volumes of oil may be released, this oil will probably not spread over a sufficient area to affect anything but local climate. However as noted above several uncertainties remain.

7. CONCLUSIONS

Examination of terms of the sea ice heat budget indicates maximum effect of oil would occur when it covers the ice, lowers the albedo, allowing increased absorption of solar energy. This would lead to earlier melting and later formation of first-year sea ice. If an oil cover could be maintained on perennial ice it would lead to decay of this type of ice in a few years and its replacement with first-year ice. The effects of oil on the large-scale heat budget of the Beaufort Sea and Arctic Ocean are dependent on the scale of oil release. For the scenario for exploratory drilling, of one blowout, or even for a much larger release of oil, the area covered by oil would be too small to affect the large-scale heat budget of the Beaufort Sea, let alone of the Arctic Ocean as a whole.

To assess adequately the effects of oil releases from the operational phase of the Beaufort Sea oil field, and possibly from other Arctic oil fields, the rate of weathering or loss of oil from the surface must be known better.

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