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Oil and Ice in the Arctic Ocean: Possible Large-Scale Interactions

Abstract. *The diffusion and transport mechanisms generated by the pack ice dynamics of the Beaufort Sea, combined with the slow rate of biodegradation of oil under Arctic conditions, would combine to diffuse an oil spill over the sea and eventually deposit the oil on the ice surface, where it would lower the natural albedo over a large area.*

There has been considerable speculation concerning the biological effects of oil spills on both the Arctic tundra and in the Arctic Ocean. Because of the slow rate of biological degradation of oil at near-zero temperatures in temperate waters, biologists (*1, 2*) have suggested that, once oil has entered the Arctic Ocean, it might remain there for periods of the order of 50 years. We wish to discuss here some of the possible physical interactions between the highly mobile Arctic pack ice and an oil spill.

The Arctic pack ice covers an area of about 10^7 km^2 with an average thickness between 3 and 4 m. Many investigators (*3–5*) have shown that this thin veneer of ice is extremely important in determining the heat exchange between the ocean and atmosphere and have pointed out that, if the ice cover were removed from the Arctic, it might not reform. This sensitivity is attributable to the fact that during the months of June and July the Arctic above 70°N receives more radiation than any other comparable area on Earth. Because of the large amount of summer radiation to which it is exposed, the ice is very sensitive to small changes in albedo. On the basis of an examination of the present Arctic radiation and heat budget, Fletcher (*5, 6*) has argued that, if the ice pack were removed from the Arctic Ocean, the heat absorbed by the open ocean during the summer might be sufficient to prevent formation of ice during the winter. Because his argument is based on measurements over the present Arctic, it neither accounts for nor predicts the changes in both the planetary circulation and the cloud cover that might result, so that it is not known whether an open Arctic Ocean would remain open.

On the basis of a sophisticated one-dimensional thermodynamic model of sea ice, Maykut and Untersteiner (*3*) have shown quantitatively how changes in the albedo of sea ice affect its equilibrium thickness. Their model shows that a 10 percent reduction in the albedo of the ice during the period from 1 June to 30 August yields a 60 percent reduction in equilibrium thickness, and that a 20 percent reduction in the albedo causes the ice to disappear after 2 years. They also have demonstrated that elimination of the evaporative heat flux from the surface of the ice during the same period yields a 40 percent reduction in the equilibrium thickness. Maykut and Untersteiner have concluded that "modification of the snow or ice surface is the most effective means of large-scale ice removal. . . . The ideal material [for spreading on the surface] would be dark, nontoxic, lighter than water, slowly soluble in water, and have a low emissivity." A substance which satisfies a number of these requirements is oil.

Any consideration of the impact of oil on the Arctic Ocean must include the extremely dynamic character of the Arctic sea ice. The mobility of the pack ice on the open ocean would make oil cleanups within the ice immensely more difficult than on tundra or glacier ice. First, any oil spilled within the pack ice would be swept up in a continuously deforming matrix of ice floes and leads of varying sizes which may move at velocities as great as 40 km per day and in which velocities of 5 to 15 km per day are common. Second, leads and polynyas (large leads with areas as great as 500 km^2) move through the pack with even greater velocities than the pack velocity. Third, large shearing deformations occur within the pack. In general, sea ice is one of the fastest-varying large-scale features on the surface of the earth.

Numerous investigators have worked for years to create a predictive model for the dynamics of the Arctic pack ice (*7*). Although these models differ in fundamental ways, they all demonstrate the existence of certain large-scale features of the annual Arctic ice pack circulation, namely, the Beaufort Sea gyre and the transpolar drift stream, and show for the mean annual Arctic circulation that the Beaufort Sea should be a region of ice convergence.

Whether the Beaufort Sea ice pack is strongly convergent annually, as the steady-state theories suggest, or weakly divergent and convergent periodically with perhaps a zero-average annual convergence, as observations of the drift of ice stations suggest (Fig. 1), both theory and observations agree that the anticyclonic Beaufort Sea ice gyre is a real feature of the polar circulation. The existing theoretical models and observations suggest that, once an oil spill enters the ice pack of the Beaufort Sea, it would become part of the anticyclone system, circulate around the gyre, and diffuse into and around the gyre.

We visualize three chief possible mechanisms in the pack ice which would disperse oil from the location of a spill and distribute it eventually to the surface of the ice. We call these mechanisms "lead-matrix pumping," "oiled-hummock melting," and "under-ice transport."

1) *Lead-matrix pumping.* First, let us assume that all of the oil spilled is initially deposited in the leads within the spill area. We know from numerous observations of the pack ice that families of leads regularly open and close within the ice pack and that the largest deformations within the pack seem to be associated with cyclone passages. When a family of leads full of oil closes, oil would be both incorporated into the newly formed hummocks and either pumped into another set of leads at a different orientation or pushed under the ice. Through pumping from lead array to lead array, the oil that was not incorporated into new hummocks would diffuse throughout a larger and larger area. Over the Beaufort Sea, cyclones pass approximately 1.5 times per month in the summer and once per month in the winter, so that the changing air stress field would open and close a matrix of leads within the ice pack with at least that frequency. On a smaller scale, Hibler *et al.* (*8*), in their measurements of strain in sea ice over ranges of the order of 10 km, have found that alternate convergence and divergence of the ice can occur in periods as short as a day.

If we assume that all the oil diffuses through the leads, then from laboratory (*9*) and field (*2, 10*) experiments we can estimate the maximum amount of open water covered by a spill. On the basis of laboratory experiments, Blokker (*9*) has stated that the thickness of a Middle East crude oil slick varies from 1.5×10^{-3} cm when the oil is spread on clean water to 10^{-1} cm when the oil is spread on water contaminated with surface-active agents. Experiments with Prudhoe Bay crude oil (*2, 10*) in the Arctic have indicated that the slick has a thickness between 1 and 10^{-1} cm. If, as an example, we assume an oil spill of 2×10^6 barrels (2.4×10^5 m^3) (*11*), then a slick with an average thickness of 1 cm covers 24 km^2 of open water, whereas a slick with a thickness of 1.5×10^{-3} cm covers 1.6×10^4 km^2 of open water.

On the assumption that the open water in the pack ice is uniformly distributed throughout the pack ice, we can also estimate the area of the Beaufort Sea gyre affected by the spill. During the Arctic winter, the recent estimates of open water in the gyre range from 2 to 10 percent; the 10 percent figure was obtained by recent aircraft reconnaissance, and the 2 percent figure is derived from the cruises of the submarines U.S.S. *Sargo* and *Seadragon* [cited in (*12*)]. Recent Tiros images suggest that 5 to 10 percent open water is probable. Table 1 gives the total area covered and the percentages of the areas of both the gyre and the Arctic affected, as a function of the thickness of the slick and the percentage of open water. Even on the assumption of a 25 percent loss of oil to evaporation, washup onto the Canadian or Alaskan beaches and export to the transpolar drift current, the numbers in Table 1 are instructive, especially when one recalls that these numbers are for one large oil spill which will biodegrade very slowly.

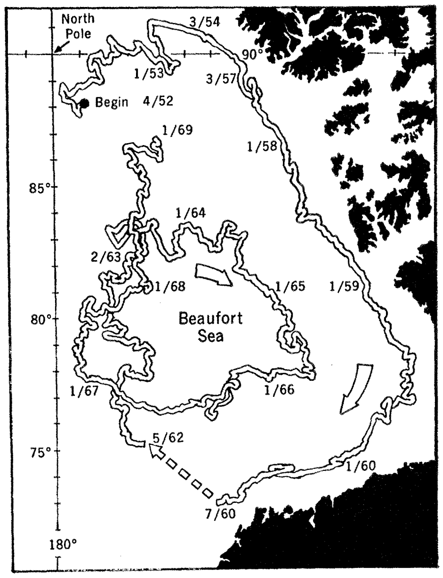

Fig. 1. The drift track of the ice island T-3 from April 1952 to January 1969 (*18*).

2) *Oiled-hummock melting.* The oil incorporated into the hummocks by the closing of oil-filled leads could have a significant effect on the ice albedo. The combination of the lower angle of incidence of one side of the hummock to the incoming solar radiation and the absorption of this radiation by the incorporated oil would cause the hummock to begin melting before the surrounding snow and ice field. The meltwater flowing from the hummock out onto the surrounding ice would carry some oil with it, thus causing an albedo decrease from both oil and meltwater in the watershed of the hummock. If we postulate a square ice floe 1 km on a side and surrounded by hummocks, with watershed areas extending out 100 m on each side, then the flow of oil and water from the hummock would affect between 20 to 40 percent of the surface of the floe.

Furthermore, because the hummocks melt before the flat ice fields, the albedo change caused by the outflow of meltwater would occur earlier than the normal albedo change in the area. This is an important point, because, in the Maykut-Untersteiner model (*3*), both the magnitude of the albedo change and the duration over which the change occurs determine the thickness of the ice. The melting of oiled hummocks, then, is an efficient way for oil to affect the heat budget of the ice pack.

3) *Under-ice transport.* Perhaps the most efficient method of diffusing the oil over a large area would come into play when the oil is either initially deposited below the ice-water interface or forced under the edge of leads by either wind shear, local ice convergence, or the turbulent generation of an oil-water emulsion which mixes vertically in the water column. Very little is known about the complete process of the formation of these oil-water emulsions, and they received little attention until after the *Torrey Canyon* spill. The

Table 1. The area of both the Beaufort Sea gyre and the Arctic Ocean affected by an oil spill of 2.4×10^5 m^3 (2×10^6 barrels). We assume that all of the oil is uniformly distributed throughout the open water in the pack. The areas are functions of both the thickness of the slick and the two values of the observed percentage of open water to ice.

Thickness (cm)	Open water (%)	Area affected (km^2)	Percentage of gyre affected	Percentage of Arctic Ocean affected
1	10	2.4×10^2	0.01	
1	2	2.4×10^3	0.06	
10^{-1}	10	2.4×10^3	0.1	
10^{-1}	2	1.2×10^4	0.6	
10^{-2}	10	2.4×10^4	1.0	
10^{-2}	2	2.4×10^5	6.0	2
1.5×10^{-3}	10	1.6×10^5	8.0	2
1.5×10^{-3}	2	8×10^5	40.0	8

emulsion formed by the Kuwait crude oil spilled by the *Torrey Canyon*, which has been called "chocolate mousse," contained as much as 80 percent water (*13*). Similar emulsions formed from the oil spilled in the wreck of the *World Glory* off the coast of South Africa in 1968 (*14*) and during the oil leakage from the offshore wells in the Santa Barbara Channel, where emulsions containing 50 percent water were observed (*15*). All of these emulsions proved to be extremely stable, and in a comprehensive study Berridge *et al.* (*16*) concluded that the stabilization was caused by complex chemical components in the nonvolatile residues and not by bacterial activity, marine organisms, or suspended solid matter.

Supporting evidence for these conclusions was dramatically provided by the spill of 108,000 barrels of bunker C fuel oil from the wreck of the *Arrow* in Chedabucto Bay, Nova Scotia, on 4 February 1970. Because the Chedabucto spill occurred in seawater with a temperature between 0° and 2°C, a thorough study of this spill (*17*) is highly relevant to this discussion of under-ice oil transport.

The bunker C oil spilled in Chedabucto Bay formed highly stable emulsions containing from 36 to 53 percent water. Within 2 weeks of the spill, oil particles were observed down to a depth of 50 m throughout the entire area of the bay (approximately 900 km^2). Oil particles were also found outside the bay in a tongue approximately 10 km wide which extended eastward from the mouth of the bay for a distance of 70 km.

Since the surface waters of the Arctic Ocean are similar in biological and physical composition to the winter waters of Chedabucto Bay, and because the motion of the rough bottom topography of the pack ice relative to the underlying ocean generates a turbulent flow, we expect that oil-water emulsions would occur after an Arctic oil spill and would be convected under the ice. When a cyclone passes over pack ice, the individual ice floes frequently have trajectories in the form of large loops, caused by the response of the ice to the air stress, which change direction over a full circle in a period of a few days. For a cyclone passing over an area in which oil or an oil emulsion was beneath the ice, the floes would move faster than the oil layer below, thus spreading the oil along the ice-water interface under a large part of the ice that moved over the initial point of spill. This would probably result in a kind of long smudge along the ice-water interface in the form of a partial loop similar to the one that an individual ice floe makes during the cyclone passage. The deep ridges, which would project through the oil layer, would complicate the spreading of the oil. As the ridges are dragged through the oil, the randomness of both the distribution and the direction of the deep ridges would result in a net lateral diffusion of oil away from the direction of drift. This diffusion along the ice bottom and the subsequent deposition of oil in concavities on the ice bottom would result in the incorporation of the oil into the ice that formed during the next freezing season. Because of the upward flux of ice caused by the alternate melting at the surface and freezing on the bottom, this oil would end up on the surface of the pack ice in about 4 years, the equilibrium age of Arctic pack ice.

From observations, such as that of the drift track of ice island T-3 shown in Fig. 1, we estimate that the transit time of an oil spill on the fringes of the Beaufort Sea around the circumference of the Beaufort gyre would be of the order of 7 to 10 years. As the spill site made its way around the Beaufort gyre, all of the above mechanisms would act to both diffuse the oil throughout the pack and put the oil on the surface of the ice. Therefore, as the source continued its journey, the area affected by the spill would grow, so that, by the time the original spill site returned to its original approximate geographic coordinates, a considerable area of the Beaufort Sea could have its albedo changed.

Of course, since the diffusion rates resulting from the proposed mechanisms are unknown, we cannot estimate the size of this affected area. Our purpose here is to form a framework for thinking about the problem of oil in the extremely sensitive and mobile environment of the Arctic Ocean and to show that there is, in our present state of ignorance, a valid basis for concern about the possible physical effects of a spill.

W. J. CAMPBELL

Ice Dynamics Project, U.S. Geological Survey, Tacoma, Washington 98416

S. MARTIN

Department of Oceanography, University of Washington, Seattle 98195

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