Sea Ice Production and Transport of Pollutants in the Laptev Sea, 1979 - 1992

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INTRODUCTION

About 900,000 km^2 of the polar pack ice is transferred annually from the Arctic Basin to the North Atlantic. The largest portion of this exported ice cover is created by the large scale divergence within the ice pack, but a significant portion of the ice cover originates in the marginal seas, either by fall freezing of the seasonally ice free waters or by wintertime advection away from the coast.

The main objective of this study is to estimate the annual production of ice in the Laptev Sea and to determine its ultimate fate. The study is motivated by the possibility that ice formed in the Laptev Sea may be an agent for the long range transport of pollutants such as radionuclides.

The strongest evidence for long range, non-diffusive, pollution transport is the ubiquitousness of "dirty ice" throughout the eastern Arctic (Pfirman *et al.*,1990, and Nürnberg *et al.*,1993). Although much of the ice is discolored by biogenic material, there is clear evidence of fine grained lithogenic material. While the biogenic material grows throughout the arctic, the lithogenic material can only be incorporated into ice formed in the coastal waters.

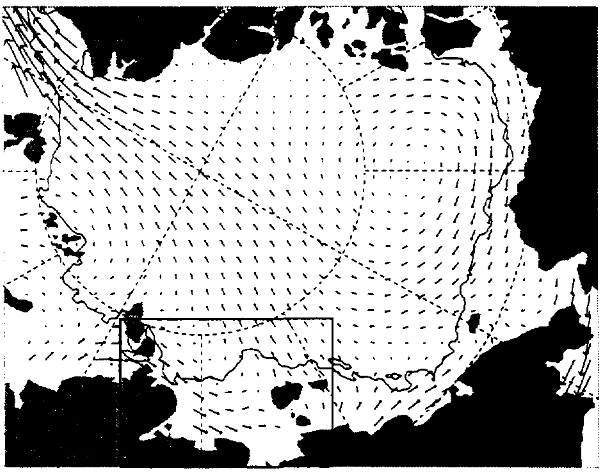

Figure 1. Mean field of ice motion and the mean position of the mid-September (mean minimum) ice edge. The Laptev Sea area is demarcated by the box in the lower part of the figure.

In this study we attempt to characterize the mean and interannual variability of ice production by investigating the winter production and subsequent melt of ice in the Laptev Sea from 1979 through 1992. The general approach is to associate pollution transport with the net exchange of ice area from the Laptev Sea to the perennial ice pack. The primary data sets supporting the study are ice charts, ice motion, and geostrophic wind.

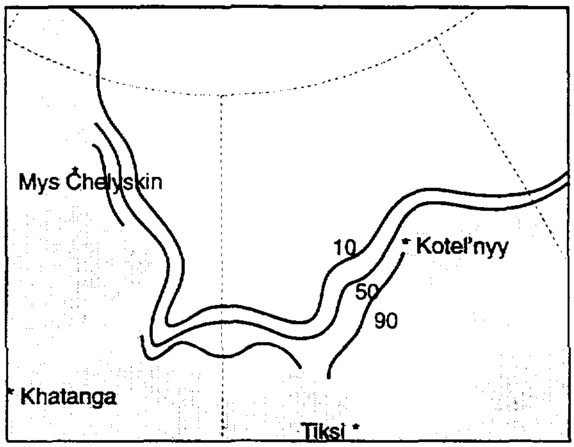

Figure 2. Contours of probability of fast ice during April. The median boundary roughly follows the 20m isobath and is relatively stationary from January through June.

MATERIALS AND METHODS

Mean monthly fields of ice motion were analyzed using observed ice motions from DARMS and Argos buoys in combination with mean monthly fields of pressure (Fig. 1). Ice charts were studied to determine the interannual variability of the fast ice (Fig. 2) and multi-year (MY) ice edges (Fig. 1). Using these ice edges and mean fields of ice motions, we were able to estimate the ice production in the Laptev Sea from 1979 to 1992.

Fast Ice

The term "fast ice" is used to describe that ice cover which is mechanically fastened to the shore or to the sea floor. As can be seen in Figure 2, there is very little spatial variability in the interannual fast ice edges. The median boundary of the fast ice edge roughly follows the 20m isobath. The fast ice reaches its full winter time extent by December and is relatively stationary from January through June.

October Ice

By mid-October freezing conditions predominate throughout the Laptev Sea. The area shoreward of the previous September main ice edge is covered by a new generation ice having thickness of 20-30 cm. For our study, we have defined three areas of October Ice Production, 1.) the Deep Water Area defined by the MY ice edge and the 50m isobath, 2.) the Shallow Water Area defined by the 50m isobath and the Fast Ice Edge, and 3.) the Very Shallow/Fast Ice Area. The Deep Water October Ice is not considered a candidate for long range transport of pollutants since we assume that the surface waters beyond the 50m isobath have low concentrations of suspended sediment, and neither is the Very Shallow / Fast Ice since this ice tends to melt in place during the fast spring melt. This leaves only the shallow water area as a possible source for long range transport of pollutants. This shallow water production area is 150,000km^2.

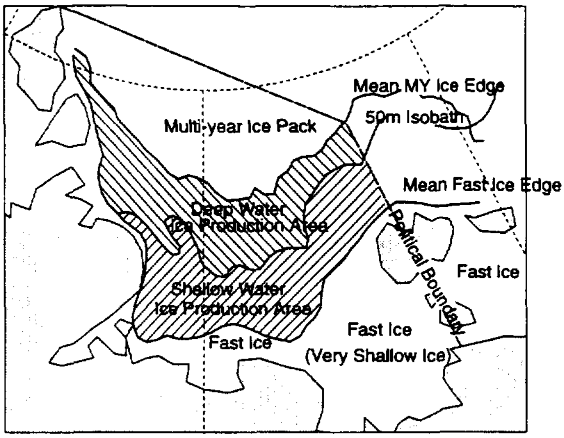

Figure 3. Mean October Ice Production Areas

Winter Flaw Lead Ice

A persistent feature of winter ice conditions in the Laptev Sea is the coastal polynya (or flaw lead) formed at the edge of the fast edge boundary. Under offshore wind the drift ice moves away from the fast ice boundary exposing the ocean to the winter atmosphere. The width of open water can range from a few hundred meters up to several kilometers. Northward of the open water a semi consolidated slurry of nilas and slush ice may extend for 10-15 km from the fast ice boundary. This band of exposed water and rapidly forming ice is often seen extending for 1800 km along the fast ice boundary.

The combination of frazil ice formation, rapidly forming new ice, and turbulently mixed shallow water leads to the incorporation of sediment and pollutants into the ice cover. For this study we assume that all new ice cover formed in the Laptev Sea from November through April is created in the winter flaw lead.

As a simple illustration of new ice cover production we consider the idealized case in which the mean field of winter ice motion advects the newly formed ice away from the flaw lead. First consider the trajectory of a single parcel of ice starting at 74.3N,125E on 1 November. Figure 4 shows monthly positions along the trajectory, beginning on 1 November and ending on 1 May. The net distance traveled is about 400 km. Now consider the trajectory of the locus of ice parcels originating along the position of the mean fast ice boundary on 1 November. The successive monthly positions of these ice parcels define a sequence of lines; adjacent pairs of lines delineate monthly ice motion.

All ice particles sharing the same line were created in the flaw lead at the same time. In this simple example the field of ice motion is held constant, so there is no difference between the November motion of particles initiated on the fast ice boundary and the April motion of particles initiated on the fast ice boundary.

As an illustration of annual ice production in the winter flaw lead, the example above points out a minor technicality. How can there be a November production of flaw lead ice when the stationary flaw lead is not established until late December? The answer is - There is no November ice produced along the flaw lead; the apparent production is due to advection of very shallow water October ice across the yet to be established fast ice boundary. So, the ice labeled November (and a portion of the ice labeled December) is really October ice. This misrepresentation is probably not important to either the ice production or the pollution incorporation argument, because, by the end of April there is little difference in thickness or other physical properties between October ice and November ice. Furthermore, the "mislabelled" November ice was probably formed under very similar conditions as is found near the flaw lead, so pollution and sediment loads should be similar.

Also shown in Figure 4 is the mean motion of the MY ice edge from its average October position to its position on 1 May. The October ice formed between the 20 m isobath and MY ice edge is now bounded by the MY pack and the flaw lead ice.

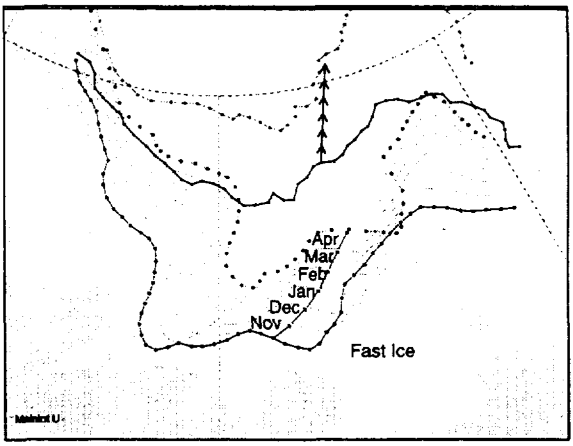

Figure 4. Idealized model of flaw lead production of ice during winter.

RESULTS

Total ice area production in the Laptev Sea may be taken as the sum of the ice produced during freeze-up, the ice produced in the winter flaw lead, and the ice produced in the fast ice zones. An alternative is to partition ice production by the water depth- ice created in water deeper than 50 m; ice produced between the 20 m and 50 m isobath; and ice produced in the very shallow regions. We hypothesize that ice produced between the 20 m and 50 m isobath is the agent for the long range.

We now separate shallow water ice production into three categories: October ice created between the 20 m and 50 m isobaths; ice cover created in the flaw lead, November through January; and ice cover created in the flaw lead, February through April. The total winter production of ice cover is given by the sum of the three categories. The surviving winter production only considers that ice formed from October through January. Shallow water ice production and melt determined from studies of the ice charts, and yearly ice motion is summarized in Table 1.

Table 1: Shallow Water Production of Ice (km^2)

Year	October	Winter	Total	Surviving
1979	132,000	233,000	365,000	245,000
1980	132,000	362,000	494,000	305,000
1981	147,000	237,000	384,000	246,000
1982	147,000	183,000	330,000	226,000
1983	147,000	280,000	427,000	324,000
1984	147,000	88,000	235,000	172,000

Table 1: Shallow Water Production of Ice (km^2)

Year	October	Winter	Total	Surviving
1985	141,000	293,000	434,000	270,000
1986	147,000	293,000	440,000	325,000
1987	99,000	220,000	319,000	225,000
1988	129,000	310,000	439,000	333,000
1989	63,000	162,000	225,000	128,000
1990	147,000	186,000	333,000	270,000
1991	140,000	243,000	283,000	270,000
1992	111,000	314,000	425,000	251,000
Mean	131,000	243,000	373,000	256,000

In a typical winter season ice is produced in the Laptev Sea by the October freeze up of the summer open water, ice free area and then by the winter flaw lead production of ice from November through May, but only ice formed in shallow water of less than 50m can possibly pick up pollutants and as Nikolaeva, *et al.*, 1970 found, ice formed after February 1 typically does not survive the summer melt and thus can not be considered a candidate for long range transport of pollutants. We found that the mean annual shallow water production rates are 131,000km^2 for october and 243,000km^2 from the winter flaw lead. About 117,000km^2 of this ice fails to survive the summer melt, leaving 256,000km^2 to be exported into the perennial ice pack, but eventually melt in the North Atlantic. Due to stresses in the ice, we estimate that this area of originating from the shallow water portion of the Laptev Sea, is reduced to account for 20% of the ice cover fluxing through the Fram Strait.

ACKNOWLEDGEMENT

Support for this research was provided by the Arctic Nuclear Waste Assessment Program of the U.S. Office of Naval Research.

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