Incorporation of sediments into sea ice in coastal polynyas in the Kara sea

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Abstract

Estimates for the mass of ice rafted sediments in coastal polynyas in the Kara Sea are given by use of a vertical numerical model. The incorporation of sediments take place as frazil ice crystals form and aggregate with sediments in suspension.

Three different cases are considered: i) The autumn freeze up where there is no sea ice initially, ii) A mean monthly coastal polynya based on monthly SSMI derived ice drift, and iii) A case study in January - March 1994 with 3 day means of ice drift from SAR images. The model is forced by observed air temperature and wind speed from nearby meteorological stations.

Results indicate that the process is capable incorporating about 10 % of the annual sediment discharge during an average winter, and that episodes with values substantially higher may take place. Several years of sediment discharge may be incorporated during an autumn freeze under high winds, and a mean monthly mass of ice rafted sediments may be incorporated during 3 days given a high northwards speed of the ice cover.

1 Introduction

Recent field observations points to the Kara Sea as a source for ice rafted sediments (IRS) with above background concentrations of ^{137} Cs (Cesium) (Meese et al. 1997) and ^{239} Pu (Plutonium) (Landa et al. 1998). The samples analysed in these studies were taken in the central Arctic Ocean and north of Svalbard, indicating the long range and non diffusive transport mechanism

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IRS can be. Levels of heavy metals and organochlorines in IRS from the Kara Sea are at the same level as for local sediments, indicating the same mechanism for these contaminants (Evenset et al. 1998). How efficient the long range transport of contaminants by Arctic sea can be in general has been discussed by Pfirman et al. (1995), and for the Kara Sea in special by Pfirman et al. (1997).

Several studies document how efficient adsorption (bounding) of different contaminants to sediments may be. This is efficient for several radio nuclides; ^{137} Cs (Oughton et al. 1997), ^{210} Pb, and ^{241} Am (Fuhrmann et al. 1997), heavy metals; Hg (Mercury) (Coquery et al. 1995), As (Arsenic) (Loring et al. 1998), and several Persistent organic pollutants (POP) like PCB, PAH, HCB, and DDT (Stumm and Morgan 1981). The adsorption varies for different contaminants, and also for parameters like the sediment composition (Carroll et al. 1997).

The potential for long range transport of these contaminants is therefore proportional to the concentrations of IRS, usually in the range 5 - 500 mg/l (mass of sediments per litre of melted ice) (Reimnitz et al. 1993,Eicken et al. 1995, Dethleff et al. 1998). Extreme values reach from none as the obvious lower limit to values as high as 2650 mg/l (Smedsrud and Eicken 2000). Levels are very patchy in nature, and most entrainment processes are probably governed by episodic events, according to most researchers. Average values are therefore only of local and temporal validity. A mean value for "dirty ice" in the Laptev Sea from August-September 1993 was found to be 156 mg/l (Eicken et al. 1995), and for the northern Kara Sea the "dirty ice" average was found to be 328.4 mg/l in August 1994 (Smedsrud and Eicken 2000). A study from south in the Kara Sea in April (winter season),when most of the entrainment is taking place, shows values between 2 - 140 mg/l, with an average of 9.9 mg/l (Dethleff et al. 1998).

The range in total annual sea ice export from the Kara Sea is $155-458\times 10^3$ km^2 (Pfirman et al. 1997). Estimates based on atmospheric forcing give an export of $\sim 278\times 10^3$ km^2 of sea ice to the Barents Sea, the rest enters the Transpolar drift (Gregor et al. 1998). Obviously, the ice grown in the Kara Sea holds a potential for rapid transport of contaminants to the Barents Sea, as well as the Arctic Ocean in general.

A general presentation of the Kara Sea is given in Paper 5, Smedsrud (2000), section 2. The mean atmospheric and oceanographic conditions are described, as well as the topography and geographical details of the Kara Shelf. Figure 1 shows the Kara Sea with surrounding islands, and is shown for later reference to the different studies described in this report.

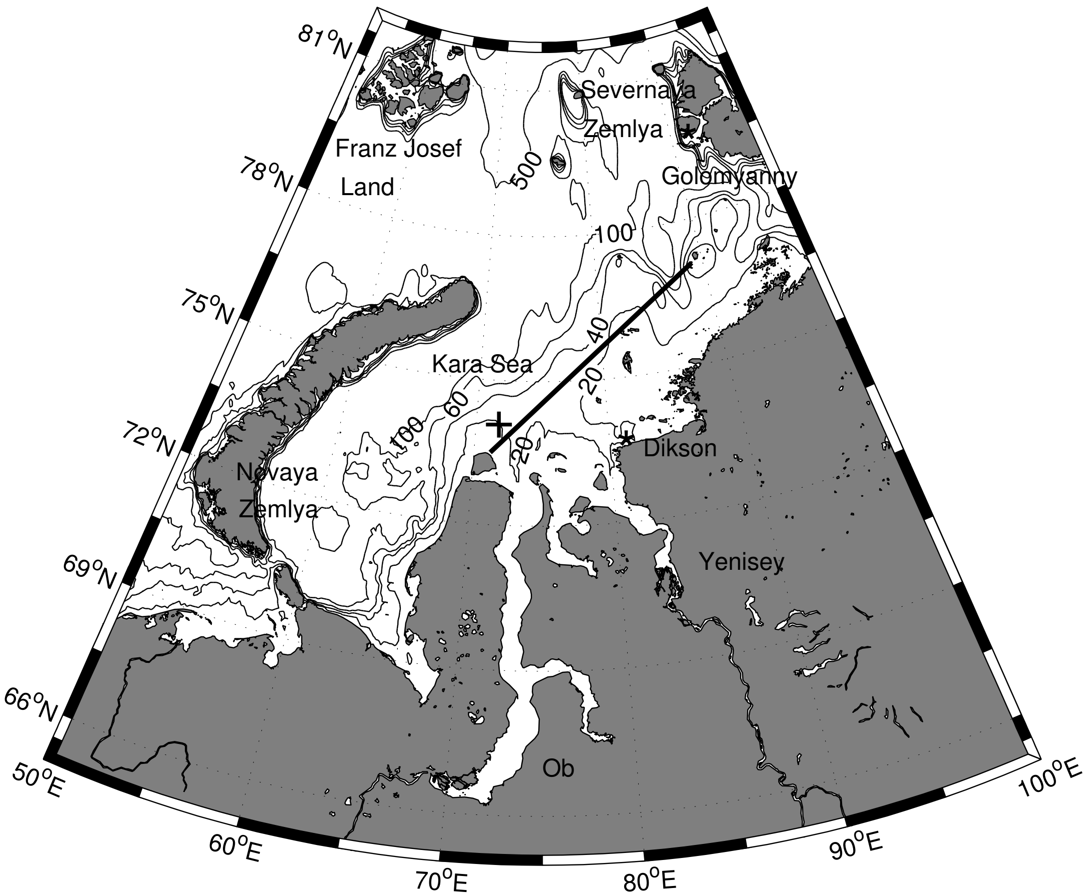

Figure 1: A map of the Kara Sea showing positions of the meteorological stations (*) and the transect used for the monthly mean polynya calculations, as well as a central point in the SAR images analysed north of the Ob estuary (+).

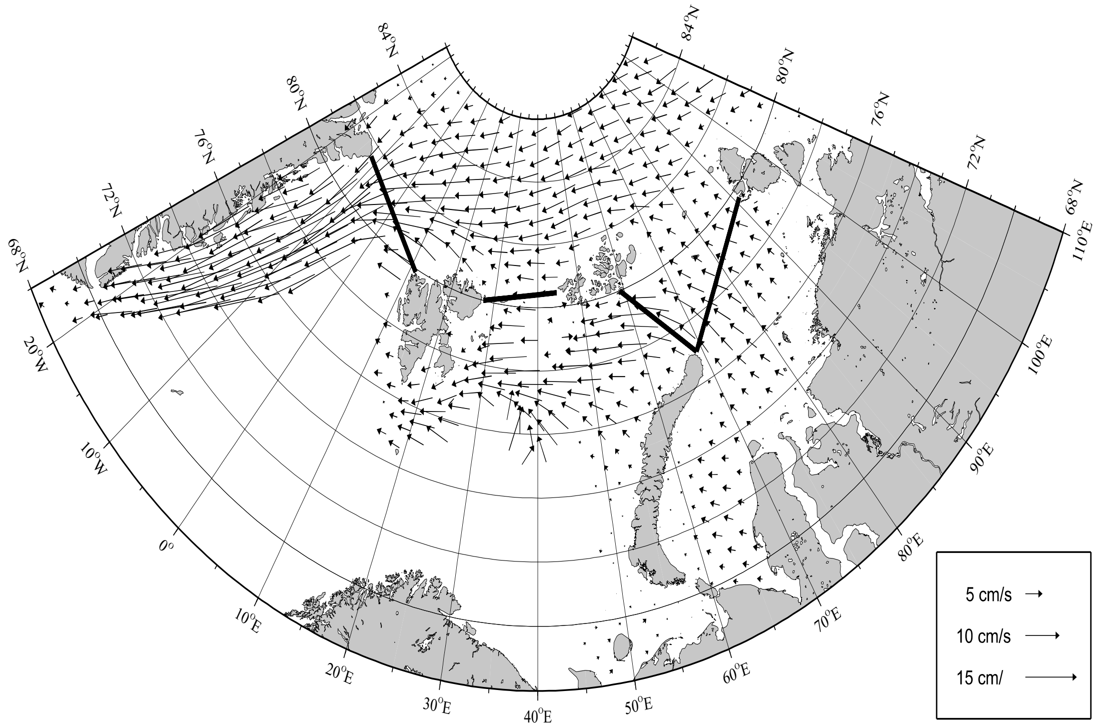

Figure 2: SSM/I derived monthly mean ice drift, January 1994. The area flux has been calculated across the given transects (Pavlova, pers. com. 1999)

Based on passive microwave data from satellites, new estimates of the ice flux variability are currently in progress (Pavlova pers. com. 2000). An example of the calculated drift is shown in figure 2. The monthly mean area flux is calculated for the transects in the period 1988 - 1994. The new results indicate that the annual flux from the Kara Sea westwards to the Barents Sea is $\sim 87 \times 10^3$ km^2, lower than the earlier estimates.

Northwards from the Kara Sea the annual flux is $\sim 243 \times 10^3$ km^2, and a large portion of this probably enters the Barents Sea from the north later as a part of the $\sim 116 \times 10^3$ km^2 annual flux there.

The confidence in the sea ice drift estimates is growing. This means that our understanding of the sediment entrainment into sea ice has become one of the less known processes in the contaminant-transport scenario.

Most of the IRS are found either on the sea ice surface, or within granular sea ice. Granular ice is clearly distinguished by the granular form of the ice crystals, in comparison to the much longer ice crystals found in the other main type of sea ice - congelation ice (Eicken et al. 1995, Smedsrud and

Eicken 2000). Congelation ice forms through congealing of (sea) water at the ice-water interface on an already existing floe. Granular ice has first frozen as frazil, separate suspended ice crystals in turbulent water at the freezing point. Granular ice with IRS is by many researchers assumed to be a result of sediment entrainment during formation of frazil ice in a coastal polynya, described as suspension freezing (Reimnitz et al. 1992). Suspension freezing includes both scavenging of suspended sediment by frazil ice (Osterkamp and Gosink 1984), and formation of anchor ice on the bottom. This anchor ice may rice with its attached sediments, and be buoyant enough to bring coarser material up to the surface.

Different approaches has been tried to model the suspension freezing process numerically. Two different vertical models have been developed and they both show the temporal nature of the process (Sherwood 2000, Eidsvik 1999). The efficiency of the aggregation (or coagulation) has in addition been estimated using a simple box model based on classic aggregation theory, and data from a laboratory experiment (Smedsrud 1998). These models have a very simple approach with modelling frazil ice growth and concentration in line with Omstedt (1985).

The aggregation process was verified to work over time scales $\sim$ 24 hours, and its efficiency was empirically indicated by laboratory experiments described in Paper 3, Smedsrud (2000). The size distributions for sediments and frazil ice were also documented. These experiments proved that the grown ice could be enriched up to 10 times compared to the initial SPM (Suspended Particulate Matter).

2 The Frazil and sediment model

Sherwood (2000) combined known models for frazil ice and sediment concentrations into a new 1-D (vertical) model. Results were presented for simultaneous concentrations of frazil ice and sediments at given locations in the Beaufort and Kara Seas, forced by typical local surface winds, and air temperatures.

In this project the Sherwood (2000) model was developed further to include frazil ice size dynamics and sediment size based aggregation. The model was compared and tuned to the experimental results in Paper 3, (Smedsrud 2000), and has received the name Frasemo (Frazil ice and sediment model).

Frasemo is written in Fortran 77, and the newest version (March 2000) is installed at the Norwegian Polar Institute in Tromsø. It consists of one file of about 3000 lines, and may be run on any platform.

All input and output is in ascii-formate, and to run the model the researcher needs to specify only three input files in a directory below the executable version.

- An initial file called "onrinit.dat". The columns (1) - (16) give the initial values for the following; (1) vertical elevation above bottom [m], (2) the temperature [°C], (3) salinity [psu], (4) eddy viscosity [m^2/s], (5) cross shore horizontal speed [m/s], (6) along shore horizontal speed [m/s], (7) - (11) the volume concentration of ice crystals (5 classes), and (12) - (16) sediments (5 classes).
- A forcing file called "onrforce.dat". The columns (1) - (5) is a time series; (1) time [seconds], (2) wind across shore [m/s], (3) wind along shore [m/s], (4) Air temperature [[° Celsius], and (5) volume flux of snow divided by area [m/s].
- A parameter file called "onrparam.dat", where all the different options may be specified.

Frasemo outputs to three different files. A time series is created for surface values and integrated values "onrts.dat". Profile are written at specified time steps (normally each hour) to the file "onrprof.dat" for all depth dependent values. In addition is all the aggregation products written to a separate file "onragg.dat" similar to the "onrprof.dat".

A set of Matlab files exists to illustrate model results and are provided with the Fortran code. As an example of the model results, the base case from the autumn freeze up study is provided, called "E30m18ms".

Future activities may benefit from the vertical model to study small scale vertical mixing and concentrations. Only minor revision will be needed to model entrainment of biota into an ice cover with the same kind of entrainment process. This process is discussed by Ackley and Sullivan (1994) for Antarctic waters.

Frasemo was initiated when Christopher R. Sherwood worked at at the Office of Naval Research (ONR), and because of this the first name of the model was ONRDP (DP for double precision Fortran variables).

Several new processes has been added to Frasemo during this project;

- Verification of classic aggregation theory for frazil-sediment aggregation, based on laboratory experiments.
- Sediment size based aggregation efficiencies. The model was compared and tuned to the measured experimental values of IRS up to 200 mg/l.
- Adding a size spectra for frazil ice crystals, ranging from 1 mm to 1 cm in radius, and for sediments, ranging from 1 - 40 μm in radius.
- Differential growth for the different sizes of frazil crystals (small crystals grows faster) (Hammar and Shen 1995).
- Secondary nucleation (production of new small crystals by collision), based on turbulence intensity (dissipation rate), and the number density of frazil crystals (Svensson and Omstedt 1998).
- Varying rise velocities for different sizes of frazil (Gosink and Osterkamp 1983), sediment, and the aggregated (hybrid) particles.
- Formation of anchor ice where frazil ice become negatively buoyant and sink towards the bottom.
- Frasemo is currently believed to describe the transition from suspended frazil to slush at a concentration of 200 g/l. The onward transition to a congealed granular ice cover with IRS is complicated and a new proposal, coordinated by Reinert Korsnes at the Norwegian Polar Institute, will address this question further. .

2.1 Entrainment during the autumn freeze up

As there are no in situ field observations of the sediment entrainment process(es), description of the entrainment processes may only be given by use of a numerical model. These models are based on laboratory experiments, and field data.

Frasemo is applied to the Kara Shelf during the autumn freeze-up in a number of different runs. Most of them are described in Paper 5, Smedsrud (2000). The model is forced by a range in wind speeds, and initiated with different vertical salinity stratifications for the depth intervals 0-20 m, 20-40m, and 40-60 m (figure 1). Results indicate that the scavenging process may be a significant contribution to the mass of IRS in sea ice in the Kara Sea.

Table 1: Calculated IRS concentrations [ton/km^2] after 48 hours in turbid sea ice for different water columns and wind speeds on the Kara Shelf during the autumn freeze up. Area is given in percent of the total 216 850 km^2 for each column. Cases where all frazil ice become negatively buoyant and tends to sink are indicated with (-). Total values are given in tons.

	E 10m	E 30m	E 50m	S 10m	S 30m	S 50m	Total
Area [%]	21.5	15.2	5.5	32.9	16.0	8.9	100.0
6 m/s	4.3	3.6	0.6	1.4	1.1	0.3	0.5×10^6
12 m/s	2104.6	12.7	3.4	3006.6	4.7	1.5	313.3×10^6
18 m/s	-	33.2	7.4	-	19.1	3.2	1.9×10^6
24 m/s	-	4715.8	10.6	-	9460.7	4.6	483.9×10^6
30 m/s	-	4435.9	12.4	-	7487.2	79.0	407.7×10^6

Infact, as shown in table 1 the total mass of IRS become higher than the annual river supply of sediment of 29×10^6 tons, if an autumn freeze-up occurs during a strong wind episode.

2.2 Entrainment in the mean winter polynya

The IRS mass entrained into sea ice during the winter will, to a large extent, be ruled by the sea ice cover itself. This is because the sea ice prohibits strong fluxes of both heat and momentum. The advection of the ice cover, and thereby creation of large leads or polynyas, is again controlled by the wind to a first approximation. The fast ice forms after the autumn freeze-up, and covers the shallow areas of the shelf out to approximately the 20 m isobath (Dmitrenko et al. 1998). A Polynya will be situated seaward of the fast ice, given a northward advection of sea ice on the Kara Shelf (Pavlov and Pfirman 1995).

The Polynya is an area where heat fluxes and turbulence can become so high that frazil ice is produced, and sediments may be efficiently resuspended. Tidal currents might add in maintaining a low, but steady, concentration of SPM in the surface layer. In addition the river supply is maintained all year round, and probably adds a substantial mass of sediments to the upper layer directly, also during the winter.

A crude estimate of the polynya area can be calculated using the northward speed of the ice cover. The monthly mean speed for the ice cover normal to the coast, U_i, has been estimated from the SSM/I satellite data (Pavlova, pers. com.) as illustrated in figure 2. The transect used is shown in figure 1.

Table 2: Monthly mean values on the Kara Shelf. Air temperature (T_a) [°C], wind speed (U_a) [m/s], ice drift (U_i) [km/day], slush formation time (t_{slush}) [hours], Width of the polynya (W_p) [km], ice rafted sediment concentration of the slush (IRS) [ton/km^2], and total sediment in sea ice values for the given months (Total) [tons].

	T_a	U_a	U_i	t_{slush}	W_p	IRS	Total
October	-9.6	6.9	1.12	44	2.05	3.8	80.9×10^3
November	-19.2	6.5	1.03	22	0.94	2.0	39.1×10^3
December	-23.5	7.4	1.33	15	0.83	1.4	36.2×10^3
January	-26.8	7.1	1.41	14	0.82	1.4	36.9×10^3
February	-26.9	7.1	0.88	14	0.51	1.4	23.0×10^3
March	-26.2	6.7	0.45	15	0.28	1.4	11.9×10^3
April	-19.2	6.5	0.36	22	0.33	2.0	13.5×10^3
May	-9.2	6.1	0.49	50	1.02	3.6	33.6×10^3

Monthly mean speeds are shown in table 2 together with the other monthly mean data used to force Frasemo.

In table 2 T_a and U_a is the mean between the two meteorological stations at Dikson and Golomyanny (Radionov 1999, Svyaschennikov 1999). U_i is the mean sea ice drift perpendicular to the transect in figure 1. t_{slush} is the time to reach an ice concentration og 100 g/l in the upper cell in Frasemo using the given T_a and U_a. W_p is the width of the polynya perpendicular to the transect, defined by surface ice concentrations less than 100 g/l. IRS is the ice rafted sediment concentration in the surface slush at t_{slush}. The total value is the monthly integrated value for each month. W_p is calculated using U_i and t_{slush}. In this way a steady state situation is described with a northward advection of sea ice, and a constant W_p for each month, used as the size of the fetch in Frasemo.

The polynya is created roughly along the 635 km transect, and over a water column of about 20 m. The stratification used is 17.7 psu in the upper mixed layer of 8 m, and a linear increase to 31.6 psu at the bottom. This is a "best guess" stratification for October and similar to the 'E30m' cases described in Paper 5 (Smedsrud 2000). Initial temperatures are set at the in situ freezing point, and initial SPM is 2 mg/l in the upper layer.

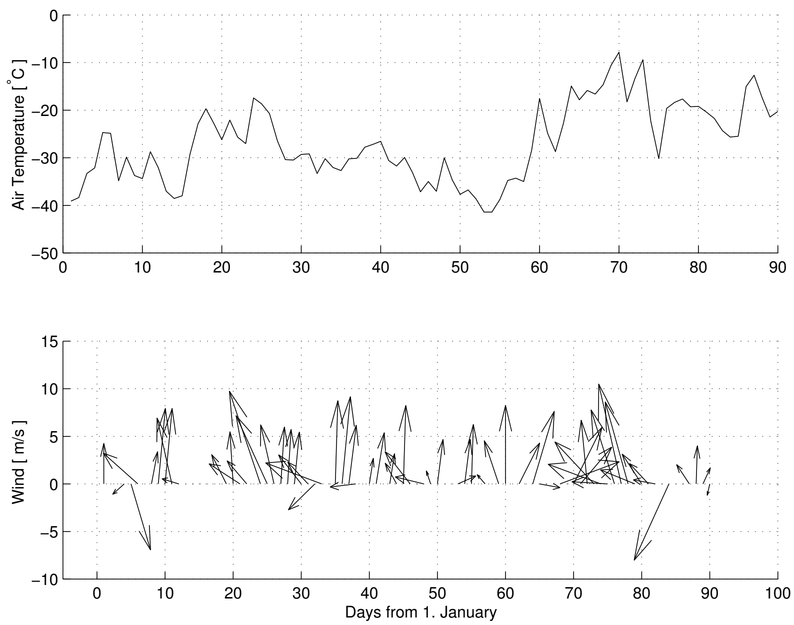

Figure 3: Dayly mean values from Dikson meteorological station from 1. January 1994 until 30. March (Svyaschennikov pers. com. 2000).

The IRS is found in the upper grid point only, and the total value is calculated using the Polynya area (635 W_p [km^2]) and the constant IRS production rate (IRS / t_{slush}) yielding a total monthly value. The overall IRS value in a winter thus becomes 265×10^3 tons of sediment, or 9.1 % of the yearly discharge from Ob and Yenisey.

2.3 Entrainment in the Ob polynya

This is a case study to investigate the influence of a time varying northward flux of sea ice and atmospheric forcing. Data from Dikson meteorological station are used in this part, and the station is only about 250 km away from the area covered by the satellite. The sea ice drift is calculated based on SAR images taken three days apart by a method described in Korsnes (1993).

For the months January to March in 1994 the range in atmospheric forcing is shown in figure 3. The mean T_a was -26.9 °C, and for U_a the range was 2 to 13 m/s.

An example of the drift is shown in figure 4, and illustrates that the drift can be quite uniform, and have a northward velocity up to 20 km/day.

The ice drift is driven mainly by the wind, and the simple parameterisa-

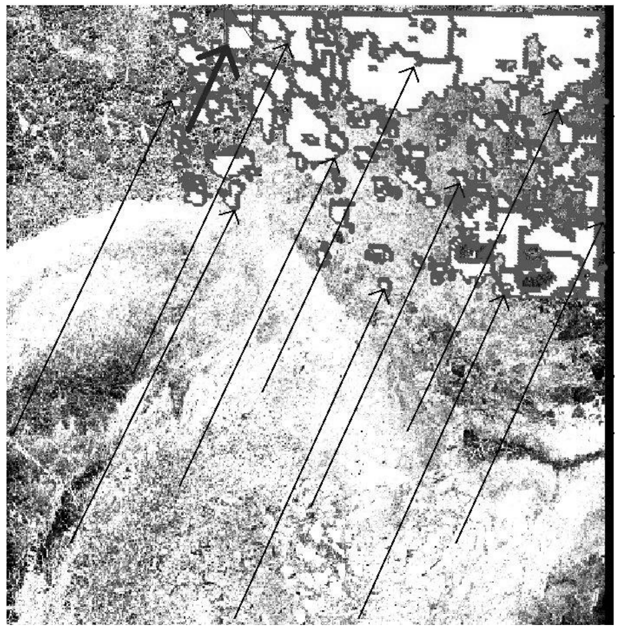

Figure 4: An example of the calculated ice drift from 17. to 20. March 1994 (days 76-79). The thick arrow is pointing northwards, and the ice drift velocities are close to 20 km/day (Korsnes pers. com. 2000).

tion that the drift is 3 % of the wind speed, and 22 ° to the right matches the 3 month time series quite well as shown in figure 5. The 3 day SAR drift is higher than the monthly means in table 2. The monthly mean SSMI-deduced drift for 1994 is 1.56 km/day, 0.40 km/day, and 0.96 km/day for January - March respectively. For the SAR-deduced drift the comparable values are 2.37 km/day, 3.00 km/day, and 3.34 km/day, about a factor of three larger. These should not be directly compared as the SAR-image covers an area of 100 km^2, and the SSMI-images covers the Kara Sea in full.

For the Frasemo runs in relation to the SAR images, 3-day means of the atmospheric conditions shown in figure 3 (T_a and U_a) were used as forcing. The range for the 3-day mean values of T_a is -40 to -13 °C, and for U_a 3.0 to 8.5 m/s. Model initialisation was chosen equal to the "Estuary" E30m depth cases described in Paper 5 (Smedsrud 2000), and the fetch was set to 5 km for all runs.

As in the case for the monthly mean polynya, the polynya width is calculated using the observed SAR-drift U_i, and t_{slush}, thus using a surface ice concentration of 100 g/l as the outer edge of the polynya. Within the given forcing t_{slush} is found to have a close to linear dependency on T_a as shown in

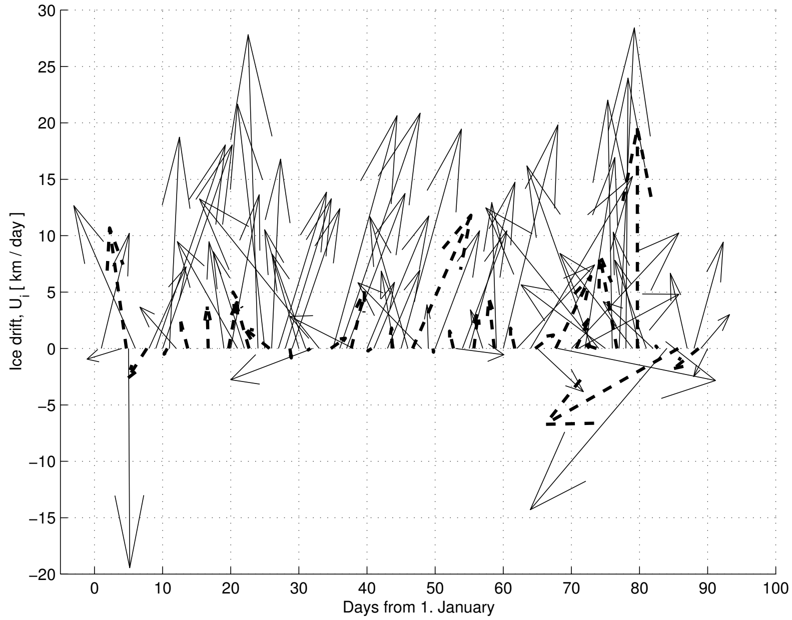

Figure 5: Ice drift, U_i north of the Ob estuary in the Kara Sea. The thin arrows are calculated dayly ice drift from wind data at Dikson meteorological station (Svyaschennikov pers. com. 2000), and the thick and dashed arrows are calculated 3-day average ice drift from SAR images (Korsnes pers. com. 2000). A central point of the SAR images is shown in figure 1.

figure 6 a).

The maximum polynya width W_p over the 3-day period then becomes 15.8 km, and in 10 of 29 periods there is no polynya due to a southwards advection of the sea ice, or no advection at all. The length of the Polynya is at least 100 km, and 200 km is used here, but it might be significantly longer than this.

For each 3-day period the t_{slush} and IRS are calculated by linear interpolation between chosen runs using the range in forcing. The calculated range for IRS at t_{slush} is 0.4 to 3.2 ton/km^2.

The $\frac{IRS}{t_{slush}}$ is the IRS production rate [ton / km^{2}h], and is found to be quite linear with wind speed for the above range in U_a and T_a. Figure 6 b) shows this relationship, and is used to calculate entrainment in each of the 3-day periods.

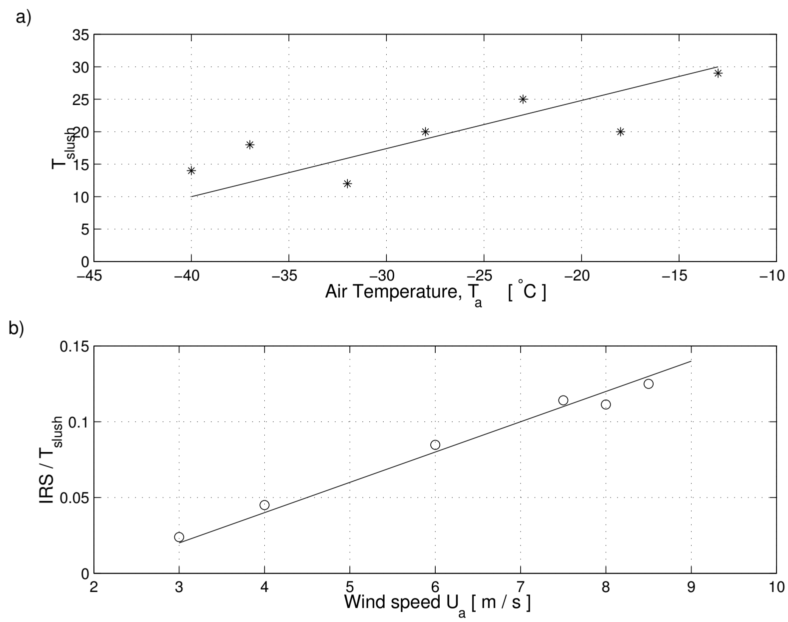

Figure 6: a) Time until a surface ice concentration of 100 g/l is reached in Frasemo (t_{slush}) as a function of the mean air temperature (T_a). b) The IRS production rate as a function of wind speed for the range of 3-day mean winds during January - March 1994.

The total mass of sediment incorporated during the 3 day period (72 hours) thus becomes;

$$72\ \frac{IRS}{t_{slush}}\ U_i\ 200\ t_{slush} \qquad [\text{ton}] \tag{1}$$

Equation (1) consist of two different parts physically. The IRS produced during the 3-day period is simply the IRS production rate multiplied with time. This takes place all over the polynya area, which is the product of the ice drift (U_i), the polynya length, and t_{slush}.

In the period January - March 1994 the total incorporated IRS is 92.6×10^3 tons. This is about 30 % larger than the sum of the mean values for these three months from table 2 - 71.8×10^3. As these cover only 200 km along the 635 km long transect in figure 1, they indicate a more efficient entrainment when using a higher time resolution. In addition this area is directly outside the Ob estuary where sediments most probably are added to the upper layer continuously during the winter.

The range in the 3-day non zero values is 0.6 to 30.5 $\times$ 10^3 tons, with most values between 2 and 10 $\times 10^3$ tons. The maximum value is from days 76-79, with the ice drift shown in figure 4. This is about the size of the mean monthly values given in table 2, and shows that the incorporation process might be very effective in situations with a high speed in the northward advection of sea ice.

3 Concluding remarks

Because there is no SPM and stratification data for October - March, basic assumptions about these parameters are crucial to the given estimates. As long as the stratification stay intact this is actually not that important, but in some cases, especially in shallow areas, the stratification might mix away, and then much more IRS will be produced (Paper 5, Smedsrud 2000). The assumption of 2 mg/l of SPM in the upper layer is probably the most important and not validated assumption, and if the upper layer SPM decreases significantly during the winter months, this will lead to lower IRS values.

These new estimate are based on the following assumptions;

(a) There must be enough small sediments (clay and fine silt) on the bottom. At some stage there is no more of these, and only larger grains are left on the bottom, and these are harder to resuspend. (b) There must also be a small resuspension by tidal currents, supplying new upper layer SPM when the IRS is removed by advection. (c) There might also be other efficient sediment entrainment processes contributing significantly to the overall flux of sediments into the sea ice.

4 Publications

This project has supported the following publications apart from this report;

- A report describing sediment laden sea ice sampled on the Kara self was finally finished (Smedsrud and Eicken 2000).
- Estimates of the sediment incorporation during the autumn freeze-up forced by different wind episodes (Paper 5, Smedsrud 2000).
- A multi disciplinary paper is in progress. This paper will cover the ice/sediment/contaminant processes, and estimates of the Kara Sea as a source of contaminated sediments to the Arctic ocean will be given. This paper will incorporate results from the above publications and this report (Carroll, Korsnes, Pavlov, Pavlova and Smedsrud).

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